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Summary Report of Working Group 3: Laser and High-Gradient Structure-Based Acceleration

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Summary Report of Working Group 3: Laser and High-Gradient Structure-Based Acceleration

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Abstract. Working Group (WG) 3 assessed current challenges in developing advanced accelerators based on RF and laser-driven electromagnetic (EM) structures and surveyed the state-of-the-art research and methods addressing these challenges. A critical challenge for EM structures is the gradient limitation imposed by RF breakdown, pulsed heating, dark current, quench, thermal breakdown and other factors, depending on structure type, pulse width, duty cycle and regime of operation. Other challenges include developing approaches to reduce cost and size while at the same time greatly increasing performance. WG 3 examined a variety of approaches to the improve gradient, cost, size, and performance of advanced accelerators including dielectric loaded structures, photonic bandgap structures, solid-state crystal structures, terahertz generation technologies, inverse FELs and undulators, micro-accelerators and light sources, high gradient structures, and RF sources. These approaches cover a large range of frequencies and span a considerable parameter space including room temperature and superconducting devices, THz and optical EM, and dielectric-based structures. The state of the art was surveyed in RF source and component development, materials development, advanced micro- and nano-fabrication technologies, and surface coatings for accelerator applications. WG 3 also attempted to address challenges beyond gradient limitation, including simulation challenges, high order mode characterization, measurement, and damping, field distributions producing low emittance, power efficiency, and impact of fabrication tolerances.

Keywords: accelerating structure, dielectric loaded structures, photonic bandgap structures, solid-state crystal structures, terahertz, inverse FELs, undulators, micro-accelerators, light sources, high gradient structures, RF sources, laser driven acceleration.
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OVERVIEW

This report provides an overview of the presentations and discussion in Working Group 3 on Laser and High-Gradient Structure-Based Acceleration. In previous years the emphasis was primarily on technologies applicable to future high-energy colliders. With the 2012 Workshop, there has been a small, but noticeable shift to R&D and technologies for a broader range of applications. The drive toward more compact, less expensive, and higher performance accelerators is stimulated by emerging applications, that in addition to discovery science tools include compact light sources, advanced radiography, and the detection of materials of interest with accelerator-based radiation sources in a field environment. Some of the R&D approaches examined at this workshop seek to leverage dramatic advances in laser and nanofabrication technologies that are being driven by applications other than accelerators. Approximately 45 papers were presented across nine topical areas that included dielectric loaded structures, photonic bandgap structures, solid-state crystal structures, terahertz technologies (joint with WG4 and WG5), inverse FELs and undulators, computation (joint with WG2), micro-accelerators and light sources, high gradient structures, and RF sources.

PHOTONIC BANDGAP STRUCTURES

Since the first demonstration of acceleration in a room temperature photonic bandgap (PBG) structure at MIT in 2005, these structures have been a subject of intense research because of their potential to reduce long-range wakefields. E. Simakov of Los Alamos described an approach using a higher frequency superconducting niobium PBG structure to raise the beam breakup limit in high current accelerators. Since the experience base for building superconducting PBG structures from niobium is in its infancy, two 2.1 GHz PBG resonators were built by Niowave and tested at Los Alamos. This work demonstrated proof-of-principle operation of superconducting RF PBG cavities with a maximum gradient of 15 MV/m at 1.9 K, very close to theoretical predictions.

Attempting to push the gradient limitations of superconducting PBG cavities, Simakov designed a new superconducting resonator with elliptical rods that have 40% lower peak surface magnetic fields than the round rod version, with high order mode (HOM) suppression as good as the round rod resonator. The fabrication and testing of this design is planned for 2013. This superconducting PBG technology holds the promise of significantly reducing the size of superconducting accelerators and increasing the brightness for high power FELs.

Research is also moving forward on multi-cell accelerating structures incorporating PBG cells. S. Arsenyev is designing a superconducting five-cell module with one PBG cell flanked on both sides by two elliptical cells. The design is such that the probability of quench in the PBG cell is no higher than in the other elliptical cells. The design is also optimized for HOM suppression by breaking the symmetry of the regular triangular lattice.

Room temperature copper PBG technology continues in development with the fabrication of a 16-cell structure at 11.7 GHz by Simakov to measure wakefield effects using the electron beam from the Argonne Wakefield Accelerator (AWA). B. Munroe of MIT observed pulsed heating in a round rod PBG producing a temperature rise exceeding 200 K and causing damage. A new room temperature structure has been designed with elliptical rods that reduce the surface magnetic field and consequent temperature rise to less than 100K. A breakdown probability of 3.6 x 10^{-3}/pulse/m was achieved at 128 MV/m gradient and 150 ns pulse width. The PBG cavity with elliptical rods achieved twice the gradient of round rods at the same breakdown probability.

Michael Shapiro of MIT is investigating both metallic and dielectric PBG structures operating at 23 and 17 GHz, respectively, in a TM_{02}-like mode. A TM_{02} PBG structure with sapphire rods has been designed that has the advantages of no H-field enhancement at the rods and a larger permissible beam line cross-section. The TM_{01} mode is not confined. This design could conceivably be used up to THz frequencies. Removing radial rows of rods (along the radius) allows for damping of HOMs. A high power test at 17 GHz is planned that should achieve 100 MV/m. Detailed simulations continue on metallic structures to examine wakefields and to look at behavior at the Dirac point at the crossing of dispersion curves (in the propagation band, not in the bandgap). Cold testing showed that a highly overmoded cavity operating at the Dirac point demonstrates single mode operation at 23 GHz (in a 11GHz cavity). The Dirac point approach could be promising for high power microwave applications because this type of cavity could be used as a klystron output cavity.

SOLID STATE CRYSTAL STRUCTURES

In the push to higher gradients, another approach is to use laser energy to generate the accelerating fields in novel micro-structures. This approach utilizes micro-electro-mechanical systems (MEMS) and photolithography fabrication techniques to produce tiny structures into which laser energy can be coupled to produce intense electric fields in the desired configuration to accelerate beams with high efficiency. This approach gives rise to the concept of "the accelerator on a chip." Acceleration using laser-driven photonic crystal structures takes advantage of two technologies that today have a major impact on hardware advancement: lasers and semiconductor manufacturing. State-of-the-art semiconductor fabrication techniques enable highly reliable, mass production of devices. At the same time the rapid development of high power, high pulse repetition rate lasers is moving forward at an exponential rate while the cost/watt is similarly decreasing exponentially. This advancement will continue and is happening independently of the accelerator field; however if the accelerator field can effectively tap these developments then revolutionary advancements are possible. The dielectric structures have high breakdown thresholds and therefore are capable of high gradients. Because the structures are physically small with periods on the order of a micrometer or less, they are suited to mass production using MEMS and other techniques.

K. Soong at Stanford/SLAC described the effort to produce a complete grating-based laser driven accelerator. The accelerator includes the electron source and a cascade of structures for acceleration, focusing, deflection, and diagnostics. The significance of this work is that it will demonstrate the integration of photolithographically compatible accelerator components using monolithic semiconductor manufacturing techniques. Staging lower energy modules in series can produce higher energy accelerators. Materials under consideration for use in these structures are SiO_2, silicon, and copper. SiO_2 is the material of choice because it is the most robust. Silicon is the most developed for complicated fabrication techniques but has an order of magnitude lower breakdown threshold. There is a 100x difference between the damage threshold of copper and SiO_2, with SiO_2 being the more robust.

E. Peralta of SLAC described work to design, fabricate, and test a fused silica transmission-based dual layer grating structure for direct laser acceleration. Fabrication was done at the Stanford Nanofabrication Laboratory using lithographic techniques. This design simplifies the coupling of the laser energy into the device. Since the laser beam enters the structure in a distributed fashion with the laser field normal to the beam path there is no group velocity mismatch or complicated modes to excite and control. Beam tests with 1 ps bunches at the NLCTA succeeded in achieving 5-7% beam transmission through an 800 nm period structure with a 1.2 μm gap.

Silicon "woodpile" photonic crystal structures at the micron scale exhibit electromagnetic behavior very similar to conventional disk-loaded waveguide accelerator cells making the woodpile structure a good candidate for high-gradient laser driven acceleration. J. England and Z. Wu described design procedures and simulation results for coupler designs to couple the laser energy into the structure. Observing the similarities between conventional disk-loaded waveguide and the woodpile waveguide, several approaches to coupler design implemented for multi-cell RF cavity structures were applied to the woodpile accelerator design. The three different methods used included the traveling wave match method based on the S-matrix, the periodic VSWR method, and the TE to TM coupling iris design. Simulations of a carefully designed mode-launching coupler show 95% transmission efficiency from the silicon-on-insulator waveguide to the woodpile guide.

Another approach to advanced particle acceleration hopes to leverage significant developments in the fiber optics industry on photonic crystal fibers. J. England of SLAC described his approach to couple laser energy into an optical fiber for the purpose of accelerating beam. One of the technical challenges is to detect and characterize the speed of light modes in such fiber structures. England used a speed-of-light electron bunch from the NLCTA beam (60 MeV, 1 ps) to excite the structure and characterized the Cherenkov wakefield excitation in the fiber. Although commercial hollow-core fiber was used for the experiment, it is not optimized for use as a particle accelerator. The experiments in the future are planning to use single-mode fibers optimized for accelerator applications.

G. Shvets at UT Austin is investigating a novel approach for a compact solid state accelerator based on surface waves in a structure composed of two SiC layers epitaxially grown on silicon slabs, separated by the acceleration channel. This structure has been experimentally shown to support both accelerating and deflecting surface modes. This unconventional approach using a semiconductor material provides a possible path to get around the limitations of conventional approaches with metals that break down and dielectrics that charge up. Prism coupling is used to couple the laser energy into the structure.

The problem of acceleration of nonrelativistic beams to an energy high enough for injection into a relativistic dielectric laser accelerator is being investigated by J. Breuer at the Max Planck Institute of Quantum Optics. This work has achieved a proof of concept demonstration of acceleration of non-relativistic electrons using a fused silica transmission grating and Ti:Sa laser pulses. With a single grating and 100 nJ pulse energy at 100 nm distance, an energy gain of 280 eV was achieved with a gradient of 50 MeV/m.

Wakefield and beam dynamics simulations of the grating structure were presented by B. Montazeri of SLAC/Stanford. Simulations are examining energy loss, instability, and beam deflections. The goal is to fully characterize the accelerator and optimize the final design.

DIELECTRIC LOADED STRUCTURES

An X-band standing wave dielectric loaded accelerating structure was developed and fabricated by C. Jing at Euclid Techlabs and tested at Argonne. In order to build up a high gradient with limited RF power a standing wave structure was chosen. During testing multipactor prevented the gradient from going beyond 10 MV/m. A new design is underway to suppress multipactor by using a several kG solenoidal magnetic field.

O. Sinitsyn at U. MD. has developed a new 3D self-consistent model for multipactoring in dielectric loaded accelerator structures that agrees well with available experimental data. The simulations take into account the radial and axial motion and show that an external magnetic field can be used for multipactor suppression.

TERAHERTZ

S. Antipov of Euclid Techlabs has developed an approach for tabletop terahertz generation using a rectangular (DC) beam with a linear energy chirp. The beam's self-wake modulates the beam energy. A chicane then converts the energy modulation into a beam density modulation. Using this technique bunching has been demonstrated in the THz regime. Results were described from an experiment at the ATF at BNL. This approach has a tuning range from 0.3 to 1.5 THz with an energy per pulse in the millijoule range and presents an alternative to generating THz radiation using a high-energy short-bunch such as FACET.

Antipov is also investigating the use of diamond for dielectric accelerating structures because of its low loss, high breakdown threshold, and high thermal conductivity. Measurements have been done of THz wakefields produced by a subpicosecond, relativistic electron bunch in a diamond loaded accelerating structure. The fields produced by a drive bunch accelerated a trailing witness bunch. The energy gain of the witness bunch was measured as a function of separation distance from the drive bunch, which describes the time structure of the generated wakefield.

INVERSE FREE ELECTRON LASERS AND UNDULATORS

Inverse Free Electron Lasers (IFELs) are attractive accelerators for applications requiring hundreds of MeV to few GeV electron beams in a compact (on the scale of several meters) footprint, such as inverse Compton scattering based x- and γ-ray sources and soft x-ray FELs. Two IFEL experiments that build on previous IFEL proof of principle work are currently underway. S. Anderson described an IFEL accelerator at LLNL being built in collaboration with UCLA. The key technology development of this project is to use a short-pulse (100 fs) Ti:Sapphire laser to drive the accelerator. Using 800 nm radiation and the strongly tapered, 50 cm long UCLA/Kurchatov undulator, 150 MeV energy gain is predicted. This IFEL will operate at 10 Hz repetition rate so that it can be evaluated in terms of emittance preservation of the accelerated beam.

J. Duris of UCLA presented the RUBICON IFEL experiment being performed at BNL by collaboration between UCLA, RadiaBeam Technologies, and BNL. This experiment uses a helical permanent magnet undulator design that has increased accelerating gradient compared to planar undulators using the same laser intensity. The experimental design gives 112 MV/m average accelerating gradient and uses the BNL-ATF CO_2 laser. Laser recirculation is planned for a late stage of the experiment that would enable the acceleration of electron bunch trains. The novel undulator has been installed at BNL and initial experiments have shown IFEL induced energy spread. Experiments are continuing in summer 2012.

J. Hirshfield presented work developing RF undulators for compact XFEL applications on behalf of a collaboration among Institute of Applied Physics in Novgorod, Russia, Yale University, Omega-P Inc., and Columbia University. The development of high power RF sources at high frequency enables the use of RF undulators with smaller periods and larger apertures than conventional permanent magnet devices, and with fast dynamic control possible. Several undulator designs were presented which use the Omega-P/Yale 34 GHz magnicon RF source and produce 1.4–2.7 nm radiation using a 0.5 m long undulator and a 660 MeV beam. A near cut off TM_{11} mode cavity design was found to be very promising due to low input power requirements and simple design.

MICRO-ACCELERATORS AND LIGHT SOURCES

Several research groups are developing optically driven “accelerator on a chip” technologies for x-ray light source applications with a focus on integration of the electron source, accelerating structures and FEL undulators at the optical scale. J. Rosenzweig presented the Galaxie project, an all-optical FEL. Galaxie uses an optically gated X-band RF gun with flat beam conversion to match into a slab-symmetric dielectric accelerator structure followed by an optical (or potentially THz) undulator producing radiation in the quantum SASE FEL regime. The laser driver for this project is a novel 5 μm wavelength source. Naranjo presented extensive RF structure and beam dynamics analysis of the accelerator structure.

The Micro-Accelerator Platform (MAP) is another project with the goal of miniaturizing accelerators for novel applications. R. Yoder presented experiment and simulation results of work on a MAP resonant accelerator structure driven with 800 nm light. This device has been successfully fabricated and electron beam has been transmitted through the structure. Dielectric laser acceleration experiments are planned for the immediate future. Progress on the MAP relativistic electron beam source was presented by J. McNeur. The gun is a standing wave structure resonant at 800 nm incorporating a field-enhanced wedge emitter electron source. Simulations show good electron beam dynamics in the transition between low and high beta acceleration.

HIGH GRADIENT STRUCTURES

The continuing development of high gradient, normal conducting RF structures has focused on experimental and theoretical investigation of the RF breakdown process, dark current related breakdown, dark current emission and surface properties, and the physics of multipactoring. W. Gai presented work from ANL, Tsinghua, and CERN in which field and photoemission were both measured in an S-band photo-gun with a Cu cathode. Traditional Fowler-Nordheim analysis of the field emission resulted in a very large beta value inconsistent with the measured surface profile. Concurrently, photoemission was observed with 3.1 eV (low energy) photons at all field levels, implying the existence of low work function sites. An alternate analysis of the dark current data using variable β and ϕ fit the data well using low ϕ emitter sites.

F. Wang of SLAC presented two RF breakdown studies. In the first a 2-pin waveguide test structure was developed in order to study the breakdown dependence on local power flow. By varying the input power levels and the pin positioning breakdown rates will be measured with fixed E and B fields but varying nearby power flow. This work is intended to isolate some of the effects contributing to RF breakdown and to provide a more coherent picture of the breakdown process. In the second study, F. Wang presented a dark current associated breakdown model established to understand the performance degeneration of muon accelerator cavities with external magnetic field and the physics of structure high power processing, and to explain the muon cavity breakdown phenomena and the physics of RF conditioning.

R. Kishek of University of Maryland identified a new form of resonant multipactor termed the 'ping pong' mode, involving a combination of one-surface and two-surface impacts. The theory of the ping pong mode was presented and excellent agreement with simulations was observed. The new type of multipactoring results in a broader area of parameter space where multipactor can occur and has consequences for cylindrical dielectric-loaded waveguides and for magnetic insulation.

L. Faillace of RadiaBeam Technologies presented work on a high-gradient S-band standing wave structure intended to achieve 50 MeV/m accelerating gradient. The structure takes advantage of methodology and innovative design solutions developed for the X-band structures by NLCTA collaboration at SLAC, including optimized coupler design, precision surface processing and cleaning techniques, reduced pulsed heating RF cycle dynamics and improved RF thermal load management. The goal of this work is to offer a compact drop-in replacement for a conventional S-band section in research and industrial applications such as drivers for compact light sources, and medical and security systems.

RF SOURCES

A variety of new RF sources were presented in WG 3 featuring high frequency, PPM focusing, annular beam configurations, multi-frequency output, and high ratio pulse compression. R. Ives presented a number of new sources in development at Calabazas Creek Research, Inc. These included S-band and L-band periodic permanent magnet (PPM) focused klystrons, an L-band, 10 MW annular beam klystron, multiple beam inductive output tubes (IOTs), and an X-band klystron with pulse shaping for increased efficiency.

S. Gold from NRL presented work on an active high power X-band RF pulse compressor using electron beam switching. Active pulse compressors offer improved compression ratios and higher efficiencies than passive designs. Tests of an X-band two-channel active pulse compressor with a transmission-line energy storage cavity demonstrated 165 MW in a 20 ns pulse at ~18x compression, using a 9.2 MW, 1.1 μs drive pulse from the NRL Magnicon Facility.

J. Hirshfield presented a new magnicon RF source that will power a number of current advanced accelerator R&D and particle physics experiments. The magnicon design triples the input X-band frequency using a TE_{311} mode output cavity. A tube is under construction designed to operate 24/7, with output power ~25 MW in Ka-band at a 10 Hz repetition rate in pulses up to 1.3 μs long at the frequency 34.3 GHz.

Finally, Y. Jiang from Yale presented work on a multi-frequency test stand for RF breakdown studies. The motivation for the test stand is to develop and test high gradient multi-harmonic mode cavities. These cavities have a number of potential advantages including utilizing the 'anode-cathode' effect, exposure time shortening, and hot spot shifting. A bimodal test cavity has been designed and is being constructed. The test stand is driven by a dual frequency RF source consisting of an XK-5 S-band klystron and a multi-harmonic amplifier which can generate phase-locked output at the 2^{nd} or 7^{th} harmonic.

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