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ACCELERATOR OPTIMIZATION THROUGH LIV.DAT

C.P. Welsch#
Cockcroft Institute and The University of Liverpool, Liverpool L69 3BX, UK
on behalf of the LIV.DAT Consortium

Abstract

The Liverpool Big Data Science (LIV.DAT) Center for Doctoral Training (CDT) is a hub for training students in managing, analyzing and interpreting large, complex datasets and high rates of data flow. LIV.DAT offers a unique training approach addressing some of the biggest challenges in data intensive science to tackle a growing skills gap. It currently provides training to a cohort of 15 PhD students with a second cohort of similar size starting in October 2018. Their research projects address R&D challenges in astro, nuclear, particle and accelerator physics. This paper outlines the aims of LIV.DAT and presents initial research results from modeling studies of the physics and biology of proton beam therapy using a Monte Carlo approach, as well as plasma-beam interaction in the cases of AWAKE and EuPRAXIA. It also summarizes the training within LIV.DAT.

INTRODUCTION

LIV.DAT, the Liverpool Centre for Doctoral Training in Data intensive science, is a hub for training students in Big Data science [1]. They apply these skills to both data from astrophysics, nuclear and particle physics research and also to problems posed by industry. LIV.DAT aims at providing training for three cohorts of PhD students with around 15 students following the program in each year. Both the University of Liverpool (UoL) and Liverpool John Moores University (LJMU) design and build scientific instruments and have developed strong links to many international research laboratories. The CDT also capitalizes on the Liverpool Big Data Network (LBDN) [2], a pan-UoL initiative set up in 2013 in response to Big Data being one of the "Eight Great technologies". As well as providing a focus for relevant existing MSc provision, LBDN now comprises some 100 academics drawn from many different academic disciplines and united by a common interest in developing and applying Big Data. LBDN includes world experts in, for example, Monte Carlo analysis, Deep Learning and Data Analytics. It is also closely coupled to the Virtual Engineering Centre (VEC), a UoL office at STFC's Daresbury site and the core of a strategic partnership between UoL and STFC's Hartree center. By providing a defined interface between UoL, Hartree and industry, VEC has been successful at attracting industrial contracts from large organizations with a keen interest in Big Data. The VEC and also the LBDN will provide opportunities for student placements and also routes to employment for our graduates. Many organizations have identified a shortage of people with Big Data skills. LIV.DAT helps address that shortage.

RESEARCH

Managing, analyzing and interpreting large, complex datasets and high rates of data flow is a growing challenge for many areas of science and industry. Recent years have witnessed a dramatic increase of data in many fields of science and engineering , due to the advancement of sensors, mobile devices, biotechnology, digital communication and internet applications. Very little targeted training is provided internationally, and in the UK in particular, to address a growing skills gap in this area. LIV.DAT provides a comprehensive training programme to its three student cohorts to address this problem. The focus of the centre is on addressing the data challenges presented by research in astronomy, nuclear, particle and accelerator physics. R&D is structured across the following 3 main work packages: Monte Carlo and Model Definition, Deep Learning and HPC, and Data Analysis. Detailed R&D plans, including student placements were agreed at the project start and supervisory teams identified so that student could be recruited right after project start.

- Monte Carlo (MC) methods are powerful tools for everything from modelling the birth and evolution of the universe to performing the numerical integrals needed to calculate the cross sections for particle interactions. They are used extensively in astrophysics, nuclear physics and particle physics;
- HPC and Deep or Machine Learning (ML) forms the core of the R&D program in work package 2. Students learn how to access and use high performance computer cluster in order to simulate problems that cannot be dealt with on desktop computers;
- Data Analysis benefits from the results and predictions of MC simulations and increasingly uses ML for data handling. It is essential to extract the physics from any measurements.

All three work packages are highly relevant for accelerator science. Beam control and manipulation, beam dynamics studies and detailed analysis of beam diagnostics output data all directly benefit performance enhancements. This is true for linear and circular machines, any particle species and energy, i.e the results within LIV.DAT are highly relevant for a large number of projects within accelerator science.

In the following, progress made in two specific accelerator R&D projects is outlined.

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c.p.welsch@liverpool.ac.uk

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Physics and Biology of Proton Beam Therapy

There is increasing evidence that protons, particularly when their energy is close to that of the Bragg peak, induce a different range of DNA damage in the cells they pass through than do x-rays. There is also evidence that this proton-induced damage leads to an alternative cellular DNA damage response to that resulting from x-ray-induced damage, mediated by different DNA damage signaling and repair pathways [3]. Selina Dhinsey is a PhD student at UoL, benefiting from work carried out in the group of Jason Parsons where molecular biology techniques are used to study the effects of proton beams on cancerous and normal cells. Within LIV.DAT, she combines this data with Monte Carlo simulations of beam-cell interactions over a range of proton energies (up to 60 MeV) to help improve our understanding of the radiobiology of proton beam therapy.

Experimental work will be carried out using the proton beam at the Clatterbridge Cancer Centre (CCC), which has been treating patients with ocular melanomas since 1989. Here, 62.5 MeV protons are produced using a fixed energy AVF cyclotron (Scanditronix MC 60) [4]. The site also contains 8 linear accelerators [5]. Following experimental work, modelling and characterization of the treatment beam will be performed if required. The results of this work will form the basis of models that will be used to enhance treatment planning. Currently, although we have knowledge of physical responses to proton radiation, there is a lack of understanding of the biological response [1]. In particular, more experimental data is required to understand the effects of proton irradiation on cancerous cells. The aim here is to create a robust model of this interaction, allowing better exploitation of proton beams in radiation therapy. The complex DNA damage that protons induce, with multiple strand breaks occurring within small regions in the DNA, has been observed to require a significantly longer repair time than the less complex damage caused by x-rays [6]. The hope is that improved modelling and treatment planning will enable this type of damage to cancerous cells to be maximized, and that this improves the treatment outcomes.

The first stage of the project involves improving the speed and precision of experimental identification of DNA damage following irradiation, using image analysis techniques. Currently the Comet Assay method [7] is used. For example, HeLa cells are embedded in 1% agarose after irradiation and undergo lysis where the cell membrane is broken down. Under electrophoresis, the DNA separates out due to the damage it was subject to during irradiation. For higher damage the cells separate out more resulting in a comet like shape with a distinguishable tail, see Fig.1. The analysis of the damaged cells is currently carried out manually and it is here that an automated process would be implemented.

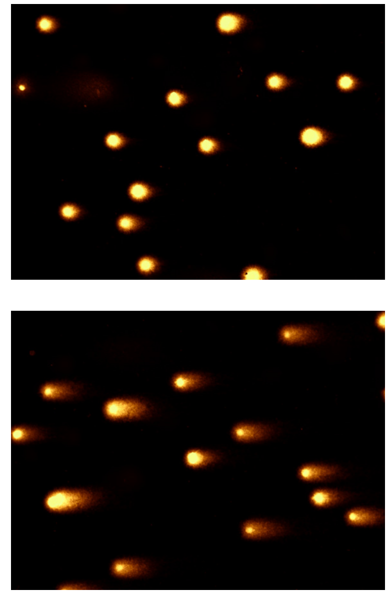

Figure 1: Top) An image taken of control cells that have not been irradiated, and therefore show no tails when undergoing electrophoresis. Bottom) An image taken of irradiated cells after undergoing electrophoresis, where the comet-like structure of a 'tail' can be seen, indicating damage.

The aim is to create tools to automatically analyze the microscope images of the damaged cells, providing measurements of the comet shape (tail length, width etc.). The intention is to speed up analysis and to allow a more differentiated categorization of the levels of DNA damage in the cells.

Enhanced Models of Plasma-beam Interaction

The Development of Enhanced Models of the Plasma-beam Interaction is the goal of Aravinda Perera at UoL who works closely with specialist software developer Tech-X . He targets the Advanced Wakefield Experiment (AWAKE) which became the first ever proton-beam driven plasma wakefield acceleration (PFWA) experiment in 2016 [8], see Fig. 2. PWFA works by driving an electron 'Langmuir' wave in a plasma, using a relativistic beam of charged particles or an intense inhomogeneous laser-pulse. The driver causes transverse expulsion of plasma electrons, leaving behind a net positively charged region of ions (assumed immobile on this timescale) that provide a restoring force on the electrons. As they return to axis, they either overshoot or are repelled back outwards by their space-charge fields, oscillating radially at, nominally, the characteristic plasma frequency. This sets up a series of high and low electron density regions that follow the relativistic driver, spaced by a wavelength corresponding to the plasma frequency and the driver velocity, between which the longitudinal electric field can reach up to 50 GV/m. A witness beam then injected at the right position into this field can, at first approximation, be continuously accelerated, in phase with the wake.

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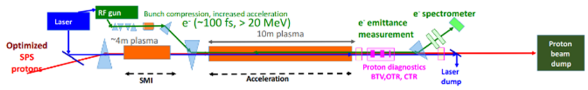

Figure 2. AWAKE experimental schematic [8]

Using a proton beam driver, as in AWAKE, allows limitations on acceleration length due to energy depletion of an electron beam or non-linear optical effects on a laser pulse, to be overcome. The absence of sufficiently energetic proton beams short enough to efficiently drive a wake in an appropriately dense plasma means that AWAKE settles for the SPS proton beam, which is 100× too long. However, after injection, the electromagnetic plasma wakefield generated by the beam head causes the beam to be self-modulated into a train of short micro-bunches, positioned to resonantly drive the wake [9]. Recent results from AWAKE Run 1 Phase 1 have reported the observation of self-modulated bunches driving a stable wake, see Fig. 3 [10].

Phase 2, which has started in 2018, will examine the witness electron beam acceleration process. However, there remains much scope for improvement, particularly in time for Run 2 due to start in 2021. The use of multiple micro-bunches means that the phase of the wake along the train is modified by each of them, causing them to be transversely defocused over a short propagation length, leading to a premature drop in wakefield amplitude. Existing partial solutions to maintain a stable wake use combinations of plasma density steps and ramps, and have been verified by Particle-In-Cell (PIC) simulation [11]. However, while helpful, they are admittedly ad-hoc [12], and sharp density steps are difficult to achieve [13]. This warrants the development of a theory of controlling the self-modulation process. Achieving higher accelerating gradients requires the wake to enter a 'quasi-non-linear' regime, where the plasma density perturbation is on the order of its unperturbed density. This regime shares characteristics of both extremes of complete plasma electron evacuation (blow-out regime) and small perturbation (linear regime). However, the behavior of a witness beam in such a wake is still not well understood. Contrary to the expectation that it would not allow emittance preservation of a witness beam due to an inharmonic restoring force, preliminary simulations show signs of constraint in emittance growth [14]. The principle whose viability AWAKE aims to verify holds great potential for the future of particle accelerators, giving urgent value to developing a comprehensive model of this regime, as well as for experimental verification within the AWAKE plasma channel through novel diagnostic methods. In particular, there has been much development over the last decade in using betatron radiation to diagnose beams within plasma wakes [15-16]. However, existing betatron-radiation theory and related experimental methods are tailored for use in the blow-out regime. There is also a lack of PIC and other simulation codes streamlined for simulations involving radiation-based diagnostics.

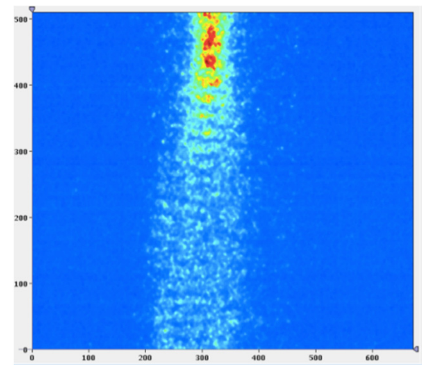

Figure 3. AWAKE milestone; first observation of proton beam self-modulation, reported in 2016. [8]

The first stage of Aravinda Perera's project aims to develop an enhanced model of multi-bunch-driven plasma wakes, with a view to constraining wakefield amplitude loss due to bunch defocusing. In parallel, it will aim to explore witness beam dynamics in quasi-non-linear wakefields through PIC simulations. This would enable theoretical and simulation studies of betatron radiation in this regime, informing implementation of diagnostic methods to exploit this effect, and experimental verification of electron beam behavior. The collaboration with Tech-X will look into development of new efficient algorithms to simulate and extract radiation data from existing PIC methods.

TRAINING

The projects within LIV.DAT are very demanding in their own right, but in combination within each student cohort and across all three cohorts will allow tackle some of the biggest challenges in using Big Data Science to advance a whole entire range scientific disciplines. This is a fertile ground for the training of PhD students. The LIV.DAT training program is designed to address a wide range of employment skills with the aim to provide all students with the skills required for a future career in both, academia and industry. The training program builds on existing modules drawn from the UoL MSc Big Data and HPC program. The students undertake 45 credits from this MSc program in year 1, including mandatory courses on data mining and data analysis. In addition, they have already followed on international school on MC Simulations [17], a researcher skills training with researchers from the AVA network [18], and most recently an HPC training week, hosted by Tech-X.

SUMMARY AND OUTLOOK

The LIV.DAT CDT has started in October 2017 with a first cohort of 14 students. A second cohort will now start in 2018, covering R&D across three scientific work packages, all related to Big Data Science. Progress was illustrated on the example of two projects focusing on accelerator science and a brief overview of the training program was also given.

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