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Ultimate Gradient in Solid-State Accelerators

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INTRODUCTION

The microwave accelerator originated with Hansen's notion of a resonant accelerator cavity (1), later incorporated into a multi-cavity concept (2), implemented on the 1-GeV/100-m scale (3), and eventually the 20-GeV/3-km (4) and 50-GeV (5) scales. Today, a 1-TeV/30-km machine is ready for engineering design (6,7). Extension of colliders to higher energy and larger scale is technically feasible, but as discussion continues of the next collider, it is natural to wonder about the *last* collider. Such a machine would be limited, at least, by physical scale, and thus one is led to ask, for a particular operating wavelength, what is the ultimate accelerating gradient? And can it be employed in a collider? Efforts to conceive of a compact collider based on a high-gradient accelerator meet with numerous problems, as abstracted in Fig. 1. In this work we discuss these problems, and efforts in progress to solve them.

To appreciate the difficulties, consider the "conventional" picture of a collider (8), naively extrapolated to 5-TeV center-of-momentum, with an accelerating gradient of 1 GeV/m, and luminosity of 10^{35} cm^{-2} s^{-1}. A synopsis reads something like this. There exists no tube adequate to power such a linac. If one were found, it would melt the accelerator structure surface in a single machine pulse, if operated at a conventional frequency, 10^1 GHz or lower. At high frequencies, even if one could fabricate a small-scale structure, the correspondingly high electromagnetic wakefields would cause the intense beam to self-destruct. Ohmic heating would still be problematic due to the mechanical stress of thermal cycling. At any frequency, the average power requirements would exceed 1 GW, requiring a dedicated power plant. The optical system focusing the beams into collision would exceed 20 km in length, dwarfing the linac. In collision, the beams would destroy each other by means of their intense fields. Realizing that the problems of this collider concept are intractable, one concludes that the ultimate machine must look different.

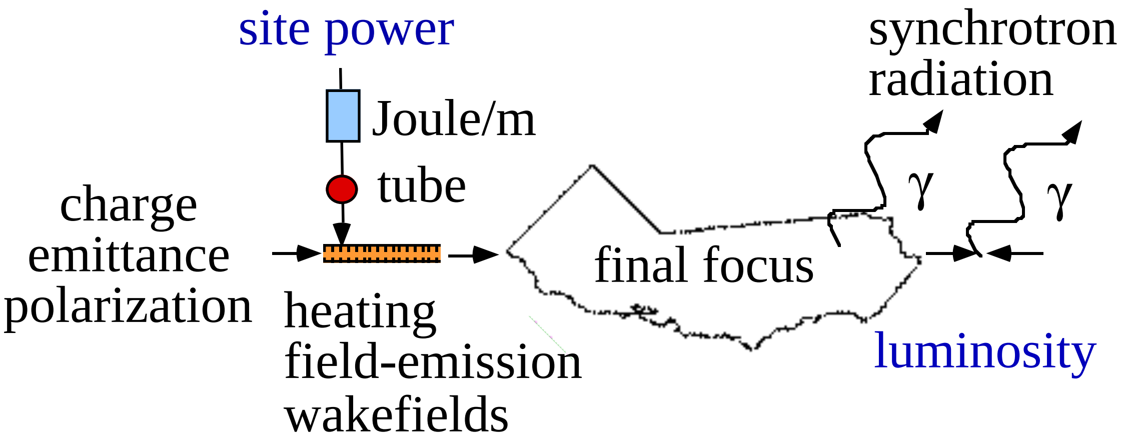

FIGURE 1. Problems for a compact-collider.

Work reported by F. Zimmermann in these proceedings discards the naive collider picture, and suggests that many of the problems arising after the linac may be solvable in principle (9). With his work, one can conceive, for the first time, of a compact final focus, colliding beams in an orderly, efficient fashion. To make a compact collider, one still requires a high-gradient accelerator, and it is here that we will concentrate our attention.

"High-gradient" we will take to mean 1 GeV/m or higher. We will find that high gradients favor high operating frequency, and at 1 GeV/m we will be interested in frequencies in the range of 10^2 GHz and higher. Over the last decade, fabrication of solid-state structures on the corresponding sub-cm scale has become conceivable (10), and we will emphasize these. We pick a particular operating frequency, 91.392 GHz (W-Band), for numerical examples. This frequency is convenient in that it is a harmonic of existing beamlines ("$32 \times$SLAC"), making possible certain tests with beam. Moreover, research in W-Band benefits from years of development for applications throughout society (11), as well as recent scrutiny for accelerator applications (12-14). By our choice of frequency, we do not mean to suggest that higher frequencies are somehow less interesting. In fact application of higher-harmonics (up to 10^2 of the linac fundamental) appears to be essential (9). We keep in mind too that for a particular frequency, there is likely an ultimate energy attainable; thus the implications of high-field research for higher frequencies are of abiding interest.

First we summarize the research problems posed by high-gradient, and then we discuss new structure concepts. We go on to explore a particular structure in detail, with parameters along the lines of (9). We emphasize at the outset that the ultimate gradient in a solid-state collider-linac is unknown; our interest is to identify the research required to determine such a figure experimentally. Eventually one hopes to answer questions along the lines of: How do we build a 1-m linac producing a beam of energy 1 GeV or higher, with a technology appropriate for a 5-TeV, 10^{35} cm^{-2} s^{-1} collider?

PROBLEMS OF HIGH-GRADIENT

There are three problems in operating a solid-state structure with high electric field: the absence of a power source (15), field-emission (16), and pulsed-heating (17). Related empirically to field-emission are the phenomena of trapping and breakdown.

Power source development has a learning curve spanning decades, if previous experience is a guide (18,19). Thus one is delighted to find that the problem of a high-power mm-wave amplifier was solved about a decade ago. Research begun with the two-beam accelerator (TBA) concept (20) found application in plasma-heating, and eventually resulted in demonstration of GW power levels at frequencies up to 140 GHz (21). With such a source one could directly power a W-Band accelerator to gradients in excess of 1 GeV/m. Thus one may declare the problem of a power source solved "in principle". In practice, for the induction-linac TBA, one is interested in additional studies of drive beam-dynamics, phase-stability, output coupling, and overall system efficiency and reliability (15,22). Henke has proposed a beat-wave coupled TBA premised on an rf linac (23). For this or other novel TBA driver concepts, the primary challenge is drive beam stability, subject to the constraint that the drive linac should be capable of delivering a stored energy per unit length of 10^1 J/m. For two 2.5-km linacs operated at 120 Hz, this corresponds to 10^1 MW, and is probably the maximum consistent with a reasonable site power.

At the same time, to design a prototype linac one requires experience in the requisite manipulations of high-power mm-waves, and the complete process of structure fabrication. For this a high-power amplifier is indispensable (24). Happily, one finds that, because W-Band forms a "window" in the atmosphere, tube development there is quite active. However, the highest power commercial amplifier puts out only about 5 kW (25). The highest power W-Band research amplifier is a gyroklystron found at the Naval Research Lab (26), and is approaching the 0.1 MW level. Design of a low-voltage miniature klystron is being pursued (27,28). With power combining (29), an array of such tubes may be capable of 1 MW. With active pulse-compression (30,31), the 10^{-6} s modulator pulse can be matched to the 10^{-8} s W-Band structure fill-time scale, and power levels higher by a factor of 10^1 - 10^2 are conceivable. Meanwhile, a 1-GeV/m W-Band linac will require 200-400 MW with a pulse-length of 10-20 ns; thus one prefers, if not a TBA driver, a 10^1 MW tube, with an active pulse compression system. The short wavelength favors a fast-wave interaction, and there are quite a few to choose from (32-34); of these the gyroklystron is the most advanced and a design study for the 10^1 MW level is complete (35). Depending on the tube-type, research problems include permanent magnet design and fabrication, three-dimensional gun design, high current density cathode materials, suppression of oscillation and spurious modes, and output coupling from an overmoded interaction region. All concepts require a microwave network implemented with quasi-optics (36) to avoid the 1-dB/ft nominal attenuation in fundamental mode guide (WR10) in transport to the linac.

With a working source, one could embark on a study of the phenomenology associated with high-gradient at the operating wavelength, and begin to observe the consequences of choices made in structure fabrication, assembly and handling. Experience at X-Band (37,38), and other frequencies (39,40) is a guide. *Field emission* refers to the tunneling of electrons from the accelerator structure, in the presence of a large electric field (41), and was first recognized in microwave linacs by P.B. Wilson (42). In practice, field-emission appears as a signal from a scintillator and photo-multiplier tube. Up-to-date discussions of field-emission are found in Padamsee, Knobloch and Hays (43) and Wang and Loew (16). One can attempt to appreciate field-emission on elementary grounds, considering an electron tunneling through a one-dimensional potential of depth ϕ, the work-function, perturbed by a uniform electric field, E. The uncertainty in the electron momentum, Δp, is given by $e\phi \approx \Delta p^2/2m$, with m the electron mass. The uncertainty in position is $\Delta x \approx \hbar / 2\Delta p$, with $\hbar$ Planck's constant. This corresponds to an uncertainty in energy on the order of $\Delta\varepsilon \approx eE\Delta x$, with $-e$ the electron charge. When $\Delta\varepsilon \approx e\phi$, one expects to find electrons emitted. Thus on elementary grounds one expects the threshold for field-emission to lie in the range $E_0 \approx (8em\phi^3)^{1/2}/\hbar \approx 10^{11}$ V/m, for copper, with $\phi \approx 4.65$ V. A more detailed calculation shows that emitted current density emitted varies as $J \propto (\beta E)^{2.5}\exp(-0.6E_0/\beta E)$, where E is the theoretical surface field and $\beta = 1$. This result employs a time-average valid when the rf period is longer than the tunneling time, $\Delta t \approx \hbar / 2\Delta\varepsilon$, or 10^{-14} s, for copper at 1 GeV/m. In practice, this result is employed with β as a phenomenological fit parameter, referred to as the "field-enhancement factor". It is typically of order 50-200.

The challenge for high-gradient operation is to understand why typical β's are so large, and to make them smaller by an order of magnitude. The phenomenon of large β is nowadays attributed to the presence of metallic or dielectric impurities ("flakes") on the surface; these lower the local work function and lead to enhanced "field-emission", assisted by flake geometry and transient plasma formation. The result looked for in field-emission studies is a *process* that results in a structure working reliably at high-power. This process would include a recipe for fabrication, assembly, cleaning, processing, and any other steps bearing on the problems of material behavior subject to intense electromagnetic fields (44,45). It is known that cleanliness, bakeout, high-pressure water-rinse, coatings, and sundry habits are helpful, but at present there is no generally-acclaimed recipe for normal conducting linacs (16). For a high-frequency linac, where fill-time is short, one is interested in the transient features of field emission. Recent work by Srinivasan-Rao, *et al.*, indicates that on the nanosecond time-scale lower β is achievable (46).

Once electrons are field-emitted they are available to be accelerated, and for a large field they may be *trapped*, *i.e.*, accelerated to relativistic speeds, reaching synchronism with the accelerating wave. From the binding-field expression (3), one can show that for acceleration from rest in a sinusoidal wave, with phase-velocity equal to the speed-of-light, the condition for trapping is $G>\pi mc^2/e$, with G the gradient, λ the wavelength of the sinusoid, and c the speed of light. If geometry permits, this trapped current may be detected with a Faraday cup or observed on a screen (47); in a long linac, it is lost in transit through a finite bandwidth magnetic lattice, and appears as a background signal on nearby radiation-sensitive beamline instruments (48). Such *dark-current* also has implications, not thoroughly explored as yet, for anomalous loading of the rf system and higher-mode excitation. To operate a linac at high-gradient one would prefer either to avoid the presence of free-electrons in the linac, or to incorporate them into the design. For example, all plasma linacs, when operated above the trapping threshold, are dark-current linacs. (This threshold also corresponds to the regime of non-linear plasma response.) At W-Band, the onset of trapping occurs for a gradient of 0.5 GeV/m, with trapping fraction of 50% at 1 GeV/m.

We don't argue here that field-emission or trapping place limits on gradient, although such a conclusion might be warranted depending on the linac and collider concept. Instead, we point out that they appear together with *breakdown*, a phenomenon that, in practice, is disruptive to circuit behavior. Breakdown refers to three coincident symptoms in the operation of a high-power microwave circuit: intrapulse rise in reflected energy, increase in X-rays (scintillator readings), and degradation of vacuum (rise in ion-pump currents). Higher frequencies may also be observed from the circuit, although it is not common practice to look for them. Where a viewport has been provided for, breakdown events are observable by visible light. It is found in practice that breakdown is preceded by an increase in field-emission, and for this reason one is inclined to surmise that the phenomena are related. Empirically it is known that breakdown threshold depends on pulse length, and it is common practice to condition a structure up to high-power, by operation at a short pulse length, with dithering of the operating frequency. One may surmise that this pulse-length dependence also favors higher frequencies, where natural structure fill-times are shorter. It is known that breakdown thresholds are lower in klystron output cavities (45), and this invites speculation about the influence of ionizing radiation. In sum, one is inclined to view field-emission, trapping and breakdown as parts of one problem: an uncontrolled free-electron population. This transient medium disrupts and re-directs energy transfer in the otherwise orderly microwave circuit. It should be avoided, or, failing that, rendered repeatable, and incorporated into the circuit design, as is proposed in plasma accelerators.

Pulsed-heating refers to the heating of the structure boundary in a single pulse, due to Ohmic dissipation. Its importance to high-gradient structures was first noted by P.B. Wilson (49), and it is thought to represent the most severe limit on gradient, due to cyclic fatigue. At X-Band, and 1-GeV/m the pulsed temperature rise is enough to melt the copper surface; at W-Band, the result is 700 K. Meanwhile, it has been argued that a temperature rise of only 40 K is probably the maximum acceptable figure, due to cyclic stress and cracking of the surface (50,51). At the same time, while autopsied structures often have a finish reminiscent of the lunar surface, they still function as a circuit. To understand this, D. Pritzkau is undertaking a series of pulsed-heating studies to obtain detailed data on degradation in tune and quality factor over the requisite astronomical number of pulses, for particular materials and fabrication processes (17). Pulsed-heating confronts directly the question of the structure material and integrity and appears to be the most fundamental motivation for advanced structure concepts.

ADVANCED STRUCTURE CONCEPTS

There are four ideas for raising pulsed-heat damage thresholds at high-field: disposable accelerators (presently, plasma accelerators), advanced materials, composite structures, and active circuits. The subject of plasma accelerators is discussed at length in these proceedings.

Advanced materials include both dielectrics and conductors. Dielectric accelerator concepts begin with the Cherenkov wakefield accelerator (52,53), and the dielectric RFQ of Caspers (54). In the meantime, a resonantly excited dielectric accelerator has been proposed (55). For high-field applications, diamond shows promise. Diamond has a high thermal conductivity $\kappa \approx 1.5 - 2.0 \times 10^{3}$ W/K-m (56), and can hold off fields of 1 GV/m (57). In addition, the loss tangent is quite low, $\tan\delta < 5 \times 10^{-4}$ at W-Band (58). Not all features of diamond are convenient, however. Temperature coefficient of expansion is $\alpha \approx 1.2 \times 10^{-6} / {}^{\circ}\mathrm{C}$, and thus differential expansion relative to the substrate is an issue. Field emission and secondary electron emission are practical concerns. Advanced conductors include the categories of Glidcop (59), Zr-OFC (60), and other dispersion-hardened copper alloys (61). These have the strength of steel, depending on their history, and electrical and thermal properties commensurate with copper. For completeness we note too that operation of structures at low temperature offers some promise; however, one is sobered by previous experience indicating that the high-quality factors attainable can be lost in high-power operation (16).

The application of advanced materials, and the broader problems of fabrication, design for fabrication, and microwave measurements (to assess fabrication) are being pursued by D.T. Palmer (62) with emphasis on electro-discharge machining. A parallel effort is in progress by Henke (13) with emphasis on fabrication by deep X-ray lithography, "LIGA" (63), following work of Kang, *et al.* (64). Silicon processing technology was the first to show promise in this area (65) and may point the way to still higher frequencies.

Application of composite structures for pulsed-heat reduction has been analyzed by X. Lin, in these proceedings (66). He has shown theoretically that application of diamond to the interior of an accelerating structure can significantly reduce pulsed temperature rise. Fabrication, high-power studies at X-Band, and short-pulse field emission studies are being pursued. Application of composite structures promises other benefits at high-field (44,45).

Active circuits external to the accelerator have been studied for some years, for application at conventional wavelengths (30,31). Active elements *integrated* into the structure are a relatively new area (67). For switch operation in the presence of large fields, silicon, with its 10^7 V/m dielectric strength will be inadequate, and thus diamond (68), and plasma (30) are of interest. For diamond, the bandgap is $\varepsilon \approx 5.5\,\mathrm{eV}$, so that excitation by 220-nm wavelengths or shorter is required. Carrier lifetime depends on the purity, and can range from 15 ns down to 30 ps, with a value of 1 ns noted in (69) for synthetic diamond. Application to switching benefits from the development of active elements for pulsed power (70).

In the meantime, small-scale structures have a significant disadvantage that must be addressed in structure design: large transverse wakefields. Historically there have been four approaches to the problem of higher-modes in accelerating structures: [1] ignore them, [2] use lower intensity beams, and a stronger magnetic lattice, [3] damp and detune them, and/or [4] employ them for structure alignment. The first approach was tried on the Two-Mile Accelerator, the Livermore Advanced Test Accelerator (ATA), and later again on the Stanford Linear Collider (SLC). Each time it failed, and defaulted to the second approach. As to the third approach, detuning of higher-modes encourages destructive interference in multi-bunch operation. Damping removes the microwave energy from the beam-orbit. Detuning was first employed on the Two-Mile linac, and involved detuning three cells of each 86-cell structure in a number of sectors in the linac (71). Damping was first employed operationally, and successfully on the Livermore induction linacs, ETA and ATA (72), later appearing in the choke-mode geometry of T. Shintake (73), and a travelling-wave structure ("DDS") that accomplishes both damping and detuning (74). The fourth approach was tried on ATA, the two-mile linac (75), and, most recently on the DDS structure, where M. Seidel, *et al.*, provided the first definitive measurements of "absolute beam position" in a microwave linac (76).

This all suggests that damping, detuning, and use of the structure as a self-registered beam position monitor are essential aspects of advanced structure design. (Their scarcity in the plasma accelerator literature suggests a rich field of study.) Application of asymmetric structures requires a detailed understanding of higher multipole content (77), and, for a working collider, compensation by means of lumped multipole cavities, or incorporation into the lattice design. Ultimately reduction of a novel structure design to practice requires not just design, fabrication, and bench-measurement, but experimental study with beam. The capability to perform studies of miniature structures with beam, at MW power levels, is a prominent feature of work reported by M.E. Hill (78).

The first figure of merit for wakefields in a collider is single-bunch, wakefield-induced growth in the action variable, *i.e.*, beam orbit jitter in units of the beam size. A linac functioning as a jitter-amplifier can exhibit diverse interactions between feedback systems, ground-vibration, structure misalignments, rf kicks, and other dynamical sub-systems; where machine-protection invokes a rate-limit, diagnosis and correction of errors in linac setup can be stymied (79). Thus to avoid compounding those features of beam dynamics that are hidden from the instrumentation, the linac should not amplify incoming beam offsets. The scaling for amplification in a W-Band linac is given in (80), where end-to-end quads of equal gradient and thickness l are considered. Quadrupole gradient is limited by achievable pole-tip field and pole aperture. A structure operating at free-space wavelength λ, and optimized for good $[R/Q]$, has a maximum interior transverse dimension of $\lambda/2$, and therefore can accommodate a pole-tip radius no less than $\lambda/4 \approx 0.82$ mm, at W-Band. For a 1 T pole-tip field maximum gradient is then 1.2×10^3 T/m. A gradient of 600 T/m implies, at 10 GeV, minimum $\beta_+ \approx 1.0$ m, and quad length $l \approx 0.30$ m. With acceleration, and scaling the optical functions so as to maintain constant phase-advance per period, one finds $\beta_\pm, l \propto \gamma^{1/2}$. Quad length at the linac exit (2500 GeV) is then $l \approx 4.7$ m, and $\beta_+ \approx 15.8$ m. One can show that such a linac is stable, with injection at 10 GeV and beam-port radius $R \approx 0.18\lambda$, for a 60 pC bunch with length $l_b \approx 30\ \mu$m.

The effect of wakefields on collider parameters is to constrain efficiency and luminosity. Efficiency prefers higher structure $[R/Q]$, and this improves with smaller beam-port aperture. Luminosity improves with higher bunch-charge. Taking all considerations together, one prefers shorter bunch length and stronger focusing mechanisms. Thus manipulation and diagnosis of short bunches and design of miniature magnets are important research problems. Meanwhile, fabrication of micro-electromagnets with 0.4-T flux density, 100-μm diameter and sub-millisecond switching time has been demonstrated (81).

Closely related to these is the subject of beamline instrumentation. Monitoring of bunch lengths below $30\ \mu$m will require manipulation of THz frequencies. Where the final focus employs $\beta_* \approx 150\ \mu$m, monitoring of beam-timing in collision will require phase-measurements accurate to a few degrees at W-Band, without averaging (82). With normalized beam emittance of $\varepsilon_{nx,y} \approx 10^{-7}$ m-rad, maximum beam-size at the exit of a 2.5 TeV machine is $\sigma_{x,y} \approx 0.6\ \mu$m. Thus linac orbit analysis will require single-shot beam position resolution below the 100-nm level. Machine tune-up will be aided by a pulse-to-pulse emittance measurement (83), something not presently available on the SLC. Instruments for machine protection bear serious scrutiny, as given to the matter of SLC collimators (84). Ideally, to protect accelerating structures from beam-damage, one would prefer to employ *disposable* spoilers and collimators, and to this end, laser collimation and resonant collimation are being studied (9).

Structure research is critical to the injector as well. The assumed single-bunch normalized emittance 10^{-7} m-rad and charge of 60 pC are roughly consistent with expected scalings for rf photocathode guns. However, the scaled gradient approaches 1 GeV/m. Thus the problem of high-gradient appears as well in the injector, and one requires innovation comparable to that in the linac structure. A possible solution is the pulsed photocathode gun (85). In addition, phasing and laser stability requirements are severe (86). Combined with the problem of polarization, the injector poses a broad research problem.

With some glimpse of the problems of high gradient, and the research efforts past and present, let us go on to look at the details of a particular new structure concept, an example of an "active" accelerator.

AN ACTIVE LINAC

A conventional travelling-wave accelerator consists of a linear array of resonant cavities that serve a combined function as a transmission line and an accelerator. Resonant excitation establishes a high-electric field with a minimum power level set by losses in the circuit. By design the field is largely longitudinal and suitable for acceleration. Due to the long time-scale for resonant filling this accelerator concept suffers from single-pulse temperature rise at the surface of an accelerator cell, when operated at too high a gradient. This may be expressed in terms of pulse-width T_p, for a rectangular accelerator cell, as (68)

$$\Delta T \approx \frac{0.84}{\sqrt{\kappa C}}\left(\frac{\delta}{\lambda}\right)\frac{G^2 T_p^{1/2}}{[R/Q]}\eta_g \eta_t .$$

For room-temperature copper the thermal conductivity is $\kappa = 401\,\mathrm{W/K-m}$, and the volume specific heat capacity is C=3.45×10^6 J/K-m^3. The conductivity of copper $\sigma \approx 5.8\times10^7$ mho/m determines the skin-depth $\delta \approx 2.1\,\mu\mathrm{m}$ $f^{-1/2}$ (GHz), with $f = c/\lambda$ the frequency, and λ the free-space wavelength. The quantity η_t depends on the waveform shape, with η_t=1 for a square-wave, while η_g depends on the cavity shape, with η_g =1 for a symmetric rectangular pillbox. Maximum $[R/Q] \approx 221.3\,\Omega$ occurs for cell width and height $\lambda/2^{1/2}$, and gap 0.371λ. With beam ports $[R/Q]$ is easily lowered by a factor of two.

To obtain the benefits of resonant filling, with reduced pulsed heating, we must consider other than a passive circuit. For example, Fig. 2 depicts a resonant line coupled by means of fast switches to a series of parallel transmission lines composed of accelerator cavities. Operation consists of three steps: [1] resonant filling of the primary line with mm-wave power P_1, provided by an external power source on the natural field decrement time scale of 10^{-8} s [2] rapid closing of the switches on a time scale well under 10^{-9} s [3] propagation of a short sub-nanosecond burst of mm-waves down the secondary line, as single electron bunches arrive in parallel, to be accelerated as they pass through each secondary line, roughly orthogonal to the direction of mm-wave propagation. A detailed treatment of this concept has been given in work with Tantawi (68), with the geometrical implementation of Fig. 3.

For low loss, the primary line should be implemented as an overmoded standing-wave cavity. To simplify the problem of fabrication, we have chosen a single-depth geometry in Fig. 3, although ultimately one would prefer a greater depth for the primary. In the first approximation, both the primary cell, and the secondary cell are rectangular pillboxes, excited in the TE_{10m} mode, with m=1 for the secondary cell, and, we suppose, $m = 15$, for the primary cell. Such an idealized geometry permits analytic calculation of the circuit parameters. Minimum stored energy density on the primary line favors maximum $[R/Q]/L$, with L the primary period. However, too small a transit angle implies a lower wall quality factor, a thin and more fragile, structure, and fewer beamlines. For simplicity we optimize instead the stored energy per secondary line, maximizing the secondary-cell $[R/Q]$. For $f = 91.392$ GHz, cell depth is 2.3 mm, secondary period $w_2 \approx 2.3$ mm and $L \approx 1.2$ mm. Secondary wall quality factor $Q_{w1} \approx 2.7 \times 10^3$, assuming a surface roughness much less than $\delta \approx 0.22\mu$m. The pulse length discharged from the primary line is $T_p = 2m/f \approx 0.33$ ns. The primary wall quality factor is $Q_{w1} \approx 9.9 \times 10^3$, and the natural decrement time is $2Q_{w1}/\omega \approx 34.6$ ns; with critical coupling, the loaded fill-time for the primary cavity is $T_1 \approx 17.3$ ns.

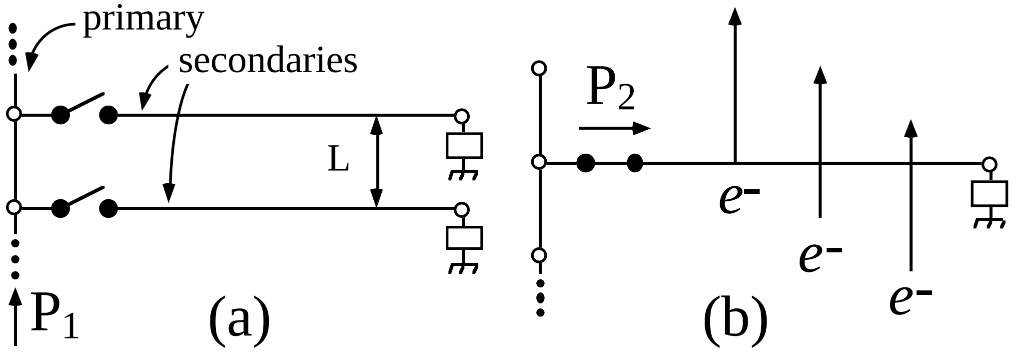

FIGURE 2. Concept for an active linac, consisting of a resonant storage line, coupled by means of switches to a periodic array of transmission lines. In **(a)** the primary resonant line is charged, and in **(b)** the switches have closed, discharging each primary period into the associated secondary transmission line.

An additional constraint arises due to transient operation of the secondary line. To minimize dispersion, phase-advance per cell should be near an odd multiple of $\pi/2$. Tapering is indicated to compensate wall losses. Despite these measures, the transient waveform discharged down the secondary eventually disperses and the transient peaking voltage appears on only a limited number of secondary cells (beamlines), a number set by the initial group velocity on the line, $\beta_g(0)c$, and Q_{w2}. For example, for $\beta_g(0)=0.174$, maximum $N_2=35$. Detailed computation of transient waveforms is straightforward since, after switch-closure, the circuit-equivalent of Fig. 3 corresponds to a simple chain of N_2 coupled cavities. To illustrate the resulting scalings we consider a numerical example with $N_1=25$ and a design gradient of $G \approx 1.01$ GeV/m. The desired accelerating voltage in the first cell is $V \approx 1.2 \times 10^6$ V, corresponding to stored energy $U_2=V^2/4k_l \approx 11.9$ mJ, with $k_l = \omega[R/Q]/4$ the loss-factor. The peak power required from the discharging primary cell is determined by the product of the initial group velocity and energy density in the secondary, $U_2/w_2 \approx 5.1$J/m, and is $U_1/T_p \approx 2.7 \times 10^2$ MW. The stored energy requirement in one primary period is then $U_1 \approx 88$ mJ, and the stored energy density in the primary line prior to discharge is $U_1/L \approx 72$ J/m. The maximum pulsed temperature rise in the circuit is $\Delta T \approx 126$ K, for an input pulse length of 18.6 ns, corresponding to $P_1 \approx 2.9 \times 10^2$ MW. With single-bunch charge of 60 pC, voltage droop due to beam-loading is 5% at $n=35$. Thus in contrast to a conventional collinear structure, the beam-induced wakefield disperses and its effect on other bunches is diminished.

An important improvement to this design would seek additional pulse compression by relaxing the single-depth constraint. In the limit of a larger primary cavity, with Q_{w1} and vertical dimension larger by a factor of $O(10^1)$, one could power a

1-m, 1-GeV, $N_2 \approx 15$ beamline linac with a single power feed providing 4×10^2 MW in a $0.2\,\mu$s pulse. Pulsed temperature rise in the secondary would be under $100\,\mathrm{K}$, and under $40\,\mathrm{K}$ in the primary. The challenge of designing such a primary cavity lies in the problem of good coupling to the secondary line, so as to maintain a short discharge time-scale, equivalent to an external Q after switch closure of $Q_e \approx 10^2$. To incorporate a parallel beam linac in Zimmermann's final focus picture, still more work is required, insofar as the beams considered here arrive at staggered time-intervals. For temporal beam combining, they should arrive almost simultaneously, and this implies a shorter secondary line, fewer beamlines, and higher charge per bunch. Thus additional work remains to fashion these concepts into a working parameter set for a collider.

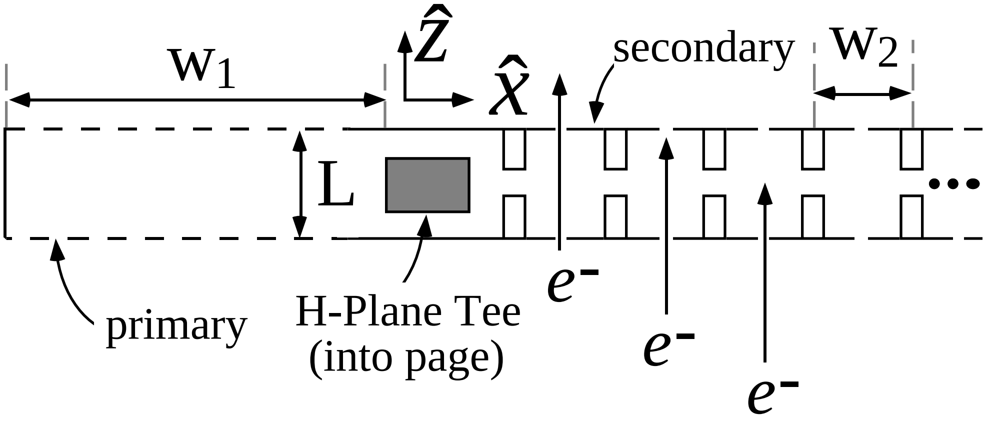

FIGURE 3. A single period of the geometry implementing the circuit scheme of Fig. 2. Each accelerator structure consists of N_1 such periods extending in z. The secondary line extends to the right (in x) for N_2 periods (beamlines).

SUMMARY

The challenges posed by high-gradient operation are critical to the future of high-energy physics. While fundamental questions remain as to the ultimate gradient "in copper", we have indicated that there is more to life than copper, that the limits derived for passive copper structures are not in themselves fundamental, that one can do better. Advanced materials, composite structures and active elements show great promise for accelerator design. The ultimate gradient in a solid-state collider-linac is not known, but it could be several orders of magnitude beyond the 20-40 MeV/m gradients employed today.

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