Institution: University of Warwick

Unit of Assessment: B9 - Physics

Title of case study: EPOCH open source code: fundamental to improving productivity and delivering cost-savings for the UK defence industry & high-tech SMEs (b9ICS-1)

Period when the underpinning research was undertaken: 2007 - ongoing

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Tony Arber	Professor	2000-present
Keith Bennett	Associate Professor	2010-present
Christopher Brady	Research Fellow	2007-2017

Period when the claimed impact occurred: 2014 - ongoing

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

Research at Warwick led to development of the EPOCH (Extendable PIC Open Collaboration) open source software package. EPOCH is used by the Atomic Weapons Establishment (AWE) in its work to support the UK's nuclear deterrent and national security. For AWE, EPOCH is an important component of its experimental planning, and its use represents an estimated saving of GBP2,500,000 to the organisation. The package is also used by the Defence Science and Technology Laboratory (DSTL) enabling important simulations which de-risk the organisation's activities. In all, the software has more than 1,400 users, including high-tech SMEs such as Fluid Gravity Engineering Ltd which has saved GBP100,000 on development and GBP10,000 annual maintenance costs.

2. Underpinning research (indicative maximum 500 words)

At the 2007 European Physical Society Plasma Physics meeting in Warsaw, it became clear that UK academics were being hindered by their lack of access to plasma kinetic simulation codes – so called particle-in-cell (PIC) codes. These were in widespread use in the US and European laboratories outside the UK; however, these codes were not open access and UK research was restricted to ad-hoc collaborations with overseas code developers. We had neither control over this code development nor the opportunity to lead the advancements in algorithm design required for the next generation of laser-plasma facilities or laser-driven fusion.

Preparatory work began at Warwick in 2007 on the core, classical PIC algorithm which would be at the centre of EPOCH (Extendable PIC Open Collaboration). This initial study seeded an EPSRC grant, starting 2010, led by Warwick and included Oxford and Imperial. The code design was chosen to allow use across all applications, e.g. laser-plasma, fusion research, laser-solid interactions, QED-plasmas; as a result, the code also covered the feature sets needed by industry.

The key innovation implemented in EPOCH, and absent in other kinetic codes worldwide, were its extension as a multi-physics and multi-scale code. The multi-physics extensions included collisions, radiation, ionisation and QED (quantum-electrodynamics) effects while the multi-scale extensions allowed the PIC scheme to be pushed to smaller scales (QED) and at the other extreme towards fluid limits. The research that underpinned these developments was as follows:

1. *Computer science and algorithms*. The core algorithm **[3.1, 3.2]** was designed at Warwick with modern data structures to allow easy addition of physics packages and particle manipulation. A portable, self-defining data format (SDF) for output data was developed to allow scaling to tens of thousands of cores.

2. *Long scale-length, slow physics*. Traditional PIC codes assume a collision-less plasma; however, for both long time-scale simulations and experiments with laser-solid interaction this is no longer valid. The EPOCH project has developed schemes for including relativistic binary collisions, as well has a hybrid scheme with resistive background fluids **[3.2]**. These routines were initially developed at Imperial but have since been extended to correctly handle relativistic binary collisions by Warwick.
3. *Short-scale, fast physics*. Significant novel algorithmic development was required to allow the inclusion of QED processes **[3.3, 3.4, 3.5, 3.6]**. This enabled a consistent treatment of non-linear quantum-corrected synchrotron emission, and the subsequent electron-positron pair production through the interaction of those synchrotron photons with the background laser – the Breit-Wheeler process. Oxford and York developed QED physics tables that were implemented at Warwick.

The primary research that underpinned EPOCH was based on collaboration between Warwick, York, Oxford and Imperial, with additional support from AWE. Warwick was the lead institute responsible for control of the source code, optimisation, documentation, training and core algorithms. Warwick also led computer science related issues on input and output, data format and parallelisation. The software had its first major, including QED and collisions, public release in July 2012. Since 2016 EPOCH has been fully maintained and developed by the team at Warwick. It is the combination of the novel physics packages and computer science related extensions that have led to the industrial impact.

3. References to the research

Below are some highlight papers from the Warwick group and grants awarded to the EPOCH project.

Algorithm development papers

[3.1] Ridgers, C.P., Kirk, J.G., Duclous, R., Blackburn, T.G., **Brady, C.S. , Bennett, K., Arber, T.D.** and Bell, A.R. (2014) *Modelling gamma-ray photon emission and pair production in high-intensity laser–matter interactions.* Journal of Computational Physics, 260. pp. 273-285. doi: 10.1016/j.jcp.2013.12.007

[3.2] **Arber, T.D. , Bennett, K., Brady, C.S.,** Lawrence-Douglas, A., Ramsay, M.G., **Sircombe, N.J.,** Gillies, P., Evans, R.G., Schmitz, H., Bell, A.R. and Ridgers, C.P. (2015) *Contemporary particle-in-cell approach to laser-plasma modelling.* Plasma Physics and Controlled Fusion, 57 (11). 113001. doi: 10.1088/0741-3335/57/11/113001

Warwick Group Peer-reviewed highlights based on using EPOCH from the Warwick group

[3.3] Ridgers, C., **Brady, C.S.**, Duclous, R., Kirk, J., **Bennett, K., Arber, T.D**., Robinson, A. and Bell, A.R. (2012) *Dense electron-positron plasmas and ultraintense gamma rays from laser-irradiated solids.* Physical Review Letters, Vol.108 (16). p. 165006. doi: 10.1103/PhysRevLett.108.165006

[3.4] **Brady, C.S.,** Ridgers, C., **Arber, T.D. ,** Bell, A. and Kirk, J. (2012) *Laser absorption in relativistically underdense plasmas by synchrotron radiation.* Physical Review Letters, Vol.109 (24). p. 245006. doi: 10.1103/PhysRevLett.109.245006

[3.5] Ridgers, C.P., **Brady, C.S.,** Duclous, R., Kirk, J.G., **Bennett, K., Arber, T.D.** and Bell, A. (2013) *Dense electron-positron plasmas and bursts of gamma-rays from laser-generated quantum electrodynamic plasmas.* Physics of Plasmas, Volume 20 (5). Article 056701. doi: 10.1063/1.4801513

[3.6] **Brady, C.S**., Ridgers, C.P**., Arber, T.D**. and Bell, A.R. (2014) *Synchrotron radiation, pair production, and longitudinal electron motion during 10-100 PW laser solid interactions.* Physics of Plasmas, Volume 21 (Number 3). Article 033108. doi: 10.1063/1.4869245

Grants awarded

[G1] T.D. Arber was PI on 'Multi-scale simulations of intense laser plasma interactions' funded by EPSRC (EP/G054940/1, EP/G056803/1, EP/G055165/1) from January 2010 to March 2014 with a total value of GBP1,050,000 across Warwick, Oxford and Imperial.

[G2] K. Bennett was PI, **T.D. Arber** Co-I, on 'Extension and optimisation of the EPOCH code' funded by EPSRC (EP/P02212X/1) from September 2017 to August 2019 with a value of GBP236,478.

[G3] T.D. Arber has been PI of the 'The Plasma High End Computing Consortium' funded by EPSRC from May 2013 until June 2022 across two awards (EP/L000237/1 and EP/R029148/1) with a total value of GBP506,502. This includes rolling funding at 40% FTE for support of UK codes including EPOCH.

[G4] T.D. Arber is PI of the 'Collaborative Computational Project in Plasma Physics' funded by EPSRC (EP/M022463/1) from July 2015 to March 2020 at a total cost of GBP125,995. This project includes funding for annual EPOCH training workshops.

[G5] T.D. Arber is Warwick PI on a project lead by R. Scott (Rutherford Appleton Laboratory) on 'Plasma kinetics, pre-heat, and the emergence of strong shocks in laser fusion' funded by EPSRC (EP/P026486/1, EP/P023460/1, EP/P026796/1) from July 2017 until July 2020 at total costs across Warwick RAL and York of GBP1,100,000. This project uses EPOCH to predict plasma kinetics for shock ignition.

[G6] T.D. Arber and **S. Jarvis** are Co-Directors of the 'Centre for Computational Plasma Physics' funded by AWE plc. from June 2014 until July 2020 across two awards with a total value of GBP472,000. This funding part supports maintenance of EPOCH.

4. Details of the impact

AWE (the Atomic Weapons Establishment) plays a key strategic role in the UK's deterrent and National Nuclear Security. Its work presents significant scientific and technical challenges, which require the development and implementation of cutting-edge science and computational methodologies.

The University of Warwick has had a long relationship with AWE, cemented by the formation of a Centre for Computational Plasma Physics in 2013. This strategic partnership was built on the development of the EPOCH massively parallel kinetic code, which has been actively used at AWE during the REF period, to help plan and understand laser-plasma experiments; in particular experiments utilising the petawatt class laser in the ORION facility, sited at AWE's Aldermaston campus.

The Orion facility consists of 12 high-powered laser beams able to heat compressed matter to millions of degrees in nano-seconds (*Nature*, Vol 464, 156 (2010)). Experimental campaigns (including 85% of the experiments on ORION) are primarily in support of the UK nuclear deterrent and national security. These experiments are important in providing validation of data in the plasma regime to underwrite understanding of the performance of the deterrent and hence are central to AWE's core business.

The Deputy Chief Scientist at AWE writes: "*Over approximately ten years of integrated engagement between AWE staff and the EPOCH team, who are based primarily at the University of Warwick, the code has developed from a basic research tool into a practical and important component of our experimental planning, well beyond validation of EPOCH itself*.

"The experimental campaigns are primarily in support of the UK nuclear deterrent and national security… These campaigns are important in providing validation of data in the plasma regime to underwrite our understanding of the performance of the deterrent and hence, are important to our core business.

"In parallel, this work increases our value to the US as worthy collaborators under the 1958 US–UK Mutual Defence Agreement, the importance of which cannot be overstated."

The Deputy Chief Scientist estimates the equivalent AWE capability achieved unilaterally would have cost an estimated £2.5 to £3million [GBP3,000,000] over the ten-year timeframe **[5.1]**.

He adds: "*Without EPOCH we would not be able to develop or analyse these experiments on facilities such as ORION; it also enables us to innovate new experiments and engage on wider problems of interest with peers in the US National Laboratory complex, and with Universities. Progressing this scientific work not only strengthens our knowledge but our people capability to continue to support the Nation*.'' **[5.1].**

EPOCH is also used by the Defence Science and Technology Laboratory (DSTL) where simulations conducted in EPOCH allow an understanding of the physical properties of electron beams as they propagate through media over range which cannot be deduced by other means.

PULSAR Project Manager at DSTL regards EPOCH "*as a benchmark model for predicting the performance of proposed future military sensing concepts".* He states that: "*Had DSTL undertaken the development of EPOCH [itself] and paid for training courses, we estimate the cost would have been in the region of £560k [GBP560,000] and added 2 years to the project. Access to expert advice has also been extremely valuable and has saved us many months of wasted effort*" **[5.2]**. He adds that *"in the long term the project aims to not only provide step change military capabilities for the military, but also has the potential utility and cost reduction for civilian applications such as the oil and gas industry*" **[5.3]**.

EPOCH has more than 1,400 users in total, including high-tech SMEs such as Fluid Gravity Engineering Ltd. (FGE). FGE specialise in aspects of computational physics, with a client base spread across numerous sectors including civil space, maritime, oil and gas. The data analysis and visualisation requirements of FGE closely match that of the plasma physics community so this was a natural industrial link. As an SME, significantly smaller than AWE for instance, EPOCH has had a significant impact on FGE's productivity over the last six years with the director of FGE commenting – *"The work undertaken in the EPOCH project has allowed us to consolidate some parts of our required code structure across the company, improving output and reducing our costs in that area. We have ten research scientists within the company who regularly use the VisIT and SDF tools in their everyday work. If the VisIT/SDF framework was not available then we would have had to spend… [in the] order [of] £100k [GBP100,000] to develop, and £10k [GBP10,000] per annum to maintain a similar capability. Linking to work under the EPOCH project has thus enabled us to concentrate further investment into application areas that expand our current contracts and customer base within the UK"* **[5.4]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1] Written Statement from Deputy Chief Scientist, **AWE:** letter received confirming the importance of the research to their ongoing research programme and on the ORION laser facility in particular. Letter dated 8th October 2020

[5.2] Written Statement from PULSAR Project Manager, **DSTL** Fort Halstead: letter received confirming the role of EPOCH in DSTL's plans to develop sensing capability for the military. Letter dated 28th May 2020.

[5.3] Written Statement from PULSAR Project Manager, **DSTL** Fort Halstead: letter received confirming the role of EPOCH in DSTL's plans to develop sensing capability for the military. Letter dated 22nd October 2018

[5.4] Written Statement from Director, **Fluid Gravity Engineering Ltd**: letter received confirming the importance of the EPOCH project to maintaining the productivity of this high-tech SME. Letter dated 24th June 2019