EM Structure Based and Vacuum Acceleration

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Abstract. Physical and technical issues governing structure-based and vacuum acceleration of charged particles are reviewed, with emphasis on practical aspects.

INTRODUCTION

The importance of particle acceleration may be judged from the number of applications which require some sort of accelerated beam. In addition to accelerator-based high energy physics research, non-academic applications include medical imaging and treatment, structural biology by x-ray diffraction, pulse radiography, cargo inspection, material processing, food and medical instrument sterilization, and so on. Many of these applications are already well served by existing technologies and will profit only marginally from developments in accelerator technology. Other applications are poorly served, such as structural biology, which is conducted at synchrotron radiation facilities, and medical treatment using proton accelerators, the machines for which are rare because they are complex and costly. Developments in very compact, high brightness and high gradient accelerators will change how accelerators are used for such applications, and potentially enable new ones.

Physical Principles and Technical Considerations

The physical principles governing particle accelerators are relatively few. Since acceleration is exclusively by electromagnetic (EM) forces, Maxwell's equations and the Lorentz force provide a complete description. Since large electrostatic fields are difficult to produce, electromagnetic fields are used, and since such fields tend to diffract away, guiding structures are often used for confinement. Consequently, several general theorems apply.

The Rayleigh-Helmholtz Reciprocity theorem[1] in essence states that mutual inductance, in the absence of nonlinear media, is reciprocal. For accelerators, this requires that any structure capable of accelerating a charged particle beam will cause the beam to radiate energy into the accelerating mode on passing through the structure.

The Lawson-Woodward Theorem[2] applies to the specific case of straight-line motion of particles in vacuum. It states, in essence, that there can be no net energy

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exchange by a first-order process (i.e. acceleration force depends on the first power of the applied field strength) between a free space EM wave and a passing particle beam in the absence of nearby boundaries or deflections of the beam trajectory. Examples of boundary-free acceleration mechanisms that do not violate L-W include the inverse free electron laser (trajectories are not straight) and ponderomotive acceleration (second-order process).

The Panofsky-Wenzel Theorem[3] relates the longitudinal and transverse components of EM waves. One consequence is that TE modes do not kick transversely, and TM modes kick in proportion to the transverse variation of the longitudinal field.

Coupling energy between an EM wave and a particle over long distances requires that the particle spend more time in the accelerating phase than in the decelerating phase of the wave. How this is achieved, and for what fraction of the time the particle is being accelerated, forms one way to classify accelerating methods. Methods which rely on a wave that is matched in phase velocity to the particle beam are *synchronous*, and have an infinite interaction distance over which they accelerate. Conventional microwave accelerators fall into this category. *Quasi-synchronous* describes acceleration methods for which the EM wave has a phase velocity slightly above the particle velocity, and for which the interaction length is limited by the dephasing length, typically many hundreds of wavelengths. In this case the particle/wave interaction must be interrupted periodically, either with boundaries or the wiggle motion of the particle. The Inverse Free Electron Laser (IFEL) and Crossed Gaussian beam accelerators fall into this category. *Ponderomotive* acceleration is second-order acceleration resulting from particles being pushed away from increases in energy density.

Technical Considerations

Gradient Limitations

Gradients are limited, on physical principles, to the pair-production threshold ($\sim 10^{18}$ V/m), above which e^+e^- pairs will form and quench the field. The presence of nearby boundaries limits attainable field stresses to what the boundary materials can withstand, which is in theory limited by ionization to a few volts per Angstrom ($\sim 10^{10}$ V/m), but in practice to gradients very much less than this.

Material damage and voltage breakdown are the mechanisms which limit the gradient. Material damage occurs through several processes, including direct beam strike, explosive field emission, ion bombardment, multipactoring, arc discharge, and cyclic fatigue from pulsed heating. Some of these processes tend to be self-limiting, either because the structure properties become significantly altered (e.g. beam loading from dark current changes the cavity impedance disrupting power flow into the cavity) or because the source of the problem has been destroyed (e.g. explosive field emission leading to the ablation of the surface emitter). Other processes cause damage to accumulate over time.

Breakdown studies using single cell cavities[4] and multicell cavities[5,6] show substantial erosion of the high electric field surfaces on the irises. Simulations of rf

breakdown[7] have suggested that the damage may arise from very large electron current densities (~10^7A/cm^2) emitted during an rf breakdown event that can flow once large ion currents are established and help neutralize the space charge. The use of tungsten in these high field areas of the 30 GHz CLIC structure has allowed conditioning to 150 MV/m gradients without damage[8].

In the absence of outright breakdown, high gradient structures still experience cyclical stresses due to pulsed heating from the applied rf power. As the fields penetrate just a few skin depths into the metal surface, the heat is deposited in a shallow layer (typically microns), resulting in localized temperature rise, and an associated stress. Experimental studies on x-band cavities[9] have showed cracking and grain dislocation of copper after 10^7 pulses at 85 K, significantly less than the 110 K limit that a straightforward calculation based on the yield strength of copper would indicate[10].

For laser pulses, the primary damage mechanisms are thermal ablation (i.e. pulsed heating of surface material to the boiling point) and multiphoton ionization, with a gradual transition from one mechanism to the other occurring for pulse durations shorter than ~10 ps[11]. For pulses significantly shorter than 10 ps, the damage threshold is independent of the pulse length, permitting an increase in surface electric fields without damage.

Luminosity Requirements

For high energy accelerator applications, luminosity is a key requirement. Beamstrahlung limits horizontal spot size reduction, making increase in beam power and decrease in vertical spot size the only degrees of freedom for achieving luminosity. For the next generation linear collider, 0.5 TeV center-of-mass energy and 5.5×10^{33}/cm^2/s luminosities are required. Present NLC-Ib parameters result in a 9.6 MW average beam power[12]. As cross sections scale inversely with the center-of-mass energy squared, luminosities must increase to compensate, and beam powers must also increase. Power efficiency from wall plug to beam power is therefore very important for future high energy colliders.

Increasing the beam power can be accomplished a number of ways, each with significant side effects. The machine repetition rate can be increased, but this requires either high average power from the sources, or a large recirculating power, if the power pulse is stored and reused on successive machine shots. The number of beam micropulses within the power pulse can be increased, and the charge within a single micropulse can be increased, but each change will make the long- and short-range wakefields stronger. The development of high order mode (HOM) dampened structures (such as the NLC DDS structure) or structures that radiate away the HOMs (such as the photonic band gap structure) will be needed to control beam breakup.

Decreasing the vertical spot size requires better vertical beam emittance, which requires better sources or a reduction in the micropulse charge. In addition, however, ground motion at the interaction point must be more carefully damped out to maintain the smaller spots in collision.

The availability of power sources is also an important factor in determining what methods are worth exploring and what gradients are possible. The accelerating gradient depends directly on the stored energy density, which in turn is directly dependent on the source power and wavelength $G \sim P\lambda^{-2}$. This ratio is a structure-independent figure of merit for comparing the ability of various power sources to produce gradient. Figure 1 shows the source energy density for various microwave tubes, the CLIC two beam accelerator, free electron masers and lasers (FEMs and FELs), and finally lasers.

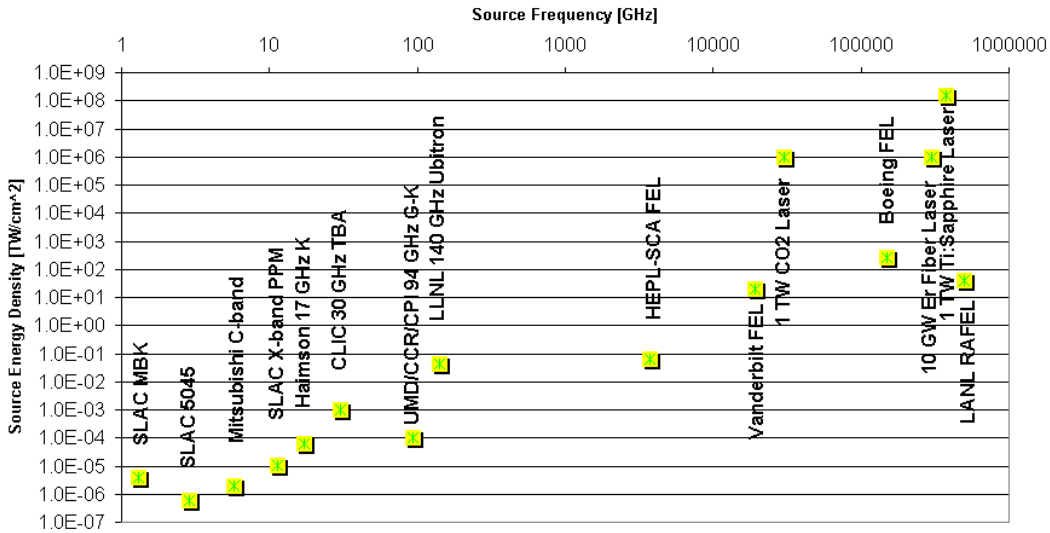

FIGURE 1. Power sources for accelerators plotted by output energy density, $P\lambda^{-2}$ as a function of source frequency.

Figure 2 shows wall-plug to photon efficiencies for the same group of power sources. Power output from conventional microwave tubes scales with the transverse cross-sectional area of the device, with various geometric tricks (e.g. using higher-order mode interactions, annular or sheet beams, and so on) making possible significant increases in power, but without changing the fundamental scaling of the device, $P \propto \lambda^2$. Lasers have no such power scaling with frequency.

Traditionally, lasers have suffered from very poor power efficiencies, with the CO_2 laser being among the best at 3-5%. By comparison, microwave tubes surpassing 50% wall plug to rf efficiency have been available for decades. Laser power efficiency depends largely on two aspects, the first is the power efficiency of the pump, the second is the "quantum defect", or difference in energy between the pumping transition and the lasing transition of the media. Flash lamp pumping suffers from both poor electrical efficiency and poor spectral efficiency, with only a narrow portion of the broadband output from the flashlamp contributing to the laser output. Solid state diode pumping, by contrast, is both electrically and spectrally efficient, with wall-plug to pump photon efficiencies of 50% and precise spectral overlap with the pumping

transition possible. Research on new laser materials has led to a wealth of media that have small quantum defects, with the best having slope efficiencies (i.e. ratio of optical power out to optical pumping power in) approaching 86.9%[13]. Combined with diode pumping, these lasers have wall-plug to photon efficiencies that rival microwave tubes.

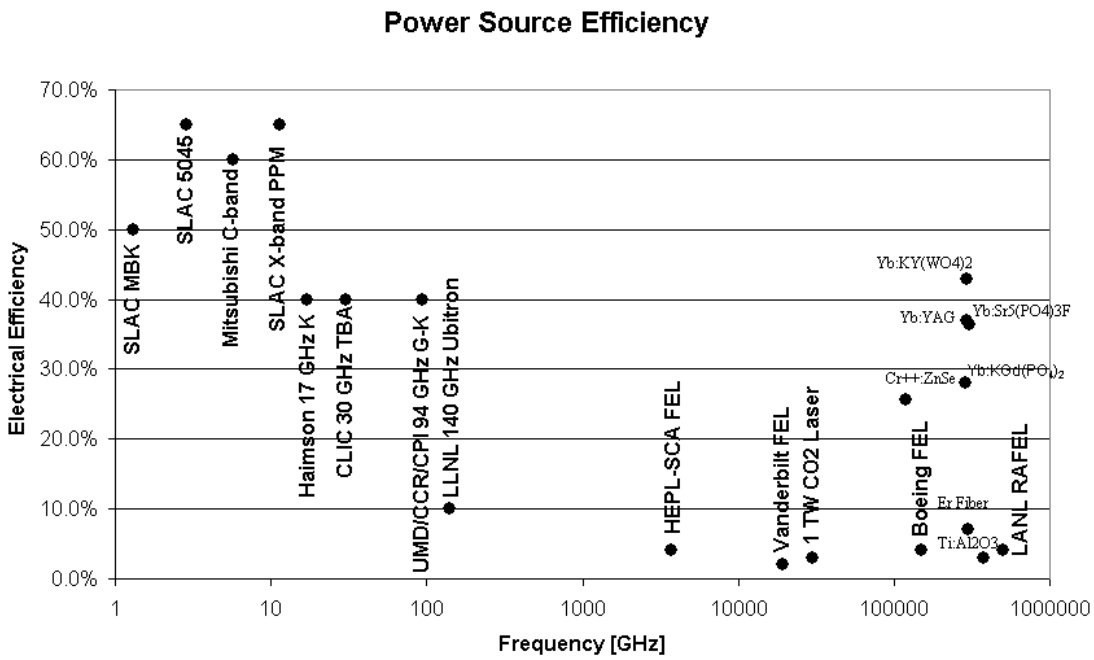

FIGURE 2. Power sources for accelerators plotted by efficiency. For microwave and millimeter wave tubes, the power efficiency of the tube is plotted (excluding modulator and pulse compressor efficiencies). For laser efficiency, wall-plug-to-photon efficiencies are shown.

A key development in laser research has been the demonstration of locking of the optical carrier to an external reference. Typical mode-locked lasers have precisely determined pulse envelopes within which the optical carrier has slowly evolving phase. Several groups worldwide[14,15] have succeeded in locking the optical carrier to an external microwave reference, a key step to phase synchronization of many lasers, as is needed for a large accelerator.

Structure Fabrication Methods

The availability of inexpensive fabrication methods for making structures is an important factor determining what methods are practical. As many acceleration methods rely on structures whose dimensions and dimensional tolerances are strictly determined by the power source wavelength, the availability and cost of fabrication methods will strongly influence which accelerating methods are practical. Figure 3 below summarizes the capabilities of some common methods used or proposed for use in making accelerator structures. The left end of each bar represents the largest object

that can be handled by the process. The right end and diamond represent the smallest machinable feature size and dimensional tolerance, respectively.

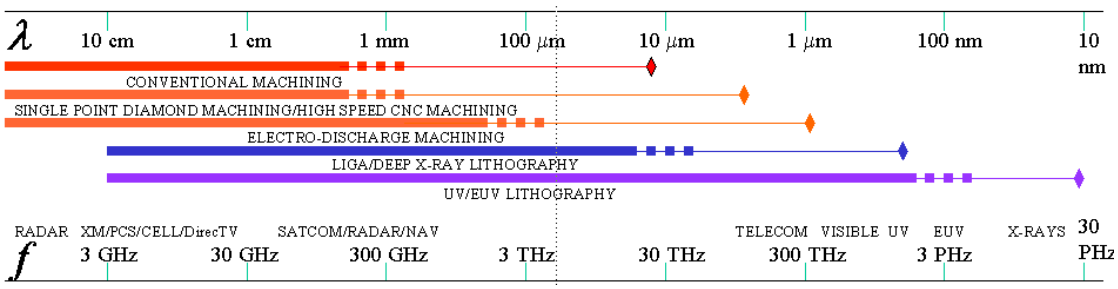

FIGURE 3. Usable dimensional range and tolerance of fabrication methods used or proposed for accelerator structures.

Conventional machining has evolved to include single point diamond machining and ultra high speed (>100krpm) milling, each capable of excellent accuracy and surface finish and tolerances approaching a few microns. Adiabatic stamping has been proposed for mass producing accelerator cavities either in approximate form for later machining (as for the NLC), or in final form. Electrodischarge Machining (EDM) can achieve dimensional accuracy of 1 μm.

Lithographic fabrication techniques have not been used extensively in accelerator R&D except for occasional prototypes. Lithography typically requires structures to be objects of extrusion unless multiple process steps are used. Unlike conventional machining, the complexity of the structure does not significantly influence either the fabrication cost or the yield. LIGA (Lithography, Electroformation and Moulding) offers promise for making millimeter-scale metal structures with a precision approaching 1 micron. Semiconductor lithography techniques are appropriate for still smaller structures, typically in the few tens of microns at most, but is capable of holding tolerances in the 10 nm range.

Economic Considerations

Cost is perhaps the most important practical consideration influencing accelerator design and development. For any application, whether it is high energy accelerators, medical or industrial machines, reliability and low cost are essential. In addition, the up-front research and development costs are also relevant. Historically, the government has funded a great deal of the R&D required to produce most of the technical components for its accelerators, with early computer development, klystrons, superconducting cable, and microwave accelerating structures being some of the more outstanding examples.

Industrial R&D has grown to a level that now significantly exceeds government R&D. The US government will spend approximately $7.7 billion of net revenues of $2.1 trillion on science research conducted by the DOE and NSF in 2002[16]. By contrast, the semiconductor industry alone had revenues of $168.6 billion in 1999 and spent 13% or nearly $22 billion on R&D[17]. The top R&D investor in the industry, Intel, alone spent $4.5 billion in 2001[18]. The telecommunications industry is projected

to have had revenues (including services) in 2001 of $1 trillion[19], of which an estimated $105.4 billion was equipment sales[20]. In 2001 the thirty largest telecommunications companies together spent $25 billion in R&D, with the largest R&D investor, Lucent, spending $7.4 billion[18].

With such vast resources being invested in various technologies, it is natural to ask whether any of it is applicable to accelerators. Much of the R&D work will not be applicable, but if it is possible to benefit from industry experience on a significant portion of the technical components, it will greatly leverage accelerator R&D efforts.

CONCLUSION

Electromagnetic structure based and vacuum acceleration remains an active area of accelerator research, with real progress possible on several fronts. Material damage remains the central issue for obtaining high gradients in structures of any kind. Continued progress in fabrication methods and in power sources, particularly two-beam rf sources and lasers, will also be key to improving gradient and power efficiency.

Real progress on vacuum acceleration (either ponderomotive or higher order multiphoton process-based) will depend on the availability of extraordinary lasers capable of producing the peak power required. Making these schemes practical will depend on making these very large laser systems power efficient, but the potential for extreme gradients in the absence of boundaries makes this an interesting challenge.

Laser acceleration using dielectric structures produced by lithographic methods offers great promise as a way of capitalizing not only on the extraordinary power available from lasers, but on the wealth of research and development carried out by the semiconductor and telecommunications industries. Recent gains in laser efficiency and carrier phase locking are evidence of rapid progress in lasers, and an indication of the exciting developments to come.

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