SLAC-PUB-7932
August 1998

Advanced Concepts for High-Gradient Acceleration

David H. Whittum

Stanford Linear Accelerator Center, Stanford University,
Stanford, California 94309

The promise of high-gradient accelerator research is a future for physics beyond the 5-TeV energy scale. Looking beyond what can be engineered today, we examine basic research directions for colliders of the future, from mm-waves to lasers, and from solid-state to plasmas, with attention to material damage, beam-dynamics, a workable collision scheme, and energetics.

Invited talk presented at the
19th International Linear Accelerator Conference (LINAC98)
Chicago, Illinois, 23-28 August, 1998

Work supported by U.S. Department of Energy contract DE-AC03-76SF00515

ADVANCED CONCEPTS FOR HIGH-GRADIENT ACCELERATION*

D. H. Whittum
SLAC, Stanford University, Stanford, California 94309 USA

Abstract

The promise of high-gradient accelerator research is a future for physics beyond the 5-TeV energy scale. Looking beyond what can be engineered today, we examine basic research directions for colliders of the future, from mm-waves to lasers, and from solid-state to plasmas, with attention to material damage, beam-dynamics, a workable collision scheme, and energetics.

1 INTRODUCTION

The technology of colliders could be scaled to energies well beyond the frontier of high energy physics today, but for limits to physical size. To reach beyond the next-generation machines requires not scaling nor engineering, but basic research in beam physics. The need for "advanced accelerator research" is not new; the subject extends back decades, to the beginnings of high-energy physics, the invention of the klystron by the Varian brothers, the resonant-cavity accelerator by Hansen, and strong-focusing by Christofilos. However it is only in the last decade that it has become recognized as the critical path for experimental particle physics in our lifetime. Here we consider one view of the latest chapters in the story of high-gradient accelerators for colliders.

In Sec. 2, we review the relevance of high-gradient to a collider. We then review the state of research in high-gradient acceleration mechanisms. Solid-state accelerators are covered in Sec. 3, and plasma-accelerators in Sec. 4. Conclusions are offered in Sec. 5.

2 COMPACT COLLIDER

Efforts to conceive of a compact collider meet with numerous difficulties. For example, if one were to extrapolate the "conventional" picture of a collider [1] to 5-TeV center-of-mass energy, a luminosity of 10^{35} $cm^{-2}s^{-1}$, and an accelerating gradient of 1 GeV/m, one would hear objections at every turn. At conventional frequencies, one would need a multi-GW power source that doesn't exist. Even if one had such a source, it would ablate the accelerator structure surface in a single pulse, due to Ohmic heating. At high frequencies, the peak power requirement would be lower, but Ohmic heating would still be untenable, due to copper fatigue from thermal cycling. In addition, high-frequency structures are difficult to fabricate. Even if one could fabricate 10^5 of them, and align them, their wakefields would destroy the beams. Even if the beams survived the linac, then to focus them one would need a 20 km optical system. With such a big machine, why bother with high gradient? In collision the beams would pinch each other producing mostly backgrounds, so why bother at all?

These problems can be taken either as discouragement, or motivation. Actually it appears that most of them are simply symptoms of a naive collider concept. A different concept for a collider has been described by Zimmermann [2], as seen in Fig. 1, with parameters as in Table 1. To avoid beam disruption, neutralized beams or $\gamma\gamma$ collisions are employed. To form a compact final focus, chromatic correction is abandoned. Instead, it is assumed that each main linac is followed by two much shorter accelerators operated at harmonics of the fundamental. To improve luminosity for a given site-power, one combines single bunches from the linac. This requires a half-chicane, and synchrotron radiation there requires that bends be gentle, extending over 1.3 km. Control of single-bunch beam dynamics in the linac is consistent with permanent magnet quadrupoles.

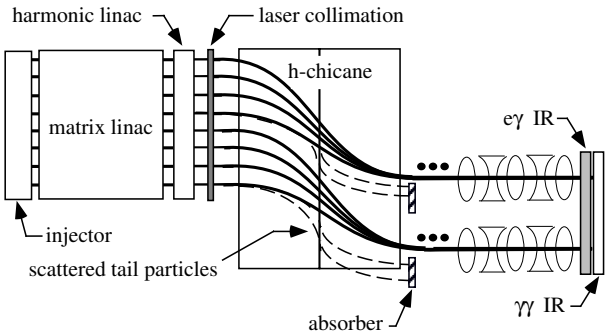

Figure 1: A new concept for a compact collider, as described by Zimmermann [2].

Even if one accepts that such concepts could be reduced to practice, one significant problem remains: how to make a high-gradient linac? This linac should be frugal with stored energy per unit length, and should be consistent with multi-beam collisions, either through beam-combining as seen in Fig. 1, multiplexed collisions, or a continuous focus in the interaction region. For example, if one could collide each of 50 bunches, the luminosity corresponding to Table 1 would approach 10^{35} $cm^{-2}s^{-1}$. In the meantime, work of [2] suggests that the collider problems-of-principle soon may be reduced to just

* Work supported by DE-AC03-76F00515.

one: the accelerator. Let us consider then recent work on advanced accelerator concepts.

Table 1: Example Parameters for a Compact Collider.

parameter	W-Band example
center of mass energy	5 TeV
gradient	1 GeV/m
collision spot-size	1.8 nm
normalized emittance	10^{-7} m-rad
charge per linac bunch	60 pC
frequency	91.392 GHz
repetition frequency	120 Hz
main linac length	2.5 km
harmonic linac length	0.1 km

3 SOLID-STATE STRUCTURES

At high-gradient, solid-state structures are prone to breakdown [3] and cyclic stress arising from pulsed Ohmic heating [4]. Associated with breakdown are the phenomena of field-emission and trapping. A discussion of the phenomenology can be found in [5]. To summarize, breakdown is inhibited on short time-scales. Trapping occurs for gradient-wavelength product $G\lambda$>1.6 MeV. All such considerations favor short-wavelength for high-gradient. For G>1 GeV/m, frequencies of 10^2 GHz and higher are indicated. However, it is difficult to conceive of a resonantly-excited structure that can survive the Ohmic heating associated with such gradients. Thus pulsed-heating is the first motivation for research into new structure concepts.

There are four research directions one might pursue to lower cyclic stress limits: disposable (plasma) accelerators, advanced materials, composite structures, and active circuits. Plasma accelerators are discussed in the next section. Advanced materials include dispersion-strengthened conducting alloys [6], and dielectrics. Dielectric accelerators include wakefield-driven [7], and resonantly-driven [8] structures. Lin has analyzed a composite structure employing a diamond layer to reduce pulsed heating [9]. Diamond is attractive due to its high thermal conductivity, high dielectric strength, and low loss tangent [10,11]. Active circuits have been studied for some years, for applications external to the accelerator [12]; incorporation into the structure is a relatively new area [13]. One new concept for an active accelerator is seen in Fig. 2, employing a high-Q resonant cavity coupled by switches to loaded transmission lines, forming a matrix of accelerating cells. [14]. For the active element, silicon is inadequate at high-fields, and thus plasma and diamond are of interest. Use of diamond as the photoconductor requires 220-nm photons; carrier lifetime is adequate depending on the purity.

While the ultimate gradient attainable in a solid-state accelerator is unknown today, it appears that application of strengthened copper alloys, diamond layers, and active circuits may permit more than an order of magnitude improvement in stress-limited gradient.

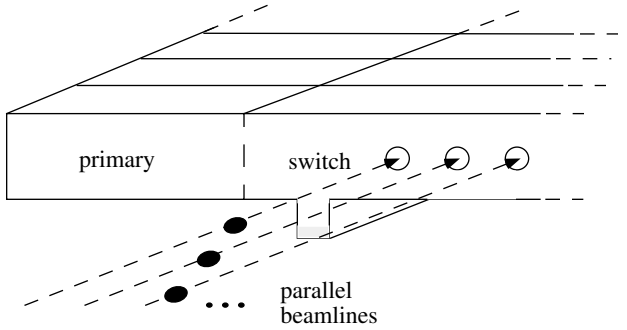

Figure 2: A new concept for an accelerator, employing an active circuit and parallel beamlines.

Structure fabrication and bench-measurement are critical to structure development. At W-Band (75-110 GHz) such work is being pursued by Kang, *et al.*, [15] via deep X-ray lithography, and D.T. Palmer via electrodischarge machining [16]. The primary challenge for fabrication at present is bonding. Brazing appears difficult due to the detuning effect of fillets; diffusion bonding is discussed in [16]. Meanwhile, good tune and quality factor have yet to be demonstrated in a multi-cell W-Band structure. In the meantime, other fabrication techniques merit attention, particularly where they may be extensible to the THz range [17].

A short-wavelength structure also requires a power source. To-date power levels adequate for 1-GeV/m fields have been demonstrated up to 140 GHz [18], and there in a mode consistent with the two-beam accelerator (TBA) concept. For TBA-driven colliders one is interested to assess drive beam stability at beam currents consistent with the stored energy requirement for the linac, typically 10^1 J/m. Tube concepts at 10^2 GHz meanwhile are making rapid progress at the 10^{-1} MW level [19,20], and a 10^1 MW design study is complete [21].

For structure dimensions in the 10^{-5} m range, lasers are adequate to produce GeV/m gradients, limited by structure damage [22]. However, it is important to keep in mind that for first-order accelerators [R/Q] is a crucial figure of merit for the energetics of the machine. Theoretical maximum in idealized cylindrical or rectangular geometries is 221 Ω, and this diminishes rapidly as the volume of the accelerating cell or the beam-port is enlarged. Higher-mode losses must be accounted for, particularly for small beam-ports [23].

For all short-wavelength solid-state structures, machine issues are in an early state. A glimpse of what is to come can be seen in the work on SLC collimator damage [24]. For structure protection, laser and resonant spoliation and collimation are being pursued [2]. Associated beamline instrumentation will require: manipulation of THz frequencies and beyond for bunch-length and beam-timing

information; beam position monitor resolution below the 10^{-7} m level for orbit analysis; single-pulse emittance measurement [25] for tune-up; use of the structure as a self-registered beam-position monitor [26] for control of emittance.

Given the benefits of harmonic-acceleration for energy-spread compensation [2], a linac proposed to operate at frequency f, should be accompanied by concepts for frequencies extending up to 10^2 f. Thus one is inevitably interested in structure development across the spectrum. Note that harmonic structures need not meet the same stringent requirements as the main linac structures, so that [R/Q], efficiency and gradient can be lower.

Structure research for the injector is equally critical. While the parameters of Table 1 are consistent with expected scalings for rf photocathode guns, the scaled field approaches 1 GV/m. Thus the problems of high-gradient appear in the injector as well. Possible alternatives include a pulsed photocathode-gun [27]. An injector providing a low-emittance, high-polarization electron beam remains a critical problem.

4 PLASMA STRUCTURES

The first plasma wakefield experiments employed a uniform plasma, demonstrating the principles of operation with injected beam; plasma wakefields were observed to exhibit a high Q, of order 10^2, in the linear regime (small $G\lambda$) [28]. In the intervening years, the plasma beat-wave accelerator has produced 2 GeV/m, and the laser wakefield accelerator, 100 GeV/m [29]. In a uniform plasma, however, the laser-driven concepts are limited by the diffraction of the drive pulse; thus observed beam spectra extend up to only 10^2 MeV.

To extend the interaction length numerous groups are presently pursuing experimental studies of laser-driven wakefield acceleration in a hollow plasma channel as seen in Fig. 3. Such a channel can serve as an optical fiber, permitting acceleration over many Rayleigh lengths [30]. With these efforts, and continued work on beam-driven wakefields [31], it is quite likely that a 1 GeV beam spectrum will be produced from a plasma accelerator, within the next year.

As the plasma accelerator concepts develop into a new generation of experiments, oriented on 1-GeV spectra and staging, it is timely to compare them quantiatively to the conventional multi-cell accelerator. Schroeder, *et al*., have recently analyzed the plasma channel in such a fashion [32], providing the first rigorous characterization as an accelerator. Let us summarize this work briefly.

In a uniform channel, there are two free parameters, the plasma frequency ω_p and the channel radius, b, measured in units of the plasma skin-depth $B=\omega_p b/c$. The accelerating mode of a plasma channel may be characterized by an [R/Q] (per plasma period) a function only of B, and a resonant frequency scaling with ω_p and a function of B. Moreover, Schroeder has discovered that for this monopole excitation, and for each higher azimuthal harmonic, the channel supports *only one* synchronous mode. This is possible since the channel is axially uniform, eliminating diffractive losses, and the plasma susceptibility is negative, suppressing Cherenkov losses.

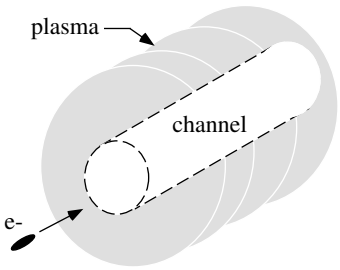

Figure 3: A hollow channel in a plasma can function as an accelerating structure.

The "single-mode" character of the channel implies lower parasitic losses than in a scaled conducting structure, and permits *shorter* bunches and *higher* single-bunch charge than in a scaled collider design. Analysis of the dipole mode shows that for multi-bunch operation, channels can be stagger-tuned to inhibit beam break-up. However, multi-bunch operation requires good Q for the accelerating mode and this requires a sharp-edged channel [33]. The high Q of the uniform plasma has not yet been demonstrated experimentally in the channel geometry, and vigorous efforts are underway to produce and diagnose tailored plasma channels [30].

The promise of this work is an accelerator concept superior in principle to the conventional circuit, immune to damage, and operating with an existing power source. The first challenge for such a disposable accelerator is accurate structure fabrication and diagnosis "on-the-fly", at the machine repetition frequency. To operate a series of such structures in concert, phasing and alignment must be provided for. Finally, incorporation into a multi-beam collision scheme should be addressed.

5 CONCLUSIONS

While the naive extrapolation of the conventional collider concept is fraught with problems, more sophisticated collision schemes are conceivable. In the last two years, we have seen new results emerge across the spectrum that appear capable of solving the problems of the compact collider, and its high-gradient linac. Work summarized here was not arrived at by scaling known technology, nor by contemplating only what can be engineered. Advanced accelerator research today is simply basic physics research, carrying us into the state- of-the-art in laser science, micro-fabrication, instrumentation and mm-wave and infrared technology --- and to the frontiers of plasma, beam, and high-energy physics. The results of

recent years suggest that the next-generation colliders will not be the last.

6 ACKNOWLEDGEMENTS

Collaboration with Carl Schroeder, Sami Tantawi, Jonathan Wurtele, and Frank Zimmermann was essential. Conversations with Wim Leemans were most helpful. I thank Angie Seymour for her support.

7 REFERENCES

[1] R. B. Palmer, *Ann. Rev. Nucl. Part. Sci.* **40** 529-592 (1990).

[2] F. Zimmermann, "New Final Focus Concepts at 5 TeV and Beyond", *Advanced Accelerator Concepts*, W. Lawson, ed., (to be published), SLAC-PUB-7883.

[3] J.W. Wang and G.A. Loew, "Field-emission and RF breakdown in high-gradient room-temperature linac structures", *Proc. Joint School RF Engineering for Accelerators* (IOP, to be published), SLAC-PUB-7684.

[4] D. Pritzkau, *et al.*, "Experimental study of pulsed-heating of electromagnetic cavities", *Proc. 1997 Particle Accelerator Conference,* (IEEE, New York, to be published).

[5] D. Whittum, "Ultimate gradient in solid-state accelerators", *Advanced Accelerator Concepts*, W. Lawson, ed., (to be published), SLAC-PUB-7910.

[6] A.V. Nadkarni, "Dispersion strengthened copper properties and applications", in *High Conductivity Copper and Aluminium Alloys*, E. Ling and P.W. Taubenblat, eds. (AIME, Los Angeles, 1984) pp. 77-101.

[7] W. Gai, *et al.*, *Phys. Rev. Lett.* **61** (1988) pp. 98-100.

[8] J. Rosenzweig, A. Murokh, and C. Pellegrini, *Phys. Rev. Lett.* **74** (1995) pp. 2467-2470.

[9] X. Lin, "Diamond coating in accelerating structure", *Advanced Accelerator Concepts*, W. Lawson, ed., (to be published).

[10] L.S. Pan and D.R. Kania, eds., *Diamond: Electronic Properties and Applications* (Kluwer, Boston, 1995).

[11] M. Thumm, *International Journal of Infrared and Millimeter Waves* **19** (1998) pp. 3-14.

[12] S.G. Tantawi, "Active high power RF pulse compression using optically switched resonant delay lines", *Advanced Accelerator Concepts*, AIP Conf. Proc. **398** (AIP, New York, 1997) pp. 813-821; M.I. Petelin, A.L. Vikharev and J.L. Hirshifield, "Pulse compressor based on electrically switched Bragg reflectors", *ibid.*, pp. 822-831.

[13] C. Bamber, *et al.*, *Nucl. Instrum. Meth.* **A 327** (1993) pp. 227-252.

[14] D.H. Whittum and S.G. Tantawi, "Switched matrix accelerator" (submitted to Rev. Sci. Instrum.), SLAC-PUB-7848.

[15] Y.W. Kang, *et al.*, *Rev. Sci. Instrum.* **66** (1995) pp. 1-5 and "DXRL Fabrication and Measurement of Millimeter-Wave Accelerating Structures" (these proceedings).

[16] D.T. Palmer, "W-Band structure research at SLAC", *Advanced Accelerator Concepts*, W. Lawson, ed., (to be published).

[17] T.L. Willeke and A.D. Feinerman, *J. Vac. Sci. Tech.* **B 14** (1996) pp. 2524-2530.

[18] S.L. Allen, *et al.*, "Generation of high-power 140 GHz microwaves with an FEL for the MTX experiment", *Proc. 1993 Part. Acc. Conf.* (IEEE, New York, 1993) pp. 1551-1553.

[19] M. Blank, *et al.*, "Experimental investigation of a W-Band gyroklystron amplifier", *Proc. 1997 Part. Acc. Conf.* (IEEE, New York, to be published).

[20] G. Caryotakis, *Phys. Plasmas* **5** (1998) pp. 1590-1598.

[21] M.R. Arjona and W. Lawson, "Design of a 7-MW, 95-GHz, three-cavity gyroklystron" (submitted to *IEEE Trans. Plasma Sci.*).

[22] T. Plettner, *et al.*, *Advanced Accelerator Concepts*, W. Lawson, ed., (to be published).

[23] F. Zimmermann, *et al.*, "Wakefields in a mm-wave linac", *ibid.*

[24] F.-J. Decker, *et al.*, "Design and wakefield performance of the new SLC collimators", *Proc. XVIII International Linac Conference* (CERN, Geneva, 1996) pp. 137-139, SLAC-PUB-7261.

[25] J.-S. Kim, *et al.*, "Pulse-to-pulse emittance measurement system", FARTECH Inc., 3146 Bunch Ave., San Diego, CA 92122 (unpublished).

[26] M. Seidel, *et al.*, *Nucl. Instrum. Meth.* **A 404** (1998) pp. 231-236.

[27] T. Srinivasan-Rao, *et al.*, "Optimization of gun parameters for a pulsed power electron gun", *Advanced Accelerator Concepts*, W. Lawson, ed., (to be published).

[28] J.B. Rosenzweig, *et al.*, *Phys. Fluids* **B 2** (1990) 1376.

[29] W. Leemans, "Summary of the Plasma Acceleration Working-Group", *Advanced Accelerator Concepts*, W. Lawson, ed., (to be published).

[30] T.C. Chiou, *et al., Phys. Plasmas* **2** (1995) 310.

[31] R. Assmann, *et al.,* "Proposal for a 1-GeV Plasma Wakefield Acceleration Experiment at SLAC", SLAC E-157

[32] C.B. Schroeder, J.S. Wurtele, and D.H. Whittum, "Multimode analysis of the plasma channel accelerator" (submitted to *Phys. Rev. Lett.).*

[33] B.A. Shadwick and J.S. Wurtele, "Numerical studies of wake excitation in plasma channels", *Proc. 6th European Part. Accelerator Conf.* (to be published).