Horizon 2020

Excellent Science

Call: ERC-2017-STG

(Call for proposals for ERC Starting Grant)

Topic: ERC-2017-STG

Type of action: ERC-STG

(Starting Grant)

Proposal number: 759546

Proposal acronym: EPIC

Deadline Id: ERC-2017-STG

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How to fill in the forms

The administrative forms must be filled in for each proposal using the templates available in the submission system. Some data fields in the administrative forms are pre-filled based on the previous steps in the submission wizard.

1 - General information

Topic	ERC-2017-STG
Call Identifier	ERC-2017-STG
Type of Action	ERC-STG
Deadline Id	ERC-2017-STG

Acronym: EPIC

Proposal title*: Energy transfer Processes at gas/wall Interfaces under extreme Conditions

Note that for technical reasons, the following characters are not accepted in the Proposal Title and will be removed: < > " &

Duration in months*: *60*

Primary ERC Review Panel*: PE8

Secondary ERC Review Panel: (if applicable)

ERC Keyword 1*: *Fluid mechanics, hydraulic-, turbo-, and piston engines*

Please select, if applicable, the ERC keyword(s) that best characterise the subject of your proposal in order of priority.

ERC Keyword 2: *Not applicable*

ERC Keyword 3: *Not applicable*

ERC Keyword 4: *Not applicable*

Free keywords: *laser diagnostic measurements, heat transfer, flame quenching*

Abstract*

In the future, high-efficiency (low CO2) vehicles will be powered in part by reinvented internal combustion (IC) engines that are "downsized" and operate with new combustion modes. These engine concepts are subject to problems such as increased transient heat transfer and flame quenching in small passages. Near-wall transient heat transfer is not well-understood in engine environments; the gas is not constant in pressure, temperature, or velocity such that physical processes quickly digress from established theory. EPIC is uniquely placed to address these problems. A novel constant-volume chamber, offering realistic engine passages but with optical access, and which emulates the pressure/temperature time curve of a real engine, will be developed. This chamber will make it possible to measure the highly transient and highly variable processes at the gas/wall interface (including a highly dynamic flame front) for single- and two-wall passages. Measurements will be made using a suite of advanced laser diagnostics; a novel aspect of the proposed work as they have not been used in combination to study such a problem before. Hybrid fs/ps rotational coherent Raman (i.e. CARS) in a line format will provide transient gas temperature and species profiles normal to the wall surface in high-risk/high-gain

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packages. PIV/PTV measurements will further elucidate flow dynamics at the surface. Planar OH-LIF will help interpret CARS measurements and provide necessary details of flame transport and quenching. As the flame approaches the surface, phosphor thermometry will measure wall temperature and heat flux to elucidate the highly dynamic inter-coupling between flame and wall. EPIC will provide substantial breakthroughs in knowledge by measuring unsteady boundary layer development and understanding its influence on flame quenching for single- and two-wall surfaces. As such, EPIC will provide the fundamental knowledge that supports cleaner combustion technology for the future.

Remaining characters 8

In order to best review your application, do you agree that the above non-confidential proposal title and abstract can be used, without disclosing your identity, when contacting potential reviewers?* ◉ Yes ○ No

Has this proposal (or a very similar one) been submitted in the past 2 years in response to a call for proposals under the 7th Framework Programme, Horizon 2020 or any other EU programme(s)? ○ Yes ◉ No

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Declarations

1) The Principal Investigator declares to have the explicit consent of all applicants on their participation and on the content of this proposal.*	☒
2) The Principal Investigator declares that the information contained in this proposal is correct and complete.	☒
3) The Principal Investigator declares that this proposal complies with ethical principles (including the highest standards of research integrity — as set out, for instance, in the European Code of Conduct for Research Integrity — and including, in particular, avoiding fabrication, falsification, plagiarism or other research misconduct).	☒

4) The Principal Investigator hereby declares that *(please select one of the three options below)*:

- in case of multiple participants in the proposal, the coordinator has carried out the self-check of the financial capacity of the organisation on http://ec.europa.eu/research/participants/portal/desktop/en/organisations/lfv.html or to be covered by a financial viability check in an EU project for the last closed financial year.Where the result was “weak” or “insufficient”, the Principal Investigator confirms being aware of the measures that may be imposed in accordance with the H2020 Grants Manual (Chapter on Financial capacity check).	○
- in case of multiple participants in the proposal, the coordinator is exempt from the financial capacity check being a public body including international organisations, higher or secondary education establishment or a legal entity, whose viability is guaranteed by a Member State or associated country, as defined in the H2020 Grants Manual (Chapter on Financial capacity check).	○
- in case of a sole participant in the proposal, the applicant is exempt from the financial capacity check.	◉
5) The Principal Investigator hereby declares that each applicant has confirmed to have the financial and operational capacity to carry out the proposed action. Where the proposal is to be retained for EU funding, each beneficiary applicant will be required to present a formal declaration in this respect.	☒

The Principal Investigator is only responsible for the correctness of the information relating to his/her own organisation. Each applicant remains responsible for the correctness of the information related to him and declared above. Where the proposal to be retained for EU funding, the coordinator and each beneficiary applicant will be required to present a formal declaration in this respect.

According to Article 131 of the Financial Regulation of 25 October 2012 on the financial rules applicable to the general budget of the Union (Official Journal L 298 of 26.10.2012, p. 1) and Article 145 of its Rules of Application (Official Journal L 362, 31.12.2012, p.1) applicants found guilty of misrepresentation may be subject to administrative and financial penalties under certain conditions.

Personal data protection

The assessment of your grant application will involve the collection and processing of personal data (such as your name, address and CV), which will be performed pursuant to Regulation (EC) No 45/2001 on the protection of individuals with regard to the processing of personal data by the Community institutions and bodies and on the free movement of such data. Unless indicated otherwise, your replies to the questions in this form and any personal data requested are required to assess your grant application in accordance with the specifications of the call for proposals and will be processed solely for that purpose. Details concerning the purposes and means of the processing of your personal data as well as information on how to exercise your rights are available in the privacy statement. Applicants may lodge a complaint about the processing of their personal data with the European Data Protection Supervisor at any time.

Your personal data may be registered in the Early Detection and Exclusion system of the European Commission (EDES), the new system established by the Commission to reinforce the protection of the Union's financial interests and to ensure sound financial management, in accordance with the provisions of articles 105a and 108 of the revised EU Financial Regulation (FR) (Regulation (EU, EURATOM) 2015/1929 of the European Parliament and of the Council of 28 October 2015 amending Regulation (EU, EURATOM) No 966/2012) and articles 143 - 144 of the corresponding Rules of Application (RAP) (COMMISSION DELEGATED REGULATION (EU) 2015/2462 of 30 October 2015 amending Delegated Regulation (EU) No 1268/2012) for more information see the Privacy statement for the EDES Database).

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List of participants

#	Participant Legal Name	Country
1	THE UNIVERSITY OF EDINBURGH	United Kingdom

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2 - Administrative data of participating organisations

Host Institution

PIC	***Legal name***
999974941	*THE UNIVERSITY OF EDINBURGH*

Short name: UEDIN

Address of the organisation

Street OLD COLLEGE, SOUTH BRIDGE

Town EDINBURGH

Postcode EH8 9YL

Country United Kingdom

Webpage www.ed.ac.uk

Legal Status of your organisation

Research and Innovation legal statuses

Public body .... yes

Legal person .... yes

Non-profit .... yes

International organisation .... no

International organisation of European interest .... no

Secondary or Higher education establishment .... yes

Research organisation .... yes

Enterprise Data

SME self-declared status........ 2007 - no

SME self-assessment .... unknown

SME validation sme........ 2007 - no

Based on the above details of the Beneficiary Registry the organisation is not an SME (small- and medium-sized enterprise) for the call.

NACE Code: 853 - Higher education

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Department(s) carrying out the proposed work

Department 1

Department name	School of Engineering	☐ not applicable
	☐ Same as organisation address	
Street	Mayfield Road	
Town	Edinburgh	
Postcode	EH9 3DW	
Country	United Kingdom	

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Principal Investigator

The following information of the Principal Investigator is used to personalise the communications to applicants and the evaluation reports. Please make sure that your personal information is accurate and please inform the ERC in case your e-mail address changes by using the call specific e-mail address:

For Starting Grant Applicants: ERC-2017-StG-applicants@ec.europa.eu

The name and e-mail of contact persons including the Principal Investigator, Host Institution contact are read-only in the administrative form, only additional details can be edited here. To give access rights and contact details of contact persons, please save and close this form, then go back to Step 4 of the submission wizard and save the changes.

ORCID ID	0000-0001-5958-8855		
Researcher ID	O-3079-2016		
Last Name*	PETERSON	Last Name at Birth	Peterson
First Name(s)*	Brian	Gender*	(•) Male ( ) Female
Title	Dr.	Country of residence*	United Kingdom
Nationality*	United States	Country of Birth*	United States
Date of Birth* (DD/MM/YYYY)	02/09/1980	Place of Birth*	Albuquerque, New Mexico

Contact address

Current organisation name	University of Edinburgh
Current Department/Faculty/Institute/ Laboratory name	School of Engineering / Institute of Multi-scale Thermo-fluids

☐ Same as organisation address

Street	Mayfield Road		
Postcode/Cedex	EH9 3DZ	Town*	Edinburgh
Phone*	+440 1316505572	Country*	United Kingdom
Phone2 / Mobile	+xxx xxxxxxxxx		
E-mail*	brian.peterson@ed.ac.uk		

Contact address of the Host Institution and contact person

The name and e-mail of Host Institution contact persons are read-only in the administrative form, only additional details can be edited here. To give access rights and contact details of Host Institution, please save and close this form, then go back to Step 4 of the submission wizard and save the changes. Please note that the submission is blocked without a contact person and e-mail address for the Host Institution.

Organisation Legal Name **THE UNIVERSITY OF EDINBURGH**

First name* **Alan** Last name* **Kennedy**

E-Mail* **europe@eri.ed.ac.uk**

Position in org. *Administrator*

Department *THE UNIVERSITY OF EDINBURGH* ☒ Same as organisation

☒ Same as organisation address

Street OLD COLLEGE, SOUTH BRIDGE

Town EDINBURGH Postcode EH8 9YL

Country United Kingdom

Phone *+xxx xxxxxxxxx* Phone2/Mobile *+xxx xxxxxxxxx*

Other contact persons

First Name	***Last Name***	***E-mail***	***Phone***
Katherine	Quinn	katherine.quinn@ed.ac.uk	

3 - Budget

Participant Number in this proposal	Organisation Short Name	Organisation Country	Total eligible costs/€ (including 25% indirect costs) ?	Requested grant/€
1	UEDIN	UK	1 499 351	1 499 351
Total			1 499 351	1 499 351

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4 - Ethics issues table

1. HUMAN EMBRYOS/FOETUSES		Page
Does your research involve Human Embryonic Stem Cells (hESCs)?	○ Yes ● No	
Does your research involve the use of human embryos?	○ Yes ● No	
Does your research involve the use of human foetal tissues / cells?	○ Yes ● No	
2. HUMANS		**Page**
Does your research involve human participants?	○ Yes ● No	
Does your research involve physical interventions on the study participants?	○ Yes ● No	
3. HUMAN CELLS / TISSUES		**Page**
Does your research involve human cells or tissues (other than from Human Embryos/ Foetuses, i.e. section 1)?	○ Yes ● No	
4. PERSONAL DATA		**Page**
Does your research involve personal data collection and/or processing?	○ Yes ● No	
Does your research involve further processing of previously collected personal data (secondary use)?	○ Yes ● No	
5. ANIMALS		**Page**
Does your research involve animals?	○ Yes ● No	
6. THIRD COUNTRIES		**Page**
In case non-EU countries are involved, do the research related activities undertaken in these countries raise potential ethics issues?	○ Yes ● No	
Do you plan to use local resources (e.g. animal and/or human tissue samples, genetic material, live animals, human remains, materials of historical value, endangered fauna or flora samples, etc.)?	○ Yes ● No	
Do you plan to import any material - including personal data - from non-EU countries into the EU?	○ Yes ● No	
Do you plan to export any material - including personal data - from the EU to non-EU countries?	○ Yes ● No	
In case your research involves low and/or lower middle income countries, are any benefits-sharing actions planned?	○ Yes ● No	
Could the situation in the country put the individuals taking part in the research at risk?	○ Yes ● No	

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7. ENVIRONMENT & HEALTH and SAFETY		Page
Does your research involve the use of elements that may cause harm to the environment, to animals or plants?	◯ Yes ◉ No	
Does your research deal with endangered fauna and/or flora and/or protected areas?	◯ Yes ◉ No	
Does your research involve the use of elements that may cause harm to humans, including research staff?	◯ Yes ◉ No	
8. DUAL USE		**Page**
Does your research involve dual-use items in the sense of Regulation 428/2009, or other items for which an authorisation is required?	◯ Yes ◉ No	
9. EXCLUSIVE FOCUS ON CIVIL APPLICATIONS		**Page**
Could your research raise concerns regarding the exclusive focus on civil applications?	◯ Yes ◉ No	
10. MISUSE		**Page**
Does your research have the potential for misuse of research results?	◯ Yes ◉ No	
11. OTHER ETHICS ISSUES		**Page**
Are there any other ethics issues that should be taken into consideration? Please specify	◯ Yes ◉ No	

I confirm that I have taken into account all ethics issues described above and that, if any ethics issues apply, I will complete the ethics self-assessment and attach the required documents. ☒

[How to Complete your Ethics Self-Assessment]

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5 - Call specific questions

Academic Training	
Are you a medical doctor or do you hold a degree in medicine? Please note that if you have also been awarded a PhD, your medical degree may be your first eligible degree.	◯ Yes ⦿ No
Date of earliest award (PhD or equivalent)* - DD/MM/YYYY	19/12/2010
With respect to the earliest award (PhD or equivalent), I request an extension of the eligibility window, (indicate number of days) [see the ERC 2017 Work Programme and the Information for Applicants to the Starting and Consolidator Grant 2017 Calls].	◯ Yes ⦿ No
Eligibility	
Please indicate your percentage of working time in an EU Member State or Associated Country over the period of the grant: Please note that you are expected to spend a minimum of 50% of your total working time in an EU Member State or Associated Country.	60,00
I acknowledge that I am aware of the eligibility requirements for applying for this ERC call as specified in the ERC Annual Work Program , and certify that, to the best of my knowledge my application is in compliance with all these requirements. I understand that my proposal may be declared ineligible at any point during the evaluation or granting process if it is found not to be compliant with these eligibility criteria.*	☒
Data-Related Questions and Data Protection (Consent to any question below is entirely voluntary. A positive or negative answer will not affect the evaluation of your project proposal in any form and will not be communicated to the evaluators of your project.)	
For communication purposes only, the ERC asks for your permission to publish, in whatever form and medium, your name, the proposal title, the proposal acronym, the panel, and host institution, should your proposal be retained for funding.	⦿ Yes ◯ No
Some national and regional public research funding authorities run schemes to fund ERC applicants that score highly in the ERC's evaluation but which can not be funded by the ERC due to its limited budget. In case your proposal could not be selected for funding by the ERC do you consent to allow the ERC to disclose the results of your evaluation (score and ranking range) together with your name, non-confidential proposal title and abstract, proposal acronym, host institution and your contact details to such authorities?	⦿ Yes ◯ No
The ERC is sometimes contacted for lists of ERC funded researchers by institutions that are awarding prizes to excellent researchers. Do you consent to allow the ERC to disclose your name, non-confidential proposal title and abstract, proposal acronym, host institution and your contact details to such institutions?	⦿ Yes ◯ No

Proposal ID **759546** *Acronym* **EPIC**

The Scientific Council of the ERC has developed a monitoring and evaluation strategy in order to help it fulfil its obligations to establish the ERC's overall strategy and to monitor and quality control the programme's implementation from the scientific perspective. As provided by section 3.10 of the ERC Rules for Submission: a range of projects and studies may be initiated for purposes related to monitoring, study and evaluating the implementation of ERC actions. Do you consent to allow the third parties carrying out these projects and studies to process the content of your proposal including your personal data and the respective evaluation data? The privacy statement on the processing operations of applicants and beneficiaries data for H2020 available on the Participant Portal explains further how your personal data is secured.	(•) Yes ( ) No

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Excluded Reviewers

You can provide up to three names of persons that should not act as an evaluator in the evaluation of the proposal for potential competitive reasons.

First Name	Marcus
Last Name	Alden
Institution	Combustion Physics at Lund University
Town	Lund
Country	Sweden
Webpage	http://www.forbrf.lth.se/english/staff/professors/marcus-alden/

First Name	Per-Erik
Last Name	Bengtsson
Institution	Combustion Physics Lund University
Town	Lund
Country	Sweden
Webpage	http://www.forbrf.lth.se/english/staff/professors/per-erik-bengtsson/

Extended Open Research Data Pilot in Horizon 2020

If selected, all applicants will participate in the Pilot on Open Research Data in Horizon 2020[1] , which aims to improve and maximise access to and re-use of research data generated by actions.

However, participation in the Pilot is flexible in the sense that it does not mean that **all** research data needs to be open. After the action has started, participants will formulate a Data Management Plan (DMP), which should address the relevant aspects of making data FAIR - findable, accessible, interoperable and re-usable, including what data the project will generate, whether and how it will be made accessible for verification and re-use, and how it will be curated and preserved. Through this DMP projects can define certain datasets to remain closed according to the principle "as open as possible, as closed as necessary". A Data Management Plan does **not** have to be submitted at the proposal stage.

Furthermore, applicants also have the possibility to opt out of this Pilot completely at any stage (before or after the grant signature), thereby freeing themselves retroactively from the associated obligations.

Please note that participation in this Pilot does not constitute part of the evaluation process. Proposals will not be penalised for opting out.

We wish to opt out of the Pilot on Open Research Data in Horizon 2020.	○ Yes	◉ No

[1] *According to article 43.2 of Regulation (EU) No 1290/2013 of the European Parliament and of the Council, of 11 December 2013, laying down the rules for participation and dissemination in "Horizon 2020 - the Framework Programme for Research and Innovation (2014-2020)" and repealing Regulation (EC) No 1906/2006.*

ERC Starting Grant 2017
Research proposal [Part B1]
(Part B1 is evaluated both in Step 1 and Step 2,
Part B2 is evaluated in Step 2 only)

Energy transfer Processes at gas/wall Interfaces under extreme Conditions

EPIC

Cover Page:

- Brian Peterson
- University of Edinburgh, Edinburgh, Scotland, UK

- Proposal duration: 60 months

In the future, high-efficiency (low CO_2) vehicles will be powered in part by reinvented internal combustion (IC) engines that are "downsized" and operate with new combustion modes. These engine concepts are subject to problems such as increased transient heat transfer and flame quenching in small passages. Near-wall transient heat transfer is not well-understood in engine environments; the gas is not constant in pressure, temperature, or velocity such that physical processes quickly digress from established theory. EPIC is uniquely placed to address these problems. A novel constant-volume chamber, offering realistic engine passages but with optical access, and which emulates the pressure/temperature time curve of a real engine, will be developed. This chamber will make it possible to measure the highly transient and highly variable processes at the gas/wall interface (including a highly dynamic flame front) for single- and two-wall passages. Measurements will be made using a suite of advanced laser diagnostics; a novel aspect of the proposed work as they have not been used in combination to study such a problem before. Hybrid fs/ps rotational coherent Raman (i.e. CARS) in a line format will provide transient gas temperature and species profiles normal to the wall surface in high-risk/high-gain packages. PIV/PTV measurements will further elucidate flow dynamics at the surface. Planar OH-LIF will help interpret CARS measurements and provide necessary details of flame transport and quenching. As the flame approaches the surface, phosphor thermometry will measure wall temperature and heat flux to elucidate the highly dynamic inter-coupling between flame and wall. EPIC will provide substantial breakthroughs in knowledge by measuring unsteady boundary layer development and understanding its influence on flame quenching for single- and two-wall surfaces. As such, EPIC will provide the fundamental knowledge that supports cleaner combustion technology for the future.

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Section B1a: Extended Synopsis

EPIC Overview & Objectives: Transient heat loss and flame quenching at gas/wall interfaces are major problems preventing the development of new high efficiency (low CO_2 emitting) internal combustion (IC) engine technologies. EPIC is uniquely designed to provide fundamental ground-breaking experimental research as a first and necessary step in the solution of these critical but unresolved problems.

EPIC objectives are:

1) Development of a novel experimental facility to investigate the highly transient and highly variable processes at the gas/wall interface using novel measurements in objectives (2) – (5).
2) Experimentally measure, for the first time, the temporally and spatially transient thermal-boundary layer under transient pressure rises to identify leading mechanisms of heat loss as fluid pressure increases.
3) Experimentally quantify, for the first time, the local flame and fresh-gas heat loss that defines flame quenching at high pressures for single- and two-wall passages.
4) Simultaneously measure surface temperature and flame distribution to establish correlations that describe the relationship between flame quenching and surface heat flux for single- and two-wall passages.
5) Simultaneously measure, for the first time, the detailed thermal and flow transport in the boundary layer to support the development of predictive theoretical boundary layer models.

These ground-breaking experimental measurements will be performed using a suite of advanced optical diagnostics. This is a novel aspect of the work as the diagnostics have not been used in combination to study such a problem before. The diagnostics include: (*i*) hybrid femtosecond/picosecond (fs/ps) rotational coherent anti-Stokes Raman Spectroscopy (CARS), (*ii*) hydroxyl radical planar laser induced fluorescence (OH-PLIF), (*iii*) phosphor thermometry, and (*iv*) particle tracking velocimetry (PTV). These unique measurements will provide key fundamental knowledge that supports the reinvention of the IC engine for cleaner combustion technology.

Enabling New Opportunity - Dr. Brian Peterson (**BP**) is establishing a world-leading laboratory that focuses on basic experimental research to study fundamental processes that underpins the success of cleaner combustion technologies. He has a strong track-record in the development of advanced laser diagnostics for combustion research. **BP** is developing an advanced program that teams experimental and numerical modelling groups to jointly address the challenges in combustion science. He is actively collaborating with 9 EU computational groups[1] who are modelling his comprehensive engine velocimetry database[2]. **EPIC will enable BP** to establish a world-leading laboratory with a unique set of experimental tools to provide novel discoveries in combustion science over the long term. **EPIC will also enable BP** to establish a "thermal database" for numerical modelling, which will underpin the success of several EU research programs[1] over the long term, and help research more effectively overcome the technical barriers that will enable cleaner vehicle powertrains.

1. State of the art and objectives

1.1 Technological pathways towards cleaner IC engine technology

The European automotive research council[3], and other councils worldwide[4-7], have identified (*i*) ***downsizing***, (*ii*) ***boosting*** and (*iii*) ***dilute combustion*** as critical technological **pathways** to achieve 10-40% gains in fuel efficiency from internal combustion (IC) gasoline engines. Improving engine efficiency is recognized as the most-effective short-to-midterm route for vehicle CO_2 reduction[8-9]. Engine **heat loss is a major problem** that prevents all of these pathways from reaching their efficiency gains. Near-wall heat transfer, comprised of complex mutual sub-processes between hot fresh-gas (or flame) and chamber surfaces, is the primary mechanism of heat loss from the combustion chamber[10-12]. The transient processes of thermal transport at the gas/wall interface are **not well enough understood** to guide the future development of these pathways.

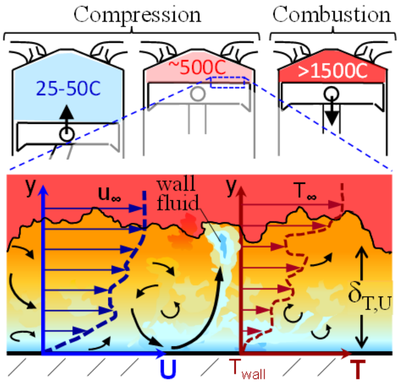

Fig. 1: Illustration of thermal transport in boundary layer during compression

1.2 Thermal transport at the gas/wall interface

In IC engines, thermal transport from hot gases to chamber surfaces is inherent (see Fig. 1 (top)). During compression, the gas temperature can increase an order of magnitude, while solid boundaries are externally cooled[10-12]. In the fluid adjacent to solid boundaries, a thermal boundary layer is formed (δ_T) and gas temperatures rapidly decrease to wall temperatures near the surface. The turbulent flow adjacent to the wall (also with unique boundary layer, δ_U) can transport cold fluid from the wall and into the core gas. Mass and energy transfer in boundary layers reduces core gas temperatures and contributes to parasitic energy losses.

In IC engines, thermal transport in boundary layers is complex; not only

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because $\delta_{T,U}$ are both unsteady, but because the outer fluid is not constant in pressure, temperature, or velocity. Appropriately, $\delta_{T,U}$ are not spatially uniform or fully-developed; they quickly digress from boundary layer theory[13-14]. Consequently, thermal transport in boundary layers **is not well understood** in engine environments.

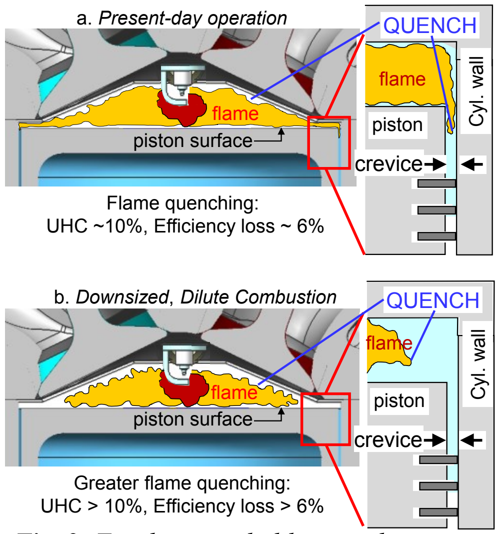

Fig. 2: *For downsized, dilute combustion pathways the flame is susceptible to quench a greater distance from surfaces, thereby reducing fuel savings and raising emissions.*

Combustion is initiated at the end of compression and gas temperatures increase further. Figure 2a illustrates the combustion process as it occurs in a spark-ignition (SI) engine. A flame (red) is initiated near the spark plug and propagates towards the chamber walls. As the high-temperature flame approaches the wall, the flame loses heat towards the wall and the flame quenches (i.e. extinguishes) a short distance from the chamber wall. This leaves behind a thin layer of unburned hydrocarbons (UHC) adjacent to walls[10-12,15]. For present-day operation, approximately 10% of the fuel escapes the burning process via flame quenching. This results in a direct loss of power and efficiency of approximately 6%[15].

Heat loss and flame quenching are greatest within the piston crevice, a 0.1-0.5 mm passage between the piston and cylinder wall (see Fig. 2). The flame only penetrates a short distance before it endures severe heat loss and quenches (Fig. 2a). The piston crevice is the greatest contributor to UHC emissions for well-burning combustion events[10-12,15-17]. Although crevices and thermal boundary layers represent a small volume within the chamber (< 5%), they can contain up to 35% of the fresh gases[10,18,19]. Thus, heat transfer in these areas significantly affects engine efficiency and emissions.

1.3 Heat loss influencing technical pathway development

Near-wall heat loss is expected to play a more dominant role in engine performance for *downsized, boosted* and *dilute combustion* pathways[6,20]. *Downsizing* increases the surface-to-volume ratios such that the fresh gas and flame will be more exposed to the cold walls. Meanwhile, higher gas densities associated with *boosting* will push a larger percentage of gas near the wall and into crevices where heat loss is largest. Thus, fresh gas and the flame are expected to lose more heat towards walls and the flame will quench a further distance from the wall. *Dilute combustion* on the other hand, is designed to operate with lower flame temperatures, thereby reducing heat transfer towards surfaces. Unfortunately, lower flame temperatures will reduce flame speed and directly increase the flame quenching distance[11,21-24]. Figure 2b depicts the anticipated flame propagation near walls for the proposed *technological pathways*; **flame quenching occurs a further distance from surfaces, increasing UHC emissions and reducing anticipated efficiency savings**.

1.4 Laser diagnostics for scientific measurements of transient thermal processes

Transient heat transfer and flame quenching processes at the gas/wall interface are **poorly understood** to help guide engineers towards *downsized*, *boosted*, and *dilute combustion* technologies. Laser diagnostics have revolutionized our understanding of physical and chemical processes in combustion and they provide experimental guidance for improving combustion technology. This section briefly discusses available diagnostics developed in EPIC and **identifies new opportunities to advance the state-of-the-art**.

1.4.1 Gas temperature in thermal boundary layer

To resolve the governing processes of heat exchange at the gas/wall interface, measurements of the temporally and spatially transient thermal boundary layer (δ_T, Fig. 1) are required. This goal **has not been achieved** in engine environments. Recently, a hybrid femtosecond/picosecond (fs/ps) rotational coherent anti-Stokes Raman spectroscopy (CARS) approach has been developed that is capable of resolving one-dimensional (1D) temperature profiles normal to surfaces[25-26]. This diagnostic has unmatched capabilities and it has resolved the instantaneous boundary layer with both high spatial resolution and measurement precision. It has been used successfully to resolve the complete transient boundary layer for near-wall reacting flows in open environments and atmospheric conditions. **Now is the time to develop** fs/ps rotational CARS for high-pressure chamber environments to understand the physics of gas/wall heat transfer in order to guide the development of new *downsized* engine technologies.

1.4.2 Flow velocity

High-resolution particle image velocimetry (termed µPIV) in combination with particle tracking velocimetry (PTV) has been used to measure flow transport in boundary layers in optically accessible IC engines[27,28].

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Detailed flow measurements **have not been performed** simultaneously with temperature measurements in boundary layers. Doing so would provide **substantial breakthroughs in the physical understanding** of unsteady heat transfer at gas/wall interfaces.

1.4.3 Wall temperature and flame distribution

Knowledge of gas/wall heat transfer processes requires detailed measurements of surface temperature. Phosphor thermometry is an optical technique capable of spatially resolving surface temperature in IC engines[29-35]. Although surface temperature measurements provide information about the heat received by the surface, **further information is required** to understand how this heat loss affects gas phase processes such as flame quenching near surfaces. Flame imaging techniques such as planar laser induced fluorescence (PLIF) of the hydroxyl radical (OH) can provide useful information about the flame's interaction with the surface. Performing surface temperature and flame imaging measurements simultaneously would **provide relevant correlations** of surface temperature vs flame position to understand flame quenching (i.e. efficiency loss) and high surface heat flux that can cause surface damage.

1.4 Objectives

Transient heat transfer and flame quenching are governed by several complex, coupled processes. Laser diagnostics have been used to study various aspects of these processes, but they have not yet been used in combination to solve this multi-parameter problem in engine-relevant environments. EPIC proposes to use a suite of advanced laser diagnostics to generate new knowledge on transient heat transfer and flame quenching processes. This is a novel aspect of the work as the **diagnostics have not been used in combination** to study such a problem before. Measurements will be performed in a novel fixed-volume chamber to measure the highly transient and variable processes for single- and two-wall passages under high pressures for the first time.

2. Methodology

EPIC is comprised of a logical sequence of five work packages (WPs) that will be conducted at U. Edinburgh. Risks are mitigation strategies are presented for each WP.

WP1 Development of Experimental Facility

A novel fixed-volume chamber will be developed for application of advanced laser diagnostic techniques to study near-wall processes at high pressure and within principal engine geometries. This chamber (based on a design by Linne et al.[36]) provides a simplified, yet practical environment that successfully emulates the pressure rise and decay of a real IC engine. An enclosed fuel-air mixture is ignited and heat release induces an exponential pressure rise as seen during a compression stroke. At a specified chamber pressure, a dump-valve is activated to initiate an exponential pressure decay. An orifice plate upstream the dump-valve controls the exit flow and pressure decay rate to match that of an IC engine.

Although the proposed chamber will have a similar operation to that of Linne et al.[36], the geometry and components have been specifically designed for detailed studies of near-wall heat transfer and flame quenching. Figure 3 shows the chamber. A stationary wall will be placed in the chamber test section to act as a piston position at end-of-compression. The 'piston' will be placed at a fixed distance from the front window to simulate a piston crevice. Optical access is granted above the piston and within the crevice by 5 quartz glass windows (top/bottom, two side, and a large front window).

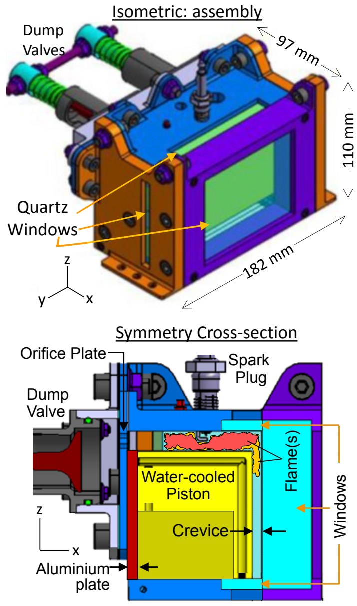

Fig. 3: Experimental facility for heat transfer and flame quenching studies.

The main advantage of this chamber is that it provides a simplified, yet relevant engine environment to systematically study heat transfer and flame quenching for single-wall and two-wall surfaces (i.e. crevices). The chamber is designed specifically for application of advanced laser diagnostics to provide quantitative, multi-parameter measurements near surfaces that are not possible in optically accessible engines.

<u>WP1 Risks</u>: The chamber is based on an existing design and its function has been demonstrated. Prof. Mark Linne (**ML**, EPIC team member at U. Edinburgh and designer of original chamber[36]) is supporting the new chamber fabrication and testing. **WP1 is low-risk** and it enables the opportunities in WP 2-5 (**high-gain**).

WP2 Thermal boundary layer development (unburnt gas)

In this WP, fs/ps CARS will be used to measure gas temperature along a line to quantify, for the first time, the transient thermal boundary layer development as fluid pressure increases. Two measurement locations are of interest: (a) above the piston and (b) in the crevice. Measurements, performed at 1kHz, will commence

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at ignition to resolve spatially unburned gas temperatures as chamber pressure increases. This objective only concerns measurements before the flame enters the measurement space.

Figure 4 shows that a laser sheet crossing (green) will be placed perpendicular (⊥) or parallel (‖) to surfaces. Perpendicular orientations will be used to temporally resolve the boundary layer shape and size, while parallel orientations will probe the gas temperature variation along the surface. Access into the crevice provides a unique opportunity to measure temperature distributions that have thus far been unresolved in IC engines. The crevice spacing (0.2-0.5 mm) is often smaller than δ_T until high pressures are reached. A detailed physical model describing this wall-normal temperature development does not exist in the literature. Measurements parallel to crevice surfaces will detail the gas loss with crevice depth.

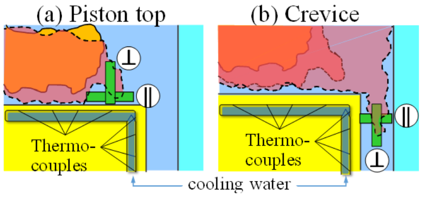

Fig. 4: *(Green) 1D CARS measurement location/orientation above the piston and in the crevice.*

<u>WP2 Risks</u>: fs/ps CARS has not been performed near surfaces in high-pressure chambers, but would provide spatially resolved thermal boundary layer temperatures under transient pressure events for the first time (**high-gain**). Beam steering from refractive index gradients can cause challenges (**high-risk**). The proposed fs/ps CARS method utilizes a novel phase matching approach[37] that will make laser sheet alignment more manageable. In addition, the spectrometer opening can be increased to allow CARS signal to enter despite beam steering. Spectral resolution will decrease, but **gas temperature can be obtained** from O_2/N_2 signal and **manage the risks**. Furthermore, Dr. Chris Kliewer (**CK**, designer of 1D fs/ps CARS) and **ML,** both of whom have extensive experience with fs lasers and CARS, are participating in this WP.

WP3 Flame-wall interactions: 1D CARS and OH-PLIF

Flame-wall interactions will be studied using fs/ps CARS. The setup will be the same as described in WP2 (Fig. 4), but will now concern measurements as the flame enters the measurement space. Details of single-wall quenching will be studied above the piston surface, while two-wall quenching processes will be studied in the crevice. Once optimized, CARS will be performed simultaneously with OH-PLIF measurements to describe the 2D flame distribution as it progresses into the 1D measurement space. Investigations will evaluate new aspects of flame-wall interactions such as:

1) Flame cooling as it enters the boundary layer
2) Wall-normal heat flux (i.e. heat lost) as flame approaches (or propagates alongside) the wall
3) Single- and two-wall quenching distances
4) Correlations of heat flux and quenching distance

Systematic studies will be conducted to understand how these processes change with (i) chamber pressure, (ii) fuel properties, (iii) fuel-air ratio, (iv) wall temperature, and (v) crevice spacing.

<u>WP3 Risks</u>: WP3 is **high-risk** (similar to WP2) and equally **high-gain** as it can identify the leading mechanisms of flame quenching (i.e. efficiency loss) in engine passages. Beam steering can be more serious as larger density gradients can exist at the flame front. If beam steering is too strong, point-wise fs/ps CARS will be performed, providing temporally resolved, single-point temperature measurements in the boundary layer during flame-wall interaction. This **contingency plan** still provides **gains** in diagnostic development that will provide new quantitative findings on flame quenching in engine passages.

WP4 Flame-wall interactions: OH-PLIF and surface temperature distributions

Further investigations of flame-wall interactions will be pursued with surface temperature (phosphor thermometry) and wall heat flux (thermocouples) measurements. The phosphor $Gd_3Ga_5O_{12}$:Cr has been used in combustion environments[34] and will be used in this study. These measurements will be combined with OH-PLIF to resolve the 2D flame front distribution. Measurements will be performed with kHz repetition rates to resolve flame-wall impingement, quenching, and heat deposited in the walls. Similar to WP3, measurements will be concentrated above the piston and within the crevice region for complementary analysis. However, measurements in WP4 will alternatively provide correlations between wall temperature distribution and the flame distribution in the chamber. Similar systematic studies can be pursued as in WP3.

<u>WP4 Risks</u>: these methods are well-established, but have never been combined. **BP** has experience with OH-PLIF and phosphor thermometry. **WP4 is low-risk** and findings will provide new correlations of surface temperature and flame position to identify mechanisms of flame quenching (i.e. efficiency loss) and high surface heat flux that can damage surfaces (**high-gain**).

WP5 Simultaneous 1D CARS and PIV/PTV

Detailed measurements of thermal boundary layer development in WP2 would be a great accomplishment. Further understanding of the near-wall thermal transport requires flow field measurements. For this purpose,

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we will evaluate combined 1D CARS and PIV/PTV measurements. This is foreseen as the **highest risk/gain** WP; such measurements have not been performed and each measurement by itself is considered a great leap in measurement science. Such findings would provide new knowledge that has prevented researchers from understanding unsteady heat transfer for decades.

Measurements will first be performed outside of the chamber in a "flow over flat plate" experiment. This will allow us to first determine if the PTV seeding medium (e.g. 1µm oil droplets transported in the flow) will interfere with the detection of the CARS signal. Optimal seeding densities will be determined and experiments will provide new knowledge on flow and temperatures in the boundary layer over a hot plate. If seeding densities are too large, point-wise fs/ps CARS measurements will be evaluated as a means to provide detailed measurements on heat transfer processes. Measurements will then be conducted in the chamber to study flow and temperatures near the surface. Seeding densities and fs/ps CARS measurement volumes will be optimized and trade-offs in spatial resolution may be necessary for simultaneous measurements.

WP5 Risks: WP5 is **high-risk** since high seeding densities required to resolve flow in the boundary layer can disturb 1D fs/ps CARS measurements. The flow over the flat plate experiment will systematically determine the optimal settings for each diagnostic. Such an experiment is feasible and will produce new knowledge on fundamental turbulent heat transfer and produce advances in diagnostic capabilities (**high-gain**). In the chamber, point-wise CARS measurements can be performed if seeding densities are problematic. Alternatively, PIV/PTV can be performed separately and provide powerful complementary information to the 1D temperature measurements in WP2. Together these **contingency plans** will generate new knowledge that will support development of theoretical boundary layer models for engines (**high-gain**).

4. Funding Request

Dr. Brian Peterson (**BP**) is allocating 60% of his time towards EPIC. Funding is requested for **BP** and a post-doctoral research assistant (**PDRA**, 60 months). Funding is requested for equipment: OH-PLIF laser system (WP2-4, €419,510). Consumables are requested to build the chamber and purchase auxiliary optic components (€83,408). Funding is also requested for travel and publications. The total budget is €1,499,351.

5. Project Management

BP is responsible for the management of this project. He has a strong track record for the development and application of advanced laser diagnostics for combustion science. He has considerable experience with PIV, LIF and phosphor thermometry. **BP** and his colleague **ML** are already working with Dr. Chris Kliewer (**CK)** (Sandia National Laboratories, USA) to develop fs/ps rotational CARS at Edinburgh. **CK** is the developer of this technique and currently it does not exist elsewhere in the EU.

EPIC Team & Tasks: **BP** will participate in all aspects of the work. A **PDRA** (ERC funded) and **two PhD students** (Edinburgh funded) will be hired for EPIC. Their participation is listed in the work schedule below. An additional PhD student, Mr. Torge Mecker (**TM**), has already been hired (Edinburgh funded) to assist in fs/ps rotational CARS development at Edinburgh. **TM** will spend one year at Sandia National Laboratories to work with **CK** to apply fs/ps CARS and develop a code. **CK** is eager to participate in EPIC and may visit Edinburgh for experiments. **ML** is also participating in the development of fs/ps CARS at Edinburgh. **ML** has extensive experience with fs laser systems and Raman Spectroscopy. **ML** has also designed a similar chamber as the one proposed; he is participating in the development of the new chamber. Andreas Dreizler (**AD,** TU Darmstadt**)** will participate in WP4. A **PhD student** from Darmstadt is likely come to Edinburgh to participate in experiments.

Participants	Work Package	Year 1	Year 2	Year 3	Year 4	Year 5
PDRA, PhD1, BP, ML	WP 1					
PDRA, TM, PhD1, BP, ML, CK	WP 2					
PDRA, PhD1, PhD2, BP, ML, CK	WP 3					
PhD2, BP, AD	WP 4					
PDRA, PhD1, PhD2, BP, ML, CK	WP 5					

6. Project Feasibility

Risks have been accessed for all WPs. Mitigation strategies and contingency plans have been presented to show that high-risks can be managed and the state-of-the-art will be advanced for contingency plans. EPIC personnel are appropriate; **BP** is well-equipped to lead EPIC**.** A **PDRA** and **3 PhD students** (Edinburgh funded) will be devoted to EPIC. **ML**, **CK**, and **AD** enthusiastically support EPIC and **BP**; they will actively participate in WPs. The chamber has been designed, but not yet fabricated. Together **ML**, **CK**, **TM**, and **BP** are already developing fs/ps rotational CARS at Edinburgh. The schedule is manageable; many tasks coincide and can be fulfilled simultaneously (e.g. WP2&3 can be performed simultaneously).

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Section b: Curriculum Vitae (max. 2 pages)

PERSONAL INFORMATION

Peterson, Brian (**BP**)

Researcher unique identifier(s): Researcher ID: O-3079-2016; ORCID: 0000-0001-5958-8855

Date of birth: 02 September 1980

Nationality: United States

URL for web site: https://www.eng.ed.ac.uk/about/people/dr-brian-peterson

RESEARCH EXCELLENCE

Dr. Peterson's research has focused on answering some of the most fascinating scientific problems in combustion energy science. He has pioneered the art of simultaneous laser diagnostic measurements which have provided unique multi-parameter and volumetric measurements of leading vector and scalar processes in combustion systems. His detailed flow and combustion measurements have also been supporting research programs worldwide. **BP** has developed a comprehensive velocimetry database[2] for engine flows which is currently supporting research worldwide; 10 international numerical modelling groups are simulating his database. **BP** has founded the "*Darmstadt Engine Workshop*" (http://www.rsm.tu-darmstadt.de) to facilitate a close collaborative relationship with his modelling partners. He co-organizes this workshop with TU Darmstadt (every 10 months) to study the detailed physics of reacting and non-reacting flows in IC engines. Through this, **BP** has empowered an improved understanding of the methods used to predict and measure flow and combustion within engine research. The *European Research Community On Flow, Turbulence And Combustion* is currently considering **BP's** database as the model database for "Best Practices in Combustion CFD". **EPIC will enable BP** to establish a necessary "thermal database" for numerical modelling, which will underpin the success of several EU research groups for the long-term, and help overcome technical barriers that will enable cleaner combustion transport.

EDUCATION

2010	PhD Department of Mechanical Engineering, University of Michigan, United States of America Thesis Advisor: Prof. Dr. rer, nat. Volker Sick
2005	Masters of Science Department of Mechanical Engineering, University of Michigan, United States of America

CURRENT POSITION

2015 – present	Lecturer / Assistant Professor School of Engineering, University of Edinburgh, Scotland, UK

PREVIOUS POSITIONS

2014 – 2015	Post-doctoral Researcher Combustion Research Facility, Sandia National Laboratories, United States.
2011 – 2014	Post-doctoral Researcher Reactive Flows and Diagnostics, Technische Universität (TU) Darmstadt, Germany.
2005 – 2010	Graduate Research Assistant (Masters and PhD) Department of Mechanical Engineering, University of Michigan, United States.

SUPERVISION OF GRADUATE STUDENTS

2015 – 2016	4 Master students; School of Engineering, University of Edinburgh, Scotland, UK.
2011 – 2012	2 PhD students & 3 Master students; Department of Mechanical Engineering, Reactive Flows and Diagnostics sub-division at TU Darmstadt, Germany.

TEACHING ACTIVITIES

2016 – present	Engineering Thermodynamics 2, School of Engineering, University of Edinburgh, Scotland UK.
2015 – present	Mechanical Engineering Group Project 4, School of Engineering, University of Edinburgh, Scotland UK.
2005 – 2006	Graduate Student Instructor, Mechanical Engineering Laboratory I, Department of Mechanical Engineering, University of Michigan, United States.

ORGANISATION OF SCIENTIFIC MEETINGS

2014 – present	Founder & co-organizer of *Darmstadt Engine Workshop*; TU Darmstadt, Germany, 32

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	participants (see also Major Collaborations). Five international workshops have resulted.
2016	Session chair for "Velocity / Temperature Measurements" at *18th International Symposium on Applications of Laser Diagnostics to Fluid Mechanics.*
2015	Session chair for "Time-resolved Diagnostics for Reactive, Turbulent Flows" at Gordon Research Conference on Laser Diagnostics in Combustion.
2014 – 2015	Co-chair of Spray G in Engines for Engine Combustion Network (120 participants).
2013 – 2014	Co-chair of Engine, Flow and Combustion section of the Engine Combustion Network (120 participants).
2014	Session chair for "PIV / LIF Applications" at *17th International Symposium on Applications of Laser Diagnostics to Fluid Mechanics.*

INSTITUTIONAL RESPONSIBILITIES

2016 – 2020	Graduate Student Co-Advisor, University of Edinburgh, Scotland, UK
2015 – present	Resource Allocation Committee, University of Edinburgh, Scotland, UK
2015 – present	Academic Committee, University of Edinburgh, Scotland, UK

MEMBERSHIPS OF SCIENTIFIC SOCIETIES

Member of Combustion Institute and Society of Automotive Engineers

REVIEWER OF JOURNALS

Applied Physics B; Energy & Fuels; Experiments in Fluids;, Flow Turbulence and Combustion; Journal of Fluid Mechanics; Proceedings of the Combustion Institute; Sensors; Society of Automotive Engineers

MAJOR COLLABORATIONS

BP is founder and co-organizer of the *Darmstadt Engine Workshop*. Here he has a close collaboration with his previous work institution (TU Darmstadt) in addition to 10 other academic institutional groups (below) who are modelling his comprehensive velocimetry database. The workshop is a close collaboration and information exchange between experimental (Dr. Peterson) and modelling groups who wish to improve the methods used to predict and investigate turbulent flows within the engine research and design process. The workshop occurs every 10 months in Darmstadt, Germany.

- Germany: TU Darmstadt, RWTH Aachen, U. Duisburg-Essen, TU Freiberg; Switzerland: ETH Zürich; France: IFPen; Italy: Poli. Milano; UK: Cambridge, Imperial College London; Brazil: U. São Paulo.

BP is collaborating with Sandia National Laboratories (USA) to strengthen fs/ps rotational CARS capabilities at Edinburgh. A PhD student has already been hired and will spend a year at Sandia for measurements and development of a CARS code. The fs/ps CARS system does not yet exist in the EU. **BP** is further collaborating with TU Darmstadt for thermographic phosphor measurements in optical engines.

PUBLICATIONS

- 16 Refereed Journal Publications (h-index 10, GoogleScholar); (1 in press & 3 in *SAE Int. J. Engines* (i.e an engineering journal not yet recognized by WebofScience (negotiations are underway)).
  - 319 citations (GoogleScholar, including citations from engineering journals and theses)
  - 7192 downloads (Scopus)
- 13 Non-referred Conference Publications

INVITED SEMINARS

- 1 Plenary Lecture at Gordon Research Conference 2013, Waterville Valley, NH, USA
- 23 Invited Seminar Presentations
- 11 Conference Presentations

AWARDS

2010 Proquest Distinguished Dissertation Award – University of Michigan (top 5% theses of 2010)

RESEARCH FUNDING

2016 – 2021	*In-situ Chemical Measurement and Imaging Diagnostics for Energy Processing Engineering* Engineering and Physical Science Research Council, UK	£1,023,516
2012 – 2014	*Experimental Investigation of Turbulence-chemistry interaction for flame kernel development in a spark-ignition (SI) engine* Deutsche Forschungsgemeinschaft, Germany	€ 192,000

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Appendix: All on-going and submitted grants and funding of the PI (Funding ID)

<u>*Mandatory information*</u> *(does not count towards the page limits)*

On-going Grants

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*
In-situ Chemical Measurement and Imaging Diagnostics for Energy Process Engineering.	Engineering and Physical Science Research Council (EPSRC), UK	€1,177,043	2016-2021	Co-PI	N/A

Grant applications

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*
Experimental investigation of turbulence-chemistry interaction for flame kernel development in a spark-ignition (SI) engine	Deutsche Forschungsgemeinschaft (DFG), German Government	€ 192,000	2012-2014	Sole-PI	N/A

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Section c: Early achievements track-record (max. 2 pages)

Dr. Brian Peterson's (**BP**) research is in laser diagnostics & combustion science. He has a strong track record in advanced laser diagnostics for IC engines. He is well-known for combining PIV and LIF to study scientifically relevant problems in practical systems. **BP** also pioneered applications of tomographic PIV and magnetic resonance velocimetry (MRV) to measure quantitatively the three-dimensional engine flow for the first time within a volumetric domain. **BP** has established research independence; he has been awarded project funding as a sole-PI during his post-doc at TU Darmstadt. Of his 16 peer-reviewed journal articles and 13 conference publications, 17 are first-authored and 18 publications are independent of his PhD advisor. He has given 24 invited lectures and presented 11 conference presentations. He has established one of the most comprehensive velocimetry databases in engine research[2]. The *European Research Community On Flow, Turbulence And Combustion* is considering **BP's** database as the model database for "Best Practices in Combustion CFD" (www.ercoftac.org). This database has also established an international workshop for turbulence and combustion for engine research (*Darmstadt Engine Workshop*, 32 participants, http://www.rsm.tu-darmstadt.de). **BP** is founder and co-organizer of this workshop (10 month occurrence). U. Edinburgh is investing roughly €2.3 million in **BP**'s research including 85m^2 of renovated lab space and an optically accessible research engine. Sandia National Labs and TU Darmstadt are teaming with **BP** to help establish fs/ps rotational CARS and phosphor thermometry capabilities at Edinburgh.

5 RELEVANT PUBLICATIONS

Selected manuscripts most relevant to the work proposed. Bibliometric indicators are provided according to GoogleScholar; this includes citations from several engineering journals and theses. [Hirsch index = 10]

1. "High-speed PIV and LIF imaging of temperature stratification in an internal combustion engine", **B. Peterson**, E. Baum, B. Böhm, V. Sick, A. Dreizler, *Proceedings of the Combustion Institute* **34**, 3653-3660 (2013) [citations: 34; 2468 downloads].
   - *Simultaneous high-speed toluene LIF and PIV were developed for gas-phase temperature and flow velocity in an optical engine. Findings detailed the evolution of gas-phase heat loss to chamber surfaces. Measurements however, were not able to resolve the instantaneous thermal boundary layer. More-suitably, thermal boundary layer measurements using fs/ps CARS would provide substantial breakthroughs in our physical understanding of unsteady heat transfer.*
2. "Evaluation of toluene LIF thermometry detection strategies applied in an internal combustion engine", **B. Peterson**, E. Baum, B. Böhm, V. Sick, A. Dreizler, *Applied Physics B* **117**, 151-175 (2014) [citations: 10; 1200 downloads].
   - *Simultaneous LIF and PIV were conducted to further study gas temperature cooling at solid surfaces. Measurements revealed the transport of cold gas pockets along the piston surface after compression. Coldest temperatures were found to outgas from the piston crevice, indicating that the gas experiences the greatest heat loss in the crevice. Detailed studies of heat transfer in piston crevices still do not exist in the literature.*
3. "On the validation of LES applied to internal combustion engine flows: Part 1: comprehensive experimental database", E. Baum**, B. Peterson**, B. Böhm, A. Dreizler, *Flow Turbulence and Combustion* **92**, 269-297 (2014) [citations: 32; 1200 downloads].
   - *A comprehensive experimental velocimetry database is presented for the development and validation of computational models. This work generated much interest from numerical modelling groups and was the sole manuscript that initiated the 'Darmstadt Engine Workshop' (http://www.rsm.tu-darmstadt.de). Dr. Peterson is founder and co-organizer of the workshop. Currently, 9 modelling groups (international) are simulating our experiments. The work in this ERC proposal will provide a complementary thermal database.*
4. "On the ignition and flame development in a spray-guided direct-injection spark-ignition engine", **B. Peterson**, D.L. Reuss, V. Sick, *Combustion and Flame* **161**, 240-255 (2014) [citations: 29; 2240 downloads].
   - *Measurements of simultaneous high-speed biacetyl LIF and PIV were performed to study physical processes leading to well- and poor-burning events in a spray-guided engine. Measurements of mixture fraction and flow velocity detailed the physical processes leading to flame quenching. Flames would separate from fuel pockets and would extinguish as the lost excessive heat to surroundings. This study complements the proposed studies of flame quenching at surfaces.*
5. "Early flame propagation in a spark-ignition engine measured with quasi-4D diagnostics", **B. Peterson**, E. Baum, B. Böhm, A. Dreizler, *Proceedings of the Combustion Institute* **35**, 3829-3837 (2015) [citations: 10; 1044 downloads].

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- *Measurements of dual-plane OH-PLIF and stereoscopic PIV were performed to measure local advection and flame displacement speed to characterize flame propagation in a spark-ignition engine. Measurements resolve detailed flame propagation near surfaces as well as in the chamber. In the ERC proposal, OH-PLIF measurements technique will be used to understand flame propagation and quenching near surfaces.*

INVITED PRESENTATIONS (24 total presentations; 10 shown)

1. "The use of simultaneous, multi-parameter diagnostics for reacting and non-reacting flows", B. Peterson, School of Advanced Optic Technologies: Young Researchers Award Seminar, University of Erlangen Nuremburg, Germany, Feb. 26, (2016).
2. "Advancing diagnostic methodologies towards multi-dimensional and volumetric measurements for IC engine research", B. Peterson, 22nd International Workshop from School of Advanced Optic Technologies, University of Erlangen Nuremburg, Germany, March 16-17, (2015).
3. "Spray-induced temperature and mixing stratification dynamics in direct-injection engines", B. Peterson, Departmental Seminar, Sandia National Laboratories, US, Sept. 22nd, (2014).
4. "On the ignition and detailed flame propagation in spark-ignition engines", B. Peterson, Departmental Seminar, IFPen Energies Nouvelles, Rueil-Malmaison, France, July 11th, (2014).
5. "Advancing optical and laser diagnostic techniques for quantitative measurements in internal combustion systems", B. Peterson, Departmental Seminar, Mechanical Engineering Department at University of Alabama, Tuscaloosa, Alabama, US, March 24th, (2014)
6. "Novel laser and optical-based measurements for internal combustion engine research", B. Peterson, Departmental Seminar, Sandia National Laboratories, US, Jan. 7th, (2014).
7. "High-speed flow and temperature imaging of fuel injection in a direct-injection spark-ignition engine", B. Peterson, Departmental Seminar, University of Cambridge, UK, Nov. 21st, (2013)
8. "Novel laser and optical-based diagnostic measurements for internal combustion engine research", B. Peterson, Departmental Seminar at King Abdullah University of Science and Technology (KAUST), Thuwal, Saudia Arabia, Oct. 28th, (2013).
9. "Towards multi-parameter and three-dimensional diagnostic measurements in IC engines", B. Peterson Plenary Lecture at Gordon Research Conference for Laser Diagnostics in Combustion Waterville Valley, NH, US, Aug. 15th, (2013).
10. "Characterization of early flame propagation in a spark-ignited optical engine", B. Peterson, Departmental Seminar at ETH Zürich, Zürich, Switzerland, Sept. 2nd, (2013).

CONFERENCE PRESENTATIONS

1. "Assessment and application of tomographic PIV for the spray-induced flow in an IC engine", B. Peterson. *36th International Symposium on Combustion*, Seoul, South Korea, Aug. 1-5th, (2016).
2. "Evaluation of spray-induced turbulence during the induction stroke of a four-stroke single-cylinder optical engine", B. Peterson. *18th Int. Symp. On Applications of Laser and Imaging Techniques to Fluid Mechanics,* Lisbon Portugal, July 4-7th, (2016).
3. "Influence of direct-injection on the volumetric flow field in a gasoline engine captured by tomographic PIV", B. Peterson. *12th International Congress, Engine Combustion Processes: Current Problems and Modern Technologies*. Ludwigsburg, Germany, March 12-13th, (2015).
4. "Early flame propagation in a spark-ignition engine measured with quasi 4D-diagnostics", B. Peterson. *35th International Symposium on Combustion*, San Francisco, California US, Aug. 3-8th, (2014).
5. "Spray-induced temperature stratification dynamics in a gasoline direct-injection engine", B. Peterson. *35th International Symposium on Combustion*, San Francisco, California US, Aug. 3-8th, (2014).
6. "Analysis of the turbulent in-cylinder flow in an IC engine using tomographic and planar PIV measurements", B. Peterson. *17th Int. Symp. On Applications of Laser Techniques to Fluid Mechanics*, Lisbon, Portugal, July 7-10th, (2014).
7. "High-speed flow and temperature imaging of fuel injection in a direct-injection spark-ignition engine", B. Peterson. *11th International Congress of Engine Combustion Processes: Current Problems and Modern Technologies*. Ludwigsburg, Germany, March 14-15th, (2013).
8. "High-speed PIV and LIF imaging of temperature stratification in an internal combustion engine", B. Peterson. *34th International Symposium on Combustion*, Warsaw, Poland, July 29th - Aug 3rd, (2012).
9. "Advantages of high-speed imaging in engine research", *10th Congress in Engine Combustion Processes: Current Problems and Modern Techniques*, München, Germany, March 24-25th, (2011).
10. "High-speed imaging analysis of misfires in a spray-guided direct-injection engine", B. Peterson. *33rd International Symposium on Combustion*, Beijing, China, Aug. 1-6th, (2010).
11. "Simultaneous flow field and fuel concentration measurements for ignition studies in a spray-guided spark-ignition direct-injection optical engine", B. Peterson. *6th US National Combustion Meeting*, Ann Arbor, MI, US, March 20-22nd, (2009).

AWARDS

1. 2010 Proquest Distinguished Dissertation Award, University of Michigan (top 10 theses of 2010).

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ERC Starting Grant 2017
Research proposal [Part B2)]

Part B2: *The scientific proposal* (max. 15 pages)

Energy transfer Processes at gas/wall Interfaces under extreme Conditions EPIC

Proposal Overview
The European automotive research council[1], and other councils worldwide[2-6], are calling for the reinvention of the internal combustion (IC) engine towards downsized, boosted, and dilute combustion strategies. This call is designed to produce high-efficiency engines that can also be used as range extenders for electric vehicles. These engines, however, are subject to increased transient heat loss and flame quenching near surfaces that will limit gains in fuel efficiency. Processes of transient heat transfer and flame quenching at high pressures are **not well enough understood** to help guide the future development of clean combustion technology.

EPIC objectives are designed to provide fundamental knowledge that supports the reinvention of IC engines for high-efficiency, low CO_2 emitting vehicles. This will be performed with fundamental ground-breaking experimental research to address the unsolved problems of transient heat transfer and flame-wall quenching in engine relevant systems at high pressures. EPIC will **advance the state-of-the-art** in two fields of research: 1) thermal-fluids in combustion science and 2) advanced laser diagnostics.

EPIC methodologies involve the development of a novel fixed-volume chamber in combination with a suite of advanced laser diagnostics. The chamber will provide a relevant, yet controllable engine environment to study the highly transient and highly variable processes at the gas/wall interface for realistic single- and two-wall engine passages. A hybrid femtosecond / picosecond (fs/ps) rotational coherent anti-Stokes Raman spectroscopy (CARS) in a line format (i.e. 1D) will provide transient gas temperature profiles normal to the surface to study boundary layer development at high pressures. Particle tracking velocimetry (PTV) will elucidate flow dynamics at surfaces and phosphor thermometry will measure wall temperature distributions. Hydroxyl (OH) planar laser induced fluorescence (PLIF) will be used with 1D CARS and phosphor thermometry to measure the dynamic coupling between heat loss at walls and flame quenching.

Dr. Peterson (**BP**) is well-suited to lead EPIC. He has an outstanding track record in the development of advanced laser diagnostics to study fundamental processes in combustion science. In particular, **BP** has pioneered developments of simultaneous particle image velocimetry (PIV) and PLIF diagnostics to study multi-parameter physics of flame quenching, thermal gas cooling, and flame propagation in IC engines[7-11] – all of these processes and diagnostics are relevant to EPIC. **BP** and his colleague Prof. Mark Linne (**ML**) are teaming with Dr. Chris Kliewer (**CK**, Sandia National Labs, USA) to develop 1D fs/ps rotation CARS at U. Edinburgh. This diagnostic approach does not yet exist in the EU and has recently provided exciting findings on transient heat transfer in combustion systems. Prof. Andreas Dreizler (**AD**, TU Darmstadt, Germany) is also teaming with **BP** to support phosphor thermometry studies and participate in studies performed in the novel chamber. U. Edinburgh is equipped to host EPIC work packages with a newly renovated laboratory ($85m^2$) and substantial financial support for equipment and PhD students.

High-risk/high-gain packages are mainly associated with 1D fs/ps rotational CARS applied near surfaces in a high pressure environment. This novel diagnostic has not been performed in such environments and beam steering associated with large density gradients could cause challenges. We will discuss several methods for managing these risks and we describe how the state-of-the-art will advance in all circumstances.

At the conclusion of EPIC several new studies will have been performed to address unsolved problems of unsteady heat transfer and flame quenching in high pressure, engine relevant systems. EPIC will enable **BP** to establish a world-leading laboratory with a unique set of experimental tools to provide ground-breaking discoveries in combustion science for the long term. EPIC will also enable **BP** to further develop his program that is teaming experimental and numerical modelling groups that jointly address the challenges in combustion science. This work will allow **BP** to establish a comprehensive engine "*thermal database*" to coincide with his existing engine "*velocimetry database*"[12], which will underpin the success of several EU research groups over the long term, and help research more effectively overcome the technical barriers that prevent cleaner vehicle powertrains.

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Section a. State-of-the-art and objectives

1.1 Technology pathways towards high-efficiency vehicles

The internal combustion (IC) engine, which powers over 96% of the vehicles sold today[2], has a significant impact on society and the environment. The European automotive research council[1] (and others councils world-wide[2-6]) have identified high-efficiency vehicles as the most-effective short-to-midterm route for CO_2 reduction. All council outlooks indicate that IC engines will play an active role in high-efficiency vehicles well into the future, as both primary powertrains and as range extenders for electric vehicles. This need has called for the reinvention of IC engines that are ***downsized***, operate with higher power densities (e.g. ***boosted***) and operate under completely new strategies such as ***dilute combustion***. These advanced IC engines are expected to provide 10-40% fuel savings[2-4]. However, these engines will be subject to problems with increased transient heat transfer, which could reduce fuel savings and increase emissions.

Transient heat transfer is a topic that has existed in the engine community since the invention of the engine. Through decades of research, scientists agree that heat transfer may well be one of the most-complex set of processes in engines that remains poorly understood[14,15]. Near-wall transient heat transfer, involving the complex mutual interactions of the hot fresh-gas (or flame) and chamber surfaces, is one of the primary mechanisms of heat loss that negatively affects fuel conversion efficiency. These losses will become more pronounced in high-efficiency engines that are *downsized*, *boosted* and operate under *dilute combustion* strategies. A detailed understanding of thermal processes at the gas/wall interface is required for the development of cleaner, more efficient engine technology. It is precisely this **gap in existing research that EPIC will address** by providing ground-breaking experimental research to address the critical, unresolved problems of transient heat transfer.

1.2 Thermal transport at the gas/wall interface

Thermal transport at the gas/wall interface is already inherent before combustion (see Fig. 1). During compression, the gas temperature can increase an order of magnitude, while solid boundaries are externally cooled[14-16]. In the fluid adjacent to solid boundaries, a thermal boundary layer is formed (δ_T) and gas temperatures rapidly decrease to wall temperatures near the surface. The turbulent flow adjacent to the wall (also with unique boundary layer, δ_U) can transport cold fluid from the wall and into the core gas. Mass and energy transfer in boundary layers reduces the core gas temperature and contributes to parasitic energy losses.

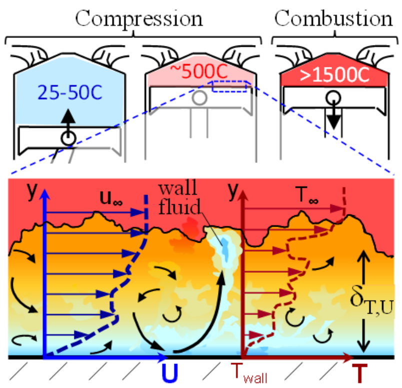

Fig. 1*: Illustration of thermal transport in boundary layer during compression.*

In IC engines, thermal transport in boundary layers is complex; not only because $\delta_{T,U}$ are both unsteady, but because the outer fluid is not constant in pressure, temperature, or velocity. Appropriately, $\delta_{T,U}$ are not spatially uniform or fully-developed; they quickly digress from boundary layer theory[17,18]. Consequently, thermal transport in boundary layers **is not well understood** in engine environments.

Combustion is initiated at the end of compression and gas temperatures increase further. Figure 2a illustrates the combustion process as it occurs in a spark-ignition (SI) engine. A flame is initiated near the spark plug and propagates towards the chamber walls. As the high-temperature flame approaches the wall, it first encounters the colder fluid in the boundary layer where reactions rates are delayed[19]. Heat is quickly lost towards the walls and the flame quenches a short distance from the chamber walls. This leaves behind a thin layer of unburned hydrocarbons (UHC) adjacent to walls[14-16,20]. For present-day operation, approximately 10% of the fuel can escape the burning process via flame quenching. This results in a direct loss of power and efficiency of approximately 6%[20].

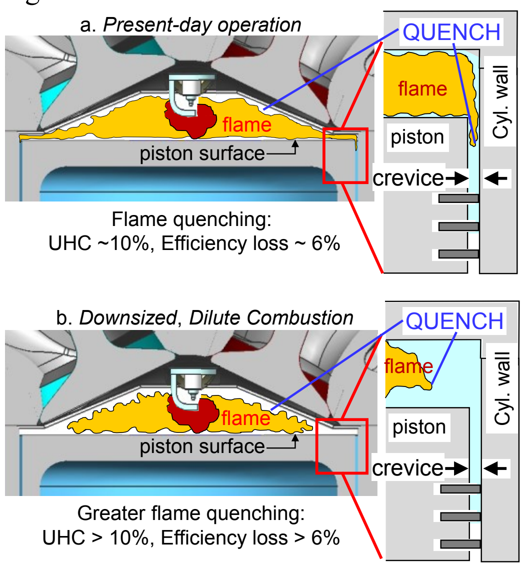

Fig. 2: *For downsized dilute combustion pathways the flame is susceptible to quench a greater distance from surfaces, thereby reducing fuel savings and raising emissions.*

Heat loss and flame quenching are greatest within the piston crevice, a 0.1-0.5 mm passage between the piston and cylinder wall (see Fig. 2). The fuel-air charge enters the crevice during compression, while the flame only penetrates a short distance before it endures severe heat loss and quenches. Currently the

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piston crevice is the greatest contributor to UHC emissions for well-burning combustion events[14-16,20-22]. Although crevices and thermal boundary layers represent a small volume within the chamber (< 5%), they can contain up to 35% of the fresh gases[15,19,23]. Thus, heat transfer in these areas is significant in terms of engine performance.

1.3 Heat loss influencing high-efficiency engine strategies

Near-wall heat loss is expected to play a more dominant role in engine performance for *downsized, boosted* and *dilute combustion* pathways[4,24]. *Downsizing* increases the surface-to-volume ratios such that the fresh gas and flame will be more exposed to the cold walls. Meanwhile, higher gas densities associated with *boosting* will push a larger percentage of gas near the wall and into crevices where heat loss is largest. Thus, fresh gas and the flame are expected to lose more heat towards walls and the flame will quench a further distance from the wall. Greater heat loss from the gas also means greater heat gain to chamber surfaces. Surface damage and aging is also a concern as technologies push towards smaller chambers and higher power densities.

Dilute combustion is designed to operate with lower flame temperatures, thereby reducing heat transfer towards surfaces. However, lower flame temperatures will reduce flame speed and directly increase the flame quenching distance[14,25-27]. Figure 2b depicts the anticipated flame propagation near walls for the aforementioned pathways; flame quenching occurs a further distance from surfaces, reducing anticipated efficiency savings and increasing UHC emissions. These emissions will likely not be removed from the three-way catalytic converter, since the catalyst does not operate effectively when the fuel-air mixture deviates from stoichiometry.

2. Laser diagnostics for scientific measurements of transient thermal processes

Transient heat transfer and flame quenching processes at the gas/wall interface are not well enough understood to help guide engineers for the reinvention of the IC engine towards *downsized*, *boosted*, and *dilute combustion* technologies. Advanced tools are needed to understand the underlying physical process of transient heat transfer in engine chambers. Numerical simulations are often the tool of choice within engine research and development. Engine simulations, however, are not fully predictive; they can be limited in their ability to resolve entirely new processes. Accurate heat transfer modelling is limited by the lack of experimental guidance to fully resolve the dynamic thermal processes at the gas/wall interface.

Laser and optical-based diagnostics have become an indispensable experimental tool to understand physical processes of combustion and provide experimental guidance to numerical modelling. This section briefly describes recent advancements in laser diagnostics to study transient heat transfer and flame processes at gas/wall interfaces. The discussion is designed to identify **new opportunities, which are pursued in this proposal**. The discussion focuses on diagnostics that quantitatively measure important parameters for engine heat transfer: gas temperature, flow velocity, wall temperature and flame distribution.

2.1.1 Gas Temperature

Recognized as one of the most-important parameters in heat transfer, gas temperature is also one of the most difficult parameters to accurately measure in IC engines. **PLIF thermometry** is a common methodology to measure 2D gas temperature distributions in IC engines[29]. Dr. Peterson has considerable experience using PLIF thermometry to study gas cooling near chamber surfaces[8-9]. His recent PLIF findings, combined with particle image velocimetry (PIV) for simultaneous temperature and flow velocity, are summarized in Fig. 3. During compression, gases were cooled non-uniformly at the piston surface and transported according to the velocity field. During expansion, the coldest gases were released from the piston crevice, indicating that this region experiences the greatest gas heat loss and can contribute significantly to parasitic engine losses. Although findings quantified temperature distributions resulting from heat loss at surfaces, they were not able to resolve the governing heat exchange processes at the gas/wall interface. For this, detailed temperature measurements in the thermal boundary layer are required. PLIF often suffers from poor measurement precision at high temperature and limited spatial resolution such that it is not suited to accurately resolve temperature distributions in the boundary layer.

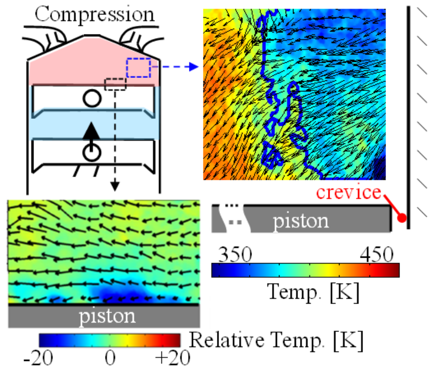

***Fig. 3**: Gas cooling near surfaces in the engine chamber. Coldest gas distributions outgas from crevices.*

Resolving temperatures in the boundary layer is considered to be a remarkable achievement in IC engines. In the 1990's, Lucht et al.[30,31] used vibrational **coherent anti-Stokes Raman spectroscopy (CARS)** to achieve point-wise temperature measurements near the cylinder head surface in an optically accessible engine. Figure 4 shows this impressive achievement. The temperature at each point was evaluated with ensemble-averaged

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Raman Spectra (i.e. 160 data measurements from statistically independent events). The measurement volume was traversed from the surface to provide the next measurement in space. While a remarkable achievement at that time, the measurements only provided a point-wise ensemble-average temperature, which is not suited to resolve unsteady heat transfer phenomenon.

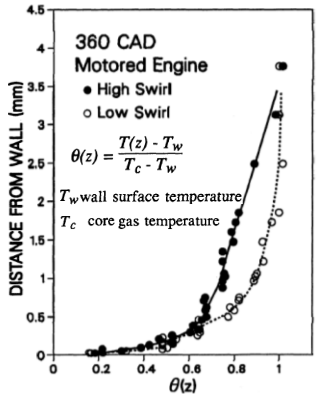

***Fig. 4**: Ensemble-average temperature profile in boundary layer in an engine*[30].

Our team member, Dr. Chris Kliewer at Sandia National Laboratories (USA), has recently developed a **hybrid fs/ps rotational CARS** technique capable of capturing Raman signatures of a number of relevant species concentrations and gas temperature along a line in space (i.e. one-dimensional (1D) temperature measurements)[32-33]. This has provided a recent renaissance of CARS for near-wall applications to study boundary layer and flame quenching near surfaces[34-35]. Bohlin et al.[34] demonstrated the fs/ps CARS technique in a generic burner configuration (Fig. 5a). Figure 5 b/c shows some of the latest ground-breaking results; instantaneous, spatially resolved wall-normal temperature profiles were successfully measured as the flame stabilized at an interface. Measurements were performed at 1.0 kHz repetition rate, which additionally resolved flame-wall interactions. Figure 5c shows the temperature profile (color-scale) normal to the wall (x-axis) as time progresses (y-axis). Measurements reveals the high temperature flame reach the wall surface at t = 0 ms. The flame loses heat near the wall and quenches. As a result, the flame regresses and stabilizes ~1 mm away from the wall.

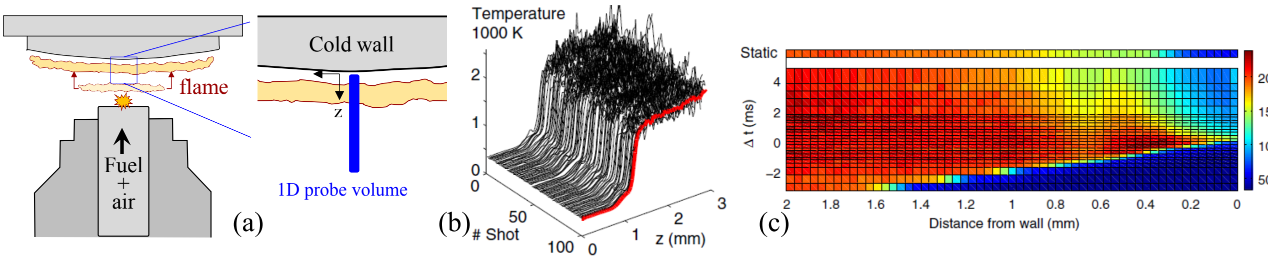

***Fig. 5:** (a) Hybrid fs/ps rotational CARS applied in a burner, (b) instantaneous temperature profiles at the surface of the burner, (c) transient map of temperature showing the flame wall interaction near the burner surface. (b-c) images are taken from REF 32.*

The 1D fs/ps CARS technique developed by Dr. Kliewer provides unmatched capabilities that have revitalized our team's efforts to study unsteady heat transfer and flame quenching in combustion systems. Thus far, this technique has only been applied in open environments at atmospheric conditions. There is a **strong need to develop** 1D fs/ps rotational CARS for engine environments (i.e. high-pressure chambers). In particular, this technique should be suitable to resolve the unsteady thermal boundary layer development as the outer fluid pressure increases. Additionally, detailed gas temperature distributions in crevices should be investigated to better predict parasitic heat losses.

2.1.2 Flow Velocity

Particle image velocimetry (PIV) is a well-established method for recording instantaneous flow fields[36]. The use of high-resolution PIV (termed μ-PIV) in combination with **particle tracking velocimetry (PTV)** has been adapted to study unsteady flows near surfaces[37-38]. Impressively enough, Jainski et al.[38] utilized PIV/PTV to resolve flow field measurements down to the viscous sublayer in an IC engine. Measurements revealed turbulent vortical structures within the boundary layer, thus revealing the highly transient flow behaviour near engine walls. Figure 6 shows the wall-normal boundary layer at different crank-angle degrees. Analysis revealed that the log-law[18] theory did not accurately describe the experimental boundary layer structure in the outer layer (i.e. $30 < y^+ < 50$). These findings are now guiding new computational models to predict more accurately transient flow transport at gas/wall interfaces[39].

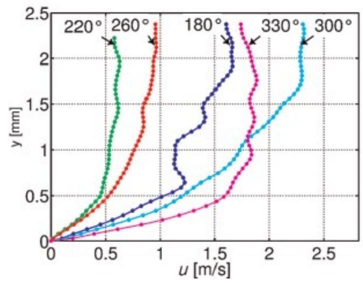

***Fig. 6:** Velocity profiles in boundary layer of an IC engine*[38].

Detailed flow measurements **have not been performed simultaneously** with temperature measurements in boundary layers. The pursuit of simultaneous PIV/PTV and fs/ps rotational CARS measurements would **provide substantial breakthroughs** in the physical understanding of unsteady heat transfer at the gas/wall interface. It is first necessary however, to assess how PIV seeding particles within the CARS probe volume would affect the ability to resolve Raman spectra. Accordingly, feasibility studies of CARS with seeding introduced should first be performed to advance the state-of-the-art diagnostic capabilities.

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2.1.3 Surface temperature and flame distribution

Phosphor thermometry is a recently developed optical technique capable of measuring two-dimensional (2D) surface temperature distributions[40]. For phosphor thermometry, a phosphor coating comprised of a rare-earth or transition metal doped ceramic is applied to a surface of interest and excited with a UV laser pulse. The temperature-dependent luminescence signal is recorded with a photodiode or digital camera. Under the assumption of thermal equilibrium between coating and the surface, the signal provides a spatially resolved measurement of surface temperature.

Phosphor thermometry has been used to measure 2D surface temperature distributions during compression and combustion in IC engines[41-46]. Although it provides quantitative information of the heat received by the surface, further information is required to understand how this heat loss affects gas phase processes such as flame quenching near surfaces. Detailed measurements of the flame distribution near surfaces would provide critical information enabling one to analyze better the locally distributed heat loss along the flame surface. **Planar laser induced fluorescence (PLIF)** imaging of the hydroxyl radical (**OH**) is a suitable technique that spatially resolves flame surfaces, but has not been simultaneously combined with phosphor thermometry measurements in engine environments. Such measurements could be used to establish correlations that describe the relationship between flame quenching and surface heat flux. This effort would also progress diagnostic development towards multi-parameter capabilities. **BP** has experience with both phosphor thermometry and OH-PLIF[7,46].

2.2 General Remarks on the Literature – Identifying Opportunities

Recent advancements in advanced laser diagnostics have provided ground-breaking capabilities to measure the unsteady physical processes of heat transfer and flame quenching near surfaces. It is quite clear that these processes are governed by many parameters. However, most studies thus far have used a single diagnostic methodology to investigate a multi-parameter problem. There is a strong **need to develop the use of multiple diagnostic methodologies** that provides additional information to address unresolved questions of unsteady heat transfer and flame quenching.

There is also a clear **need to develop diagnostic methodologies for engine environments** (i.e. high-pressure chambers). There are many complexities associated with IC engines that challenge the ability to study the most pertinent scientific questions. For example, engines have moving surfaces such that boundary and flow conditions are not well controlled. Additionally, measurement access is not always available, especially in crevices. Thus, a simplified experimental facility with the same pressure/temperature environment, but with controllable boundary conditions and simplified optical access is required for systematic studies. **Now is the time to develop these unique tools** that address critical scientific questions in order to support high-efficiency engine technology and help mitigate global climate change.

3. Objectives of EPIC

EPIC will develop and utilise a unique set of experimental tools to address critical, unanswered questions of unsteady heat transfer and flame quenching at high, transient pressures. EPIC will advance the state-of-the-art in terms of (*i*) advanced diagnostic development and (*ii*) scientific knowledge that supports the reinvention of IC engines towards high-efficiency vehicle powertrains. **EPIC objectives** are:

1) Development of a novel experimental facility to investigate the highly transient and highly variable processes at the gas/wall interface using novel measurements in objectives (2) – (5).
2) Development of fs/ps rotational CARS to measure experimentally, for the first time, the temporally and spatially transient thermal-boundary layer under transient pressure rises to identify the leading mechanisms of heat loss as fluid pressure increases.
3) Simultaneous fs/ps rotational CARS and OH-PLIF measurements to quantify, for the first time, the local flame and fresh-gas heat loss that defines flame quenching at high pressures for single- and two-wall passages.
4) Simultaneous phosphor and OH-PLIF measurements to measure surface temperature and flame distribution to establish correlations that describe the relationship between flame quenching and surface heat flux for single- and two-wall passages.
5) Development and assessment of simultaneous fs/ps rotational CARS and PTV to measure, for the first time, the detailed thermal and flow transport in the boundary layer to support the development of predictive theoretical boundary layer models.

Section b. Methodology

General Overview

EPIC aims to generate new knowledge on unsteady heat transfer and flame-wall processes at high, transient pressures. **BP** will lead this program at U. Edinburgh. He will be heavily involved in all aspects of the

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research. He will hire **two new PhD students** (funded by U. Edinburgh) and a post-doctoral research assistant (**PDRA**, ERC funded). Their tasks are outlined in the Work Packages (WP). Furthermore, an **additional PhD student** (Mr. Torge Mecker, **TM**) at Edinburgh has already been hired and will spend one year at Sandia National Laboratories (SNL) to work with Dr. Chris Kliewer (**CK**) to apply fs/ps CARS measurements and develop a CARS code to analyse experimental spectra. The code will then be used and further developed at U. Edinburgh for the experiments in WP2-WP5. **CK** is eager to team with **BP** and the EPIC team to develop fs/ps CARS for high pressures applications at U. Edinburgh.

Prof. Mark Linne (**ML**, U. Edinburgh) also has experience with CARS and fs laser systems. **ML** is **TM's** PhD advisor and **TM's** work is dedicated to the fs/ps CARS development at Edinburgh. **ML** also has extensive experience building a similar experimental facility to the one proposed in WP1. **ML** is supporting **BP** during the design and testing phases of the chamber. Prof. Andreas Dreizler (**AD**, TU Darmstadt) is enthusiastically supporting **BP** for phosphor thermometry. **BP** is already actively participating in experimental measurements at Darmstadt to measure surface temperature measurements in IC engines. This work is complementary, but separate from EPIC.

U. Edinburgh is also making significant investments in support of **BP's** work, including funds (approx. £600k) for a renovated laboratory (85m^2 of space), and about £1.5 million for equipment, including an optically accessible research engine and a high pressure, high temperature optically accessible spray chamber (not requested from ERC but essential for the ground breaking research proposed in EPIC). U. Edinburgh has the available infrastructure to perform all tasks listed in the WPs.

The following discussion describes the WPs and tasks that will be undertaken in EPIC to achieve all objectives. Several WPs are high-risk / high-gain. Risks are discussed for each WP. Mitigation strategies and contingency plans are presented to show that high-risks can be managed and describe how the state-of-the-art will be advanced in all circumstances.

WP1 Development of experimental facility

A novel fixed-volume chamber (referred to as the *EPIC chamber*) will be developed for application of advanced laser diagnostic techniques to study near-wall processes at high pressures and within principle engine geometries. The chamber (based on a design by Linne et al.[47]) provides a simplified, yet practical environment that successfully emulates the pressure/temperature rise and decay of a real IC engine. The chamber, initially at a vacuum, is filled with a homogeneous fuel-air charge to a specified pressure at which point the flow stops and the chamber is sealed. The enclosed mixture is ignited by a spark plug (laser ignition also possible) and heat release induces an exponential pressure rise. The pressure rise emulates the pressure-time curve during a compression stroke. At a specified chamber pressure, a dump valve is activated to initiate an exponential pressure decay. An orifice plate, upstream the dump valve, controls the exit flow and the pressure decay rate. This pressure decay emulates the pressure-time curve during an expansion stroke. Previous work[47] demonstrated that this operation provides the thermodynamic processes and time-scales consistent to that of a real engine.

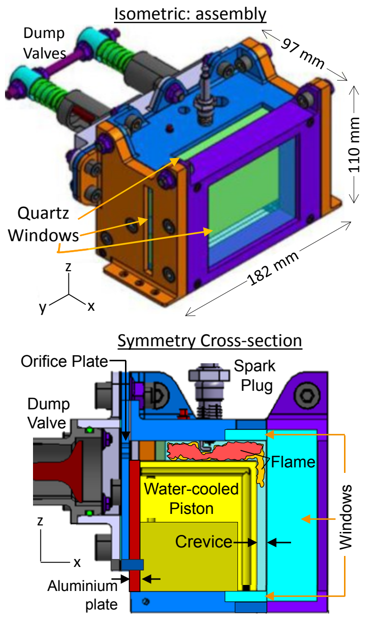

Fig. 7: Experimental facility for heat transfer and flame quenching studies.

Although the EPIC chamber will have a similar operation to that of Linne et al.[47], the geometry and components will be uniquely designed for detailed studies of near-wall heat transfer and flame quenching for single- and two-wall engine passages. The chamber is designed specifically for application of advanced laser diagnostics to provide quantitative, multi-parameter measurements near surfaces that are not possible in optically accessible engines. The proposed chamber is shown in Figure 7 and entirely novel aspects of the chamber are described below.

- A stationary, rectangular, water-cooled 'piston' is placed in the chamber test section. Its position represents a piston position at the end-of-compression. The piston is secured to the back wall and extends the entire cross-section towards the front window. The front surface is placed a fixed distance from the front window to simulate a piston crevice. An aluminium plate with uniform thickness placed on the back wall will select the crevice spacing. The spacing can be adjusted using various plate thicknesses. Spacings from 0.25 – 1.0 mm will be used to simulate a piston engine crevices. Larger spacings can be selected to provide systematic studies of heat transfer and flame quenching as a function of crevice spacing.

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- The EPIC chamber offers realistic engine passages, but with full optical access – a novel aspect, not exclusively available with optical engines. Optical access is granted above the piston and within the crevice by 5 quartz glass windows: top/bottom, two on each side, and a large front window. The window placement and chamber dimensions are designed specifically for application of advanced laser diagnostics. The *y-z* dimensions allow for CARS laser beams to enter/exit the side or top/bottom windows without damaging windows from the high laser power densities. The front window can be used to aid laser alignment, but also used for simultaneous diagnostics. These aspects provide a unique opportunity for quantitative, multi-parameter measurements near surfaces that are **not possible in optically accessible engines**.
- A feedback control system will control charge filling, firing, dump-valve activation, and charge evacuation procedures. This will provide repeatable operation to collect appropriate sample statistics.
- A single nozzle, gaseous N_2 injector can be fitted into the cylinder head upstream the spark plug. This can be used to produce flow turbulence. Alternatively, fans can be designed into the cylinder head to produce similar homogeneous turbulence levels achieved in fan-stirred chambers. This would be performed for a spare, cylinder head to provide flexibility and opportunity, while not limiting operation time.
- The chamber test section is connected to the back wall / piston / dump-valve section using 8 bolts. The test section can be removed from the back end to clean optical components. Alternative component designs are also being considered (e.g. spare cylinder head with fans). Additionally, the front panel with large front window can be removed and replaced with a water-cooled aluminium front panel (Fig. 8) to provide the same surface material and wall temperature on both sides of the crevice. Furthermore, alternative side walls with windows of a larger horizontal dimension can replace the longer vertical windows.

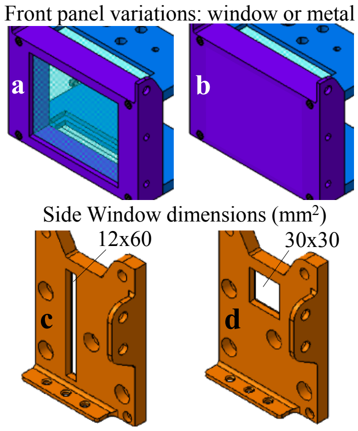

Fig. 8: *(a,b) front panel with and without window, (c,d) two configurations of the side window design.*

Design: Chamber design has already been initiated in a Master's of Engineering project at Edinburgh. A computer-aided design model has been developed (Fig. 7) and structural integrity has been verified using finite element analysis (FEA). Several orifice plates have been designed to control the exponential pressure decay for up to 30 bar chamber pressure. Pressure rise rates have been calculated for stoichiometric mixtures for isooctane (C_8H_{18}) mixtures and for ethylene (C_2H_4) mixtures (equivalence ratio $\Phi = 0.5 - 1.0$). C_8H_{18} represent realistic fuels used in IC engines, while C_2H_4 will provide a faster pressure rise rate. Rise rates for both fuels emulate those during compression and ignition for real engines.

Manufacture & Testing: components will be manufactured and after assembly the chamber will be hydrostatically tested. Dump-valve activation upon reaching a specific chamber pressure is also important for controllability and safety. This aspect will first be tested for low chamber pressures and dilute fuel mixtures to assert safety precaution and prevent chamber damage. The full metal front panel will be used during initial testing. Once functional, testing will commence for stoichiometric mixtures and then with all optical components. Any necessary adjustments will be performed to improve functionality and repeatability.

Repeatability & Flame-Pressure Characterization: as a flame propagates, gas expansion and heat release will raise the chamber pressure similar to that in a real engine. Flame propagation (and thus pressure-rise) is expected to be more repeatable than in IC engines because of far less variations in the flow field. Chamber pressure will be characterized with respect to global flame position. This is important for WP2 and WP3 as measurements will be performed when the flame's position (and thus chamber pressure) is relative to a fixed measurement location. OH-PLIF and chemiluminescence imaging will be used to produce 2D flame positon PDFs as a function of pressure. This will nicely characterize combustion performance and repeatability. This will also help select a suitable ignition location and exact measurement location for WP2 and WP3.

The tasks and schedule for WP1 are listed below**:**

1. Design of feedback control unit
2. Purchasing equipment
3. Manufacturing
4. Testing / potential improvements
5. Repeatability & flame-pressure characterization

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Schedule for WP1: ***Years 1 & 2*** *(5 yr. project)*

Task no.	Year 1				Year 2			
	I	II	III	IV	I	II	III	IV
1								
2								
3								
4								
5								

WP1 Management: Tasks will be performed by **PhD 1** and the **PDRA**. They will be supervised by **BP,** who will also participate in all aspects of the work. **ML,** having already built a similar chamber, will support further design, fabrication and testing.

WP1 Risks: The EPIC chamber is based on an existing design and its function has been demonstrated. **ML** (designer of original chamber) is supporting fabrication and testing. Manufacture and testing may require small design iterations, which impose additional time for chamber completion. Chamber fabrication and testing still is feasible for 1.5 yrs. **WP1 is low-risk** and it enables the opportunities in WP 2-5 (**high-gain**).

WP2: Thermal boundary layer development (unburnt gas)
In this WP, we will adapt fs/ps rotational CARS for high pressure, chamber environments. Experiments will be performed to measure, for the first time, the temporally and spatially transient thermal-boundary layer under transient pressure rises to identify leading mechanisms of heat loss for single- and two-wall passages.

The fs/ps rotational CARS method is a novel diagnostic strategy, developed by Dr. Chris Kliewer (**CK**) at Sandia National Laboratories (USA) to measure spatially and temporally gas temperatures and species concentrations along a line in space[32-35]. The high-peak power from short fs pulses excites the Raman coherence very effectively, yielding high signal levels, which allow the lasers to be focused into sheets to enable 1D measurements at the laser sheet crossing. This is opposed to nanosecond CARS which provides a point-wise measurement at the crossing of three laser beams (see Fig. 9 for comparison). The fs/ps CARS approach only uses two lasers opposed to three; the pump/Stokes signal is created from the same fs laser source, providing a novel phase matching scheme[33]. This has simplified the technique for the work proposed since only two laser beams need alignment. Furthermore, fs amplifiers offer kilohertz (kHz) repetition rates, providing **new opportunities** to measure temporally correlated processes, which was previously unavailable until now.

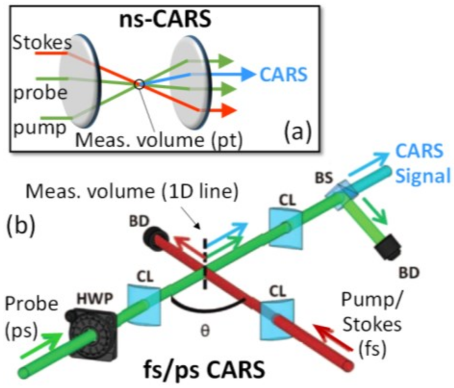

Fig. 9: *Description of (a) general ns-CARS setup and (b)1D fs/ps rotational CARS. (b) is taken from REF 33.*

In our setup, a fs laser producing a pulse duration of 35 fs will be used as the pump/Stokes beams. The ps-probe will be generated using second-harmonic bandwidth compression (SHBC) as demonstrated by Kearny and Scoglietti[48]. SHBC will convert the 35 fs-pulse at 800 nm wavelength to generate a ps pulse at 400nm with excellent spectral brightness. The CARS signal will be collected into a spectrometer and recorded by a high-speed digital camera. An example experimental setup is shown in Fig. 10. The pump/Stokes laser sheet and probe laser sheet can enter through the side window and exit through the other side. Depending on the desired location of measurement volume (i.e. laser sheet crossing), several laser sheet arrangements are possible; the pump/Stokes sheets can also enter through the front window or top/bottom windows. This is a unique aspect of the chamber, which is designed specifically for sophisticated diagnostics such as fs/ps rotational CARS.

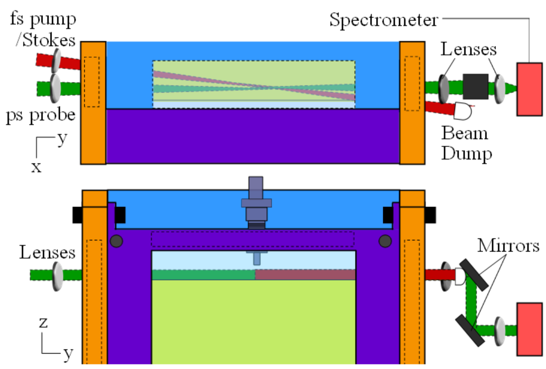

Fig. 10: *example setup of fs/ps rotational CARS in the chamber*

The fs/ps rotational CARS method has not been adapted in high pressure chamber environments. This WP thus **embarks into new territories** for this diagnostic development. It can be foreseen as a high-risk. Beam steering from refractive index gradients can cause beam misalignment and difficulties in detection. Large density gradients near surfaces can further impose beam steering effects.

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A logical work plan is needed to provide a path towards success. Logically, the fs/ps CARS will first be optimized in an open environment. Once this is optimized, we will apply this technique within Edinburgh's high pressure / high temperature (HP/HT) spray chamber (away from surfaces) to understand how to manage refractive index gradients. Once this is successful, measurements will be performed in the EPIC chamber.

As experiments are performed in the EPIC chamber, two measurement locations are of interest: (a) <u>above the piston</u> and (b) <u>in the crevice</u>. Measurements will be performed at 1 kHz. They will commence at ignition timing to spatially resolve unburned gas temperature as chamber pressure increases. This objective only concerns measurements *before* the flame enters the measurement space, but in principle these can be the same experiments performed in WP3 *as* the flame enters the measurement space. As shown in Fig. 11, the CARS measurement line (green) will be placed perpendicular (⊥) or parallel (‖) to surfaces.

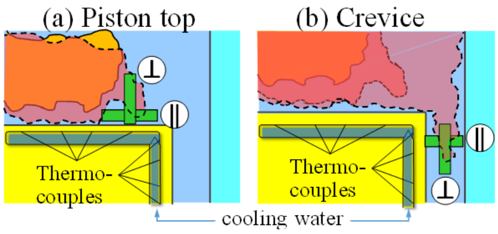

Fig. 11: *(a-b) 1D CARS measurement location/orientation (green) above the piston and in the crevice.*

<u>Above the piston</u>: the goal of these measurements is to record, for the first time, the spatially and temporally varying thermal boundary layer shape and size as fluid pressure increases. This will be performed as the CARS 1D measurement is perpendicular (⊥) to the surface. The boundary layer shape and size are important parameters that are required to predict accurately the heat transfer in theoretical models[15,18]. However, these quantities have not been experimentally resolved in a transient pressure environment as proposed here. Measurements will **provide incredible findings** that will identify the leading mechanisms of transient heat loss and support theoretical model and engine simulation development. The measurements, performed at 1 kHz recording rate, will record the instantaneous 1D temperature profiles as the flame approaches the measurements volume. Measurements will be analysed as a function of fluid pressure and flame position relative to the measurement volume. Parallel orientations (‖) will record the gas temperature variation along the surface for complementary findings. Measurements are relevant for single-wall configurations.

<u>In the crevice</u>: measurements in the crevice are aimed to resolve temperature distributions in for two-wall engine relevant passages. This is a unique aspect of the EPIC chamber that provides **another opportunity** for new knowledge. Optical engines do not provide optical access into the crevice to the same extent as the proposed chamber. A dynamically varying thermal boundary layer will exist on both sides of the crevice. This will produce entirely different gas/wall coupling than the single-wall configuration (i.e. above the piston). Details of thermal transport in two-wall engine passages **have not been investigated** and the theory is not well understood. Probe volumes perpendicular (⊥) to surfaces will record the dynamic coupling between boundary layers of each wall. Probe volumes parallel (‖) will record the temperature variance with crevice distance. Measurements will be performed with different crevice spacings to underpin the physics of two-wall thermal transport under transient, high pressures and support development of theoretical modelling.

Although CARS measurements will concentrate on unburnt gas temperatures, it is important to record the flame distribution relative to the probe volume to interpret the temperature profiles. As shown in Fig. 11, the flame can approach a portion of the probe volume, while other regions remain further away. Imaging the 2D flame front within the chamber is important in order to interpret unburnt gas temperature profiles that are influenced by an approaching flame. To achieve this, OH-PLIF measurements will be performed simultaneously with fs/ps CARS. This will essentially be the same setup as proposed in WP3 and will provide many new opportunities to evaluate data, such as analyzing the unburnt temperature profiles in relation to flame front location.

The tasks and schedule associated with WP2 are shown below:

1. Develop CARS code for Edinburgh
2. Optimize fs/ps CARS in open environment
3. Fs/ps CARS in HP/HT spray chamber
4. Fs/ps CARS in EPIC chamber
5. OH-PLIF in EPIC chamber
6. OH-PLIF and fs/ps CARS in EPIC chamber

Schedule for WP2

Task no	*Year 1*		*Year 2*		*Year 3*		*Year 4*		*Year 5*	
1										
2										
3										
4										
5										
6										

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WP2 Management: Task 1 will be performed by **TM**. **ML** is **TM's** thesis advisor and **TM** will spend one year at SNL to work with **CK** to develop a CARS code and perform preliminary measurements. As **TM** returns to Edinburgh, the **PDRA** and **TM** will optimize CARS in an open environment. The setup will be optimized and then taken to the HP/HT spray chamber (**PDRA** + **TM**). **PhD1** will perform OH-PLIF measurements in the EPIC chamber (as part of WP1, task 5). **PhD1** and the **PDRA** will then perform CARS measurements in the EPIC chamber, followed by simultaneous OH-PLIF and 1D CARS. **CK** will also visit Edinburgh and participate in measurements. All students will be supervised by **BP** and **ML,** who will also participate in all aspects of the work.

WP2 Risks: Beam steering from refractive index gradients and large density gradients at surfaces can cause challenges to resolve CARS signals (i.e. gas temperatures) (**high-risk**). The proposed fs/ps CARS method utilizes a novel phase matching approach[32] that will make laser sheet alignment more manageable. In addition, the spectrometer opening can be increased to allow CARS signal to enter despite some beam steering. Spectral resolution will decrease, but gas temperature can be obtained from O_2/N_2 signal to **manage the risks**. Spectra can also be normalized to N_2 signals, to achieve temperature measurements and **further mitigate risks**. Laser sheet alignment is expected to take some time in the EPIC chamber, but optical access from the sides, top/bottom, and front window should provide the flexibility required to optimize CARS. Adapting the fs/ps rotational CARS to high pressure environments will advance the diagnostic's development for WP3 and 5 (**high-gain**). Measurements will provide new knowledge of the leading mechanisms of transient heat loss for single- and two-wall passages under a transient pressure environment (**high-gain**). Findings are designed to support the development of more accurate theoretical heat transfer models for the long term (**high-gain**).

WP3: Flame-wall interactions: 1D CARS and OH-PLIF

Flame-wall interactions (FWI) are important considerations during the design process of downsized IC engines. They have considerable implications on fuel conversion efficiency and longevity of chamber surfaces. With recent trends towards downsizing and boosting, FWI has received more attention. The nature of FWI often depends on flame approach. There are two common methods by which a flame approaches a surface: (1) "head-on" where the flame burning is normal to the surface and (2) "side-wall" where the flame burning is parallel to the surface[24,50,51] (see Fig. 12). Each arrangement will have different governing processes that will affect flame heat loss and quenching such that the FWI can be different. Most recently, EPIC team member **CK** demonstrated exciting new capabilities of 1D fs/ps CARS to study processes involved for head-on and side-wall arrangements[34,35]. For the first time, spatially resolved wall-normal temperature and species measurements were resolved to study physical processes of flame approach, heat loss, quenching, and pollutant formation at the surface. Studies have only been performed in a generic burner at atmospheric conditions. Processes will be inherently different at high pressures and in different geometries.

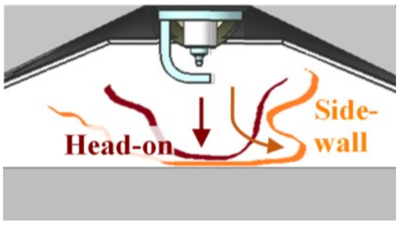

***Fig. 12:** Description of head-on and side-wall flame approach in an engine environment. Illustration is similar to that shown in REF 24.*

In this WP, fs/ps CARS and OH-LIF will be used to study FWI in the EPIC chamber. Measurements will be the same measurements performed in WP2 (task 6), but objectives will now focus on when the flame enters the measurement volume (see Fig. 13). As such, the experimental setup and equipment will be the same as described in WP2. Measurement locations will be placed (a) above the piston and (b) in the crevice. For each measurement location, the ignition location can be adjusted via laser ignition so that the flame arrives at the measurement volume at similar chamber pressures.

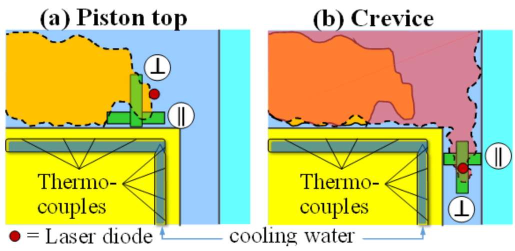

***Fig. 13:** location/orientation of CARS measurement volumes (green) for WP4.*

A laser diode will be used to detect flame arrival at a given location, which will then be used to activate the dump valve and simulate the expansion stroke. For repeatable combustion operation (WP1, task 5), this will be similar to conditioning the dump valve to a given chamber pressure, but will be more specific to flame location. After valve activation, chamber pressure will decrease and flame development will subside. A lingering flame will lose heat to the surrounding surfaces and begin to quench as it does in a real engine.

The 1D CARS measurement volume will be placed perpendicular (⊥) or parallel (||) to surfaces (Fig. 13; studies conducted separately). 1D CARS will be performed with OH-PLIF to provide valuable details of how a 2D flame front approaches and travels through the CARS volume. This additional information of the 2D

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flame front distribution is important when the flame does not enter the CARS volume uniformly. Both diagnostics will operate at 1 kHz repetition rate.

<u>Above the piston</u>: measurements will study FWI for a single-wall configuration. 1D CARS measurements will provide detailed gas and flame temperature information as the flame approaches the wall. Of particular importance is to understand the flame cooling as the flame enters the boundary layer adjacent to the wall. Concurrently, measurements will quantify the gas heat flux perpendicular and parallel to walls as the flame approaches (or propagates alongside) the wall. For flame quenching studies, the laser diode will be placed close to the 1D CARS measurement volume (e.g. Fig. 13a) such that the dump valve is activated shortly after the flame enters the 1D space. Chamber pressure will decrease but the flame will progress to the wall where it will experience excessive heat loss and quench similar to that for dilute combustion or downsized strategies. Alternatively, the laser diode can be placed downstream the CARS volume to study the severe burnt gas heat fluxes towards surfaces.

<u>In the crevice</u>: measurements will study FWI for a two-wall configuration, where side-wall flame propagation will be predominant. Of particular importance is the gas heat loss and flame quenching behavior in the crevice. The 1D CARS volume perpendicular to surfaces will quantify the gas and flame heat loss at both walls. This can be studied when the front panel wall is quartz or aluminium (i.e. same material/temp. as the piston). Measurements parallel to the crevice will measure gas and flame temperatures with respect to crevice depth. This will provide new measurements of two-wall quenching distances and accurately describe flame penetration (and resulting unburned gas) within crevices. These measurements are unique because they cannot be performed for crevices in optical engines. Furthermore, crevices are the largest contributor UHC emissions; detailed processes in crevices will create new knowledge to support emission reduction in the chamber, which would otherwise not be completely removed by catalysts for dilute combustion strategies.

For both measurement locations, systematic studies will be conducted to understand how underlying physical processes change with:

1. Chamber pressure
2. Wall temperature
3. Crevice spacing
4. Fuel-air ratio
5. Fuel properties (C_8H_{18} or C_2H_4)

Because the experiments in WP3 will principally be the same WP2 (task 6), the tasks preceding 1D CARS and OH-PLIF in the chamber will be similar to tasks 1-5 in WP2. These are not repeated for brevity. Instead, the schedule below simply shows the timeline of the systematic studies (1-5) described above.

Schedule for WP3

Systematic Studies	*Year 1*		*Year 2*		*Year 3*		*Year 4*		*Year 5*	
1-5										

<u>WP3 Management</u>: Tasks previous to these studies are found in WP2. Studies shown above will be performed by the **PDRA** and **PhD1**. Both **BP** and **ML** will participate in experiments and supervise the students during data analysis. **CK** will visit Edinburgh and also participate in experiments.

<u>WP3 Risks</u>: WP3 is **high-risk** (similar to WP2) and equally **high-gain** as it can identify the leading mechanisms of flame quenching (i.e. efficiency loss) in engine passages. Beam steering can be more serious as larger density gradients can exist at the flame front. If beam steering is too strong, point-wise fs/ps CARS will be performed, providing, for the first time, temporally resolved, single-point temperature measurements in the boundary layer during flame-wall interaction. Spectra can also be normalized to N_2 signals, to achieve temperature measurements to **mitigate risks**. This contingency plan still provides **gains** in diagnostic development that will **produce new experimental findings** on FWI for single- and two-wall passages.

WP4: Flame-wall interactions: phosphor thermometry and OH-PLIF

Thus far, WPs have focused primarily on studying physical processes in the gas-phase. Further knowledge of gas/wall heat transfer and FWI processes requires detailed measurements of surface temperature. This aspect is especially important with regards to boosted engine strategies, where higher power densities will push reactions closer to walls, resulting in greater heat transfer towards engine surfaces.

In this WP, investigations of FWI will be pursued in the EPIC chamber using phosphor thermometry (surface temperature) and thermocouples (wall heat flux) measurements. These measurements will be combined with OH-LIF to quantify the 2D flame distribution relative to surfaces. Measurements will be performed with kHz repetition rates to resolve flame-wall impingement, quenching, and heat deposited in the walls. Within the literature, simultaneous surface temperature and flame distribution measurements have not been reported. Moreover, surface temperature measurements have not been reported for piston crevices. WP4 can **immediately provide new insights** for FWI and heat deposited for single- and two-wall surfaces.

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For phosphor thermometry, the phosphor $Gd_3Ga_5O_{12}$:Cr will be used because it is suitable for combustion environments[45]. After excitation from UV light, the phosphorescence will be temporally resolved using a high-speed CMOS camera operating at 100's of kHz. This detection method is known as the "liftetime" approach[40] and is chosen because it typically offers superior measurement precision than the other detection method, the "ratio" method[52]. Our EPIC team member, **AD** at TU Darmstadt has demonstrated that $Gd_3Ga_5O_{12}$:Cr doped with Cerium (Ce) can decrease the phosphorescence "afterglow" allowing temperature measurements at a rate up to 1 kHz[45]. We will also pursue this method at Edinburgh and a PhD student from Darmstadt will participate in experiments.

Similar to WP3, measurements will be concentrated (a) <u>above the piston</u> and (b) <u>in the crevice</u> for complementary analysis. Figure 14 shows an example experimental setup (above the piston) to describe the approach of the multiple diagnostic measurements. UV laser light at 266 nm will be reflected by a dichroitic mirror and enter through the top window and illuminate the phosphor coating applied to the piston surface. The temporally resolved phosphor decay of the 2D surface will be captured by the CMOS camera normal the illuminated surface. The OH-LIF laser light at 283.1 nm will enter through the large front window and excite the OH radicals in the flame. OH fluorescence detection will be captured through the side window by an intensified camera, which will be normal to the UV laser sheet. To detect the fine details of flame structure, the intensified camera will be equipped with a long distance microscope. Lastly, surface heat flux will be calculated from the surface temperature and thermocouple measurements by assuming 1D heat conduction. Several thermocouples will be used to provide spatially distributed heat flux measurements.

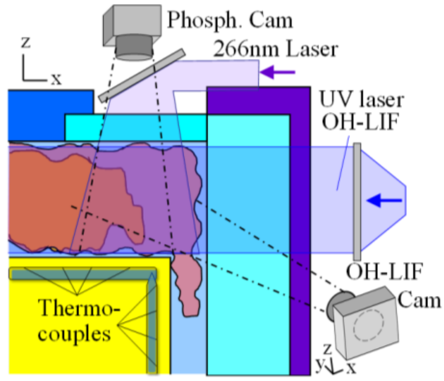

Fig. 14: *example setup of OH-PLIF and phosphor thermometry in WP4.*

<u>Above the piston</u>**:** data will be collected and compared for "head-on" and "side-wall" flame impingement arrangements to identify the different mechanisms that lead to enhanced heat transfer and flame quenching. Surface temperature and heat flux will be analyzed as a function of (1) the flame's distance to the wall and (2) the time after flame-wall impingement. As the flame moves past the surface, measurements will quantify the heat fluxes from the burnt gas and these will be compared to heat fluxes associated the flame front approach. As the dump valve is activated (same procedure as described in WP3), surface temperature and heat flux will be measured as the flame idles near the surface and quenches. A simplified model, similar to the approach of Boust et al.[51], will be pursued to describe the relationship between quenching distance and surface heat flux for single-wall quenching at high pressures.

<u>In the crevice</u>: the phosphor coating will be applied to the side of the piston and the phosphor camera will view the surface through the front window (experimental setup not shown). The FWI will be that of the side-wall mechanism. Surface temperature and heat flux will be measured as function of flame penetration into the crevice. Surface temperatures and flame distribution will be compared to those on the piston top with side-wall flame propagation. In these narrow passages, heat loss will be greater such that flame quenching can be more prevalent. For the first time, measurements would quantify surface temperatures and heat fluxes to describe mechanisms of flame quenching in crevice volumes.

For both measurement locations, systematic studies will be conducted to identify how underlying physical processes change with: (1) wall temp., (2) fuel-air ratio, (3) fuel (C_8H_{18} or C_2H_4), and (4) crevice spacing.

The tasks and schedule associated with WP4 are shown below:

1. Phosphor setup and testing
2. OH-PLIF setup and testing
3. Simultaneous OH-PLIF / phosphor thermometry

Schedule for WP4

Task no	*Year 1*		*Year 2*		*Year 3*		*Year 4*		*Year 5*	
1			■	■						
2				■	■					
3					■	■				

<u>WP4 Management</u>: **PhD2** will begin applying phosphor thermometry to the chamber in year 2. After the initial measurements are functional, the student will simply add the OH-PLIF laser and camera into the existing setup. These tasks will coincide with tasks 5/6 of WP2/3 (OH-PLIF in EPIC chamber). **BP** will help the student with experiments as he has experience with phosphor thermometry and OH-PLIF. Additionally, our EPIC team member, **AD** from TU Darmstadt, will participate in this work. For these efforts, a **PhD student from Darmstadt** will come to Edinburgh and participate in the experiments.

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WP4 Risks: these methods are well-established, but have never been combined. Dr. Peterson has experience with OH-PLIF and phosphor thermometry. **WP4 is low-risk** and findings will provide new correlations of surface temperature and flame position to identify mechanisms of flame quenching (i.e. efficiency loss) and high surface heat flux that can damage surfaces (**high-gain**).

WP5: Development and assessment of 1D CARS and PIV/PTV
Detailed measurements of thermal boundary layer development in WP2 would be a great accomplishment. Further understanding of the near-wall heat loss requires complementary flow field measurements. The PIV/PTV approach has proven to be a suitable method to study boundary layer flows in engine environments[37-38]. Simultaneous 1D CARS and PIV/PTV measurements would considerably advance the diagnostic state-of-the-art and would provide substantial knowledge of gas transport and heat loss at surfaces. For this purpose, we will combine 1D fs/ps CARS with PTV for simultaneous temperature and gas velocity measurements.

For PIV/PTV applications, aerosol particles (e.g. silicone oil droplets) are seeded into the fluid to track particle displacement[36]. Particles are sufficiently small (~1 – 3 μm) to faithfully follow the fluid flow. To resolve boundary layer flows, a high spatial resolution from PIV/PTV is needed. This, in turn, requires high seeding densities, which may disturb CARS measurements. Simultaneous applications of CARS and PIV have been performed, but were limited to sparse particle densities and point-wise ns-CARS[49]. **Now is the time** to investigate the feasibility of 1D CARS measurements in the presence of particle densities in order to underpin the leading physical mechanisms of turbulent heat transfer in boundary layer flows.

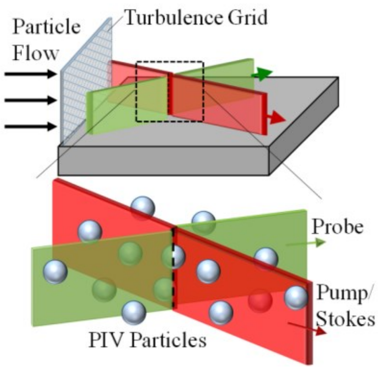

Fig. 15: *example setup of 1D fs/ps rotational CARS over a flat plate with particle seeding.*

For this WP, 1D CARS measurements will first be performed on a simple “flow over a flat plate” (see Fig. 15). Seeding will be introduced into the flow and CARS laser sheets will be placed near the plate surface. Measurements will focus on evaluating 1D CARS temperature measurements as a function of seeding density. Once maximum seeding densities have been determined, we will investigate the applicability to study boundary layer flows. For relatively low seeding densities, boundary layer flow and temperature will be studied for the flow over a hot flat plate. A turbulence grid will be added to underpin turbulent boundary layer development as function of Reynolds number. If high seeding densities disturb 1D CARS signals, temporally-resolved point-wise fs/ps CARS measurements will be pursued as a means to provide unique measurements on heat transfer processes.

When 1D CARS measurements are optimized and seeding densities defined, measurements will then be performed in the HP/HT spray chamber. Measurements will be performed in the center of the chamber away from surfaces. This will assess the capability of measuring temperature and flow velocity at high pressures. Measurements will then be performed in the EPIC chamber to identify leading mechanisms of heat transfer and compare findings to those on the flat plate. Seeding densities and fs/ps CARS measurement volumes will be optimized and trade-offs in spatial resolution may be necessary for simultaneous measurements.

The tasks and schedule associated with WP5 are shown below:

1. Design flow over flat plate
2. PIV/PTV of flow over flat plate
3. 1D CARS and PIV/PTV (flow over flat plate)
4. 1D CARS and PIV/PTV in HP/HT spray chamber
5. 1D CARS and PIV/PTV in EPIC chamber

Schedule for WP5

Task no	*Year 1*		*Year 2*		*Year 3*		*Year 4*		*Year 5*	
1	■									
2		■	■							
3		■	■	■						
4				■	■					
5						■	■	■	■	■

WP5 Management: This WP is designed to coincide with the timing of WP2. **PhD2** will begin with experiment design. The **PDRA**, **TM**, and **PhD2** will perform 1D CARS and PTV measurements for the flow over the hot flat plate to underpin leading mechanisms of turbulent heat transfer in boundary layers. This task will coincide with WP2, task 2 (CARS in open environment). The **PDRA**, **TM**, and **PhD1** will then conduct measurements in the HP/HT spray chamber (coincides with WP2, task 3). Measurements will produce temperature/velocity correlations for high pressure flows. The **PDRA** and **PhD2** will perform measurements in the EPIC chamber to identify leading mechanisms of heat transfer and compare findings to those in task 3.

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<u>WP5 Risks</u>: WP5 is **high-risk** since high seeding densities required to resolve flow in the boundary layer can disturb 1D fs/ps CARS measurements. The flow over the flat plate experiment will systematically determine the optimal settings for each diagnostic. Such an experiment is feasible and will produce new knowledge on fundamental turbulent heat transfer and produce advances in diagnostic capabilities (**high-gain**). In the chamber, point-wise CARS measurements can be performed if seeding densities are problematic. Alternatively, PIV/PTV can be performed separately and provide powerful complementary information to the 1D temperature measurements in WP2. Together these **contingency plans** will generate new knowledge that will support development of theoretical boundary layer models for engines (**high-gain**).

4. Conclusions – A logical sequence of WPs will be performed to provide a comprehensive fundamental knowledgebase to help solve unanswered questions of transient heat transfer and flame-wall quenching. A unique set of experimental tools developed will enable several breakthroughs in laser diagnostic and combustion research: (1) development of a novel facility to measure the highly transient processes at the gas/wall interface, (2) resolve key processes of boundary layer development under transient high pressures, (3) identify and compare mechanisms of transient heat loss for single- and two-wall engine passages, (4) identify and compare mechanisms of flame quenching for single- and two-wall passages under high pressures, (5) investigate relationships of FWI for head-on and side-wall flame propagation under high pressures, (6) identify fundamental relationships between gas temperature and velocity in boundary layer flows for multiple environments, and (7) develop, combine, and assess advanced diagnostics for high-pressure, engine relevant environments. This work supports the development of predictive theoretical modelling, over the long term, to more effectively overcome the technical barriers currently hindering the development of cleaner vehicle powertrains.

5. Project Feasibility - The success of EPIC will depend on the development of the chamber (WP1) and the development of advanced diagnostic applications (WPs 2-5). The chamber is based on existing design and its function has been successfully demonstrated. **BP** and his EPIC team members are well-versed in all of the laser diagnostics proposed. Risks have been accessed for all WPs. Mitigation strategies and contingency plans have been presented to show that high-risks can be managed and the state-of-the-art will be advanced in all scenarios. The EPIC personnel are appropriate. **BP** will be involved in all aspects of EPIC together with **3 PhD students** and a **PDRA**. An **additional PhD student** from TUD will participate in WP4. **ML**, **CK**, and **AD** enthusiastically support EPIC and **BP**; they will be highly engaged in the WPs. The schedule is manageable; many tasks coincide and can be fulfilled simultaneously (e.g. WP2&3 experiments in the EPIC chamber can be performed simultaneously). Furthermore, experiments will be performed outside of the EPIC chamber (e.g. flow over flat plate, or HP/HT spray chamber) to enable progression of other work packages, while the chamber is in use or being developed.

6. Enabling future opportunity - BP is establishing a world-leading laboratory that focuses on basic experimental research to study fundamental processes which underpins the success of cleaner combustion technologies. The unique tools developed within **EPIC will enable BP** to establish a world-leading laboratory with many **long-term opportunities** to help remove technical barriers that will enable high efficiency (low CO_2 emitting) powertrains. Example related research **following the success of EPIC** are:

- EPIC's research will be combined with other research fields such as **material science** and **bio-fuels**. Chamber surfaces can be fabricated with different thermal barrier coatings to identify their effect on the underlying mechanisms that mitigate heat loss. This will identify solutions to achieve large efficiency gains for *downsized*, *boosted*, and *dilute combustion* strategies. A fuel-film applicator can be fabricated on chamber surfaces to investigate FWI interaction at the gas/fuel-wall interface that will help support the development of lower soot emitting direct-injection engines operating with bio-fuels.
- New regulations have placed great emphasis on the immediate **reduction of soot and nitric oxides (NO_X)** from diesel engines. Phosphor thermometry and CARS can be combined with two-color pyrometry[54] (diagnostic not used in EPIC) to underpin the correlations between soot radiative heat transfer and soot emission production for diesel sprays. Experiments will be conducted in the HP/HT spray chamber, but also suited for the optical engine at Edinburgh.
- OH-PLIF and CARS can be used for fundamental studies of unwanted gasoline **pre-ignition** (i.e super-knock) for various fuel/oil droplet mixtures at high pressures and temperatures in the HP/HT spray chamber. Studies will support the development of *downsized, boosted,* technologies.
- OH-PLIF, CARS, and phosphor thermometry can be used investigate severe heat fluxes associated with **acoustic instabilities**[55] in gas turbine environments.
- Following EPIC, AD has agreed to bring his head-on or side-wall quenching burners[34,35] to Edinburgh. There is a strong mutual interest to apply 1D fs/ps CARS and PIV/PTV for simultaneous velocity and temperature measurements to improve our fundamental understanding of FWI in these facilities. Further

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development of fs/ps rotational CARS can also enable ultra-broadband (i.e. multiple species measurements) and 2D imaging capabilities in these environments.

BP is also developing a strong program that teams experimental and numerical modelling groups to jointly address the challenges in combustion science. He is actively collaborating with 9 EU computational groups[53] who are modelling his comprehensive engine velocimetry database[12]. **EPIC will further enable BP** to establish a "*thermal database*" for numerical modelling, which will **underpin the success of several EU research groups**[53] over the long term, and help research more effectively overcome the technical barriers that will enable cleaner vehicle powertrains.

Section c. Resources (including project costs)
The project is intended to last 60 months (5 years). Dr. Peterson (**BP**) will devote 60% of his time to the project. Funding is requested for a post-doctoral research assistant (**PDRA**) for the full duration of the project. Costing is also allocated for a laboratory technician (10% time).
Equipment cost (€419,510) will account for the OH-PLIF laser system. This laser system is high-speed Nd:YAG laser that will pump a high-repetition rate Dye laser. This equipment is necessary for WP 2-5 and will be used continuously starting from year 2. **Consumables** (€83,408): The chamber will cost €43,680, including auxiliary components, control system, manufacture, and maintenance. A long distance microscope (€25,818) will be purchased for the use of OH-LIF and PIV/PTV applications (WPs 2-5). Costing is allocated for the experimental setup for the flow over the flat plate (WP3, €2,600) and an oven for research will be required for phosphor thermometry calibration purposes (WP5, €9,750). **Publications costs** (€19,020) will be required for open access. The publications of choice are: (Elsevier) Combustion and flame; Proceedings of the Combustion Institute; (Springer) Experiments in Fluids; Flow, Turbulence and Combustion; Applied Physics B; International Journal of Heat and Mass Transfer; (The Optical Society) Optics Letters; Optics Express. These journals represent the highest journal within **BP's** research field. Costs will provide open access for 10-12 publications. **Travel Costs** (€25,350). Travel will consist of at least 1 conference per year (PI and PDRA or PhD; €4,550 total per year) every year of the proposal. Conferences of interest are: International Combustion Symposium, Gordon Research Conference on Laser Diagnostics in Combustion, International Conference on Heat and Mass Transfer, and the International Symposium on Applications of Laser and Imaging Techniques to Fluid Mechanics. Registration fees for each conference are on average around €600 per person. Flights, hotels and meals usually average around €1500 per person. The costs for conference travel (€4,550 per year) are justified. Travel costs (€1,800) are requested to fly team members (e.g. **CK**) to Edinburgh to participate in experiments. An additional €800 is requested for travelling expenses for interviewing PDRA candidates.

Cost Category			**Total in Euro**
Direct Costs	**Personnel**	PI	€285,347
		Senior Staff	€0
		Postdocs	€331,650
		Students	€0
		Other	€30,296
	i. Total Direct Costs for Personnel (in Euro)		€647,293
	Travel		€25,350
	Equipment		€419,510
	Other goods and services	Consumables	€83,408
		Publications (including Open Access fees), etc.	€18,720
		Other (Audit)	€ 5,200
	ii. Total Other Direct Costs (in Euro)		€552,481
A – Total Direct Costs (i + ii) (in Euro)			€1,199,481
B – Indirect Costs (overheads) 25% of Direct Costs (in Euro)			€299,870
C1 – Subcontracting Costs (no overheads) (in Euro)			€0
C2 – Other Direct Costs with no overheads (in Euro)			€0
Total Estimated Eligible Costs (A + B + C) (in Euro)			€1,499,351
Total Requested EU Contribution (in Euro)			€1,499,351

Please indicate the duration of the project in months:	**60**
Please indicate the % of working time the PI dedicates to the project over the period of the grant:	**60%**

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17 October 2016

COMMITMENT OF THE HOST INSTITUTION

Commitment of the host institution for ERC Calls 2017

The University of Edinburgh, which is the *applicant legal entity*, confirms its intention to sign a supplementary agreement with *Brian Peterson* in which the obligations listed below will be addressed should the proposal entitled *EPIC: Energy transfer Processes at gas/wall Interfaces under extreme Conditions* be retained.

Performance obligations of the *applicant legal entity* that will become the beneficiary of the H2020 ERC Grant Agreement (hereafter referred to as the Agreement), should the proposal be retained and the preparation of the Agreement be successfully concluded:

The *applicant legal entity* commits itself to hosting [*and engaging*] the *principal investigator* for the duration of the grant to:

a) ensure that the work will be performed under the scientific guidance of the *principal investigator* who is expected to devote:

- *in the case of a Starting Grant at least 50% of her/his total working time* to the ERC-funded project (action) and spend at least 50% of her/his total working time in an EU Member State or associated country;
- in the case of a *Consolidator Grant at least 40% of her/his total working time* to the ERC-funded project (action) and spend at least 50% of her/his total working time in an EU Member State or associated country;
- *in the case of an Advanced Grant at least 30% of her/his total working time* to the ERC-funded project (action) and spend at least 50% of her/his total working time in an EU Member State or associated country.

b) carry out the work to be performed, as it will be identified in Annex 1 of the Agreement, taking into consideration the specific role of the *principal investigator*;

c) enter — before signature of the Agreement — into a *'supplementary agreement'* with the *principal investigator*, that specifies the obligation of the *applicant legal entity* to meet its obligations under the Agreement;

d) provide *the principal investigator* with a copy of the signed Agreement;

e) guarantee the *principal investigator's* scientific independence, in particular for the:

i) use of the budget to achieve the scientific objectives;

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ii) authority to publish as senior author and invite as co-authors those who have contributed substantially to the work;
iii) preparation of scientific reports for the project (action);
iv) selection and supervision of the other *team members* (hosted *[and engaged]* by the *applicant legal entity* or other legal entities), in line with the profiles needed to conduct the research and in accordance with the *applicant legal entity's* usual management practices;
v) possibility to apply independently for funding;
vi) access to appropriate space and facilities for conducting the research;

f) provide – during the implementation of the project (action) – research support to the *principal investigator* and the team members (regarding infrastructure, equipment, access rights, products and other services necessary for conducting the research);

g) support the *principal investigator* and provide administrative assistance, in particular for the:
i) general management of the work and his/her team
ii) scientific reporting, especially ensuring that the team members send their scientific results to the *principal investigator*;
iii) financial reporting, especially providing timely and clear financial information;
iv) application of the *applicant legal entity's* usual management practices;
v) general logistics of the project (action);
vi) access to the electronic exchange system (see Article 52 of the Agreement);

h) inform the *principal investigator* immediately (in writing) of any events or circumstances likely to affect the Agreement (see Article 17 of the Agreement);

i) ensure that the *principal investigator* enjoys adequate:
i) conditions for annual, sickness and parental leave;
ii) occupational health and safety standards;
iii) insurance under the general social security scheme, such as pension rights;

j) allow the transfer of the Agreement to a new beneficiary ('portability'; see Article 56a of the Agreement).

k) take all measures to implement the principles set out in the Commission Recommendation on the European Charter for Researchers and the Code of Conduct for the Recruitment of Researchers - in particular regarding working conditions, transparent recruitment processes based on merit and career development – and ensure that the *principal investigator*, researchers and third parties involved in the project (action) are aware of them.

For the institution: The University of Edinburgh
Name: Hamish Macandrew
Function: Head of Research Support Office
Email: hamish.macandrew@ed.ac.uk
Signature of legal representative:

Stamp of institution:

The University of Edinburgh
Old College, South Bridge
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The University of Michigan

to all who may read these letters, Greetings:

Hereby it is certified that upon recommendation of

The Horace H. Rackham School of Graduate Studies

The Regents of The University of Michigan have conferred upon

Brian R. Peterson

in recognition of the satisfactory fulfillment of the prescribed requirements

the degree of

Doctor of Philosophy

(Mechanical Engineering)

with all the rights, privileges, and honors thereto pertaining here and elsewhere.

Dated at Ann Arbor, Michigan, this nineteenth day of December, two thousand and ten.

Mary Sue Coleman
President

Sally J. Churchill
Vice President and Secretary

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