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White Paper

Optimizing Quantum Scale-Up with FDC Analytics: Powering the Million-Qubit Vision

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Optimizing Quantum Scale-Up with FDC Analytics – Powering the SuperComputer Million-Qubit Vision

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Executive Summary

Figure 1: Majorana q Quantum Chip.
Photo Credit: John Brecher for Microsoft

Microsoft's recent unveiling of the Majorana 1 chip—a quantum processing unit (QPU) built on topological qubits using indium arsenide and aluminum—marks a bold step toward scalable quantum computing. With a roadmap to achieve **one million qubits** on a single chip, Microsoft aims to deliver practical, fault-tolerant quantum systems within years, not decades. However, scaling from eight qubits to a million demands unprecedented precision in fabrication, particularly in the Molecular Beam Epitaxy (MBE) process that defines the chip's topological superconductor architecture.

Fault Detection and Classification (FDC) analytics offers a transformative solution to meet this challenge. By harnessing advanced data acquisition, robust validation, Dynamic Time Warping (DTW), FDC outlier removal, equipment health monitoring, and process optimization, FDC analytics can improve the reliability, consistency, and scalability of quantum chip production. This white paper explores how FDC empowers engineers to overcome manufacturing hurdles, delivering a quantum future that revolutionizes industries from healthcare to materials science.

Introduction: The Quantum Scaling Challenge

Quantum computing promises to solve problems beyond the reach of classical systems—simulating complex molecules, optimizing global supply chains, or breaking cryptographic codes. Microsoft's Majorana 1, with its eight topological qubits, leverages a novel material stack fabricated via Molecular Beam Epitaxy (MBE) to achieve inherent error resistance. Yet, scaling this to a million qubits requires more than innovative physics; it demands a manufacturing process that is repeatable, defect-free, and optimized at atomic scales.

MBE, the cornerstone of Microsoft's approach, deposits indium arsenide and aluminum atom-by-atom to form nanowires hosting Majorana zero modes (MZMs). Any deviation—be it in material composition, layer thickness, or equipment stability—can disrupt these fragile quantum states. Traditional quality control struggles with the complexity and variability of such processes. Enter FDC analytics: a data-driven framework that transforms raw sensor data into actionable insights, ensuring Microsoft's quantum vision becomes reality.

FDC Analytics: The Key to Quantum Scalability

1. Precision Data Acquisition – The Foundation of FDC

The Challenge: MBE operates in an ultra-high vacuum with variables like beam flux, substrate temperature, and pressure fluctuating in real time. Capturing these dynamics is critical to understanding process health.

FDC Solution: Deploy a multi-sensor ecosystem—RHEED (Reflection High-Energy Electron Diffraction) for layer growth, mass spectrometers for flux rates, thermocouples for temperature, and various other sensors —to generate high-fidelity time series data. These data streams, sampled at sub-second intervals, provide a comprehensive view of each MBE run.

Benefit: Engineers gain granular visibility into the process, enabling FDC to detect subtle anomalies that could compromise qubit stability.

WHAT IS RHEED?

Reflection High-Energy Electron Diffraction (RHEED) is a surface-sensitive technique used to monitor the growth of crystalline films in real time, atom-by-atom. Here's how it works:

- **A beam of high-energy electrons (typically 5–50 keV) is fired at a shallow angle (1–3°) toward the surface of a substrate or growing film.**
- **The electrons diffract off the ordered atomic structure of the surface, creating a pattern of spots, streaks, or rings on a fluorescent screen.**
- **This diffraction pattern reveals the surface's crystallinity, smoothness, and growth dynamics as layers form.**

Why is RHEED Important?

- **Data Acquisition: The oscillation pattern becomes a time series (intensity vs. time) that can be analyzed.**
- **Fault Detection: If oscillations deviate from a "normal" reference (e.g., a barycentric average), DTW flags potential faults—like flux instability or substrate flaws.**
- **Process Insight: It ensures the indium arsenide/aluminum interface forms with the precision needed for Majorana zero modes.**

2. Data Validation – Ensuring Trustworthy Insights

The Challenge: Noisy or misaligned sensor data can mislead fault detection, especially in a process as sensitive as MBE where topological properties hinge on atomic precision.
FDC Solution: Validate data using statistical checks (e.g., range thresholds) and cross-correlation across sensors to confirm consistency. For instance, RHEED oscillations should align with expected growth rates based on flux measurements.
Benefit: Clean, validated datasets feed into downstream analytics, ensuring DTW and classification models operate on reliable inputs—critical for scaling production across wafers.

3. Dynamic Time Warping (DTW) – Aligning the Quantum Pulse

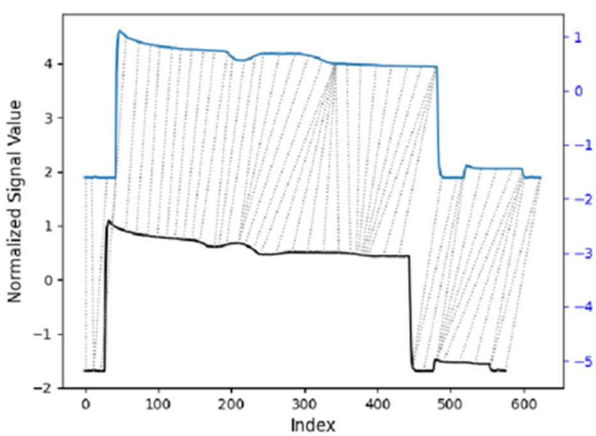

Figure 2:
DTW Temporally Aligns Data to a Reference Trace

The Challenge: MBE growth cycles vary in timing due to equipment quirks or material differences, yet the underlying patterns (e.g., oscillation shapes) remain key to quality. Traditional Euclidean metrics fail here.
FDC Solution: DTW aligns time series data—like RHEED intensity or flux profiles—non-linearly against a reference curve (e.g., a barycenter of "ideal" runs). By warping the time axis, DTW measures true similarity, flagging deviations like irregular oscillations that may signal defects.
Benefit: Engineers can detect faults or classify material states (e.g., "normal" vs. "contaminated") despite temporal shifts, ensuring uniformity as qubit counts scale.

4. FDC Outlier Removal – Filtering the Noise

The Challenge: Outliers—say, a flux spike from a clogged effusion cell—can skew reference curves and mask true process trends, jeopardizing million-qubit consistency.
FDC Solution: Use DTW-based clustering (e.g., k-means with DTW distance) to identify outliers, then refine reference curves with DTW Barycenter Averaging (DBA). DBA iteratively aligns and averages "normal" cycles, excluding anomalies that exceed a DTW distance threshold. Finally, remove outlier process curves using univariate followed by multivariate outlier removal techniques.
Benefit: A robust, representative reference curve emerges, enabling precise fault detection and classification across thousands of MBE runs—a must for large-scale

production.

5. Equipment Health Monitoring – Proactive Reliability

The Challenge: MBE equipment (e.g., effusion cells, cryopumps) degrades over time, introducing variability that threatens qubit quality as production ramps up.
FDC Solution: Monitor equipment sensor data (e.g., pressure trends, cell temperatures) with DTW against a barycenter of known to be "healthy" operation. Anomalies—like a slow pressure rise—signal maintenance needs before they impact output.
Benefit: Predictive maintenance minimizes downtime and ensures the ultra-high vacuum and precision required for indium arsenide/aluminum layers, supporting Microsoft's ambitions goals.

Figure 3 : Advanced FDC Process Control Software Enables Extreme Precision in Manufacturing

6. Process Optimization – Scaling with Efficiency

The Challenge: Achieving a million qubits demands not just defect-free chips but an optimized MBE process that balances speed, cost, and quality.
FDC Solution: Analyze historical FDC data with DTW to correlate process parameters (e.g., flux ratios, growth rates) with successful topological outcomes. Refine these into an optimal reference curve via DBA, guiding real-time adjustments.
Benefit: Engineers reduce trial-and-error, accelerating development cycles and ensuring each chip meets the stringent standards for fault-tolerant quantum computing.

The FDC Advantage: From Eight Qubits to a Million

Microsoft's Majorana 1 demonstrates eight topological qubits with millisecond coherence times—a leap in stability. Scaling this to a million requires fabricating thousands of identical nanowires across larger wafers, each hosting stable MZMs. FDC analytics bridges this gap:

- **Yield Improvement**: Early fault detection and outlier removal cut defective chips, boosting production efficiency.
- **Consistency**: DTW and DBA ensure uniformity, critical for networking qubits into a cohesive million-qubit system.
- **Scalability**: Equipment health monitoring and process optimization sustain reliability as manufacturing scales, aligning with Microsoft's vision of a single-chip, fridge-sized solution.

FDC in Action

Consider an MBE run producing indium arsenide/aluminum nanowires:

- **Data Acquisition**: RHEED tracks growth oscillations; flux sensors monitor deposition rates.
- **Validation**: Cross-checks confirm data integrity.
- **DTW**: A flux drop is flagged by comparing to a DBA reference, revealing a cell issue.
- **Outlier Removal**: An anomalous run is excluded, refining the "normal" barycenter.
- **Equipment Health**: Pressure trends predict pump maintenance, averting failure.
- **Optimization**: Adjusted flux ratios from FDC insights enhance MZM stability.

Result? A higher yield of qubit-ready chips, paving the way for Microsoft's million-qubit milestone.

Conclusion: FDC Analytics – The Quantum Enabler

Microsoft's quantum leap hinges on mastering MBE at scale—a task where FDC analytics shines. By integrating precise data acquisition, rigorous validation, DTW-powered fault detection, outlier removal, equipment monitoring, and process optimization, FDC transforms manufacturing challenges into opportunities. For engineers, this means not just meeting the million-qubit target but exceeding it with a process that's robust, repeatable, and ready for the quantum era.

Call to Action: Ready to optimize your quantum fabrication? Contact Galaxy to explore how FDC analytics can accelerate your path to scalable, fault-tolerant precision manufacturing.

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