MSc Quantum Computing and Quantum Technologies

Course descriptions

QY1. Quantum Computing
Elements of Quantum Mechanics. States of quantum systems. Vectors and operators in Hilbert space. Two-state quantum systems. Bras and Kets. The quantum bit (qubit). Qubit representation in the Bloch sphere. Quantum registers. Basis states of qubits and quantum registers. One-qubit quantum gates: The Hadamard, the phase-shift and the inertial quantum gates. Pauli quantum gates. Two-qubit quantum gates: The controlled-not (CNOT) and the controlled-phase-shift quantum gates. Three-qubit quantum gates: The controlled-controlled-Not (CCNOT) and the Fredkin quantum gates. The circuit model of quantum computation. Quantum circuits and the principle of quantum computation. Quantum computations. The Deutsch quantum algorithm. The Grover quantum algorithm. Quantum Fourier transform. Entanglement. The Shor quantum algorithm. Quantum teleportation. The quantum computer simulator (QCS). The Qiskit quantum simulator. Quantum algorithms on real quantum computers.

QY2. Quantum Devices
Semiconducting devices: quantum wells - 2DEG devices (HEMT) -quantum dots - Coulomb blockade- Single Electron Transistor (SET) - Tunnel FET. Superconducting devices: Josephson effect - Josephson junctions - superconducting electronic circuits - dc and ac squid sensors. Molecular Magnets: definition (description of the compounds) - organic molecules - transition metal and rare earth ions mono-and poly-nuclear compounds - molecular spins (endohedral fullerenes and/or encapsulated atoms) - impurities in solids

QY3. Quantum Algorithms and Quantum Information
Quantum computing in noisy environments. Quantum error correction. The nine-qubit error correcting code. Stabilizer codes. Surface error correcting codes. The density operator. The reduced density operator. Pure and mixed quantum states. Measurement and partial measurement of quantum states. Ensembles of quantum states. Quantum simulators. Quantum algorithms. Entropy and quantum information. Von Neumann entropy. Elements of quantum cryptography: quantum key distribution. The BB84 and novel quantum key distribution protocols. The quantum walk model of quantum computation. Quantum walks in one and two dimensions. Adiabatic quantum computation. The quantum Ising model for optimization. Variational quantum algorithms and eigensolvers. Applications of quantum computing.

QY4. Qubit devices
CMOS qubits (QD FET - P-dopants in Si devices – Nitrogen vacancies in Diamond – topological insulators) - Superconducting qubits - Molecular magnets – Atom traps

QE1. Optical and quantum communications
Essential basics: Wave nature of light, E/M waves, physical optics, optical waveguiding. Key components and modules: Optical fiber (operation, characteristics, types), passive elements (couplers, isolators, filters, multiplexers/demultiplexers), active devices (sources, modulators, amplifiers, photodetectors). Optical signal processing: Optical nonlinearities, nonlinear media, modern switching and limitations, optical switches and gates, applications to sequential and combinational circuits, optical interconnects, photonic integration. Optical communications systems: Basic parts, technological evolution, performance limitations and characterization, design of real systems. Optical communications networks: Topologies, Wavelength Division Multiplexing, optical data centers, optical access networks, passive optical networks. Optical quantum communications: Concept, infrastructure, networks, limitations, challenges.

QE2. Computational Biology
What is life? From molecules to organisms and back. Fundamentals of evolution. Genomes, sequencing, sequences, and their databases. Homology and similarity: sequence alignments. Database searches: BLAST and friends. Protein families, motifs, and their databases. Connecting the dots: sequence-based phylogenetic analysis and clustering. Gene expression, networks, pathways and their databases. Genetic variation: characterization, analysis and databases. Atoms, molecules and energy: getting up-close-and-personal with life. Structures illustrated: from the double helix to the ribosome. Making structures: homology modelling, docking and drug design. Protein folding: energy, structure, function and evolution.

QE3. Nanoelectronics
Quantum mechanical description of nanomaterials - Nanoelectronic and spintronic devices: quantum dots, nanowires, nanopillars, quantum transport and tunneling effects, magnetoresistance, spin-dependent electron transport, molecular electronics, and graphene and 2D nanomaterials.

QE4. Quantum Solid State Physics
Semiconductor nanostructures – Quantum confinement – Semiconductor heterostructures – Quantum Hall effect – Semiconductor/dielectric tunnel junctions – Superconductivity and physics of superconductors - Static Magnetic properties (Hyperfine interactions, Spin orbit coupling and single ion anisotropy, Exchange coupling) - Dynamic Magnetic properties (Real and imaginary magnetic susceptibility, Spin Relaxation times, Rabi oscillations).

QE5. Applied Quantum Mechanics
Basic features: Schrödinger’s equation, operators, expectation values, probability density and probability current density, superposition principle, eigenvalues, uncertainty principle. One dimensional problems: free-particle, symmetric quantum wells, combination of infinite and finite-barrier potential well, delta function potential, combination of delta function potentials and heterostructures or quantum wells, triangular potential. Scattering in one dimension: transmission and reflection coefficients, tunneling and resonant tunneling in simple and complex barriers, the propagation matrix method, WKB approximation for tunneling. Periodic potential and the Kronig-Penney model. Additional mathematical issues: More on operators, eigenstates and the measurement problem, Dirac notation. Harmonic oscillator: Algebraic method of the harmonic oscillator, creation and annihilation operators, calculation of the wavefunctions with the algebraic method and calculation of expectation values, Stark effect in the harmonic oscillator, quantization of the LC circuit, quantization of lattice vibrations-phonons, free electron in a magnetic field - Landau states and connection to the semiclassical orbit. Electron in a central potential: angular momentum, application to spherical "hard" potential and finite spherical potential, solution for hydrogen-like systems and applications in excitons in semiconductors. Spin: an intrinsic angular momentum and its description, addition of angular momentum. Approximation methods: time-independent non-degenerate perturbation theory and time-independent degenerate perturbation theory and their applications, the variational method, WKB approximation for stationary states and its applications, the sudden approximation. Identical particles, Pauli exclusion principle and the symmetry of the wavefunctions. Applications in atoms, molecules, nanostructures, and solids.

QE6. Artificial Intelligence and Applications
Overview of the current Artificial Intelligence (AI) domain. AI applications. Current and future AI challenges in a Quantum Computing world. The interaction of Quantum Physics and AI. Introduction to the scientific method for AI. Hypothesis testing as a research tool. Risks and pitfalls in hypothesis testing. Scientific error and lies. Scientific reviewing.

Communicating research results. Legal and ethical challenges of AI. Societal impact of AI and Quantum Computing.

QE7. Python Programming and Applications

Introduction to data programming. Python programming. Data stream processing. Data acquisition: web services, streams, data transfer. Octave/Matlab/R for data analysis. Optimisation considerations, vectorisation, GPUs. Use-case combining batch processing, streaming and analysis; quantum physics data analysis use case. Open quantum computing in Python (ProjectQ).

QE8. Quantum Control

The purpose of this course is to introduce the student to basic quantum dynamics and to different methods for its control using external fields, as well as to show the connection of the quantum control methods in applications in quantum technologies. The course syllabus include: Coherent vs incoherent dynamics. Incoherent dynamics and rate equations. Coherent dynamics, time-dependent Schrödinger equation, and probability amplitudes. Open quantum systems and the relevant equations for the density operator. Dynamics of specific quantum systems, for example, the two-level quantum system. Weak field dynamics, time-dependent perturbation theory, and coherent control of weak excitation by a field and its harmonics. Fermi’s golden rule. Exactly solvable models for the control of quantum dynamics in two and three-level systems and their applications. Adiabatic methods for the control of quantum dynamics, rapid adiabatic passage (RAP) and stimulated Raman adiabatic passage (STIRAP), and their applications. Shortcut to adiabaticity and its applications. Optimal control and its applications. Other methods of quantum control and their applications. Examples of applications of quantum control methods in quantum technologies and connection to current research.

QE9. Quantum Machine Learning

What is machine learning, data mining and quantum computing? Preliminaries from Probability and Stochastic Processes. Learning theory: Data-Driven Models, Feature Space, Classification, Regression, Supervised and Unsupervised Learning, Generalization Performance, Model Complexity. Brief review on quantum mechanics and quantum computations. Unsupervised Learning: Principal Component Analysis, K-Means and K-Medians Clustering, Hierarchical Clustering, Density-Based Clustering. Pattern Recognition and Neural Networks: The Perceptron, Feed-forward Networks, Deep Learning, Computational Complexity. Supervised Learning and Support Vector Machines: K-Nearest Neighbors, Optimal Margin Classifiers, Soft Margins, Nonlinearity and Kernel Functions, Least-Squares Formulation, Generalization Performance, Multiclass Problems, Computational Complexity. Regression Analysis: Linear Least Squares, Nonlinear Regression, Nonparametric Regression, Computational Complexity. Clustering and Quantum Computing: Quantum Random Access Memory, Calculating Dot Products, Quantum Principal Component Analysis, Quantum K-Means, Quantum K-Medians, Quantum Hierarchical Clustering, Computational Complexity. Quantum Pattern Recognition: The Quantum Perceptron, Quantum Neural Networks, Computational Complexity. Quantum Classification: Nearest Neighbors, Support Vector Machines with Grover's Search, Support Vector Machines with Exponential Speedup, Computational Complexity.

QE10. Natural and Unconventional computing

Cellular automata. Rules and evolution of cellular automata. Quantum Cellular Automata. Computing processes in biological systems. The computing amoeba. Bio-inspired computation systems. Memristors and memristive circuits. In-Memopry-Computing. Memristive computation architectures and systems. Memristive learning cellular automata.

Memristive Quantum Simulators and Circuits. Neurons and Neuromorphic computation. Emergent computing. Crowd dynamics. Swarm intelligence. Cytosceleton computing models. Random walks. Cellular ants computing.

QE11. Linear Algebra for Quantum Mechanics

Eigenvalues and eigenvectors. Matrix diagonalization. Jordan canonical form. Vector spaces and vector subspaces. Linear dependence and linear independence. Basis of a vector space. Dimension of a vector space. Inner products. Inner product spaces. Best approximation. Orthogonal projection. Gram-Smidt orthonormalization. Linear operators. Adjoint operators. Operators in inner product spaces. Orthonormal operators. Isomorphisms. Normal operators. Transformation of symmetric matrices to diagonal form.

QE14. Quantum Optics

The purpose of this course is to introduce the student to basic quantum optics phenomena and connect them with applications in quantum technologies. The course syllabus include: Semiclassical light-matter interaction, probability amplitude approach, two-level system, and Rabi oscillations. Optical Bloch equations. Nonlinear optical response of the two-level system. Three-level systems, CPT and EIT. Quantization of the electromagnetic field, (Fock states, coherent states, squeezed states and their properties). Correlations and photon statistics. Spatial and temporal coherence. Intensity fluctuations, Hanbury Brown & Twiss Experiment. Quantized light-matter interaction and the Jaynes-Cummings model. Dressed state picture. Quantum Rabi oscillations and collapse and revival. Wigner-Weisskopf theory of spontaneous emission. Resonance fluorescence and the Mollow triplet. Cavity quantum electrodynamics, quantum systems in cavities. Applications of quantum optics in quantum technologies.