『Quantum computing and measurement standards』

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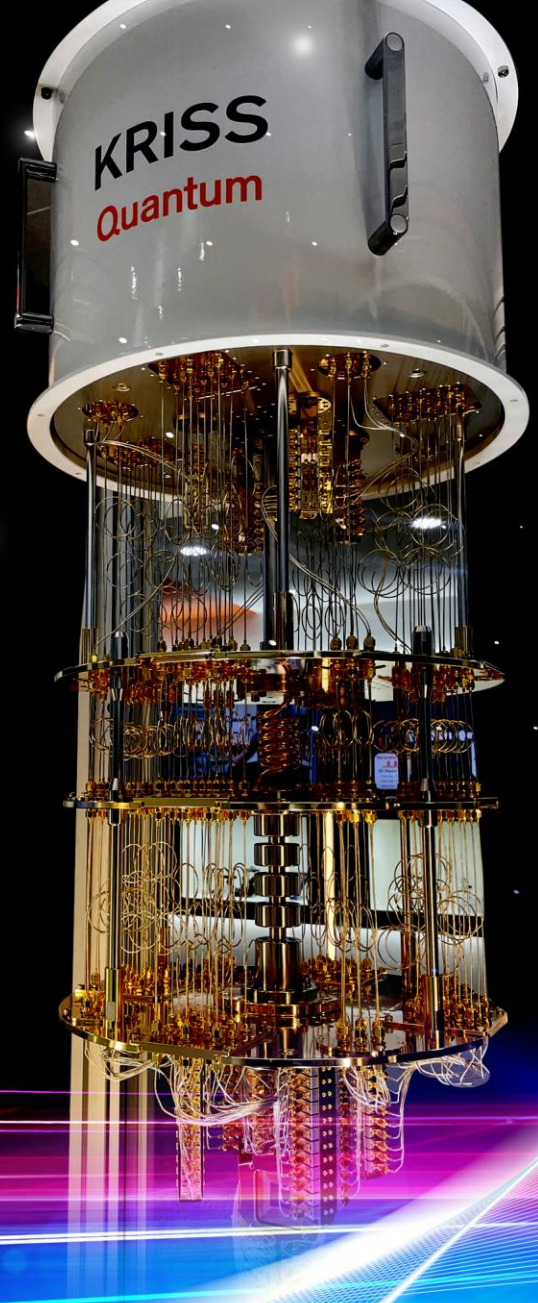
KRISS

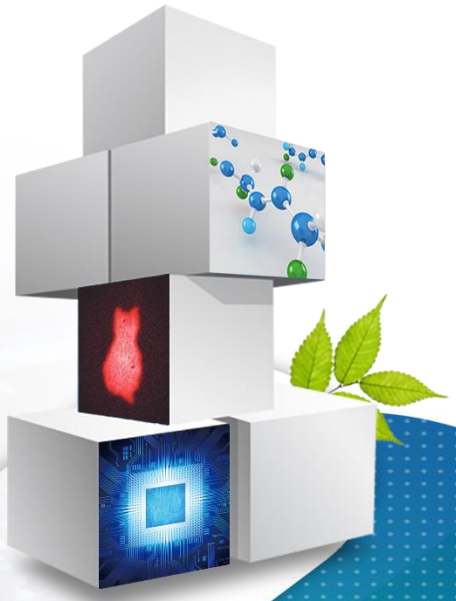
2024. 10. 17.



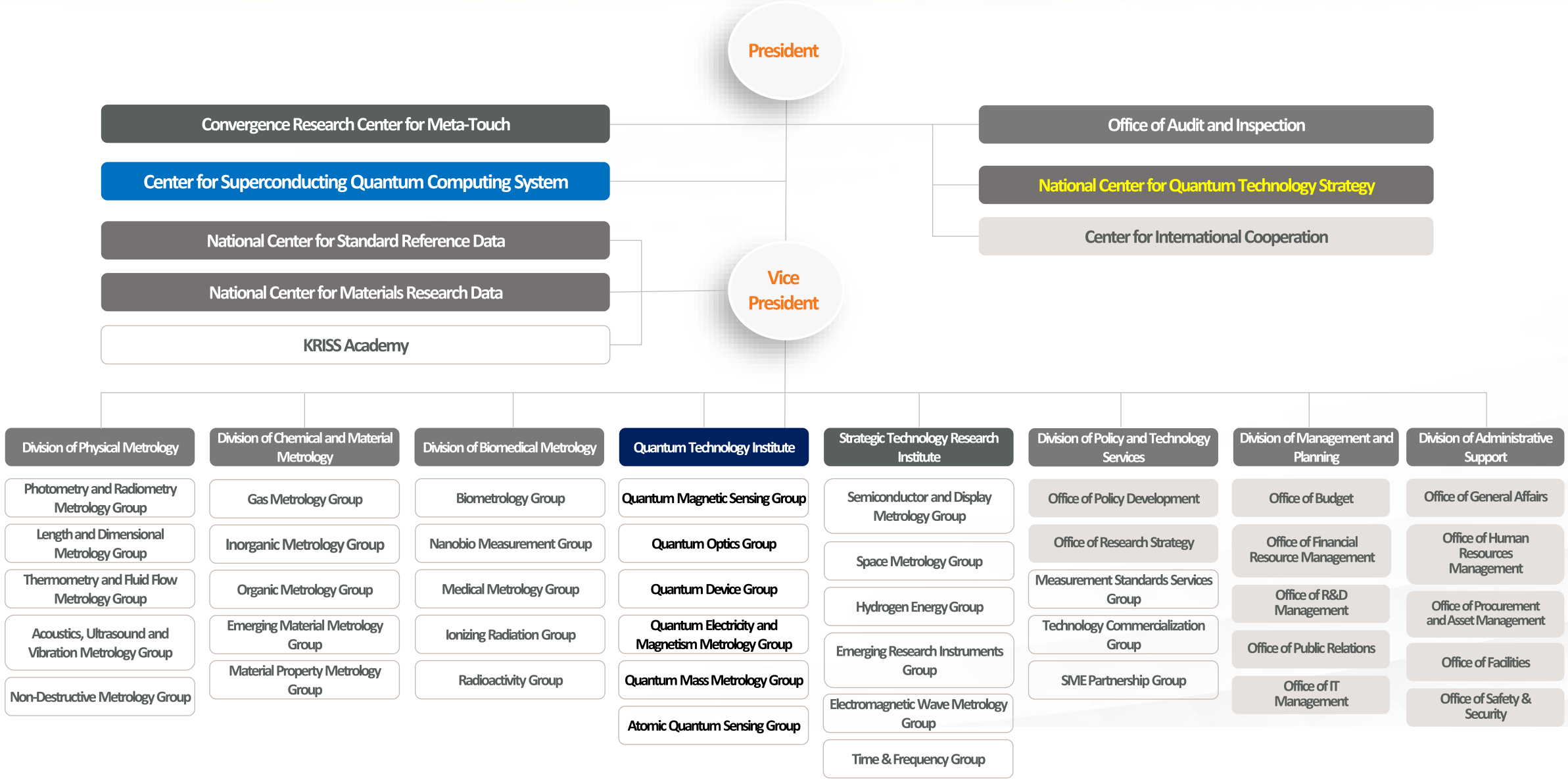
KRISS

KRISS 한국표준과학연구원

Content



Organization of KRISS



Quantum technologies and Standards

Quantum for precision measurements and standards

- Quantum hall resistance standard
- Josephson voltage standard
- Single electron tunneling
- SQUID* for precision measurements
  (SQUID*: Superconducting QUantum Interference Device)

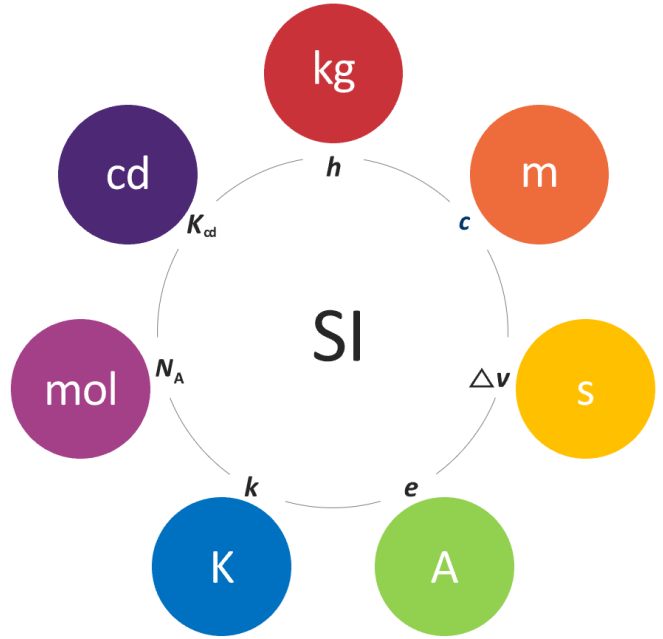
- Atom clock
- Luminosity standard
- Quantum gravity meter

…

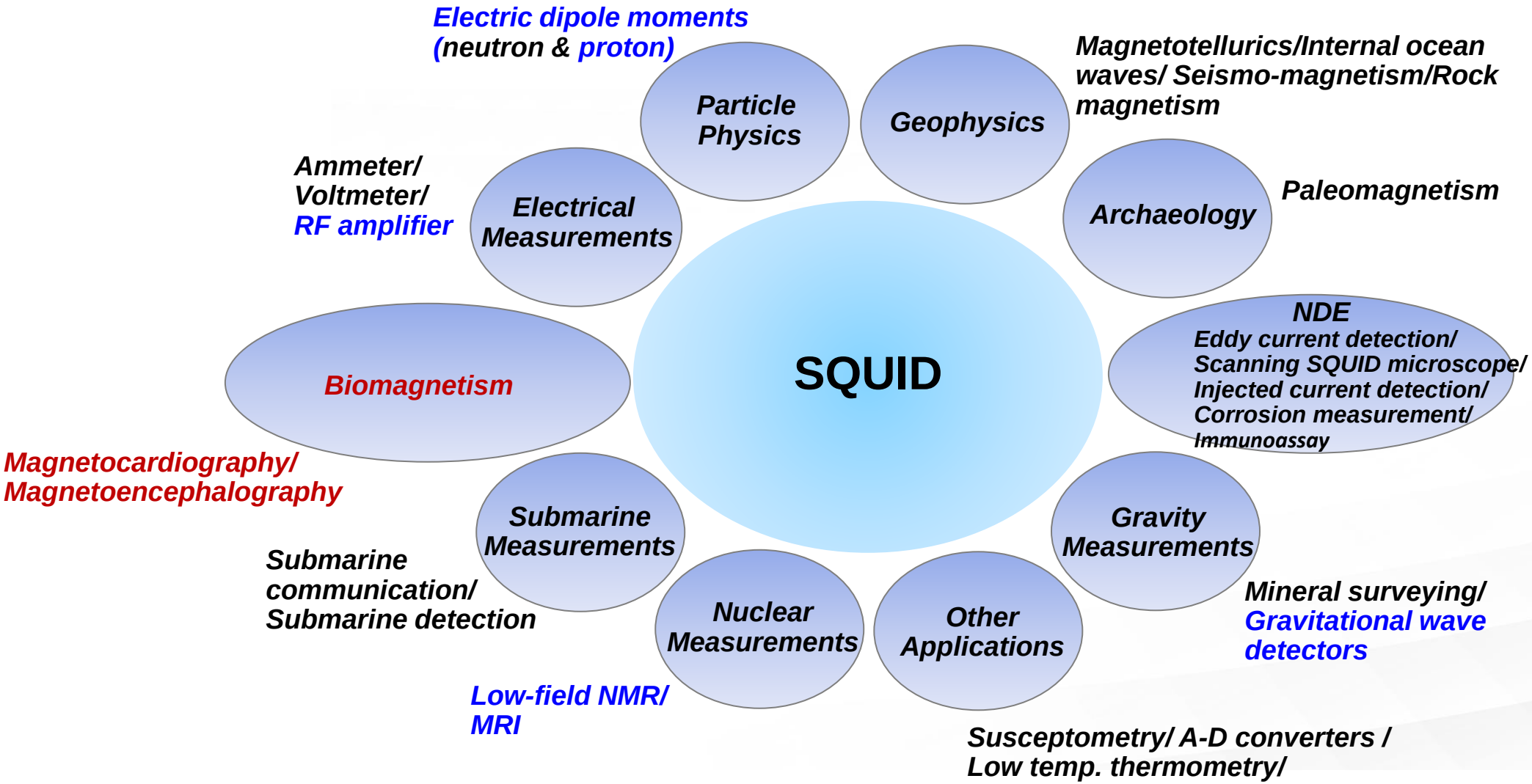
Quantum Technologies

Accelerates and improves

<Measurements and Standards>



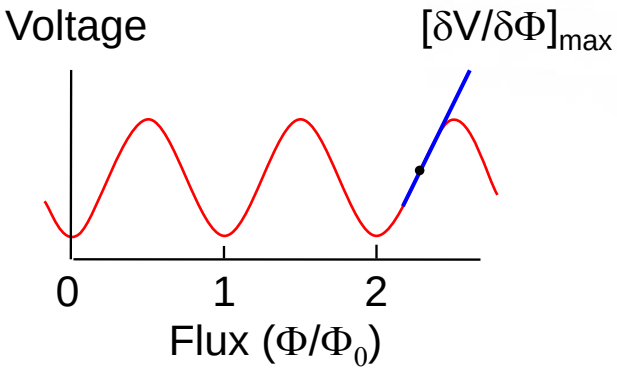
SQUID applications



Advanced SQUID technology in KRISS

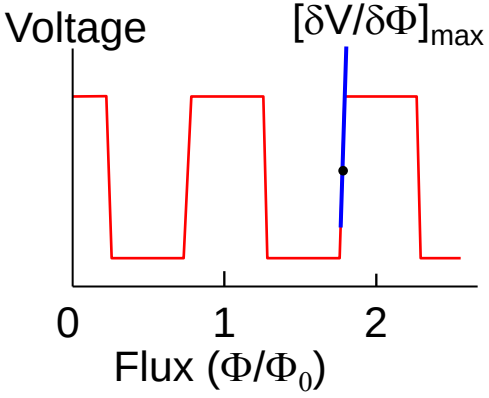
<Standard DC SQUID>

Flux modulation curve



<Double Relaxation Oscillation SQUID (DROS)>

Flux modulation curve



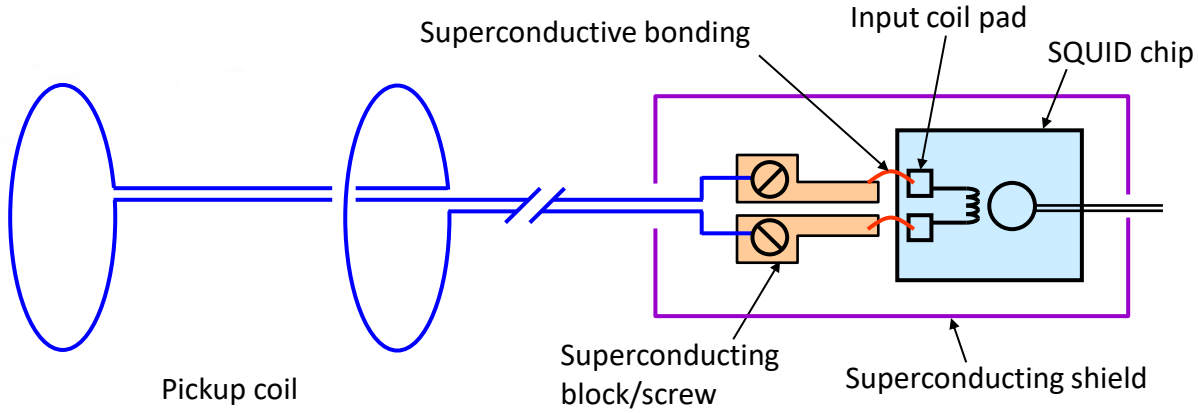
High flux-to-voltage transfer:

$[\delta V/\delta\Phi]_{max} > 1\ mV/\Phi_0$

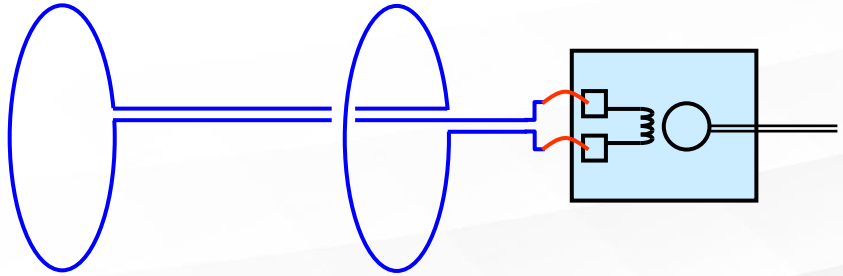
Large modulation amplitude

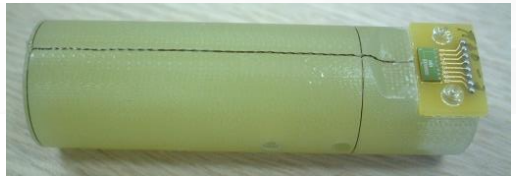
$\Rightarrow$ Simpler readout circuits

<Standard pickup coil structure>



<Compact pickup coil>





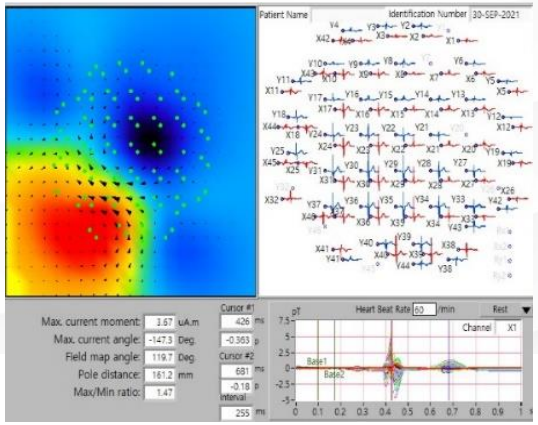
MagnetoCardioGraphy (MCG) measurement

<Helium recycling>

<Laboratory>

<Commercialization: Technology licensing>

<Analysis software>



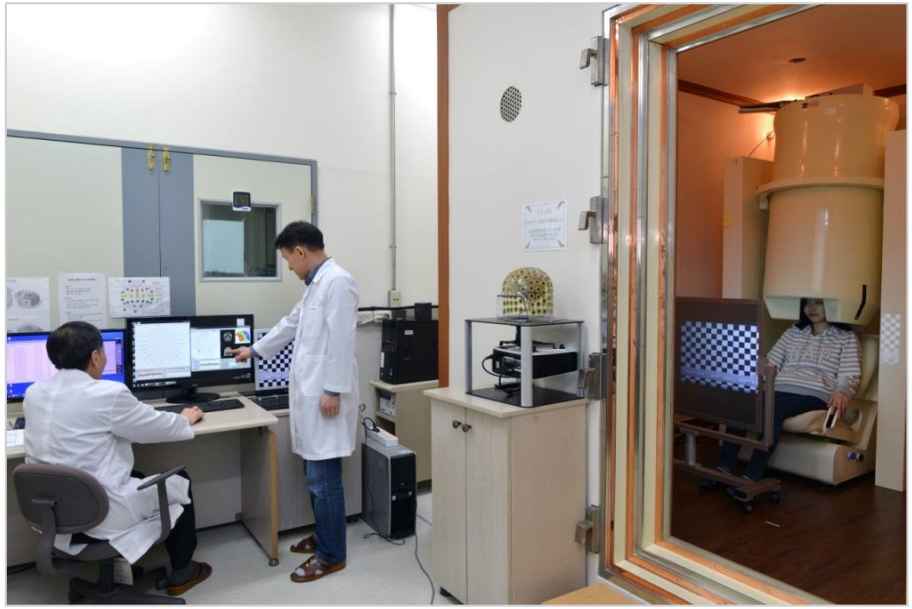
Complete recycling of helium
→ **No refill of liquid helium**

Second-order gradiometer
→ **Thin (economic) shielded room**

- **Non-invasive**
- **High diagnostic accuracy**
  - **Ischemia**
  - **Arrhythmia**
- **FDA certificate**

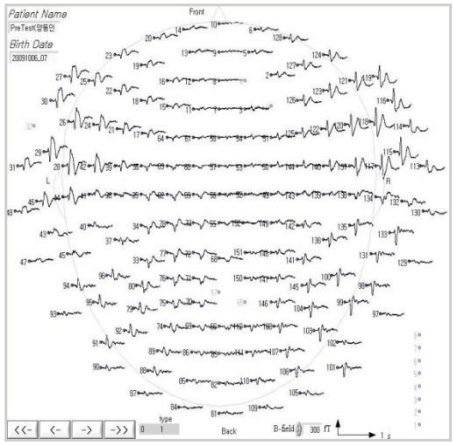
MagnetoEncephaloGraphy (MEG) measurement

<MEG system>



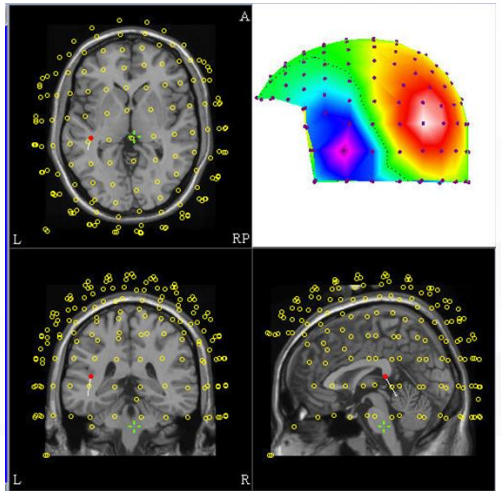
<Sensor helmet>

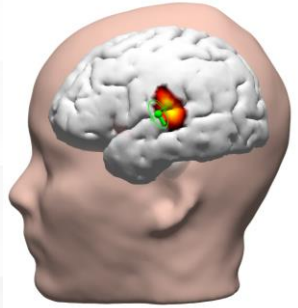
<Signal processing>



<SQUID>

<Source localization>

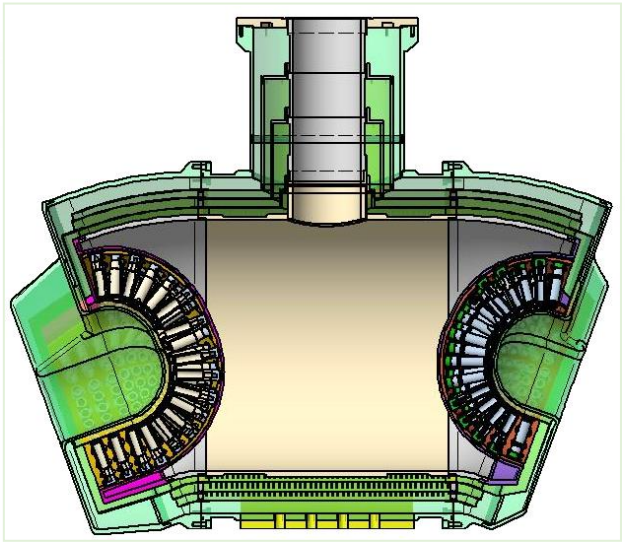




- High temporal/spatial resolution
- Non-contact & Non-invasive
- Measure neural activity directly

Dual-helmet MEG: LifeSpan measurement

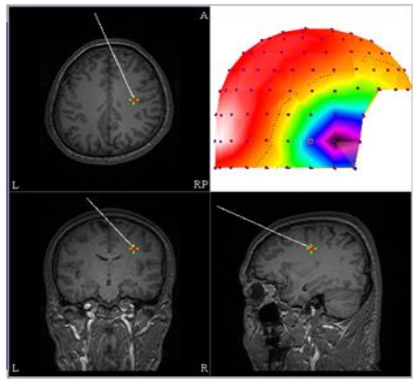
<Dual-helmet dewar>



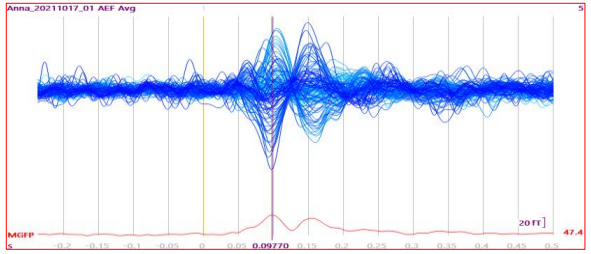
<Adult helmet>

<Pediatric helmet>

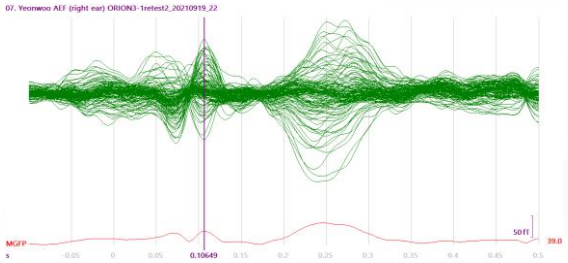
<Localization of epileptic focus>



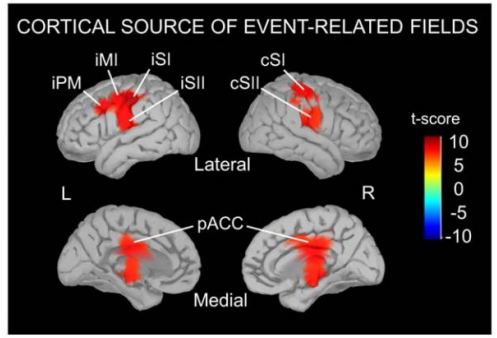
<Adult auditory response>



<Pediatric auditory response>



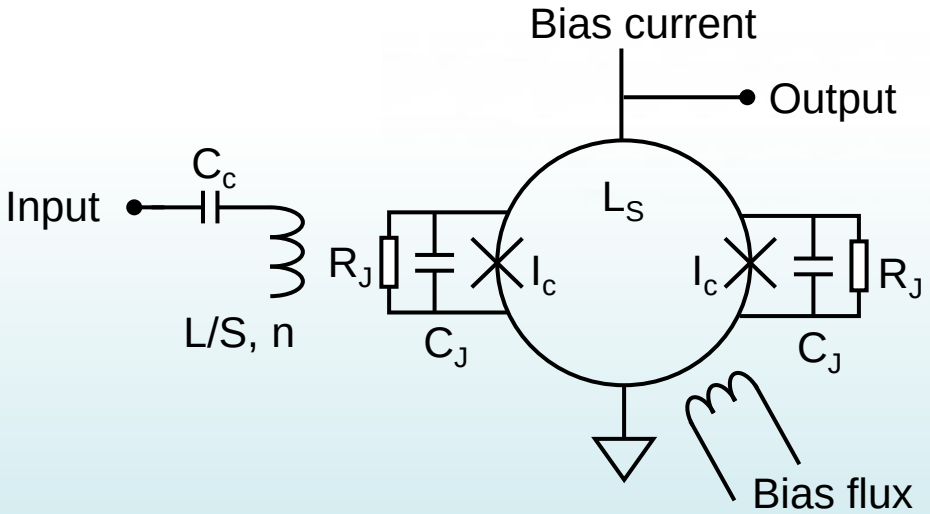
<Cognitive processing>



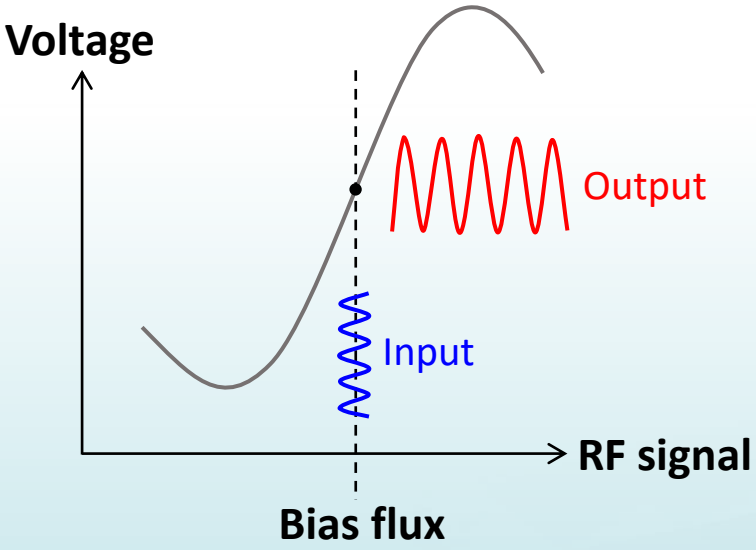
- Social interaction
- Brain development
- Autism

SQUID microstrip radio-frequency amplifier

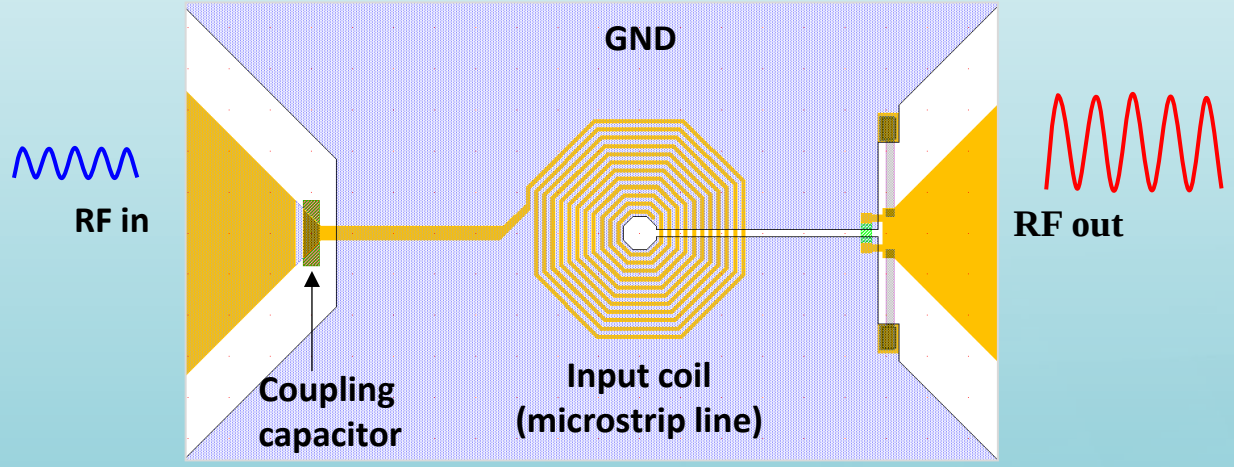
<Schematic diagram of SQUID RF amplifier>



<Concept of RF amplification>



<SQUID layout>



Used for axion-search experiments

- High magnetic field (~ 5 T)
- 50 mK

Quantum technology market

	Quantum computing	Quantum communication	Quantum sensing
2035	$28B–$72B	$11B–$15B	$0.5B–$2.7B
2040	$45B–$131B	$24B–$36B	$1B–$6B

(Conservative) (Optimistic)

Potential economic value from quantum computing in 2035

~$0.9T–$2T

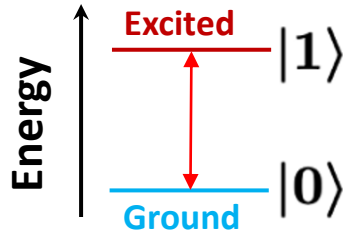
potential economic value across four industries by 2035: chemicals, life sciences, finance, and mobility[1]

Quantum Technology Monitor, McKinsey & Company (2024)

Platforms for quantum computing

2-level system

<State>



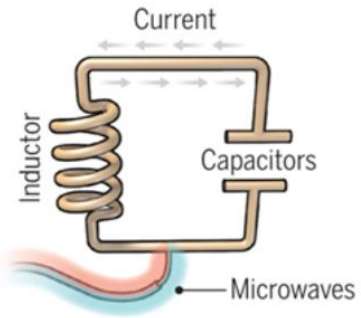
$$E_{01} = E_1 - E_0 = \hbar\omega_{01}$$

Quantization of state + Superposition of states + Entanglement of qubits
→ Quantum computing

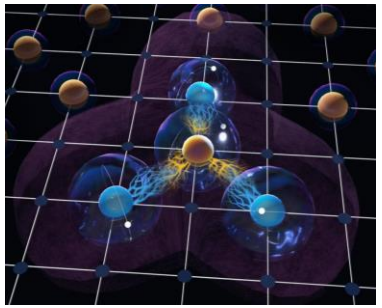
Natural
- Ion, spin, neutral atom, photon, …

Artificial
- Superconducting device, …

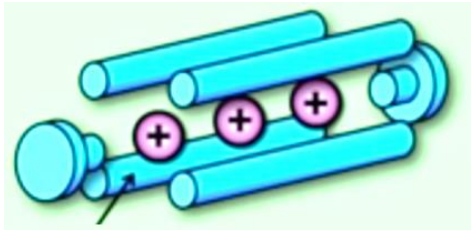
Types of platform



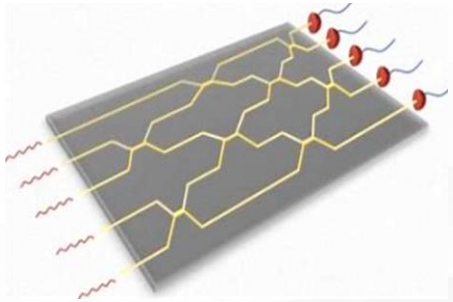
Superconducting loops



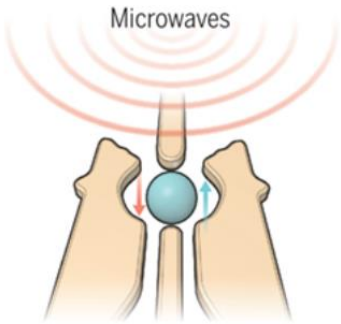
Neutral atoms



Trapped ions



Photonic circuits



Silicon quantum dots

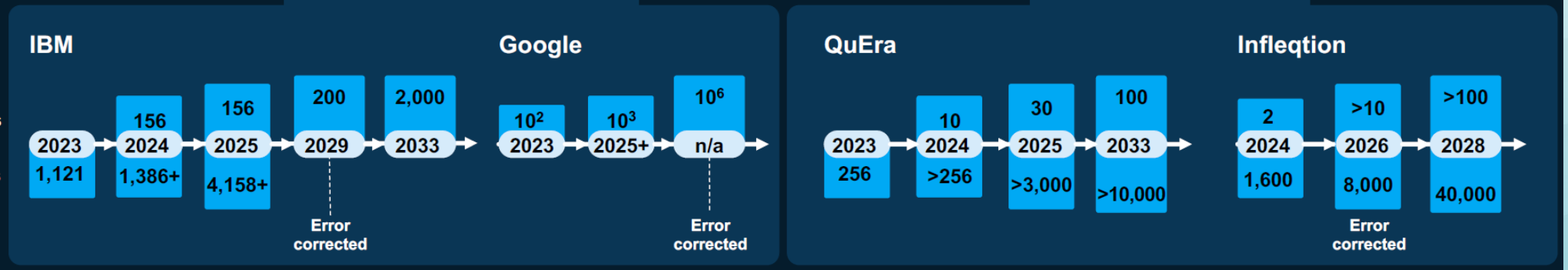
…

Progress of quantum computing

Not exhaustive

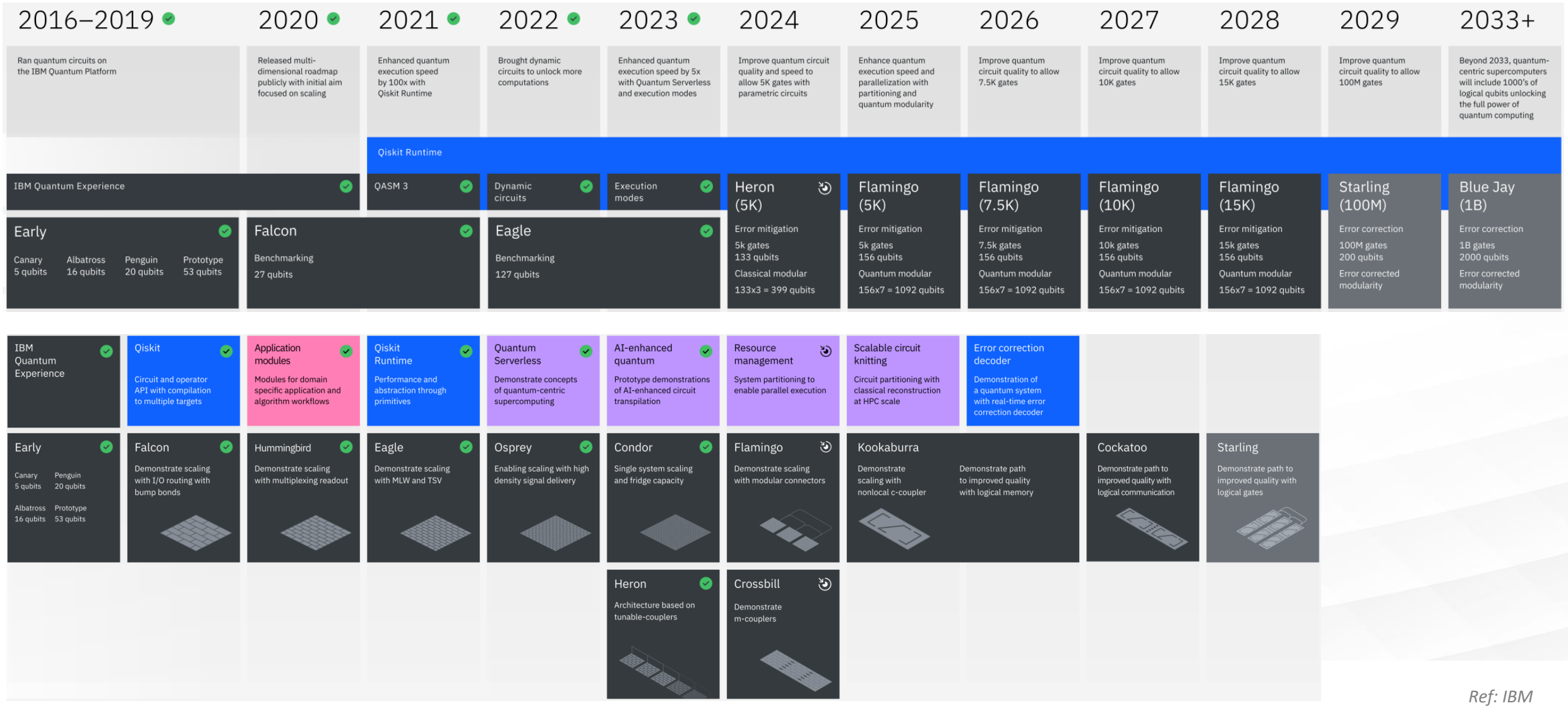
Technology	Photonic networks	Superconducting (SC) circuits	Spin qubits[1]	Neutral atoms	Trapped ions
Qubit description	Occupation of a photonic waveguide	Difference in energy states of Cooper pairs between two sides of a Josephson tunnel junction	Electron spins of different materials (eg, an electron trapped within a silicon quantum dot or a color center in an insulator) controlled by laser light or microwave radiation	Internal energy levels of neutral atoms trapped by laser fields	Internal energy levels of ions trapped by electromagnetic fields
Physical qubit count[2]	216 Xanadu 256 PsiQuantum	1,121 IBM 84 Rigetti 127 Google 64 Fujitsu 64 Microsoft 16 Alice & Bob	12 Intel	256 QuEra 1,180 Atom Computing 1,600 Infleqtion	36 IonQ 20 Alpine Quantum Technologies

Example road map[2]



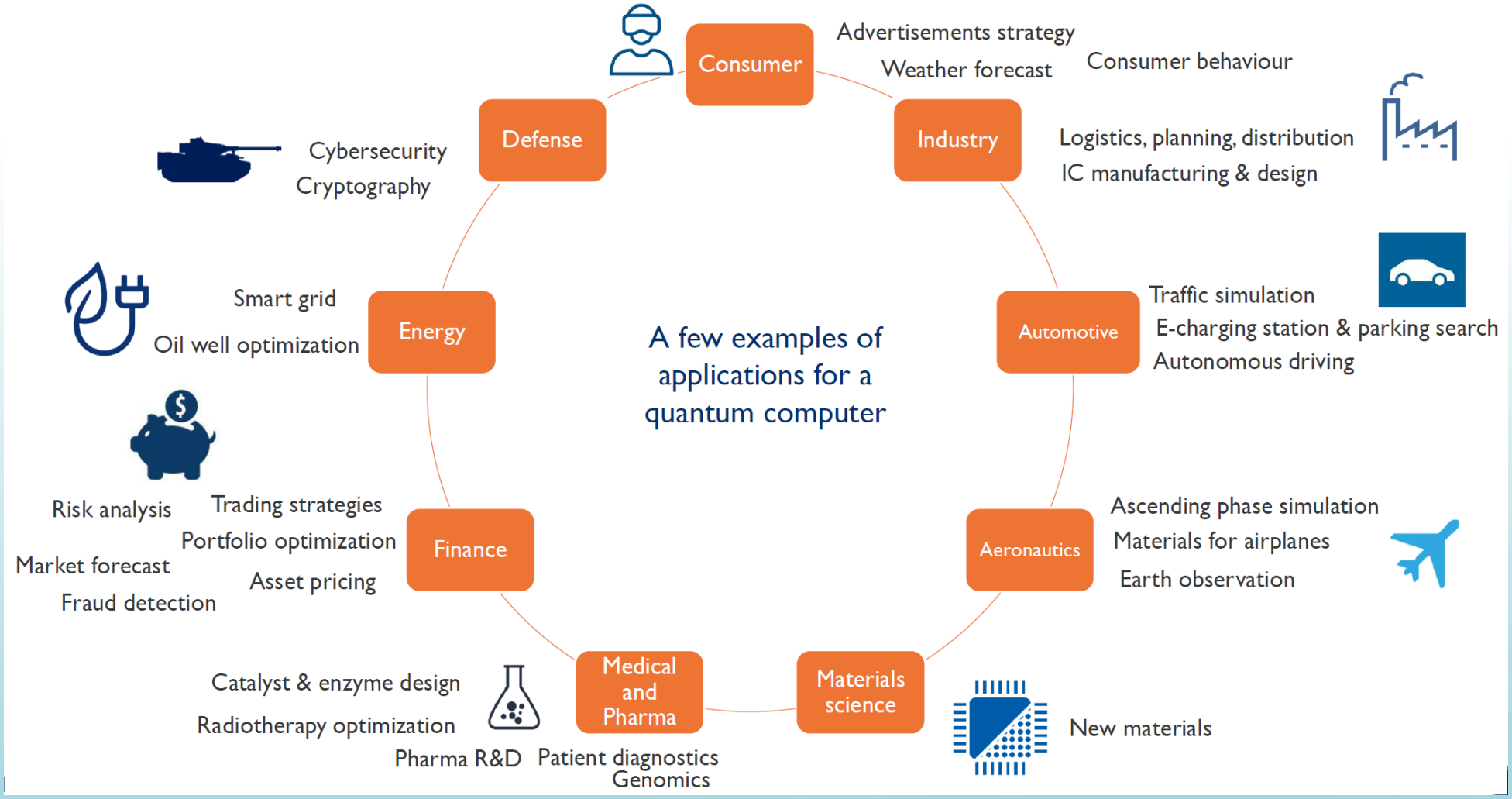
Quantum Technology Monitor, McKinsey & Company (2024)

IBM Quantum roadmap (superconducting)



Ref: IBM

Potential applications of Quantum computing



Ref: Yole Development

Roadmap for KRISS superconducting QC project

Title: Establishment of superconducting quantum computing infrastructure

Phase I

- Period: 2022.6. - 2025.3.
- Development of 20-qubit system and demonstration of cloud service

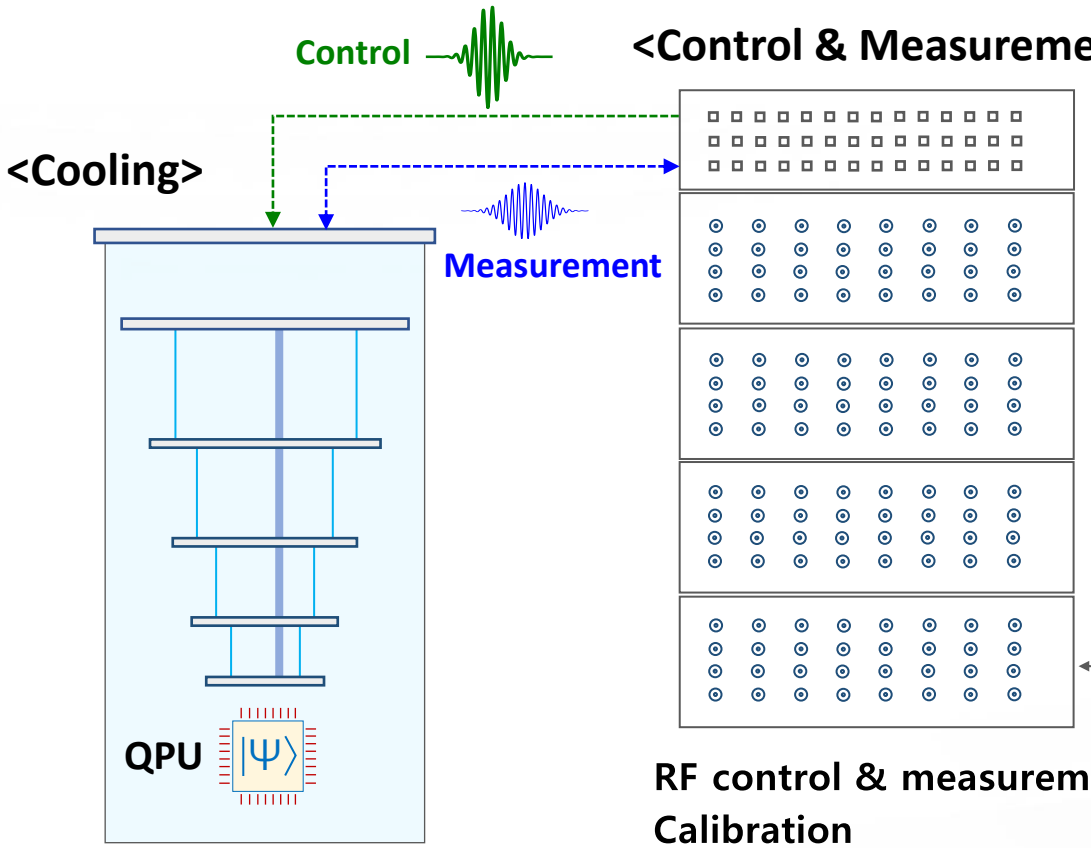
Phase II

- Period: 2025.3. - 2027.3.
- Development of 50-qubit system and demonstration of cloud service

Participating institutions

- KRISS: PI
- Sungkyunkwan University (SKKU)
- Ulsan University of Science and Technology (UNIST)
- Korea Institute of Science & Technology Information (KISTI)
- 3 Universities (Kyunghee U., Seoul Nat'l U., Yonsei U.)

Structure of the on-going project in KRISS



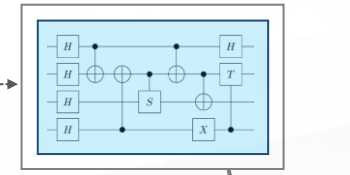
QPU chip design
QPU chip fabrication
3D integration

RF packaging
QPU characterization

Cooling
Quantum-limited amp.
Shielding/Filtering

RF control & measurement
Calibration

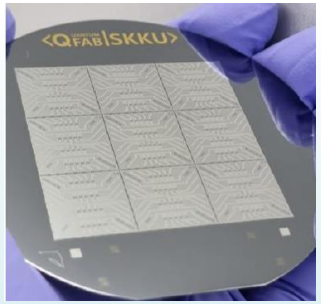
<Quantum circuit (Algorithm)>

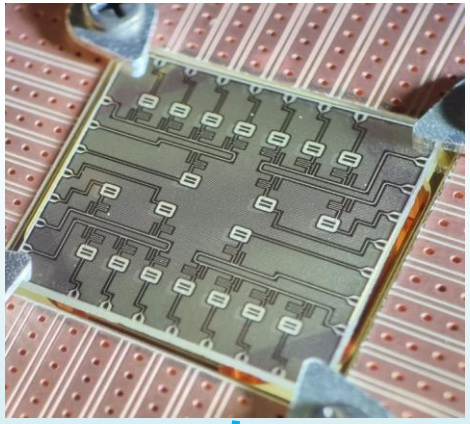


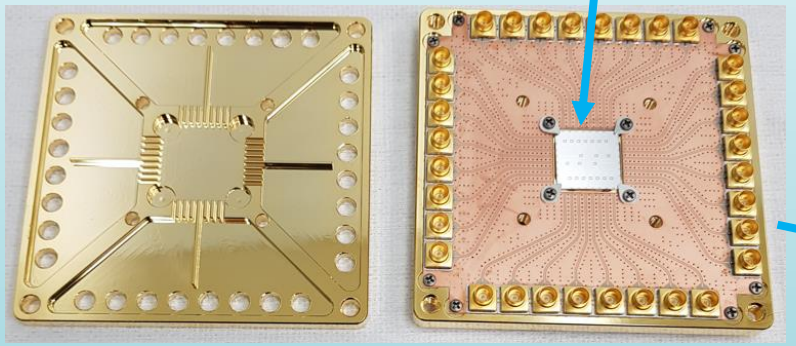
Cloud

20-qubit system in KRISS

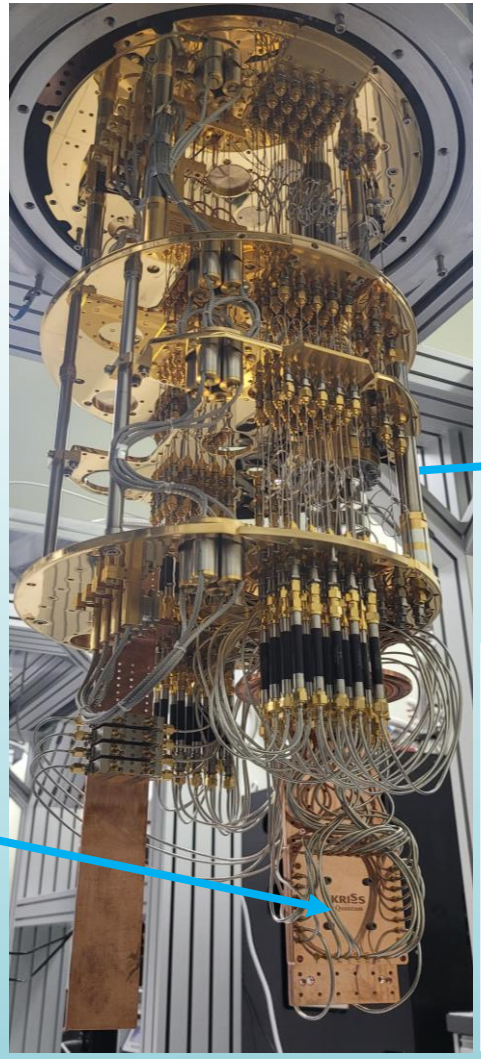
< QPU >







< Dilution refrigerator inside >

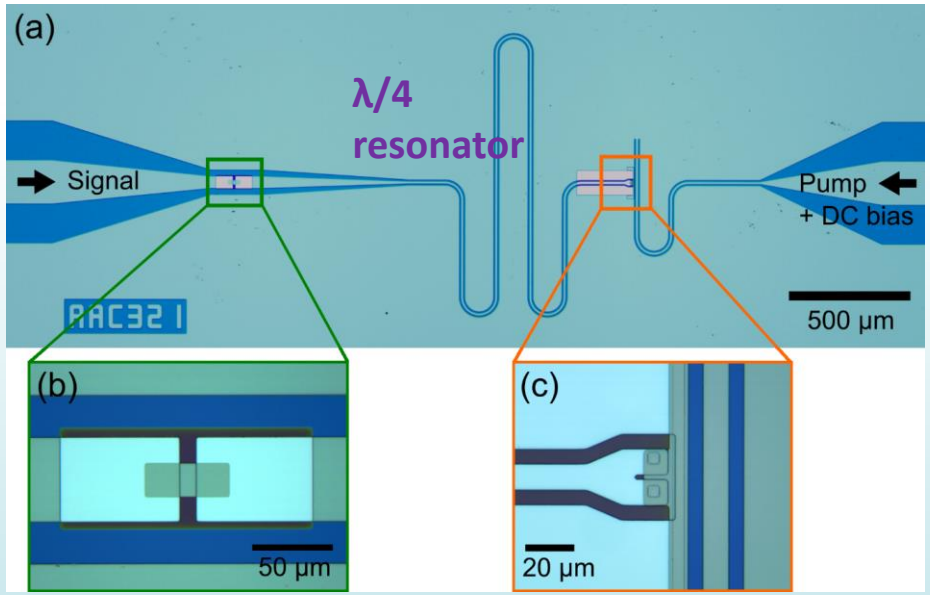


- CuNi coax
- NbTi cable
- HEMTs
- Dual-isolators
- Low pass filter
- IR low pass filter
- 20Q QPU chip
- Cryo mu-metal shield
- Copper clamp
- RT amplifier

< Dilution refrigerator and RF system>

Josephson parametric amplifier (JPA)

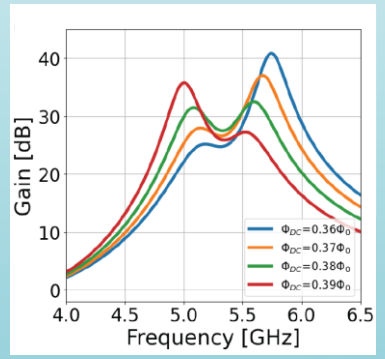
<IMPA (Impedance matched parametric amplifier)>



Coupling capacitor

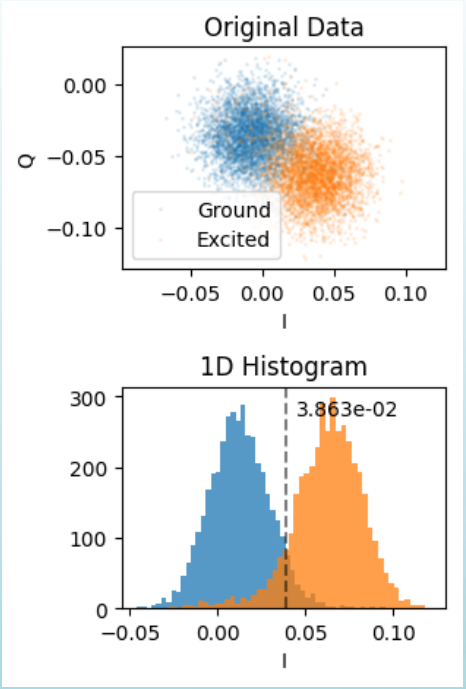
SQUID

<Gain curve>

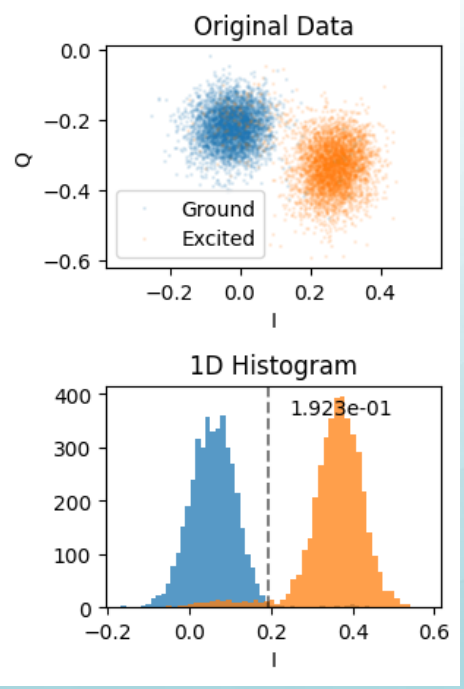


<Improvement of readout fidelity>

JPA off

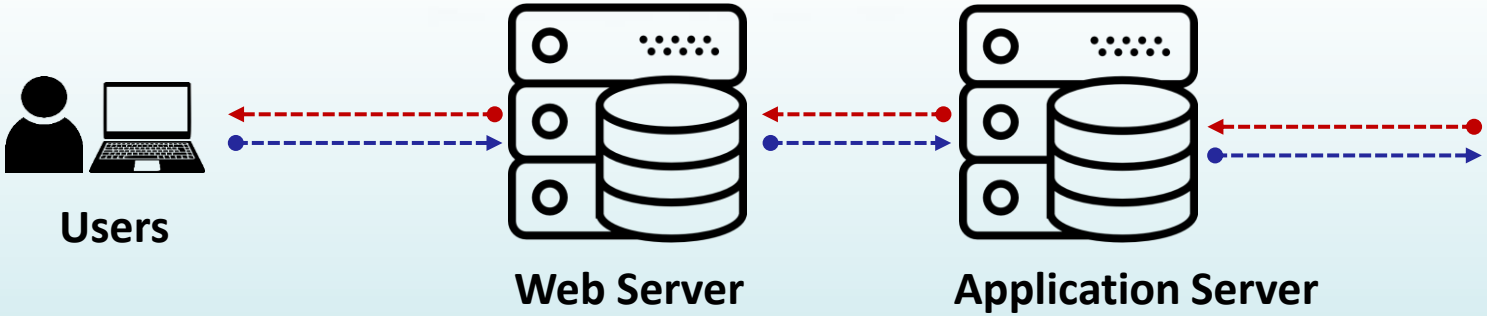


JPA on



Cloud network for Quantum computing

Frontend **Backend**



@ KISTI

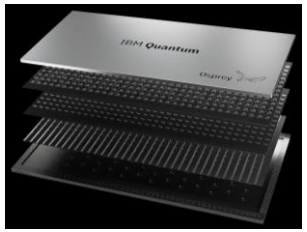
20Q/50Q systems @ KRISS

- Energy
- Chemistry
- Material science
- Biology
- Traffic
- Climate

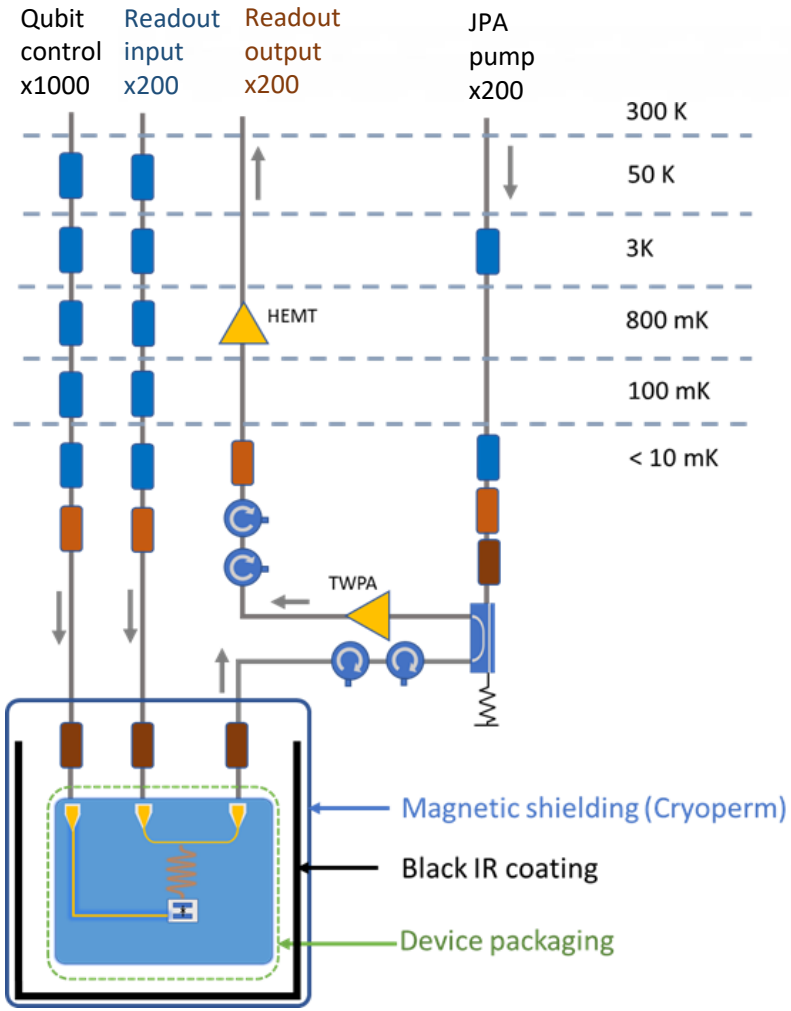
…

Ecosystem for QC: Quantum transformation (QX)

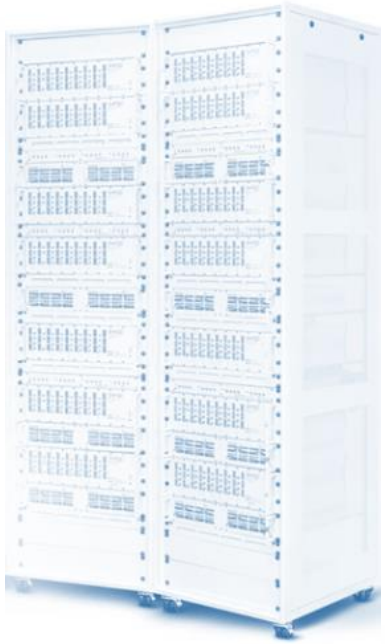
<1000-Q components (inside fridge)>



Ref: IBM



<Control & Measurement>



<1000-Q components>

No.	Item	Q'ty
1	Dilution refrigerator	1
2	Cables (CuNi)	2600
3	Cables (NbTi)	200
4	HEMT amplifier	200
5	IR filter	2600
6	Low pass filter	2600
7	Circulator	200
8	Isolator	400
9	Switches	200
10	Terminator	200
11	Directional coupler	200
12	DC wiring	200
13	Quantum-limited amplifier	200
14	QPU chip	1

No standards for characterizing QPU

IQM Spark™ (Superconducting quantum computer)

Median single-qubit gate fidelity	≥ 99.7%
Median two-qubit gate (CZ) fidelity	≥ 98.0%
Single-qubit gate duration	≤ 40 ns
Two-qubit gate (CZ) duration	≤ 100 ns
Median readout fidelity	≥ 95%
Quantum volume	≥ 8
Q-score	5
Qubits in a GHZ state with a fidelity > 0.5	5
CLOPS_v	≥ 2400

IonQ Harmony (Trapped-ion quantum computer)

Performance	
Algorithmic Qubits (#AQ)	#AQ 9
Physical Qubits	11
2QG Fidelity	97.3%
1QG Fidelity	99.6%

Standardization of QPU

- Terminology (definition of parameters)
- Key performance (Specifications)
- RR test for small-scale QPU chips
- Platform dependent

Metrology for QC components at low temperature

Components

- Cables
- Attenuators
- Low-noise amplifiers (HEMTs)
- Filters (Low-pass and infrared)
- Isolators (Circulators)
- Directional couplers
- Magnetic shield

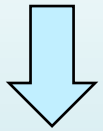
...

Parameters

- Impedance
- Insertion loss
- Return loss
- Frequency range
- Cut-off frequency
- Bandwidth
- Gain
- Noise temperature
- Isolation
- Coupling
- Tolerance
- Directivity
- Shielding factor

...

Conventional (300 K) metrology



QX

Cryogenic (4 K ~ 10 mK) metrology

Valid for other platforms (Neutral atoms, trapped ions, …)

Next-generation (Scaled-up) Quantum computer

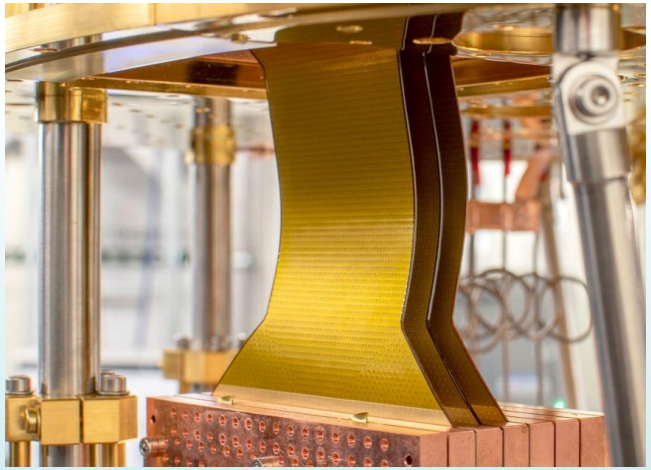
High-density multi-channel cable/connector assembly

<Coaxial cables>

<High-density (Modular)>

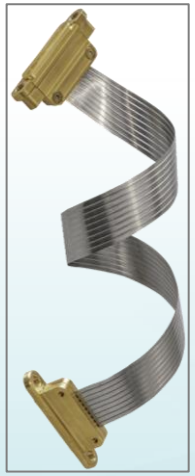
Ref: BlueFors

<Flat cable>



Ref: IBM

<Flexible cable>



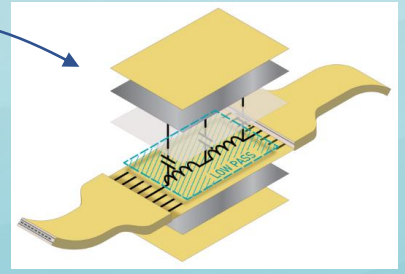
Ref: Maybell

Development direction:

- Integration of connectors and cables
- Flexible cable
- High-density components (Passive and Active)

<Flexible cable + Components>

Integrated



Ref: Delft Circuits

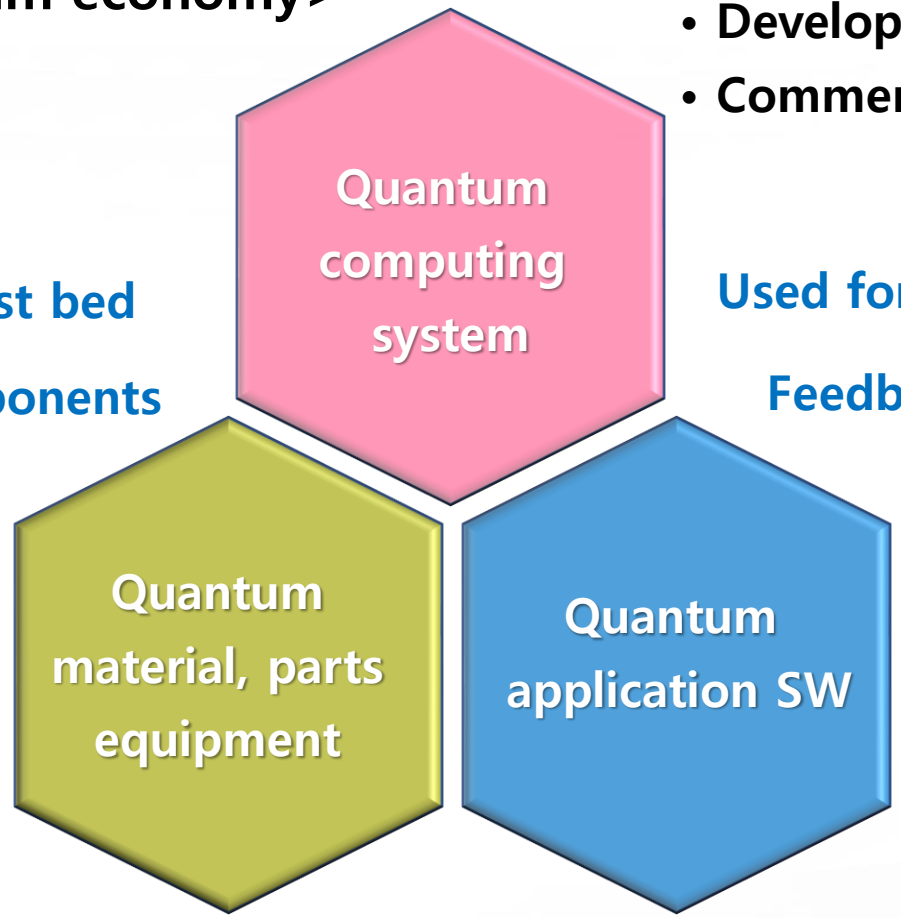
<Metrology>

Calibration at cryogenic temperatures

Reference signal sources

Ecosystem for Quantum computing

<Realization of quantum economy>



- Development of QC system
- Commercialization of QC system

Test bed

Used for algorithm development

Optimization of components

Feedback on HW system performance

- Commercialization
- Global supply chain

- Development of application area
- Explorer new industry

Quantum computing and precision measurements

Quantum + AI

- Faster data processing
- Faster analysis of measurement data (data fitting and simulation)
- Faster measurement (: less data point) → Shorter measurement time
- Improvement in measurement uncertainty

Mutual impact (at present)

Thank You!

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