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| **Institution:** Royal Holloway, University of London | | |
| **Unit of Assessment:** 12 Engineering | | |
| **Title of case study:** Transforming the manufacture and global market in enabling technologies for Free Electron Lasers | | |
| **Period when the underpinning research was undertaken:** 2004-2020 | | |
| **Details of staff conducting the underpinning research from the submitting unit:** | | |
| **Name(s):** | **Role(s) (e.g. job title):** | **Period(s) employed by submitting HEI:** |
| Professor Stewart Boogert | Head of School | 2005-date |
| Dr Alexey Lyapin | Senior Researcher | 2010-date |
| **Period when the claimed impact occurred:** 2014-2020 | | |
| **Is this case study continued from a case study submitted in 2014?** N | | |

## 1. Summary of the impact

At Royal Holloway, Professor Boogert and Dr Lyapin developed Cavity Beam Position Monitors. In 2019 RHUL licensed their design to a UK enterprise company FMB-Oxford. Following this FMB-Oxford launched the first commercial off-the-shelf CBPM. This represented FMB's entry into the electron beam diagnostic market. Slovenia based Instrumentation Technologies has aligned its electronics product to ensure compatibility with the FMB-Oxford CBPM. As a result, the two companies now offer a complete sensor and electronics solution for Free Electron Lasers. The technology developed by RHUL allows Free Electron Lasers facilities easy access to advanced position diagnostics, thus shortening their development and upgrade cycles. In 2020 FMB-Oxford and Instrumentation Technologies won their first contracts to supply a complete Cavity Beam Position Monitor system to ELI-Beamlines, a European centre of scientific excellence in the Czech Republic.

## 2. Underpinning research

Research lead by Professor Stewart Boogert and Dr Alexey Lyapin resulted in high precision particle beam diagnostic devices, called Cavity Beam Position Monitors (CBPM). CBPMs can detect a transverse offset of a bunch of electrons as small as 1/10,000,000th of a metre within a linear accelerator's vacuum chamber.

A CBPM system consists of three major components. Firstly, an electromagnetic transducer – a hollow metal wall resonator located in the accelerator beamline, which converts a small amount of the particle beam's energy into high-frequency oscillating signals. Secondly, the resulting microvolt level signals are detected using high sensitivity electronics and converted to a lower frequency analogue signal. Thirdly, this signal is digitised and undergoes digital processing for noise reduction and extraction of quantities containing position information. At this stage, the computations also apply calibration constants to convert the raw measured signals into position information.

Cavity sensors are complex devices designed with ultra-high vacuum and microwave requirements in mind. Typically, expensive manufacturing techniques such as diamond cutting and vacuum brazing are called upon when fabricating these devices. The RHUL Group used a different approach applying a careful evaluation and management of the mechanical tolerance budget while relaxing the most critical tolerances. Special pressure seals replaced vacuum brazing. The new strategy helped to reduce the manufacturing costs making the devices commercially viable and ready for industrialisation.

Professor Boogert and Dr. Lyapin facilitated numerous improvements in design and production of CBPM sensors [R1-3,6]. They have been the driving force behind "NanoBPM" – a critical demonstrator experiment that ran at the ATF facility (High Energy Research Laboratory, KEK, Japan) between 2005 and 2008. This experiment reliably demonstrated sub-20 nanometre precision is achievable with CBPMs aiding their adoption by major international laboratories in projects such as LCLS (SLAC, USA), European XFEL (DESY, Germany), SwissFEL (PSI, Switzerland).

RHUL Accelerator Group's research extends to all parts of CBPM systems: analogue processing electronics [R2, 3 and 6], signal processing and automated machine learning algorithms [R2,4-6]. They helped designing and operating large systems consisting of 30 to 40 BPMs [R2]. The resulting know-how allowed them to design a CBPM system easy to manufacture and use in an accelerator.

The original purpose of research into CBPMs was to enable the precise control of the accelerated beams of electrons and positrons in future high energy accelerators. Here the requirement is to safely guide the beams to their collision point through a potentially 30-kilometre long collider, which would need 1,000's of beam position monitors, with 100's of CBPMs deployed in critical areas. A linear collider would produce copious quantities of elusive fundamental particles such as Higgs bosons and Top quarks for particle physicists to study.

## 3. References to the research

### Papers

RHUL Accelerator Group is recognised internationally for advancing the area of electron beam diagnostics and facilitating some of the most influential experiments. This research has been published in multiple peer-reviewed articles, primarily in filed leading Physical Review Accelerators and Beams (impact factor 1.623) and Journal of Instrumentation (1.366):

R 1. Walston, S., Boogert, S., Lyapin, A. et al., *Performance of a high resolution cavity beam position monitor system,* Nuclear Instruments and Methods in Physics Research Section A, vol. 578, issue 1, pp 1-22, DOI: 10.1016/j.nima.2007.04.162 (2007)

R 2. Kim, YI, Boogert, ST, Lyapin, A et al., *Cavity beam position monitor system for the Accelerator Test Facility 2*, Physical Review Special Topics: Accelerators and Beams, vol 15, no. 4, 042801, DOI: 10.1103/PhysRevSTAB.15.042801 (2012)

R 3. Cullinan, FJ, Boogert, ST, A, Lyapin et al., *Long bunch trains measured using a prototype cavity beam position monitor for the Compact Linear Collider,* Physical Review Special Topics: Accelerators and Beams, vol 18, pp. 1-14, DOI: 10.1103/PhysRevSTAB.18.112802 (2015)

R 4. Snuverink, J, Boogert, S, Lyapin, A et al., *Measurements and simulations of wakefields at the Accelerator Test Facility 2*, Physical Review Special Topics: Accelerators and Beams, vol 19, no. 9, 091002, pp. 1-9, DOI: 10.1103/PhysRevAccelBeams.19.091002 (2016)

R 5. Kim, YI, Boogert, ST, Lyapin, A et al., *Principal Component Analysis of cavity beam position monitor signals*, Journal of Instrumentation, vol 9, no. 02, pp. P02007, DOI: 10.1088/1748-0221/9/02/P02007 (2014)

R 6. Lyapin, A, Boogert, S et al., *Results from a prototype chicane-based energy spectrometer for a Linear Collider*, Journal of Instrumentation, Vol. 6, No. 02, P02002, DOI: 10.1088/1748-0221/6/02/P02002 (2011)

### Funding

The research had been funded by a series of research grants, including as part of larger collaborations and institutional grants:
£93,400, Nov 07 - Apr 09, LC-ABD WP 9 Cavity BPM energy spectrometer, STFC
£1,092,393, Apr 09 - Mar 12, The John Adams Institute for Accelerator Science, STFC
£1,980,389, Sep 12 - Mar 17, The John Adams Institute for Accelerator Science, STFC
£1,840,222, Apr 17 - Mar 21, The John Adams Institute for Accelerator Science, STFC
£262,155, Oct 13 - Dec 17, Industrialisation of precision cavity beam position monitors, STFC (in partnership with FMB-Oxford)

£88,451, Apr 20 - Mar 21, Fast, high precision, low-cost position diagnostic for free electron lasers, STFC (an offspring project)

**4. Details of the impact**

This impact case is based on Cavity Beam Position Monitors (CBPM) application in Free Electron Lasers (FEL). Free Electron Lasers are driven by electron accelerators to generate short, bight and coherent pulses of X-rays. This light can be used to understand materials and chemistry at extremely small time and/or spatial scales. CBPMs enable sub-micrometre control of the electron beam producing the X-rays. CBPMs are one of the enabling technologies underpinning day-to-day FEL operation with a direct impact on user experience with a wide range of applications, including health technologies and communication devices.

**Transforming the manufacture of Cavity Beam Position Monitors via industrial partnerships**
Royal Holloway's research has met the demand for affordable and easy-to-use CBPMs that came with the introduction of FELs. By forming partnerships with industry-innovators in the UK and EU (FMB-Oxford and Instrumentation Technologies, iTech) their research generated industrialised low-cost CBPM sensors and processing electronics.

Researchers at RHUL optimised their CBPM designs for FELs. Industrialisation of CBPMs was strengthened by STFC's GBP262,155 Industrial Partnerships grant award with FMB-Oxford. The collaboration resulted in the development of several CBPM prototypes, which were successfully produced and tested to demonstrate the industrialisation of the process [S1]. This led directly to manufacture of the world's first off-the-shelf CBPM aimed at FEL applications. RHUL researchers provided Instrumentation Technologies (iTech) the specifications such that they could align their processing electronics product to ensure compatibility with FMB-Oxford [S5]. This transformed their business model by turning them from a competitor with FMB-Oxford into a partner, enhancing both companies' commercial offering.

**Creating commercial advantage**
The commercial and industrial need for FEL X-rays spans engineering, chemicals and catalysts, and pharmaceuticals [FEL Strategic Review, STFC]. A 2017 study revealed that 54 FELs were operating, with 20 more planned or under construction at the time. Each facility is typically a capital investment between GBP250,000,000 and GBP1,000,000,000 with annual running costs in the millions [EUXFEL]. FELs remain heavily oversubscribed. For example, in 2019, European XFEL received 239 beam time requests, while only 56 were successful.

RHUL's research collaboration with FMB-Oxford has changed the way the company positions itself in this specialist market. Working with RHUL enabled the company to become world leaders the new area of electron beam diagnostics and expand its presence in FEL instrumentation.

*FMB-Oxford* is a UK based SME with a turnover of around GBP6,000,000 per year employing 50 staff. It supplies 3rd and 4th generation light sources with X-ray beamline components. The company has an exceedingly strong track record in X-ray beamlines and instrumentation, supplying to most of the major UK, European and international X-ray laboratories (including Diamond Light Source, European Synchroton Radiation Facility, European Free Electron Laser). [text removed for publication] [S9], [text removed for publication]. As a result, a new line of products has been created [S3] that makes FMB-Oxford the first supplier in the world to have an off-the-shelf CBPM sensor. FMB's former Managing Director Nigel Boulding, now company's Chief Technology Adviser, explains what this has meant to the company:


*CBPM sensor featured at FMB's International Particle Accelerator Conference stand in 2019* [C]

*"The development and introduction of the Cavity BPM product range will provide a distinct commercial advantage to FMB Oxford in a new market area. As the demand for instrumentation is growing from smaller FELs and FEL type facilities, a singular position in the market can be secured with this unique off-the shelf solution. Indeed, the first commercial contract from ELI-BL was won in April 2020 for delivery in April 2021 and FMB-Oxford is currently engaging with the market to secure future business."* [S1]
FMB-Oxford started marketing the system in 2019 and now have a corresponding product page in their online catalogue [S4]. The first contract to supply a system of 7 sensors won in April 2020 amounted to approximately EUR150,000.
*Instrumentation Technologies* (or iTech) employs around 40 staff and is a Slovenia based vendor of electronics for accelerators with a turnover in the order of EUR7,000,000. Its products include specialist electronics for beam position and loss measurements, timing synchronisation as well as more generic data acquisition solutions. "Libera CavityBPM" is a recent addition to its product line. The device combines analogue front-end with digital electronics for data acquisition and processing with integrated user interface and easy online network-enabled access to measured data. Following interactions with RHUL researchers, this product was adapted by iTech for use with FMB's CBPM sensors.

Manuel Cargnelutti, head of "Libera – Solutions for Particle Accelerators" division at iTech explains RHUL's role in opening new business opportunities: *"Our interaction with RHUL's group has helped us strengthening our position in the niche market of CBPM instrumentation. We established a contact with FMB-Oxford to exploit the commercial synergy. As a result, we've been able to bid for the delivery of CBPM electronics for the ELI-BL system and achieve approximately 70,000 Euro in sales in 2019-2020. We have been able to position ourselves as a possible supplier for the CLARA CBPM electronics with a potential of further business sizing to 300,000 Euro."* [S5]

Both iTech and FMB-Oxford have been operating in the market of synchrotron light sources for decades. However, FELs are a relatively new market for both companies. RHUL's influence helped FMB-Oxford step into the new territory of electron beam diagnostics and cemented iTech's advantage in CBPM electronics.

**Creating a high-value supply chain for FELs**
Royal Holloway's research led industry leaders to build partnerships that allowed them to expand into new products via high-value supply chains. iTech's Libera CavityBPM had been developed as an independent and potentially competing device analogous to the signal processing electronics developed by FMB-Oxford and RHUL. Royal Holloway's researchers facilitated a collaboration between the two companies by recognising their complementary expertise. Each company historically served two different sectors within the accelerator community, and their collaboration created a single supply chain for a wider customer base bringing commercial benefits to both companies.

Manuel Cargnelutti confirmed RHUL's influence on the company's technology: "*Thanks to Prof. Boogert's and Dr. Lyapin's initiative, we expanded our exposure to new projects and customers. I must stress that the co-operation between FMB-Oxford and iTech is entirely the result of RHUL's initiative. Without their involvement we would not have considered aligning our products. Together we are able to provide prospective clients with a high value supply chain that ensures a proven solution with optimal performance."* [S5]

As a direct consequence of RHUL's technological innovation, and less than a year since launching its new product, FMB-Oxford was awarded the first contract to supply CBPM sensors to *ELI-BL*, one of the new European centres of scientific excellence in the Czech Republic. ELI-

BL hosts the *LUIS* facility – a novel compact laser-plasma driven linear accelerator and compact FEL. The machine will provide soft X-rays to industrial users and researchers. ELI-BL's Alexender Molodozhentsev, LUIS Group Leader, explains that the ability to procure the entire system from the two collaborating, field-leading companies was the deciding factor:
*"We are a small group constructing a challenging novel light source, so we have a strong preference to outsource subsystems where possible. Doing our own development costs us valuable time, while we are focused on delivering the beam to our users. Being able to procure a complete off-the-shelf CBPM system from FMB-Oxford and Instrumentation Technologies means that we can concentrate our efforts on the commissioning of the beamline."* [S6]
The two companies are currently engaging with further potential clients, such as a university in the Netherlands with a requirement of just one monitor and a national laboratory in the UK that will need a system of over 20 sensors. There is also a potential business opportunity to deliver at least 262 CBPM systems for the International Linear Collider project. FMB-iTech product is already gaining interest as the international community, and the hosting state (Japan) make advances towards constructing this gigantic high energy physics machine.

**The broader impact of FEL Facilities**
International FEL facilities have been using CBPMs based on Professor Boogert and Dr Lyapin's earlier underpinning research for many years, for example European XFEL [S7] came online in 2017 and LCLS [S8] in 2009. The users of these facilities have produced a vast number of high profile publications on a broad range of applications from revealing the structure of proteins to uncovering the hidden inner layers in ancient paintings. The impact of FELs produces wide social and commercial benefits improving our day-to-day life, including new medical treatments and miniaturized communications devices. The newly available commercial elements for FELs presented in this case study will promote new facilities, enhancing user access and the impact that is generated from their research.

## 5. Sources to corroborate the impact


S1. Testimonial, Mr. Nigel Boulding, Chief Technology Adviser, FMB Oxford Limited, October 2020
S2. Trifold product brochure: Cavity Beam Position Monitors, FMB Oxford Limited, https://www.fmb-oxford.com/wp-content/uploads/bsk-pdf-manager/Cavity_BPM_Trifold_52.pdf, checked: June 2020
S3. FMB-Oxford's IPAC2019 industrial exhibition stand, as blogged on LinkedIn, FMB Oxford Limited, retrieved November 2019
S4. Product webpage: Cavity Beam Position Monitors, FMB Oxford Limited, https://www.fmb-oxford.com/products/detectors-diagnostics/beam-position-monitors/cavity-beam-position-monitor/, checked: June 2020
S5. Testimonial, Mr Manuel Cargnelutti, Head of Libera Business Unit, Instrumentation Technologies, June 2020.
S6. Testimonial, Dr Alexanser Molodozhentsev, LUIS group leader, ELI-Beamlines, July 2020
S7. Conference proceeding submitted by European XFEL group citing [R1], D. Lipka et al, *FLASH undulator BPM commissioning and beam characterization results*, TUPF07, International Beam Instrumentation Conference 2014, Monterey, California, USA, https://accelconf.web.cern.ch/ibic2014/papers/tupf07.pdf
S8. Conference proceeding submitted by LCLS group citing [R1], S. Smith et al, *Commissioning and performance of LCLS cavity BPMs*, TU3GRC05, Particle Accelerator Conference 2009, Vancouver, British Columbia, Canada, https://accelconf.web.cern.ch/PAC2009/papers/tu3grc05.pdf
S9. [text removed for publication]