Advanced Diagnostics for Intense Pulsed Electron Beams for Thrust Area 1: Science of WMD Sensing and Recognition
Idaho State University – FRBAA09-1-2-0032

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I. ABSTRACT

High power electron beams are notoriously difficult to accurately characterize and there are good reasons for this. The typical e-beam facility is not very reproducible from shot-to-shot and has self-fields and electron energy distributions that vary rapidly in time and space. On the other hand, ISIS (3-8 MeV, 2-9kA), the unique pulsed-power facility at ISU, has a mono-energetic electron beam and can operate very reproducibly (< 5%) from shot-to-shot. This project aims at taking advantage of the ISIS facility to develop improved and innovative new tools for characterizing pulsed e-beams, new tools that would be especially valuable in applications requiring strict control of beam parameters with narrow margin of error.

II. SCOPE

This proposal is in support of the Basic and Applied Sciences Directorate and the JSTO, and is titled *Advanced Diagnostics for Intense Pulsed Electron Beams for Thrust Area 1: Science of WMD Sensing and Recognition*. It pertains to exploration and exploitation of the interactions between materials and photons, and subsequent generation of information about high energy electrons, photons and electromagnetic (EM) fields in the environment.

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Objective The objective of this project, Advanced Diagnostics for Intense Pulsed Electron Beams, is to conduct research at Idaho State University (ISU) with the aim of developing advanced diagnostics techniques and tools for high-power electron beam generating devices, with emphasis on the Idaho State University's (ISU) ISIS pulse power accelerator but also applicable on other comparable installations. The particular goal of the proposed research is to improve existing and develop new and innovative methods for characterizing the energy distribution, time structure and transverse profile of high-power pulsed electron beams. The techniques to be researched include: Electron beam energy spectrum reconstruction from electron dose-depth profiles in carbon and aluminum; Optimized capacitive and inductive diagnostics probes for voltage, current and beam centroid position monitoring, and infrared (IR) and gamma-ray imaging of the electron beam's transverse profile. Yet another important objective of this project is to train and prepare ISU students in the field of pulse power and intense electron beams generation and diagnostics.

Background The "golden era" of pulse power accelerator technology has probably been about 40 years ago. Even though nowadays several pulse power electron beam generation installations are around and well, doing exceptionally good job in wide range of WMD-related research, the funding in the field has gradually decreased during the years. This has caused a significant lost of expertise as knowledgeable and experienced researchers retired and few (or none at all) students took interest in the matter. For the same reason, little progress has been made in the diagnostics techniques for both the pulse power part and the electron beams generated by these devices. The proposed research effort aims at revisiting some fundamental and traditionally difficult diagnostics problems in that field.

First, it addresses the issue of measuring the energy distribution of electrons in an intense electron beam. Since for kiloamp, space charge dominated beams, like e.g. the one produced by ISIS, no direct spectroscopy is feasible, we propose to study an indirect method whereas the electron energy distribution is inferred from the way the electrons deposit their energy upon passing through matter. Second, we set out to reconsider the design of capacitive and inductive diagnostics probes equipped with state-of-the-art computational and material resources, with the aim of coming up with a better, optimized design. Third, we propose to study the possibilities of non-destructive, stand-off, real time imaging of the electron beam's distribution using infrared and/or gamma radiation produced by it within the beam line exit window. Because the proposed project involves three relatively heterogeneous tasks, their corresponding backgrounds are discussed in more details below under the detailed task description.

Programmatics This effort will support the DTRA initiative *Thrust area 1: Science of WMD Sensing and Recognition,* calling for fundamental research on the interactions of energetic particles and EM fields with materials and the possibilities of using them for WMD detection. The broad scope of this research initiative and the demands of quality diagnostics and tight control of intense particle beam generating pulse power devices require a team with expertise in pulse power, accelerator physics, and information theory and data processing. Dr. Vesselin Dimitrov will be the Principal Investigator and will be primarily responsible for simulations, modeling and software development, design of the imaging setup and supervision of the students. Dr. Wendland Beezhold will be working on the project concerning electron beam and X-ray field generation, radiation shielding and diagnostic probes design and will be helping working with the students. All work will be performed at the Idaho Accelerator Center of the Idaho State University in Pocatello, ID.

Relevance

This research project will train two graduate students in applied physics / engineering with an emphasis on pulse power and high intensity electron beams. The effort will also produce fast, precise and reliable diagnostic techniques for characterization of pulse power installations and their intense electron beams that will be utilized for defense relevant research and training of future students.

III. CREDENTIALS

Summary of Credentials

The Idaho Accelerator Center has more than ten operating accelerators in five research facilities with over 30,000 sq. ft. of laboratory space. This is possibly the most operating accelerators of any university in North America. The IAC and the PI, Dr. Dimitrov in particular, have unique experience with exploitation and the control of pulse power devices generating intense electron beams. IAC has two pulse power machines with peak current in the kA range, which have been at IAC for more than 5 years and have produced more than 11,000 shots.

Summary of Qualifications for PI and Key Personnel

The PI, Dr. Vesselin Dimitrov has an extensive background in nuclear physics. Since 2004 he played a decisive role in the commissioning of the ISIS accelerator and is currently the ISIS Principle Investigator at the IAC. He has valuable expertise and experience with electron beam diagnostics and controls and with numerical simulations of beam dynamics and radiation transport and deposition with software tools like MCNPX and LSP.

Dr. Wendland Beezhold is a former Research Professor of Physics and current Professor Emeritus in the Idaho State University (ISU) Physics Department, and a former ISIS Principal Investigator at the Idaho Accelerator Center (IAC). Prior coming to ISU, he spent about 28 years at Sandia National Laboratories (SNL) in Albuquerque, NM. While at SNL, his interests, publications, and areas of research were primarily in radiation science, ion beam/solid interactions, ion implantation in semiconductors, ion and electron beam accelerators, magnetic fusion energy materials problems, inertial confinement fusion, high power pulsed accelerators, radiation dosimetry, the development and use of laboratory radiation sources to simulate nuclear radiation effects, and the study of the effects of radiation on electronics and materials. Dr. Beezhold's national-level activities have included 1) serving on several DOE National Laboratory advisory committees during the 1990's, 2) serving as secretary to the Joint DTRA/Sandia National Laboratories Joint Simulation Working Group during the 1980's, and 3) serving as the elected Chair and Past Chair of the Hardened Electronics and Radiation Technology (HEART) Conference Steering Committee from 1993-1999. During the period 2003-2006 he has also been a consultant to Sandia National Laboratories and to the DoD Defense Threat Reduction Agency (DTRA).

Summary of Facilities to Perform the Proposed Work

The pulsed electron accelerator ISIS is located in the ISIS wing at the main IAC campus. In its current configuration it produces a 35ns long pulse of 6MeV, 9kA electron beam, and can be readily reconfigured for 8MeV, 2.5kA electron beam. The short turn-around time allows for about 15 shots/hour and the parameters of the generated pulses have very good reproducibility. The above characteristics make ISIS unique among the US pulse power radiation-generating facilities both with respect to turn-around time and cost per shot. IAC also possesses a 25 MeV Linac, a 44 MeV Short Pulsed Linac which are located in Accelerator Hall #1 at the main IAC campus, as well as a NEC Pelletron tandem proton/deuteron accelerator with terminal voltage of 6.5MV located in IAC's ISIS wing. ISU's Department of Physics together with IAC run a high-performance computer cluster. IAC is also in the process of acquiring and commissioning of a workstation equipped with NVIDIA's Tesla computing unit C2050 with ~1 teraflop massively parallel capabilities, which will be used for the computer simulations.

IV. WORK TO BE PERFORMED

A. **General** This project consists of one mostly theoretical and three predominantly experimental tasks. The theoretical one aims at developing a method for electron energy spectrum reconstruction from the depth profile of the deposited dose.

B. **Summary**

Year #1 (FY11):

Task 1: Bayesian electron spectrum reconstruction from dose-depth profiles in carbon and aluminum: Theoretical study and justification for the choice of the variational functional to be used in the Bayesian deconvolution.

Task 2: Analysis, optimization and calibration of capacitive (D-dots) and inductive (B-dots) probes: Acquiring, installation and testing of electro-magnetic (EM) field simulation software.

Task 3: Development of an infra-red (IR) and X-ray (pinhole) imaging beam profile monitor for ISIS: Conceptual design of the custom X-ray pinhole camera. Choice of an IR setup.

Year #2 (FY12):

Task 1: Bayesian electron spectrum reconstruction from dose-depth profiles in carbon and aluminum: Monte-Carlo simulations and experimental validation of the dose-depth response function in carbon and aluminum on a fine energy grid and taking into account the electrons' angular distribution.

Task 2: Analysis, optimization and calibration of capacitive (D-dots) and inductive (B-dots) probes: Creating a realistic EM model of key ISIS components equipped with capacitive and inductive probes.

Task 3: Development of an IR and X-ray (pinhole) imaging beam profile monitor for ISIS: Detailed design, assembly and installation of the custom X-ray pinhole camera. Acquiring and installation of the appropriate IR camera setup.

Year #3 (FY13):

Task 1: Bayesian electron spectrum reconstruction from dose-depth profiles in carbon and aluminum: Developing of Bayesian deconvolution software. Validation of the software against Monte-Carlo models and measurements on the ISIS' electron beam.

Task 2: Analysis, optimization and calibration of capacitive (D-dots) and inductive (B-dots) probes: Optimization of the capacitive and the inductive probes. Manufacture and calibration of the new probes.

Task 3: Development of an IR and X-ray (pinhole) imaging beam profile monitor for ISIS: Perform experiments and establish optimal conditions for imaging of the ISIS' exit window in X-rays and IR for different electron beam configurations.

C. Detailed Tasks

Task 1: Bayesian electron spectrum reconstruction from dose-depth profiles in carbon and aluminum

The shape of the dose-depth profiles in various materials has been long identified as a promising starting point for deducing electron energy distributions. The particular procedure relies on knowing the relevant response function – the dose-depth profile corresponding to monoenergetic beam – and deconvolving the measured dose-depth distribution with that response function to obtain an estimate for the energy distribution of the impinging electrons. Upon discretization, the response function becomes a response matrix R, the dose-depth profile becomes a measured vector $\boldsymbol{d}$, and the initial electrons' energy distribution becomes an unknown vector $\boldsymbol{x}$ obeying the relation

Clearly, in order to solve for $\boldsymbol{x}$, all one need is to find the inverse of the response matrix R. Unfortunately, R is usually either singular or extremely ill-conditioned, so its inverse does not exist or is not well defined. Adding members of the null space of R to $\boldsymbol{x}$ does not change $R\boldsymbol{x}$, and, moreover, small changes in $\boldsymbol{d}$ can cause very large changes in $\boldsymbol{x}=R^{-1}\boldsymbol{d}$. Thus, the straight-forward solution is neither unique nor stable.

The above ill-posed inverse problem is by no means unique for our specific task. It occurs in image processing, spectral enhancement and many other tasks involving making decisions based on experimental measurements and/or observations. The customary approach to finding a reasonable solution has been to minimize the 2-norm $||R\boldsymbol{x}-\boldsymbol{d}||_2$ subject to a "regularization" condition, serving to enforce certain degree of smoothness on the resulting energy distribution and thus mitigating the various overfitting artefacts like unphysical oscillations and negative values. In their most part, the regularization conditions used, e.g. Tikhonov's regularization, do not follow from a rigorous theory are more or less arbitrarily chosen, which makes it very difficult to assess their precision and reliability. A notable exception is a class of approaches firmly rooted in probability theory and going under the name of "Bayesian". In a Bayesian approach, instead of an ill-posed logical deduction problem, the task at hand is regarded as a well-posed inference problem, the goal being to infer the original electron energy distribution from available experimental constraints. The name "Bayesian" is, arguably, somewhat of a misnomer. It comes from the use of the Bayes' theorem, which in itself is an almost trivial consequence of the probability theory's product rule. Where Bayes' theorem becomes helpful in constructive sense is when the probabilities involved are interpreted as reflecting a prior knowledge, a likelihood function and a posterior knowledge, thus turning it from a statement about conditional probabilities to a rigorous rule for updating one's state of knowledge upon receiving new information. Among the various practical implementations of these ideas a special role is played by the Jaynes' Maximum Entropy (ME) principle, which amounts to a rule for calculating a posterior probability distribution as the one which maximizes an entropy functional subject to the available constraints:

For quite some time it has been considered proven that the unique form of the entropy functional to be used above is the Shannon-Jaynes one

Regardless, various researchers have found different forms more useful and desirable under specific circumstances. Couple of years ago the PI of the present project pointed out that the accepted "proofs" of the uniqueness of the above form were flawed, and suggested a different expression involving the so-called Fisher information ——— .

As a first subtask in this task, we will elaborate on the unique characterization of the entropy functional form from general principles. We will re-emphasize the flaws in the accepted derivations of the Shannon-Jaynes form and rigorously characterize another unique form to be used in the absence of an informative prior. Our belief is that it will turn out to be the Fisher information form.

As a second subtask, we will reformulate the deconvolution problem in terms of the new entropy functional and develop the corresponding software implementation. This will produce a Bayesian deconvolution suite which will hopefully be useful in a wide range of situations well beyond the particular task of electron energy spectrum reconstruction.

As a third subtask, the response matrix for electron propagation in aluminum and carbon will be modeled with Monte-Carlo calculations. For the modeling, the MCNPX and LSP codes will be used, both available and licensed at IAC. A special attention will be paid to the effect of the beam emittance on the initial part of the dose-depth profile.

As a fourth and last subtask in this task, the results of the second and third subtasks above will be used to reconstruct the electron energy distribution of the ISIS beam for two or three different regimes of operating the accelerator. Methods will be devised to verify and validate the code's results against measurements of actual beam parametes. Note that direct spectroscopy of a kiloamp beam in not feasible, so indirect methods will be sought for and used for this verification.

At present, couple of groups – mainly in medical electron accelerators field - have reported efforts directed at reconstructing electron spectra from dose-depth profiles. Even though, as mentioned above, the methods used by them are ad-hoc ones, they were precisely tweaked for the particular accelerator beams such as to produce very reasonable results. The Bayesian method above is not guaranteed, although it is very likely, to perform better in these particular cases. However, it will deliver, by construction, the best possible results consistent with the data – in the sense that nothing is assumed beyond what is contained in these data. Therefore, it should be applicable like a black box, without the need of fine tuning, to different beams from different devices with guaranteed optimal results with no spurious components.

Task 2: Analysis, optimization and calibration of capacitive (D-dots) and inductive (B-dots) probes

The objective of this task is to better understand, optimize and calibrate a set of capacitive and inductive diagnostics probes for pulse power electron accelerators. These probes, sometimes called D-dots (the capacitive ones) and B-dots (the inductive ones) serve to provide quantitative temporal information for the electric potential and the electric current at various locations of pulse power devices, including, but not limited to, the produced high intensity electron beams. Due to the extremely high power involved, improper tuning, imprecise timing and other relatively minor malfunctions within such devices can not only prevent them from functioning properly, but also cause significant damage to and outright destruction of parts of these devices. For instance, the ISIS accelerator at IAC stores several *kJ* of energy and turns it into a voltage pulse of 35ns duration, delivering $\sim 10^{11} W$. On one occasion, a short due to a breakdown or flashover downstream launched a opposite polarity reflected pulse propagating back upstream, which caused permanent failure of insulating components not designed for holding voltages of the wrong polarity. Therefore, close monitoring of the voltages and currents at key components of pulse power devices is a necessity for their reliable operation and control. Further, arrays of B-dots can be used as non-destructive sensors allowing the deduction of the centroid position as well as other low-order moments of high-intensity electron beams produced by such devices. Thus, it is difficult to overestimate the importance of good diagnostics probes for the reliable and optimal exploitation of pulse power accelerators.

Most of the fundamental advances in pulse power accelerator technology were achieved in the sixties and seventies of the last century. From about the same time is also the design of the currently used diagnostics probes. We propose to revisit the issue, taking advantage of up to date computer (hardware and software) technology and utilizing modern advanced materials, with the goal of developing modern optimized capacitive and inductive probes. To that end, we envision the following subtasks:

First, appropriate software tools for 3D electromagnetic (EM) simulations will be selected, acquired and installed. In view of the significant cost of such commercial tools (several tens of thousands of dollars), a careful analysis of the simulation needs, the available open source tools and their capabilities, and the available commercial software will be performed, resulting in a choice of optimal combination of commercial and free tools for the job at hand.

Second, EM models of key components of the ISIS injector and electron beam line will be set up. With the help of these models the electric and magnetic fields at the positions of the diagnostics probes will be evaluated for a number of different modes of operation of the accelerator.

Third, EM models of capacitive and inductive probes will be designed. The parameters of these models will be optimized with respect to frequency response, signal to noise ratio and cost of the probe. The possibilities of using modern superparamagnetic materials, based on nano-particle technology, in the inductive probes will be explored. Prototypes according to the optimal designs will be produced and characterized.

Although the capacitive and inductive probes within this task will be designed and optimized with regard to the ISIS accelerator and its beam, the outcome of this activity can potentially benefit other pulse power devices as well. On one hand, it will be a relatively straight forward task to adapt the developed probe models to different geometries and conditions as necessary. On the other hand, a design taking advantage of modern advanced materials for improving the response of the probe will obviously be of use in much more different environments than the one it was developed for.

Task 3: Development of an IR and X-ray (pinhole) imaging beam profile monitor for ISIS

The objective of this task is to develop a non-destructive method for obtaining real time information for intense electron beam's transverse profile from a significant stand-off. While the diagnostics probes from Task 2 are capable of providing information for some of the lowest moments of the distribution of electrons in the beam, a more detailed picture is often needed. One such occasion is when the electron beam is used to produce short intense bursts of gamma rays for sensing of nuclear materials or testing electronic devices for radiation hardness. Under the circumstances gamma ray dose rates beyond 10^{12} rad/s are desirable, which poses very stringent requirements for the design of the bremsstrahlung converter. The transverse electron beam profile is one of the inputs of crucial importance for such a design. There are, of course, various known methods for monitoring these profiles. However, they either require very many shots for one measurement (e.g. various "moving wire" methods), involve putting obstacles in the beam path which either attenuate the beam or can be destroyed by it and contaminate accelerator's vacuum (e.g. methods based on detection of optical transition radiation (OTR)), or require significant processing time after the shot and have no stand-off option (e.g. using radiochromic films). There are also OTR sensors with a thin metal foil at 45 deg to the beam axis. These arrangements, however, significantly alter the symmetry of the beam line and can cause highly undesirable perturbations to the beam propagation.

We propose a different approach, where the accelerator's beam line titanium exit window (perpendicular to the beam axis) is used as an imaging sensor for the beam profile. On passage through the exit window electrons of the beam interact with window's material. There are two main effects of this interaction of interest here: the energy deposition (absorbed dose) in window's material with subsequent raise of its temperature, and the generation of bremsstrahlung radiation from electrons scattered out of the beam.

With regard of the first effect, and with titanium's heat capacity being about *0.5kJ/(kg K)*, the temperature change per *1 kGy* absorbed dose can be estimated to about *2K/kGy*. For a typical ISIS shot the absorbed dose in the center of the Ti window is of the order of tens *kGy*, hence significant temperature deviations are expected. A fast gated infrared (IR) camera should be able to register a momentary picture of the window's temperature distribution some tens of nanoseconds after the shot. The local temperature raise above the environmental value will be proportional to the absorbed dose, which, in turn, is proportional to the electron fluence density. For known electron energy and pulse duration this pins down the average electron density as well. In fact, for many applications the transverse dose profile is actually even more interesting than the electron density.

With regard to the second effect, the momentary intensity of the produced gamma rays is proportional to the electron flux density, albeit more sensitive to the electron's energy than the absorbed dose. If we are able to form an image of the exit window in gamma rays, its momentary brightness will be representative for the electron flux density. While it is extremely difficult to do so with the hard part of the generated gamma spectrum, it can be achieved with its soft part which carries most of the intensity anyway. One way to do it is to employ a high-Z material – shielded pinhole or coded aperture camera with thin sensitive medium not very responsive to hard gamma rays.

The proposed subtasks for this research are:

First, design and assemble a pinhole/coded aperture gamma-ray camera, including

a) MCNPX simulations and decisions on shielding material, its practical thickness and aperture and camera geometry;
b) Choice of registering material optimal thickness - thin enough not to be sensitive to higher energy (about and above 0.1MeV) gammas which would not be efficiently shielded, and sensitive to low-energy gammas. The result of this choice will determine whether a simple pinhole geometry or a coded aperture will be used, therefore a) and b) may need to be iterated one or two times;

Second, choice and acquisition of a fast gated IR imaging setup. Several options exist and will be evaluated with respect to cost, sensitivity and susceptibility to ionizing radiation. The conventional approach is to equip a relatively inexpensive IR camera with generation-3 channel plate image intensifier/gate. This would provide excellent timing characteristics and high sensitivity in exchange of elevated noise and significant cost. Another option is to try to directly gate a high-end camera's CCD using its charge drain electrode. This would have lower acquisition cost but would require more "in-house" work and may not provide sufficient output for reliable imaging. Before deciding in favor of one or the other, measurements will be made of the integral IR output of a typical ISIS shot.

Third, measurements will be taken with the two setups (the gamma-ray camera and the IR camera) and their results will be compared between themselves and with thin radiochromic film imaging. Measurement conditions will be optimized for maximal signal-to-noise figure.

Finally, it should be noted that the gamma-ray imaging device developed within this project will also have the potential to be very useful in assessing the gamma radiation environment and identifying radiation leaks in pulse power electron accelerator facilities.

V. PERFORMANCE SCHEDULE

In order to minimize beam charges all four tasks will be advanced concurrently and the necessary experiments will be performed simultaneously during the same beam time window.

Task #	Subtask name	Year 1	Year 2	Year 3
1	Theoretical study and justification for the choice of the variational functional to be used in the Bayesian deconvolution.	———		
1	Monte-Carlo simulations and experimental validation of the dose-depth response function in carbon and aluminum on a fine energy grid and taking into account the electrons' angular distribution.		———	
1	Validation of the software against Monte-Carlo models and measurements on the ISIS' electron beam.			———
2	Acquiring, installation and testing of electro-magnetic (EM) field simulation software	———		
2	Creating a realistic EM model of key ISIS components equipped with capacitive and inductive probes.		———	
2	Optimization of the capacitive and the inductive probes. Manufacture and calibration of the probes.			———
3	Conceptual design of the custom X-ray pinhole camera. Choice of an IR setup	———		
3	Detailed design, assembly and installation of the custom X-ray pinhole camera. Acquiring and installation of the appropriate IR camera setup		———	
3	Perform experiments and establish optimal conditions for imaging of the ISIS' exit window in X-rays and IR for different electron beam configurations			———