Quantum Sensing Research at NIM

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National Institute of Metrology(NIM), CHINA

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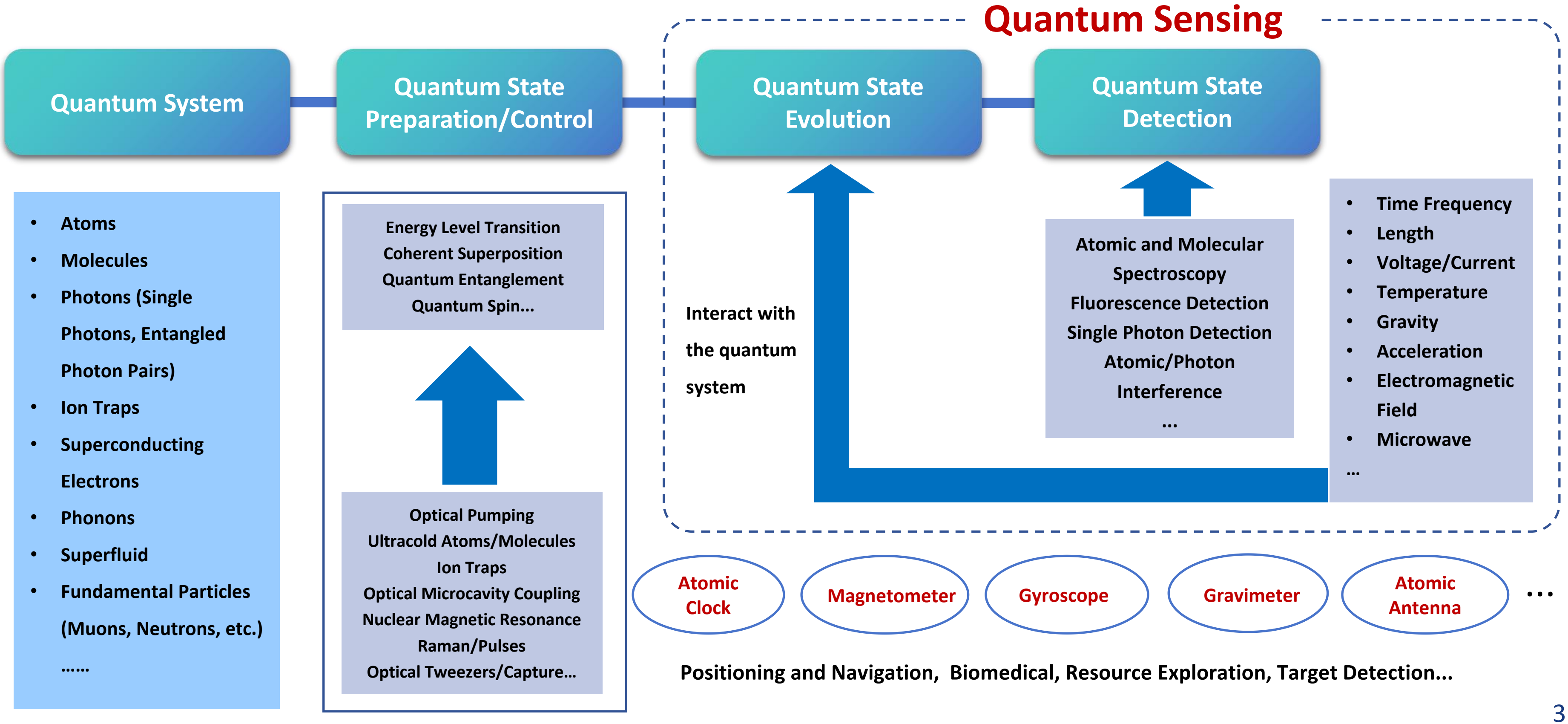
Bureau International des Poids et Mesures

Contents

1.1 Basic Principles

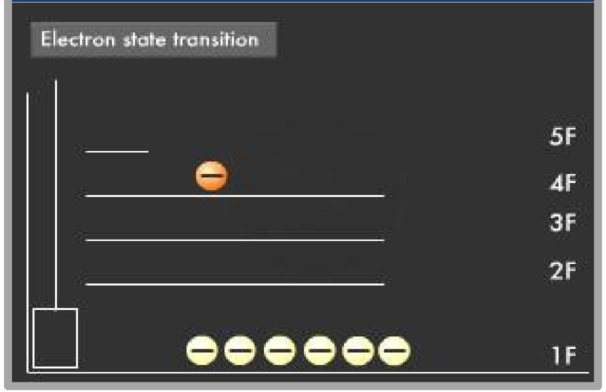


1.1 Basic Principles

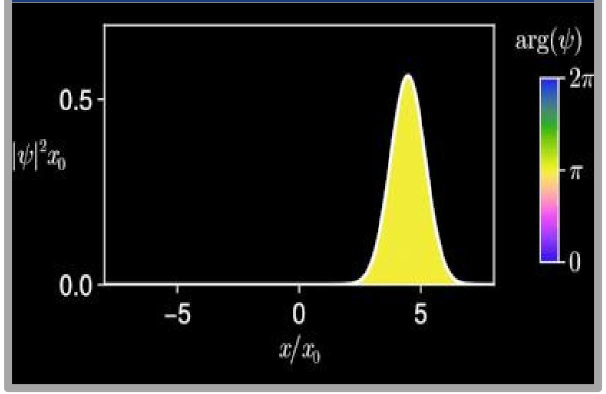
Different techniques

By leveraging the **quantum states of elementary particles**, high-precision measurement of physical quantities is achieved **through manipulation of energy levels, quantum coherent superposition, and entanglement**, exceeding the accuracy limits of classical methods.

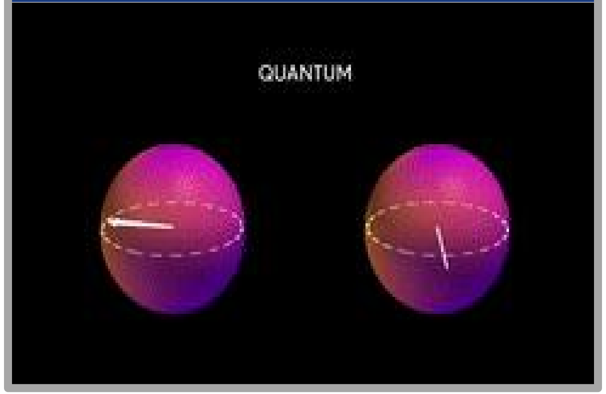
Energy level manipulation



Quantum coherence



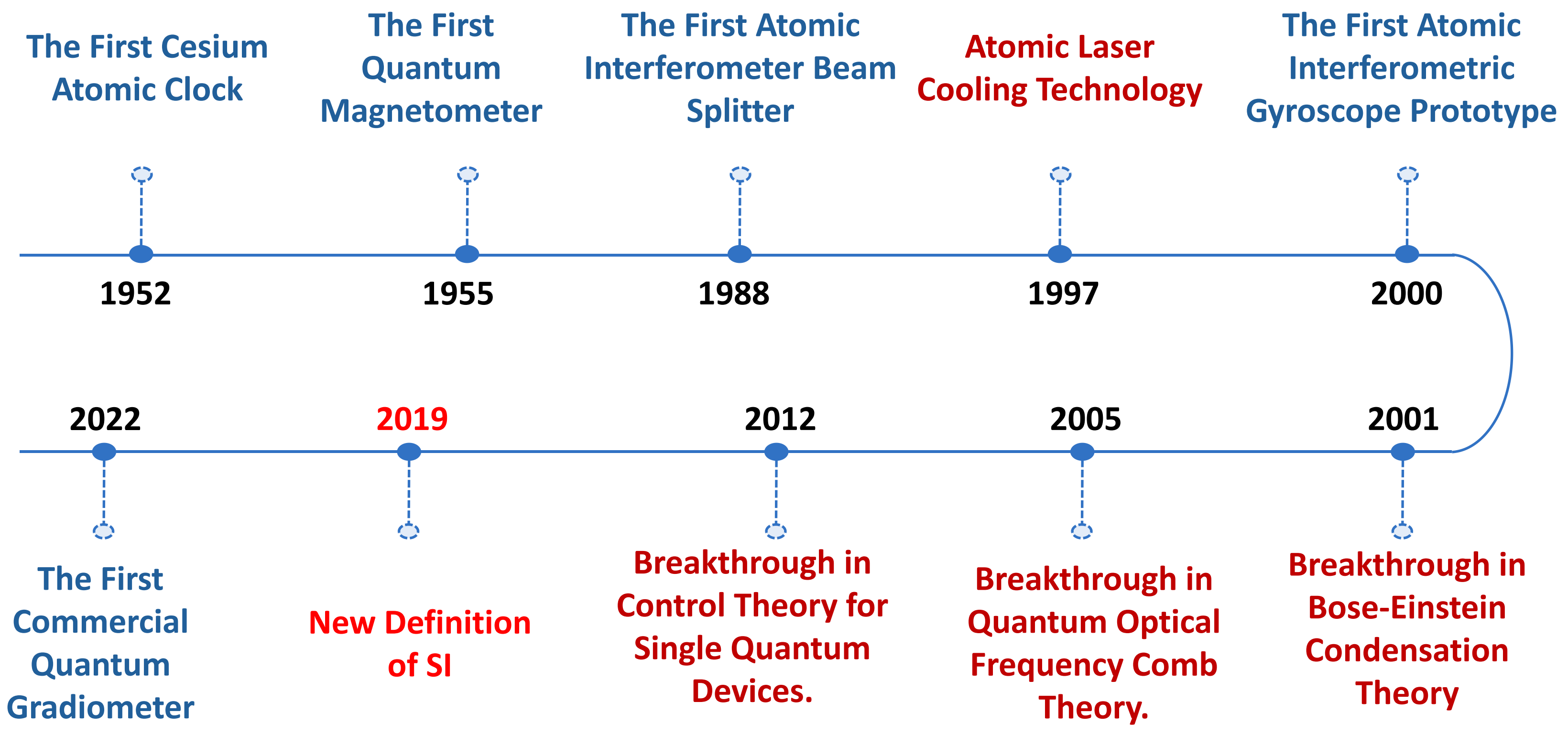
Quantum entanglement



1.1 Basic Principles

Neutral atoms Ion traps	**Quantum clock**	Microwave Clock Optical Clock	Molecular Clock Chip-Scale Atomic Clock	
Neutral atoms Solid-state spins (ensemble) Superconducting circuits Solid-state spins (single spin)	**Quantum magnetometer**	SQUID Magnetometer NV Center Magnetometer	SERF Magnetometer CPT Magnetometer	
Neutral atoms	**Quantum Gravimeter /Quantum Gradiometer**	Cold Atom Gravimeter		
Neutral atoms Rydberg atoms Solid-state spins (single spin)	**Quantum Accelerometer/ Quantum Gyroscope**	NMR Gyroscope Center Gyroscope SERF Gyroscope	Atomic Interferometer Gyroscope Atomic Interferometer Accelerometer NV Center Accelerometer	
Rydberg atoms	**Quantum Field Strength Meter**	Atomic Antenna		
Solid-state spins Others	**Quantum Thermometer**	Microcavity Thermometer	NV Center Thermometer	
Others 。。。	**Quantum Radar**	Quantum-Enhanced Radar	Interferometric Radar	Quantum Illuminating Radar

1.2 Development Overview



1.3 Technology Advantages

Quantum sensing provides **higher accuracy, sensitivity, resolution, measurement range, non-Invasive /non-destructive or self-calibration capability** , surpassing the performance limits of classical sensors.

	Time frequency	Magnetic field	Electric field	Gravity	Inertia
Type	Atomic Clock	Quantum Magnetometer	Quantum Electric field Meter	Quantum Gravimeter/Gravity Gradiometer	Quantum Accelerometer/ Gyroscope
Technology	Frequency of Internal Energy Level Transitions in Atoms	Atomic Spin Resonance, Superconducting Effect, Optical Interference, Diamond NV Center	Rydberg atoms Quantum coherence	Measurement of Atomic Interference After Laser Manipulation of Cold Atom Beam	Cold Atoms, NV Centers, Nuclear Magnetic Resonance (NMR)
Advantage	• High Stability and Accuracy • Stable Operation Over Long Periods	• High Precision and Extremely High Sensitivity • Capable of Detecting Subtle Magnetic Field Changes	• High Sensitivity • Extremely Broadband frequency • Self-calibration • Small size	• High Precision and Sensitivity with No Drift in Indicators • Especially Suitable for Dynamic Environments	• Outstanding Precision and Sensitivity • Lower Drift Error

Contents

Quantum Sensing Research at NIM

Time/Frequency

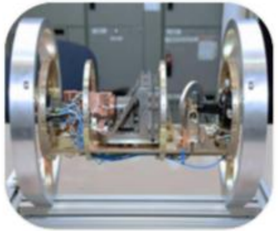
Quantum Clock

Gravity

Quantum Gravimeter
Quantum Gradiometer

Magnetic Field

Quantum Magnetometer



Electric Field

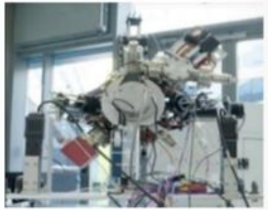
Quantum Field Strength Meter

Temperature

Quantum Thermometer

Inertia

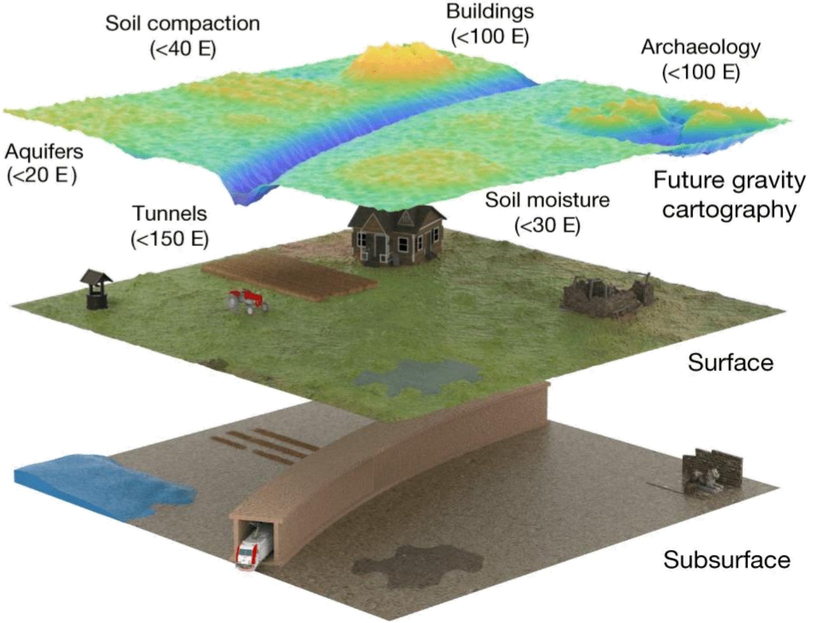
Quantum Accelerometer
Quantum Gyroscope

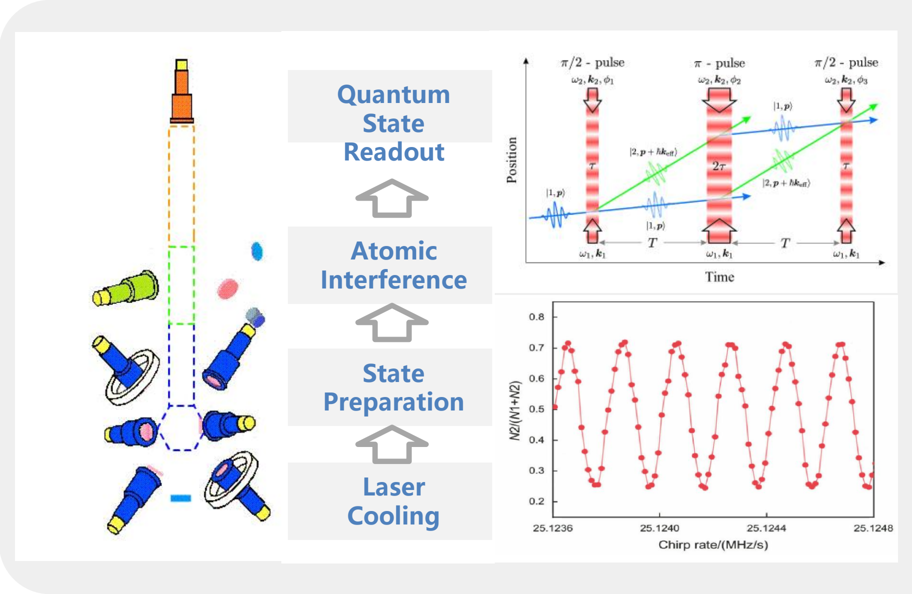


2.1 Gravity Sensing

Industry Requirement

Existing subsurface survey and mapping tools can **only see the top layer, measure inconsistently under different ground conditions, and are completely unable to operate in high-vibration environments.**

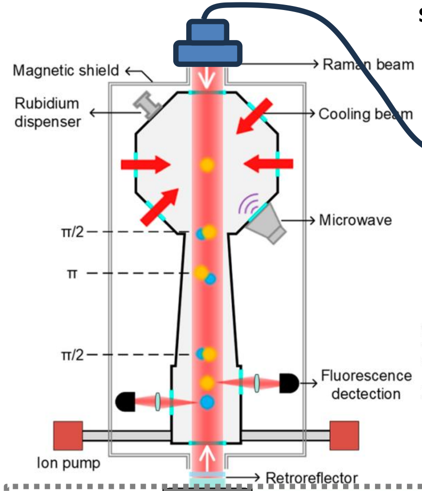




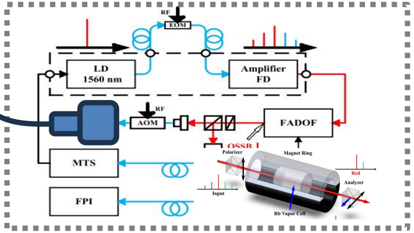
Source: Delta g official website

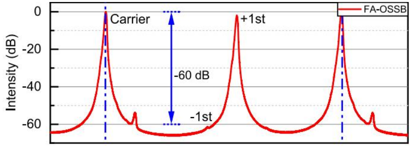
2.1 Transportable Atomic Gravimeter at NIM

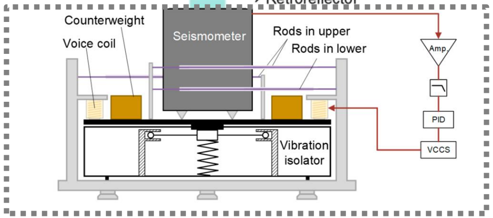
NIM-AGRb2 transportable atomic gravimeter

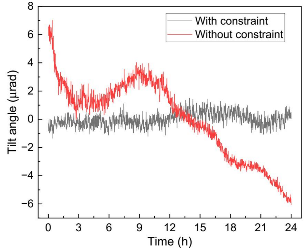


single-sideband (OSSB) Raman laser



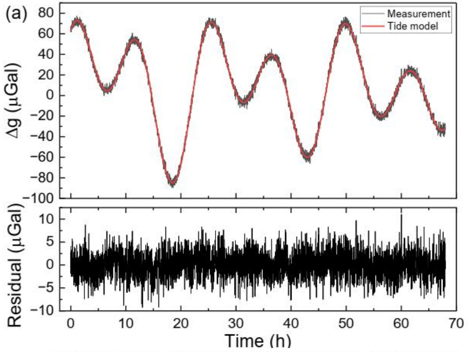


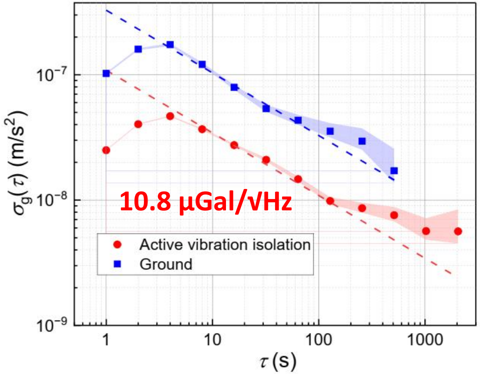




single degree of freedom active vibration isolation platform

Application in seismic observation station



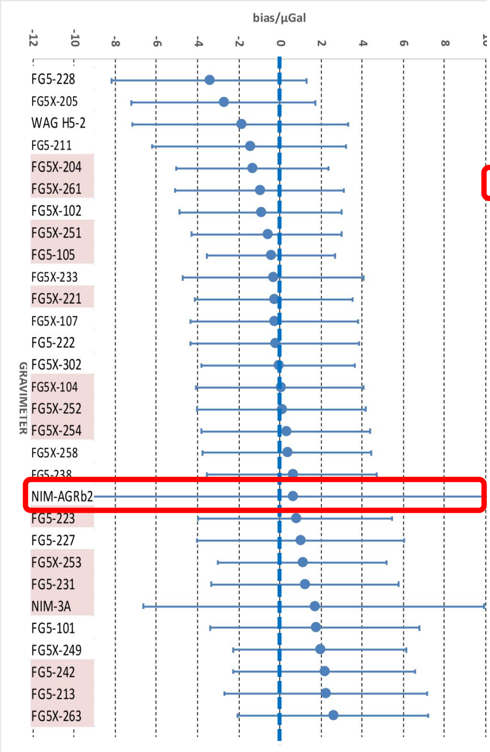


2.1 Transportable Atomic Gravimeter at NIM

2023 11th International Comparison of Absolute Gravimeter(ICAG-2023)

Transport to Table Mountain Geophysical Observatory (TMGO) Boulder, Colorado

Comparison Final Report (2024.10)

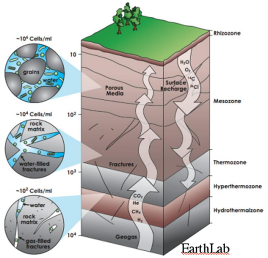


Gravimeter	δ/μGal	U/μGal
FG5-242	2.13	4.42
FG5-223	0.75	4.71
FG5-105	-0.44	3.12
WAG H5-2	-1.92	5.23
NIM-3A	1.66	8.27
FG5X-249	1.94	4.19
NIM-AGRb2	0.59	9.82
FG5-231	1.21	4.57
FG5X-251	-0.64	3.66
FG5X-221	-0.31	3.84
FG5-228	-3.45	4.74
FG5-101	1.70	5.07
FG5-227	1.00	5.04
FG5X-263	2.58	4.63
FG5-238	0.59	4.11
FG5-213	2.23	4.90
FG5X-104	0.00	4.09
FG5X-252	0.08	4.10
FG5X-253	1.09	4.09
FG5X-261	-1.00	4.09
FG5-211	-1.48	4.72
FG5X-233	-0.33	4.38
FG5X-254	0.30	4.09
FG5-222	-0.24	4.10
FG5X-258	0.33	4.10
FG5X-302	-0.07	3.71
FG5X-107	-0.27	4.09
FG5X-205	-2.73	4.48
FG5X-102	-0.92	3.93
FG5X-204	-1.36	3.70

2.2 Magnetic Field Sensing

Industry Requirement

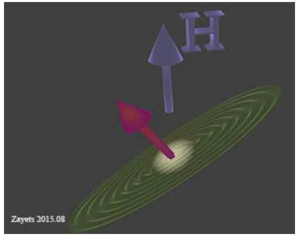
Traditional sensors are affected by environmental and operational conditions. The quantum sensor measures can detect **extremely weak** magnetic fields with **high accuracy and sensitivity**, and are **less susceptible to environmental interference.**

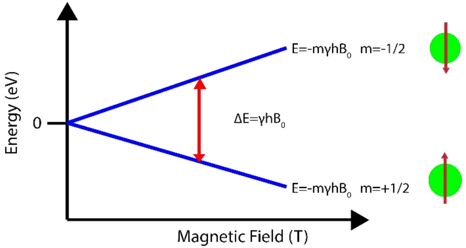


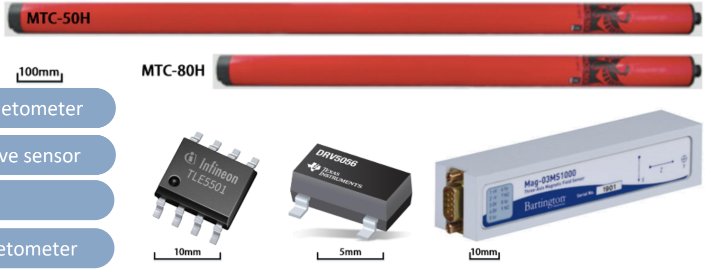
Geophysics

Fundamental physics

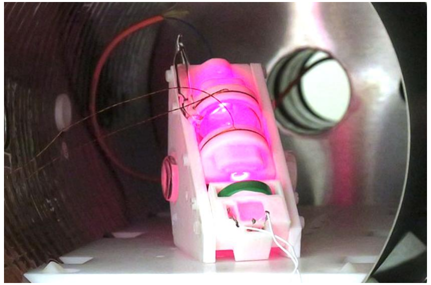
MCG/MEG

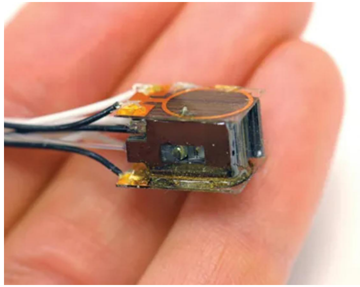






- (a) Induction magnetometer
- (b) Magnetoresistive sensor
- (c) Hall sensor
- (d) Fluxgate Magnetometer



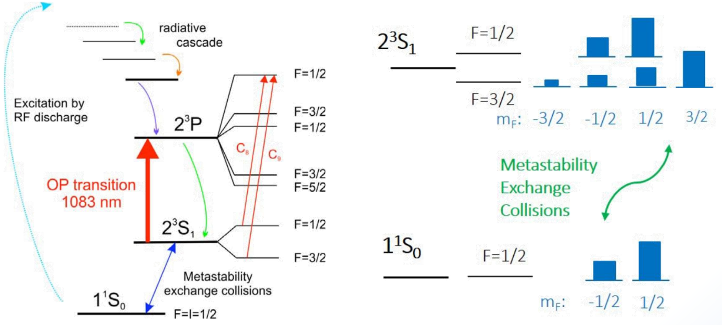


Traditional magnetometer: based on electromagnetic induction and other effects, accuracy and sensitivity are limited.

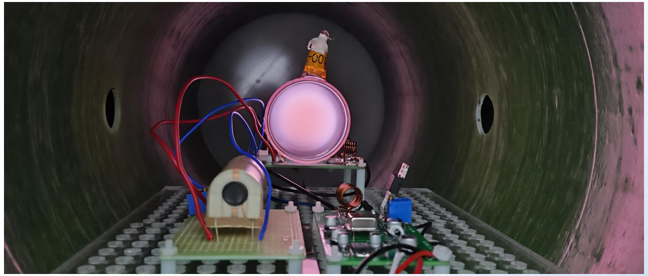
Atomic or NV magnetometers : based on energy level splitting or spin precession

2.2 Atomic magnetic sensing at NIM

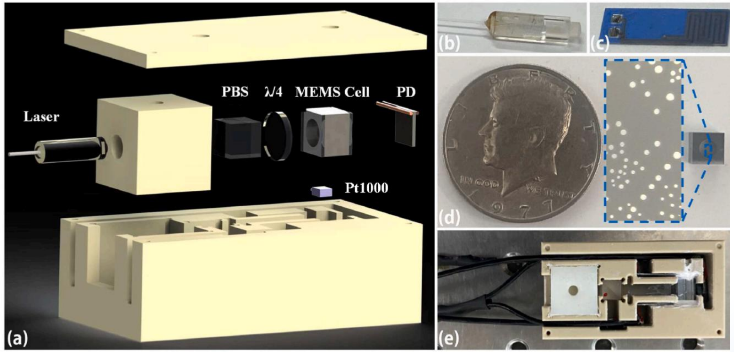
The traceability of the unit Tesla in a ultra-low field range



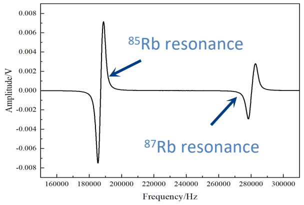
Metastability Exchange Optical Pumping (MEOP) of ^{3}He

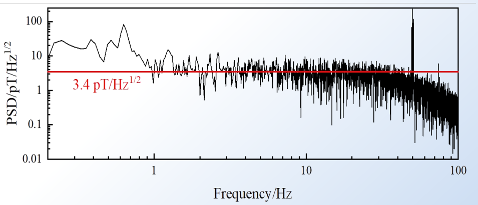


Compact atomic magnetometer with MEMS cell



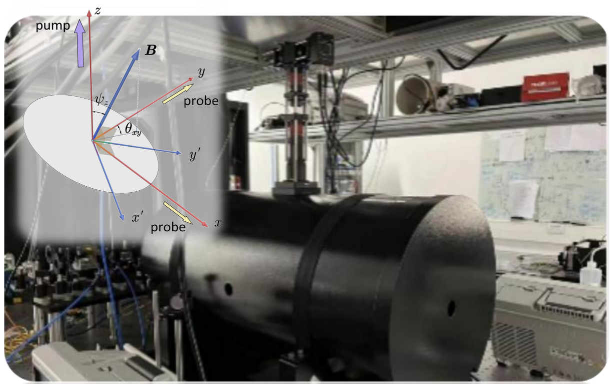
With self-developed MEMS Rb cell, we demonstrated a compact geomagnetic sensor, which achieved a sensitivity of 3.4 $pT/Hz^{1/2}$.

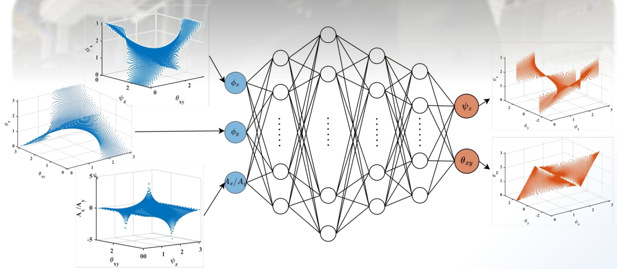


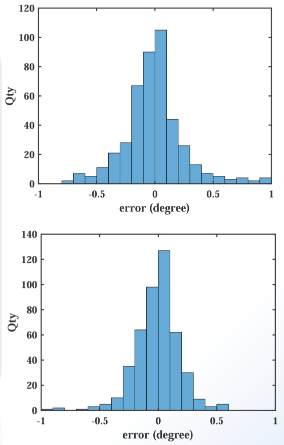


2.2 Atomic magnetic sensing at NIM

Vector atomic magnetometer with artificial neutral network



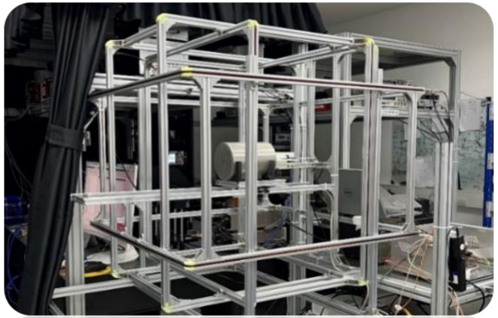


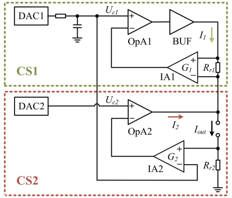


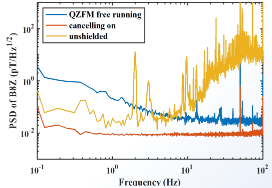
The average error of magnetic field angle is less than 0.3°.

Neural network maps the phase signal to magnetic field direction and corrects errors automatically.

Ultra-high sensitivity vector unshielded SERF magnetometer







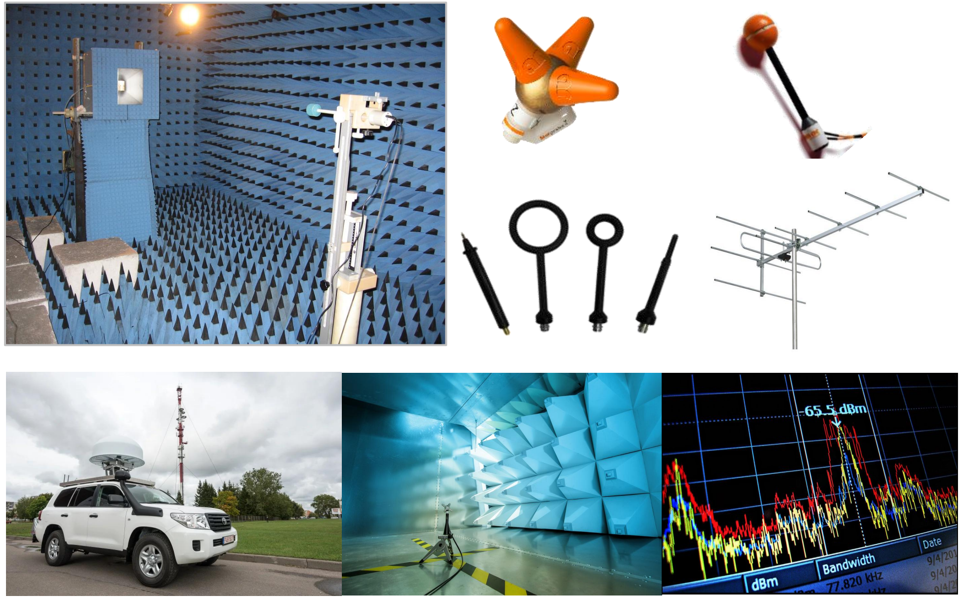
Greatly broaden the measurement range of SERF magnetometer based on ultra-precision magnetic compensation and achieved a three-axis measurement.

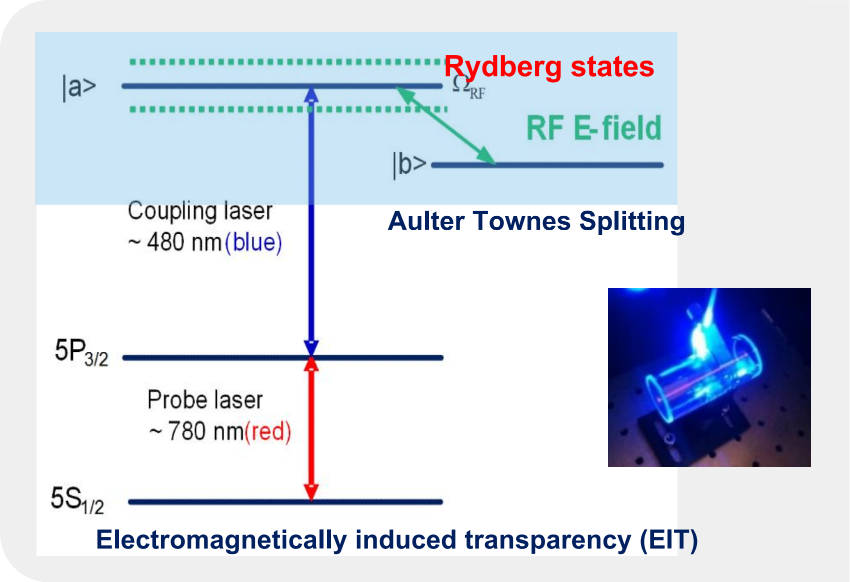
The three-axis sensitivity of the magnetic field is better than 100 fT/Hz$^{1/2}$.

2.3 RF Electric-field Sensing

Industry Requirement

Radio-frequency antenna, receiver, and analyzers have **limitations in sensitivity, bandwidth, accuracy, spatial resolution, and need calibration in a standard RF E-field,** the industrial needs of modern communication and information transmission cannot be met.





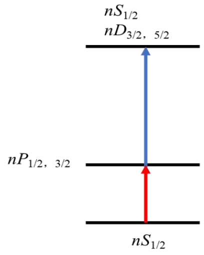
2.3 RF Electric-field Sensing Research at NIM

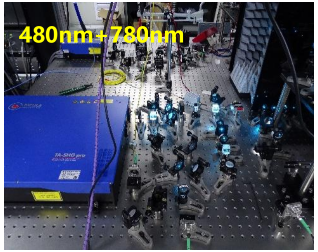
The novel preparation of Rydberg atoms

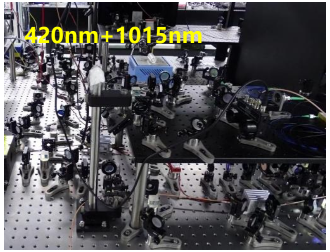
China National Standard of the People's Republic of China： GB/T 43735-2024

"Methods for the preparation of Rydberg atoms for quantum precision measurement"

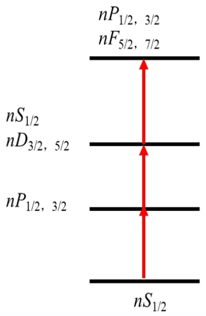
- Two-photon excitation method

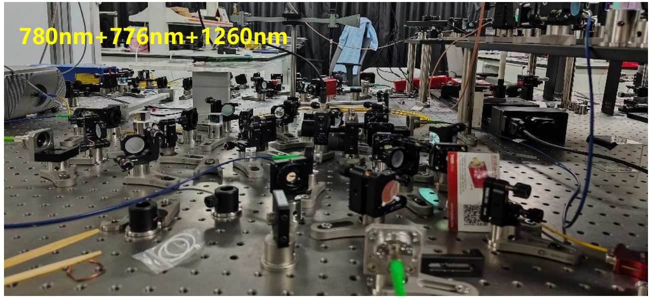




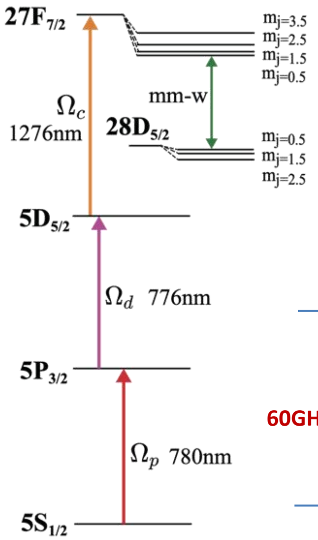


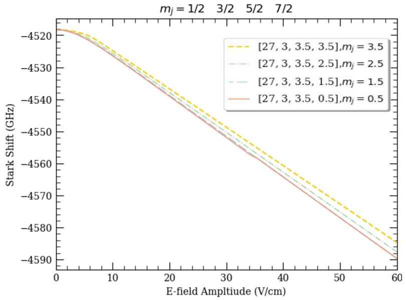
- Three-photon excitation method

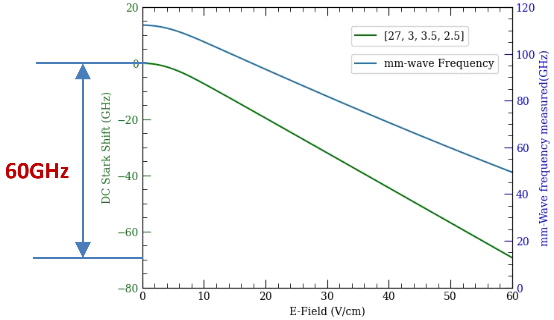




Millimeter-Wave Spectrum Analyzer





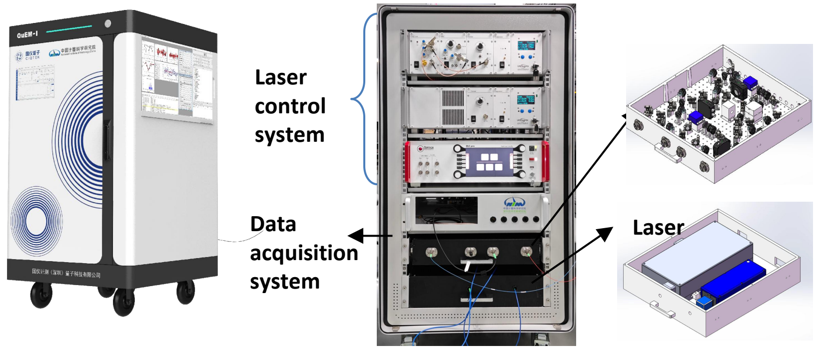


- Continuous mm-wave frequency electric field detection based on DC Stark effect
- Frequency range: 49.34 GHz - 112.30 GHz (n=27)

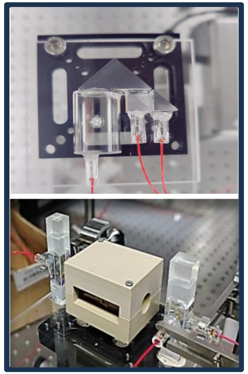
2.3 RF Electric-field Sensing Research at NIM

Quantum Microwave E-filed Meter

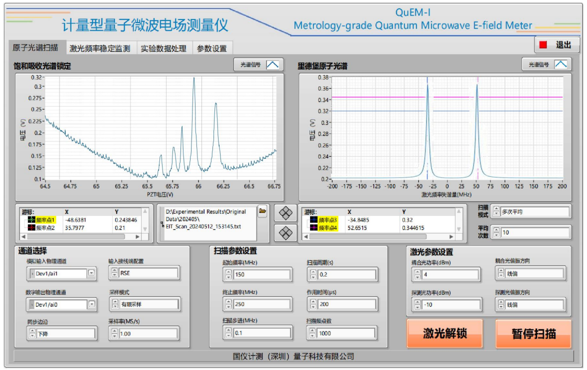
- Mainframe



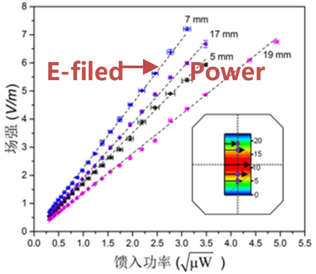
- Atomic sensor



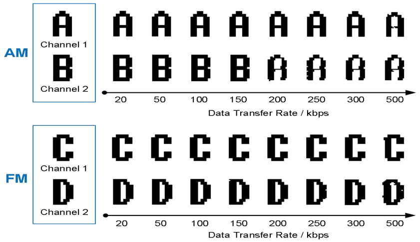
- Software interface

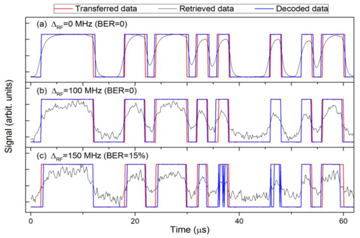


Application： Microwave power meter



Application： Atomic communication

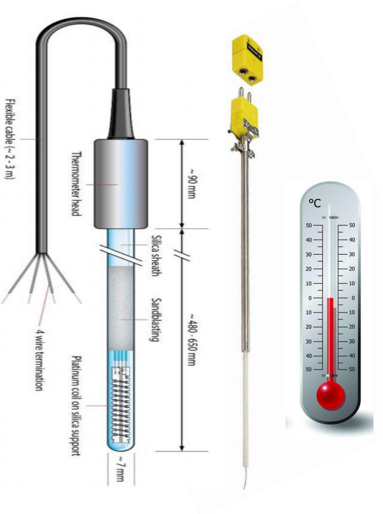


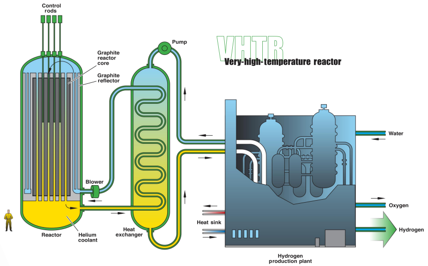


2.4 Temperature Sensing

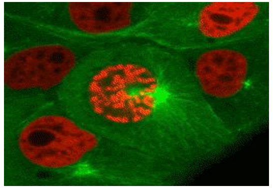
Industry Requirement

Traditional temperature sensors **are easily affected by environmental interference**, such as external magnetic fields, irradiation, thermal cycles or vibration, and are difficult for **high-resolution thermal sensing**.

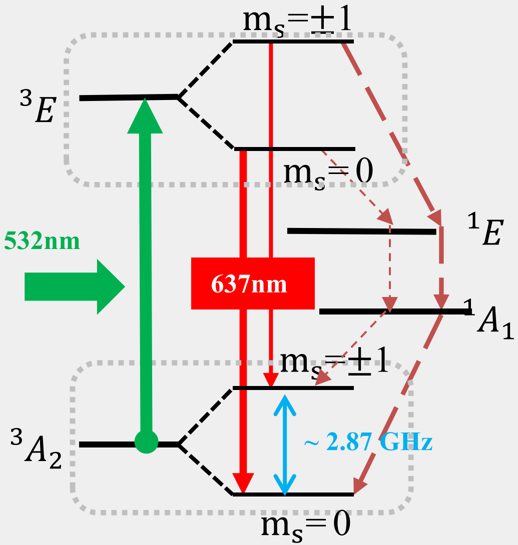


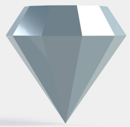


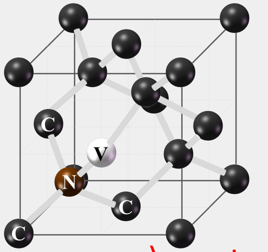
extreme environment
(very high temperature reactor)



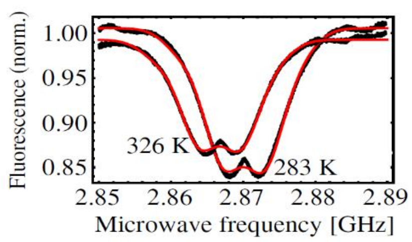
high spatial resolution







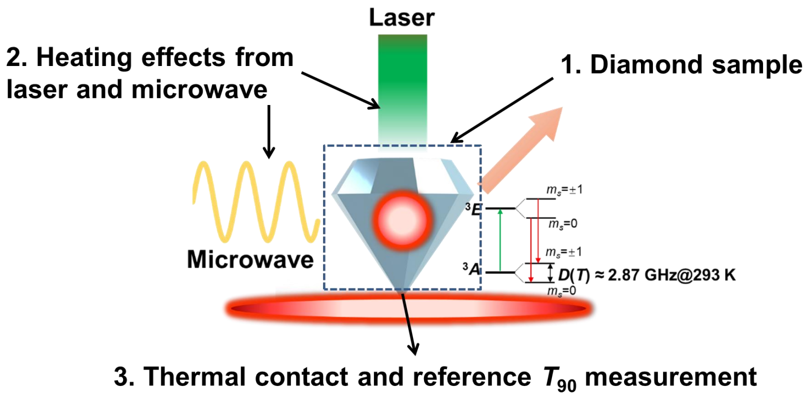
NV (nitrogen-vacancy) center of a diamond

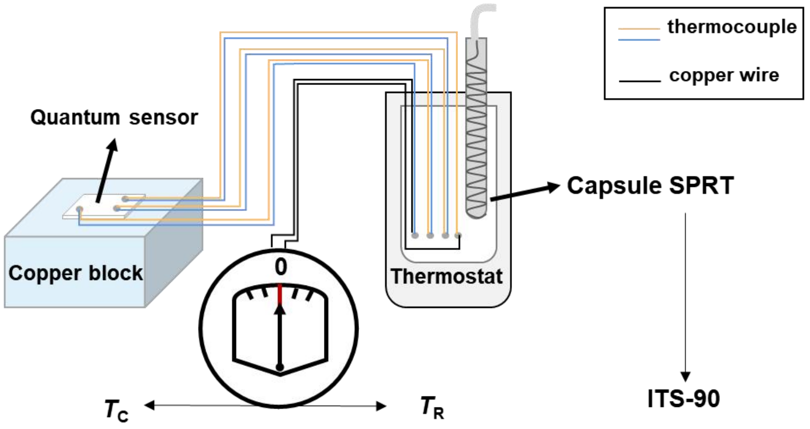


Optical Detected Magnetic Resonance (ODMR)

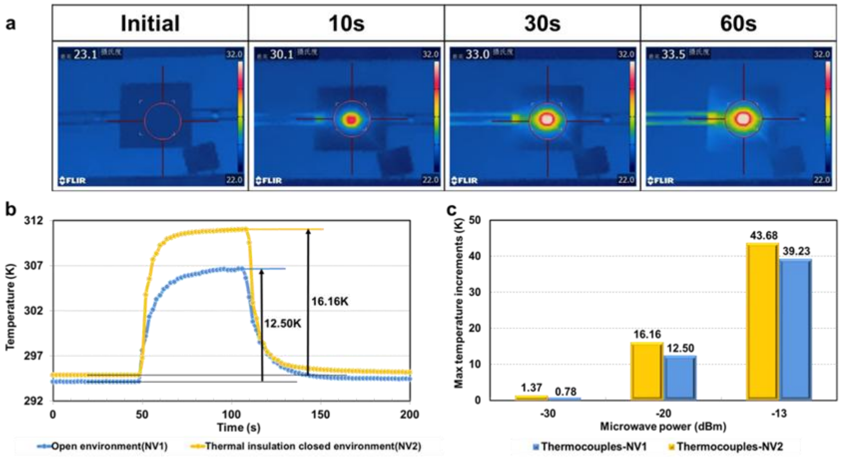
2.4 Micro-nano Thermometry Using NV Centers at NIM

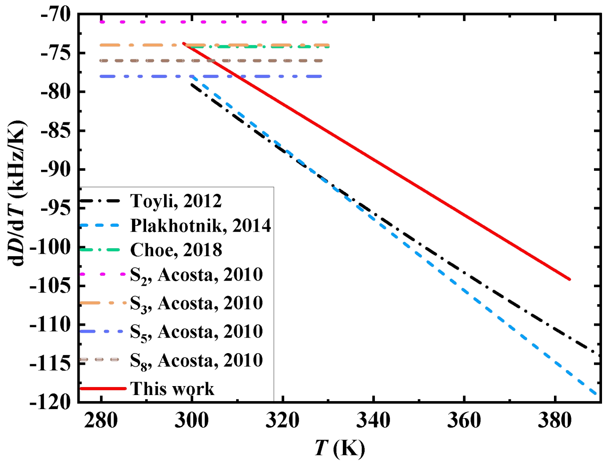
- Various sizes: 20 nm- mm； wide temperature range: 100 K~700 K; biological friendly, stable, economical
- NV-center based temperature sensing capability relies on the ODMR measurement, which introduces systematic errors
- Optical Detected Magnetic Resonance (ODMR) systems were set up for metrological research

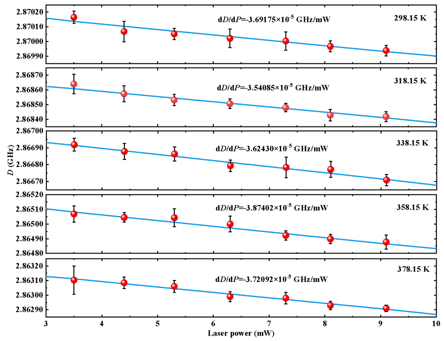


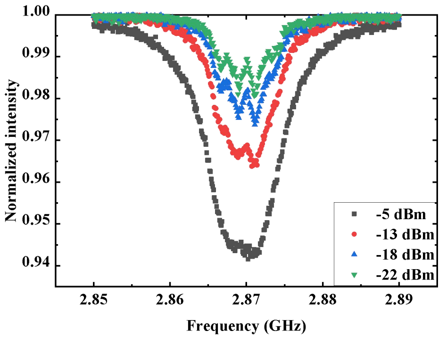


2.4 Micro-nano Thermometry Using NV Centers at NIM







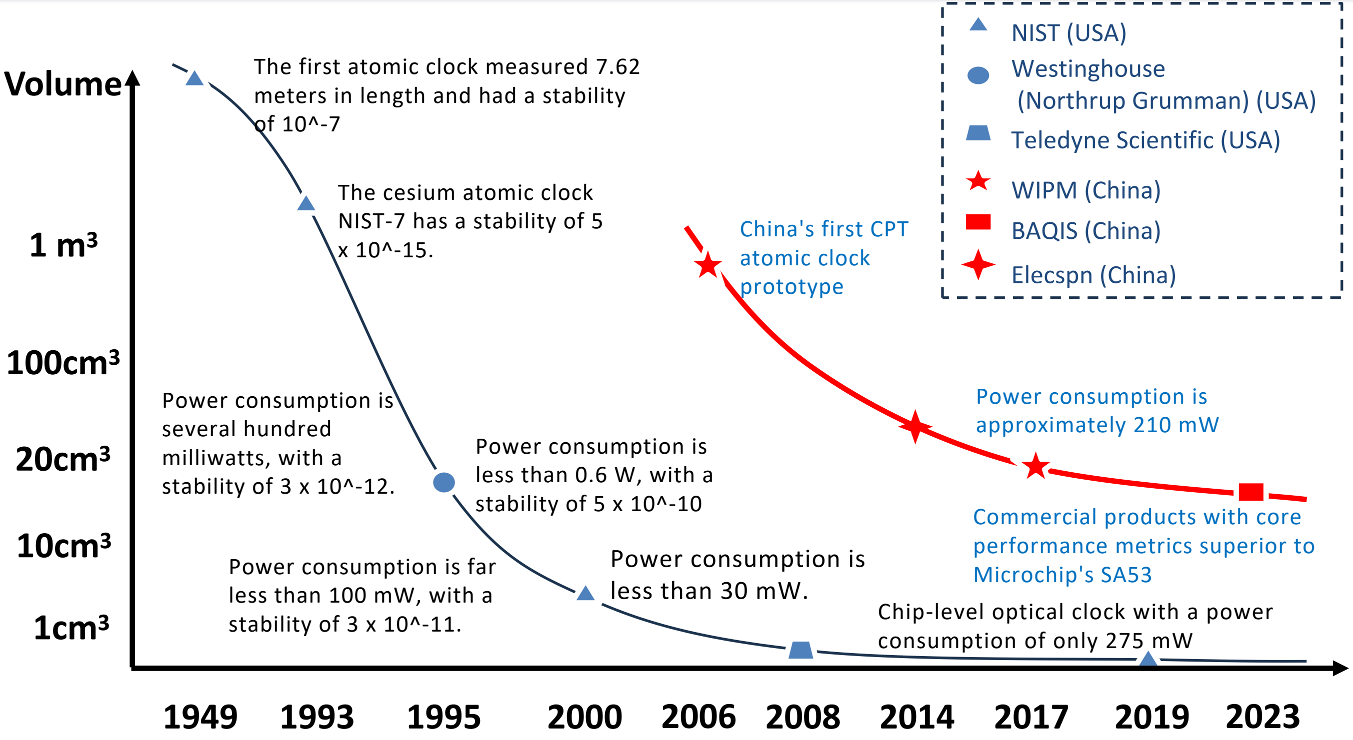


- various results showed that systematic uncertainty research is needed for its promising future as a standard micro-nano meter scale thermometry
- Metrology can accelerate the practical application of NV center thermometer

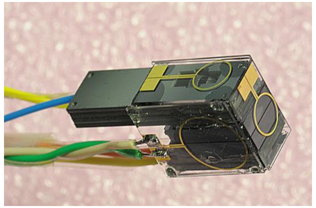
Contents

4.1 Embedded Systems/Miniaturization

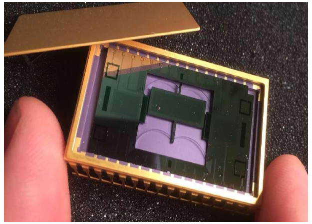
Reduce size and power consumption, real-time monitoring and feedback.



Chip-scale atomic clock



Compact atomic magnetometer

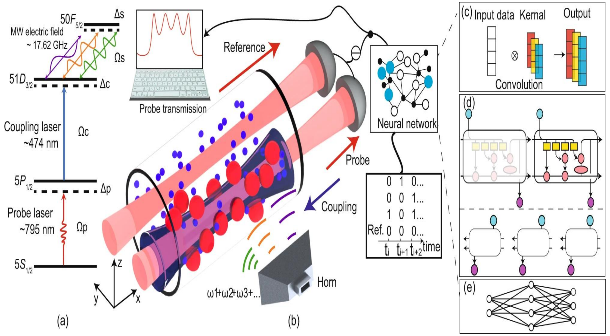


MEMS gravimeter

4.2 Integration of AI Techniques

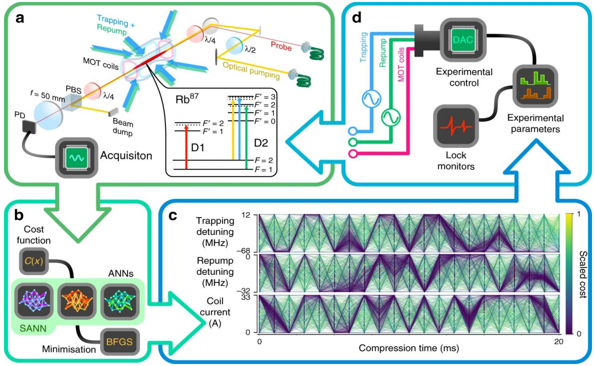
AI-driven quantum sensing systems can enhance signal-to-noise ratios, suppress background noise, and extract valuable information from noisy or incomplete data, enabling more reliable and accurate measurements in challenging environments.

Deep learning enhanced Rydberg multifrequency microwave recognition



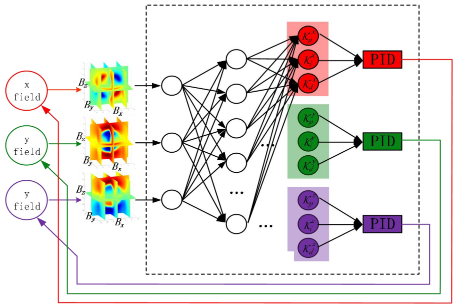
Nat Commun 13, 1997 (2022).

Multiparameter optimisation of a magneto-optical trap using deep learning

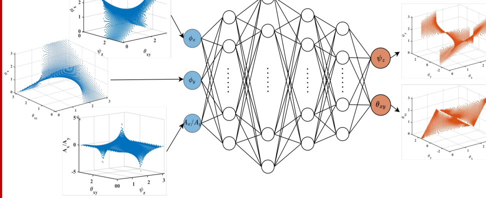


Nat Commun 9, 4360 (2018).

Recent work at NIM



Neural network-based magnetic field zero-locking control in unshielded SERF magnetometer



J. Qin, J. Xu, Z. Jiang, J. Qu. *Appl. Phys. Lett.* 2 2024; 125 (10): 102405.

Artificial intelligence and machine learning for quantum technologies, Phys. Rev. A 107, 010101, 2023

4.3 Future Applications in Industry

The application scope and fields of quantum sensors are rapidly expanding, **covering multiple key areas such as communications, healthcare, scientific research and resource exploration.**

Scientific Research

Currently advancing scientific research into the microscopic world.

Future quantum sensors will reveal viral mechanisms and explore dark matter.

Communications

Currently, CPT atomic clocks are replacing traditional crystal oscillators.

In the future, molecular clocks and chip-scale optical clocks are expected to further enhance 5G and 6G communication performance.

Healthcare

Currently focused on biomagnetic measurement.

Future quantum magnetometers will enable high-resolution imaging in brain science and brain-machine interfaces.

Resource Exploration

It has over 30 years of application history in resource exploration and other areas.

In the future, it is expected that quantum gravimeters will generate high-resolution exploration maps of deep minerals.

Contents

Summary

- Benefitting from the inherent advantages of quantum systems, quantum sensing has significant advantages over classical sensors in terms of sensitivity, stability, and traceability.
- NIM keeps pace with this cutting-edge research technology and has conducted a series of studies in fields of quantum sensing of magnetic fields, electric fields, temperature, and gravity.
- Future development of quantum sensors including miniaturization, multidimensional information perception (Integration of AI and cloud calculation) , etc.
- Quantum sensing has tremendous potential for development and broad industrial application prospects.

Thank you

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