Institution: Coventry University
Unit of Assessment: UoA10 Mathematical Sciences
1. Unit context and structure, research and impact strategy

Context and structure of research

Mathematical sciences at Coventry are grounded on a tradition of excellence in the fields of statistical physics (SP) and fluid mechanics (FM) represented by two well-established groups. Though distinct in remit, they are united by a common ethos well-described as bottom-up, open, silo-breaking, and outward-looking, be it to other disciplines, other methods, other institutions, or cultures beyond academia and management. The highly multinational composition of our staff and the Unit's ability to recruit scientific excellence forms the basis of its strength, solidly rooted in its international network of academic and non-academic partners within and outside the world of applied mathematics.

From 2014, to bolster the Unit's natural aspiration toward interdisciplinarity, the University created the Centre for Fluid and Complex Systems (FCS), with Potherat as Executive Director and Kenna as Deputy Director. FCS gathers SP and FM groups with two sister groups covering engineering applications of fluid mechanics and flow measurement. The Centre's remit is to grow fundamental and impactful research in these fields into a broader mission of addressing natural, industrial and societal problems with the mathematical rigour imbued into the Centre by the SP and FM groups. Recognising mathematics as one its pockets of excellence, the University invested strategically in three areas to support the Unit's trajectory of growth: 1) recruitment of staff at the dawn of promising careers; 2) Joint post-graduate (PGR) studentships with partners within our network; 3) strategic investment in facilities and equipment to bolster the Unit's link to experimental and computational research. The success of this strategy is evidenced by the main metrics rise since REF2014: grant funding increased by 79%, industrial funding by 725% and PhD completions by 325%. Headcount grew from 13 staff (of which 9 (9 FTE) were submitted to REF2014 to 17 (17 FTE), all submitted to REF2021 and forming about half of FCS (30.6 FTE).

Research objectives

Research plans in 2014

The plans for this successful growth were set out in objectives announced in REF2014:

1. Establish an International Doctoral Training College (IDTC) in statistical physics and fluid dynamics with University investment.

EVIDENCE: Drawing on the Unit's extensive international network, we established a doctoral cohort based on the co-tutelle model that awards a jointly-funded Ph from two partner institutions. This includes the L4 International Doctoral College for the Statistical Physics of Complex Systems, a partnership between the Universities of Leipzig (Germany), Lorraine (France), the Institute of Condensed Matter Physics (Ukraine) and FCS, as well as co-tutelles with Warwick and Grenoble-Alpes (UGA).

2. The statistical physics group will continue to expand into cross-disciplinary research in sociology, humanities, urban development and public transport, and scientific computing, whilst maintaining its research into classical and quantum critical phenomena.

EVIDENCE: Since REF2014 the group has produced eight publications in scientometrics, impacted REF itself ('Counting what Counts Confidently' (CCC) ICS), 13 papers in comparative mythology, including one Proceedings of the National Academy of Sciences of the United States of America (PNAS) highlighted by editors as "exemplar" for digital humanities and reached the 'real world' through industry (Tata Steel). Its firm grounding in statistical physics is evidenced by the outputs submitted to REF2021, and 10 PhD completions.

3. Research in fluid dynamics will be built on current strengths, international partnerships and new appointments to broaden the group's expertise.

EVIDENCE: Six academic appointments supported the former group's strategic evolution into a fluid mechanics group with a wider remit drawing on its traditional strengths in MHD. Stability, turbulence, non-Newtonian, rotating, geophysical flows and convection beyond MHD now cover 64% of FM's submitted outputs and 57% of its PhD completions.

4. The MHD group will focus on theoretical studies of instabilities, transition and turbulence in liquid metals, Alfven waves and convection as a platform to further develop applications in the fields of MHD, geophysics, material processing and studies of MHD instabilities in aluminium reduction cells.

EVIDENCE: FM worked extensively on stability transition and turbulence (aligned to most FM outputs and completions) through in-house expertise, and existing and new collaborations. FM expanded into planetary and astrophysical fluid dynamics with appointments (Kim, Horn, Park Vantieghem) and external funding from EPSRC, Leverhulme and Royal Astronomical Society (RAS) worth £625k. Industry-funded research on aluminium grew over 100-fold with new industrial partners alongside FCS staff in UoA12 (see 'interdisciplinarity').

Research objectives during the period

Thematic developments since 2014 strengthened the then MHD group (now FM) and the SP group (now including complexity). This interwoven growth paid careful heed to our own pioneering research in academic critical mass and group-size (CCC ICS). Growth targeted a limited but overlapping range of themes to maximise both the excellence and the impact that the Unit overall delivers.

Research in SP is centred around investigations into the fundamentals and applications of phase transitions and critical phenomena. Methodologies range from pure and applied mathematical to computational. Curiosity-driven interdisciplinary interests extend to cosmology, biology, medicine, sociology, scientometrics and humanities. This diversity is tied together through phase-transition-like concepts of emergent phenomena uniting activities in complex systems, complexity, and data science. Applying the rigour and concepts of fundamental physics in imaginative ways has led to solid impact on industry, policy and through public engagement. Funding comes from H2020 grants (with L4), Leverhulme, Deutsche Forschungsgemeinschaft (DFG) and Royal Society.

SP1: Critical phenomena have been at the heart of the SP group since its foundation in 2006. Shared goals of understanding universal concepts in pure and random-field spin models tie together the entire group, as illustrated by Kenna and Fytas' work on pure and impure systems

motivated by fundamental questions and experiments. Multiple visits funded by FP7 IRSES and Izmailian's Marie Curie International Incoming (MCII) Fellowship illustrate diversity and depth of collaboration.

SP2: Computational methodologies support all the group's activities. Weigel's strength in massive computer simulations and new numerical techniques combines with Yavorskyi's work on Monte Carlo, molecular dynamics, combinatorial and heuristic optimisation. Both extensively harness the power of graphics processing units. Del Genio and Kim's appointments expanded our computational strength beyond *SP1*.

SP3: The group's interests in *polymers and bio-physics* (von Ferber, Foster, Platini) firmly links with *SP1* and *SP2*. Del Genio and Kim extend the biological theme, bringing further cohesion between the group and the wider community.

SP4: Interdisciplinary sociophysics and humanities transcend the foundations, methodologies and applications of *SP1-3*. Self-reflective analyses of RAE2008 and REF2014 developed into quantification of the notion of critical mass in research. This ultimately helped halt the usage of metrics in REF2021, establishing a scientometrics research strand in SP, with collaborations and lay partners (Ofqual, CAMRA: CCC ICS). Further exploratory endeavours, supported by H2020 and European Science Foundation funding, led to pioneering work in the humanities ('Maths Meet Myths' (MMM) ICS) and industrial partnerships (Tata Steel). The group's specialism in analysing medieval texts was enriched by del Genio, linking it to activity against infectious agents (thus to *SP2* and SP3), and Kim's interdisciplinary work on self-organisation and non-equilibrium processes.

Research in FM: The group links mathematical fluid mechanics to extensive, rigorous experiments covered by close-knit academic and industrial partnerships. These include [text removed for publication] and world-leading experimental and computational facilities (CNRS-Laboratoire National des Champs Magnetiques Intenses Grenoble (LNCMI), Helmholz Zentrum Dresden-Rosendorf (HZDR), UCLA Spinlab, Warwick, Ecole Polytechnique's LadhyX, Karlsruhe Institute of Technology (KIT), Harvard-Smithsonian Astrophysics Observatory, (HSAO, USA), where we either conduct experiments or provide theoretical contributions. Four themes, grown out of the former MHD group, cover this extended remit:

FM1: Fundamental and applied MHD continues the group's traditional leadership in liquid metal MHD, specifically on MHD instabilities (e.g. in liquid metal batteries, by Priede), fundamentals and simulations of MHD turbulence (Potherat) are supported by Leverhulme, the Royal Society, academic partners (LNCMI, HZDR, KIT) and industry [text removed for publication].

FM2: Instabilities and transition to turbulence illustrates how the group's traditional expertise has developed into new but connected subjects. Traditional areas of strength (pipes and MHD duct flows by Pringle, Priede and Potherat) expanded with new collaborations (Monash, and Pringle with Teaca). EPSRC support and appointments widened the theme to non-Newtonian, rotating flows (Griffiths), the impactful field of high-speed aerodynamics, astrophysical flows (Park) and convection (Horn, Kumar, [text removed for publication]).

FM3: Turbulence in fluids and plasmas is rooted in the group's traditional expertise in MHD and expanded through new talents and international collaborations too (Warwick, UCLA, HZDR). Kim

combined techniques from SP and FM to model fusion plasmas while Horn, Kumar, Potherat, with UCLA and Warwick, ignited research on rotating and convective turbulence connected to *FM4*.

FM4: Planetary and astrophysical flows was founded by Potherat in 2013 through collaboration (Sreenivasan - IIS Bengalore, Debray – LNCMI) and a Leverhulme grant. This theme has blossomed with extensive funding and appointments. Leverhulme, Royal Society and EPSRC funded Potherat's "Little Earth Experiment" (LEE) at LNCMI, modelling rotating magnetoconvection in the polar region of the earth's liquid core, while Horn's pioneering work on centrifugal buoyancy directly concerns rotating convection experiments and the generation of tornadoes. Park and Kim's work on stellar interiors and spin-down supported by Leverhulme, together with Teaca's work funded by EPSRC on the solar wind, expanded this theme to astrophysical flows.

Future research plans

Having achieved a solid, coherent expansion in remit, the next phase of the Unit's evolution will be one of consolidation, growing our now well-established themes and harvesting the full potential of our internal and external collaborations, including those acquired through appointments, within the tight collaborative structure so carefully nurtured.

Fundamental research will remain at the core of the SP group. Wald's recent appointment (from Lorraine) will boost Platini's activities in non-equilibrium and open quantum systems. This strand, along with SP1 fundamentals and network science (del Genio, Kim), will seek funding from UKRI and interdisciplinary funders, while computational methods will tighten the links between them. These funding routes will also amplify SP's lead in taking digital humanities beyond documentation or data mining, further imbuing it with concepts from statistical physics, with an ambition to leave a lasting legacy for the benefit of the full academic community.

Similarly, the Unit has considerably expanded its experimental footprint over the past REF cycle, having created and built our own suite of world-unique experimental facilities located in its new Coventry laboratory (particulate and shear flows), at Warwick (rotating flows) and LNCMI (rotating-magneto-convection and MHD turbulence). Together with our partnerships, they underpin the Unit's strategy to tackle natural and industrial challenges with a tightly joint mathematical and experimental approach.

Research in FM will develop along the four established themes, bolstered by our increasing grant success, including our new STFC platform grant on solar studies, Potherat's Leverhulme grant on planetary cores, Griffith's EPSRC grant on innovative drag reduction. Applying high-order spectral elements methods, acquired through collaboration with Monash and by appointing Kumar, to flow simulation and control will expand our work [text removed for publication] to a wider range of industrial flows with [text removed for publication], and further nascent partnerships. Grants will further fuel the thematic expansion on planetary and astrophysical flows, with added impulse from our experimental pool, and recently appointed staff (Horn, Kim, Park). Industrial and UKRI funding will grow the transdisciplinary pole on aluminium that links FM with engineering within FCS.

Impact strategy

The Unit is proud that its impact strategy is based on curiosity-driven research, on nurturing creativity from students to senior staff alike to build sustainable sources of impact. A good example of support for this curiosity driven approach is evidenced by us funding two interns to analyse social networks in "Game of Thrones" television program. The work produced impact-forming part

of the MMM ICS and a PNAS paper. This inclusive approach sourced much of our impact in this REF cycle. It generated engagements with policy makers, direct impact on REF2021 and international counterparts (CCC ICS). We built solid partnerships with Tata Steel, Wolfram Research and others (MMM ICS), and also achieved extensive public engagement. The bottom-up approach is reflected in the Centre's tight integration of the mathematics and engineering groups. By speaking in a single voice, applied and fundamental expertise display clear pathways from mathematical methods to concrete applications of a mathematically rigorous approach to the challenges of external stakeholders.

This challenge led agenda is effectively implemented by favouring long-term partnerships with stakeholders built around their strategic scientific, technological and societal challenges. Tackling these challenges raises long-term questions of fundamental science, whose answers generate scientific output of the highest originality, significance and rigour, with guaranteed impact. [text removed for publication], and the transition to turbulence in multiphase pipe flows (National Engineering Laboratory, NEL). These supported three post-docs, one PhD student and two outputs submitted to REF2021.

Likewise, media exposure is gained through disciplines that better engage with the public (e.g. humanities), and through trusted relationships with quality media. MMM is a prime example of simultaneous impact of mathematics on cultural preservation and holding public authorities to account.

Sustainability of the impact strategy is supported in two ways: Upstream, FCS' industry income funds a permanent research associate to conduct short term experimental work aiming at (1) securing long-term support from new and existing partners (including the collaboration with [text removed for publication]), and (2) effectively responding to short-turnaround enquiries that may hold longer term potential. Downstream, the University funded a dedicated impact officer to support the Unit's two ICS in 2019-2020, facilitating contact with Ofqual and CAMRA and feeding impact.

Future impact strategy

Our future impact strategy is founded on strong relationships with industrial partners and our willingness to engage with colleagues in other disciplines – particularly social sciences and humanities. For example, the trusted partnership with Tata Steel, unique in statistical physics, sees a PhD student interweaving our analysis of medieval text with natural language processing (NLP) industrial needs. We aim to replicate this approach in offering a unique mathematical bridge between humanities and industry.

The solid partnerships with industrial stakeholders established during this REF cycle pave the way for a sustained and broader generation of impact. E.g., our industry-funded research on stability and control of metallurgical processes is now growing into an equally strong and sustainable source of impact.

The challenge now is to broaden and optimise such impact with professional assistance while maintaining academic rigour. First, we will embed impact more endemically in research pursuits, especially at the earliest stage of our research projects. Second, as our pool of strategic non-academic partners grows and consolidates, we need commensurate support mechanisms for generating and collecting impact. We aim to coordinate both through the appointment of a new

associate professor in complex systems, specifically to extend the implementation of the impact agenda, supporting other academics and liaising with the University's professional services.

Interdisciplinary research

FCS sits against the backdrop of Coventry's strong engineering and applied-sciences history. Interdisciplinarity is built into its mission of applying mathematics to real-life problems. This drove the Unit's expansion in this REF cycle, as demonstrated above. The engineering connection bolstered the Unit's research, as the volume of industrial income testifies (35% of external income). Explicit examples include the theme of aluminium production and manufacturing involving Rio Tinto, CastAlum and [text removed for publication] with Abdelfatah, Jewkes, Pedcenko (UoA12) and Potherat, Priede, Kumar (UoA10). FM's expansion into planetary and astrophysical flows combines experiments and theory. These experiments are notoriously difficult to conduct, and the Unit is the only one in the UK, and one of a handful in the world, that combines applied mathematics and experimental physics to tackle liquid planetary cores. This specificity is supported by Leverhulme, EPSRC, reinforced by Kim, Horn and Park's appointments (*FM4*) and by Low and von Ferber's research in cosmology and astrophysics.

"Fluid" and "Complex" in the Centre's title respectively reflect the flexible nature of these applications, grounded on a solid fluid mechanics base, and the interdisciplinarity with other areas based on statistical physics. A recent review (https://doi.org/10.1145/3344548) identified FCS research in traditional epic narratives as one of four focal points in the digital humanities of character networks. Our recent PNAS (https://doi.org/10.1073/pnas.2006465117) takes quantitative narratology beyond even these, addressing questions of cognitive limits and Russian formalist literary theories (Kenna, Platini). The appointment of del Genio now takes common interests in medieval texts to computational biophysics and algorithms with impact on plant fertility (https://doi.org/10.1101/2020.10.03.324764). Mathematics' connection to the biosphere has grown from Platini's interdisciplinary work on gene expression and Kim's impactful modelling of metastatic tumours and cardiac functions. Thus, interdisciplinarity side has doubled in size over this REF cycle and continues to grow.

Open research and research integrity

All our outputs are openly available on the arXiv, the University's repository and personal websites. Industrial partnerships contribute to the culture of openness too as all contracts include provision for the publication of fundamentals researched in the pursuit of concrete questions, whilst protecting the partner's intellectual property of their industrial process (two outputs submitted). The primacy of research integrity is at the core of our training programme mandating all staff and students attend and pass these courses. It is also one of our multidisciplinary research interests. Our pioneering mathematical methods that expose cultural misappropriation in a wider context (Kenna, MMM impact case study) have been taken up by other researchers in their work on research ethics (e.g., doi :10.1088/1742-6596/955/1/012034). This immersive approach encourages quick diffusion of research integrity amongst staff through our internal seminars and our naturally vibrant environment.

2. People

Staffing strategy and development and recruitment policy

Strategic, measured growth has been driven continuously since 2006 by hiring 20 first-class early to mid-career researchers and nurturing their career paths. The success of this strategy over the cycle is evidenced by three EPSRC ECR grants (Pringle, Teaca, Griffiths awarded 12/2020: 100% success rate, five out of six within FCS), one Royal Society Newton Fellowship (Kumar, M), one DFG Postdoctoral Fellowship (Horn), one EU MCII Fellowship (Izmailian), one Royal Society Wolson Research Merit Award (Potherat, appointed reader in 2007), and a professorship promotion (Weigel, appointed senior lecturer in 2011). The Unit also attracts successful senior academics with Kim appointed from Sheffield to reinforce interdisciplinarity.

New staff are aligned and integrated alongside existing staff to accelerate the Unit's strategic forays into new fields connected to its pillars of excellence. University investment funded a well-managed expansion from a headcount of 13 in 2014 (nine submitted to REF2014) to 17 in 2020 with eight permanent FT appointments: one professor (Kim, 2019), six assistant professors (Del Genio 2018, Griffiths 2018, Horn 2019, Kumar 2020, Vantieghem 2016) and one lecturer (Dallaston 2017). Two left (Dallaston 2019, Vantieghem 2018) and two retired (Molokov 2017, von Ferber 2019). The recruitment strategy provided the Unit with a well-balanced range of seniority, currently five professors, two associate professors, nine assistant professors and one lecturer. Future recruitment strategy will maintain organic growth. Synergetic recruitment naturally reinforces international collaborations and targeted recruitment bolsters links with non-academic impact-enabling partners.

Kumar's appointment is a representative example where the convergence of industrial partnership and high-profile international collaboration generated new expertise to open a new branch of fundamental and impactful research. [text removed for publication].

Our increased income has supported 17.3 post-doc-years (13 individuals, of which Kumar was appointed assistant professor. The relatively low throughput of staff is healthy: newcomers bring energy and FCS' nurturing environment equips staff with skills to obtain attractive positions in other leading universities. These consolidate our collaborative research network, as evidenced by 21% of our submitted outputs being co-authored with former staff members or PhD students. This also illustrates the enduring association with FCS that its positive and collegiate environment nurtures.

Workload allocation and support for ECRs

The Unit believes in the model of research enriched teaching. All staff share their time between FCS for research, and the School of Computing, Mathematics and Electronics for teaching. To bolster research, associate and full professors are granted research time allocations of between 60% and 80%, in exchange for their higher contribution to all aspects of the Centre (external funding, PGR supervision, international agenda, centre management and supporting ECRs).

ECRs (lecturers and assistant professors) benefit from support to accelerate their research career development. They start with 40% of their time protected for research and reduced teaching in their first year of appointment. Strong performances are rewarded with increased research time to 60%. ECRs are mentored by senior members of the Centre and encouraged to apply for external and internal ECR grant schemes (e.g. Griffiths and Horn obtained PhD studentships through the University's Trailblazer scheme for ECRs). An informal, collegiate approach to grant-writing, a

rigorous peer-review process and early involvement in projects by senior staff ensure that ECRs take maximum advantage of the Centre's experience in attracting funding. EPSRC new investigator grants are specifically targeted, with a record of three successful, one awaiting outcome, three under development and none rejected, demonstrating the effectiveness of this approach. ECRs without a teaching qualification are supported to take the PGCert qualification within the first two years of their appointment and the University sponsors fellowships of the Higher Education Academy (HEA) for all.

The Unit chooses a generous continued protection of research time over sabbatical leave but still works with the School to free-up up to a semester to support individual initiatives, whether to generate impact, establish new partnerships or pursue strategic funding avenues. Performance is measured humanely, over periods over several years, and taking individual boundary conditions into account. This gives staff the freedom to choose the form of their research contribution and to engage in risky, exploratory research. Impact generation (measured through extra-academic collaboration, contribution to case studies) carries the same weight as more traditional grant or publication success.

An open promotion scheme rewards research performance linked to biannual reviews. A Readership and Professorial Conferment Committee considers senior promotions based on external peer review. Promotion is based solely on meeting criteria. Weigel was promoted to professor in 2020 and Griffiths seconded to associate head of school (grade 9) in 2019. These promotions illustrate the Unit's supportive environment where the first class ECR and MCRs prioritised by the recruitment strategy build successful careers in the long term.

Research students

The growth of the postgraduate cohort has been key to the Unit's expansion (+ 325% from REF2014) and lies at the core of its international agenda via the co-tutelle model. Quality is evidenced by the 100% completions with submission within four years, recorded over this cycle.

Training, support, monitoring, supervision and integration

PGRs are fully integrated into every aspect of the Centre's life: they are co-located with staff, represented in the Centre's governance and are encouraged to start bidding for support (three grants from RAS covering travel, equipment were won by PGRs). PGRs run biweekly seminars attended by staff and students, providing an opportunity to receive feedback and introducing them to the Centre's collegial and multidisciplinary ethos from the outset.

Co-tutelles guarantee that students spend at least 30% of their time at partner institutions, receiving beneficial exposure to different research cultures and methods, be it from other universities, other countries or industry. Sixteen PGRs from Lorraine, Monash, the Ukrainian Academy of Sciences and UCLA visited Coventry, funded by FCS's visiting researcher scheme and Royal Society International Exchange Grants. Conversely, practically all of the Unit's students visited partner universities.

PGRs are allocated their own desks and supported daily by a Research Degree Lead embedded in the Centre. They elect representatives supporting their integration, are invited in the University's PGR forum and benefit from Faculty support of £1100/studentship. FCS supports £700/year/student for presentations at international conferences and enhanced mentoring in their final 18 months and grants closely monitored extensions to secure submission within four years.

Recruitment and cohort composition

Co-tutelles drove the growth of the PGR cohort, awarding six dual-degrees PhD with Warwick (1), Grenoble-Alpes (1), and the L4 international doctoral college formed of CU with Lorraine (2), L'viv (1), Leipzig (1). These contributed to the total of 17 completions (0.14/FTE/annum), a 325% (resp. 55 %) increase from REF 2014. The co-tutelle model which we pioneered nationally in 2010 was since adopted as Coventry's main PhD funding mechanism and is now allocated yearly on a competitive basis. In the 2018, 2019 and 2020 calls, FCS won a total of 53 such grants forming the baseline of the mathematics cohort until 2025-26.

Further increase in completion numbers arose out of the Unit's growing ability to attract internal (3 completions) and external funding, from the Leverhulme Trust (2), overseas governments (2), industry (3). Funding offered by the University matches EPSRC in level and duration. In 2020, FCS was awarded STFC PGR accreditation. Together with a transfer in of one EPSRC funded student from Sheffield - this puts the Unit in a good position to attract UKRI-funded studentships in the next REF cycle.

The quality of the Unit's international collaborations fed into recruitment and co-supervision to drive the quality of students exceptionally high (evidenced by Kelig Aujogue's 2016 RAS Patricia Tomkins Prize and the 19% of papers submitted to this exercise co-authored with a PGR student supervised by the Unit's staff). Examples of achievements through new collaborations with co-tutelles include Potherat with Thomas (Warwick) supporting two co-tutelle PhD students (one completed, one on-going). They combined ideas from MHD turbulence and experimental facilities in Warwick to elucidate anisotropy mechanism in rotating turbulence in two *J. Fluid Mech.* papers (one submitted).

PGR recruitment benefits from the same care regarding EDI as staff recruitment. Additionally, reaching out to students individually, as during the final year undergraduate projects, offers an effective mechanism for inclusion at PGR recruitment, especially so due to Coventry's leadership in EDI with undergraduates. Three students (one on-going) recruited in this way enriched the cohort, alongside recruitment through our network and other routes.

Equality, diversity and engagement

All staff benefit from the University's EDI training package. Recruitment panels are balanced for all diversities. Advertising processes are checked for gender neutrality and maximum inclusion. Our international network favours EDI in exposing its naturally diverse population to the Unit's research. As a result, the Unit boasts a very high multinational diversity, with 13 nationalities (four UK, nine EU, three Asia, one Ukraine) including 23% BAME staff, well above sector average (9%).
In terms of gender diversity, the Unit started the cycle no better than the national average for STEM subjects. However, given our research has triggered national protests at misogynist iconography (MMM), gender parity is an issue FCS is acutely aware of. We now place gender balance to the fore in recruitment drives: two of the last three appointments were female. We hope to help balance genders in mathematical sciences, humanities and social sciences through bringing together disciplines traditionally perceived to lean towards a specific gender.
Consideration for protected characteristics naturally blends with our flexible and collegial approach to management, in line with our ethos of openness and desire to include all. Support is provided as appropriate for flexible hours, remote working, leave, managing health conditions, for all aspects of academic life, from specific support for grant applications to provisions for leadership roles.

The Unit engages with outreach activities, with students and the general population, through research-inspired teaching and events: staff supervise undergraduate research projects and showcase our research at University open days, science fairs and events such as “Pint of Science” and Christmas lectures. The Unit even took advantage of his interdisciplinary work on Myths and Networks to raise mathematics awareness amongst primary school children (MMM ICS). These initiatives take mathematics to the masses in such a way to welcome any gender or ethnicity to our community.

3. Income, infrastructure and facilities

Research funding and strategies for generating income

Our income strategy draws on the dual fundamental and applied nature of the Unit’s research. Sustainable income is secured through long-term partnerships with industry, while higher-risk curiosity-driven research attracts funding from prestigious charities (e.g. Royal Society and Leverhulme Trust). The strategies, favouring the appointment of first class ECRs and blending engineering and mathematics within FCS, helped us open a stream of income from UKRI, starting with NIA in this REF cycle. We now aim to build on this as both our recruits and the synergy in FCS mature within the next cycle.

Testifying to the success of this strategy, income reflects the Unit’s evolution since 2014. Total income more than doubled from £689k to £1.7M (+147%) whilst staff numbers only increased by 31%. UKRI and charity income grew from £230k to £627k (+173%) and other non-industrial sources to £489k (+26%). This was achieved through staff recruitment (two EPSRC NIA within period, Pringle, Teaca, and now Griffiths in 12/2020) and high-profile E/MCRs staff recruited since 2006 who, in naturally growing their research profile, attracted five grants from the Leverhulme Trust to work on the growing topics of planetary and astrophysical flows and socio-physics (Kenna, Kim, Potherat). At the same time, the partnerships with non-academic stakeholders increased our industrial income from £72k to £591k (+724%). For example, significant and impactful fundamental research funded by our industry partners involves the question of transition to turbulence for multiphase flows pipelines (Potherat & Pringle with NEL, £80k), [text removed for publication]. Consultancy serves as a steppingstone for longer collaborations [text removed for publication]. This funding produced 30% of the submitted journal papers (around four times as many in total), and the research it supported will largely contribute to the next REF period. Research supported by the Leverhulme Trust hit headlines with a PNAS paper on ‘Game of Thrones’ as a spin-off of Kenna’s work (MMM ICS). Kelig Aujogue RAS thesis prize was awarded for the first experimental model of magnetoconvection in the earth core supported by Potherat’s Leverhulme grant.

The Unit has been able to expand its remit towards complexity, planetary and astrophysical flows through grant success.. Most of this latter theme was supported by two grants from the Leverhulme Trust, funding Potherat’s “LEE”, and EPSRC funding Teaca to establish a new paradigm in plasma heating mechanisms of the solar wind, one of the outstanding problems in solar physics. Kim’s work on self-organisation supported by a Leverhulme Fellowship not only covers astrophysics but further links up with SP and Priede’s work on astrophysically relevant instabilities will be supported by our first STFC platform grant in the next cycle.

Complexity and the two ICS it generated grew out of Kenna’s Leverhulme grant on the application of networks to the analysis of literary narratives and from the interaction with Lviv’, and ICMP, amongst others nurtured by Von Ferber and Weigel’s two IRSES (H2020) grants.

The Unit's traditional strengths were accelerated by grant income too supporting, for example, Potherat's work on MHD turbulence (Leverhulme and Royal Society Grants), Pringle's work on pipe flows (EPSRC) and Kenna and Izmailian's joint work on exact models in statistical physics (MCII Fellowship).

Organisational, operational infrastructure and facilities supporting research and impact

The Unit's office space is designed by its academics themselves to optimally deliver its needs in terms of individual offices, collaborative space and co-location of post-graduate students. FCS also has dedicated laboratory space where mathematics staff developed unique experimental facilities with cutting edge-visualisation techniques based on optical and electromagnetic methods, This was established in the REF period at a cost of £900k. Our 12m transparent pipe is the only setup capable of simultaneously mapping fluid and particles in transitional pipe flows (https://aip.scitation.org/doi/10.1063/1.5129062) while our Couette flow rig [text removed for publication] is the only experimental realisation of the classical plane MHD Couette flow and can be operated in Coventry or with the LNCMI's magnets in Grenoble. [text removed for publication].

The laboratory is staffed with two technical staff, one being 100% dedicated to UoA10 fluids experiments. Both hold expertise in experimental techniques with liquid metals and electrolytes that is unique in the UK and attracted both industry funding and fundamental research grants ([text removed for publication], NEL, Rio-Tinto, Leverhulme and Royal Society). They also manage multi-site projects with e.g. LNCMI and Warwick. The value of their contribution is reflected in the technical staff's shared authorship of our technical publications (four papers in *Exp. Fluids and Rev. Sci. Instrumm*).

The Unit is the main user of the University's HPC facilities. Established in 2016 and upgraded in 2020 with a total university investment of £740k, the system boasts 4032 cores, 12 TB RAM with over 100TB storage, with plans for regular upgrades. It supports most of the Unit's computational work and is a key asset in attracting funding and project delivery. It is complemented by 7 workstations and 2 data servers for numerical and experimental data.

In 2020, the University invested £930k to equip FCS with dedicated workstations and data storage (£74k), and equipment to expand the Unit's specialism in bespoke flow visualisation techniques to 3D visualisation (£327k, shared with engineering research). The sustainability of investment is demonstrated by the £280k committed in 2021 for a bespoke magnet to conduct joint experiments with HZDR. Along with rigs at LNCMI and Warwick these facilities and staff are one of the Unit's key assets to attract and support PGRs, grant and industry funding and deliver the Unit's approach blending mathematics, computations and rigorous experiments. Having developed into a key vector of growth during this cycle, it is already producing material for the next.

The Unit is supported by FCS' dedicated Operations Manager who ensures efficient cooperation with University-wide professional services and four staff to support bidding, project management, delivery and administration. These, along with the Centre Director, liaise directly with the Doctoral School for PGR education and oversee all aspects of FCS' governance.

Collaboration

Being the UK's sole heir to Cambridge and Warwick's pioneering research in liquid metal MHD from the 1960s, the Unit maintains a lead-role in this field, through partnerships with HZDR, TU-

Ilmenau and KIT. Through partnership with LNCMI, the only facility in the world to deliver high magnetic fields (>10 T) in sufficient volumes to conduct fluid mechanics experiments, the Unit holds a world-leading position in experimental MHD turbulence and in the technique of optical visualisation of MHD flows it pioneered. Potherat runs three facilities there: the MHD Couette flow rig, LEE, and the modular "FLOWCUBE", to study turbulence and waves in liquid metals (funding Royal Society, CNRS/UGA, Coventry). The partnership generated eight papers in e.g., *J. Fluid Mech and PRL*, supported two co-tutelle PhD (one in progress), five post-docs and attracted £425k in grant and industry funding. Another partnership with Warwick on rotating flows used Thomas' two specialist rotating tables, to produced two papers in *J. Fluid Mech*, supported two co-tutelle PhD thus driving the growth the "turbulence and transition" theme.

These partnerships more than double the Unit's experimental footprint and simultaneously deliver on most aspects of the Unit's strategy: the thematic expansion (planets and turbulence), consolidation of core strength (MHD and turbulence), industrial [text removed for publication], international and co-tutelle strategies as well as embedding experiments with mathematics.

Core to the SP is the L4 International Collaboration on Statistical Physics of Complex Systems, officially established in 2016 to formalise 18 years of exceptionally close collaboration. The founding declaration (http://users.complexity-coventry.org/~kenna/L4.pdf) defines its goals as: "(i) Provide critical mass to facilitate the best possible collaborative research by making available a wide range of knowledge and trusted expertise to each member of L4; (ii) Enhance visibility on the world stage and thereby to enhance the impact of our research for the benefit of humankind; (iii) Provide world-leading PhD and graduate-student experience for research students by offering a comprehensive set of taught modules and a stimulating international research environment [..] (iv) Secure external funding for the long-term buoyancy and viability of the collaboration." All of these are achieved and continuing: The Franco-German funding that boosts L4 is matched by funding from Coventry, Lviv, two H2020 IRSES grants and numerous small grants. Additional funding brings in deep relations with Yerevan, Extremadura, and many other groups. On the extra-academic side, forays into complexity with L4 have sparked collaboration with Tata Steel, Wolfram research, Ofqual and others.

Similar symbiosis exists between other co-tutelles and our other collaborations (UGA, Warwick and others discussed in section 2). The mutual benefit of collaborations and income extends beyond L4, with LTHE-CNRS/ENS-Paris, Monash and UGA (three Royal Society grants, Fytas, Potherat).

Significance of benefits-in-kind

Income also benefits from the strength of our international network, through in-kind support drawn through access to facilities, co-tutelle funding, sponsored visits and grants jointly held in partner institutions, in the order of £1M.

The extensive sharing of experimental facilities is best exemplified by the access to LNCMI's magnets through European Magnetic Field Laboratory (EMFL), funded by EPSRC Grant EP/N01085X/1-2 (led by Nottingham, worth £646k in-kind to the Unit, covering magnet costs, travel and subsistence). Additional in-kind support from LNCMI includes technician and workshop time, magnet access outside EMFL (approx. £70k over the cycle). Access to other equipment is not always monetised but enables research feeding into outputs or supports co-tutelle students, as for example Warwick's rotating tables.

Staff also partook in bidding and projects through grants accessible to our partners. These supported the joint work and 10 PhD co-tutelle students, travel expenses. They include two Excellence Grants from UGA (€105k supporting two co-tutelle PhD students and travel), an "Instrumentation aux limites" grant for equipment from CNRS with LNCMI (2014, €24k), and travel and subsistence grants in Armenian State Committee of Science (Kenna with Izamelian, 2 grants totalling €45k), Yerevan Institute of Physics (Kenna with Izmaelian €14k) and a Spanish Government grant supporting two years of a post-doc on disordered media in Extremadura (Kenna with Lorenzo).

4. Collaboration and contribution to the research base, economy and society

Effectiveness of research collaborations, networks and partnerships

The key role played by research collaboration in every aspect of the Unit's life and growth has been highlighted throughout this document, be it in terms of outputs, multidisciplinarity, experimental capabilities, funding attractiveness and delivery, staffing or PGR cohort.
Key to collaborations' effectiveness is that the network is not static, nor does it only rely exclusively on large-scale decade-long collaborations (such as HZDR, LNCMI, and L4). On the contrary, it is continuously expanding through new staff, new connections and through complementary expertise. Examples of such new collaborations having produced joint outputs include INSA-Lyon (Potherat), HZDR (Horn), UCLA's Spinlab (Horn), Ecole Polytechnique (Park) and HSAO (Kim). The co-tutelle network too is fast expanding with five new agreements signed since 2019, now at recruitment stage, and another four in development. A further three formal joint-supervisions exist outside of the co-tutelle network.

New collaborations in turn attract travel grants and in-kind (through co-tutelle funding and invitations) before growing to a larger scale. Amongst many other examples, the combination of the Unit's traditional expertise in stability and MHD (Potherat) with expertise in high order spectral elements methods from Monash (Sheard) gained Royal Society support through the International Exchange scheme. With two co-supervised PhD students they elucidated the fundamentals of transition to turbulence in MHD duct flows in fusion-relevant regimes to reveal that igniting the subcritical turbulence in liquid metals extracting heat from fusion reactors would require promoters. Since 2017, collaborations have been nurtured though FCS' invited researcher scheme that funds incoming researchers to Coventry for a period of up to a several months (eight visitors, totalling 137 days from institutions across our network as diverse as Alikhanyan National Science Laboratory, Yerevan (Armenia), UGA, INSA, ICMP, UCLA). Conversely, our staff regularly receive funded, invited and honorary positions in partner institutions across our network and beyond. Seminar series play an important role in promoting collaborations and impact too, through invitations and discipline mixing within and outside FCS. Weekly specialised seminars target mathematics and engineering while monthly FCS-wide seminar bring both communities together, as do bi-weekly PGR seminars.

Relationships with key research users and beneficiaries

Aside of participations in conferences where connections are naturally formed, two specific vectors foster the inter-academic connections. Firstly, newly appointed staff connect the Unit to their existing network. For example, del Genio and Kim's appointments led to two co-tutellle agreements with Warwick, and Horn jointly supervises a PGR in UCLA with Aurnou, whose interests match those of *FM4* in planetary flows. Secondly, the specific expertise developed by the Unit attracts

new relationships. Examples include Hillner (Sheffield) who sought Kenna's expertise in digital humanities leading to a joint grant from the Leverhulme Trust, and Sheard (Monash) who connected with Potherat to drive a new line of research combining high order spectral elements methods and MHD, leading to five joint journal papers, one joint Royal Society grant, leading to three PhDs.

Besides traditional academic dissemination and networking, the Unit actively reaches out to non-academic beneficiaries through several routes: (A) Active participation in conferences interfacing academic research and industry, such as the Electromagnetic Processing of Materials series (2015), and the Maths Meets Myths workshop chaired by Kenna in 2014; (B) Media and our network carry the Unit's reputation. Our network extends as former staff and PhD students gain strategic posts in Industry; (C) The University's "Enterprise Network" Unit who promotes connections between academia and all external stakeholders; and (D) Sheer curiosity. The numerous partnerships with [text removed for publication], (A), CAMRA (B, D), [text removed for publication], Tata Steel (B,D), NEL (C), Ofqual (C), Wolfram (B), all secured in this period provide evidence of the success of this approach.

Impact

Besides the impact in the two ICS, our funded extra-academic partnerships established since 2014 through routes (A)-(C) sourced an entire new stream of impact to feed into the next cycle. [text removed for publication].

The full extent of MMM and CCC's impact cannot be captured by the ICS. As one of many examples, Kenna's work on scientometrics and academic group size earnt him an invitation as one of seven members of the International Advisory Council to the Strategic Academic Unit at the Higher School of Economics (HSE, Moscow). This impact percolated nationwide, as the *Russian Foundation for Basic Research* funded report *Measuring University Engagement* (http://hdl.handle.net/10995/85208) extensively relies on Kenna's work.

Engagement

Significant engagement accompanies the Unit's interdisciplinary expansion. In reaching out to deep cultural roots, not only did MMM engage with all layers of the Irish population and influence national politics, it also promoted mathematics amongst children through the appeal myths have for them (see MMM). These activities raised Kenna to the rank of public figure, being named three times one of the "trailblazers, creators, groundbreakers and trendsetters" of "The Irish in Britain 2016" by the *Irish Post* (2016-2018) and having two personal wikipedia pages created for him (https://en.wikipedia.org/wiki/Ralph_Kenna).

Contribution to the sustainability of the discipline

The Unit strongly believes that interdisciplinarity holds the key to the sustainability of its core fields and places it at the centre of its strategy, as demonstrated throughout this document. Interdisciplinarity favours inclusion and diversity too, as it generates interest from the wider population and maximises the pool of potential talent to take it forward. In addition to the Unit's strategies and actions (sections 1-2), staff promote interdisciplinarity and open research through associate editor roles in multidisciplinary and open access journals (Advances in Complex Systems, Condensed Matter Physics, Entropy, PLOS one, Royal Society Open Science and the Springer-Nature series "Simulating the Past").

The University directs part of its PGR funding to UNESCO Grand Challenges, and in 2020 to COVID, which it distributes competitively through fully funded PhD studentships. Kim and Potherat secured three of them to work on modelling human heart, non-equilibrium SP at nanoscale and droplets filtration in conduits.

Wider influence

Aside from the deep connections to the community that co-tutelles and other joint supervisions warrant, the Unit influences its core subjects through staff participation in high-level committees, panels and senior roles including Kenna's prestigious advisor role for HSE and Fytas's committee member of the IOP's computational physics group. Reflecting the Unit's leadership in MHD, Potherat is a member of the Selection Committee of the EMFL, a H2020-funded network gathering Europe's four world-class laboratories providing competitive access to large high magnetic fields and chairs HYDROMAG (http://hydromag.eu), an international association promoting communication and exchange between scientists and engineers working on flows in magnetic fields (approx. 300 members). As evidence of influence in the more general UK mathematics community, Potherat and Kim regularly take part in EPSRC mathematics panels.

All members of the Unit regularly review manuscripts for leading journals (e.g. *Phys. Rev. A, E, Fluid, Lett, J. Fluid Mech, Nature, PNAS* etc.), proposals for national and other major funding bodies in the UK (UKRI, Royal Society, Welcome Trust, Leverhulme), Chile, Canada, France, Germany, Israel, Latvia, Romania, USA amongst others, and examine PhDs nationally and internationally in occasions too numerous to be extensively accounted for.

The Unit's prominence in its traditional remit was recognised through invitations for 15 keynote and six plenary lectures (Horn, Kenna, Potherat, Weigel), multiple invited talks and the award of the organisation in Coventry of three editions of well-established conferences series (over 200 participants): the 39th MECCO conference in statistical physics (Kenna, chair and member of MECO international advisory board), 32nd Conference in Computational Physics (2020, postponed to 2021-COVID, Weigel chair) and the 12th PAMIR conference in fundamental and applied MHD (2022, Potherat chair). MECO39 ignited an initiative to publicise the history of statistical physics (https://en.wikipedia.or/wiki/Middle_European_Cooperation_in_Statistical_Physics, https://sites.google.com/site/mecoconferencephysics). The Unit takes numerous initiative to bring scientific communities together through the chairing smaller scale workshops or mini-symposia (<100 participants). In doing so they also drive the action of the wide-reaching learned societies that support them: 11 workshops were chaired in the cycle, including under the umbrella of the London Mathematical Society (del Genio), the British Applied Mathematics Conference (Kim), IUTAM (Potherat with Davoust (UGA)), EuroMech (Potherat) and EPSRC (Kenna, Weigel).

Prizes and research highlights in journals reflect both the esteem in which our staff and their work is held within our network but also at national level: Kenna (2019) received the title of Doctor Honoris Causa from the Academic Council of the ICMP of the National Acad. Sci. of Ukraine. Prizes awarded both traditional strengths but also new research forays as Potherat was awarded a Royal Society Wolfson Merit Award (2015-19) for both his work on MHD and plans in turbulence and planetary flows and Potherat's PhD student Kelig Aujogue won the 2016 RAS Patricia Tomkins Prize for the best thesis in instrumentation in Geo- and Astrophysics. Lead Journals including Phys. Rev. Lett, J. Fluid Mech, EPL (Kenna authored the most downloaded EPL paper), New. J. Phys, Phys. Fluids highlighted nine of our staff's papers and featured them on three journal covers.

In addition to conference organisation, the Unit's staff contribute to shaping their discipline through participation in editorial boards of nine journals: del Genio (Chaos, Solitons & Fractals), Fytas (PLOS One), Kenna (Adv. Complex Systems, Frontiers in Physics, Condensed matter physics), Low (J. Geometry and Symmetry in Physics), Priede (magnetohydrodynamics), Potherat (Royal Society Open Science), Weigel (Comput. Phys. Comm.). They also acted as guest editors for eight journal special issues: del Genio (J. Symb. Comp., Bulletin of the AMS), Fytas (Eur. Phys. J. Special Topics), Kim (Entropy x3, Plasma, Mathematical Biosciences in engineering), and three times as series editor: Kenna (Springer Computational Social Sciences), Weigel (Eur. Phys. J. Special Topics x2).