

Institution: University of Strathclyde
Unit of Assessment: Sub-panel 9 – Physics
Title of case study: Applications of microwave and mm-wave sources and amplifiers for the defence, security and health sectors
<p>1. Summary of the impact (indicative maximum 100 words)</p> <p>Radiation sources and amplifiers, in the spectral region from microwave to terahertz, are extensively used in UK industry and public sectors such as security, defence, health and the environment. Companies, including e2v Technologies plc. (e2v) and TMD Technologies Ltd. (TMD), have developed and sold new radiation products based on post-1996 research undertaken at the University of Strathclyde. Their devices accessed new frequency ranges with considerable increases in power and bandwidth. The designs were transferred to industry, where devices have been constructed, jobs created, policy changed and considerable investments made. These sources have had extensive beneficial impact through applications in defence, surveillance, materials processing, health sciences and environmental monitoring.</p>
<p>2. Underpinning research (indicative maximum 500 words)</p> <p>Context: From 1995 the Department's Atoms, Beams and Plasmas (ABP) group conducted fundamental research on new sources for electron cyclotron resonant heating of fusion plasmas. Their work identified a pathway to production of significantly improved radiation sources and amplifiers, while also providing understanding of the underpinning fundamental physics. Industrial companies quickly appreciated the potential impact and became closely involved from an early stage. The driving motivation was to combine the power of a gyrotron with the bandwidth of a Travelling Wave Tube (TWT) amplifier, which had not been demonstrated until the ABP group did so in 2000. This is extremely important for applications since it allows large amounts of energy to be delivered in a small time window. The research included experimental demonstrations of new electron optics, sources and amplifiers in the microwave and mm-wave regimes, complemented by full theoretical analysis.</p> <p>Key Findings: A key insight was that novel structures could couple together two wave modes to create new wave propagation behaviour, radically different from the behaviour achieved using only individual wave modes. Following the group's 1996 Physical Review Letter (Ref. 1), a series of calculations and numerical modelling studies underpinning proof of principle laboratory research experiments were undertaken in the period to 2000. Prototype designs for new advanced masers and amplifiers were designed and constructed, and the resulting knowledge transferred to industry. Helical waveguide structures were shown to provide unique wave propagation characteristics, the value of which was proven by operation of a gyrotron travelling wave amplifier (gyro-TWA) at two specific frequencies (9.1 and 9.4 GHz) in 1998 (Ref. 2). This was driven by magnetrons donated by e2v.</p> <p>A 2000 Physical Review Letter (Ref. 3) extended the demonstration to high power operation across a wide frequency band by use of a conventional broadband TWT amplifier (built by TMD) as the input source. Joint EPSRC/DSTL support enabled the helix concept to be developed as a frequency dispersive medium. Subsequently microwave pulse compression was introduced, raising the power by approximately x25 in shorter pulses, as reported in 2004 (Ref. 4). From 2005 research supported by QinetiQ Ltd on two-dimensional Bragg structures demonstrated enhanced single mode selection (Ref. 5). The company MBDA UK Ltd. continued to develop the high voltage power supply used in the QinetiQ programme and now uses it to run a novel high power microwave source UK test facility.</p> <p>Subsequent research led to a cusp electron gun enabling higher power gyro-TWA operation. This work was sponsored by Elekta Oncology Systems through the PPARC Faraday Partnership and developed in collaboration with e2v and TMD. From 2010 an ultra-wideband W-band (88GHz to 102GHz) oscillator was developed based on the cusp electron gun. This led to a world record in combined frequency bandwidth and power performance (Ref. 6), validating this new technology for</p>

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Thomas Keating Ltd. for the biochemical spectroscopy market and for ThruVision for surveillance applications.

Key Researchers: This research by the Atoms, Beams and Plasmas Group in the Department of Physics was led by Adrian Cross, Kevin Ronald and Alan Phelps, with contributions from Senior Research Fellows Simon Cooke, Wenlong He, Colin Whyte and Alan Young. Cross, Ronald and Phelps held academic appointments in the Department of Physics at the time of the research.

Adrian Cross: 'Research only' contract from 1993 – 2000, Lecturer from 2001, Senior Lecturer from 2003, Reader since 2006. Alan Phelps: Professor since 1993 to present. Kevin Ronald: 'Research only' contract from 1995, Lecturer from 2006, Senior Lecturer since 2011.

The research includes contributions from Russian research visitors to the ABP group (G. Denisov, V. Bratman and S. Samsonov).

3. References to the research (indicative maximum of six references)

References 1-3 best represent the quality of the underpinning research

1. S.J. Cooke, A.W. Cross, W. He, A.D.R. Phelps, *Experimental operation of a cyclotron auto-resonance maser oscillator at the second harmonic*.

Phys. Rev. Lett., 77, p4836 (1996). DOI: 10.1103/PhysRevLett.77.4836

2. G.G. Denisov, V.L. Bratman, A.W. Cross, W. He, A.D.R. Phelps, K. Ronald, S.V. Samsonov, C.G. Whyte, *Gyrotron traveling wave amplifier with a helical interaction waveguide*.

Phys. Rev. Lett., 81, p5680 (1998). DOI: 10.1103/PhysRevLett.81.5680 (100 cites)

3. V.L. Bratman, A.W. Cross, G.G. Denisov, W. He, A.D.R. Phelps, K. Ronald, S.V. Samsonov, C.G. Whyte, A.R. Young, *High-gain wide-band gyrotron traveling wave amplifier with a helically corrugated waveguide*.

Phys. Rev. Lett., 84, p2746 (2000). DOI: 10.1103/PhysRevLett.84.2746 (83 cites)

4. S.V. Samsonov, A.D.R. Phelps, V.L. Bratman, G. Burt, G.G. Denisov, A.W. Cross, K. Ronald, W. He, H. Yin, *Compression of frequency-modulated pulses using helically corrugated waveguides and its potential for generating multigigawatt rf radiation*.

Phys. Rev. Lett., 92, 118301 (2004). DOI: 10.1103/PhysRevLett.92.118301

5. I.V. Konoplev, P. McGrane, W. He, A.W. Cross, A.D.R. Phelps, C.G. Whyte, K. Ronald, C.W. Robertson, *Experimental study of coaxial free-electron maser based on two-dimensional distributed feedback*.

Phys. Rev. Lett., 96, 035002 (2006). DOI: 10.1103/PhysRevLett.96.035002

6. W. He, C.R. Donaldson, L. Zhang, K. Ronald, P. McElhinney, A.W. Cross, *High Power Wideband Gyrotron Backward Wave Oscillator Operating towards the Terahertz Region*.

Phys. Rev. Lett., 110, 165101 (2013). DOI: 10.1103/PhysRevLett.110.165101

Notes: The journal Physical Review Letters (references 1-6) is recognised as publishing the highest quality original, fundamental research.

Other evidence for quality of research (grants, patents etc.)

The total grant funding awarded for this work so far is approximately £12M, from sources including RCUK, EU, DERA, dstl, and several industrial partners. For example, £1.6M funding came from DERA in the period 1995-2000, over £1M from e2v from 2006 onwards and Qinetiq invested £375k in 2000 and £280k in 2003. Major EPSRC awards include £507k in 2007 (EP/ E058868/1), £771k in 2009 (EP/G036659/1) and £686k in 2009 (EP/ G011087/1).

4. Details of the impact (indicative maximum 750 words)

Process from research to impact: Fundamental research into new sources and amplifiers was conducted by the ABP group, publishing regularly in leading journals, and its potential impact was

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identified soon after the early work in 1996. The ABP researchers led the initial and follow-on work, all conducted at Strathclyde, funded by a series of KT awards (approx. £6M) alongside research council grants (approx. £6M). Companies such as e2v and TMD were involved at an early stage, building prototypes and using them to conduct trials which have changed their thinking and business plans. In 2001 it was agreed that defence applications would be taken up by Defence Science and Technology Laboratory (dstl), whilst Strathclyde would be free to pursue opportunities in other sectors. e2v's Group Chief Technology Officer confirms:

"Your group is one of only three critical and on-going University partnerships supported by e2v and we regard the combination of theoretical and practical capabilities as unique" (Source 1).

Description of impact: During the period 2008-13, the devices in question have had impact in a wide range of sectors. For example, a Principal Scientist at dstl writes that the Strathclyde research *"has impacted on a range of applications including Defence, Energy, Environmental Monitoring and Security."* (Source 2). The enhanced power delivered by these sources is highly significant, for example in radar applications, where the useful range is approximately doubled by the x10 increase in power over conventional sources. In addition the increased bandwidth leads to improved signal-to-noise performance. The Chief Scientific Advisor at ThruVision (a division of Digital Barriers plc.) writes of *"applications of the high power capability of the Strathclyde sources enabling stand-off, real-time detection, in all weather conditions [and] over increased distances (>100m)."* (Source 3). The impact, therefore, is bringing societal as well as economic benefits. Many jobs have been created, as detailed below.

Reach and Significance: Dstl is the key scientific advisor to the MoD and is an authority on the impact of developments such as those in this case. A Principal Scientist at dstl writes *"The breakthrough work in achieving efficient instantaneous wide bandwidth operation from both the FEM and Gyro-TWA was demonstrated by the ABP group in 1998-2000 and ... has changed the course of high power amplifier research internationally."* (Source 2). In 2009/10 e2v manufactured a gyrotron traveling wave amplifier (gyro-TWA amplifier) identical in design to the prototype designed and constructed at Strathclyde University. In February 2011, e2v made a public announcement of their factory manufactured gyro-TWA at the International Vacuum Electronics Conference (IVEC), Bangalore, India (Source 4).

The first prototype device was sold in 2012, with e2v technologies CTO stating that

"The fully funded development and prototyping programme resulted in sales of [text removed for publication] for e2v and e2v placed subcontracts on a range of consortium members.....e2v continues to work actively with its consortium partners to develop the technology and broaden the range of applications" (Source 1).

He goes on to state that the emphatic demonstration of performance presents the UK-MOD with a decision about implementation into operational systems, the commercial impact of which he estimates at [text removed for publication]. The Russian research collaborators have since made sources for material processing, through a company called Gycom Ltd. who build and sell gyrotrons for the ITER project as well as for industrial heating applications. The impact of Strathclyde's research continues to expand into new applications through additional company engagement. For non-defence sectors, a market survey by Talavera Science identified a potential market value of \$260M for enhancement to nuclear magnetic resonance and electron paramagnetic resonance spectrometers and \$5M for cloud profiling radar. Competitor high power amplifiers cost approx. £200k per unit and the 50x improvement in power-bandwidth product in gyro-TWA devices commands a premium price. Impact that has already been delivered in this area includes the design effort and planning by magnet suppliers, such as Cryogenics Ltd., to establish magnets that can be used with gyro-TWA sources. At the same time companies such as Thomas Keating Ltd. have invested time to ensure the manufacturability of the components required for the gyro-TWA.

In the period 2008-2011, TMD Technologies Ltd supported research and design work at

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Strathclyde University to provide a Ka band gyro-TWA. They are now developing the manufacturing capability for this higher frequency gyro-TWA. This also gave rise to a KTA project with some £170k from TMD to develop practical methods for high frequency amplifiers. The Technical Director of TMD writes of Strathclyde's contributions through the "*many notable breakthroughs and achievements in microwave source research*" and of the strong relationship with Strathclyde Physics to realise the impact of this technology (Source 5).

In the Healthcare / Biology sectors the applications are in enhanced NMR spectroscopy, via Dynamic Nuclear Polarisation (DNP), and EPR spectroscopy. This has influenced development work in a number of companies. Since 2011, Thomas Keating Instruments have been working on the manufacture of a W-band gyro-TWA based on Strathclyde's research. Dr. Wenlong He has led work to upgrade the measurement equipment at Strathclyde to access the higher frequency range. The Strathclyde amplifiers allow the design of more advanced DNP transfer schemes to greatly improve performance of EPR and Nuclear Magnetic Resonance machines. The use of a gyro-TWA as a radio-frequency source for a medical linear accelerator has been investigated by Elekta Oncology Systems.

Environmental applications include the monitoring of space debris (through funded work at Chilbolton Laboratory), millimetre wave weather radar (work on comparisons with airborne LIDAR conducted by the MET Office) and the monitoring of volcanic ash clouds. The increased bandwidth of these sources leads to improved signal-to-noise performance and the enhanced power approximately doubles the usable range compared to conventional instruments.

A significant number of jobs have been created as a result of this research, estimated to be in excess of 40 although precise numbers are not available due to the sector. The companies concerned, as well as dstl, have considerable and long-term development programmes employing a range of people developing new products and trialling prototypes. The applications, product development and trials have generated jobs at companies including e2v, TMD, MBDA Ltd., NHS, Selex Galileo Ltd. Culham Laboratories, Alcatel and Adtek, principally for skilled graduates. Devices have been made at e2v Chelmsford and TMD Hayes and trials are on-going at e2v Chelmsford. The dstl Principal Scientist has written that "*UK industry has benefitted with people it needs to exploit future economic opportunities.*" Amongst those employed are at least 19 former members of the ABP research group, now using skills learnt at Strathclyde.

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

Source 1: Statement from Group CTO of e2v technologies plc. corroborates the claim that the research at Strathclyde contributed directly to successful products and sales of [text removed for publication] and that jobs have been created.

Source 2: Statement from Principal Scientist, Defence Science and Technology Laboratory (dstl) corroborates the claim that the work has had major economic impact and changed policy.

Source 3: Statement from Chief Scientific Advisor at ThruVision, corroborates the claim that Thruvision the high power of the Strathclyde amplifiers is being applied in various applications

Source 4: Manufacture and Evaluation of a GyroTWA Amplifier, Michael J. Duffield and Richard North, a paper in the IVEC 2011 International Conference Proceedings, 2011, which gives the announcement of a factory-manufactured gyro-TWA by e2v, based on Strathclyde research. DOI: 10.1109/IVEC.2011.5747011

Source 5: Statement from Technical Director of TMD Technologies Ltd. can corroborate the claim that TMD, and the economy, have directly and indirectly benefited from this research and that jobs have been created.