Annexe A: New/Revised Course Content in OBTL+ Format

Course Overview

Expected Implementation in Academic Year	AY2025-2026
Semester/Trimester/Others (specify approx. Start/End date)	Semester 2
Course Author * Faculty proposing/revising the course	Rainer Helmut Dumke
Course Author Email	rdumke@ntu.edu.sg
Course Title	Quantum Hardware
Course Code	PH3410
Academic Units	3
Contact Hours	39
Research Experience Components	Not Applicable

Course Requisites (if applicable)

Pre-requisites	PH2101 Quantum Mechanics 1
Co-requisites	
Pre-requisite to	
Mutually exclusive to	
Replacement course to	
Remarks (if any)	

Course Aims

In this course you will be exposed to quantum engineering which is accelerating from laboratory science to industrial deployment. National initiatives and private investment now target concrete deliverables: scalable quantum processors and field ready quantum sensors for navigation, defense, communications, and climate monitoring. Delivering those devices requires a multidisciplinary hardware skill set cryogenics, ultra high vacuum, precision lasers, microwave and RF control, integrated photonics that is rarely taught in a single coherent course.

Course's Intended Learning Outcomes (ILOs)

Upon the successful completion of this course, you (student) would be able to:

ILO 1	Describe the operating principles, material requirements and control stacks of superconducting, ion trap, neutral atom and photonic quantum processors.
ILO 2	Explain fine structure, hyperfine and Zeeman splitting and apply these to predict transition frequencies and selection rules relevant for qubit definition.
ILO 3	Analyse laser cooling limits; design basic trapping schemes for neutral atoms and ions to reach motional ground state.
ILO 4	Compare entangling gate mechanisms across platforms, calculate expected fidelities from key noise sources, and justify hardware choices for fault tolerant architectures.
ILO 5	Derive phase shift expressions for light pulse atom interferometers under acceleration, gravity and rotation, and evaluate sensitivity using realistic noise and systematic budgets.
ILO 6	Explain Rydberg electromagnetically induced transparency spectroscopy and calculate electric field strengths from Autler–Townes splittings across microwave and radio frequency ranges.
ILO 7	Estimate magnetometer sensitivity, bandwidth and vector versus scalar measurement capability.
ILO 8	Quantitatively assess hardware overheads of surface code error correction, including cryogenic, vacuum, optical and classical control resource demands for different qubit platforms.
ILO 9	Interpret published performance metrics, datasheets and roadmaps to benchmark emerging quantum hardware and communicate informed recommendations to technical and non technical audiences.
ILO 10	Design and present a concise proposal for a novel quantum computing or sensing device, justifying feasibility, expected impact and integration within existing technology ecosystems.

Course Content

I. Foundations of Quantum Hardware

1. Atomic structure, fine/hyperfine levels & laser-cooling basics
2. Qubit / sensor definitions, coherence budgets and error channels
3. Core infrastructure: cryogenics, UHV, precision lasers & RF control

II. Quantum-Computing Platforms

1. Superconducting circuits: Josephson devices, microwave gates, read-out
2. Trapped-ion and neutral-atom arrays: trapping, Rydberg or motional gates
3. Photonic processors & emerging hybrid architectures

III. Quantum-Sensing Platforms

1. Atom-interferometric gravimeters, gradiometers and inertial units
2. Rydberg-atom electromagnetic-field sensors (RF / microwave)
3. Magnetometers with NV-diamond and alkali-vapor cells

IV. Engineering & Scalability

1. Control electronics, cryo-CMOS/FPGA stacks and packaging strategies
    1. Fault-tolerance resource overheads and heterogeneous networking
    2. Field deployment considerations: SWaP optimisation and reliability

Reading and References (if applicable)

We will draw from a mix of textbooks and contemporary research literature. These books and articles collectively cover the physics foundations, hardware implementations, sensing modalities and engineering know-how necessary to support the topics taught throughout the semester.

General Overviews

Michael A. Nielsen & Isaac L. Chuang, Quantum Computation and Quantum Information, 10th Ann. Ed., Cambridge Univ. Press (2010). ISBN: 9781107002173

Jonathan P. Dowling & Gerard J. Milburn, Quantum Technology: The Second Quantum Revolution, Taylor & Francis (2003). ISBN: 3319988239

K. Krantz et al., “A Quantum Engineer’s Guide to Superconducting Qubits,” Appl. Phys. Rev. 6, 021318 (2019).

Atomic Structure, Laser Cooling & Trapping

Harold J. Metcalf & Peter van der Straten, Laser Cooling and Trapping, Springer (1999). ISBN: 9780387987286

C.J. Foot, Atomic Physics, Oxford Univ. Press (20*05). ISBN 0198506961*

D.A. Steck, Rubidium 87 D-Line Data (revision 2.2.2, open-access PDF).

Quantum-Computing Hardware Platforms

Superconducting Circuits

7. M. Kjaergaard et al., “Superconducting Qubits: Current State of Play,” Annu. Rev. Condens. Matter Phys. 11, 369 (2020).

8. J.M. Gambetta, J.M. Chow & M. Steffen, “Building Logical Qubits in a Superconducting Quantum Computing System,” npj Quantum Inf. 3, 2 (2017).

Trapped Ions & Neutral Atoms

9. D. Leibfried et al., “Quantum Dynamics of Single Trapped Ions,” Rev. Mod. Phys. 75, 281 (2003).

10. Y. Saffman, M. Walker & K. Mølmer, “Quantum Information with Rydberg Atoms,” Rev. Mod. Phys. 82, 2313 (2010).

11. A. Browaeys & T. Lahaye, “Many-Body Physics with Individually Controlled Rydberg Atoms,” Nat. Phys. 16, 132 (2020).

Photonic Processors & Hybrids

12. T. Rudolph, “Why I Am Optimistic About the Silicon-Photonic Route to Quantum Computing,” APL Photonics 2, 030901 (2017).

13. J.-W. Wang et al., “Integrated Photonic Quantum Technologies,” Nat. Photon. 14, 273 (2020).

Quantum-Sensing Platforms

Atom Interferometry

14. A. Cronin, J. Schmiedmayer & D. Pritchard, “Optics and Interferometry with Atoms and Molecules,” Rev. Mod. Phys. 81, 1051 (2009).

15. K. Bongs et al., “Taking Atom Interferometric Quantum Sensors from the Laboratory to Real-World Applications,” Nat. Rev. Phys. 1, 731 (2019).

Rydberg Electromagnetic Sensors

16. J.P. Holloway et al., “Broadband Rydberg Atom-Based Electric-Field Probe for SI-Traceable, Self-Calibrated Measurements,” APL 104, 244102 (2014).

17. X. Simons et al., “Microwave Detection Using Rydberg Atoms in a Vapor Cell,” Phys. Rev. Applied 14, 024002 (2020).

NV-Diamond & Vapor-Cell Magnetometry

18. J.F. Barry et al., “Sensitivity Optimization for NV-Diamond Magnetometry,” Rev. Mod. Phys. 92, 015004 (2020).

19. S. Rondin et al., “Magnetometry with NV Centres in Diamond,” Rep. Prog. Phys. 77, 056503 (2014).

Engineering & Control

S. Pauka et al., “A Cryogenic Interface for Controlling Many Qubits,” Nature Electronics 4, 64 (2021).

M. Lake et al., “Integrating Classical Control and Quantum Hardware,” IEEE Trans. Quantum Engineering 2, 3104616 (2021).

NOTE: The above readings comprise the foundational readings for the course and more up-to-date relevant readings will be provided when they are available.

Planned Schedule

Week or Session	Topics or Themes	ILO	Readings	Delivery Mode	Activities
1	Foundations of Quantum Hardware	1-2	See references	In-person	Lecture
2	Superconducting Qubits I – Physics & Components	1-2	see references	In-person	Lecture
3	Superconducting Qubits II – Control, Read-out & Scaling	1-2	see references	In-person	Lecture
4	Atomic Structure Fundamentals for Quantum Technology	1-2	see references	In-person	Lecture
5	Laser Cooling & Trapping Techniques	9-10	see references	In-person	Lecture
6	Trapped Ion Quantum Computers	3-4	see references	In-person	Lectures
7	Neutral Atom Arrays & Rydberg Gates	3-4	see references	In-person	Lecture
8	Photonic Quantum Computing	5-6	see references	In-person	Lecture
9	System Level & Hybrid Architectures	5-6	see references	In-person	Lecture
10	Atom Interferometry Fundamentals	7-8	see references	In-person	Lecture
11	Atom Interferometry Applications & Engineering	7-8	see references	In-person	Lecture

Week or Session	Topics or Themes	ILO	Readings	Delivery Mode	Activities
12	Rydberg Atom Sensors for Electromagnetic Fields	7-8	see references	In-person	Lecture
13	Magnetometry with NV Centers & Alkali Vapor Cells	All	see references	In-person	Lecture

Learning and Teaching Approach

Approach	How does this approach support you in achieving the learning outcomes?
Lectures	Pre-lecture readings will be assigned, in partial flip-classroom approach. Face-to-face lectures in small class sizes for direct interaction and feedback.
Tutorials	Tutorials will have a focus on student-centred learning. Students will also share their work on the projects during the tutorial sessions.
Project	Individual-based and inquiry approach to project work

Assessment Structure

Assessment Components (includes both continuous and summative assessment)

No.	Component	ILO	Related PLO or Accreditation	Weightage	Description of Assessment Component	Team/Individual	Rubrics	Level of Understanding
1	Continuous Assessment (CA): Project(Project)	1-8		30	Refer to Rubric	Individual	Analytic	Multistructural
2	Continuous Assessment (CA): Assignment(Homework)	1-8		15	The student need to prepare a course specific homework.	Individual	Analytic	Extended Abstract
3	Summative Assessment (EXAM): Final exam(The exam will assess the students understanding of the course specific topics.)	All		50	Written Exam	Individual	Analytic	Relational
4	Continuous Assessment (CA): Class Participation(In lecture quizzes)	1-10		5	administered by Wooclap.	Individual	Analytic	Multistructural

Description of Assessment Components (if applicable)

NA

Formative Feedback

You will be given feedback in four ways:

1. By working through examples provided during lectures
2. By attending consultation hours
3. By studying the comments provided by the instructors after the grading of homework, midterm, and project

NTU Graduate Attributes/Competency Mapping

This course intends to develop the following graduate attributes and competencies (maximum 5 most relevant)

Attributes/Competency	Level
Communication	Intermediate
Curiosity	Intermediate
Problem Solving	Intermediate
Critical Thinking	Advanced
Systems Thinking	Basic

Course Policy

Policy (Academic Integrity)

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values. As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. On the use of technological tools (such as Generative AI tools), different courses / assignments have different intended learning outcomes. Students should refer to the specific assignment instructions on their use and requirements and/or consult your instructors on how you can use these tools to help your learning. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Policy (General)

You are expected to complete all assigned readings, activities, assignments, attend all classes punctually and complete all scheduled assignments by due dates. You are expected to take responsibility to follow up with assignments and course related announcements. You are expected to participate in all project critiques, class discussions and activities. All project assignments must be submitted on time. Failure to do so will affect your score.

Policy (Absenteeism)

In-class activities make up a significant portion of your course grade. Absence from class without a valid reason will affect your participation grade. Valid reasons include falling sick supported by a medical certificate and participation in NTU's approved activities supported by an excuse letter from the relevant bodies. There will be no make-up opportunities for in-class activities.

Policy (Others, if applicable)

Diversity and inclusion policy
To help accomplish this:
Integrating a diverse set of experiences is important for a more comprehensive understanding of science.
It is our goal to create an inclusive and collaborative learning environment that supports a diversity of perspectives and learning experiences, and that honours your identities; including ethnicity, gender, socioeconomic status, sexual orientation, religion or ability.
If you are neuroatypical or neurodiverse, have dyslexia or ADHD (for example), or have a social anxiety disorder or social phobia;
If you feel like your performance in the class is being impacted by your experiences outside of class;
If something was said in class (by anyone, including the instructor) that made you feel uncomfortable;
Please speak to your teaching team, our school pastoral of cer or a peer or senior (either in-person or via email) about how we can help facilitate your learning experience.
As a participant in course discussions, you should also strive to honour the diversity of your classmates. You can do this by: using preferred pronouns and names; being respectful of others opinions and actively making sure all voices are being heard; and refraining from the use of derogatory or demeaning speech or actions.
All members of the class are expected to adhere to the NTU anti-harassment policy. if you witness something that goes against this or have any other concerns, please speak to your instructors or a faculty member.

Appendix: Rubrics for Project (30%)

Oral Presentation (Assessed Individually) – 20%

Criteria	Unsatisfactory (1)	Satisfactory (2)	Good (3)	Exemplary (4)
Presentation Skills: (a) Organization (25%)	Inadequate content, with some links across slides. Takeaways are either unclear or contain some ambiguity.	Adequate content with across slides. Key takeaways for some slides clear. Citations are given, but with missing references.	Relevant content, mostly linked coherently across slides. Key takeaways for most slides are clear. Citations are appropriate and in consistent format.	Relevant contents are linked coherently across slides. Key takeaways for each slide are clear. Citations are appropriate and in consistent format.
Presentation Skills: (b) Delivery & Timing (25%)	Unclear and unengaging. Grossly under or over-estimate presentation time.	Mostly clear and understandable. Kept to allocated presentation time.	Clear and well prepared. Kept to allocated presentation time. Reasonable emphasis on own contribution	Engaging, clear and well prepared. Kept to allocated presentation time with emphasis on own contribution.
Q&A: (a) Subject Knowledge (25%)	Does not display adequate knowledge of the subject matter.	Displays some knowledge of the subject matter.	Displays good knowledge of the subject matter.	Displays comprehensive and deep knowledge of the subject matter.
Q&A: (b) Ability to Explain Answers (25%)	Unable to understand and answer questions.	Able to understand and answer some questions.	Able to understand and answer most questions.	Able to understand and answer all questions and also provide relevant information.

Written Report (Assessed Individually) – 10%

Criteria	Unsatisfactory (1)	Satisfactory (2)	Good (3)	Exemplary (4)
Organization and Clarity (25%)	Organization has inadequate connection between ideas. Writing is mostly unclear or inaccurate. Word limit not kept.	Organization displays some logical and coherent connection of ideas. Writing is mostly clear and accurate, with many errors. Word limit kept.	Organization displays mostly logical and coherent connection of ideas. Writing is mostly clear and accurate, with some errors. Word limit kept.	Organization displays logical and coherent connection of ideas. Writing is clear and accurate, with no errors. Word limit kept.
Literature Review (25%)	Unclear state of the sub-field. Reviews contain some inappropriate sources. Inadequate background or motivation.	Communicates state of sub-field. Reviews some appropriate sources. Gives some background and/or motivation.	Clearly communicates state of sub-field. Reviews appropriate sources. Gives some background and/or motivation.	Clearly and accurately communicates state of sub-field. Reviews appropriate and up-to-date sources. Gives comprehensive background and motivation.
Application of Physics (50%)	Incorrect or inappropriate use of physical theories in the modeling of problem. Inadequate explanation of methodology, assumptions, approximations or computational techniques.	Correct and appropriate use of physical theories in the modeling of problem. Some aspects of methodology, assumptions, approximations and computational techniques missing or lacking in detail.	Correct and appropriate use of physical theories in the modeling of problem. Methodology, assumptions, approximations and computational techniques mostly clearly explained.	Correct and appropriate use of physical theories in the modeling of problem. Methodology, assumptions, approximations and computational techniques clearly and comprehensively explained.