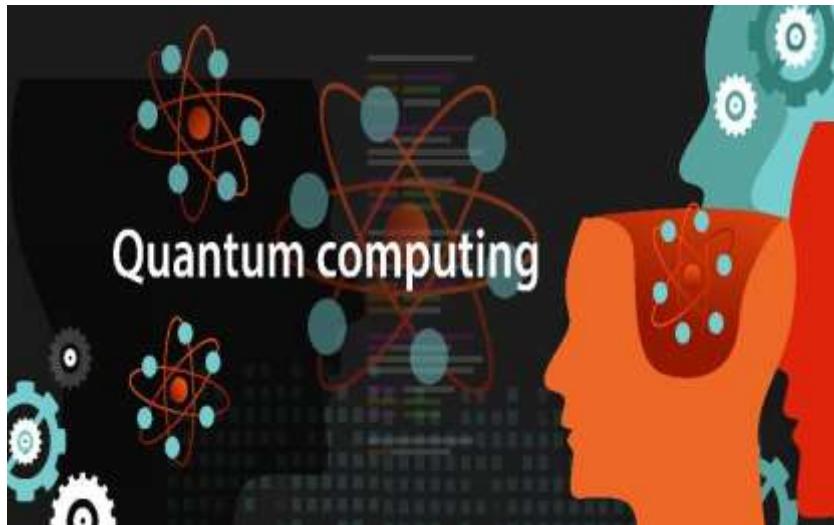


2018-2024

# Quantum Computing Industry, Technologies & Business Opportunities



*Industry 4.0 Research*

# Quantum Computing Industry, Technologies & Business Opportunities

2018-2024

**Industry 4.0 Research (A division of HSRC)**  
**601 Pennsylvania Ave. Washington D.C., U.S.A**  
**[www.Industry40marketresearch.com](http://www.Industry40marketresearch.com)**

## Table of Contents

<b>1</b>	<b>Executive Summary .....</b>	<b>17</b>
1.1	Major Findings & Conclusions .....	17
1.2	Global Quantum Computing Market – 2016-2024 .....	29
 <b>QUANTUM COMPUTING BACKGROUND .....</b>		 <b>30</b>
<b>2</b>	<b>Global Information Technology (IT) Market.....</b>	<b>30</b>
<b>3</b>	<b>Quantum Computing.....</b>	<b>31</b>
<b>4</b>	<b>Why Are Quantum Computers Attractive?.....</b>	<b>35</b>
<b>5</b>	<b>Quantum Computing Outlook .....</b>	<b>37</b>
<b>6</b>	<b>Quantum Supremacy .....</b>	<b>38</b>
<b>7</b>	<b>Quantum Technologies Timeline .....</b>	<b>40</b>
<b>8</b>	<b>Investments in Quantum Computing .....</b>	<b>47</b>
<b>9</b>	<b>Quantum Computing Technology Roadmap.....</b>	<b>48</b>
<b>10</b>	<b>Topological Quantum Computers.....</b>	<b>49</b>
<b>11</b>	<b>The 2<sup>nd</sup> Quantum Revolution .....</b>	<b>50</b>
<b>12</b>	<b>Private Sector Quantum Computing R&amp;D Activities .....</b>	<b>51</b>
<b>13</b>	<b>The Global Quantum Computing Race .....</b>	<b>54</b>
<b>14</b>	<b>China – U.S. Quantum Information Leadership Race.....</b>	<b>55</b>
<b>15</b>	<b>Government-Funded RDT&amp;E .....</b>	<b>57</b>
<b>16</b>	<b>Moore's Law Outlook .....</b>	<b>58</b>
<b>17</b>	<b>Quantum Information Bids and Projects Data .....</b>	<b>60</b>
<b>18</b>	<b>Quantum Computing Industry SWOT Analysis .....</b>	<b>66</b>
18.1	Quantum Computing Industry: Strengths .....	66
18.2	Quantum Computing Industry: Weaknesses.....	66
18.3	Quantum Computing Industry: Opportunities .....	67
18.4	Quantum Computing Industry: Threats .....	68
<b>19</b>	<b>Quantum Computing Value Chain .....</b>	<b>69</b>
 <b>VERTICAL SECTORS &amp; APPLICATIONS .....</b>		 <b>70</b>
<b>20</b>	<b>Quantum Computing Demand Side .....</b>	<b>70</b>
20.1	Quantum Computing Vertical Sectors & Applications Roadmap .....	70
20.2	Defense & Intelligence Quantum Computing .....	72

20.2.1	National Security Intelligence .....	72
20.2.2	Defense .....	74
20.3	Homeland Security & Public Safety Quantum Computing .....	74
20.3.1	Public Safety .....	74
20.3.2	Homeland Security .....	75
20.4	Government & Public Services Quantum Computing .....	75
20.5	Banking & Securities Quantum Computing .....	76
20.6	Manufacturing & Logistics Quantum Computing .....	77
20.7	Insurance Industry Quantum Computing .....	78
20.8	Healthcare & Pharmaceutical Industry Quantum Computing .....	79
20.8.1	Overview .....	79
20.8.2	Medical Diagnostics Quantum Computing.....	79
20.8.3	Medical Treatments Quantum Computing .....	80
20.8.4	Example: Combating Cancer.....	80
20.8.5	The Folding@home Project.....	81
20.8.6	Pharmacology Quantum Computing .....	81
20.8.7	Protein Folding Quantum Computing .....	82
20.9	Retail & Wholesale Industry Quantum Computing .....	82
20.9.1	Market Background .....	82
20.10	Information Technology Industry Quantum Computing.....	83
20.10.1	Software Verification & Validation .....	83
20.11	Telecommunications Industry Quantum Computing .....	83
20.12	Automotive, Aerospace & Transportation Industry Quantum Computing .....	84
20.13	Energy & Utilities Industry Quantum Computing .....	87
20.14	Web, Media & Entertainment Industry Quantum Computing .....	87
20.15	Smart Cities Quantum Computing .....	87
20.16	Cybersecurity Quantum Computing .....	88
20.17	Machine Learning .....	91
20.18	Search Engines.....	92
20.19	Business Intelligence .....	93
20.20	Software/Hardware Validation and Verification .....	93
20.21	Image and Pattern Recognition.....	94
20.22	Banking & Financial Services Industries .....	94
20.23	Financial Electronic Trading & Trading Strategies .....	95
20.24	Retail & Wholesale Industry .....	96
20.25	Energy Systems & Photovoltaics Industry .....	97
20.26	Energy Exploration Industry .....	97
20.27	Academia & National Labs.....	97
20.28	Graph Theory Problems.....	98
20.29	Material Science .....	98
20.30	Marine Science .....	99
20.31	Bioinformatics .....	100
20.32	Climate Modeling & Weather Predictions.....	100
20.33	Seismic Survey Industry .....	101
20.34	Risk Management.....	101

20.35	Simulation .....	102
20.36	Video Compression.....	103
20.37	Cryptography .....	103
20.37.1	Quantum Cryptography .....	103
20.37.2	Post-Quantum Cryptography .....	103
20.38	QC-Based Optimization Problems .....	104
20.38.1	Optimization Problems .....	104
20.38.2	Quantum-Assisted Optimization .....	104
20.38.3	Reservoir Optimization Applications .....	105
20.38.4	Utilities Management Optimization .....	105
20.39	Quantum Computing Based Machine Learning .....	106
20.39.1	Quantum Machine Learning .....	106
20.39.2	Quantum Reinforcement Learning .....	106
20.40	Big Data & Predictive Analytics.....	107
20.41	Material Science Industry.....	107
20.42	Quantum Sampling .....	108
20.43	Quantum Chemistry .....	108
20.44	Monte Carlo Simulation.....	109
<b>NATIONAL ACTIVITIES &amp; INDUSTRY .....</b>		<b>111</b>
<b>North America .....</b>		<b>111</b>
<b>21</b>	<b>U.S. Quantum Computing .....</b>	<b>111</b>
21.1	U.S. Quantum Computing Background.....	111
21.1.1	U.S. Government Quantum Computing.....	111
21.1.2	U.S. Government Investment in Quantum Computing: Introduction.....	112
21.1.3	DOD: Quantum Computing Activities, Projects & Funding .....	112
21.1.4	DOE: Quantum Computing Activities, Projects & Funding .....	113
21.1.5	NSA: Quantum Computing Activities, Projects & Funding .....	114
21.1.6	IARPA: Quantum Computing Activities, Projects & Funding .....	114
21.1.7	NIST: Quantum Computing Activities, Projects & Funding .....	115
21.1.8	NSF: Quantum Computing Activities, Projects & Funding .....	116
21.1.9	U.S.A. Supercomputing Race.....	116
21.1.10	Federal Quantum Computing Outlook - 2018-2024.....	117
21.1.11	U.S. Private Sector Quantum Computing Background .....	118
21.1.12	U.S. Quantum Computing RDT&E .....	119
21.2	The U.S.-Chinese, Quantum Technology Race .....	120
21.2.1	Scope .....	120
21.2.2	U.S. Strategic Considerations .....	121

21.2.3	Quantum Encryption and Communication Race.....	122
21.2.4	The Quantum Sensing Race .....	123
<b>22</b>	<b>Canada Quantum Computing .....</b>	<b>125</b>
22.1	Canada Quantum Computing Background .....	125
<b>Europe .....</b>		<b>126</b>
<b>23</b>	<b>EU Quantum Computing Industry &amp; R&amp;D Activities.....</b>	<b>126</b>
23.1	Introduction .....	126
23.2	EU Research Frameworks.....	127
23.3	European Commission Future & Emerging Technologies Program QC Activities.....	127
23.3.1	Funding .....	127
23.3.2	The EU Cloud Initiative .....	128
23.3.3	The EU Quantum Technology Flagship.....	129
23.3.4	The EU Quantum Technology Program .....	129
23.4	The EU Quantum Computing Industry Program .....	130
<b>24</b>	<b>UK Quantum Computing.....</b>	<b>132</b>
24.1	UK Quantum Computing Background.....	132
<b>25</b>	<b>France Quantum Computing .....</b>	<b>134</b>
25.1	France Quantum Computing Activities.....	134
25.1.1	France QC National Network.....	134
25.1.2	Quantum Computation in France .....	134
25.1.3	Quantum Group.....	135
25.1.4	Atos SE .....	135
25.1.5	IBM France.....	136
25.1.6	Paris Centre for Quantum Computing .....	137
<b>26</b>	<b>Netherlands Quantum Computing .....</b>	<b>138</b>
26.1	Netherlands Quantum Computing Activities .....	138
<b>27</b>	<b>Denmark, Sweden, Norway, Finland Quantum Computing.....</b>	<b>141</b>
27.1	Denmark, Sweden, Norway, Finland Quantum Computing Activities.....	141
<b>28</b>	<b>Germany Quantum Computing .....</b>	<b>142</b>
28.1	Germany Quantum Computing Activities .....	142
<b>29</b>	<b>Russia Quantum Computing .....</b>	<b>143</b>
29.1	Russia Quantum Computing Activities.....	143
<b>Asia-Pacific .....</b>		<b>145</b>
<b>30</b>	<b>India Quantum Computing.....</b>	<b>145</b>
30.1	India Quantum Computing Background .....	145
<b>31</b>	<b>China Quantum Computing .....</b>	<b>146</b>
31.1	China Quantum Computing Background .....	146
31.1.1	Quantum Information in China.....	146
31.1.2	Government-Funded RDT&E .....	148

31.1.3	Made in China 2025 Program.....	148
31.1.4	Chinese Quantum Computing Advances.....	149
31.1.5	PRC's Quantum Cryptography and Communications .....	150
31.1.6	PRC Quantum Sensing Programs.....	151
31.1.7	China-U.S. Quantum Information Race .....	152
31.1.8	Limitations of the U.S. Quantum Information Programs .....	153
31.1.9	U.S. vs. Chinese Intellectual Property (IP) Race .....	154
31.1.10	China Supercomputing Lead .....	156
<b>32</b>	<b>Japan Quantum Computing.....</b>	<b>158</b>
32.1	Japan Quantum Computing Activities .....	158
<b>33</b>	<b>Singapore Quantum Computing .....</b>	<b>159</b>
33.1	Singapore Quantum Computing Activities .....	159
<b>34</b>	<b>Australia Quantum Computing.....</b>	<b>160</b>
34.1	Australia Quantum Computing Activities .....	160
<b>Latin America &amp; MEA.....</b>		<b>161</b>
<b>35</b>	<b>Brazil Quantum Computing .....</b>	<b>161</b>
35.1	Brazil Quantum Computing Activities .....	161
<b>36</b>	<b>GCC Quantum Computing .....</b>	<b>162</b>
36.1	Market Background.....	162
36.2	GCC Quantum Computing Activities.....	162
<b>37</b>	<b>Israel Quantum Computing.....</b>	<b>163</b>
37.1	Israel Quantum Computing Activities .....	163
<b>COMPANIES .....</b>		<b>164</b>
<b>38</b>	<b>Quantum Computing Startups .....</b>	<b>164</b>
<b>39</b>	<b>Quantum Computing Companies.....</b>	<b>167</b>
39.1	1Qbit .....	167
39.1.1	Company Profile .....	167
39.1.2	Quantum Computing Activities .....	167
39.2	Agilent Technologies.....	168
39.2.1	Company Profile .....	168
39.2.2	Quantum Computing Activities .....	168
39.3	Aifotec AG.....	168
39.3.1	Company Profile .....	168
39.3.2	Quantum Computing Activities .....	169
39.4	Airbus Group.....	169
39.4.1	Company Profile .....	169
39.4.2	Quantum Computing Activities .....	169
39.5	Alcatel-Lucent .....	170
39.5.1	Company Profile .....	170
39.5.2	Quantum Computing Activities .....	170

39.6	Alibaba Group Holding Limited .....	170
39.6.1	Company Profile .....	170
39.6.2	Quantum Computing Activities .....	171
39.7	Anyon Systems, Inc .....	171
39.7.1	Company Profile .....	171
39.7.2	Quantum Computing Activities .....	171
39.8	Artiste-qb.net .....	172
39.8.1	Company Profile .....	172
39.8.2	Quantum Computing Activities .....	172
39.9	Avago Technologies .....	172
39.10	Booz Allen Hamilton.....	172
39.10.1	Company Profile .....	172
39.10.2	Quantum Computing Activities .....	173
39.11	British Telecommunications (BT) .....	173
39.11.1	Company Profile .....	173
39.11.2	Quantum Computing Activities .....	174
39.12	Cambridge Quantum Computing Limited.....	174
39.12.1	Company Profile .....	174
39.12.2	Quantum Computing Activities .....	174
39.13	Ciena Corporation.....	175
39.13.1	Company Profile .....	175
39.13.2	Quantum Computing Activities .....	175
39.14	Cyoptics .....	176
39.14.1	Company Profile .....	176
39.14.2	Quantum Computing Activities .....	176
39.15	D-Wave Systems Inc .....	176
39.15.1	Company Overview .....	176
39.15.2	Quantum Computing Activities .....	177
39.16	Eagle Power Technologies, Inc.....	177
39.16.1	Company Profile .....	177
39.16.2	Quantum Computing Activities .....	178
39.17	Emcore Corporation.....	178
39.17.1	Company Profile .....	178
39.17.2	Quantum Computing Activities .....	178
39.18	Enablence Technologies.....	178
39.18.1	Company Profile .....	178
39.18.2	Quantum Computing Activities .....	178
39.19	Entanglement Partners .....	179
39.20	Fathom Computing .....	179
39.20.1	Company Profile .....	179
39.20.2	Quantum Computing Activities .....	179
39.21	Finisar Corporation .....	179
39.22	Fujitsu Limited.....	180
39.22.1	Company Profile .....	180
39.22.2	Quantum Computing Activities .....	180
39.23	Google Quantum AI Lab .....	182

39.23.1	Company Profile .....	182
39.23.2	Quantum Computing Activities .....	182
39.24	H-Bar Quantum Consultants .....	183
39.25	Hewlett Packard Enterprise Company .....	183
39.25.1	Company Profile .....	183
39.25.2	Quantum Computing Activities .....	184
39.26	IBM .....	184
39.26.1	Company Profile .....	184
39.26.2	Quantum Computing Activities .....	185
39.27	ID Quantique .....	186
39.27.1	Company Profile .....	186
39.27.2	Quantum Computing Activities .....	186
39.28	Infinera Corporation .....	187
39.28.1	Company Profile .....	187
39.28.2	Quantum Computing Activities .....	187
39.29	Intel Corp. ....	188
39.29.1	Company Profile .....	188
39.29.2	Quantum Computing Activities .....	188
39.30	IonQ .....	189
39.30.1	Company Profile .....	189
39.30.2	Quantum Computing Activities .....	189
39.31	JDS Uniphase Corporation .....	189
39.32	Kaiam Corporation .....	189
39.32.1	Company Profile .....	189
39.32.2	Quantum Computing Activities .....	190
39.33	Lockheed Martin Corp. ....	190
39.33.1	Company Profile .....	190
39.33.2	Quantum Computing Activities .....	190
39.34	MagiQ Technologies, Inc. ....	191
39.34.1	Company Profile .....	191
39.34.2	Quantum Computing Activities .....	191
39.35	Microsoft Quantum Architectures and Computation Group (QuArC) .....	192
39.35.1	Company Profile .....	192
39.35.2	Quantum Computing Activities .....	192
39.36	Mitsubishi Electric Corp. ....	192
39.36.1	Company Profile .....	192
39.36.2	Quantum Computing Activities .....	193
39.37	NEC .....	194
39.37.1	Company Profile .....	194
39.37.2	Quantum Computing Activities .....	194
39.38	Nokia Bell Labs .....	195
39.38.1	Company Profile .....	195
39.38.2	Quantum Computing Activities .....	195
39.39	NTT Basic Research Laboratories & NTT Secure Platform Laboratories .....	195

39.39.1	Company Profile .....	195
39.39.2	Quantum Computing Activities .....	196
39.40	Optalysys Ltd. ....	196
39.40.1	Company Profile .....	196
39.40.2	Quantum Computing Activities .....	196
39.41	Post-Quantum.....	197
39.41.1	Company Profile .....	197
39.41.2	Quantum Computing Activities .....	197
39.42	QbitLogic.....	197
39.42.1	Company Profile .....	197
39.42.2	Quantum Computing Activities .....	197
39.43	QC Ware Corp. ....	198
39.43.1	Company Profile .....	198
39.43.2	Quantum Computing Activities .....	198
39.44	Quantum Circuits .....	198
39.44.1	Company Profile .....	198
39.45	Quantum Hardware Inc.....	199
39.45.1	Company Profile .....	199
39.45.2	Quantum Computing Activities .....	199
39.46	QuantumCTek.....	199
39.46.1	Company Profile .....	199
39.46.2	Quantum Computing Activities .....	199
39.47	Qubitekk.....	199
39.47.1	Company Profile .....	199
39.47.2	Quantum Computing Activities .....	200
39.48	Quintessence Labs .....	200
39.48.1	Company Profile .....	200
39.48.2	Quantum Computing Activities .....	200
39.49	QxBranch.....	200
39.50	Raytheon BBN .....	201
39.50.1	Company Profile .....	201
39.50.2	Quantum Computing Activities .....	201
39.51	Rigetti Computing .....	202
39.51.1	Company Profile .....	202
39.51.2	Quantum Computing Activities .....	202
39.52	SeQureNet.....	203
39.53	SK Telecom .....	203
39.53.1	Company Profile .....	203
39.53.2	Quantum Computing Activities .....	203
39.54	Sparrow Quantum.....	204
39.54.1	Company Profile .....	204
39.54.2	Quantum Computing Activities .....	204
39.55	Toshiba .....	204
39.55.1	Company Profile .....	204
39.55.2	Quantum Computing Activities .....	204
39.56	Xanadu .....	205

<b>APPENDICES.....</b>	<b>206</b>
<b>40 Appendix A: Introduction to Quantum Computing.....</b>	<b>206</b>
40.1 Superposition .....	208
40.2 Entanglement.....	208
40.2.1 Ion-based Qubits .....	209
40.2.2 Superconducting Qubits .....	210
40.2.3 Solid-State Spin Qubits .....	210
<b>41 Appendix B: Quantum Information Technologies .....</b>	<b>211</b>
41.1 Quantum Information .....	211
41.2 Shared Principles.....	211
41.3 Quantum Computing.....	211
41.4 Quantum Cryptography:.....	212
41.5 Quantum Sensing .....	213
<b>42 Appendix C: Quantum Computing Hardware.....</b>	<b>215</b>
<b>43 Appendix D: Quantum Computing Software.....</b>	<b>216</b>
43.1 Introduction to Quantum Algorithms.....	216
<b>44 Appendix E: Quantum Encryption .....</b>	<b>217</b>
44.1 Background.....	217
44.2 Key Findings .....	217
44.3 Spooks Reacting at a Distance .....	219
<b>45 Appendix F: Global 50 Top Supercomputers.....</b>	<b>221</b>
<b>46 Appendix G: Industry Investment in Quantum Computing – 2006-2016 .....</b>	<b>226</b>
<b>47 Appendix H: NQIT R&amp;D Projects .....</b>	<b>230</b>
47.1 Background.....	230
47.2 Architectures, Standards and Systems Integration .....	230
47.3 Ion Trap Node Engineering .....	230
47.4 Atom-photon Interfaces.....	231
47.5 Photonic Network Engineering.....	231
47.6 Solid State Node Engineering .....	231
47.7 Secure Communications and Verification .....	232
47.8 Networked Quantum Sensors .....	232
47.9 Quantum Digital Simulation .....	232
47.10 Hybrid Classical/Quantum Computing .....	233
47.11 Capabilities and Support.....	233
<b>48 Appendix I: Exascale Computing.....</b>	<b>234</b>
48.1 Exascale Computing Definition .....	234
48.2 U.S. Exascale Computing Activities .....	234
48.3 China Exascale Computing Activities.....	234
48.4 EU Exascale Computing Activities .....	234
48.5 Japan Exascale Computing Activities .....	235
48.6 India Exascale Computing Activities .....	235

48.7	Exascale Computing Challenges .....	235
<b>49</b>	<b>Appendix J: Key Quantum Computing Patents .....</b>	<b>236</b>
49.1	Patents List .....	236
49.2	Quantum Computing Patent Filing by Country .....	244
<b>50</b>	<b>Appendix K: Links to 31 Quantum Computing Academic Research Centers .....</b>	<b>245</b>
<b>51</b>	<b>Appendix L: 2017 Quantum Conferences Links .....</b>	<b>247</b>
<b>52</b>	<b>Appendix M: Glossary.....</b>	<b>251</b>
<b>53</b>	<b>Appendix N: References .....</b>	<b>253</b>
<b>54</b>	<b>Scope &amp; Methodology .....</b>	<b>270</b>
54.1	Research Scope .....	270
54.2	Research Methodology .....	270
<b>55</b>	<b>Disclaimer &amp; Copyright .....</b>	<b>272</b>

## List of Tables

Table 1 - Global Quantum Computing Market* [\$M] by Region – 2016-2024 .....	29
Table 2 - Global Quantum Computing Market* AGRs [%] by Region – 2016-2024.....	29
Table 3 - The Global IT Market [\$B] & Market Share [%] By Revenue Source – 2017 .....	30
Table 4 - Global IT Market Share [%] By Region – 2016 .....	30
Table 5 - Global IT Market [\$B] By Industry – 2016 .....	30
Table 6 - Quantum Computing Investment by Investor.....	47
Table 7 - Government-Funded RDT&E by Country – 2016 .....	57
Table 8 - Quantum Information 2014-2017 Bids and Projects .....	60
Table 9 - European Quantum Technology Program Expected Applications .....	130
Table 10 - Startup Quantum Computing Companies .....	164
Table 11 - Commercial Investment in Quantum Computing – 2006-2016 .....	226

## List of Figures

Figure 1 - Quantum Computing Applications Organogram .....	28
Figure 2 - Three Types of Quantum Computing and Applications .....	32
Figure 3 - TNO Quantum Technologies Timeline Outlook – 2015-2035 .....	46
Figure 4 - Quantum Computing Technology Roadmap.....	48
Figure 5 - Leading IT Companies and Defense Contractors Investing in Quantum Computing.....	52
Figure 6 - Leading Quantum Computing Companies Technology Approaches.....	53
Figure 7 - Quantum Computing, Patent Applications by Country to 2015.....	55
Figure 8 - Quantum Patent Applications Timeline 2000-2015.....	56
Figure 9 - Quantum Computing: Vertical Sectors & Applications Roadmap .....	70
Figure 10 - QC Promises to Aerospace Activities .....	86
Figure 11 - The UK QC Research Hubs .....	133
Figure 12 - QuTech Focus Areas.....	138
Figure 13 - Dutch Quantum Computing Research Centers .....	139
Figure 14 - The Dutch 2016-2022 H2020 QC Research Program .....	140
Figure 15 - China Quantum Computing, Patent Applications Status.....	154
Figure 16 - China Quantum Patent Applications Timeline Vs. The U.S. Japan, Europe & Korea .....	155
Figure 17 - Quantum Computing Investor – Company Relationship .....	165
Figure 18 - Qubit Explanation .....	208
Figure 19 - Quantum Entanglement.....	209
Figure 20 - Control Systems for the Ion-Trap System.....	233
Figure 21 - Quantum Computing, Quantum Cryptography and Sensors Quantum Patent Applications by Country 2000 to 2015 .....	244
Figure 22 - Patent Applications by Country – 2000-2015.....	244