SELECTED ADVANCED ACCELERATION CONCEPTS*

J. L. Hirshfield**
Department of Physics, Yale University, New Haven, CT 06511, and
Omega-P, Inc., New Haven, CT 06511

Abstract

A précis is given of a critical review of a few advanced acceleration concepts that involve neither plasma nor periodic metallic slow-wave structures. These so-called "vacuum accelerators" are either externally driven using powerful rf or laser sources, or internally driven using strong wake fields set up by a train of drive bunches. Merits and limitations of each concept are given, and speculations are advanced on the potential of each to mature into a practical accelerator for use as a tool in high-energy physics or other scientific applications.

INTRODUCTION

Recent Particle Accelerator Conferences and Advanced Accelerator Concepts Workshops have included a category of ideas under the rubric *Electromagnetic Structure-Based Acceleration*—a catchall for concepts not involving plasma or traditional disk-loaded metallic structures [1]. Division of such concepts into slow-wave and fast-wave interactions is not uncommon.

Slow-wave concepts can involve dielectric-loaded waveguides excited at either microwave or optical wave-lengths. Early experiments with dielectric-lined metallic-wall cylindrical microwave structures [2] showed that design and fabrication issues at the input coupler and the dielectric-wall interface demanded serious attention if the anticipated accelerating gradient was to be achieved. The nature of the limitations to achievement of accelerating gradients competitive with those for disk-loaded metallic structures is a topic of continuing research [3]. Other slow-wave concepts include planar dielectric structures (see below) and photonic band gap structures [4]. Any of these guided wave structures can be driven externally, using rf or laser pulses, or internally using wake fields from one or more driving bunches. Fast-wave concepts include the inverse free electron laser IFEL [5], and the laser autoresonance cyclotron accelerator LACARA [6].

The selected acceleration concepts discussed in this paper include a multi-cavity proton accelerator MCPC and LACARA, as examples of externally-driven fast-wave interactions, and wake field acceleration in a planar dielectric-lined structure—a beam-driven slow-wave interaction. Speculations are advanced on the potential of each to mature into practical accelerators for use as tools in high-energy physics or other scientific applications.

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**jay.hirshfield@yale.edu Collaborators include Changbiao Wang, J.-Y. Fang, T. C. Marshall, S. Shchelkunov, V. P. Yakovlev, and M. A. LaPointe.

MULTI-CAVITY PROTON CYCLOTRON

The currently-favored choice for a high intensity 1-GeV class proton accelerator for a high-power neutron spallation source is a superconducting linac (SCL). For example, a 700 MHz SCL with an average acceleration gradient of 8.6 MV/m has been described for proton acceleration from 0.20 to 1.2 GeV in a 10 MW source [7]. In paper TPPG056 in these Proceedings, Wang *et al* give parameters for a >100 MW, 1 GeV proton accelerator that uses a cascade of TE_{111} cavities in a nearly-uniform 8-T magnetic field [8]. This multi-cavity proton cyclotron MCPC has the virtues of a relatively high effective acceleration gradient (~40 MV/m), modest surface fields on the walls of the room-temperature cavities (<7 MV/m), high efficiency (~70% at 122 mA), large beam apertures, intrinsic beam stability, wide injection phase window (2 rf cycles in the first cavity), and intrinsic beam scanning over a target. Against these appealing attributes one must weigh the need for a large superconducting solenoid—25 m long and ~4 m in diameter in the example given by Wang—in contrast to 120 m of superconducting rf cavities in the SCL mentioned above. MCPC is not likely to be practical for acceleration beyond several GeV, on account of the required very strong magnetic field. Nevertheless, this new concept for a fast-wave proton accelerator could be a viable candidate to drive a very high power neutron spallation source or, at lower current, for a compact GeV class versatile proton source. Testing of a four-cavity electron counterpart has been proposed.

LASER CYCLOTRON AUTORESONANCE ACCELERATOR

The Woodward-Lawson-Palmer (WLS) theorem states that no net acceleration is afforded a charged particle interacting linearly with, and passing without interruption along, an unbounded plane electromagnetic wave. Thus authentic vacuum acceleration requires a proximate medium to slow and/or refract the wave, a mirror or prism to deflect the wave, or the presence of another field such as a static magnetic field *B*. The *B*-field WLS theorem-breaker is the key to LACARA—laser cyclotron auto-resonance accelerator, an experimental test version of which is to be installed at ATF-BNL as soon as a long-delayed 6-T solenoid magnet is built and installed. For a two-meter interaction length, corresponding to five Rayleigh lengths for an 0.8 TW, 10.6 µm CO_2 laser focused to a waist radius of 1.2 mm, acceleration from 50 to 100 MeV is predicted for all electrons in an injected nC bunch [6]. This vacuum laser-acceleration scheme differs in several important respects from most other laser-based accelerators: in LACARA all electrons receive nearly the same energy gain; energy gain is possible over many Rayleigh lengths; no material medium or gas is close to the beam path; and slippage between laser pulse and a typical beam bunch is tolerably small. Acceleration gradient scales roughly with the square root of laser power, but falls as beam energy grows. Curiously, the required resonance *B*-field strength falls as the energy increases, in conformity with the autoresonance condition. In practice, the precise resonant *B*-field profile is not necessary, since the interaction typically occurs over only a small number of orbit gyrations—of the order of the number of Rayleigh lengths. On account of falling acceleration gradient with increased energy, LACARA is not likely a candidate for electron acceleration to energies above a few 100 MeV but, as will be discussed below, it has a unique property that enables generation of fs bunches which themselves could drive a high-gradient, high-energy accelerator.

FORMING FEMTOSECOND PLANAR BUNCHES FROM A LACARA BEAM

After exiting LACARA, as the strong solenoidal *B*-field tapers smoothly towards zero, individual electron orbits follow diverging linear paths that are sequentially displaced in azimuth at the optical frequency. When a 10.6 µm CO_2 laser is used, these paths recycle every 35.3 fs. For a LACARA as described above with an injected 50 MeV beam having rms emittance of 1.5 nm, the orbits trace a donut with a diameter of about 3 mm and a thickness of about 0.5 mm on a beam stop 150 cm from the LACARA center. If a hole is cut in the beam stop to pass 10% of the beam, then a sequence of 3.5 fs bunches emerges through it [6]. (The beam stop must of course be thick enough to stop the other 90% of the beam.) If several such holes are cut into the beam stop, then several trains of 3.5 fs (~ 1 µm) bunches emerge, following paths that diverge from one another. These separate trains can be reunited using quadrupole lenses. For a 1 ps, 1 nC bunch accelerated in LACARA, each train would contain 28 3.5 fs bunches, each with a charge of 3.5 pC. This scheme is the optical counterpart of the microwave "choppertron" [9]. Obviously, the size of the hole in the beam stop can be altered to form bunch widths larger or smaller than 3.5 fs, and the number of reunited trains of such bunches can be selected as well. Such variations can be effected merely by changing a single element in the arrangement—the beam stop.

Formation of a roundish beam chopped as described above into a beam with planar transverse profile has been shown possible by use of a single quadrupole lens [10]. For the 3.5 fs bunch example above, a quad of strength 3.5 $kG\text{-}cm^{-1}$ is able to form a profile of width 3400 µm and height 68 µm (a 50:1 aspect ratio) at a distance of 21.5 cm from the beam stop. A train of 28 or more such 1-µm long planar bunches would thus be generated for subsequent use, for example as discussed next.

MICRON-SCALE HIGH GRADIENT WAKE FIELD ACCELERATOR DRIVEN BY FS PLANAR ELECTRON BUNCHES

In paper TPPG038 of these *Proceedings*, Fang *et al* show calculations and simulations for the wake fields set up by a train of fs planar bunches prepared using a LACARA beam, as described above, that pass through the vacuum channel between two parallel planar dielectric-lined metal plates [11]. The structure analyzed in [11] employed two 1.9 µm thick, 300 µm high slabs with relative dielectric constant ε = 3.0 deposited on copper, with a vacuum gap of 15.0 µm. Such a configuration is appealing for generation of intense wake fields for acceleration because it can be fabricated using microelectronics technology, it is fixed and rigid and thus suitable for assembly in a manifold staged array, it supports intense wake fields from pC planar bunches, and it supports relatively weak higher-order modes that can even provide transverse focusing.

A single 1 pC, 3.3 fs bunch with height 150 µm and width 10 µm can be shown to generate a wake field with a peak accelerating gradient of 70 MV/m, mainly in the lowest TM-like mode of the structure; constructive superposition of the wake fields of ten such bunches, each spaced by the wake field period, can be shown to generate a peak accelerating gradient of 618 MV/m for a test bunch at a distance of 1.14 mm behind the drive train. At this location, higher-order transverse wake forces can be shown to be focusing, yielding a 5×10 μm^2 beam spot about 6 cm along the structure, with stable betatron oscillations in transverse beam profile that persist for at least 50 cm along the structure. This result suggests that acceleration to the GeV level could be possible in a single module of such a structure, without need for external focusing.

Simulations using the PIC code KARAT for the same structure show that superposition of longitudinal wake fields occur much as in the computed results, but only in a • erenkov radiation zone that trails each drive bunch; close to the structure entrance a transition radiation zone exists with fields much weaker than those nearer the bunch; in an intermediate zone • erenkov and transition radiation overlap and interfere with one another. A theoretical model yielding comparable results for a single wake field mode in a solid cylindrical dielectric waveguide has been recently published [12]. These complicated effects near the structure entrance are not fully understood but, in any case, should not be of undue influence for structures whose lengths far exceed their largest transverse dimension. One can still conclude that stable ~GV/m accelerating wake fields can be excited by a periodic train of planar bunches in a dielectric-lined micron-scale planar structure.

OPINIONS AND SPECULATIONS

Exploration of novel advanced accelerator concepts is a fascinating and rewarding pastime. However, if utility to the scientific community and benefit to society at large are to be taken into account, it is—in the author's opinion—incumbent upon researchers to occasionally take stock of their work and speculate as to whether a practical accelerator might emerge after maturation of any of the new concepts that they study. In particular, for use as a tool in future high energy physics research, an accelerator must not face insurmountable basic obstacles preventing it from reaching the TeV energy range for electrons and positrons, and tens-of-TeV energies for protons. In addition, the beam luminosity must not be prevented by insurmountable obstacles from reaching the range 10^{34} cm^{-2} sec^{-1}. On the other hand, if the accelerator is to be used in other areas of research or applications, different practical criteria will apply. For example, a proton driver for a high-power neutron spallation source or sub-critical nuclear reactor would require GeV-level energy and 10-100 MW beam power; while an electron beam source with femtosecond or attosecond bunches for direct excitation and study of atomic, chemical, biological, or nuclear transients (or for indirect excitation using x-rays generated by the bunches) would need be of moderate energy (probably 100's of MeV at most), moderate charge/bunch (sub-nC), but with good energy resolution, low emittance, and good bunch length definition. Considerations for industrial or medical accelerators invoke additional questions of size, cost, efficiency, and shielding.

In view of what is stated above for the several vacuum acceleration concepts discussed in this paper, it appears to be beyond present understanding for either MCPC or LACARA to reach TeV energies; the former because of the unrealizable magnetic field strength required, the latter because of the inverse relationship between acceleration gradient and beam energy. However, it seems that each concept might be developed for other applications; MCPC for a high-power proton driver, and LACARA to prepare a beam for chopping into fs or sub-fs bunches. The planar wake field accelerator concept is perhaps capable of staging, and thus could conceivably be operated with many stages each providing GeV-level energy gains. This would require a mechanical design capable of maintaining stable micron-scale tolerances over meter-long structures.

Achievement of high luminosity for MCPC translates to the issues of beam extraction and emittance, since high average current appears to pose no limitation. But for LACARA and a planar wake field accelerator driven by a beam prepared in LACARA, achievement of high luminosity translates into need for a TW-level CO_2 laser with a pulse repetition rate of 100's of kHz. The author is unqualified to speculate on the likelihood for realization of such a laser, not to mention its cost.

These evident limitations notwithstanding, it is the author's opinion that continued study of these and other advanced accelerator concepts is definitely warranted, not only to deepen basic physical understanding, but also to guard against missing out on any unforeseen discovery that might significantly alter the prospects.

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