ENGINEERING MOTION BELOW 100 MK, WHERE EVERY MW MATTERS

Quantum processors need more than good qubits. They also need equipment that can test many devices efficiently at their operating temperature. To address this challenge, JPE is developing a cryogenic probe system for wafer-level quantum-chip testing below 100 mK, enabling more scalable and cost-effective characterisation of quantum devices. The system builds on JPE's experience in precision positioning, cryogenic mechatronics and complex system development. The integration with a dilution refrigerator platform is being investigated within a joint R&D effort with Bluefors.

AUTHOR'S NOTE

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Testing in the extreme cold

A classical computer uses bits that are either 0 or 1, while a quantum computer uses qubits. Qubits can perform operations that are not possible with classical bits, but they are also very sensitive. Heat, electromagnetic radiation, magnetic fields, vibration and even the measurement electronics can affect their behaviour. Superconducting qubits therefore operate in a dilution refrigerator, typically around 20 mK. At this temperature, the device is superconducting and thermal noise is low enough for accurate quantum measurements [1,2].



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Concept of the cryogenic probe system, comprising mK probing modules with an overall envelope of approximately Ø 470 mm × 460 mm, integrated into the lower part of a dilution refrigerator. The system combines in-situ positioning with temporary electrical contact at mK temperature. The rectangular access opening and modular architecture provide a scalable platform for future extensions, such as a cryogenic load-lock for automated wafer handling and loading.

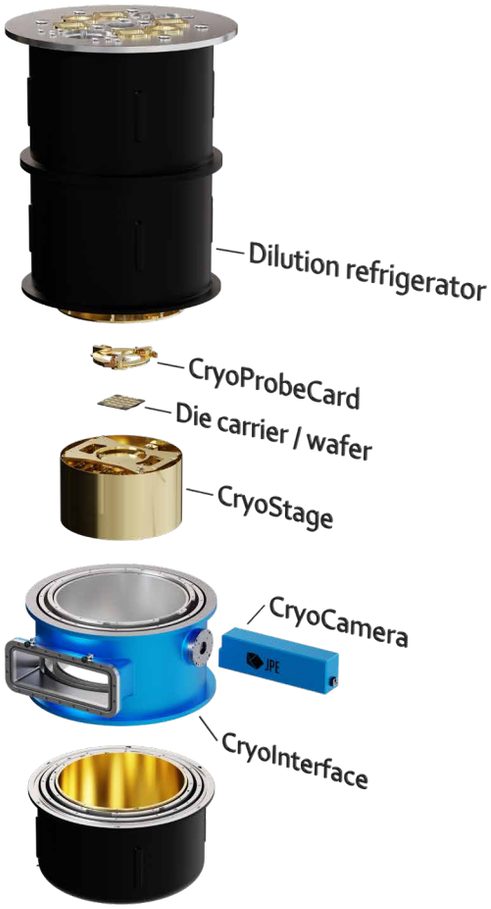
Today's superconducting processors usually contain anywhere from a few dozen to a hundred physical qubits in a size of approximately 20 mm x 20 mm. Google's Willow processor contains 105 qubits and IBM's Eagle contains 127 [3,4]. A useful fault-tolerant quantum computer will require far more. The exact number depends on the architecture and error-correction method, but estimates range from hundreds of thousands to more than one million physical qubits [5,6,7], which requires large-scale infrastructures.

This creates a test and yield problem. The fabrication process may produce individual structures with good yield using the semiconductor infrastructure, yet a larger quantum processor only works well when all qubits, resonators, couplers and interconnects fall within their required range. Room-temperature measurements can screen basic electrical structures, but they cannot show the complete quantum performance. Each superconducting chip, and ultimately each qubit, must therefore be measured and tuned near its operating temperature at the millikelvin (mK) level. Cryogenic testing is not only a final quality check. It is also an important feedback loop for chip design and fabrication.

From packaged chips to cryogenic probing

Today, a superconducting quantum chip is usually diced, wire-bonded and packaged before it is tested at mK temperature. The package provides mechanical support, electrical connections and shielding. The complete assembly is loaded into a dilution refrigerator, cooled down, measured and warmed up again. Depending on the system and measurements, one test cycle can take days. This method is suitable for laboratory research, but it does not scale well. Much of the cycle is overhead rather than measurement time: preparing the chip, connecting it and cooling the complete setup. As the number of devices grows, this overhead becomes a serious bottleneck towards a useful quantum computer.

The semiconductor industry solved a similar problem with wafer probing in ambient environment. A probe station aligns a wafer below a probe card. Electrically conductive



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Modular breakdown of the architecture into dilution refrigerator, CryoProbeCard, CryoStage moving a wafer or die carrier, CryoCamera and CryoInterface.

probes touch the contact pads of one die, the die is tested and the stage moves to the next die. Devices are tested before packaging, so problems are found early and process information is collected across the wafer.

The same approach is attractive for quantum devices. A cryogenic probe system can test a wafer or a set of unpackaged dies in one cooldown. The stage moves from device to device, while the probe card and measurement infrastructure are reused. This removes repeated packaging from early screening, can increase characterisation throughput by more than a factor of ten (by testing many devices within a single cryogenic cycle and distributing the loading, cooldown and warm-up overhead across them), and shortens the chip-development feedback loop

At first glance, this seems like a straightforward adaptation of existing wafer-probing technology. However, the challenge lies in the extreme operating environment. Superconducting quantum devices must be characterised at mK temperatures, in high vacuum, while maintaining a low-noise environment with minimal thermal, mechanical and electromagnetic disturbances. At 20 mK, only a few tens of microwatts of cooling power are available at the coldest stage of the dilution refrigerator. As a result, every movement, measurement cable, optical component and heat leak becomes part of the engineering problem. Designing an mK probe system therefore becomes as much a challenge in environmental control as in precision positioning.

Cryogenic wafer probers already exist at higher temperatures. Commercial systems operate around 4 K or below 2 K [8,9]. These temperatures are still far above the approximately 20 mK operating point used for many superconducting qubit measurements. Bringing wafer-level probing into the mK regime is therefore not simply a matter of making an existing probe station colder. It requires a fundamentally different balance between cooling power, heat generation, shielding, motion and system integration. This is the technological gap that Bluefors, a leading supplier of dilution refrigerators, and JPE are addressing through a joint R&D effort on mK probing. Figure 1 shows the current concept.

One architecture, five modules

The current development architecture consists of five modules (Figure 2). Bluefors is responsible for the dilution refrigerator platform, while JPE develops four modules that are designed for integration into this dilution refrigerator architecture. Together, the partners are investigating how these modules interact and can be integrated to enable mK probing. The modular approach provides flexibility for different system configurations and supports future scalability towards larger cryogenic platforms and increasing quantum-chip sizes.

The CryoStage moves a wafer or a carrier with multiple dies in X, Y and Rz; a Z motion then brings the devices into contact with the probes. The CryoCamera measures the alignment between the probes and the contact pads. The CryoProbeCard contains the temporary electrical contacts and helps create a controlled environment around the quantum device. The CryoInterface connects the JPE modules and the loading path to the dilution refrigerator [10,11]. This split makes the development manageable, but it does not make the modules independent. The stage affects heat input and vibration. The camera needs optical access, but light can heat or disturb the device. The probe card must combine accurate contact, signal quality, shielding and thermalisation. All modules compete for limited space inside the dilution refrigerator.

This is where complex system development becomes important. JPE translates the measurement needs into system and module requirements, defines the interfaces and checks the complete performance chain. A local improvement is only useful when it does not create a new problem elsewhere. For example, a stiffer connection can improve motion performance but also increase the heat path to the cold stage. The modular architecture also supports step-by-step validation. A module can first be tested separately and later in a more representative assembly. This reduces design risk, simplifies system integration and allows the design to change as quantum-device requirements develop.

The CryoStage: motion without continuous heat

The CryoStage aligns a device below the probe card and establishes probe contact. The statically determined gantry design allows long-stroke positioning across a 150-mm wafer, small orientation corrections of ±2°, sub-micrometer resolution, and micrometer-level alignment accuracy and stability. A vertical motion mechanism makes or releases probe contact. The stage must remain accurate after cooling

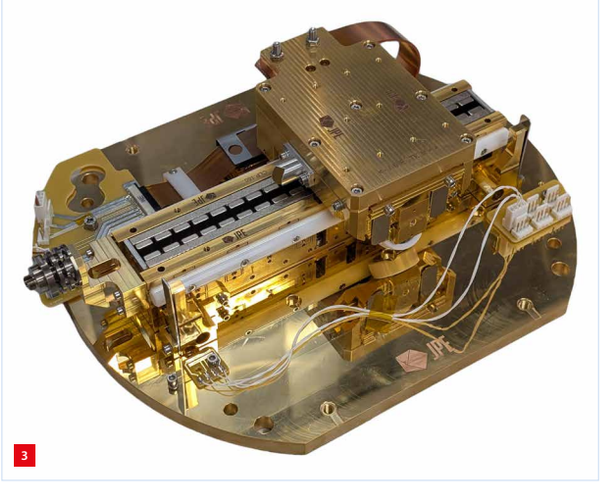
from room temperature to mK temperature, despite the large thermal contraction and extreme operating conditions associated with cryogenic environments. Motion also produces heat. Every movement introduces heat that must be removed before the next sensitive measurement can start. The CryoStage must therefore move fast enough to support throughput, while dissipating little enough to keep the thermal recovery time short.

For this reason, JPE is developing an electromagnetic motion principle based on Lorentz forces, instead of the piezo-based stick-slip motion commonly used for cryogenic positioning. The new principle is intended to provide faster continuous motion over long strokes (> 150 mm), lower motion dissipation and longer service life. After positioning, a mechanical holding function keeps the carriage in place. The drive and interferometric metrology can then be switched off, so they add zero dissipation during the quantum measurement [5,10]. This motion principle is used in JPE's Cryogenic Linear Positioner, or CLP (Figure 3). Several CLPs form the multi-axis CryoStage. Using the same basic axis technology simplifies the architecture and allows development from a single axis towards the complete stage.

Operating at mK temperatures means that not all system behaviour can be predicted with sufficient confidence from simulation or analytical models alone. Friction, thermal contraction, heat transport and dynamic effects must be validated experimentally. Prototype testing therefore plays a central role in the development of the CryoStage and helps reduce risk before moving towards larger system integration.

From components to a working machine

Good component specifications are not enough. Micrometer-level motion is useful only when the probe tips still align with the contact pads after cooldown. Fast motion is useful only when the resulting heat can be removed quickly. Stable contact is useful only when the electrical path preserves the required signal and the device is sufficiently shielded.



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The Cryogenic Linear Positioner (CLP) with an outer envelope of approximately 250 mm x 100 mm x 80 mm; this electromagnetic CLP is used as a modular axis building block for the CryoStage.

The development therefore follows the complete performance chain. At axis level, JPE characterises displacement, force, braking, dissipation and repeatability. At stage level, the combined axes must preserve alignment, stiffness and orthogonality. During system integration, the camera, probe card, thermal links, cabling and shielding are added. The final test is not whether each module works on its own. The complete system must position a new device, make reliable contact and return to a stable measurement condition. That is the central systems-engineering challenge.

Towards a scalable test infrastructure

Quantum computing is still developing, and no single test architecture will suit every qubit technology. However, one need is already clear: more devices must be tested with shorter feedback loops and less manual preparation per device. For JPE, its cryogenic probe-system development brings together more than fifteen years of cryogenic mechatronics experience with system architecture, precision motion, optics and probe integration. The CLP is an important enabling technology, but the main value lies in the complete modular system. Scaling quantum devices requires both specialised components and the system engineering needed to make them work together.

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