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Influence of IQT on research in ICT, part 5

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***Abstract*—The advanced Quantum Information Technologies subject for Ph.D. students in Electronics Engineering and ICT consists of three parts. A few review lectures concentrate on topics which may be of interest for the students due to their fields of research done individually in their theses. The lectures indicate the diversity of the QIT field, resting on physics and applied mathematics, but possessing wide application range in quantum computing, communications and metrology. The individual IQT seminars prepared by Ph.D. students are as closely related to their real theses as possible. Important part of the seminar is a discussion among the students. The task was to enrich, possibly with a quantum layer, the current research efforts in ICT. And to imagine, what value such a quantum enrichment adds to the research. The result is sometimes astonishing, especially in such cases when quantum layer may be functionally deeply embedded. The final part was to write a short paragraph to a common paper related to individual quantum layer addition to the own research. The paper presents some results of such experiment and is a continuation of previous papers of the same style.**

***Keywords*—Quantum information technology; QIT, teaching of QIT; Ph.D. students view on QIT; QIT implementation in ICT theses; Ionising Radiation; Microwave Materials; Quantum Materials; Quantum Acoustics; Power Grids; Electromagnetic Field Simulation**

I. INTRODUCTION

ADVANCED lecture for a group of diverse Ph.D. students is a demanding task. They are strongly concentrated on their individual research efforts. Timing of their Ph.D. study is demanding and they try to omit things which do not help them to go forward with the research. The subject on the Quantum Information Technology is designed in this way as not to slow down their work but to help and perhaps shed a new light on their research from a completely different yet very modern and promising perspective, the quantum one. The quantum perspective, especially when used against your serious personal research effort, is really very useful in the most of cases. Quantum integrated circuits are natural extensions of photonic integrated circuits. Quantum methods are used in simulations of large high energy experiments. Quantum simulators and annealers are used for research on molecular dynamics in material engineering and technology. IQT is used in a number of security solutions. A lot of photonic crystal technologies may be extended into quantum level. Quantum sensors include also a new generation of ionizing radiation devices and systems. Quantum dot dynamics is used in cancer diagnostics and therapy. IQT is used in automobiles and in aeronautics. Artificial Neural Network are extended successfully to quantum version. Power engineering start to adapt some quantum methods. IQT promise for faster and more precise genome sequencing and data analysis. Smart quantum antennas may enter into operation in G6 technology. Quantum batteries combine new materials and start to use quantum supercapacitors. IQT will be indispensable in banking and other security solutions. the era of advanced technology, healthcare providers are increasingly exploring the potential of digital health solutions for remote patient monitoring and treatment using Internet-connected sensors and medical devices. Wireless Body Area Network (WBAN) serves as a critical enabler of remote health monitoring by providing cost-effective and efficient real-time solutions.

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II. RADIATION EFFECTS IN QUANTUM COMPUTERS

Currently, more satellites are being sent to space than ever, and their level of sophistication has only increased in recent years. To meet future market demands regarding the efficiency or security of computing in space, the next step in the evolution is to deploy systems that incorporate quantum computing in space. The European Space Agency (ESA) has outlined very ambitious goals for the European space industry to develop the infrastructure of quantum systems and deploy them in space before 2040 [1]. Among others, ESA envisions quantum networking, Quantum Key Distribution (QKD) [2], quantum sensors, or general quantum computing as key enabling technologies for the space industry [3]. Operating quantum computers in space will require electronics and qubit subsystems that remain reliable under the effects of ionising radiation. Currently, we lack data on the operation of quantum systems in harsh ionising radiation, with only limited terrestrial data available [4]. This could significantly limit the potential of future quantum computers in space and has to be resolved before they are deployed in the target environment.

A very good potential candidate for space deployment is the MIKOK trapped ion quantum computer, which is being developed by the Warsaw University of Technology [5]. Therefore, further discussion is focused on its possible susceptibility to the effects of ionising radiation as well as potential radiation-hardening strategies. It consists of the ion trap for quantum computing and dedicated electronic subsystems to control its operation, such as the SINARA electronic stack, Commercial-off-the-shelf (COTS) based control and readout electronics and a dedicated operating system. Both parts, the quantum and the more traditionally designed electronics stacks, are susceptible to the effects of ionising radiation, albeit the results can be very different. Such a system fits the goals outlined by the ESA in its technology vision. Nevertheless, it requires detailed verification for the operation in a space environment, in order to reach the reliability targets for space missions.

The case study is split into two parts: first, the possible effects and hardening strategies are discussed in the quantum part of the computer. Then, the possible effects and prevention strategies in the electronics stack are studied. Last but not least, the possible radiation test campaign at the CERN Highly-Accelerated Mixed Field Facility (CHARM) at CERN is proposed and evaluated.

Interactions of energetic particles with qubits can depopulate or repopulate trapped-ion energy levels, causing qubit loss or unwanted state transitions that bias measurement statistics, making calculations useless [6]. [7]. A visualisation of the effects of the energetic particle interaction with a qubit is presented in the figure 1. Therefore, it is vital to either understand how radiation will interact with the qubits and counter it or develop appropriate hardening strategies. Shielding and detection must therefore be co-designed with control electronics to achieve stringent reliability levels. Shielding could be developed as either passive or active, using built-in features of a blade trap quantum computer. Passive shielding can possibly be achieved using the latest state-of-the-art knowledge, such as passive stacks of hydrogen-rich and high-Z materials around the trap to reduce the amount of energetic particles that reach the computer. Moreover, the inherent architecture of the MIKOK computer could be used for shielding, using the electromagnetic field in the ion trap as an active shield. Last but not least, onboard particle detectors with algorithms that detect incoming particles and flag or veto this in the calculations could also be used for radiation hardening [8]. The quantum computers could then account for radiation-induced transients instead of interpreting them as algorithmic errors.

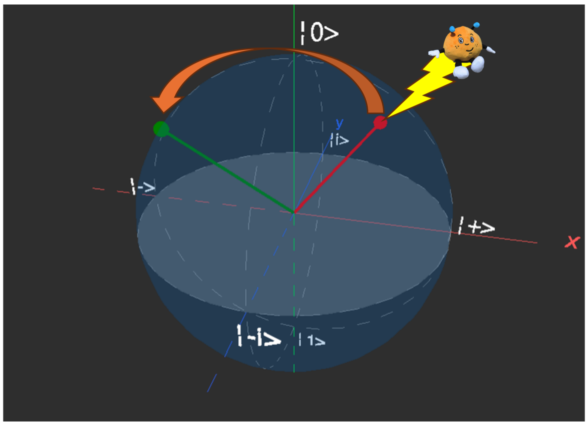

Fig. 1. Effects of an energetic particle hitting a qubit.

The electronic stack controlling and using the results of the quantum computer is very sophisticated. It consists of laser sources, readout and control hardware, dedicated operating system, and many more [5]. Moreover, it is made mostly of COTS components, not designed for a space environment. Therefore, to facilitate the overall system qualification process and fit the Space 4.0 approach for space development, this part of the system could be verified at the system level. It would also enable the operational verification of the entire electronic system running with the dedicated operating system, enabling the identification of any high-level system faults that could become critical while operating in space. Such an approach would streamline the entire verification process and enable the verification of the whole system at once, instead of testing each component separately. The biggest obstacle is the selection of a test facility where such verification is feasible.

Such a test camping, allowing verification of both the quantum and the electronic part, could be feasible at the CERN CHARM facility. It is a mixed-field irradiation test facility where systems can be exposed to radiation over long intervals of time. Moreover, the does each system receives can be tuned depending on the placement of the it inside the facility. Together with in situ recording of system metrics and quantum performance, such a test would allow quantifying error rates and classifying their nature under controlled radiation environment. Data from these runs would be used to evaluate the overall operation of the MIKOK quantum computer under ionising radiation and assess the observability of possible errors.

The expected outcome would be the first controlled radiation study of a full quantum computer, which would constitute a very important step towards enabling space-qualified quantum processing. The results could improve - orbit data processing, error observability, and reduce possible downtime by turning resets, data errors, or silent data corruptions into detectable and recoverable events. This would support safer operation of critical satellite functions such as secure connectivity, Earth-observation processing, and services based on data centres in space. By establishing reliability engineering in system-level evidence and extending it to the quantum layer, the work charts a realistic path to deploy COTS-centric quantum computers in future missions while long-term radiation-tolerant components mature

III. MATERIALS MEASUREMENT FOR IQT

A. *Measurement method - Q-SSR fixture*

The Q-SSR fixture [9] is derived from classical cylindrical resonator concepts but incorporates several key innovations. The resonator body is a metallic cylindrical cavity operating predominantly in TE_{0np} modes, with the electric field tangential to the azimuthal direction and concentrated in the central region of the cavity. Instead of small posts, as in an SPDR [10], the Q-SSR uses two large dielectric plates that extend across the entire cross-section of the cavity. In the canonical implementation these plates are made of high-purity sapphire, chosen for its high unloaded Q-factor, mechanical rigidity, and well-known dielectric properties over a wide frequency and temperature range.

Between the two sapphire plates a slot is formed, into which the sample under test is inserted. For the purposes of this project, the fixture is designed to accommodate thick samples such as bulk sapphire wafers and COP sheets with thicknesses from a few hundred micrometers up to several millimetres. The sample typically fills the cross-section of the cavity in the radial direction, while its thickness is defined by spacers or the mechanical design of the slot. This “sandwiched” geometry ensures that the electromagnetic field interacts strongly with the sample volume, which is essential for high sensitivity when working with very low loss materials.

A distinctive feature of the resonator is the Q-choke structure [11]. In a conventional Q-SCR approach, a single annular corrugation is machined into the cavity walls and loaded with a lossy material to attenuate undesirable modes and limit radiation losses. In the Q-SSR, this idea is extended to a multi-ring choke. Several concentric grooves are integrated into the top and bottom covers of the cavity, and an outer ring surrounds the main resonator body. This multi-stage choke significantly improves isolation of the desired TE_{0np} modes from external circuitry and suppresses parasitic modes. As a result, the quality factor remains high even when thick samples are introduced, which is crucial for resolving the very small additional losses introduced by sapphire or COP.

Coupling to the resonator is typically realized via weakly coupled loops or probes introduced through the cavity sidewall. The coupling is adjusted so that the loaded quality factor is dominated by dielectric and conductor losses rather than by coupling losses. In practical operation, the Q-SSR is connected to a vector network analyzer (VNA) via coaxial cables, and the S-parameters are recorded over a frequency band that includes several TE_{0np} resonances. The same setup can be used at room temperature or housed in a cryostat for low-temperature characterization, which is a key requirement for materials used in quantum hardware.

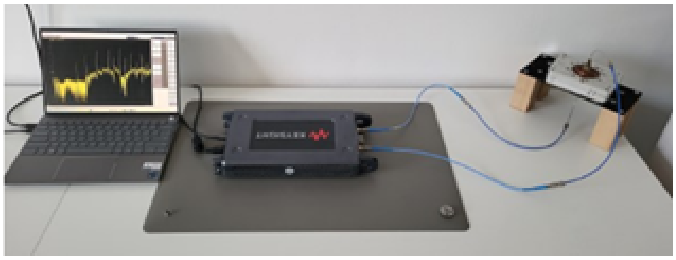

Fig. 2. Q-SSR whole measurement setup with sample inserted into air slot.

B. Materials and measurement procedure

The primary materials of interest in this project are thick sapphire and COP substrates. Sapphire is a standard substrate for many superconducting qubit platforms, high-Q planar resonators, and other elements of quantum information processors. Its very low microwave loss tangent at cryogenic temperatures and excellent thermal properties make it highly attractive for these applications. COP, on the other hand, is a low-loss amorphous polymer often used as a substrate or packaging material in microwave and photonic circuits thanks to its low water uptake, good processability, and stable dielectric properties.

From the point of view of resonator measurements, both materials are “thick” compared to typical thin films or laminates. Their thickness is often defined by mechanical constraints or by matching to the overall device architecture [12], and can easily reach hundreds of micrometers or several millimetres. In the Q-SSR method, such thicknesses are not a limitation; instead, they are explicitly supported by the geometry of the resonator. The sample is inserted into the central slot between the sapphire plates; for sapphire measurements this slot can accommodate a bulk wafer, while for COP characterization the sample may be a machined plate or a stack of sheets.

The measurement procedure consists of the following steps:

1) **Reference measurement of the empty resonator.** The cavity is assembled with only the built-in sapphire plates, and its transmission (or reflection) response is measured with the VNA. Resonant frequencies and quality factors for several TE_{0np} modes are extracted by fitting each peak with an appropriate resonant curve model. This provides a reference dataset that encodes the geometry, conductor losses, and sapphire plate properties.
2) **Insertion of the thick sample.** The sample is placed into the slot, ensuring good alignment and repeatable positioning. For thick materials, mechanical tolerances and flatness are important to guarantee uniform contact and to avoid unwanted air gaps, which would perturb the field distribution and introduce additional uncertainty.
3) **Measurement of the loaded resonator.** With the sample in place, S-parameters are measured over the same frequency span. Each resonance is shifted in frequency and its Q-factor is modified by the presence of the sample. These changes contain information about the sample’s permittivity and loss tangent.
4) **Repeatability checks.** The insertion and measurement sequence is repeated several times, possibly with disassembling and reassembling the resonator, to assess repeatability. For thick sapphire or COP samples, the dominant sources of uncertainty typically include positioning tolerances, small variations in load pressure, and the accuracy of mechanical thickness measurements.

To support high-precision extraction, sample thickness and dimensions are characterized with micrometers or coordinate-measuring tools. For quantum-technology-grade materials, the thickness variation is usually small, but even sub-percent deviations can influence resonant frequencies. These geometrical uncertainties are explicitly accounted for in the modeling-based extraction procedure.

C. Discussion for thick sapphire and COP substrates for IQT

The combination of multi-mode operation and modelling-based extraction offers several advantages specifically for thick materials used in quantum hardware.

Broadband characterization in a single fixture. Multiple TE_{0np} resonances enable the extraction of dielectric parameters at several discrete frequencies without changing the test configuration. This is particularly relevant for quantum circuits that must operate coherently over a band of readout and control frequencies.

Suitability for very low loss materials. The multi-ring Q-choke and sapphire-loaded cavity produce high unloaded Q-factors, which are necessary to resolve the small additional losses introduced by high-quality sapphire or COP. By carefully calibrating conductor and background dielectric losses, the remaining contribution can be attributed to the sample with good confidence.

Capability to handle thick substrates. Unlike some standard fixtures that assume thin sheets or introduce uncertainties when sample thickness increases, the Q-SSR is explicitly designed around a sandwiched geometry where the sample can be several millimetres thick. This makes it well aligned with real quantum device substrates, which are often not easily thinned without compromising mechanical robustness.

Consistency across multiple modes. For a properly modelled system, permittivity values extracted from different resonances should agree within a small tolerance. Any systematic trend with mode number can reveal modeling inaccuracies, inhomogeneities in the sample, or frequency-dependent loss mechanisms. This built-in cross-check increases confidence in the final material parameters used for quantum circuit design.

Extension to cryogenic operation. Because the Q-SSR is compact and mechanically robust, it can be integrated into cryostats or dilution refrigerators with only minor modifications to the couplers and mounting structures. This opens the way to direct characterization of sapphire and COP at the temperatures relevant for superconducting qubits and other quantum technologies, avoiding the need to extrapolate room-temperature data.

IV. Quantum materials

Significant progress in the study of quantum materials was initiated by the discovery of high-temperature superconductivity in copper oxides in 1986. This opened a new era in condensed matter physics and led to a dynamic expansion of our understanding of phenomena occurring at the nanoscale. Many technologies essential to modern life including communication, electronics, and computing have increasingly been based on the principles of quantum mechanics. Quantum technologies, due to their advantages over classical counterparts are currently being intensively developed [13].

Quantum materials are materials whose properties and behaviour cannot be accurately described using classical physics. This results from the dominant role of quantum phenomena, which become particularly significant at nanometre-scale dimensions. These quantum effects give rise to new, unique properties that attract broad interest in both fundamental research and technology. They find applications in quantum computing, high-capacity communication, data storage, energy harvesting, the design of novel semiconductors, and artificial intelligence systems [13], [14].

One of the quantum phenomena is quantum confinement, which occurs when particles, such as electrons, are confined to a region comparable to or smaller than their de Broglie wavelength, making their wave-like properties significant. In bulk materials, electrons form continuous energy bands due to the large number of atoms. In nanoscale structures, spatial confinement enforces specific standing wave patterns of electrons, leading to the quantization of energy levels. These levels become discrete, meaning that an electron can occupy only certain allowed energy states [13].

The smaller the region in which an electron is confined, the larger the energy gap between the valence band and the conduction band becomes. This phenomenon is particularly evident in quantum dots – nanometre-scale semiconductor crystals in which electrons or electron–hole pairs are densely packed [13].

When an electron is excited to a higher energy level, a positively charged hole is created at its previous level. The electron and the hole attract each other electrostatically (Coulomb interaction), forming a bound state called an exciton. Due to the balance between the Coulomb attraction and the kinetic energy arising from the uncertainty principle, the electron and the hole maintain an average separation, known as the Bohr radius of the exciton [13].

If the size of a quantum dot becomes comparable to or smaller than the Bohr radius of the exciton, the motion of the electron and the hole is strongly confined, which increases their kinetic energy and results in a widening of the energy gap. Quantum confinement in quantum dots is utilized in modern electronic devices, including single-electron transistors, qubits in quantum computers and light-emitting diodes [13].

Another phenomenon utilized in quantum materials is quantum tunnelling. It occurs when a particle can penetrate a potential barrier whose height exceeds its total energy. This arises from the wave-like nature of the particle: its wave function extends into the region beyond the barrier, allowing a finite probability of the particle appearing on the other side. The probability of tunnelling depends on the height and width of the barrier — the narrower and lower the barrier, the higher the likelihood of tunnelling. For this reason, observing and utilizing tunnelling often requires extremely thin, nanometre-scale layers of material [13].

Quantum mechanisms exhibit unique electronic, magnetic, and optical properties arising from quantum effects at the atomic and subatomic levels. Strong interactions between electrons in a material give rise to correlation effects and the lattice structure plays a key role in their emergence. These interactions lead to behaviours that cannot be explained by classical physics [13].

When electrons interact strongly with each other, their collective behaviour can significantly deviate from predictions of simple models. This occurs when the Coulomb interaction becomes comparable to the electrons' kinetic energy [13].

The interplay of these effects leads to the formation of various quantum phases, such as: high-temperature superconductors, where electron pairs (Cooper pairs) move through the crystal lattice, resulting in zero electrical resistance or Mott insulators, in which strong electron correlations drive a phase transition from a metal to an insulator [13].

Topology and symmetry play also a key role in quantum mechanics, influencing the properties and behaviour of materials. Topology refers to the features of objects that remain unchanged under smooth deformations. Topological properties control how materials respond to changes in their environment and remain stable even under continuous variations of parameters. As a result, a given material can exhibit unique properties arising from its topological structure [13], [15].

Symmetry describes operations that leave a system unchanged, such as rotational symmetry or time-reversal symmetry. Topology and symmetry affect the phases, properties, and behaviour of quantum systems [13], [15].

The topology of electronic states refers to the way electronic states are organized in a material, described by topological invariants. These numbers characterize the shape of electron wave functions in momentum space. A material with a non-trivial topological invariant has unique wave function structures, which guarantee special surface or edge states that are robust against small changes in the material [13], [15].

An example of such materials are topological insulators – a new type of insulator that has a bulk energy gap but can still conduct electric current along its surface due to unique metallic states arising from the topology of the bulk states [13], [15].

Quantum materials and the phenomena associated with them constitute an exceptionally rich area of research in solid-state physics and quantum physics. Their properties arise from the fundamental principles of quantum mechanics and allow the observation of effects that do not occur in classical macroscopic systems. Research on these systems not only deepens our understanding of the nature of matter but also paves the way for new technologies.

V. Quantum Acoustics

Quantum acoustics investigates the interaction between quantized mechanical vibrations (phonons) and quantum systems such as defect centres, superconducting qubits, and nano-mechanical resonators. This section provides a concise overview of two key platforms used in modern quantum acoustic sensing: nitrogen–vacancy (NV) centres in diamond and surface acoustic wave (SAW) devices. Both systems enable nanoscale measurements of magnetic fields, strain, and mechanical motion with sensitivities unattainable using classical methods.
Acoustic waves in solids can reach frequencies in the MHz–GHz range and wavelengths from millimetres down to micrometers. In the quantum regime, the mechanical motion of a solid is quantized into phonons with energy, which enables coherent control and detection of single vibrational quanta. The ability to couple phonons to quantum systems has opened the way for highly sensitive nanoscale sensors and hybrid quantum devices.

Two platforms are particularly promising: (i) optically active spin defects such as NV centres in diamond, which convert mechanical excitations into shifts of electronic energy levels, and (ii) surface acoustic waves (SAWs), which confine high-frequency phonons near the surface of piezoelectric materials and can be strongly coupled to qubits or spin systems.

A. NV Centres as Quantum Acoustic Sensors

The negatively charged NV centre in diamond is a point defect composed of a substitutional nitrogen atom adjacent to a carbon vacancy. Its electronic ground state is a spin-1 system with a zero-field splitting of $D \approx 2,87GHz$. Mechanical stress modifies the local crystal field and leads to shifts in the spin sublevels $|m_s = 0\rangle$ and $|m_s = \pm 1\rangle$. This shift is observable as changes in the optically detected magnetic resonance (ODMR) frequencies. ODMR is the central technique enabling NV-based quantum sensing. The procedure relies on two key properties. Under green laser ($\approx 532nm$) excitation, the NV centre fluoresces in the 637–800 nm range. Crucially, the $|m_s = 0\rangle$ state exhibits higher fluorescence than the $|m_s = \pm 1\rangle$ states because of a non-radiative inter-system crossing. Secondly, applying a microwave (MW) field at a frequency matching the spin transition $|0\rangle \Leftrightarrow |\pm 1\rangle$ transfers population from the bright state to the dark states, reducing the detected optical intensity.

By sweeping the microwave frequency and monitoring fluorescence, one obtains characteristic resonance dips at the transition frequencies. Their positions follow the spin Hamiltonian

$$H = DS_z^2 + \gamma_e B \cdot S + H_{strain}$$

where $\gamma_e \approx 2,8MHz/G$ is the electron gyromagnetic ratio. Any perturbation that shifts the energy levels — magnetic field, temperature, or mechanical strain — produces a shift of the ODMR resonance. In quantum acoustics, mechanical vibrations modulate the strain term H_{strain}, leading to periodic shifts of the ODMR dips. This allows detection of vibrations with amplitudes below the femtometre scale. Experiments have shown coupling rates on the order of hundreds of kHz for nanoscale mechanical resonators driven near their fundamental mode frequencies [16], [17]. The high spatial resolution (single-defect scale), optical readout, and room-temperature operation make NV centres a uniquely practical platform for quantum acoustic sensing.

B. Surface Acoustic Waves (SAW) in Quantum Devices

Surface acoustic waves propagate along the surface of a solid with displacements decaying exponentially with depth. They are typically generated using interdigital transducers (IDTs) on piezoelectric substrates such as $LiNbO_3$. Such transducers are often in a shape of a comb sputtered on the material, which allows for optimal detection of the signal. SAWs in the GHz range correspond to wavelengths of a few micrometers, allowing tight confinement and integration with nanoscale devices. At cryogenic temperatures, SAWs can be treated as quantized phonons. Their electric field component enables strong coupling to superconducting qubits or spin defects. Early demonstrations showed coherent emission and absorption of single propagating phonons by a transmon qubit [18], proving that SAWs can serve as quantum buses for information transfer. SAW resonators and waveguides can also be combined with NV centres in diamond, enabling strain coupling between the moving SAW field and NV spin transitions. This architecture provides a path toward chip-scale quantum

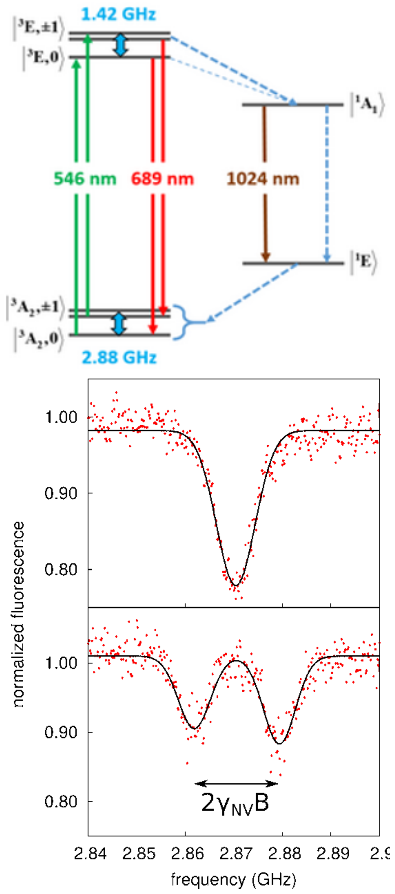

Fig. 3. Resonant frequencies splitting observed in ODMR method.

sensors capable of detecting strain, mass loading, or local changes in elastic properties with quantum-limited sensitivity. SAW devices also offer large bandwidth and compatibility with photonic and microwave circuits, making them attractive for hybrid quantum systems.

VI. Quantum Computing Algorithm for Electromagnetic Field Simulation

The quantum computing algorithms proposed for simulating electromagnetic (EM) fields generally aim to leverage the superior scaling of quantum mechanics to overcome the exponential computational burden and memory demands associated with classical methods like Finite-Difference Time-Domain (FDTD) and Finite Element Method (FEM). The sources detail several distinct quantum algorithmic frameworks for handling Maxwell's equations and related wave propagation problems.

Schrödingerisation Method [19], [20]. The Schrödingerisation approach is a core technique used to transform classical Partial Differential Equations (PDEs) with non-unitary dynamics, such as Maxwell's equations, into a system that evolves under unitary dynamics (Schrödinger-type equations).

Mechanism and Formulation: this transformation is achieved by applying a warped phase transformation that introduces one auxiliary space-like dimension. The resulting unitarily evolving system can then be solved efficiently using Hamiltonian Simulation. The method is applied to EM fields using a direct approximation combined with Yee's algorithm, which is highly popular for numerically approximating Maxwell's equations or a matrix representation based on Riemann-Silberstein vectors, combined with a spectral approach or an upwind scheme.

Handling Complexity: the Schrödingerisation framework is specifically investigated because it enables the incorporation of physical boundary conditions (including periodic, perfect conductor, and impedance boundaries) and interface problems within complex media into the unitary quantum dynamic system, which is scarce in existing literature. Complexity and Advantage: For Maxwell's equations simulated using Yee's algorithm, the gate complexity is estimated as $\frac{O(M((d+2)m^2+2m))}{log_m}$. For similar PDEs like elastic wave equations, the method has demonstrated an exponential quantum advantage in the spatial dimension (d) compared to classical algorithms. Alternative Implementation: The algorithms can also be formulated in the continuous-variable (CV) quantum framework (qumode representation) for analogue quantum simulation.

Potential-Based Hamiltonian Simulation [21]. This approach reformulates Maxwell's equations using the vector potential (A) and scalar potential (ϕ) rather than the standard electromagnetic fields E and B directly.

Key Advantage ($\nabla \cdot \mathbf{B} = 0$): using the potential representation, where $\mathbf{B} = \nabla \times \mathbf{A}$, automatically guarantees that the magnetic field divergence constraint ($\nabla \cdot \mathbf{B} = 0$) is satisfied, resolving a common challenge in numerical EM simulations.

Formulation: by applying the Lorenz gauge condition, the equations are reduced to wave equations for the potentials (Equations 6 and 7 in the source), which can then be transformed into a first-order Hamiltonian system $\frac{\partial|\psi(t)\rangle}{\partial t} = -iH|\psi(t)\rangle$ suitable for quantum simulation.

Scaling: the required number of qubits for a lattice of size N scales logarithmically, $O(log_2 N)$, offering exponential improvement in scaling with respect to the number of grid points compared to classical computation.

Logical Compression: a practical issue is the rapid growth of Hamiltonian terms when discretizing complex geometries. Logical compression can substantially mitigate this issue, proving especially effective for structures exhibiting periodicity or geometric symmetry (such as metalenses or gratings).

Information Readout: extracting the full high-resolution information requires computationally expensive quantum state tomography. Therefore, the focus is placed on efficiently extracting specific integrated values or Figures of Merit (FoMs) (observables OX) evaluated over chosen regions of interest. This method was demonstrated as a proof-of-concept for simulating wave propagation and focal behaviour through a metalens.

Variational Quantum Imaginary Time Evolution (VarQITE) [22]. VarQITE is a hybrid classical-quantum algorithm designed for solving time-dependent linear differential equations, including Maxwell's equations, and is particularly suited for Noisy Intermediate-Scale Quantum (NISQ) devices.

Methodology: the Maxwell system is semi-discretized in the spatial domain using the Method of Lines (MOL) and the Finite-Difference Time-Domain (FDTD) approximation, resulting in a Hamiltonian H. VarQITE approximates the evolution of this system by mapping it to the parameters (θt) of a parameterized quantum circuit (Ansatz) through the McLachlan's variational principle.

Advantages and Drawbacks: unlike other variational quantum algorithms (VQAs), VarQITE avoids the problem of getting stuck in local minima (barren plateaus) because the parameters are updated by solving a differential equation rather than classical optimization. However, initial studies using the Hardware Efficient Ansatz (HEA) indicated a limitation: the required circuit depth scaled exponentially with the number of qubits (which corresponds to the number of grid points), suggesting that this implementation may not provide a quantum speed-up.

Transmission Line Matrix (TLM) Based Algorithm [23], [24]. This framework adapts the classical TLM method, a numerical technique based on modelling wave pulses scattering within a mesh of transmission lines, into a quantum algorithm.

Core Objective: the algorithm is primarily aimed at solving the design problem in electromagnetics: given an initial condition and a desired final field distribution, finding the electromagnetic structure that yields that response.

Quantum Parallelism: the method encodes multiple electromagnetic structures (e.g., configurations of free space vs. perfect electric conductor cells) into a structure Hilbert space (HS). The simulation leverages quantum parallelism to evolve a linear superposition of the responses of these structures simultaneously in time.

Implementation: the core operations include the Scattering Operator (S) and the Connection Operator (Γ), combined into the unitary time evolution operator $U = \Gamma \cdot S$. These operators can be implemented using standard quantum gates (CNOT, TOFFOLI, and single-qubit gates).

Critical Challenge (Coefficient-Booster Module): the primary limitation is that after simulation, the desired structure must be extracted from the superposition using measurement. The probability of obtaining the correct structure may be very low. An essential, unresolved, open problem is the design of a coefficient-booster module to unitarily increase the probability of measuring the structures with the desired response.

These distinct approaches showcase different strategies for mapping classical EM problems onto quantum hardware, balancing the need for unitary dynamics, ease of implementation on NISQ devices, efficient resource scaling, and specific application goals (like EM analysis versus EM design).

VII. Usage of Quantum Technologies in Power Grids

Uninterrupted and safe supply of electricity to the customers is one of the most important issues in modern economy and in politics. It is crucial for almost every country in the world [25]. Stability of these countries and prosperity of their people depend on it. The main goals of every power system are [26]: reliability – ensuring continuous and uninterrupted supply of electricity, supply of electric energy at the lowest possible cost, efficient operations and maintenance of stable voltage and frequency.

One of the most important parts of power system engineering, which helps a lot in achieving these goals is power system protection. The main objectives of this branch of power engineering are: selectivity – ensuring that only section of the power system affected by fault is disconnected, safety – protection of people and property, reliability – fast and correct identification of disturbance in power system and reaction to it and maintaining system stability – preventing wide disturbances and blackouts.

To ensure this, in power system planning, maintenance and protection, there are plenty of modern solutions, improvements and cutting-edge technology. It includes modern electronic devices, new communication protocols, new computational algorithms and classic supercomputers. These solutions significantly help with dealing with the most important problem with managing power systems: their size. Every power system consists of thousands of components, each requiring data collection and the creation of plans for various power system operation and maintenance scenarios. Basically, managing power system is a big data problem and any solution that helps manage this influx of data is very welcome. However, new emerging challenges [27] for modern power systems have made the need of new, especially faster than current one approach much more needed. The first of these new, upcoming challenges is great widespread of large scale and distributed power generation systems based on renewable resources. (especially based on solar and wind energy). The second one is rapid growth of electrification of new sectors of economy, i.e. very fast growth of using electric vehicles, especially in sectors related to the transport of goods or people. These challenges bring even greater influx of data (especially variables regarding measurements, control) than before, which results in growing complexity of computational algorithms. This influx must be processed with desired speed and frequency of computations and correctly to ensure all energy systems operating objectives are achieved [28]. To address this problem, much more processing power is needed. However, classic supercomputers require huge amounts of electricity, which causes their operating costs to reach millions of dollars. Modern analysis suggest that use of quantum technologies could resolve that problems [27]. Quantum technologies can be used in following areas of power systems operations [27], [28]: contingency analysis, fault diagnosis, state estimation, power flow studies and grid optimization problems.

Contingency analysis is an analysis of a "what if" scenario. The purpose of it is to investigate any possible outcome of outage of any facility in the power system. Currently, most contingency scenarios are based on "n-1" criterion. This criterion ensures that power system is able to maintain its stability in case of failure of one of the grid objects. However, due to increase of distributed and renewable resources-based power generators and also our higher dependency on electricity in almost every aspect of life, there are ideas to make this criterion higher, i.e. "n-3" or even "n-5". These criterion results in large growth of possible scenarios to create and analyze. In case of power system with 500 objects, "n-3" criterion could result in more than 20 million scenarios [27], which cannot be analyzed in reasonable time with the use of classical approach. The goal of fault diagnosis is correct and smooth identification and reaction on failures appearing in power system. It plays key role in preventing issues with stability and blackouts in power systems by detecting sources of disturbances in them. Usage of quantum computing in this area could improve it a lot. Results of using hybrid deep learning based on quantum computing are promising. Results of research, conducted on standard IEEE 30 bus power system model, show that this method in terms of speed and results outperformed classical ones [29] – shorter response time, lower rate of false alarms.

Usage of quantum computations could also help us reduce time and quality of power system state estimation – process which transforms data collected from power system into estimated static-state of the power system. These results (i.e. voltage magnitude, phase angle) are further used in other analyses regarding power systems. However, limitations of current quantum computers allow only to conduct analysis on small-scale micro-grids. Power flow studies are investigations of the flow of electric energy in power systems in its normal steady state of operation. Recent tests showed that quantum approach may present the same results as classical.

Grid optimization problems are related to the optimal use and allocation of available resources in order to make the operation of power system as cost-effective as possible. These problems are:

Unit commitment – scheduling operation of generation units to meet demand and minimize generation cost. Due to many generators in various locations, using different types of fuel, it is difficult to complete the analysis in reasonable time. Using quantum approach could make this analysis faster. However, currently there is no success in that area with the use of quantum technologies.

Facility location – allocation – analysis that helps decide on the location of a new facility, taking into account available resources, available transportation network, available workers, and environmental, economic, and political constraints. Recent results show that analyses performed with quantum computing could be 42 times faster than classical ones [27].

Load, generation and weather forecast - Due to increasing dependance on solar and wind energy the ability to more accurate weather forecast could help improve the accuracy of load and generation forecasts.

As you can see, there are many areas of power systems engineering that could benefit from development of quantum technologies. Use of mature quantum technologies could help power engineers to maintain and control power systems and ensure that their fundamental goals are met for many years to come, despite emerging challenges.

VIII. Discussion and Conclusions

The collected case studies show that a "quantum layer" can be embedded into diverse ICT research topics, such as Ph.D theses. In radiation effects for quantum computers, the space-qualification perspective for the MIKOK trapped-ion system links was established. Realistic test path at CHARM was proposed, which would treat the quantum processor and its COTS-based control electronics as a multi-layer reliability problem. In microwave materials, the Q-SSR fixture demonstrates that broadband, high-Q, and potentially cryogenic characterisation of thick sapphire and COP substrates is feasible in a single, modelling-assisted setup closely matching real quantum hardware.

The sections on quantum materials and quantum acoustics underline how concepts such as quantum confinement, topology, and phonon–qubit coupling form a common language for engineering robust quantum states used in computation, sensing, and transduction. NV-centre and SAW-based platforms exemplify nanoscale, quantum-limited sensing architectures that naturally connect to material choices and microwave design. The survey of quantum algorithms for electromagnetic simulation (Schrödingerisation, potential-based Hamiltonian simulation, VarQITE, and TLM-inspired methods) indicates a rich toolbox with promising scaling, but also highlights practical limitations related to Hamiltonian complexity.

Last but not least, in power systems, quantum technologies are positioned as complementary tools for selected large-scale, data-intensive tasks such as contingency analysis, fault diagnosis, and optimisation. Overall, the experience of this course confirms that asking students to enrich their own ICT topics with an IQT component is an effective didactic strategy: it produces concrete, technically grounded research directions and encourages cross-disciplinary thinking. The discussions provided in this study, guided by the perspectives of diverse engineering students engaged in specialised research areas, have unveiled the intricate interplay between QIT and domains like radiation studies, electronics' materials, acoustics and power grid calculations.

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