# Millimeter-Wave Drivers for Future Linear Colliders

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## Abstract

The challenges for high-gradient mm-wave driven colliders are reviewed. Requirements on power sources are examined, and a particular tube is considered for illustration. Research topics relevant to a compact 1 GeV linac are noted throughout.

## Introduction

High-energy physics is an experimental science whose reach is limited by its instruments, accelerators[1]. While theorists look toward the 5 TeV frontier[2], the highest energy linear collider, the Stanford Linear Collider (SLC) operates at 0.05 TeV[3]. This disparity reflects the status and the cost of the technology required to meet the collider scalings[4], relations that determine the useful event rate and the accelerator size and power consumption in terms of a couple dozen major machine parameters. It is an open question how or whether a 5 TeV center-of-mass energy machine could be built. There is no technical solution at present for such a machine, but if one could be found, *without* innovation in rf technology, it would be somewhere between 30 and 300 km long[5].

To escape this trend toward great lengths, a high-gradient accelerator is required. For example, a 5 TeV collider fitting on the existing SLAC site, would require a gradient of 1 GeV/m or more. Yet it is impossible to conceive of an electron collider operating with such a gradient relying on known collider technology. Inventions are required. This is why accelerator physicists are interested in the subject.

In this work, we look beyond what can be engineered today, and ask what manner of basic research, in high power microwave systems might be fruitful for the machines of the future.

## Problems of High Gradient

For the linac proper one must account for *trapping*, *breakdown*, and *pulsed heating*. These phenomena are represented quantitatively in Fig. 1. Trapping refers to the acceleration from rest of field-emitted electrons in the structure; trapping fraction is a function of the product $G\lambda$ of the gradient $G$ and the rf wavelength $\lambda$, and may be computed using the binding field expression[6].

Breakdown is a phenomenological problem at present, but it does exhibit a clear pulse length dependence. The curve in Fig. 1 is an extrapolation for pulse length equal to the natural fill-time of a travelling wave structure with attenuation parameter $\tau \sim 1$[7]. Pulsed heating refers to the deposition of heat, by Ohmic loss, in the conducting structure, in a single pulse. For a pulsed temperature rise $\Delta T$, the corresponding gradient is given by,

$$G\left(\frac{GeV}{m}\right) = 0.25\left(\frac{\Delta T}{40°K}\right)^{1/2}\left(\frac{f}{91.4GHz}\right)^{1/4}$$

for idealized rectangular pillbox cells, in a constant gradient structure with attenuation parameter $\tau$=1, and pulse length equal to a fill time.

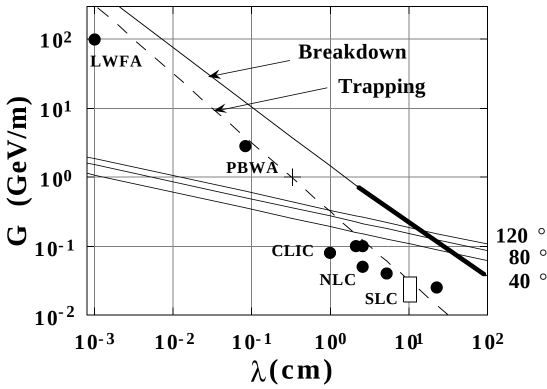

Figure: 1 Current state of the art in high-gradient accelerator research.

Also seen in Fig. 1 are gradients achieved at present, including results for Laser Wakefield Accelerator (LWFA), Plasma Beat-Wave Accelerator (PBWA)[8], and several 0.5TeV collider concepts[9]. The block marked "SLC" extends from 20MV/m as for a typical structure, to 40MV/m as for certain higher gradient structures on the linac.

These scalings imply that *high-gradient* requires *short-wavelength*. For a 1 GeV/m linac, interest begins in the *W-Band*, 75-110GHz. We have added a cross-mark in Fig. 1 as a helpful landmark, corresponding to 1 GeV/m. The corresponding frequency is close to 91.4GHz (3.3mm), the 32nd harmonic of the SLC fundamental frequency, 2.856GHz.

The curves of pulsed temperature rise, in Fig. 1, make clear that such a linac will suffer severe pulsed heating, and the *conventional* travelling wave structure we have taken as our paradigm, will surely fail short of 1 GeV/m. To be sure, it is yet an open question exactly what cyclic pulsed temperature rise a structure can withstand and this is the subject of ongoing research on materials under conditions of high-power pulsed rf[10,11].

In addition, based on experience at longer wavelengths, one would expect to find serious problems with field emission[7]. Even with a very low field enhancement factor of 5, a gradient of 1 GeV/m would produce explosive electron emission. At the same time, there is experimental evidence that field emission is inhibited on short, ns time-scales[12], and this is encouraging insofar as the natural fill time for a W-Band structure is on the order of 10ns, and contemplated exposure times are below 1ns.

## Structures

The scalings for accelerating structures determine the essential considerations for the rf drivers. For copper accelerators, optimized for *[R/Q]*, the scaling for wall quality factor, $Q \propto f^{1/2}$ implies a $Q$ of 2500 at W-Band, and a field decrement time $T$~10ns. Achieving the theoretical $Q$ at W-Band is not taken to be a straightforward matter, as the skin-depth $\delta$~0.2µm and thus surface finish is an issue[13]. Theoretically one may obtain *[R/Q]*~220Ω per cell, but in practice, with realistic beam-passing apertures, *[R/Q]*~90Ω is typical. The corresponding shunt impedance per unit length is 220MΩ/m.

The more serious constraint here is the fabrication tolerance due to random cell-to-cell frequency errors. For a structure of length $L_s$, with group velocity $\beta_g c$, operated at free-space wavelength $\lambda$, these are characterized by

$$\delta \approx \frac{1}{2} \frac{\delta\omega^2}{\omega^2} \frac{\theta}{\beta_g},$$

with $\theta$ the design phase-advance per cell, and $\delta\omega/\omega$ the fractional frequency detuning error of one cell. The loss in no-load voltage for a Gaussian distribution in $\delta$ with rms $\sigma_\delta$ is

$$\frac{\delta V_{NL}}{V_{NL}} \approx -\tfrac{1}{2}(N+1)\sigma_\delta^2,$$

with $N$ the number of cells. This scaling implies a fabrication tolerance at the level of 2µm for a W-Band structure operating within 95% of optimal no-load gradient. Fabrication of such structures at the level of 3.5µm is now an accomplished fact[14]. A related, but less significant constraint is the tolerance on uniform errors. For a uniform fractional deviation $\delta\omega/\omega$ from synchronism, the loss in voltage is given by

$$\frac{\delta V_{NL}}{V_{NL}} \approx -\tfrac{1}{6}\left(2\pi \frac{L_s}{\lambda} \frac{\delta\omega}{\omega} \frac{1}{\beta_g}\right)^2 .$$

This corresponds to a ±10MHz detuning at the 5% level in voltage.

After fabrication, perhaps the most significant objection to short wavelength structures has been wakefields. Wakefields, it has been demonstrated[15] can be dealt with in a constructive fashion, making use of the structure itself as a beam-position monitor, and permitting, in principle, precision structure alignment. The most significant consequences of wakefields at W-Band are a limit to the charge per bunch, to 60pC or less, and the problem of magnetic lattice fabrication[16].

One additional problem arises in planar structures: quadrupole field components[17]. These would likely require dedicated quadrupole-mode structures to compensate their effect on the beam.

Given the inextricable relation between energy storage and bandwidth in a passive structure, together with the high-bandwidth implied by the short pulse needed to control pulsed heating, active elements are of great interest at W-Band. A high-power microwave switch permits resonant energy storage in a large volume, holding down fields and pulsed heating. "*Q*-switching" then permits fields to be discharged in a short, sub-ns time interval, lowering the pulsed heating. As to the choice of photoconductor, diamond looks promising. The thermal conductivity of diamond is 4-5 times that of copper, $\kappa$~1500-2000W/°K-m. The bandgap is 5.4eV, so that excitation by 220nm wavelengths or shorter is required. Experience with diamond as a photo-conductor indicates that fields of order 100MV/m-1000MV/m can be held off on a µs time scale[18].

## Tube Requirements

There are two known, and quite different routes to a power source for a high-gradient mm-wave linac. The first is the class of concepts known as two-beam accelerators[19]. For these concepts one has no particular concern about generating adequate peak power in the appropriate pulse length. Induction linac driven FELs have produced 2GW at wavelengths from 1cm to 2mm[20,21]. Instead research areas of interest concern the more subtle issues of drive-beam stability and phase stability, issues that can be adequately addressed only by the construction and operation of a prototype facility. In fact, facilities exist that have some affinity for such work, for example, The LELIA accelerator, operated at the Centre d'Etudes Scientifiques et Techniques d'Aquitaine (CESTA), generates a 1 kA, 2.2 MeV beam with an 80 nsec (FWHM) pulse length[19].

The second route to high peak power at W-Band is through a modulator-driven amplifier, a "tube". As far as accelerators are concerned, the present state of the art in W-Band tubes is quite similar to that of S-Band tubes in the pre-Mark III days[22]. Commercial amplifiers at W-Band provide at most 3-5 kW[23]. Gyroklystron tube research has resulted in 67 kW power levels [24]. A planar ubitron has been operated at 250 kW[25]. Regardless of the kind of driver, to reach 1 GeV/m, one needs power levels in the range of 200 MW, for pulse lengths of order 10 ns. Two-beam concepts would generate 200MW directly in a 10ns pulse. Tubes on the other hand would be matched to a typical modulator pulse length of 1µs and would generate lower peak powers, but would require pulse compression.

For tubes, a useful research goal, matched to the linac requirements would include 5MW over a 1µs pulse, and an active pulse compression system. As for the tube itself, there are at present four identified lines of research and development: (a) sheet beam klystron (b) sheet beam ubitron (c) gyro-TWT and (d) gyroklystron. Of these, the gyroklystron is perhaps the most advanced [24]. A low-voltage sheet beam klystron, would open up many new possibilities for powering an accelerator [27]. Most prominent among these is the possibility of an integrated power source, as opposed to one high-voltage source followed by power splitting to multiple structures. Given the problems of attenuation (1dB/ft) in a fundamental mode waveguide network, and the complications of transport and mode-conversion in overmoded guide, a source module integrated with the structure is an attractive proposition. Power levels in excess of 100kW and pulse lengths of order a microsecond have been considered for low-voltage (50kV) tubes.

## Planar Ubitron

For illustration, let us consider a particular concept for a 5MW, 1µs tube: a planar ubitron. To save development time and cost, it is desirable to fashion a tube that could run on an existing modulator. This sets the beam voltage in the 500kV range, let us say 480kV. To characterize performance, we employ a dispersion relation including waveguide corrections, space-charge, emittance, energy-spread, and low-energy corrections. To reach a saturation power of 5MW without tapering the wiggler, requires then a beam current of 295A, corresponding to 0.9µperv. The wiggler wavelength should be on the order of 1cm and 1.16 cm appears optimum. One hopes eventually to arrive at a tube adequate as a collider power source, and for this reason, the design should be consistent with the use of permanent magnets, even if the first series of tubes makes use of electromagnets. This constrains the wiggler gap to a small value, 0.4cm. Focusing in the vertical is provided by the wiggler itself. One long quadrupole can be employed to focus in the horizontal, at the expense of some vertical focusing. This magnet layout is similar to that employed for the 30 MW X-Band FEL at KEK[28]. With these parameters, the peak wiggler field on-axis, at optimal gain is 5.1kG, well within the 7kG Halbach limit for NdFeB with Vanadium Permendur. These wiggler parameters are less demanding than those produced by Cheng, *et al.* [25]. Without tapering, the signal saturates in 60cm, with 1kW input.

The gun for such a tube has never been designed, and thus is a prominent research problem. It is likewise prominent in the sheet-beam klystron line of development. Needless to say, long-lived cathodes with much higher loading would be quite helpful for such devices. Leaving a 50% beam-clearance in height and width, the current density in the wiggler is then 750A/cm$^2$ [15]. At 10A/cm$^2$ at the cathode, this would require 75x convergence, *i.e.*, convergence in both planes, and therefore, 3D gun design, a challenging problem. If we ask for a very ambitious cathode loading of 100 A/cm$^2$, the required convergence is *x* 7.5, and the gun design could approach that of a section of a cylindrical diode; in this case avoidance of large fields and gun arcing will be a concern.

To inhibit tube oscillation, a high power driver would be quite helpful. With 1kW input, and gain of 37dB, the tube becomes unstable against oscillations at a VSWR of 1.03 at the output. This highlights the fact that there are actually two categories of tube development required, the high-power amplifier and the driver itself. Commericial drivers are not only too expensive, they are close to inadequate.

Other features to be investigated for this tube are: (a)beam transport (b)beam collection (c)output coupling and (d)the gun. Beam transport is being modelled with a three-dimensional particle in-cell simulation. Beam collection in the first tube, at low repetition rate (10Hz) could simply amount to the dispersal of the beam on the vertical waveguide walls, after the wiggler exit, over the natural 5cm space-charge spreading length of the beam. Output coupling from TE$_{01}$ in overmoded guide, and the matter of a window will be important problems for the output assembly.

It should be emphasized that the immediate purpose of a 5MW tube would not be the powering of an accelerator. Such a tube would be first an invaluable research instrument for studies of field emission, breakdown, and structure damage. It would permit studies of pulse compression in the pulse length range of interest. It would also permit tests of structures at intermediate gradients (100MV/m), without pulse compression. Eventually, however, such a tube could be extended by wiggler tapering to the 20MW level. At such a power level and with an active pulse compression network, and active structures, it is conceivable to power a 1 GeV, 1 meter linac with eight tubes.

## Conclusions

The challenges for a high-gradient mm-wave linac are immense, and this is what makes the field interesting in the first place, to physicists. It has been forty years since the advent of the first 1 GeV linac[5], 220 ft long, powered by 21 home-built klystrons, putting out 20MW---30dB more than anyone thought a klystron could put out a decade before[18]. Perhaps the next wave of power tube development will occur at W-Band.

## Acknowledgments

I am indebted to Perry B. Wilson for his encouragement and many helpful conversations. This work has benefited from numerous conversations with Ping J. Chou, Al Menegat, Glenn Scheitrum, Mike Seidel, Robert H. Siemann, Daryl Sprehn and Xiaoxi Xu. Supported by DOE Contract DE-AC03-76SF00515.

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