

Pa Quantum Metrology: the present and the future

21st November 2022

Quantum Electronics in EMN-Q

Hansjörg Scherer (PTB)



Q

QUANTUM TECHNOLOGIES

# **My personal functions**

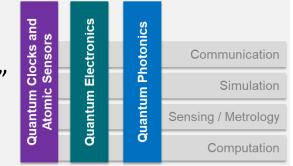




### In EMN-Q:

Vice Chair,

Section Coordinator "Quantum Electronics" together with two Vice Coordinators: Félicien Schopfer (LNE) Antti Manninen (VTT-MIKES)



# "Quantum Electronics" in EMN-Q



# Two sub-fields

 $\rightarrow$  two roadmaps in the Strategic Research Agenda (SRA) of EMN-Q:

#### Quantum Metrology & Sensing 1.3 Industry & economy Instrumentation manufacturers, measurement and calibration services, trade harmonization **Triggers &** 1.2 Society Medical & life sciences, consumer protection, environmental protection Needs 1.1 Science & technology Foundations of quantum physics. SI traceability and fundamental consistency tests 2.5 Measurement & calibration services for QT industry and products 2.4 Standardization of QT products and related metrology 2.3 Technology transfer & commercialization of QT and related metrology tools and methods Targets 2.2 Advanced measurement science to support OT developments 2.1 SI unit realization & dissemination 3.2 Systems & products: "QT systems and products for metrology" Metrological Application 3.1 Support & services: "Metrology for QT" 4.8 Quantum metrology toolbox ("quantum multimeter") 4.7 Quantum-enhanced measurement schemes 4.6 Quantum-enhanced sensors & detectors 4.5 Fundamental metrology experiments Experimental Realization 4.4 Quantum-enhanced measurement bridges 4.3 Quantum current standards & charge devices (single-charge-based) 4.2 Quantum resistance & impedance standards 4.1 Quantum voltage standards & systems (JAWS technology) 5.3 Basic engineering Performance electronics, cryogenic and magnet technologies Enabling Science & 5.2 Materials & fabrication Materials science and engineering, nano-scale device and circuit fabrication technologies Technology 5.1 Fundamental science Solid-state quantum physics, quantum state engineering 2030 2020 2023

# **Quantum Computing**

Triggers & needs	Quantum Computers harnesses non-classical resources of quantum systems to solve important problems that are intractable on classical computers.					
				5.4 Practic	al QC in the cloud	
Fargets,			5.3 Standar	dization and	benchmarking	
applications,	5.2 Metrology of software					
services	5.1 Test and measurement services for QC systems and components					
Software				4.2	Applications in chemistry, Fintech, ML	
	4.1 Software for benchmarking and validation					
			3.4 RF metr	rology for QC	systems	
Metrological	3.3 Metrology of materials and surfaces					
validation		3.2 Measure	ement protocols for qubits ar	nd processors		
	3.1 Metrology of key enabling technologies					
	2.3 Development and optimization of fabrication processes					
nabling echnologies	2.2 Systems, subsystems and packaging					
centrologico	2.1 Components & devices: qubits, couplers, microtraps					
	1.2 Algorithms&metrics development					
Science	1.1 Develop	ment of NISQ pro	cessors		1.3 Error corrected qubits	
20	21		2023		2030	

# "Quantum Electronics" in EMN-Q

# **Quantum Metrology & Sensing:**

- Quantum voltage standards / systems based on the Josephson effect
- Quantum resistance and impedance standards / systems based on the quantum Hall effect(s)
- Quantum current standards and single-charge devices based on single-charge transport
- → Integrated quantum metrology systems e.g., quantum "multimeters" integrating different standards (in cryogen-free setups)

"Quantum classical" methodologies, based on "1<sup>st</sup> generation QT", established in NMIs.

Quantum-enhanced measurement systems, sensors and detectors

e.g., Josephson and digital impedance bridges, cryogenic current comparators, magnetometry with nitrogen-vacancy centres in diamond crystals, single-electron detectors ...



# "Quantum Electronics" in EMN-Q

# **Quantum Computing:**

- Qubits and qubit couplers (superconducting)
- Quantum-enhanced methods for qubit readout (measurement) and qubit control (manipulation)

e.g., superconducting amplifiers with quantum-limited noise performance, rf/microwave measurement methods and systems ... "2nd generation QT":

• Standardised protocols, methods and software

e.g., for benchmarking and validation of qubits processors data analysis





Entangled quantum states, quantum-limited / quantum nondemolition techniques.

EURA

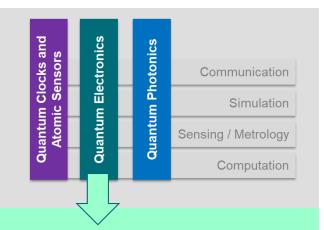
# **Stakeholders in EMN-Q**



#### EMN-Q counts 284 stakeholders

#### in total, for all three pillars

- Industrial company
- Research organisation
- Academic institute
- Quantum Flagship body/project
- Other type of organisation (e.g. standardisation bodies)



#### From these: **70** stakeholders in "Quantum Electronics"

#### From these: 30 stakeholders are industrial companies

Stakeholder involvement is

central to EMN-Q!

20 of these industrial stakeholders have contacts to PTB ...

# **Industry Stakeholders in EMN-Q "Qu-Electronics"** with contacts to PTB



Measurement systems & instrumentation, highperformance electronics (enabling technologies):

•	Magnicon	MAGNÍCON Como Prystori meseché dadi ustavimecholom	DE
•	Sympuls	SYM PULS	DE
•	Signal Conversion	Signal Conversion Ltd.	UK
•	Applicos		NL
•	Guildline Instruments	GUILDLINE	CA
•	Zurich Instruments	Zurich Instruments	СН
•	Grimm Aerosol Technik		DE

Cryogenic systems (enabling technologies):

- Entropy
   DE
   Oxford Instruments
   OXFORD NANOSCIENCE
   UK
- Oxford Instrume
- Bluefors

technologies):	
A COLOR	

°BLUEFORS

#### Quantum standards, systems & detectors (applications):

👷 supracon' • Supracon AG DF **Measurement International** CA ٠ SE Graphensic . **Graphene Waves** US GRAPHENE ٠ Qzabre CH . Mami CH Qnami .

Industrial calibration labs (applications):

esz calibration & metrology
1A Cal
1A Cal

Quantum computing (applications):

- IBM Research Quantum Europe CH
  - IQM FI/DE

.

FI

Industry Stakeholder Products: Examples Josephson Voltage Standards



# **DC and AC 'quantum voltmeters'** (up to 10 V, few kHz), commercially available, suppliers in DE, US.



# Industry Stakeholder Products: Examples Quantum Hall Resistance Standards

**Graphene devices** commercially available, suppliers in SE, US.

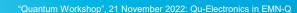


TECHNOLOGIES

graphensic







# Industry Stakeholder Products: Examples Cryogenic Current Comparators



... for high-end resistance bridges used in quantum Hall resistance metrology. Commercially available, suppliers in DE, UK.

> SQUID electronics

Digital double current source incl. nanovoltmeter

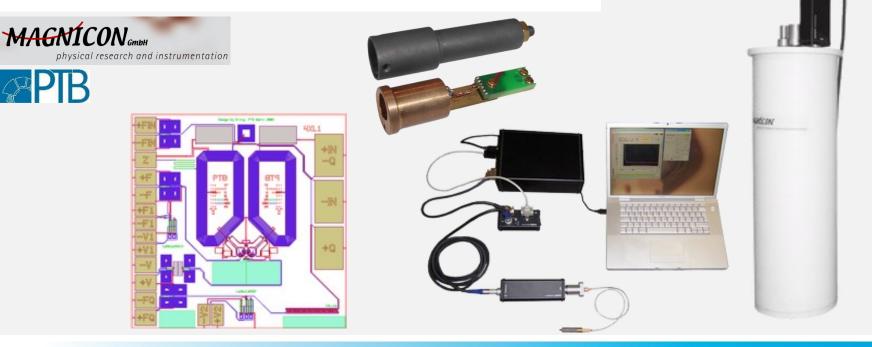
CCC with SQUID null detector (in Nb screen)





# Industry Stakeholder Products: Examples SQUID Sensors & Systems

... for various applications. Commercially available, many suppliers world-wide.

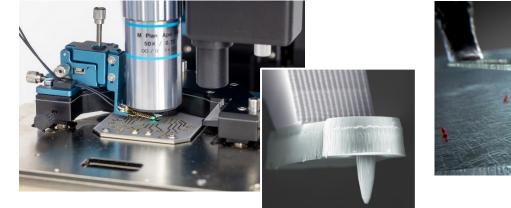


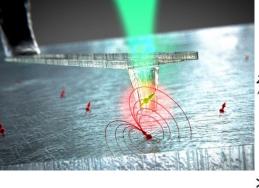
QUANTUM TECHNOLOGIES **EURAMET** 

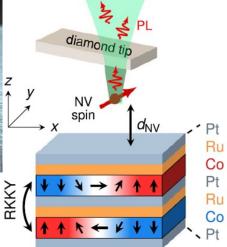
# Industry Stakeholder Products: Examples Scanning Magnetic Microscopy Sensors & Systems



... using nitrogen-vacancy centres. Commercially available, e.g., suppliers in CH.







laser excitation





Finco *et al., Nat Commun* **12**, 767 (2021). https://doi.org/10.1038/s41467-021-20995-x

#### Project cooperation with NMIs

EMN-Q in "Framework Partnership Agreement" (FPA)

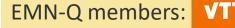


FPA for "open testing and experimentation for quantum technologies": 'Qu-Test' Call: HORIZON-CL4-2021-DIGITAL-EMERGING-02 Topic: HORIZON-CL4-2021-DIGITAL-EMERGING-02-22

- Partnership of European testbeds for quantum technology, coordinated by TNO (NL)
- composed of distributed infrastructures with globally unique equipment and competencies across Europe.

Goal: To provide European industry with the necessary support in terms of infrastructure and know-how to move faster to the market and create a robust supply chain for the quantum technology market.

> LABORATOIRE NATIONAL DE MÉTROLOGIE



SYRTE Pobservatoire | PSL

# EMN-Q in "Framework Partnership Agreement" (FPA)



QUANTUM TECHNOLOGIES

# FPA for "open testing and experimentation for quantum technologies": 'Qu-Test'

"Qu-Electronics" in red

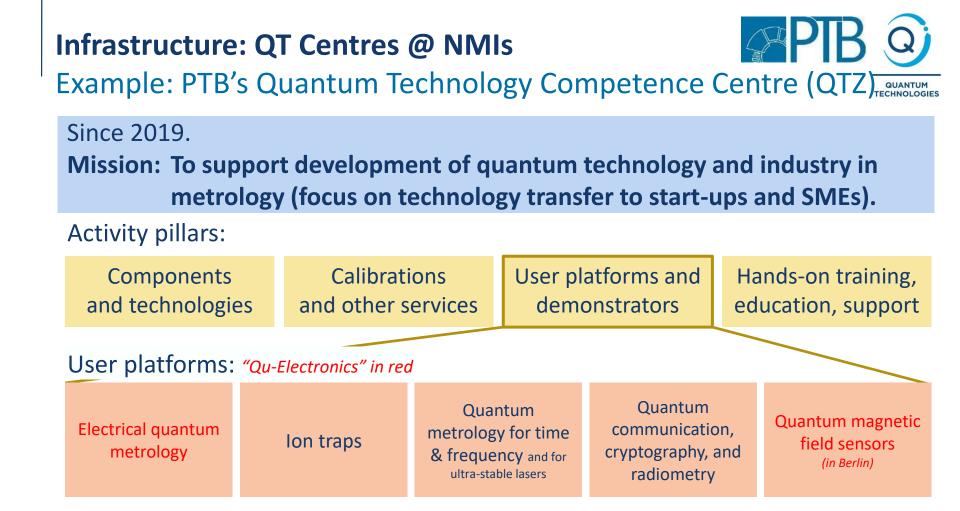
Testbed 1		Quantum Computing	Cryogenic quantum devices, cryogenic qubits (superconducting and semiconducting, photonic) and ion traps.
Testbed 2		Quantum Communication	Devices for Quantum Key Distribution (QKD) and Quantum Random Number Generation (QRNG).
Testbed 3	∿~))		Sensing and metrology instruments provided by industry, and quantum sensors (e.g., clocks, gravimeters, magnetometers).

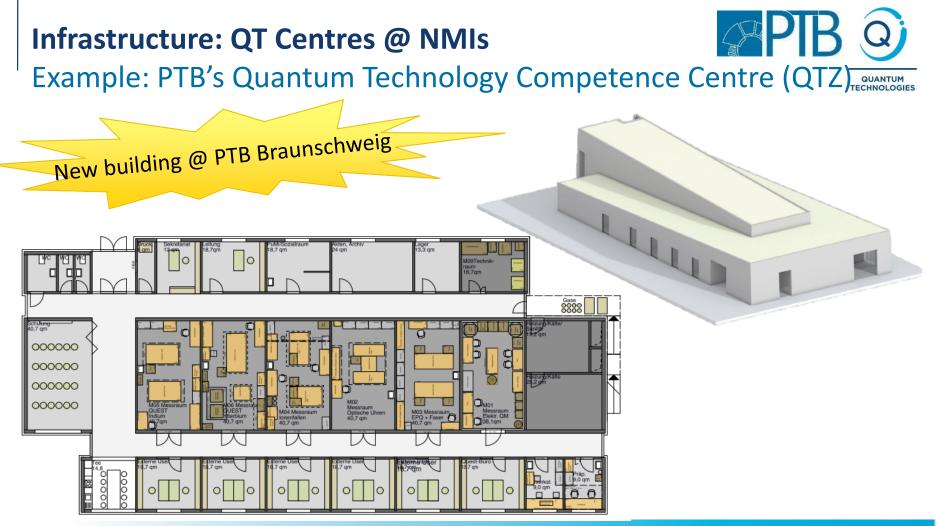
# **EMN-Q Infrastructure in FPA 'Qu-Test'**



EMN-Q facilities "Qu-Electronics" in red

Piemonte Quantum Enabling Technology (nanofabrication facility)	INRIM
Cryomagnetic characterisation environments for quantum devices	
QR Labs (micro/nanofabrication facilities)	
Clean Room Centre	PTB
"Ion Traps" in the Quantum Competence Centre	
"Metrology of Ultra-Low Magnetic Fields"	
"Optical QT" in the Quantum Competence Centre	
"Single Photons" in the Quantum Competence Centre	
"Electrical Quantum Metrology" in the Quantum Competence Centre	-
Fundamental (primary standard) metrology laboratories	
Quantum electrical metrology laboratories	LNE
Nanotech Institute / Innovation Centre "NanoMesureFrance"	
Quantum Metrology Platform	1







QUANTUM TECHNOLOGIES

# Infrastructure: QT Centres @ NMIs Example: PTB's Clean Room Centre

800 m<sup>2</sup> clean room area (nominally ISO 5, practically ISO 3)



- Electron beam lithography (100 kV)
- Molecular beam epitaxy
- Thin-film technology process/fabrication lines
- Electrical quantum standards: QHR: GaAs and Graphene JVS: Niobium SET: GaAs
- Sensors: (nano) SQUIDs



#### "Quantum Workshop". 21 November 2022: Qu-Electronics in EMN-Q

# **EMN-Q in Standardisation**

#### "Qu-Electronics" topics:

#### **Enabling Technologies**

- Colour centres in (nano)diamonds and other crystals
- Superconducting quantum circuits
- Traveling wave parametric amplifier
- Semiconductor quantum dots for quantum electronics

#### **QT** Components and Subsystems

- Single-photon detectors
- Single-electron sources

• ....

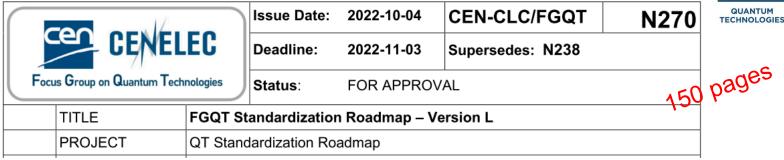
#### Quantum Computing and Quantum Simulation Systems

- Cryogenic solid-state based quantum computing architectures
- Room-temperature solid-state based quantum computing architectures

#### Quantum Metrology, Quantum Sensing, and Quantum Imaging

- Quantum magnetometers
- ...

19







# Quantum Electronics

QUANTUM TECHNOLOGIES

"Quantum Metrology: the present and the future" 21 November 2022





#### Physikalisch-Technische Bundesanstalt Braunschweig and Berlin

- **Bundesallee 100**
- 38116 Braunschweig
- Hansjörg Scherer
- Phone: 0531 592-2600
- E-Mail: hansjoerg.scherer@ptb.de
- www.ptb.de