Expression of Interest (EOI)

Questionnaire

Please indicate the name of the contact person for this submission:

Laura Gonella, University of Birmingham

Please indicate all institutions collectively involved in this submission of interest:

Brunel University
Daresbury Laboratory
RAL CMOS Sensor Design Group (CSDG)
RAL Particle Physics Division (PPD)
University of Birmingham
University of Glasgow
University of Lancaster
University of Liverpool
University of York

Please indicate the items of interest for potential equipment cooperation:

The UK experimental nuclear and particle physics communities have a wide range of expertise and strong track record of leadership in designing and building detectors for experiments at international facilities (details in the last section). This is reflected in the key technologies that have been identified as priority R&D for EIC detectors: (a) monolithic active pixel sensors (MAPS) for precision central and forward tracking and vertex reconstruction; (b) the application of Timepix sensors and fast-timing solid-state Cherenkov detectors for far-forward particle tracking; and (c) building on world-leading expertise in the design of detectors for making measurements of polarisation observables.

Please indicate what the level of potential contributions are for each item of interest:

An application for funding to UKRI has been submitted earlier this year and response is expected before the end of the year. The requested funding would support R&D activities at approximately £1M per year, for three years starting in 2021. This would contribute towards the aspirational effort explained below and detailed in the table. A further seven years of funding would be requested for the construction phase of the facility with costing to be confirmed at a later stage.

<u>(a) MAPS for Vertex and Tracking</u>
UK groups interested in the development of a MAPS based EIC Silicon Vertex and Tracking (SVT) detector are **Birmingham, Brunel, Daresbury, Lancaster, Liverpool, RAL CSDG, RAL PPD**. Together they aspire to commit a level of manpower as described in the table below for the design phase of an EIC experimental facility over the next three years to actively contribute to sensor simulation, design and characterisation, DAQ and software development, and light support

structures R&D. These groups would then join the construction of the EIC SVT detector with the aim of delivering a significant fraction of the overall detector assembly. Expertise and infrastructure capability of each group are detailed in the last section.

UK groups, together with colleagues at LBNL, are leading the development identified by the EIC Silicon Consortium as the most successful path to an EIC SVT, i.e. the development of a new generation MAPS sensor in a commercial 65 nm CMOS imaging node in collaboration with the ALICE ITS3 project. The requirements for the ITS3 and what is needed for an EIC tracking sensor have very broad overlap and the synergies of joining an already funded effort strongly increase the probabilities of success. Some institutes have already formally joined the consortium and are already involved in the work on the 65 nm sensor design with the ALICE ITS3 collaboration. ***This part of the UK EOI should thus be read in conjunction with the EIC Silicon Consortium EOI.***

As this aggressive development comes with a certain level of risk, this path forward foresees the possibility of developing an EIC MAPS sensor in a 180 nm CMOS imaging technology node as a backup solution. UK institutes have worked with a number of these technologies, such as TowerJazz and AMS/TSI, through involvement with, amongst others, the ALPIDE, MALTA, DECAL and ATLASPix MAPS sensors, and have thus developed possible alternative solutions that can be evaluated for use at an EIC SVT.

(b) Far-forward region: Timepix and fast-timing Cherenkov detectors

Developed by the Medipix collaboration, Timepix sensors provide excellent spatial and time resolutions and high rate capability, potentially ideal for particle tracking closest to the EIC beam-line, where detection of scattered electrons, protons and light ions with the smallest deflections is critical for mapping of nucleon structure and a full kinematic reach. **Glasgow**, as a founding member of the Medipix Collaboration, has a strong track record of technology development and applications and the hadron group are leading two R&D projects (supported by the Cross-Community Group at Daresbury) using the Timepix chip in other projects. For the EIC, Glasgow, who also lead an EU Horizon-2020 project in EIC detector R&D, will develop and test a Timepix-based prototype for near-beam, far-forward, particle detection. The next-generation Timepix4, which will become available within the near future, has pixel-size of 55 μm x 55 μm. Combining Timepix4 with fast Si sensors based on LGADs, for example, can bring down the timing resolution to sub-100ps, while clustering can further improve the spatial resolution. We propose to apply this technology for far-forward near-beam tracking along the ion (and possibly electron) beam directions.

In addition, timing measurements for event correlation and potentially time-of-flight measurements for particle identification at very low scattering angles, where the reaction products and scattered beam particles remain in the beam pipe, are of crucial importance to achieve a number of EIC science goals. A solid state Cherenkov radiator, e.g. build from fused silica, coupled to fast timing single photon counting devices, e.g. Micro-channel plate photomultipliers, will provide a timing signal with a resolution of about 10ps. Such a system could be seamlessly integrated into a Roman Pot in the beam line and a version of it has been operating successfully at the ATLAS experiment at LHC. The nuclear physics group at the University of Glasgow has significant expertise in the design and development of fused silica based Cherenkov detectors and the characterisation and operation of MCP-PMT and is well placed to lead the development of such a detector system. We will also investigate the potential of combining the excellent spatial resolution of Timepix and timing resolution of the Cherenkov detector in a single Roman Pot design.

(c) Polarimetry
Polarisation observables will be vitally important for the science programme at a future EIC. The hadron physics group at **York** has a wealth of experience in polarisation measurements having built the world's first large acceptance polarimeter for protons at the MAMI accelerator in Mainz. They are now developing this technology for use at Jefferson Lab and bring world leading expertise in modelling spin-dependent scattering. This experience will be brought to bear on the design and construction of an ancillary apparatus for an EIC detector to measure nucleon polarisation.

Please indicate what, if any, assumptions you made as coming from the EIC Project or the labs for your items of interest:

Until funding is confirmed/becomes available from UK funding agencies, we will rely on an adequate level of support from the EIC Detector R&D Programme, with UK groups already receiving support for the eRD18 and now eRD25 projects (Birmingham, RAL CSDG, LBNL).

Please indicate the labor contribution for the EIC experimental equipment activities:

The time commitment of members of UK institutions in the EIC efforts described in this EOI is anticipated to be as follows for the design phase over the next three years:

Institution Name	Professor	Research Professor	Staff Scientist	Postdoc	Graduate Student	Undergrad. student	Engineer	Designer	Technician	Total Sum
Birmingham	0.6			1.0	2.0		1.0		1.0	5.6
Brunel	0.2				1.0	1.0				2.2
Daresbury			0.45	1.0			0.9			2.35
Lancaster										TBC
Liverpool	0.1			1.0					1.0	2.1
RAL CSDG							2.0			2.0
RAL PPD			0.2	1.0						1.2
Glasgow	0.25			1.7					0.3	2.25
York	0.1	0.15		0.7	1.0	2.0				3.95

It is anticipated that the collaborative effort of the UK to cooperate on the EIC Project is to include (at an annual basis) the FTEs as detailed in the table above. We anticipate the duration of this collaborative effort to cooperate on the EIC Project to start at the design phase and to be for a period of three years initially. Subsequently UK institutions will join the construction phase for the required length of time to deliver an EIC vertex and tracking detector, far-forward particle tracking, and polarimetry detectors, and with resources to be confirmed at a later stage.

It is worth noting at this point that this is the collaborative effort the UK aspires to provide for the delivery of an EIC experimental facility. Funding agencies have expressed interest in the EIC project and financial support is expected, but this has not yet been quantified.

Please indicate if there are timing constraints to your submission:

Timing constraints in starting the proposed activities depend on when UK funding becomes available and at what scale. As indicated above, an application has been submitted to UKRI for a total of three years of R&D funding starting in 2021. Outcome will be known by end of this year.

Please indicate any other information you feel will be helpful:

<u>Birmingham</u>
Peter Jones (nuclear physics), Paul Newman, Phil Ilten (particle physics), Laura Gonella (silicon instrumentation).
The interest of the University of Birmingham in the EIC project builds on expertise developed in previous related projects and moves towards a combined interdisciplinary effort across the Particle and Nuclear Physics groups, also exploiting expertise and local facilities for instrumentation. Newman has a strong background of work in previous and future lepton-hadron scattering experiments (H1 at HERA, LHeC) and a strong international profile in the subject as chair of the International Advisory Committee of the Deep Inelastic Scattering conference series. Jones has an equally strong history of work at previous and present heavy ion collision experiments (STAR, ALICE), including an engagement and understanding of the host Brookhaven Laboratory that is unparalleled in the UK. Gonella is a central figure in silicon detector development and production across a range of large-scale production and R&D projects (ATLAS ITk, RD50, AIDA2020).
Previous and continuing Birmingham work on the EIC includes vertex and tracking detector R&D, also extending to simulations that prepare the way for future physics exploitation in the area of charm and beauty production (Gonella, Jones, Ilten) and evaluation of the EIC prospects for studying inclusive diffraction processes in which the proton remains intact (Newman). The group is deeply engaged in the central organisation of the current phase of the project through its user group, in particular the ongoing major thrust to produce a Yellow Report developing detector concepts and defining physics objectives. Peter Jones is one of the four Detector Working Group conveners. Paul Newman is co-convener of the Working Group on complementarity between detectors, as well as a former member of the Elections and Nominations committee.
Birmingham's early involvement in the project has leveraged significantly on the R&D capabilities of the Birmingham Instrumentation Laboratory for Particle Physics and Applications (BILPA). The BILPA clean rooms are one of two UK hybrid and module production site for the ATLAS ITk strip detector for the HL-LHC, and in combination with the Birmingham MC40 irradiation facility, the only proton irradiation site for strip sensor QA. Alongside this activity, the lab is developing a rich programme of R&D into novel sensor concepts for future collider experiments and medical applications. The EIC is now one of the main projects of the BILPA lab. The group has been awarded funds by the US DoE through the EIC Detector R&D Programme for five consecutive years (totalling $269.6k) to develop a conceptual design for a silicon vertex and tracking detector. The concept is based on Monolithic Active Pixel Sensors (MAPS), in collaboration with RAL

CSDG. The project has also been awarded funds for a MAPS submission by the STRONG 2020 (EU Horizon 2020) project (£62.5k). Together with LBNL, Birmingham has started the EIC Silicon Consortium to develop an EIC-specific sensor derived from the technology currently being developed for a second upgrade of the ALICE experiment's inner tracking system (ITS3 project) using MAPS sensors in 65 nm CMOS technology.

Brunel

Liliana Teodorescu.

Liliana Teodorescu has a diverse experience accumulated in Jlab, Babar and CMS experiments that will be brought together to contribute to the EIC program. She performed the first measurement of Lambda polarisation in an electroproduction reaction in one of the first experiments at Jlab, and multi-quark state searched at BaBar experiment. She accumulated experience on Si microstrip detector R&D and radiation hardness for the CMS tracker, and developed strong skills and interest in software development, and advanced computational and data analysis techniques.

Brunel's contribution to EIC will be to the silicon vertex and tracking detector participating initially to the simulation, design and characterization of MAPS sensors, and expanding later to related software developments.

Daresbury, Lancaster, Liverpool

Daresbury: Roy Lemmon, Marc Labiche (Nuclear), Marcello Borri (Detector Systems), John Dainton, Peter Williams, Bruno Muratori, Boris Militsyn, Peter McIntosh, Deepa Angal-Kalinin (Cockcroft).

Lancaster: Harald Fox, Daniel Muenstermann, John Dainton, Vakhtang Kartvelishvili (Particle - Experiment), Graeme Burt, Robert Apsimon (Engineering).

Liverpool: Marielle Chartier (Nuclear), Tim Jones (Particle - Experiment).

Physics: The groups' physics centres on experimental studies of the strong interaction, as described by the non-abelian gauge theory QCD, and its emergent properties including its equilibrium and non-equilibrium thermodynamics under extreme conditions of temperature and density. Their current programme uses the ALICE detector at the LHC to study QCD matter at high temperature and low density, produced using heavy ion collisions. The EIC will give the opportunity to probe QCD matter in the complementary regime of low temperature and high density, using electron-ion collisions. The groups have a particular interest in using inclusive and exclusive jets (both heavy and light flavour tagged jets, jet substructure) to probe the QCD matter produced. They have considerable experience in both physics performance and detector Monte-Carlo studies. This will allow them to make significant contributions to the physics case and the design of the EIC detector at an early stage.

Detector: The groups will bring their experience in the design and construction of Si vertexing and tracking detectors to the EIC. They have particularly strong experience in CMOS technology R&D and in building large scale vertexing and tracking detectors for high energy particle and nuclear physics experiments using this technology. As an example, Daresbury and Liverpool have recently played a leading role in the design, construction and installation of the Inner Tracking System Upgrade for the ALICE experiment at CERN, the largest CMOS MAPS detector ever built. Lancaster has contributed to the ATLAS inner tracker R&D on CMOS sensors. They work closely in this activity with other groups within STFC such as the CMOS Design Group at Rutherford and the Detector Systems Group at Daresbury, including facilities such as the Liverpool Semiconductor Detector Centre.

Glasgow

Daria Sokhan, Derek Glazier, David Ireland, Ralf Kaiser, Ken Livingston, Rachel Montgomery, Bjoern Seitz (Nuclear Hadron Physics), Richard Bates, Lars Eklund, Dima Maneuski (Particle Physics Experiment), Chris Bouchard (Particle Physics Theory).

The NHP and PPT group's interest lies deep in the physics which the EIC will address. The kinematics accessible at the EIC, opening the quark-gluon sector, will complement the exploration of the valence region studied at Jefferson Lab and presents opportunities to study nucleons and nuclei in completely new ways. The timing is also ideal, as the start of operations at the EIC are expected to coincide with the completion of much of the current Jefferson Lab programme. Glasgow is therefore strongly involved in the development of the EIC physics programme, in particular in the study of hadron structure. Daria Sokhan is co-convener of the Exclusive Reactions working group in the Yellow Report effort. These are processes that place some of the most demanding requirements on the interaction region design, but which are crucial for the 3D study of hadron structure and in the search for the gluon saturation footprint. She is also co-PI of the 325k€ "Challenges for Next-generation DIS Facilities" work package in the EU Horizon-2020 STRONG-2020 grant. The work package brings together several EU institutions on a project of detector R&D for the EIC, with Glasgow's role focused on simulation studies.

In detector development, Glasgow has expertise in electron tagging, fast timing, high-resolution sensors and Cherenkov detectors, which it is keen to apply for the EIC. The NHP group has a long and excellent leadership track-record in designing and building electron tagging systems — they have instrumented the Mainz Microtron and two experimental halls in Jefferson Lab. The PPE group leads the development of the Medipix sensors, which are applied in medical imaging as well as, in the modified Timepix form, at the LHC, and together with the NHP group they have several funded projects (supported by the Cross-Community Group at Daresbury) using them in new projects. They are now exploring the Timepix-based sensors as a solution for high-resolution far-forward ion tracking and a tagger for low-deflection electrons in the EIC, both of which are vital for access to crucial regions of phase space in exclusive processes. Investigations of the possibility to use solid state Cherenkov counters for fast timing in Roman Pots (which detect the minimum-deflection protons) have also been initiated by the NHP group. PPE have ongoing projects in R&D on fast-timing silicon LGAD sensors and are exploring their application for EIC detectors.

In addition, Glasgow is involved in the organisational structure of the EIC Users Group (EIC-UG), with Daria Sokhan being part of the committee to re-write the EIC-UG charter as the project enters a new phase in its realisation. Glasgow organised the first UK workshop on EIC interest in 2016: https://indico.cern.ch/event/565879/

RAL CSGD and PPD

Iain Sedgwick, Nicola Guerrini (CSDG), Fergus Wilson (Particle Physics Detectors).

The CMOS sensor group consists of six ASIC designers and one test engineer and has been focused on the design of CMOS Image Sensors/MAPS for science applications in a wide range of fields (particle physics, electron microscopy, X-ray, visible, high-speed and others). They have a full suite of design tools, excellent foundry relationships and the advantage of other on-site capabilities at RAL (https://www.technologysi.stfc.ac.uk/Pages/CMOS-Sensors-Design.aspx). The RAL CSDG was an earlier pioneer of MAPS technology and participated with RAL PPD in the initial

development of the ALICE ITS sensor. The design group, with RAL PPD, has continued to develop a series of prototype MAPS sensors that address the needs of HL-LHC and future circular or linear colliders. RAL CSDG group is already involved in EIC. Together with the University of Birmingham they have worked on a feasibility study into possible MAPS detectors as a part of the eRD18 project funded by the EIC Generic Detector R&D Committee and are now part with Birmingham and LBNL of the eRD25 project to develop an ITS3 derived EIC SVT detector. They are already involved in the 65 nm design activities and working on the first submission in this technology in collaboration with the ALICE ITS3 project. They are also part of the EIC Yellow Report initiative and have joined the EIC Silicon Consortium.
RAL PPD consists of approximately 80 people. The group was a member of the H1 and ZEUS collaborations at DESY and is currently a member of the ATLAS, CMS, LHCb, DUNE, Hyper-K, T2K, MICE, Lux-Zeplin, DEAP-3600, and AION collaborations, as well as the multi-disciplinary Boulby Underground Laboratory. PPD works closely with the RAL CSDG group and also has its own program of R&D on fast-timing devices, radiation effects on sensors, and HV-CMOS MAPS sensors for the LHCb Mighty Tracker prototype. The group are interested in using this expertise for the design and testing of MAPS sensors for the EIC.

York

Dan Watts, Michael Bashkanov, Stuart Fegan, Nicholas Zachariou.

The Hadron group at York has a strong interest in expanding the science possibilities at the EIC, developing associated infrastructure and leading new experimental programmes. The group has leading expertise in spin polarimetry methods, including development of the first large acceptance nucleon spin polarimeter (commissioned at the Mainz Microtron and currently underway at Jefferson Lab). The delivery of such polarimetry observables for reaction products at the EIC would significantly enhance the achievable science. This experience in polarimetry also enables the group to provide a UK lead in the development programme for precision spin polarisation determination for the proton and light ions accelerated in the EIC, needed at the sub percent level for the central science aims. In detector construction, the group led the UK infrastructure contribution to CLAS12 at Jefferson Lab, the forward tagger. Such expertise in construction and simulations for detectors in high-rate and high-field environments has direct relevance to the potential developments of forward detectors at the EIC. As a horizon-scanning initiative, the York group are starting collaboration with the Centre for Hyperpolarisation at York, with an aim to investigate completely new technologies for polarised sources and also potentially large volume polarised nucleon/ion scattering media. Such initiatives have the potential to address key challenges in the measurement of spin polarisation of high energy EIC reaction products.