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Report of the Electromagnetic-Structure Based Accelerator Concepts Working Group

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Abstract. We detail the most pressing physics and technical issues confronting short-wavelength acceleration. We review new acceleration concepts that are proposed and under development, and recent progress on technical issues such as structure fabrication and material damage. We outline key areas where work is still needed before a reliable assessment of the value of working at wavelengths below 1 cm can be made. Possible ways to enhance collaboration and progress in this important area are also discussed.

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CHALLENGES OF VERY HIGH-FREQUENCY ACCELERATION

Coherent short-wave sources (λ<1 cm or f>30 GHz) offer energy densities and pulse lengths unmatched by conventional microwave sources. In consequence, higher gradient acceleration and very short electron pulses can be produced, provided the severe technical challenges of working with very short wavelengths can be overcome. Linear acceleration of high-quality beams with such short wavelengths requires electron bunch lengths that are below ~300 fs for mm-wave (λ~1 cm) acceleration, ~10 fs for terahertz acceleration, and ~0.03 fs for optical acceleration (λ~1 μm). Such short bunches naturally produce short radiation pulses by, e.g., transition or synchrotron radiation processes.

The EM Structures Working Group reviewed these challenges, and identified the most important issues which must be resolved before potential applications of short-wavelength acceleration can be pursued. The highest priority challenges are:

- Demonstrating transport and preservation of the electron beam through small structures
- Developing suitable high-peak-power THz and mm-wave power sources
- Developing suitable fabrication methods for structures and other beamline components (magnets, diagnostics, EM transmission components, etc.)
- Developing suitable injector technologies

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- Determining the breakdown strength of materials for the wavelengths, materials, and pulse lengths of interest

In addition, the working group identified other issues which were less critical because either the issues impact operating parameter choices or because there has been progress to date indicating that these issues are not as serious. These are:

- Establish gradient limits due to thermal loading, thermo-mechanical distortion, and cyclic fatigue; evaluate repetition-rate limits
- Establish gradient limits due to Lorentz force detuning
- Quantify radiation damage from gamma rays, neutrons, and direct beam strike
- Devise methods to provide vibration/ground motion isolation/cancellation
- Develop diagnostics which can resolve beam properties on the nanometer and attosecond scales
- Develop efficient EM power couplers consistent with maintaining good beam quality
- Develop needed analytic and numerical tools
- Develop specialized beam testing facilities which can prepare test beams with the required properties
- Develop other specialized testing equipment, e.g. material damage testing apparatus
- Develop in-house fabrication and measurement capability for microstructures

NEW STRUCTURE CONCEPTS

The challenge of developing an accelerator structure that both efficiently couples EM radiation to electrons and is straightforward to fabricate is being addressed with a wealth of new concepts for accelerators. Six new accelerator concepts, spanning frequencies from the microwave range to the near-IR, were either introduced or in preparation for experimental demonstration.

In the microwave range, P. Schoessow presented work led by Euclid Techlabs to develop active materials for x-band amplification and to develop structures for using such materials to accelerate electrons [2]. Fullerene/nematic liquid crystal solutions show strong electron paramagnetic resonance (EPR) strengths, and can be optically pumped into a spin polarization inversion. The stored energy can be spontaneously released by an EM wave at the resonance frequency (which set by the media and an external magnetic field), leading to coherent amplification of the wave. Euclid Techlabs has been developing solutions with increased bandwidth and spin density for active media-based particle acceleration (or low-noise microwave amplification) near 9.3 GHz (B=0.3T). Sophisticated analytic and numerical models incorporating active materials have been developed to evaluate active media-based accelerators. Suitable structures for optically pumping and beam testing active-media accelerators are proposed and will be tested in the near future.

S. Antipov presented the work of an Illinois Institute of Technology/Argonne Wakefield Accelerator collaboration to make and test left-handed metamaterials (LHM) from discrete circuit elements [3]. A wide range of EM properties (ε,μ) can be manifested in the bulk by the collective interaction of small lumped-element circuits for wavelengths that are large compared to the characteristic circuit size. By selecting the RLC values of the circuits appropriately, materials with simultaneously negative permittivity and permeability can be simulated. Such materials exhibit negative index of refraction, and a wave vector that is oppositely directed to the group velocity. This collaboration has been constructing and testing metamaterials for accelerators for use at 10 GHz, and investigating several potential geometries for using LHMs to accelerate electrons.

M. Shapiro presented analytic and simulation work exploring surface and bulk modes of a photonic band gap crystal designed to emulate the properties of plasma [4]. By appropriately selecting the crystal lattice spacing and web thickness, a speed-of-light surface wave can be realized that can accelerate particles, and unlike the plasma equivalent, this method offers the advantages of a sharp, well-defined boundary, is purely solid-state, and is analytic tractable. Examples of crystals with accelerating modes near 21 GHz were described.

In the millimeter wave range, C. Wang presented a two-beam 34 GHz dielectric-lined accelerator (DLA) under development by an Omega-P/Yale/Columbia collaboration [1]. The structure operates in the LSM_{31} mode, and has been optimized for a 10:1 transformer ratio. Driven by a resonantly-spaced train of five 1 nC electron bunches, gradients of ~1.3 GV/m are anticipated in the accelerating channel. Since the structure is essentially a rectangular waveguide loaded with three planar dielectric slabs, fabrication is straightforward. This group has also fabricated a LSM_{216} test cavity for evaluating damage threshold of dielectric slabs, and has performed cold tests. Surface stresses of up to 0.8 GV/m can be applied with a 10 MW, 34 GHz source.

In the terahertz range, S. Tochitsky presented plans to demonstrate vacuum laser beat-wave acceleration at the UCLA-Neptune lab, and to apply it to generate an electron pulse train with terahertz time structure for radiation generation [5]. Two lasing lines of the Mars CO_2 laser will be used to produce the beat-wave with 3 or 4 THz frequency, which will ponderomotively energy modulate the 10-14 MeV electron beam. The beam will then traverse the STELLA-LBW undulator, generating 20-60 kW of THz radiation power. In addition to providing a powerful source of THz radiation, this experiment will demonstrate the laser beat-wave acceleration mechanism for the first time.

For the far-infrared range, J. Rosenzweig presented initial design studies and plans to test a high-gradient helical IFEL with optical guiding for use at 10 μm [6]. Designed to provide a factor-of-7 increase in beam energy (from 14 MeV to 100 MeV, corresponding to 107 MeV/m gain) with modest laser input power (50 GW). An open waveguide will be used to confine the laser, and a modest solenoid field (0.5 T) will guide the electrons.

G. Shvets presented work at UT Austin to develop a surface-wave accelerator using the negative permittivity material silicon carbide [7]. The structure is composed of two slabs of SiC spaced by $\lambda/3$ and illuminated normally to the electron beam propagation, with gratings used to match the free-space 10 μm radiation into the structure from each side. This simple geometry is readily produced by lithographic techniques, and the material is expected to tolerate 300 MV/m field stresses. Simulations of field enhancement and phase velocity selection by periodic arrays of holes in the SiC were also presented. Candidate structure components have been fabricated, and testing is underway. Experimental evidence for excitation of surface waves in ½ of the accelerator structure has been seen in increased losses measured as the correct coupling conditions are achieved.

REVIEW OF PROGRESS ON TECHNICAL ISSUES AND NEAR-TERM R&D PLANS

A number of reports on technical advances in methods and technologies essential to making short wavelength accelerators were presented. We summarize these reports following the list of challenges given earlier.

Demonstrating transport and preservation of the electron beam through small structures: C. Sears discussed simulations and a fabricated permanent-magnet quadrupole triplet designed to match conventional beams into laser accelerating structures for test [8]. The primary issue is that microwave linacs produce beam emittances that are orders of magnitude higher than the "matched" emittance for optical accelerators, requiring very short focal length lenses to match, and consequently a very short depth of focus.

Developing suitable high-peak-power THz power sources: C. Sung and A. Cook of UCLA reported on two different methods for producing high peak power pulses of terahertz radiation [9,10]. One effort is centered on generating the difference frequency of the 10.3 and 10.6 μm lines from two separate CO_2 lasers in a GaAs crystal, which has already yielded 2 kW peak power pulses of 200 ns duration. The second method produces terahertz power through wakefield interaction in a DLA with tightly bunched 10-15 MeV beams. Simulations predict 5 MW peak power, upgradeable to 40 MW peak when shorter bunches from the UCLA hybrid injector are available. Each source is tunable, the first depending on available laser transitions of the CO_2 molecule, the second depending on the geometry of the dielectric-line waveguide.

Developing suitable fabrication methods for structures and other beamline components (magnets, diagnostics, EM transmission components, etc.): A. Kanareykin reported on progress making CVD diamond tubes for DLAs. Diamond tubes with dimensions suitable for use in the 500-800 GHz have been successfully grown [11]. Dehydrogenating the deposited diamond has been shown to reduce multipactoring (reducing secondary yields from 60 to ~1), and will be explored.

Developing suitable injector technologies: C. Sears reported on simulations and the fabrication of components for a tunable near-IR microbuncher [8]. A hybrid undulator and dipole chicane have been fabricated and characterized for prebunching beams in the 1-2 μm range for laser accelerator structure tests.

P. Musumeci reported on an ingenious conceptual design and the benefits of using a staged optical IFEL prebuncher to greatly enhance radiation from an x-ray SASE FEL, decreasing the required undulator length [12].

Determining breakdown strength of materials for the wavelengths, materials, and pulse lengths of interest: M. Thompson reported on beam-driven wakefield tests performed on fused silica [13]. High-energy beams (28.5 GeV) were focused through capillary tubes of varying diameter, and emitted light from the end of the capillary tube monitored. A clear transition from low-intensity Cerenkov radiation to high-intensity light emission as the electron bunch length was reduced (raising both the peak field stress, and the spectral cutoff frequency) was taken as the indication of breakdown in the silica tubes. On this basis, breakdown was observed at around 4 GV/m applied surface fields, corresponding to ~2 GV/m decelerating gradient in the capillary.

B. Cowan reported on pump-probe experiments conducted on pure silicon wafers using 1550, 1700, 1900, and 2100 nm picosecond pulses [14]. Shot-by-shot data was recorded until the surface of the silicon showed sufficient physical damage to scatter the probe beam. 1550 nm is especially attractive as it is in the telecommunications band. The damage threshold was measured to be ~ 1 GV/m at 1550 nm, and showed a modest increase with increasing wavelength.

Developing diagnostics which can resolve beam properties on the nanometer and attosecond scales: A joint working session was held to hear short presentations on measurement techniques applicable to optical-scale bunches. W. Kimura and M. Uesaka reviewed techniques successfully used to date, with CTR offering greatest promise for femtosecond-class measurements. D. Kaganovich reviewed timing synchronization techniques used for plasma accelerator staging experiments. C. Sears, and discussed planned measurements of microbunching at 0.8 mm using COTR techniques. B. Cowan described use of deflection-mode PBG structures for beam position detection. S. Banna presented a metallic-post array BPM [15]. The pickup is a phased array antenna optimized to radiate in the backward direction (giving easy separation of signal and electron beam), with the difference in the relative strengths of the “left” and “right” lobes giving information about the beam’s horizontal position. L. Schachter proposed using resonances in a population-inverted gas to diagnose bunch length and radius [16]. The strength of the stimulated emission from the gas gives information about Fourier content at the gas’s resonant frequencies, and hence about the electron the bunch length.

Developing efficient EM power couplers consistent with maintaining good beam quality: M. Lincoln presented results of work to generate the TM^*_{01} mode required for free-space to TM_{01}-like mode coupling for fiber structures [17]. Experimental demonstrations of coupling into a photonic band gap fiber, with characterization of the transmitted mode’s near-field mode pattern, demonstrated good mode purity.

Developing needed analytic and numerical tools: J. Cary described code development work at Tech-X to model photonic band gap structures [18]. This class of problem is difficult as it requires solving for a high eigenmode of a highly overmoded problem (typically 10λ x 10λ in extent). Time-domain techniques for more rapidly locating and optimizing such eigenmodes were discussed.

For simulating active-media based accelerators, A. Tyuktin described theoretical analysis and numerical model development [19]. P. Schoessow described inclusion of active media in the EM simulation code Arrakis [2].

Develop specialized beam testing facilities which can prepare test beams with the required properties: S. Shchelkunoff described preparations for the LAser Cyclotron Auto-Resonance Accelerator (LACARA) experiment at BNL-ATF, which will use 10 μm laser radiation and a superconducting solenoid for the guide field [20]. Energy gains of up to 20 MeV for 800 GW power input are expected.

E. Colby reported on progress constructing the E-163 Laser Accelerator Experiment at SLAC [21]. The facility will provide 60 MeV electron beams with very low energy spread (10^{-4}), and 10 GW Ti:Sapphire laser pulses for laser acceleration experiments. The facility is open to outside users; first experimental operation is expected before the end of the year.

M. Conde reported on recent successes at the Argonne Wakefield Accelerator facility [22]. The facility provides short trains of high peak current bunches (up to 6 kA) for wakefield experiments. Recent experiments have demonstrated up to 86 MV/m gradients in x-band DLA structures. The facility serves a variety of users from industry, universities, and other national labs.

There was no recent progress to report on the issues of: (1) establishing gradient limits due to thermal loading, thermo-mechanical distortion, and cyclic fatigue, (2) establishing gradient limits due to Lorentz force detuning, (3) quantifying radiation damage from gammas, neutrons, and direct beam strike, (4) developing methods to provide vibration/ground motion isolation/cancellation, or (5) developing in-house fabrication and measurement capability for microstructures.

CONCLUSION

Excellent progress has been made on many of these issues since the 2004 AAC conference. Three first-of-kind experiments demonstrated new acceleration techniques: the MIT group demonstrated electron acceleration in a 17 GHz metallic PBG structure with 35 MV/m energy gain [23]; the Stanford/SLAC collaboration demonstrated inverse transition radiation acceleration with visible light, producing a peak axial field of 40 MV/m [24]; and the Israel Institute of Technology group experimentally demonstrated an entirely new class of acceleration mechanism—Particle Acceleration by Stimulated Emission of Radiation [25].

Material damage studies revealed that interesting gradients can indeed be achieved with real materials for terahertz and optical wavelength accelerators powered by picosecond-duration pulses. Fused silica showed a damage tolerance of 4 GV/m (peak surface field) for broadband terahertz pulses; silicon a damage tolerance of 1 GV/m for narrowband laser pulses.

With the promise of high gradient, extremely compact accelerators, and femtosecond and attosecond class electron bunches, short-wavelength acceleration is an area of growing interest. Serious technical issues remain to be addressed, but progress has been made in key areas of material damage, structure fabrication, structure design, preparation of bunches for injection, and coupling. Continued work is needed, and sharing of information, techniques, and specialized apparatus (e.g. beam test facilities, material damage studies facilities) is essential to making rapid, efficient progress. The R&D plans presented at this conference address many of the essential challenges, and will provide an excellent foundation for developing this new class of accelerator technologies.

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