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Realizing novel accelerator concepts in an X-band photo-injector

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An LDRD proposal for Laboratory-wide consideration

Realizing novel accelerator concepts in an X-band photo-injector

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NIF & Photon Science: Photon Science and Applications

Information submitted to LDRD via web-based forms:

Project Description

In this project we propose to investigate the use of novel accelerator structure cell geometry to enhance the performance of X-band photo-injectors. Making novel accelerator concepts possible involves fabrication and testing of components to ensure that the performance predicted by simulation is robustly achievable. This work is important because photo-injectors are increasingly used to provide high brightness electron beams for light sources, pushing their performance to the limits, but also requiring them to be user-facility stable. Careful investigation in both computer simulation and design, and low power testing of piece parts will enable the successful fabrication of an advanced X-band photo-injector.

Expected Results

This project will produce unique photo-injector design contributions to the international accelerator community, and firmly place the X-band work being pursued at LLNL at the forefront of research in this field. More than pursuing theoretical work, this project will make significant contribution to the technological challenges of fabricated advanced accelerator components. These advances will be directly applied in building our own X-band photo-injector, which will be the final product of this project. The expected results of this project are: (1) design of advanced photo-injector piece parts, (2) fabrication and extensive low power testing of piece parts, (3) a final advanced photo-injector design, and (4) a fabricated advanced X-band photo-injector.

Mission Relevance

This project contributes directly to the strategic road map area in the mission focus areas of Advanced Laser Optical Systems Applications and the ST&E Energy Manipulation pillar. Advanced X-band photo-injector technology will be directly useful for the MEGa-Ray project in providing both increased operating range, and improved robustness and reliability. The MEGa-Ray technology's revolutionary leap in gamma-ray brightness could be applied to many national security needs ranging from detection of highly enriched uranium to laser weapons that promise to transform battlefield and strategic defense. Improvements in the photo-injector positively affect the entire MEGa-Ray machine.

Proposed Work (max 800 characters)

We propose to (1) identify and study advanced accelerator concepts of interest in simulation, (2) design cold-test piece parts that address the fabrication issues of concern in the application of the advanced concepts, (3) cold-test the photo-injector piece parts under low power to confirm tuning and operating properties, (4) use the knowledge gained to design a full photo-injector, and (5) fabricate an advanced X-band photo-injector. We will produce physics and engineering designs for the pieces required, as well as a report on the cold test results. The final design and fabricated advanced photo-injector is the final goal of this work

(1) Introduction

Brightness of photo-produced electron beams has advanced brightness over multiple generations of designs. Very short laser pulses can produce very short electron bunches which results in high peak current. Advances in the field tend to be gradual and evolutionary. The LCLS gun, currently the state of the art, is in reality a multi-generational effort, and is based on minor changes to an established formula: the UCLA/BNL/SLAC 1.6 cell S-band gun. Percent level improvements on established results are admirable, and enable new technologies to be made more robust and capable of supporting user facilities. Game-changing advancement is enabled by moving forward to novel concepts, and establishing designs that dramatically change performance. Such concepts are inherently high risk, but offer high reward by solving problems that are ignored for safer, modest, evolutionary improvements. These concepts are often investigated theoretically as academic endeavors, and ends unto themselves. To realistically harness these advances, time must be spent in building technical knowledge and overcoming technological challenges. Though often viewed as unglamorous applied research, such a step is what enables broad acceptance and use of advanced ideas.

All photo-injectors are made with essentially pillbox cells. These are easy to make, and enable accelerator modifications to be made in an add-on manner. We are proposing the optimization of cell profile to greatly improve the performance of existing X-band photo-injector designs.

(2) Project Plan

The goal of this research is to examine advanced concepts in accelerator structures and apply them to making a realistic photo-injector. The MEGa-Ray project has chosen to operate at 11.424 GHz, in order to build a more compact accelerator system, and leverage SLAC/NLC technological achievements in high gradient acceleration. To support one rf frequency, provide timing synchronization, and meet emittance goals, a photo-injector at X-band is also being developed. The layout for the 5.5 cell X-band photo-injector is shown in Figure 1. This photo-injector consists of 5.5 pillbox cells with a dual feed racetrack coupler. This project proposes to build a similar photo-injector without using the standard pillbox cell geometry. The concepts we will be investigating involve deviation from pillbox cells including: cell contouring using adaptive algorithms, and advanced cell structures such as photonic band gap and choked-mode structures. To investigate these structures microwave simulations will be completed, and test structures will be built and tested to confirm their ability to perform in a full structure. A final design will then incorporate what is learned with the test structures, resulting in a final advanced photo-injector design, which will be built.

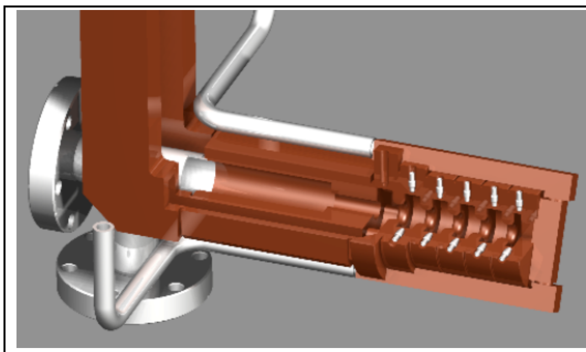
Figure 1. MEGa-Ray X-band photo-injector.

Possible directions for advanced photo-injector design include: full contouring of accelerator cells and incorporation of higher-order-mode damping by the application of either photonic band gap choked-mode structures. Advances in computation have enabled large scale optimization of accelerator structure performance. Once the parameter space is established, millions of structure variations can be made, and cavity parameters can be tuned to match the specific goals and restrictions of the application. An example is shown in Figure 2, which shows an increase in shunt impedance of 25%. This program will be adapted to optimize cavity parameters for photo-injector designs [1].

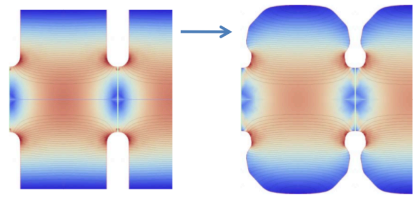

Figure 2. Pillbox contouring using and adaptive algorithm program [1].

Higher order mode damping is achieved in a variety of ways, but two of the more promising techniques involve the use of structures very far from pillbox in profile. Photonic band gap structures confines a transverse magnetic (TM_{01}) mode for accelerating electrons, but no higher order modes, that could degrade beam quality. The operating mode for such a structure is shown in Figure 3 [2]. Choked-mode structures are similar to photonic band gap structures, but vary axially rather than transversely, as shown in Figure 4 [3]. All of these structures have been built in variations, but none of them have achieved the fabrication feasibility required to reliably incorporate them into a photo-injector design. The goal of this proposed work is to demonstrate the fabrication feasibility of a beyond evolutionary photo-injector.

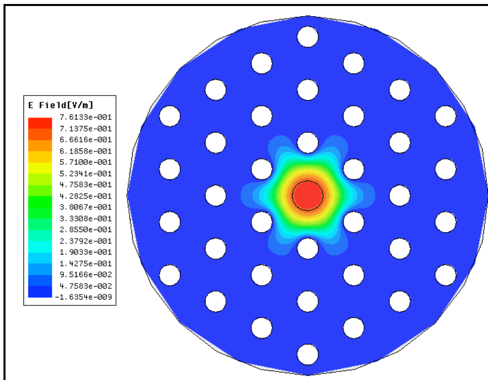

Figure 3. Photonic Band Gap structure supporting accelerating TM_{01} mode [2].

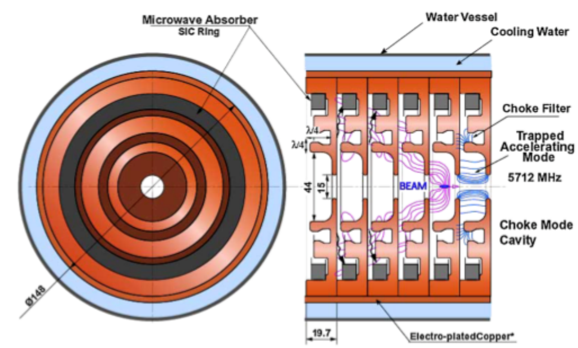

Figure 4. Choke Mode damped accelerating structure [3].

Objectives

(2.1) Advanced Concepts chosen for analysis.

Literature and first hand knowledge with advanced structures will guide the selection of advanced concepts to be investigated. These structures will be simulated using HFSS, and compared for their possible performance in an X-band photo-injector. A single complete concept will be identified for further investigation. Three months of simulations are foreseen using computational resources already available and code licenses that will be purchased.

(2.2) Design prototype parts.

The structure identified in (2.1) will be broken into cell parts that can be fabricated on an accelerated time scale, but which address the major fabrication, tuning, and tolerance issues inherent in the advanced photo-injector design. Parts will be fully modeled using HFSS, and fabrication drawings and procedures will be completed. Three months of simulation and drawing time is expected.

(2.3) Fabricate test parts.
The parts designed in (2.2) will be fabricated by an external vendor, using the purchasing experience and knowledge of the team members on previous projects. Multiple sets of parts will be procured, as well as the testing fixtures required for their testing under low power (cold-test). Some parts will require joining through brazing, or diffusion bonding. Multiple vendors are available with experience on similar parts, and will have been used to fabricate parts for MEGa-Ray, limiting the risk involved in further fabrication. Three months is expected for the fabrication and delivery of parts for cold-testing.

(2.4) Cold-test parts. Report.
Once the parts in (2.4) are fabricated, they will be extensively cold-tested to confirm their expected performance. Tuning methods will be tested, and the dynamic range achievable will be measured. Field properties will be measured by bead-pull methods, so that the field magnitude and uniformity can be measured. Wire-excitation of the structures is possible, if measuring the structure higher-order-modes is necessary. Results of cold-testing will be summarized and reported. Cold-test is enabled by synergy with MEGa-Ray objectives to perform quality assurance and cold testing of other accelerator structures for the MEGa-Ray project. The MEGa-Ray vector network analyzer will be used for all cold-test measurements, and is a great savings in terms of capital equipment use. Six months will be spent on cold-testing the test structures.

(2.5) Design new gun.
Once the results of the cold-testing procedures in (2.4) are completed, and the results are reported, a new design for a complete advanced photo-injector will begin. The design will include both electromagnetic design using HFSS, and the publishing of complete drawings for manufacture. This new design will be made possible and feasible through the work done on detailed part design, confirmation of fabrication methods, and cold-testing of achieved performance. Three months are foreseen for simulation and design drawings. Completion of objective (2.5) is strongly tied to the successful cold-testing of objective (2.4). If the parts are deemed entirely inadequate, then evaluation of the defect will prompt the choice of either an alternate vendor, or choice of alternate fabrication techniques, or even design choices if necessary. If it is possible to proceed with steps (2.5) and (2.6) with minor changes, this will occur, though at grater risk. If it is not possible to proceed, then repetition of objectives (2.1) through (2.4) may be repeated slightly more rapidly, so that the project may conclude by having vetted fabrication techniques for an advanced photo-injector, even if full fabrication was not possible.

(2.6) Build new gun.
Using the design and drawings from (2.5), a new photo-injector will be built. The complete photo-injector will be the final deliverable of both this objective and this

project. The gun will be fabricated using either the previously vetted vendors, or new vendors who can meet newly established specifications. Fabrication of a much simpler photo-injector is required for the MEGa-Ray project, and experience with the vendors used for that project will provide further valuable synergy. Fabrication of the complete gun is expected to be complete within six months. Completion of (2.6) is strongly tied to successful completion of all previous objectives, specifically (2.5) the design of the gun to be fabricated. Alternatives are discussed in (2.5).

The deliverables for this project are the design, fabrication, tuning and cold-test of advanced photo-injector components; and the design and fabrication of a novel X-band photo-injector. The full timeline for delivery of these items is shown in Figure 4.

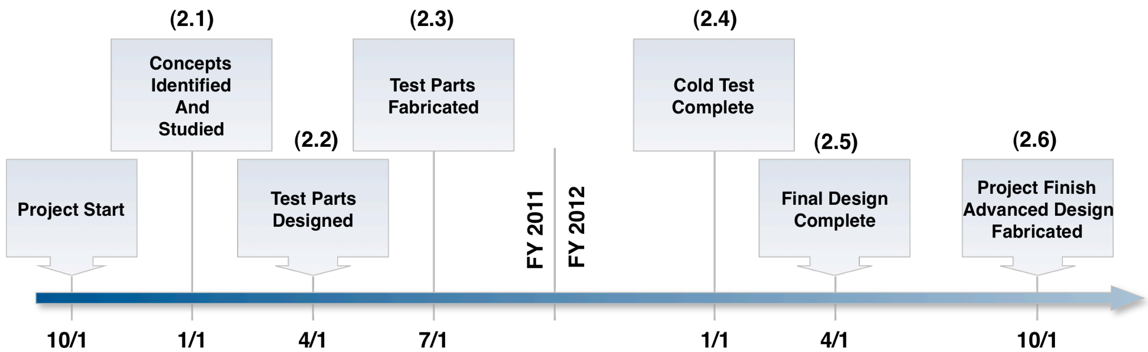

Figure 4. Full Timeline of proposed objectives with completion dates.

(3) Management Plan

The project will be managed by the PI, with the support of technical staff currently working on the MEGa-Ray project. MEGa-Ray staff involved in providing technical support and consultation include co-investigators Fred Hartemann and Scott Anderson. The PI, Roark Marsh, will carry out most of the work, with the aid of co-investigator Sam Chu. Roark Marsh will be responsible for items (2.1), (2.2), (2.4), and (2.5), and Sam Chu will be responsible for facilitating items (2.3) and (2.6). Roark Marsh completed his doctoral thesis work on designing, building, tuning, and high power testing a photonic band gap structure, at X-band: the first structure of its kind. Roark Marsh has been working on the current X-band photo-injector for MEGa-Ray, as well as future upgrades. Sam Chu has more than 15 years experience in the microwave industry, and is overseeing the microwave source, distribution, and fabrication for MEGa-Ray. The team is well placed in the community to make effective contributions under the scope of this project.

The project should be entirely supportable after the LDRD funding period, as the new design will be vetted through partial cold test, and the procedures for new/similar structures will be established. Additional funding in a third year may be sought to cold test the full advanced photo-injector, and pursue high power testing using the MEGa-Ray X-band power source.

(4) Dissemination

The results of this research will be broadly conveyed to an active international accelerator community through a combination of attendance at conferences and workshops, and publication in peer-reviewed technical journals. Results will be presented at two iterations of the International Particle Accelerator Conference, and once at the US sponsored North American Particle Accelerator Conference. Final results will be presented in the form of a peer-reviewed publication in either Physical Review Special Topics: Accelerators and Beams, or Nuclear Instruments and Methods Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.

(5) Summary

This project will produce an advanced X-band photo-injector that will have been thoroughly vetted in manufacturing processes and cold testing. The design of the initial structures for cold test will provide significant advantage over the use of a conventional design. Manufacture and testing on sample cells will provide vital feedback for achievable accuracy and performance of the structure. This information will be used in the final design of an advanced gun that provides significant improvement over existing designs. This advanced photo-injector will be built because thorough testing of the feasibility of the manufacturing processes involved was tested by cold-testing piece parts. This photo-injector will enable another generation of source applications, specifically the ability to improve linac-based light sources, such as free electron lasers and the MEGa-Ray project.

(6) References

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http://www-conf.slac.stanford.edu/icfa2010/

[2] "Experimental study of photonic band gap accelerator structures", Roark Marsh, Doctoral Thesis, Massachusetts Institute of Technology (2009).

[3] "Wakefield suppression in high gradient linacs for lepton linear colliders", Roger Jones, Physical Review Special Topics - Accelerators and Beams **12**, 104801 (2009).
http://link.aps.org/doi/10.1103/PhysRevSTAB.12.104801

LDRD Biographical Sketch

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(a) Professional Preparation

University of California, Santa Cruz	Physics	B.S. 2003
	Mathematics	B.A. 2003
	Classical Studies	B.A. 2003
Massachusetts Institute of Technology	Physics	Ph.D. 2009
LLNL, NIF/PS&A	Physics	7/2009-Present

(b) Appointments

LLNL, NIF/PS&A	Post-doctoral Research Staff	7/2009-7/2012
MIT	Graduate Research Assistant	8/2003-6/2009
	Graduate Teaching Assistant	8/2006-12/2006
LLNL, Axion Search	Undergraduate Researcher	6/2000-12/2002

(c) Awards

Particle Accelerator Conference, Vancouver, British Columbia, 2009: First Place Poster Prize

International School for Linear Colliders, Shonan Village, Japan, 2006: First Place, Distinguished Performance Award

(d) Publications

A list of:

i. "Measurement of wakefields in a 17 GHz photonic bandgap accelerator structure", Roark A. Marsh, Michael A. Shapiro, Richard J. Temkin, Evgenya I. Smirnova, John F. DeFord, Nucl. Instr. and Meth. A. Beams (2010) http://dx.doi.org/10.1016/j.nima.2010.02.111

ii. "Absolute scale power measurements of frequency-locked coherent transition radiation", Roark A. Marsh, Amit S. Kesar, and Richard J. Temkin, Phys. Rev. ST Accel. Beams 10, 082801 (2007) http://prst-ab.aps.org/abstract/PRSTAB/v10/i8/e082801

iii. "Power measurement of frequency-locked Smith-Purcell radiation", Amit S. Kesar, Roark A. Marsh, and Richard J. Temkin, Phys. Rev. ST Accel. Beams 9, 022801 (2006) http://prst-ab.aps.org/abstract/PRSTAB/v10/i8/e082801

iv. "X-Band Photonic Bandgap (PBG) Breakdown Structure Experiment", Roark A. Marsh, Michael A. Shapiro, Richard J.Temkin, Valery A. Dolgashev, Sami G. Tantawi, Proceedings of the 2009 Particle Accelerator Conference, Vancouver, British Columbia

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ix. "Photonic Bandgap (PBG) Accelerator Structure Design", Roark A. Marsh, Michael A. Shapiro, and Richard J. Temkin, Proceedings of the 2007 Particle Accelerator Conference, Albuquerque, New Mexico
http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/THPMS006.PDF

LDRD Biographical Sketch

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(a) Professional Preparation

University of Texas at Austin	Electrical Engineeing	B.S. 1983
University of Texas at Austin	Electrical Engineering	M.S. 1985
Massachusetts Institute of Technology	Nuclear Engineering	Ph.D. 1991

(b) Appointments

2009-Present RF/LINAC Engineer (X-band RF LINAC based Compton Source) IAP/LLNL

2006-2008 Project Manager Accuray Inc. (X-band LINAC based CARGO ADVANCED RADIOGRAPHY SYSTEM)

1992-2006 Senior Engineer Varian/CPI Inc. (High power CW Gyrotrons for Electron Cyclotron Heating)

(c) Award

Five exceptional contribution awards from CPI (1994, 1995, 1997, 2002, 2005)

Key Contributors Incentive from CPI (1999)

Sigma Xi Engineering Honor Society

University of Texas Engineering Scholar Awards

(d) Publications

Chu,T.S., Blank,M., Cauffman,S. Felch,K. "Design and Demonstration of a TE22,6 Mode Generator for Testing Internal Converter of a Gyrotron", Digest of IRMMW-THz 2006 International Conference, Shanghai, China, 2006.

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(a) Professional Preparation

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MIT	FELs	1987

(b) Appointments

LLNL	2001 -
University of California	1993-2001
MIT – Visiting Scientist	1988-1991
Thomson Electron Tubes	1987-2001

(d) Publications

High-field electrodynamics, CRC Press (2000)

Phys. Rev. Lett. 59, 1177 (1987)

Phys. Rev. Lett. 72, 1192 (1994)

Phys. Rev. Lett. 72, 2391 (1994)

Phys. Rev. Lett. 74, 1107 (1995)

Phys. Rev. Lett. 76, 624 (1996)

Phys. Rev. Lett. 100, 125001 (2008)

Phys. Rev. STAB 7, 060702 (2004)

Phys. Rev. STAB 8, 100702 (2005)

Phys. Rev. STAB 10, 011301 (2007)

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(a) Professional Preparation

University of Minnesota	Physics	B.S. 1995
University of California, Los Angeles	Physics	M.S. 1996, Ph.D. 2002
LLNL, Physics and Advanced Technologies	Accelerator Physics	Post-doc 2002-2005

(b) Appointments

Present — Physicist, Technical Director LLNL 100 MeV Linac
Lawrence Livermore National Laboratory,
Physical and Life Sciences, Physics Division

2007–2009 — Physicist — Lawrence Livermore National Laboratory,
NIF & Photon Science, Photon Science & Applications

2005–2007 — Physicist — Lawrence Livermore National Laboratory,
Physics and Advanced Technologies, V-Division

(c) Awards

American Physical Society — Member
2007 — NIF SPOT Award
2003 — PAT SPOT Award
1995 — Graduated Cum Laude (University of Minnesota)

(d) Publications

F. Albert, et al. "Nuclear resonance fluorescence detection of Pb-shielded ^{7}Li using a laser-based Compton scattering light source." Submitted to *Phys. Rev. Lett.* (2009).

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