Quantum Technology Roadmap Report
Consolidated from Workshops in London and Glasgow

IfM Education and Consultancy Services

Technology Strategy Board
Driving Innovation

UNIVERSITY OF CAMBRIDGE

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Contents

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1. Executive Summary

This document presents the consolidated outputs of two roadmapping workshops held in London (7th August, 2014) and Glasgow (21st August, 2014) for the commercialisation of Quantum Technologies in the UK. Both workshops were run to near-identical processes with the objectives of:

- Defining a vision for the commercialisation of Quantum Technologies in the UK
- Identifying and prioritising Trends and Drivers, and Stakeholder Perspectives that influence the development of commercial Quantum Technology Applications
- Identifying and prioritisation of Commercial Applications for Quantum Technologies
- Identifying technologies, capabilities and enablers required for the delivery of the priority applications, and
- Defining the potential timelines for each layer of the developing roadmap and the linkages between those layers

This output is to be used to help shape a National Quantum Roadmap, which can be used by everyone in the sector to inform their forward activities.

Although there were differences between the two workshops, there was much correlation between the primary findings. External influences were dominated by a recognition that Quantum Technology is an emerging area of technology, where in most instances research is proceeding ahead of clear market drivers.

The leading Trends and Drivers were identified as Research and New Technology driving the development of new applications, and data security threats in the short term. Improved sensor technologies driving new applications, and changing security threats were important in the medium term.

1. Executive Summary (2)

Prioritised stakeholder perspectives were the government's High Value Manufacturing strategy; large companies developing applications for specific challenges; and the UK defence community being early adopters and funding demonstrators.

Both workshops identified many potential applications for Quantum Technologies that could be commercialised between 2014 and 2040. In the short term, the priority applications were seen as Components for the R&D community and early adopters; Quantum Clocks for financial and telecoms applications, with secure point-to-point communications based on Quantum Key Distribution. Medium term applications commencing in 2020 and developing through to 2030 included multiple EM and Gravity imaging applications including through-ground imaging for multiple industries; inertial navigation; and second generation components. Longer terms applications focussed on gravity navigation and secure complex communications with interesting possibilities in other areas e.g. quantum computing and direct extraction of electrical power from heat.

The critical technologies and capabilities identified by participants included those short-term components essential for development of the sector: miniaturised ultra high-vacuum cells and lasers; sub-systems and micro-fabricated devices; sensors and system modules; component integration; design for manufacture and high level systems integration.

Other enablers important for the commercialisation of Quantum Technologies included funding; multiple forums for collaboration; prototypes and demonstrators; and IP protection.

The full details of the workshops and their output is included in the body of this report.

2. Outline of this Report

This report is presented in three sections:

- A summary providing the consolidated outputs, and key detail from each workshop
- Additional outputs from each workshop is provided in two separate appendices

These three sections are provided as separate files to be distributed as appropriate.

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3. Workshop Agenda and Process

- Both workshops followed a near-identical agenda and process to enable the outputs from both workshops to be compared and consolidated
- The following slides outline the agenda, objectives and process of the workshops
- The one variation between the two workshops was that in Glasgow participants were asked to identify Barriers to the short-term development of commercial Quantum Technologies applications; and corresponding actions to overcome those barriers

3.1 Agenda

Morning	
9:00	Introduction, agenda and process
9:15	Participants share perspectives
10:15	Trends, Drivers and Stakeholder Perspectives
10:30	Break
10:45	Ideate potential Applications for Quantum Technologies
11:45	Networking & Lunch
Afternoon	
12:30	Identify breakout groups for Priority Applications for Quantum Technologies
12:45	Explore Priority Applications for Quantum Technologies
13:45	Develop Outline "Application Roadmaps"
14:30	Break
14:45	Elevator pitches from groups and Carousel Review
15:45	Review and Next Steps
16:00	Close

3.2 Workshop Objectives

- Quantum Technologies have been identified by the UK Government as having huge potential for the British Economy. In line with that potential, significant investment of £270m is being made through EPSRC, Innovate UK (formerly TSB) and NPL.

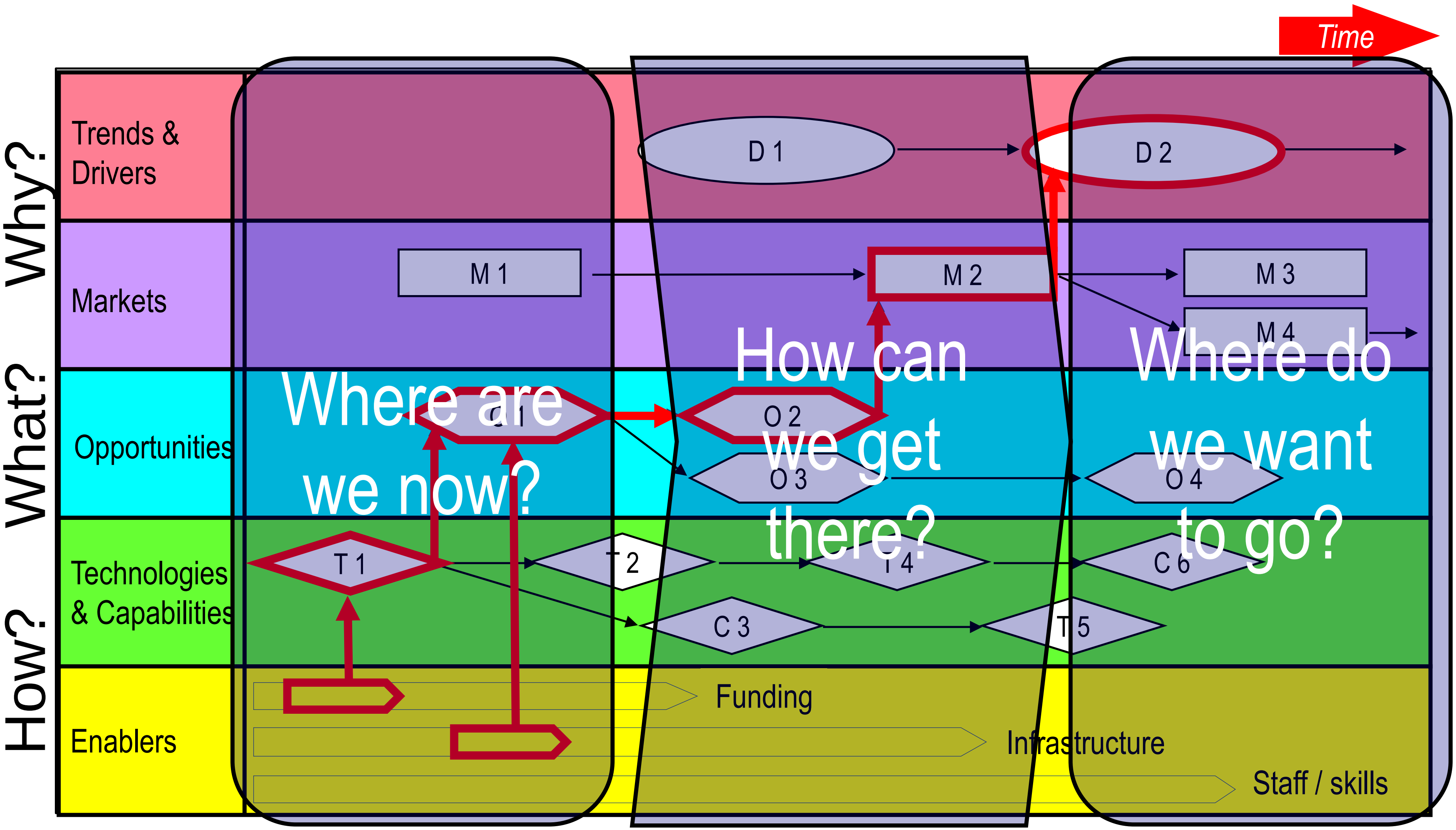
- The UK holds a strong position in the emerging science in this area. This workshop aims to inform a national strategy for the commercialisation of Quantum Technologies; and will inform future Quantum Technology Calls.

- The aims of the workshop are:

  i) to agree a vision and draft an early stage Roadmap for quantum technologies in the UK;

  ii) to articulate the primary applications for quantum technologies; and identify the core technologies; development requirements and other enablers required to commercialise those applications in the UK

3.3 Roadmapping- Linking future to present

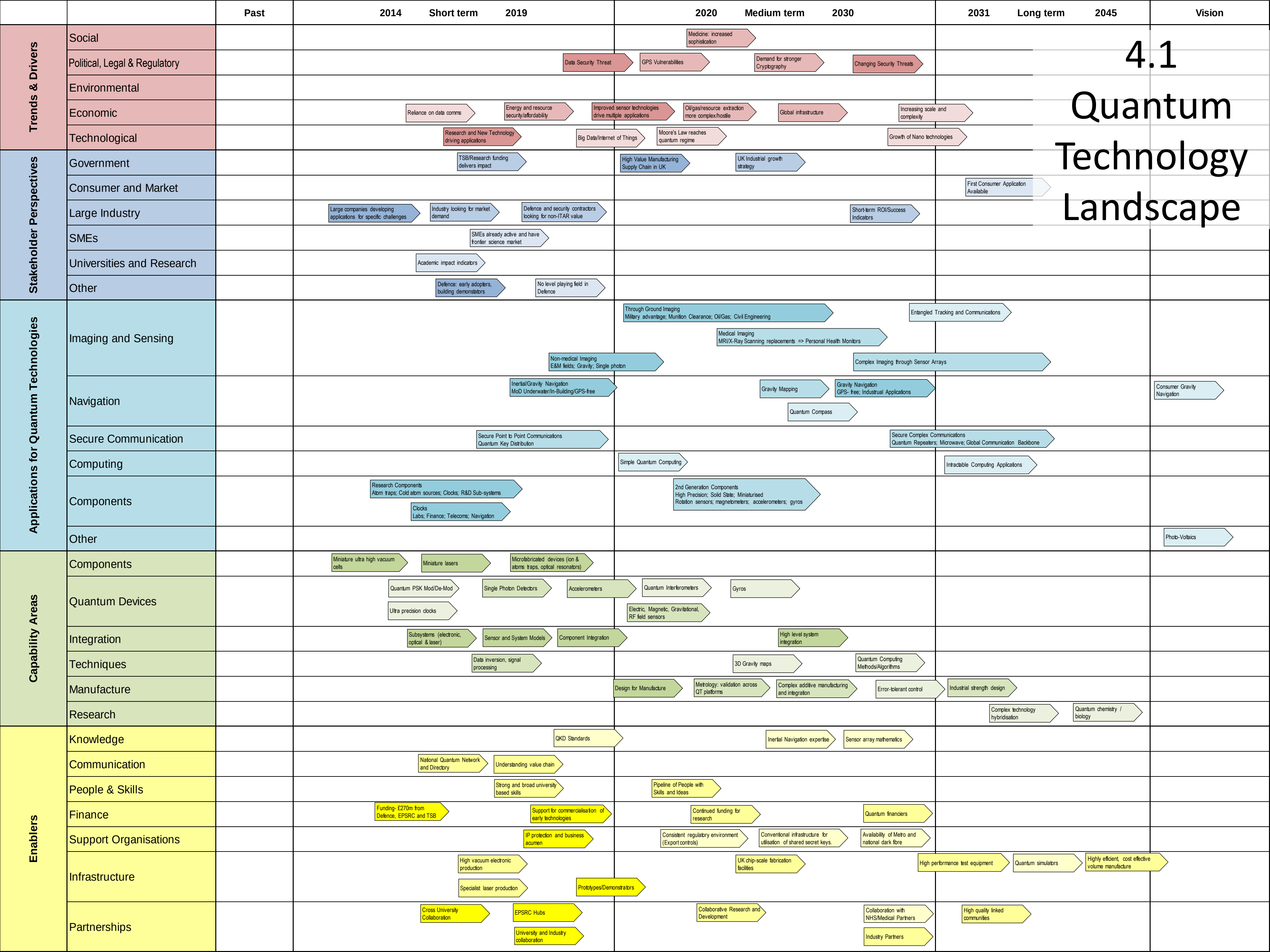


4. Roadmap Landscape

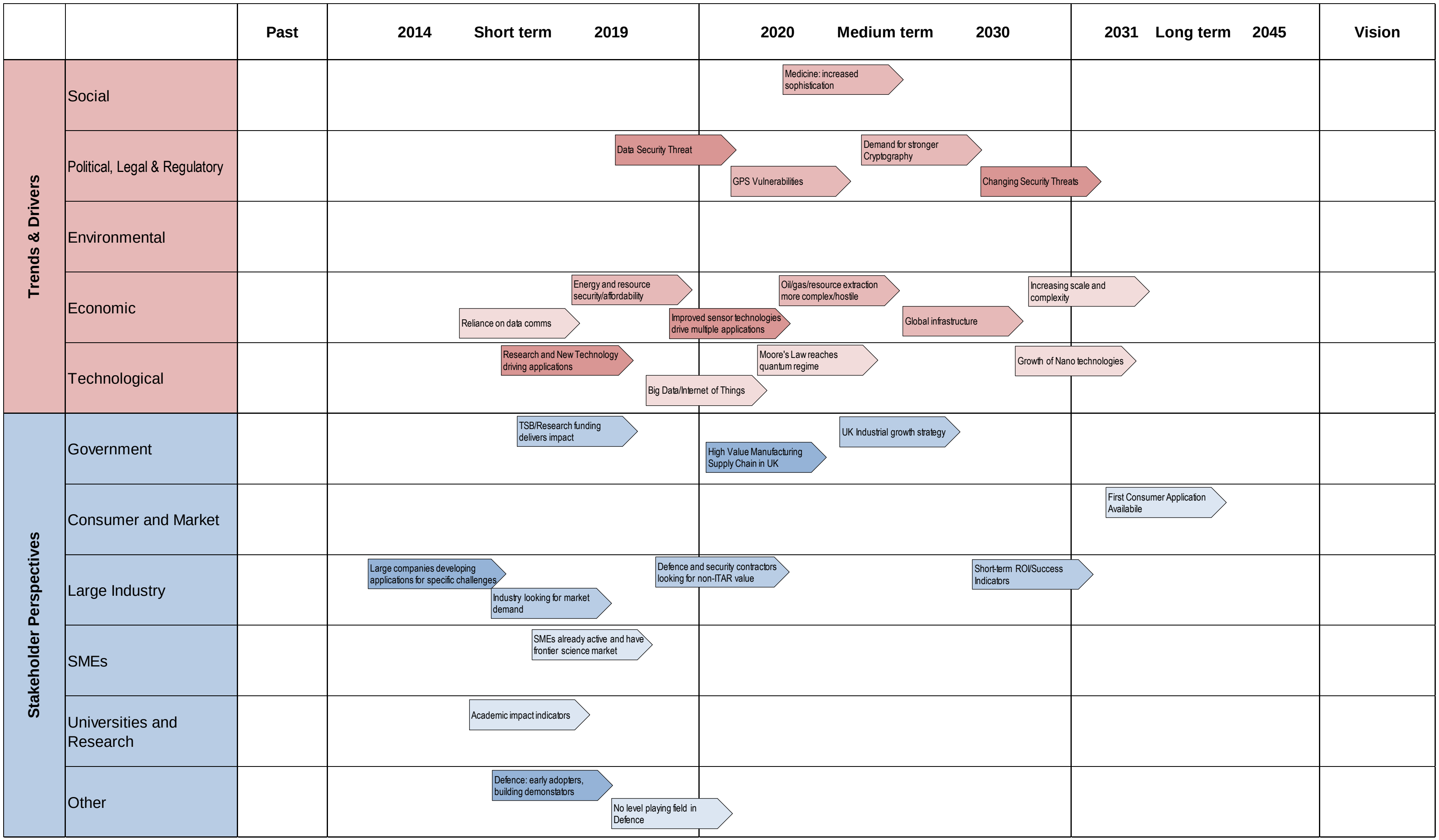
4.1	Roadmap Landscape
4.2	Trends and Stakeholder Perspective Detail
4.3	Opportunity Detail
4.4	Capability and Enabler Detail

These landscapes were built from the consolidated outputs of the two workshops. For each layer the darker colours indicate a higher priority defined by voting preferences and the number of linkages to priority opportunities for each item.

4.1 Quantum Technology Landscape



4.2 Trends and Stakeholder Perspective Detail



4.3 Opportunity Detail

		Past	2014 Short term 2019	2020 Medium term 2030	2031 Long term 2045	Vision
Applications for Quantum Technologies	Imaging and Sensing		Through Ground Imaging Military advantage; Munition Clearance; Oil/Gas; Civil Engineering Non-medical Imaging E&M fields; Gravity; Single photon	Entangled Tracking and Communications Medical Imaging MRI/X-Ray Scanning replacements => Personal Health Monitors Complex Imaging through Sensor Arrays		
	Navigation		Inertial/Gravity Navigation MoD Underwater/In-Building/GPS-free applications	Gravity Mapping Gravity Navigation GPS- free; Industrual Applications Quantum Compass		Consumer Gravity Navigation
	Secure Communication		Secure Point to Point Communications Quantum Key Distribution	Secure Complex Communications Quantum Repeaters; Microwave; Global Communication Backbone		
	Computing			Simple Quantum Computing	Intractable Computing Applications	
	Components		Research Components Atom traps; Cold atom sources; Clocks; R&D Sub-systems Clocks Labs; Finance; Telecoms; Navigation	2nd Generation Components High Precision; Solid State; Miniaturised Rotation sensors; magnetometers; accelerometers; gyros		
	Other					Photo-Voltaics

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4.4 Capability and Enabler Detail

		Past	2014 Short term 2019	2020 Medium term 2030	2031 Long term 2045	Vision
Capability Areas	Components		Miniature ultra high vacuum cells; Microfabricated devices (ion & atoms traps, optical resonators); Miniature lasers			
	Quantum Devices		Quantum PSK Mod/De-Mod; Accelerometers; Single Photon Detectors; Ultra precision clocks	Gyros; Quantum Interferometers; Electric, Magnetic, Gravitational, RF field sensors		
	Integration		Subsystems (electronic, optical & laser); Sensor and System Models; Component Integration	High level system integration		
	Techniques		Data inversion, signal processing	3D Gravity maps; Quantum Computing Methods/Algorithms		
	Manufacture			Design for Manufacture; Complex additive manufacturing and integration; Metrology: validation across QT platforms; Error-tolerant control	Industrial strength design	
	Research				Complex technology hybridisation; Quantum chemistry / biology	
Enablers	Knowledge		QKD Standards	Inertial Navigation expertise; Sensor array mathematics		
	Communication		National Quantum Network and Directory; Understanding value chain			
	People & Skills		Strong and broad university based skills	Pipeline of People with Skills and Ideas		
	Finance		Funding-£270m from Defence, EPSRC and TSB; Support for commercialisation of early technologies	Continued funding for research; Quantum financiers		
	Support Organisations		IP protection and business acumen	Consistent regulatory environment (Export controls); Conventional infrastructure for utilisation of shared secret keys.; Availability of Metro and national dark fibre networks.		
	Infrastructure		High vacuum electronic production; Specialist laser production; Prototypes/Demonstrators	UK chip-scale fabrication facilities; High performance test equipment	Highly efficient, cost effective volume manufacture; Quantum simulators	
	Partnerships		Cross University Collaboration; EPSRC Hubs; University and Industry collaboration	Collaborative Research and Development; Collaboration with NHS/Medical Partners; Industry Partners	High quality linked communities	

5. Workshop 1 Detail

5.1 Participant Alignment with Vision Statements

Quantum Technologies Vision	Industry	Research	Public Sector	Total
The UK boasts leadership in all elements of the Quantum Technology supply chain; including globally dominant primes			1	
Quantum has replaced digital technologies with transformative impacts over 2015 technologies				
Quantum technologies are the basis of ubiquitous; compact and cheap everyday objects				
High value industries including oil/gas; aviation; communucations and healthcare benefit from new applications based on Quantum Technologies	35	8	1	58
Industry and Universities work together in partnership to continue the UK's leadership of Quantum Technologies			16	

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5.2.1: Trends and Drivers Prioritisation

Rank	Driver	%
1	Improved sensor technologies drive multiple applications	20%
2	GPS Vulnerabilities	17%
3	Changing Security Threats	10%
4	Moore's Law reaches quantum regime	9%
5	Medicine: increased sophistication	7%
6	Energy and resource security/affordability	7%
7	Research and New Technology driving applications	6%
8	Changing population/demographics	4%
9	Data Security Threat	3%
10	Big Data/Internet of Things	3%
11	Demand for stronger Cryptography	3%
12	Oil/gas/resource extraction more complex/hostile	3%
13	Increasing scale and complexity	2%
14	Growth of Nano technologies	2%
15	Global infrastructure	1%
16	UK gets incoming revenue from export	1%
17	Reliance on data comms	0%
18	Need for information superiority	0%
19	Unknown societal trends and drivers	0%

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5.2.2: Stakeholder Perspectives Prioritisation

Rank	Needs	%
A	High Value Manufacturing Supply Chain in UK	18%
B	Defence: early adopters, building demonstators	12%
C	Industry looking for market demand	12%
D	Short-term ROI/Success Indicators	11%
E	TSB/Research funding delivers impact	9%
F	Large companies developing applications for specific challenges	8%
G	Defence and security contractors looking for non-ITAR value	8%
H	UK Industrial growth strategy	4%
I	US R&D base : competitor or collaborator?	4%
J	Growth in research sector	4%
K	Austerity/risk aversion	3%
L	No level playing field in Defence	3%
M	First Consumer Application Available	3%
N	Academic impact indicators	1%

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5.2.3: Prioritisation of Opportunities

Rank	Opportunity Cluster	Votes
1	Quantum Technology Components	28
2	Atomic Clocks	24
3	Medical Imaging	21
4	Short-term Gravity Navigation	20
5	Complex Communications	18
6	Simple Gravity Imagers	17
7	Complex Gravity Imaging	17
8	Point to Point Communications	13
9	Consumer Gravity Navigation	12
10	Scanners	10
11	Intractable Computing Problems	7
12	Short-term Compute Applications	7
13	Quantum Algorithms/Software	2
14	Quantum Gaming/Gambling	1
15	Multi-sensor Portals/Gate Arrays	1

5.3 Linkage Grids

- Linkage Grids show the linkages between Priority Opportunities and each of Trends and Drivers; Stakeholder Needs; Capabilities and Enablers
- A shaded intersection indicates a linkage between the Trend and Driver (for example) and the Opportunity. A darker colour indicates a stronger relationship.
- The Trends and Drivers and Stakeholder Needs linkage charts were built from linkage information provided at the individual opportunity level
- Capability and Enabler linkage charts were built from information gathered in the Opportunity Commercialisation plans

5.3.1 Consolidated Linkage Chart

Trends & Drivers

1. Improved sensor technologies drive multiple applicatio
2. GPS Vulnerabilities
3. Changing Security Threats
4. Moore's Law reaches quantum regime
5. Medicine: increased sophistication
6. Energy and resource security/affordability
7. Research and New Technology driving applications
8. Changing population/demographics
9. Data Security Threat
10. Big Data/Internet of Things
11. Demand for stronger Cryptography
12. Oil/gas/resource extraction more complex/hostile

Market Needs

1. High Value Manufacturing Supply Chain in UK
2. Defence: early adopters, building demonstrators
3. Industry looking for market demand
4. Short-term ROI/Success Indicators
5. TSB/Research funding delivers impact
6. Large companies developing applications for specific ch
7. Defence and security contractors looking for non-ITAR
8. UK Industrial growth strategy
9. US R&D base : competitor or collaborator?
10. Growth in research sector
11. Austerity/risk aversion
12. No level playing field in Defence

Capabilities

1. Component Integration
2. Subsystems (electronic, optical & laser)
3. Miniature lasers
4. High level system integration
5. Miniature ultra high vacuum cells
6. Electric, Magnetic, Gravitational, RF field sensors
7. Microfabricated devices (ion & atoms traps, optical res
8. Design for Manufacture
9. Single Photon Detectors
10. Sensor and System Models
11. Metrology: validation across QT platforms
12. Data inversion, signal processing
13. Quantum Interferometers
14. Accelerometers
15. Gyros
16. 3D Gravity maps
17. Complex additive manufacturing and integration
18. Complex technology hybridisation
19. Error-tolerant control
20. Industrial strength design

Enablers

1. University and Industry collaboration
2. Prototypes/Demonstrators
3. IP protection and business acumen
4. Funding- £270m from Defence, EPSRC and TSB
5. Continued funding for research
6. EPSRC Hubs
7. Strong and broad university based skills
8. Cross University Collaboration
9. Support for commercialisation of early technologies
10. High vacuum electronic production
11. Specialist laser production
12. UK chip-scale fabrication facilities

Market Opportunities – Trends & Drivers

Market Opportunities	1	2	3	4	5	6	7	8	9	10	11	12
A Quantum Technology Components	3						3					
B Atomic Clocks												
C Medical Imaging					3							
D Short-term Gravity Navigation		3										
E Complex Communications			3						3		3	
F Simple Gravity Imagers												
G Complex Gravity Imaging												
H Point to Point Communications									3			
I Consumer Gravity Navigation												
J Scanners	3											
Total	13	7	10	2	5	3	8	0	8	1	7	2

Market Needs

Market Opportunities	1	2	3	4	5	6	7	8	9	10	11	12
A Quantum Technology Components												
B Atomic Clocks												
C Medical Imaging												
D Short-term Gravity Navigation												
E Complex Communications												
F Simple Gravity Imagers												
G Complex Gravity Imaging												
H Point to Point Communications												
I Consumer Gravity Navigation												
J Scanners												
Total	15	13	5	5	3	6	5	5	0	0	0	0

Capabilities

Market Opportunities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A Quantum Technology Components																				
B Atomic Clocks																				
C Medical Imaging																				
D Short-term Gravity Navigation																				
E Complex Communications																				
F Simple Gravity Imagers																				
G Complex Gravity Imaging																				
H Point to Point Communications																				
I Consumer Gravity Navigation																				
J Scanners																				
Total	7	7	6	6	5	5	4	4	3	3	3	2	2	2	2	2	2	2	2	2

Enablers

Market Opportunities	1	2	3	4	5	6	7	8	9	10	11	12
A Quantum Technology Components												
B Atomic Clocks												
C Medical Imaging												
D Short-term Gravity Navigation												
E Complex Communications												
F Simple Gravity Imagers												
G Complex Gravity Imaging												
H Point to Point Communications												
I Consumer Gravity Navigation												
J Scanners												
Total	7	7	7	6	5	5	4	4	4	3	3	3

5.3.2 Trends and Drivers Linkage Grid

Rank	Driver	Quantum Technology Components	Atomic Clocks	Medical Imaging	Short-term Gravity Navigation	Complex Communications	Simple Gravity Imagers	Complex Gravity Imaging	Point to Point Communications	Consumer Gravity Navigation	Scanners
1	Improved sensor technologies drive multiple applications	3									3
2	GPS Vulnerabilities				3						
3	Changing Security Threats					3					
4	Moore's Law reaches quantum regime										
5	Medicine: increased sophistication			3							
6	Energy and resource security/affordability										
7	Research and New Technology driving applications	3									
8	Changing population/demographics										
9	Data Security Threat					3			3		
10	Big Data/Internet of Things										
11	Demand for stronger Cryptography					3					
12	Oil/gas/resource extraction more complex/hostile										
13	Increasing scale and complexity										
14	Growth of Nano technologies										
15	Global infrastructure										
16	UK gets incoming revenue from export										
17	Reliance on data comms										
18	Need for information superiority										
19	Unknown societal trends and drivers										

5.3.3 Stakeholder Needs Linkage Grid

Rank	Stakeholder Needs	Quantum Technology Components	Atomic Clocks	Medical Imaging	Short-term Gravity Navigation	Complex Communications	Simple Gravity Imagers	Complex Gravity Imaging	Point to Point Communications	Consumer Gravity Navigation	Scanners
A	High Value Manufacturing Supply Chain in UK										
B	Defence: early adopters, building demonstators										
C	Industry looking for market demand										
D	Short-term ROI/Success Indicators										
E	TSB/Research funding delivers impact										
F	Large companies developing applications for specific challenges										
G	Defence and security contractors looking for non-ITAR value										
H	UK Industrial growth strategy										
I	US R&D base : competitor or collaborator?										
J	Growth in research sector										
K	Austerity/risk aversion										
L	No level playing field in Defence										
M	First Consumer Application Available										
N	Academic impact indicators										

5.3.4 Capability Linkage Grid

Rank	Capabilities	Quantum Technology Components	Atomic Clocks	Medical Imaging	Short-term Gravity Navigation	Complex Communications	Simple Gravity Imagers	Complex Gravity Imaging	Point to Point Communications	Consumer Gravity Navigation	Scanners
1	Component Integration										
2	Subsystems (electronic, optical & laser)										
3	Miniature lasers										
4	High level system integration										
5	Miniature ultra high vacuum cells										
6	Electric, Magnetic, Gravitational, RF field sensors										
7	Microfabricated devices (ion & atoms traps, optical resonators)										
8	Design for Manufacture										
9	Single Photon Detectors										
10	Sensor and System Models										
11	Metrology: validation across QT platforms										
12	Data inversion, signal processing										
13	Quantum Interferometers										
14	Accelerometers										
15	Gyros										
16	3D Gravity maps										
17	Complex additive manufacturing and integration										
18	Complex technology hybridisation										
19	Error-tolerant control										
20	Industrial strength design										
21	Ultra precision clocks										
22	Quantum Computing Methods/Algorithms										
23	Quantum chemistry / biology										

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5.3.5 Enablers Linkage Grid

Rank	Enablers	Quantum Technology Components	Atomic Clocks	Medical Imaging	Short-term Gravity Navigation	Complex Communications	Simple Gravity Imagers	Complex Gravity Imaging	Point to Point Communications	Consumer Gravity Navigation	Scanners
1	University and Industry collaboration										
2	Prototypes/Demonstrators										
3	IP protection and business acumen										
4	Funding- £270m from Defence, EPSRC and TSB										
5	Continued funding for research										
6	EPSRC Hubs										
7	Strong and broad university based skills										
8	Cross University Collaboration										
9	Support for commercialisation of early technologies										
10	High vacuum electronic production										
11	Specialist laser production										
12	UK chip-scale fabrication facilities										
13	High quality linked communities										
14	Quantum financiers										
15	Highly efficient, cost effective volume manufacture										
16	High performance test equipment in place by investment										
17	QKD Standards										
18	Understanding value chain										
19	Inertial Navigation expertise										
20	Sensor array mathematics										
21	Consistent regulatory environment (Export controls)										
22	Conventional infrastructure for utilisation of shared secret keys.										
23	Availability of Metro and national dark fibre networks.										
24	Quantum simulators										

5.4 Topic Roadmaps and Business Plans

- Components
- Quantum Clocks
- Medical Imaging
- Inertial Navigation
- Complex Communications
- Short-term Applications of Gravity Imaging
- Long-term Applications of Gravity Imaging
- Point to Point Communications
- Consumer Gravity Navigation
- Scanners

Topic	Components	Team	RM, IR, DG, PT, NH, BC	7th August, 2014

Current State	Short Term 5 year goal?	Medium Term When?	Long Term When?	Vision When?
Science market 1000+ research, 10,000+ groups globally High value low performance Good delivery	Early adopters? No Understanding market Systems specs - feedback into design	First product subcomponent assembled Risk register Quantum catapult New developments Other markets fuel value change Defence market VC	Consumer market	Cross platform Serving all markets Standardize X platform componentry Target specs -> Roadmap detailing product milestones
R&D/Broadband stage Built with one-off components Size/weight/power	Big discrete components Base materials DEMONSTRATOR Integration	Increased reliability, cost Size reduced Systems engineering DFX FIRST COMMERCIAL PRODUCT Move IP into industry Valuation of IP	Integration increase Reliability increase Manufacturability increase Size, cost reduced SECOND COMMERCIAL PRODUCT Fully integrated product On-shoring	Fully UK based component supply chain Competitive with global components chain
Lots of academic expertise and interest Half-off systems integration "Dispersed" capabilities across different field - photonics/comms/electronics Bringing interest and capabilities into the subject Team of physicists Laser technology High vacuum technologies Electronics Low/medium semi-conductors processing and packaging	Academic research and start ups Training/staff - write courses "Quantum Engineering" TSB and other funding TSB funding not as good - EU 100% funding Bring knowledge and know-how into the UK	Single photon detectors -> "Quantum microscope" e.g. fully integrated cold atom systems Standards Acquisitions and mergers	Industry holding more prominent role	Equipment/material suppliers Ecosystem System integrators as part of supply chain Skills/capabilities within industry Industrial facilities

Topic	Components		Team	RM, IR, DG, PT, NH, BC
Current State	**Short Term**	**Medium Term**	**Long Term**	
Actions	Defining the market - roadmapping Encouragement for start ups Funding training Smart procurement Knowledge transfer TSB + industry case making Change in TS internals - Less emphasis on tech risk, some commercial Competitor analysis/analysis of global supply chains	PR publicity momentum expectations Measures of KPI Universities: quantum technology from physics engineering courses Licensable IP packages End user engagement. Attract interest		
Risks	No market Quantum not the answer Over valued IP Technical risk Foreign competion competitor analysis Applications do not allow definition of volume standard components	Can you define a standard component? UK quantum is unknown to public and policy makers Coordination Public acceptance e.g. snooping		
Barriers	Funding (opportunity) IP no freedom to operate Communication and critical mass Regulation standardization	Technology hidden from user Education abroad/awareness		

Topic	Quantum Clocks	Team	CSA, ST, PMM	7th August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When?	**Long Term** When?	**Vision** When?
Quartz watch 10^-5 Quartz 10^-9 matchbox Current CSACs are very small (symmetricon make few mm^3)	Infrastructure security GNSS denial Consumer GNSS denial	Network infrastructure timing Underwater tunnels	Lower price to £500 10^-10 or 10^-11	
CSAC 10^-10 matchbox Cold atom/ion clocks 10^-18. Big room	DEMONSTRATOR NPL/HCF 10^-11 2015	FIRST COMMERCIAL PRODUCT 2016	SECOND COMMERCIAL PRODUCT 10^-14 vapour Optical clock by 2018	Portable atomic clocks. Many flavours 10^-12 large matchox for 2016 10^-14 Yb+ ion. Sr vapour by 2018 10^-18 portable lattice clock. Large rucksack by 2020
		Miniature vacuum technology Computer control FPGA PARTS: - Frequency comb - Chip scale -> Key component	Miniature laser technology Power source (solar power management) Reliability engineering	
Actions	Early demonstraters Stage 1: DSTL/NPL Stage 2: EPSRC hubs	Push to TRL level 5	Large scale production	
Risks	NPL HCF wrong approach	Competition US	De-risk multi-path approach	
Barriers	Industrial partners on board	Cost SI Technology transfer means		

Topic	Medical	Team	AM, MLM, VF	7th August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When? 2025	**Long Term** When? 2040	**Vision** When?
Research components and instruments	MEG too insensitive Too high X-ray and proton dose Need to create new "systems making" Start ups (like teraview Oxford instruments)	Long horizon investors (5-10 years) No UK version of Philips, Siemens GE		Instruments for clinicians Use in NHS
Replace existing MEG with quantum (cure of SQUID)	Single photon detectors Single photon arrays Kromek ltd Gamma single pixel DEMONSTRATOR Nano-scale imaging demonstration Improved medical diagnostics using nano-magnetic imaging Single element magnetization -> squid sensitivity Quantum MEG demonstration	Oxford instruments? Teraview? E2V? - MEG - Low dose X-ray Non-UK (licensing?) FIRST COMMERCIAL PRODUCT As "what"	SECOND COMMERCIAL PRODUCT Validation key NHS (Off all)	Nano scale MRI Coherent anti-ramen scattering (CARS) "noise biochemical" Tells you aloud the bonds present in the matter being illuminated X-rays (ultra low power) and proton detectors for proton beaming therapies MEG and low field MRI magnetoencephalography Single photon imaging systems in THZ-IR Is it important to reduce the dose? What's the market? Reduce - yes - Damage to tissue
Physics understanding lab construction	Single photons arrays: - Magnetic - X-ray Gamma	More research instruments Medical physics research		

Topic	Medical	Team	AM, MLM, VF
Current State	**Short Term**	**Medium Term**	**Long Term**
Actions	Form medical physics exploit club Medical imaging engaging with catapult (precision medicine)	Funded co-location of SMEs on the universities TSBs to form quantum respondance in medical	
Risks	Not enough UK industrial interest UK chooses not to have medical hub Medical imaging applications in other hubs	Insufficient funding sources	
Barriers	NHS does not invest in new technologies	Validation of products	

Topic	Inertial Navigation	Team	AW, TF, ARN	7th August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When?	**Long Term** When?	**Vision** When?
Current competitive techs could replace GPS in some cases: - MEMS low price, low precision - RLG high price, medium precision		Military in GPS denied small market Industrial and emergency services Specialist high-value vehicles Agricultural vehicles	Consumer indoor/outdoor position	Looks like shoebox Industry of military apps for vehicles 10^5 per year replace existing and external
All matter	DEMONSTRATOR 1/2m x 1/2m x 1/2m 50 kg Unreliable	FIRST COMMERCIAL PRODUCT Shoebox size £10k Moderate reliability	SECOND COMMERCIAL PRODUCT £1k product Cig packet size Highly reliable	Shoebox size 1-10m accuracy over 1 hour, £1-10k, reliability not critical
	Atom interferometer principles demonstrated No components yet Necessary technology developments underway	Integrated optics Vacuum chambers and atom sources	Monolithic components	Atom interferometers miniaturised and stand alone Conventional control and processing but needs development and low price components
Actions		Strong commitment and funding from MOD (initial customer) Expectation of procurement Civilian aerospace, most likely earlier adopter. Regulation a barrier		
Risks		Foreign competition Might not work Be hard to develop improved conventional technology		
Barriers	IPR licenses Customer acceptance	Investment in upgrading fabrication facilities		

Topic	Complex Communications		Team: AL, JD, TE	7th August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When?	**Long Term** When? 2030/2035	**Vision** When? 2030/2035
Smart networks securing critical infrastructure e.g. power networks Early QKD point to point systems available now Defence/MOD classified data Data security vulnerabilities QKD promises quantifiable	Large government investments (Japan, China, US) Strong financial sector drivers	QKD standards (ETSI) Industrial standards in quantum comms Increased cloud storage results in much more private data being transferred over national networks	Quantum repeaters 15 years	Corporate communications (counter industrial espionage) Secure D/C Banks Government Defence Consumers if price is right
Size of current solutions are big - needs to be card in a chassis Data rates >10Gb/s Key refresh rate better better than 1 key per second Distance number of nodes	DEMONSTRATOR → 100G QKD on multiplexed switched network field trial →	Key distribution product (independent of a data network) Short range solution - keys and data on same fibre FIRST COMMERCIAL PRODUCT 2 Products - 1) Separate key distribution 2) Quantum distribution on top of data network →	Key distribution based on teleportation Long range solution may be dedicated key distribution network. No data on same fibre Long range solution with key and data on same fibre SECOND COMMERCIAL PRODUCT Hybrid secured network	High speed 100G+ Customer controlled QKD Medium term/non entangled Entanglement (longer term) Set top secure box for consumers/business Multinode multihop network Compact QKD technology Reliable/stable/robust
	Try to use off the shelf components to limit cost Requirement of international, global infrastructure architecture	High speed single photon detectors Compact chip scale interferometers	Component suppliers mass manufacture QKD for systems innovation Quantum optical-to-microwave/THz frequency converters	Quantum repeaters Classical and quantum combiners

Topic	Complex Communications	Team	AL, JD, TE

	Current State	Short Term	Medium Term	Long Term
Actions		Getting the message across Communcations Encouraging collaboration between industry and academia Frequent industry demonstrators to aid education process Field trial QKD prototype systems Point to point productisation EPSRC fund quantum repeater research	Funding for university spin-offs in single photon transmitters, receivers, entanglement generators, quantum repeators	
Risks		Companies not believing they really need it Credibility gap - companies not believing in it	Quantum repeaters do not work	Insufficient private revenue for technology sustainability (not big enough market)
Barriers		Regulartory environment may challenge secure comms QKD component characterisation	Making QKD units compact for mass market	

Topic	Short Term Application of Gravitational Imaging	Team	GB, NG, FH	7th August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When?	**Long Term** When?	**Vision** When? 2020
Research build equipment/no commercial products Ground penetrating radar Classical sensors not as sensitive Prohibitive settle time	Military early adopters		Survey opportunity	Defence for threat voids (100 a year) Civil survey for sink holes (100 a year) Challenges the ground penetrating market
Oil industry operate at coarser length scales	DEMONSTRATOR → Scannable sensor with processing and algorithm unit potentially with ancillary unit (with plans for integration) →	FIRST COMMERCIAL PRODUCT Single package 1m^3 at 5m 1.5m^3 →	SECOND COMMERCIAL PRODUCT Target specs Glossy paint	1m^3 sensor/scanner, 1m^3 void 10m away, £500,000, rugged and easily maintained by a trained user. Smaller voids spec in cm?
Atomic interferometer on 2m^3 kit, relatively mature sensing capability	Vacuum cells with laser feed throughs Atomic cloud inject Packaged lasers Algorithms, maths	Hardware (eng) Software (eng)	Iterate sensors and algorithms	Cold matter wave interferometry - high fidelity vacuum, cold atom source, MOT, laser technology Inversion algorithms -> at lat-long there is a void at this depth
Actions	MOD funding Further TSB funding MOD requirement specs letter of intent to buy product MOD must ensure freedom to operate for commercial exploitation	Trials - MOD sponsored MOD places an order	Work with future catapult	
Risks	Not possible to successfully develop components	New security threat changes direction of defence strategy Sensitivity of measurements in miniaturised device -> algorithm performance		
Barriers	Cannot mitigate risks to get funding Maintaining the long lived atomic clouds (vacuum) (atom injection)			

Topic	Long Term Gravity Imaging	Team	HS, JP, TG	7th August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When? 10 years	**Long Term** When? 15 - 20 yrs	**Vision** When? 2030
No - Current technology very clunky and all classical	Drivers sink hole/mine detection - bomb detection Civil maintenance Civil engineering	Military advantages tends to 100s (export) Replace classical sensors (with low swap and cost) More sensitive, more robust	Oil - advance warning of gas/water encroachment Extraction efficiency -> 10^3 sensors in a field Civil engineering tens of thousands and as price goes down -> £10K -> £1K	Oil industry navigation sensors Prospecting Civil engineering Civil maintanence
Greater sensitivity, better spacial resolution Speed of measurement cycle TRL2 quantum -> surface gravitometer TRL9 but not suitable for target apps	→ DEMONSTRATOR Single sensor miniturized, possibly 3 axis, primitive array Theory and fist tests	→ FIRST COMMERCIAL PRODUCT Domesitic - sink holes and old mines and unstable ground Military - Void/armour/ tunnels/fissile materials	→ SECOND COMMERCIAL PRODUCT Small modular systems -> golf ball size/lego set	10^-9G Packet of Pringles -> golf ball size £10K -> £150K down to £1K dollars per sensor Modular system of sensor heads Infrastructure to form arrays
Classical only Quantum -> TRL2	Technology decisions	Atom clouds/matter waves preparation and manipulation Vacuum systems Optical systems and lasers	Modularity interoperability and standardization -> Physics and electronics	Tiny vacuum 1. Lasers and fibre 2. Electronics 3. Power supply 4. Comms etc

Topic	Long Term Gravity Imaging		Team	HS, JP, TG
Current State	**Short Term**	**Medium Term**		**Long Term**
Actions	MOD fund development as early adopter	TSB/industry identify early markets Manufacturing prototype Supply chain of enabling components Enforce with future catapult for civil engineering app.		Supply chain of systems
Risks	Technical showstopper Change of government/lack of sustained political will	Competition Loss of "momentum"		System fails to deliver sufficient advantage over single sensor head
Barriers		Gaps in subsystem or component inventory Some addressed by DSTL Joining up dots in supply chain		Long term investment

Topic	Point to Point Communications	Team	TS, AS, AL	7th August, 2014

Current State	Short Term	Medium Term	Long Term	Vision
	5 year goal?	When? 5 years	When? 8 - 10 yrs	When? 2020
Better security: Replaced fixed pin with one time quantum key Principle has been demonstrated already (AP labs 2007)		Increased fraught for banks by misuse of bank cards Banks, credit cards, service providers, health Consumer to business and service provider	Consumer to consumer	Cheap point to point fibre QKD building towards more complicated networks Consumers to service providers: Banks, credit cards, security providers, government Alice unit in every smart phone and multiple shared keys
Small cost of Alice unit relative to cost of smartphone Approx £10 Small enough and light enough to fit in smartphone Small additional power consumption Overhead on phone Short range	DEMONSTRATOR Bulk component demonstrator already acheived (HP labs 2007) Integrated demonstrator next step	FIRST COMMERCIAL PRODUCT Commercial ready products in 5 years $1000 Bob $10 Alice	SECOND COMMERCIAL PRODUCT Chip scale Alice and Bob units at comparale cost FIbre combatible chip units	Cheap Alice units "many" transmitter Use expensive Bob "one" unit receiver Shared secret keys for: -Finance -ID -Passports -Entry -Data security 10 to 20K secret key bits in 1 second
Service providers need key management systems to enable implementation	Integrated optics and electronics on chip Security proofs and hacking testing			(Short term) Integrated optics and fast electronics on chip for transmitter Techinal capabiltiy for rapid prototyping Fast error correction and privacy amplification software on relevent processors Wi-Fi/Bluetooth for classical channel Ability to integrate suitable detectors and electronics in Bob unit

Topic	Point to Point Communications		Team	TS, AS, AL
Current State	**Short Term**	**Medium Term**		**Long Term**
Actions	Visibility of funding continuity sustained over about 3 years, not 6 month bursts Funding to develop integrated photonic technology for prototype, for example collaborative R&D with industry Funding user trials (TSB funding)	Establish standards for hardware interoperability and device performance Educate (lobby) a sound technology benefit Government buy-in		
Risks	Existing technologies (competitive) are more compelling to market Combination of different existing security technologies (PIN/camera)			
Barriers		Investor and public understanding -> education/lobbying Cost		

Topic	Consumer Gravity Navigation	Team	DS, EB, RD	7th August, 2014

Current State	Short Term	Medium Term	Long Term	Vision
	5 year goal?	When? 10 years	When?	When? 2040
High cost of maintaining GNSS Limited capability in certain environments of GNSS Traditional accelerometers GPS and WiFi			Consumer robots	UK 30 million Global 4 billion Displacing GPS TomTom (saving cost satellite upgrade) Personal navigation (walking, hiking, orienteering) Car drivers Private pilot (aircraft) Master (private yachts)(boats) Why would you need a quantum GravNav? What's wrong with TomTom?
Price to compete with GNSS - infrastructure and end user hardware	DEMONSTRATOR Military precursor Submarine navigation system	FIRST COMMERCIAL PRODUCT GravNav for hiking (rural) Quadrocopter (delivery) Limited navigation lanes	SECOND COMMERCIAL PRODUCT Military precursor e.g. tank navigation system and aircraft and UAB GravNav for cars/boats/planes (UAVs) Quadcopter package delivery Smart navigation (free flight)	Smart navigation (avoid crashes, avoid traffic) Package delivery (pizza by quadcopter) Navigaton Also monitoring? £80 per unit?
Existing gravity maps	Explore hybrid conventional/quantum accelerometers and gyros Explore merits of candidate gravity sensors for GravNav	Miniaturised accelerometers/gyros for GravNav Experts to integrate chosen gravity sensors in GravNav prototype	Integration with other sensors Extend GravNav products to incorporate SmartNav features (avoid crash) (avoid traffic)	

Topic	Consumer Gravity Navigation		Team	DS, EB, RD

	Current State	Short Term	Medium Term	Long Term
Actions		Confirm business need for consumer Grav	Ensure GravNavs' sensors for military apps can be transferred for consumer uses Legal and policy issues?	
Risks			Delays in miniaturisation	After technology proven for non-consumer applications
Barriers		Competition from existing GPS navigation	Legal issue Liability for navigation errors and crashes (autonomous system)	

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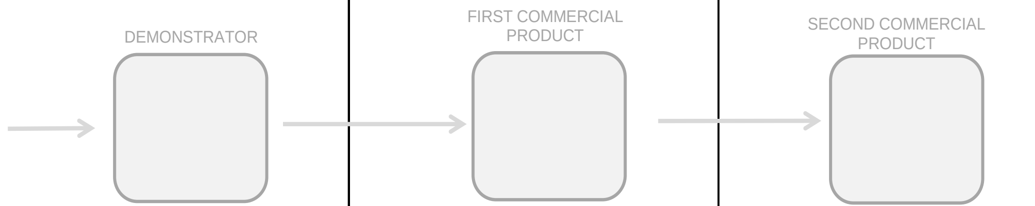
Topic	Scanners	Team		7th August, 2014
Current State	**Short Term** **5 year goal?**	**Medium Term** **When?**	**Long Term** **When?**	**Vision** **When?**
SPM Market Instrumentation (microscopes NMR) ESR	Miniaturisation of electronics	Market research/indsutry Amient- minimal sample preparation		Subcellular image structure in real time (molecular protons) Single molecule MRI Functional nanoscale imaging of materials Quantum enhance SNOM?
Speed Environment e.g. ambient vs vacuum vs cyrogenic Spacial/temperal resolution Sensitivity Chemical selectivity (spectral)	 Demonstrated 1 e-spin detection (single point) Scanning/imaging functionality incorporated (2D/3D)	Reach single nuclear spin sensitivity	Eliminate scanning (multiplexing)	Life sciences Material characterisation
Control of material structure and parity AFM SEM/STEM NMR (bulk 10^15+ spins)	Spacially controlled single ion/atom implementation Entangled THz proton sources Quantum mw THz optical multi-frequency conversion	Readout optics/electronics Entanglement for enhanced sensitivity Readout optics/electronics Printable/configurable sensor arrays	Sensor element arrays	
Actions	Identification of pre-competitive test problem demonstrator	Identify and support earlier doctors Connect to a pharma grand challenge UK government makes UK competitive for high risk R&D lead innovation Engaging with catapult precision medicine		
Risks	Size of market	Benefits reaped by international suppliers e.g. of microscopes		
Barriers		Achieving useability by non-experts		

5.5. London Workshop: Attendees

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6. Workshop 2 Detail

6.1. Participant Alignment with Vision Statements

Quantum Technologies Vision	Industry	Research	Public Sector	Total
UK is a world leader creating wealth from a £1bn+ Quantum Technology industry		13	17	53
High value industries including energy; aviation; communucations; space and civil engineering benefit from new applications based on Quantum Technologies	28	1		52
Quantum technologies are the basis of ubiquitous; compact and cheap everyday objects				
Quantum has replaced digital technologies with transformative impacts over 2015 technologies				
Industry and Universities work together in partnership to continue the UK's leadership of Quantum Technologies				

6.2. Barriers and Actions

Barrier	Action
Early-Stage Difficulties for Engaged Industry	
Start-up growth of SMEs	Build incubator systems
Short term funding for industry who want to engage	New/moved allocations to TSB or DSTL to facilitate industry funding
First mover Disadvantage	Support from government to invest in business model development
Cost of doing product design, development, validation and manufacture	Collaboration business-business to share costs. Public sector support- grants; science transformation funding
Productisation cost and market development cost	Development focus support TSB competition
Difficult for start-ups to find their feet	Funding/infrastructure for start-ups and spin-outs
Innovative disruptive technology usually via SMEs which have inherrent capacity and cashflow issues	Ensure resources are available (pounds/facilites/R&D) to underpin SME innovation
Development of Research into Commercial Applications	
Technology translation	Orchestration of all entities involved (not planning or controlling); end-to-end engineering and delivery of research to exportable product/service
Understanding systems engineering for quantum technologies	Early stage research "Engineering of Quantum reliability" Loughborough Uni
Lack of full understanding of technological and industrial robustness of quantum effect	Effective interfacing between research and industry to develop sustainable pull-through
Need to advance TRLs not invent new science	Hubs must deliver technology demonstrators
Delays to applications, successful demonstrators and loss of engagement of potential users	Co-development and funding for industry of science and industrual capability; Focused results-oriented application contracts; rigorous review of applications progress of Hubs
Technology transfer and lack of skill base in industry	Skilled individual placement from industry to academia via government funding
Inability of quantum to provide early proof of concept in industry	
Market/user understanding of potential of quantum products	Awareness raising
Too many quantum technologies to exploit, too little resource	Technology down selection: which platform technologies to develop and exploit?
TRL value of death	Prioritise techincal progress versus industrial capability
Ignorace or distrust of quantum technology from industry, government and public	Provide early proof of concept in industry
Identifying a must-have volume application for QT which cannot be done today	Directed/dedicated markets analysis to identify; productisation of today's QT
Demonstrators funded through "government"	Credible transition from lab to real application (potential)
Lack of prototype development technologies especially understanding limited theoretical knowledge	Training of researchers, improved training of CDT programmes
Effective knowledge translation	Research and innovation projects should have industrial/academic involvment not in isolation
Demonstrator Quantum Communications networks and standards development	Better links between research, system builders and network operators

6.2. Barriers and Actions (2)

Barrier	Action
Standards	
Establish trust in secure networks	Close interaction between academia, industry and govt on security analysis and hacking to help break this barrier
Space qualification of QT components/products	Disruptive technology centre at Harwell (see space IGS action plan) funding not defined
"CESG" approval for quantum key distribution devices	Investment in hacking and understanding device limitations
Creation of standards	Systems proliferate with lots of inter-connectivity
Chip Fabrication	
A funded programme of development co-ordinated effort to design and fabricate a GM wafer and package it into a FPA	Prototype single photon detector array 256x256 pixels, 512x512 pixels for the Infra-Red
No dedicated quantum platform foundries	Establish quantum foundry supplying key platform devices
Fabrication of devices and chips	UK quantum fabrication foundry with (new tools)
Legislation and Policy	
Lack of clear IP strategy	IP strategy for exploitation established
Lack of clarity on export controls	BIS/MoD to clarify rules/specification
Arguments over IP value between academics and industry	Decide who makes decisions over where fundings should be placed
Long-term stability in government vision and support	Industry needs to convince through engagement

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6.3.1: Trends and Drivers Prioritisation

Rank	Driver	%
1	Improved sensor technologies drive multiple applications	16%
2	GPS Vulnerabilities	14%
3	Data Security Threat	9%
4	Changing Security Threats	8%
5	Medicine: increased sophistication	7%
6	Research and New Technology driving applications	7%
7	Moore's Law reaches quantum regime	5%
8	Oil/gas/resource extraction more complex/hostile	5%
9	Big Data/Internet of Things	4%
10	Demand for stronger Cryptography	4%
11	Increasing scale and complexity	4%
12	Growth of Nano technologies	4%
13	Reliance on data comms	4%
14	Energy and resource security/affordability	3%
15	Global infrastructure	3%
16	Need for information superiority	1%
17	Unknown societal trends and drivers	1%
18	Changing population/demographics	0%
19	UK gets incoming revenue from export	0%

6.3.2: Stakeholder Perspectives Prioritisation

Rank	Needs	%
F	Large companies developing applications for specific challenges	15%
B	Defence: early adopters, building demonstators	13%
C	Industry looking for market demand	11%
A	High Value Manufacturing Supply Chain in UK	9%
D	Short-term ROI/Success Indicators	9%
G	Defence and security contractors looking for non-ITAR value	8%
H	UK Industrial growth strategy	6%
E	TSB/Research funding delivers impact	5%
J	Growth in research sector	5%
L	No level playing field in Defence	5%
M	First Consumer Application Availabile	5%
N	Academic impact indicators	5%
O	SMEs already active and have frontier science market	5%
I	US R&D base : competitor or collaborator?	1%
K	Austerity/risk aversion	0%

6.3.3: Prioritisation of Opportunities

Rank	Opportunity Cluster	Votes
1	Quantum Technology Components	28
2	Atomic Clocks	24
3	Medical Imaging	21
4	Short-term Gravity Navigation	20
5	Complex Communications	18
6	Simple Gravity Imagers	17
7	Complex Gravity Imaging	17
8	Point to Point Communications	13
9	Consumer Gravity Navigation	12
10	Scanners	10
11	Intractable Computing Problems	7
12	Short-term Compute Applications	7
13	Quantum Algorithms/Software	2
14	Quantum Gaming/Gambling	1
15	Multi-sensor Portals/Gate Arrays	1

6.4. Linkage Grids

- Linkage Grids show the linkages between Priority Opportunities and each of Trends and Drivers; Stakeholder Needs; Capabilities and Enablers
- A shaded intersection indicates a linkage between the Trend and Driver (for example) and the Opportunity. A darker colour indicates a stronger relationship.
- The Trends and Drivers and Stakeholder Needs linkage charts were built from linkage information provided at the individual opportunity level
- Capability and Enabler linkage charts were built from information gathered in the Opportunity Commercialisation plans

6.4.1. Workshop 2 Linkage Chart

Trends & Drivers

	Market Opportunities	1 Improved sensor technologies drive multiple appl'ns	2 GPS Vulnerabilities	3 Data Security Threat	4 Changing Security Threats	5 Medicine: increased sophistication	6 Research and New Technology driving applications	7 Moore's Law reaches quantum regime	8 Oil/gas/resource extraction more complex/hostile	9 Big Data/Internet of Things	10 Demand for stronger Cryptography	11 Increasing scale and complexity	12 Growth of Nano technologies
A	Non-Medical Imaging	3			3								
B	Navigation	3	3										
C	Clocks	3					3						
D	Research Components						3						
E	Medical Imaging	3											
F	Through Ground Imaging	3											
G	Point to point Communications			3							3		
H	Complex communications												
I	Quantum Computing												

Market Needs

	Market Opportunities	1 Large companies develop appl'ns for specific challenges	2 Defence: early adopters, building demonstators	3 Industry looking for market demand	4 High Value Manufacturing Supply Chain in UK	5 Short-term ROI/Success Indicators	6 Defence/security contractors looking for non-ITAR value	7 UK Industrial growth strategy	8 TSB/Research funding delivers impact	9 Growth in research sector	10 No level playing field in Defence	11 First Consumer Application Availabile	12 Academic impact indicators
A	Non-Medical Imaging												
B	Navigation												
C	Clocks												
D	Research Components												
E	Medical Imaging												
F	Through Ground Imaging												
G	Point to point Communications												
H	Complex communications												
I	Quantum Computing												

Capabilities

	Market Opportunities	1 Miniature ultra high vacuum cells	2 Miniature lasers	3 Ultra precision clocks	4 Component Integration	5 Electric, Magnetic, Gravitational, RF field sensors	6 Microfabricated devices (ion & atoms traps, optical resonators)	7 Data inversion, signal processing	8 Single Photon Detectors	9 Subsystems (electronic, optical & laser)	10 Sensor and System Models	11 Quantum Interferometers	12 Design for Manufacture	13 Accelerometers	14 Gyros	15 3D Gravity maps	16 Metrology: validation across QT platforms	17 Quantum Computing Methods/Algorithms	18 Complex additive manufacturing and integration	19 Complex technology hybridisation	20 Error-tolerant control
A	Non-Medical Imaging																				
B	Navigation																				
C	Clocks																				
D	Research Components																				
E	Medical Imaging																				
F	Through Ground Imaging																				
G	Point to point Communications																				
H	Complex communications																				
I	Quantum Computing																				

Enablers

	Market Opportunities	1 Strong and broad university based skills	2 Funding- £270m from Defence, EPSRC and TSB	3 University and Industry collaboration	4 Cross University Collaboration	5 QKD Standards	6 Continued funding for research	7 Prototypes/Demonstrators	8 IP protection and business acumen	9 Support for commercialisation of early technologies	10 High vacuum electronic production	11 Specialist laser production	12 EPSRC Hubs
A	Non-Medical Imaging												
B	Navigation												
C	Clocks												
D	Research Components												
E	Medical Imaging												
F	Through Ground Imaging												
G	Point to point Communications												
H	Complex communications												
I	Quantum Computing												

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6.4.2 Trends and Drivers Linkage Chart

Rank	Driver	Non-Medical Imaging	Navigation	Clocks	Research Components	Medical Imaging	Through Ground Imaging	Point to point Communications	Complex communications	Other Components	Quantum Computing
1	Improved sensor technologies drive multiple applications	3	3	3		3	3			3	
2	GPS Vulnerabilities		3								
3	Data Security Threat							3			
4	Changing Security Threats	3									
5	Medicine: increased sophistication										
6	Research and New Technology driving applications			3	3						
7	Moore's Law reaches quantum regime										
8	Oil/gas/resource extraction more complex/hostile									3	
9	Big Data/Internet of Things										
10	Demand for stronger Cryptography							3			
11	Increasing scale and complexity										
12	Growth of Nano technologies										
13	Reliance on data comms										
14	Energy and resource security/affordability										
15	Global infrastructure										

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6.4.3 Stakeholder Needs Linkage Chart

Rank	Needs	Non-Medical Imaging	Navigation	Clocks	Research Components	Medical Imaging	Through Ground Imaging	Point to point Communications	Complex communications	Other Components	Quantum Computing
F	Large companies developing applications for specific challenges										
B	Defence: early adopters, building demonstators										
C	Industry looking for market demand										
A	High Value Manufacturing Supply Chain in UK										
D	Short-term ROI/Success Indicators										
G	Defence and security contractors looking for non-ITAR value										
H	UK Industrial growth strategy										
E	TSB/Research funding delivers impact										
J	Growth in research sector										
L	No level playing field in Defence										
M	First Consumer Application Availabile										
N	Academic impact indicators										
O	SMEs already active and have frontier science market										

6.4.4 Capabilities Linkage Chart

Rank	Capabilities	Non-Medical Imaging	Navigation	Clocks	Research Components	Medical Imaging	Through Ground Imaging	Point to point Communications	Complex communications	Quantum Computing
1	Miniature ultra high vacuum cells	no information provided	■	■	■		■			■
2	Miniature lasers		■	■	■		■			■
3	Ultra precision clocks		■		■			■		
4	Component Integration		■	■	■		■		■	■
5	Electric, Magnetic, Gravitational, RF field sensors					■	■			
6	Microfabricated devices (ion & atoms traps, optical resonators)		■	■	■	■	■			■
7	Data inversion, signal processing				■	■	■	■	■	■
8	Single Photon Detectors				■	■			■	
9	Subsystems (electronic, optical & laser)		■	■	■	■	■		■	■
10	Sensor and System Models		■		■	■	■		■	■
11	Quantum Interferometers		■				■			
12	Design for Manufacture		■		■		■	■		■
13	Accelerometers		■	■	■		■			
14	Gyros		■							
15	3D Gravity maps		■				■			
16	Metrology: validation across QT platforms			■		■	■			■
17	Quantum Computing Methods/Algorithms									■
18	Complex additive manufacturing and integration		■			■	■			■
19	Complex technology hybridisation								■	■
20	Error-tolerant control									■
21	Quantum chemistry / biology					■				
22	High level system integration		■				■			■
23	Industrial strength design		■		■		■			■

6.4.5. Enablers Linkage Chart

Rank	Enablers	Non-Medical Imaging	Navigation	Clocks	Research Components	Medical Imaging	Through Ground Imaging	Point to point Communications	Complex communications	Quantum Computing
1	Strong and broad university based skills	information not provided	■		■		■		■	■
2	Funding- £270m from Defence, EPSRC and TSB		■	■	■	■	■		■	■
3	University and Industry collaboration		■	■	■	■	■		■	■
4	Cross University Collaboration		■		■	■	■		■	■
5	QKD Standards							■	■	
6	Continued funding for research			■		■	■		■	■
7	Prototypes/Demonstrators		■	■	■	■	■	■	■	■
8	IP protection and business acumen		■		■		■		■	■
9	Support for commercialisation of early technologies		■	■			■	■	■	■
10	High vacuum electronic production		■		■		■			■
11	Specialist laser production		■	■	■		■			
12	EPSRC Hubs		■	■	■	■	■		■	■
13	Consistent regulatory environment (Export controls)						■		■	■
14	UK chip-scale fabrication facilities		■	■		■	■		■	■
15	Understanding value chain			■	■		■	■	■	■
16	Conventional infrastructure for utilisation of shared secret keys.								■	
17	Availability of Metro and national dark fibre networks.								■	
18	Inertial Navigation expertise		■				■			
19	Sensor array mathematics		■				■			
20	High quality linked communities		■						■	■
21	Quantum financiers		■				■		■	■
22	Quantum simulators		■							■
23	Highly efficient, cost effective volume manufacture		■	■						■
24	High performance test equipment in place by investment		■				■			■

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6.5 Topic Roadmaps and Business Plans

- Non-Medical Imaging
- Navigation
- Clocks and Timing
- Research Components
- Medical Imaging
- Through Ground Imaging
- Point to point Communications
- Complex Communications
- Quantum Computing

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Topic	Non-medical imaging	Team	RL, PD, MP	21st August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When? 10 years	**Long Term** When? 20 years	**Vision** When?
IR cameras >> 10k SWIR <=> FIR Multispectral/multiband cameras > £				Environmental science: Pollutant tracking; Volcano alerts; Oil spill response; Tsunami Quantum technologies to deliver imaging that no conventional approach can match Instrumentation: Better microscopes; Better telescopes Defence: Ranging; Surveillance; Tracking Oil/gas: Prospecting -with gravity -with gas seepage
Hydrocarbon prospecting: - Seismic 100yr old - Other modalities explored - Crying out for gravity/hydrocarbon market massive > $1B Defence Thermal imaging 3-5 &10-12 > 40k InGa SWIR 1-2micro m >20k "Convert" lab based system to demonstrator	DEMONSTRATOR Non ITAR Geiger mode array Single photon sensitivity with time of flight Imaging/comms 6D MEMs based gravity imager 10ng/sqrt(Hz) Compact superconductivity detector and array Very low cost (single pixel) Non-visible imager 1-2 micro m (SWIR) Imaging array with polarisation sensitive pixels	Real world trial by end user FIRST COMMERCIAL PRODUCT Oil/gas/water boundary detector using gravity Low cost surveillance camera Sensing system using gravity data to enhance seismic imaging High frame rate Large FOV Time stamped SWIR $<10k	SECOND COMMERCIAL PRODUCT	

Topic	Non-medical imaging		Team	RL, PD, MP

Current State	Short Term	Medium Term	Long Term
Actions	The hubs must produce demonstrators YES this is so essential for credibility	Industry needs support to develop demonstrators into product Tax incentives for quantum R&D	Sustained funding to maintain UK discovery science and lead
Risks	Possible gap between academic invention and industry pick-up	Need customers education to drive demand Reluctant IP transfer from university to company	
Barriers		TRL gap between Universities and industry Sharing/transfer of IP	

Topic	Navigation	Team	DB, AM	21st August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When?	**Long Term** When?	**Vision** When?
GPS in phone and MSEMS gyro + acc. In build up GPS First responders and military			Medical in hospital Patient/doctor location Assisted living Vulnerable/critical personnel Advertising	Personal nav $5 1cm^3 1bn/anum Nav accuracy <0.1m Mobile phone size Nav market
Power: 10mW Size: 1cm^3	DEMONSTRATOR DSTL 5 yrs	FIRST COMMERCIAL PRODUCT Submarine 10^6cm^3 £10M 10 off months 1nm/24hrs -> 1nm/month 0.1nm/24hrs	SECOND COMMERCIAL PRODUCT High value ships £1M 1000 off/anum 24hrs 0.5m^3	12-5 hours 100m
Proof on concept achieved at component level	Proof of principle at nav	Road trial Sea trial Reduction of size and power	UK band design capability UK band quantum lab	MEMS vacuum over 2 years life Lasers (low cost)

Topic	Navigation	Team	DB, AM

Current State	Short Term	Medium Term	Long Term
Actions	DSTL/EPSRC/TSB stakeholders working in concert	Technology transfer to industry Long term outlook for development in industry Organic self sustained development	
Risks		Product champion required No market take up - market timing wrong	
Barriers		Standardization not in place High volume depends on economic variables (energy cost, infrastructure etc)	

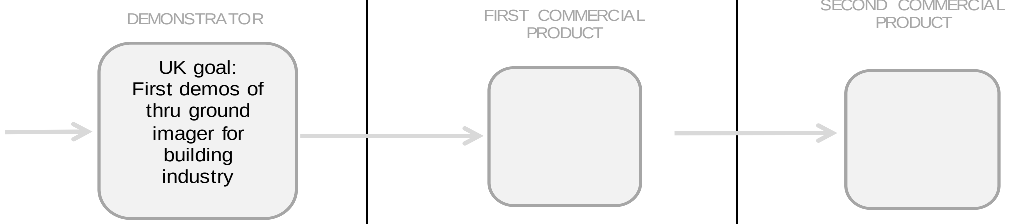
Topic	Clocks and Timing	Team	JO, PG, PL	21st August, 2014

Current State	Short Term 5 year goal?	Medium Term When?	Long Term When?	Vision When?
Thermal Clock Yes demonstrable tech. Yes CSAC competition. Demand precision timing and synchronisation High Cell Optical Clock Yes demonstrable tech demonstrated. Yes competition from e.g. US, China, Korea with same technology. Currently high end nav, earth monitoring communications		Develop and test market demand and business uses for different products in conjunction with LEPs		Markets: GNSS Defence, space communications, timing, commerce, seismology, air traffic management, network synchronisation
	DEMONSTRATOR Thermal Clock Thermal hollow core clock demo 2015/16 in UK Cold Matter Clock Demo in e.g. Airbus by 2020	FIRST COMMERCIAL PRODUCT Thermal Clock Demo -> 1st product within 2 years from demo Cold Matter Clock 1st product by 2022	SECOND COMMERCIAL PRODUCT	Thermal Clock Stability 10^-12 matchbox in 5 years £1k. Chip in 15 years £10. 24/7 reliability Numbers 1000s -> millions Why is chip cost so high (£10)? Why not $1? Cold Matter Clock High ace optical clock. Hand luggage in 10 yrs plus stability 10^-15 or better. Potentially space quality £100billion - £100 million + Numbers 100s-1000s
				Thermal Clock Single laser GHz modulation, hollow fibre technology, fast detector, ASIC control, CPT technique so research ready. Production engineering needed Research for production engineering to scale up Cold Matter Clock Multiple semi-c lasers, UHV, FPGA -> ASIC, laser cooling, optical cavity oscillator, 1Hz wide clock laser with vibration insensitivity, feedback electronics, optical fibre integration UTAS airbus, LM system integrators

Topic	Clocks and Timing	Team	JO, PG, PL

Current State	Short Term	Medium Term	Long Term
Actions		Develop incubator lab for proof of concept, both technology and business Full engagement from research group through SME to systems integrator Engage advanced Eng catapult	
Risks		Risk from US, Korea, China with competitive products and technologies Science knowledge, engineering capability needs to be sorted, market knowledge needs enhancing Mkt consumers and pushback from EU	
Barriers		Might miss particularly large consumer application e.g. e-commerce	TSB to help stimulate industry buy-in

Topic	Research components - Component supply chain	Team	DP, TC, GM	21st August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When? 2 - 7 years	**Long Term** When?	**Vision** When? 2030
Today's market: 200 new set ups for cold atom research p.d. at £500K = £100m Competition: - Thor Labs - AOSense - Cold Quanta - Toptica/Coherent/Maglabs - Many small, emerging Demand: Fundamental science research and timing MOT availability: - Cold Quanta - Toptica - Kai's via UK co.	2 year goal -Lasers -Optical std components -Vacuum equipment -Control electronics and computing -Specialist cold atom cells Fast integration and applications development Flexible Lego modules for quantum research	Next generation research kit and proof of concept systems X x £100m Application specific module built prototype systems Component driven Reduce cost Easier to integrate -> modular Driver from research: Ease of use Subsystem integration 		Future research components: -Smart, easier to use lab modules -Optical and vac systems £300m Packaged IC style atom chip/MOT sensors on the shelf Qty: Millions p.a. at £100ea. 
	Standard labs -> atomic clocks Scientific research of Bose Einstein condensate in traps			
		This is the plan for the components		

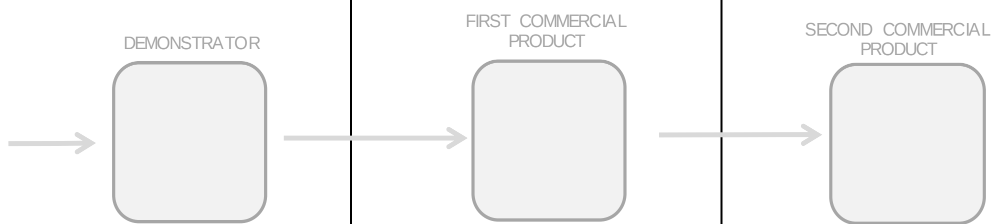


Topic	Research components - Component supply chain	Team	DP, TC, GM

	Current State	Short Term	Medium Term	Long Term
Actions		Common modules across hubs Technology down sector for demonstrators EPSERC to have pro-forma consortium IP contract for all hubs Ensure that academic and hub research matches industrial base	Scale up (BB) investment to secure value creation in UK Common supply chain development across hubs and industry Yes and eop: SI supply chain Essential to ensure feed into vibrant systems Integrate sectors	UK corp tax regime to be world's quantum centre Patent box already in place
Risks		Slow and/or insufficient funding for industry No focus Scope creep/drift in hubs program (Reversion to blue skies science) Academic and hub research not matched to industrial base	Incumbent technology (silicon) continues to improve and move the goal posts (also QSC) Lack of systems integration capability to connect/design components available	Benefits move overseas
Barriers		Productisation £ Market dev. £		Long term CAPEX investment

Topic	Medical Imaging	Team	BH, MG, SB	21st August, 2014

Current State	Short Term 5 year goal?	Medium Term When? 2024	Long Term When? 2035	Vision When?
Current product exist for same application Current products do not exist for full vision Absence of adequate sensor size and sensitivity		Very large market demand will increase government and industry demand/interest and limits to current tech		Societal health. Everyone - medical Large medical industry £1-5 billion mostly displacing some breakthrough Living large with good quality of life
Large size. Inadequate accuracy and precision. Price £100-200k? Reliable but not fit for purpose Realtime in vivo no products (we think)	Increasing performance in sensors through R&D Industry and research collaboration is essential SMEs used to commercial use Steer from larger market	Higher TRL components. Increased performance of sensors and algorithms. Better biochemistry knowledge Company -> commercial interest in UK	Multiple companies developing products Medical community involvement in trials	Realtime in Vivo diagnostics (spectroscopy, imaging) Size - small, mobile devices hand-held and deployable in operating theatre Accuracy: Better than human eyes, better than nav. Reliability medium Range - short range usually against skin. Price: less than £100,000
Drain - low performance capability but small scale high precision is available in lab. Quantum involved For realtime! CARS demonstrated in lab but not deployable and too basic/non specific Funding - exist NHS partnerships and charities Very early stage quantum: TRL 1 -> 3. Funding - no specific ch funding and H2020 exist	High quality sensors Computation, modelling biological/medical R&D to define parameters Input from wider QT initiative	Qualified components standard. Advanced manufacturing in commercial organisation Skilled analysis and interpretation Input from wider QT initiative Medical community engagement -> early adapters	Medical trailers and acceptance Input from wider QT initiative	Small sensors with high sensitivity -> system integration Breakthrough -> sensor tech High quality components at reasonable price, not ultra cheap



Topic	Medical Imaging	Team	BH, MG, SB
Current State	**Short Term**	**Medium Term**	**Long Term**
Actions	R&D -> translate -> product Company engagement Funding vision (stability) TSB - ensure companies engage through funding/facilities but with oversight -> end goal Ensure wider QT community engagement UK network	Generate relevant IP Ensure government support. Engage NHS and medical charities TSB actions -> long term funding stability vision	Continuous development and research
Risks	Tech doesn't exist which can be commercialised -> mitigation short Unknown disruptive tech - high risk Evolution or decreased price of current tech - unlikely. Regulatory issues Medical/biochem research IP doesn't exist or unknown Yield of components small	Unknown disruptive tech Current technology resistance/evolution Larger company intervention/pickup Subcomponents not all mature at right time -> ensure supply chain is there.	Disruptive tech IP extraction by buyout
Barriers	Larger industry resistance - timescale to mature component. Price point. Relevant skills in workforce	Regulatory/acceptance Medical community engagement Gov-authority or NHS to decide/accept Price -> company risk or funding to underpin Quantum component maturity and limits IP outside UK	Regulatory issues IP outside UK

Topic	Through ground imaging and gravity mapping	Team	ST, BL, KB	21st August, 2014

Current State	Short Term 5 year goal?	Medium Term When?	Long Term When?	Vision When?
Current product: - Cold atom lab demonstrators Aosense - Gravity gradiometer from Lockheed Martin based on different technology - Scintrex FG5 for gravity CA sensors 10-100 times better performing at 1/10th - 1/100th cost		See step 1		Defence £20 - 50M for 10-20 units New market On 2030/2035 timescale moving to 1000s of units ~£100M
Size <m^3 Accuracy <~1E/sqrt(Hz) Price: Simple version ~30k Defence/oil ~1M	DEMONSTRATOR 2020 through ground imaging outside lab 2025 space prototype	FIRST COMMERCIAL PRODUCT Defence 2025 gravity imanger2030 oil and gas exploration device on moving platform	SECOND COMMERCIAL PRODUCT Civil engineering sensor Space sensors	Defence: ~m^3; ~1Eotvoes/sqrt(Hz); ~£2M ~Resolution corresponding to 1/10th of depth Space: 1mE, i.e. resolution of ~km Global range First unit ~£100M; further units £10M Autonomous operation for ~3 years without failure Civil engineering: 10cm pipes of 2m depth; ~£30k Oil/gas/minerals/water: ~1E; ~£1M/instrument
Lab demonstrations exist First spin-outs started internationally on specific restricted markets EU projects and ESA projects pushing technology	Lasers, vacuum, system modelling, invention algorithms, system architecture Systems engineering			Cold atom technology - already proven in lab - laser, vacuum and system integration concepts needed at commercial level

Topic	Through ground imaging and gravity mapping	Team	ST, BL, KB

Current State	Short Term	Medium Term	Long Term
Actions	Funding for industry Systems modelling -Multi-sensor fusion Engagement with end users	Miniaturisation and cost reduction Industry investments into larger scale production	Wafer scale integration A processes
Risks	IP leakage International competition Skill protection Mitigation: concerted action across UK and stakeholders	Unknown noise sources,... Mitigation: Simulations, engineering tests Space qualification	
Barriers	Getting buy-in from chief finance officers in industry DSTL mitigating barriers Innovative funding by TSB		

Topic	Point to point QKD	Team	BV, AM, AN	21st August, 2014
Current State	**Short Term** 5 year goal?	**Medium Term** When?	**Long Term** When?	**Vision** When? 2020
Benefits hard to understand Cannot work over all existing infrastructure				Banks/finance corporation generally defence companies Government sites Satcom operators Banks, corporations, defence, healthcare, government Auto key generate and safe distribution (then used to encrypt link) PSK can be used for quantum tech - any PSK carrier Link authenticated
In lab	DEMONSTRATOR → Develop your 'carrier independent' link end boxes Simplification of the story →	Still need repeaters FIRST COMMERCIAL PRODUCT Expensive box 'corporate' →	SECOND COMMERCIAL PRODUCT Cheap box 'personal'	Simple 'offerings' resolved Encryption/authentication box

Topic	Point to Point QKD		Team	BV, AM. AN

Current State	Short Term	Medium Term	Long Term
Actions	Cofunding by TSB/X to enable market? Better explanation of QKD Explain the concept in user terms	Conduct a study to evaluate the incremental value of improved security Move from high value point-point to consumer point-point	POC
Risks	Extra security too expensive		Too expensive?
Barriers	Standards! Need to understand what is offered and what not protected "Security is a hard sell"		"Incumbents"

Topic	Complex Communications	Team	GB, MW	21st August, 2014

Current State	Short Term 5 year goal?	Medium Term When?	Long Term When?	Vision When?
Current public-key works and is used. Potential issues identified Some need for long-term security guarantees				USERS:- Government, corporate financial, critical infrastructure, ultimately SME domestic UK cyber security market £2.8billion 2013, £3.4billion 2017 Growing market some displacement
Bit-rates distance number of users. Reliability must be good (not 100%) Mostly point-to-point in operation	→ DEMONSTRATOR Integrated transmitter and receivers Repeater architectures →	FIRST COMMERCIAL PRODUCT Secure network (without repeaters) routed architectures few km →	SECOND COMMERCIAL PRODUCT Advanced secure network -> entanglement based? More nodes, longer distance	Mainly fibre based Satellite links Microwave links Free-space links to moving vehicle Multi-tiered approach Expensive, high system key rate system for high-level customers Comparable reliability to current free comms Standardisation must be established for networks Price range per node £10,000s + high-value <£10 per node (domestic user)
KM+ systems in operation in UK, China, USA, Switzerland, Japan, Australia	Miniaturised integrated transmitter + receiver modules Repeaters Examine new protocols Mass-production of components	Security analysis Integration with classical comms integration System trials Standardisation		Sub-system miniaturisation, robustness, low-cost, low-energy, inexpensive Advances required in routing, multiplexing, repeaters

Topic	Complex Communications	Team	GB, MW
Current State	**Short Term**	**Medium Term**	**Long Term**
Actions	Improve interaction between academic and industrial research groups Interact with network operators, government and other early adopters of quantum communications EPSRC/TSB funding prototype demonstrator networks	Interaction/support from standardisation and certification authorities EPSRC/TSB and other funding of component development, security research and device indepth architectures	
Risks		Work to be done on repeaters Too late acceptance of current risks	
Barriers	Price? Distances achievable? High development costs	Price issues International competition	

Topic	Quantum Computing	Team	RM, TF, LO	21st August, 2014
Current State	**Short Term**	**Medium Term**	**Long Term**	**Vision**
	5 year goal?	When? 15 years	When? 25 years	When? 2040
D-wave $10million machine. 2 machines, 1 upgrade ~ 1000 qubit. D-wave fostering startups. Well funded by banks. Software. Many platforms for quantum computers. Annealed vs gated. Solid state, cold atoms.	Quantum inspired computing: Market for failed quantum computers. Sensing/overlap with sensors groups.	Cryptography security High performance computing Finance/pharma etc mapping/attracting new markets Fit with what are the needs for high performance computing?		Start: Academia, defence, space, blue-chip tech, banking, pharma,…, consumer Specialist computing A quantum compute in/available for every home? Some price on top spec Apple Mac. 'Computer' may not be available in the form we know currently Shor/Grover what size is the market?
Defence, blue-chip tech space perceived short term demands: -> from finance, security. Measurement/standards setting quantum computing Number of qubits (10 ions, 1,000 d-wave). Decoherence, power, weight, reliability Practical purpose as an applied research/educational tool Quantum computer 'architecture' -> for donor spins in which silicon is fault tolerant	Companies selling hardware to expertise. Big Q.C. companies DEMONSTRATOR Single Qubit sensor technologies	Few qubits quantum computer for select problems Algorithm optimisation FIRST COMMERCIAL PRODUCT Quantum to classical translation. Quantum co-processor	SECOND COMMERCIAL PRODUCT	30 qubit, fully connected quantum computer 'hidden' quantum element NVQ-level IT practitioners for quantum computers Scalable - Moor's Law silicon fault tolerance -> based on surface code -> large inter-qubit spacing (~500nm) + 4x10^8 physical donor qubits -> 1x1cm chip
UCL Q-theory centre for quantum computing (foreign centre in Maryland-internation collaboration) Turing gateway Programmable w/ high level languages	Scalable architecture - technology selection Other requirements. Developing manufacturing facilities Quantum hub network Developing manufacturing facilities	Quantum computing facility Technology down-selection to a single concept for quantum computer (per application)		Manufacturing, design all well established Engineers, software, teachers etc focused on QC ubiquitous Quantum computing infrastructure

Topic	Quantum Computing	Team	RM, TF, LO
Current State	**Short Term**	**Medium Term**	**Long Term**
Actions	Supporting quantum computing (££) Collaboration between academia and industry - industry input industry lead projects	Attractive for investors - Gov, VCs, international, large companies Standardisation End-user feedback Proof of market development programmes	
Risks	Public perception is that quantum computing is quantum technologies 'Too long term?' Disagreement about down-selection Due to high R&D cost should down select happen early (< 3 years)?	Maintain/developing competitive advantage? No value-add for quantum computing Are conventional business models suitable for quantum computing?	Evolution of societal needs -> change of direction
Barriers	IP models -> idealistic (amalgamation of academic and business routes to commercialisation) Skills. Getting skills into industry Attracting foreign talent	Cost of production Efficient marketing -> public perceptions open to new ideas Regulatory procedures -> ability to export	

6.6 Glasgow Workshop Attendees

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