中国科学院上海微系统与信息技术研究所
Shanghai Institute of Microsystem and Information Technology Chinese Academy of Sciences

中国科学院超导电子学卓越创新中心
Center for Excellence in Superconducting Electronics (CENSE)

Latest development on superconductive sensors, detectors and their applications at SIMIT

Xiaoming XIE

Shanghai Institute of Microsystem and Information Technology

Chinese Academy of Sciences

ACASC-Asian ICMC 2023, Oct. 29-Nov. 1, 2023@Shanghai

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56, March 2024. Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China

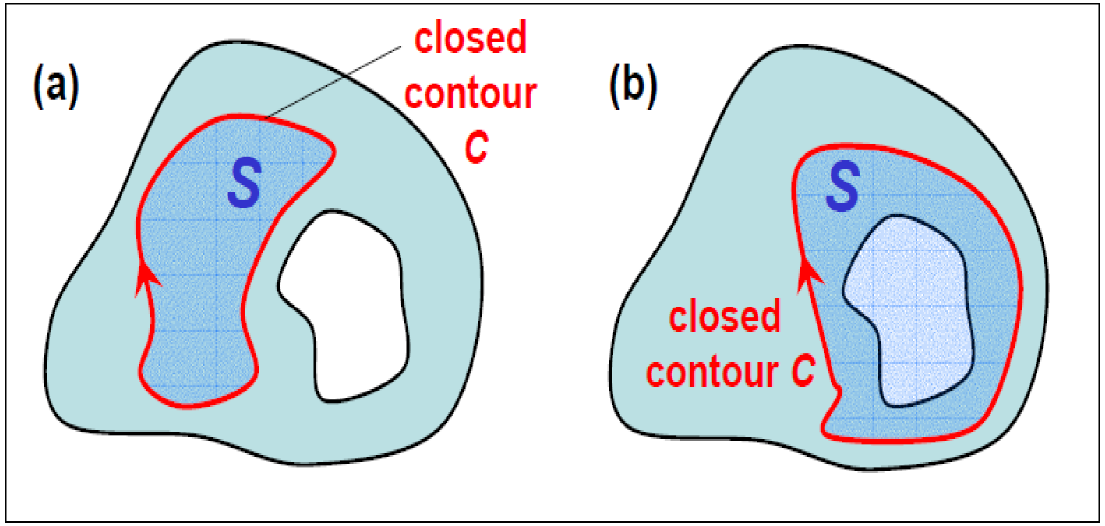
Outlines

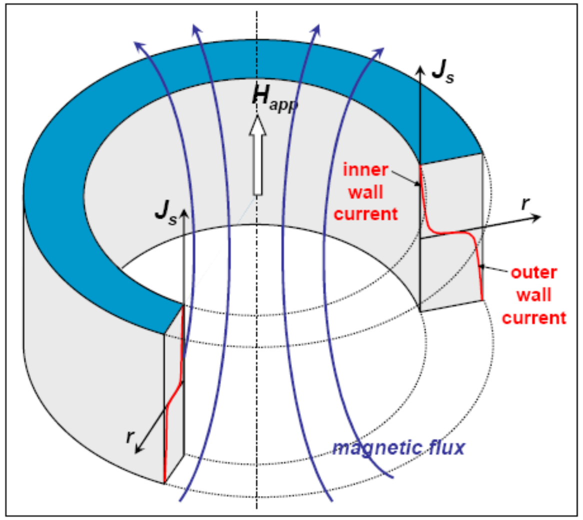
- General introduction to superconducting electronics
- SQUID sensor development and applications
- SNSPD detector development and applications

Macroscopic Quantum States

Superconductivity is an inherently quantum phenomenon manifesting itself on a macroscopic scale.

- Fritz London (1935)





$$\Psi(r,t)=\Psi_0(r,t)e^{i\theta(r,t)}; \quad |\Psi(r,t)|^2=s(r,t)$$

$$\oint(\Lambda J_s)\bullet dl+\int B\bullet dS=n\Phi_0; \quad \Phi_0=\frac{h}{2e}=2.07\times10^{-15}\ \text{vs}$$

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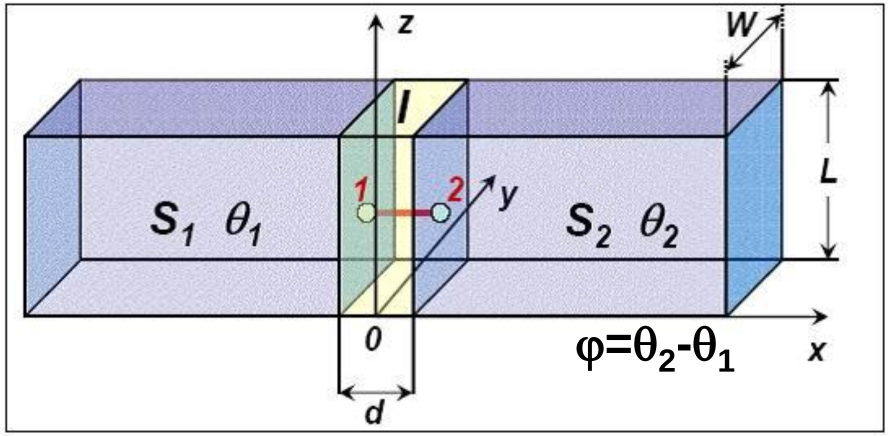
Josephson Quantum Effects

Brian David Josephson



DC effect: $V = 0 \Rightarrow I=I_0\sin(\varphi)$

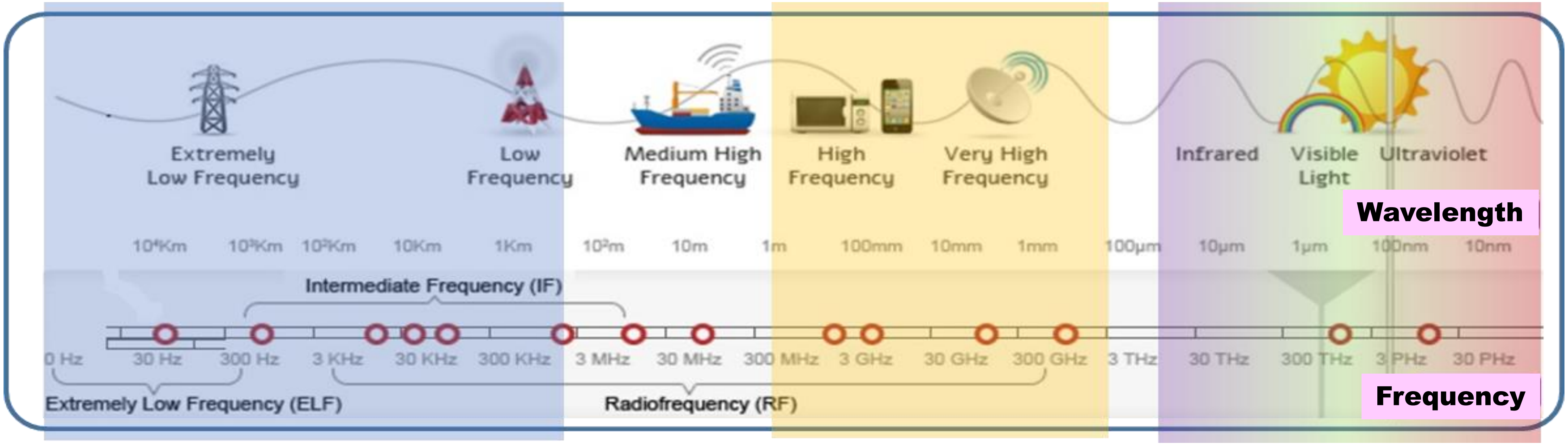
AC effect: $V \neq 0 \Rightarrow d\varphi/dt=2\pi V/\Phi_0$

Josephson equations lay the foundation of superconductive electronics

$$E_J=\int_{t0}^{t1} IV\mathrm{d}t=\int_{t0}^{t1} I_0\sin(\varphi)\frac{\Phi_0}{2\pi}\frac{\mathrm{d}\varphi}{\mathrm{d}t}\mathrm{d}t=\frac{\Phi_0 I_0}{2\pi}[1-\cos(\varphi)]=E_{J0}[1-\cos(\varphi)]$$

$E_{J0}(1\mu A) \approx 3.2\times10^{-22}$ Jule ~ 2.0 meV ~ 23K (Josephson Coupling Energy)

Sensors/Detectors & Their Applications



SQUID, detection of magnetic flux
DC to low frequency

SIS/TES/MKID/HEB
RF to Tera Hertz

SNSPD/STJ/TES
Infrared to high energy photon

- **Low noise:** quantum effects and low Johnson noise ($4K_BTR$)
- **High sensitivity**: low gap energy (μeV~meV)

Superconductivity plays indispensable roles in QIT, astronomy, deep space exploration, life sciences, geophysics, basic research etc.

Digital/Quantum Circuits for HPC

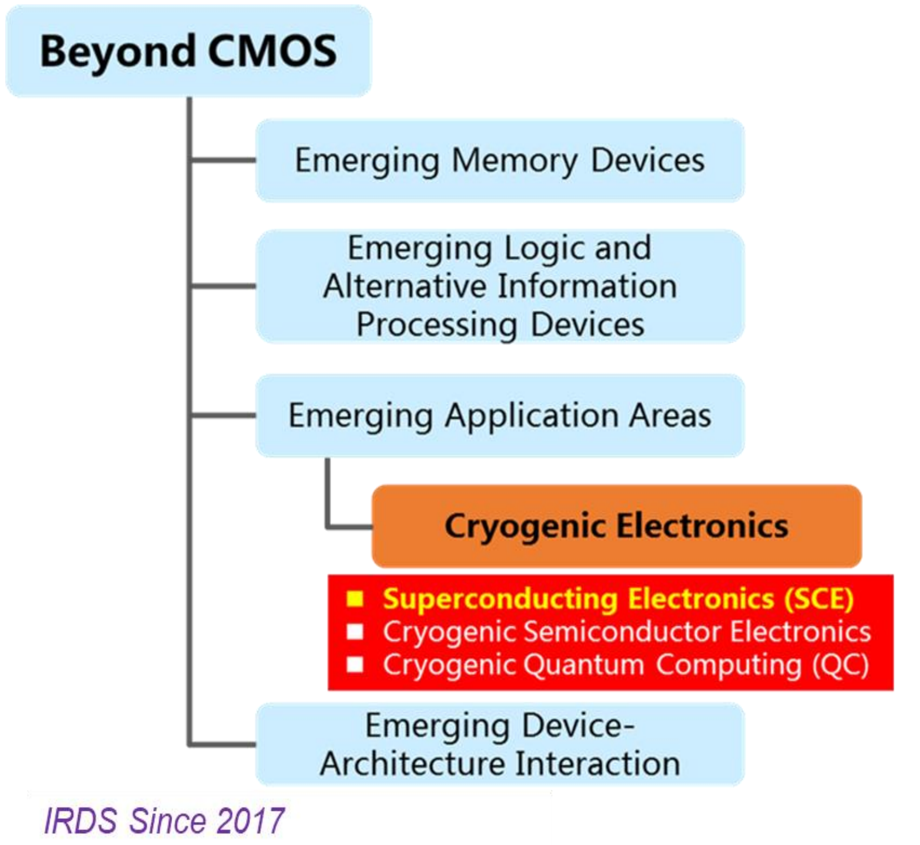
Evolution of semiconductive IC technology

ITRS (1998-2013):
International Technology Roadmap for Semiconductors

ITRS 2.0 (2014-2015):
Driver Changed from Scaling to Applications

IRDS （2016-）：
International Roadmap for Devices and Systems

Opened the Door to Non-Semiconductor Technologies



Energy efficient HPC for post Exascale era

Classical computation based on superconductive CPUs/GPUs (SFQ circuits…)

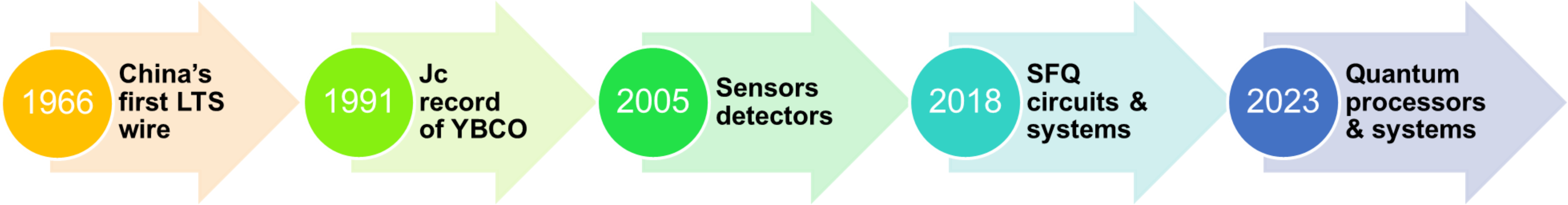
AI computation based on neuromorphic superconductive processors (SFQ circuits…)

Quantum computation based on superconductive Qubits and classical/quantum interface (AQPF circuits…)

Quantum annealing based on large scale SFQ circuits

Superconductive circuits are the enabling technologies for future heterogeneous supercomputing in a foreseeable timeframe

Superconductivity Research at SIMIT



1928 - 2000

Shanghai Institute of Metallurgy

Chinese Academy of Sciences

(SIM-CAS)

2001 -

Shanghai Institute of Microsystem and Information Technology

Chinese Academy of Sciences

(SIMIT-CAS)

China's First Dedicated Fab for SC VLSI

SELF = Superconducting ELectronics Facility

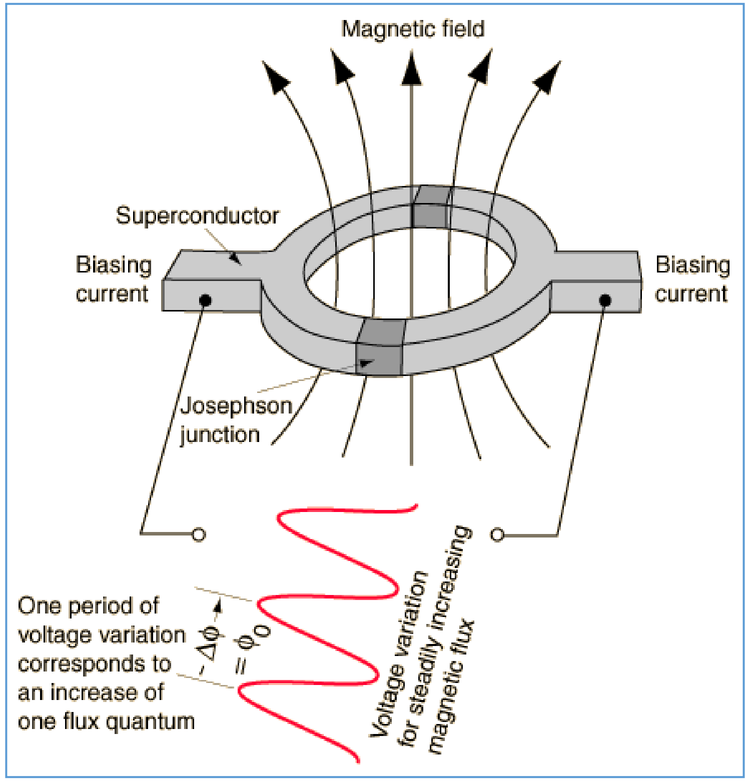
- **Scale:** 1500 m^2 clean room, including 300 m^2 for 100 class
- **Capabilities:** 4/6" 、150 nm stepper、5 nm EBL、ICP/IBE、PECVD、CMP etc.

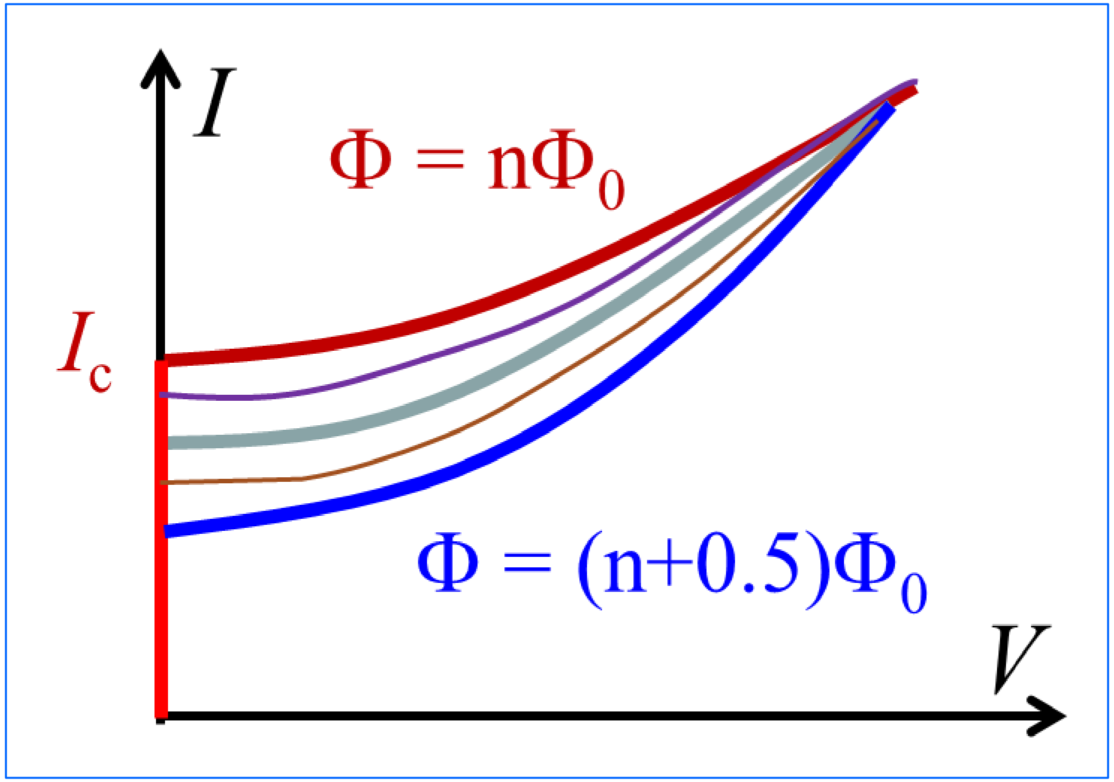
Outlines

- General introduction to superconducting electronics
- SQUID sensor development and applications
- SNSPD detector development and applications

DC SQUID

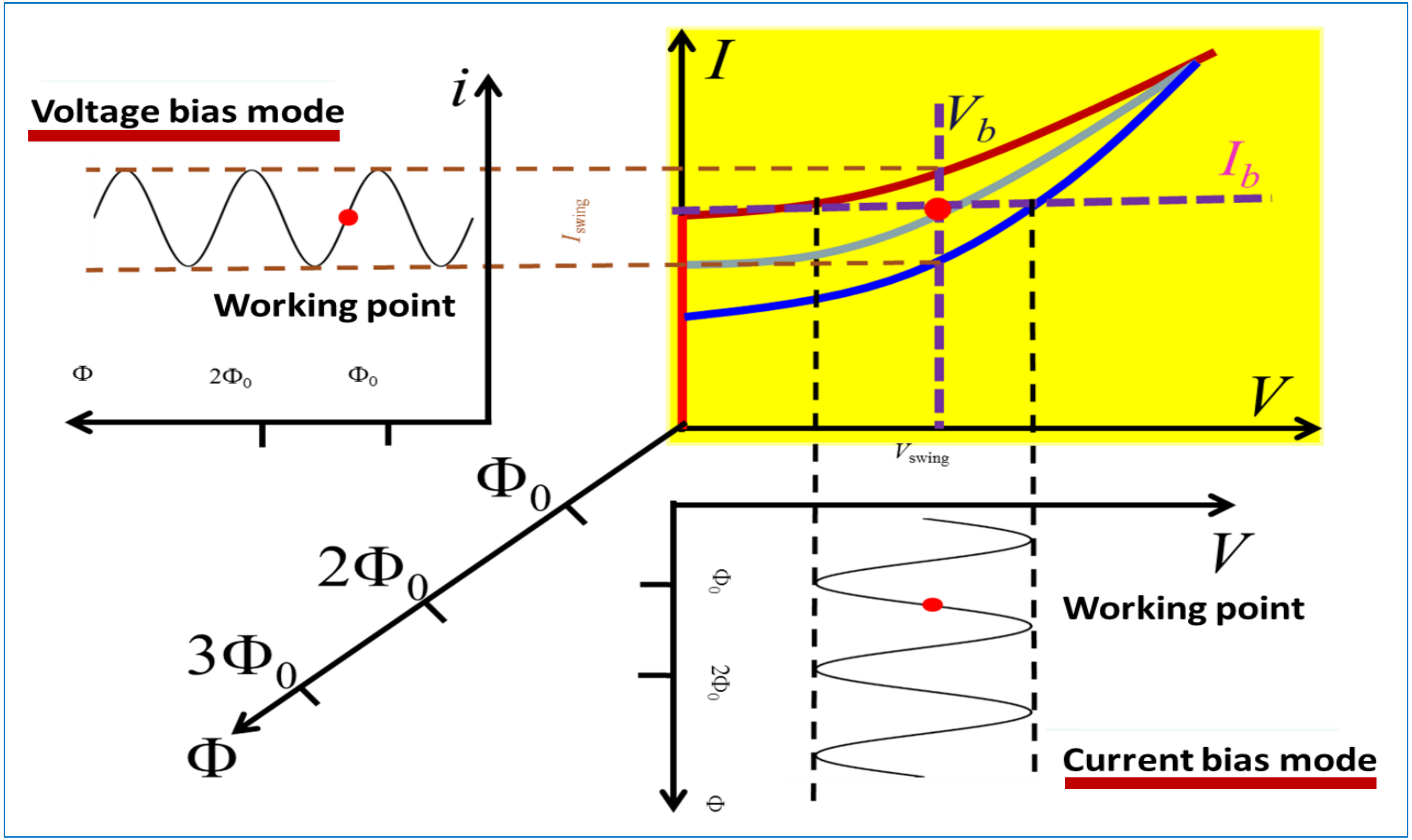
SQUID = Superconducting QUantum Interference Device



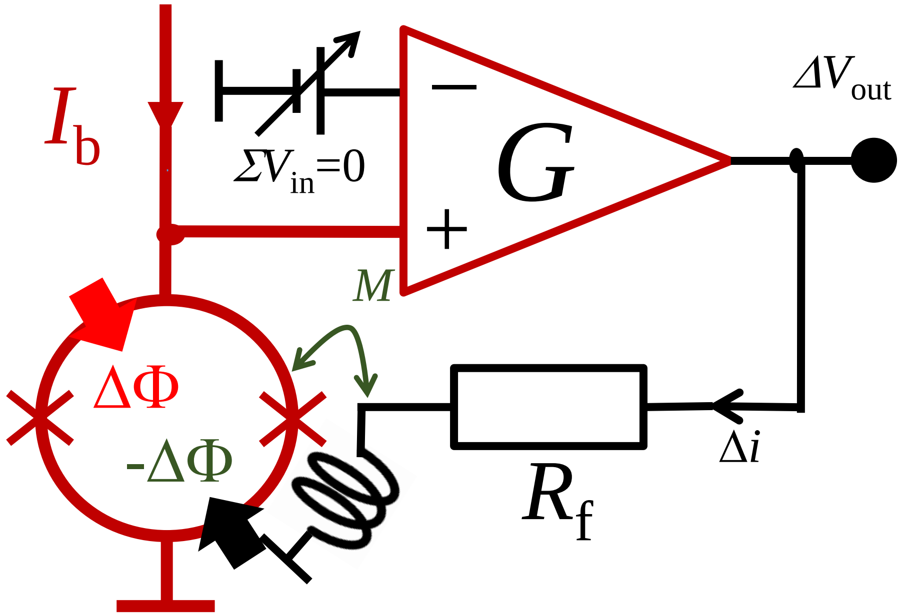


A SQUID is an ultra-sensitive two-terminal device for sensing flux threading the SQUID loop

Biasing a DC SQUID

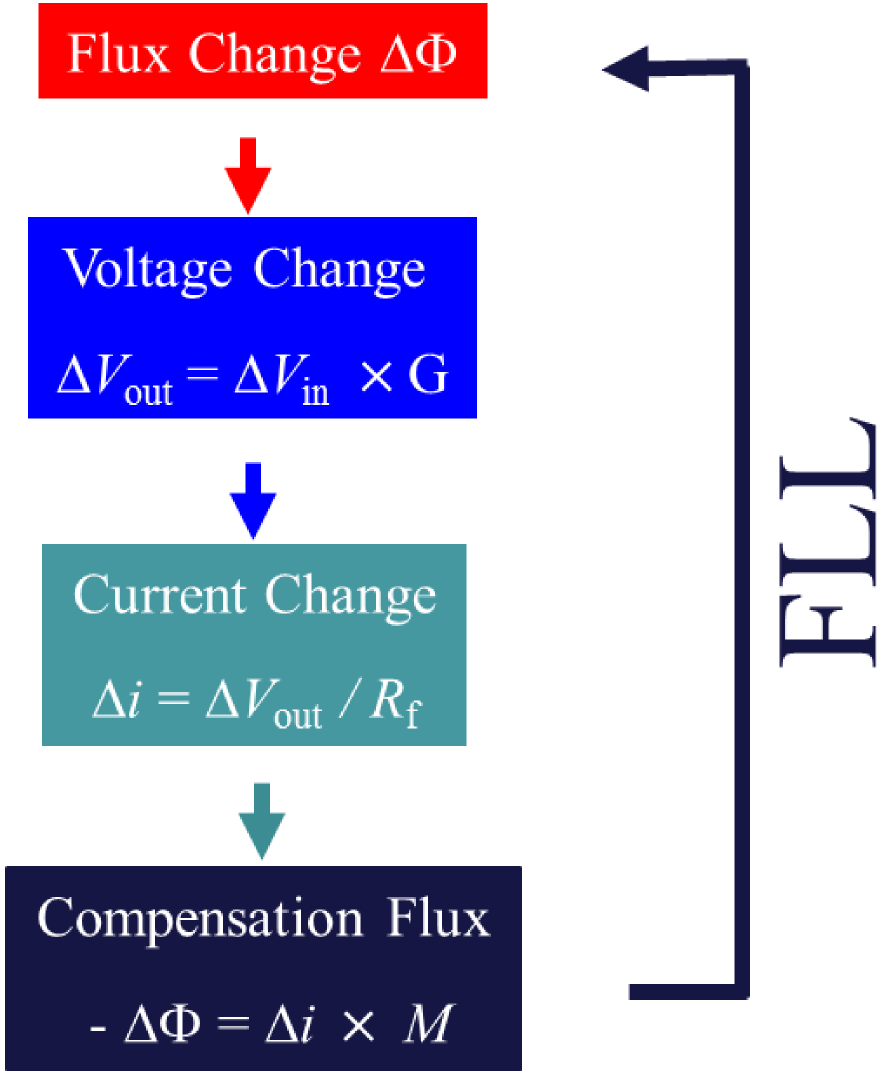


Flux Locked Loop

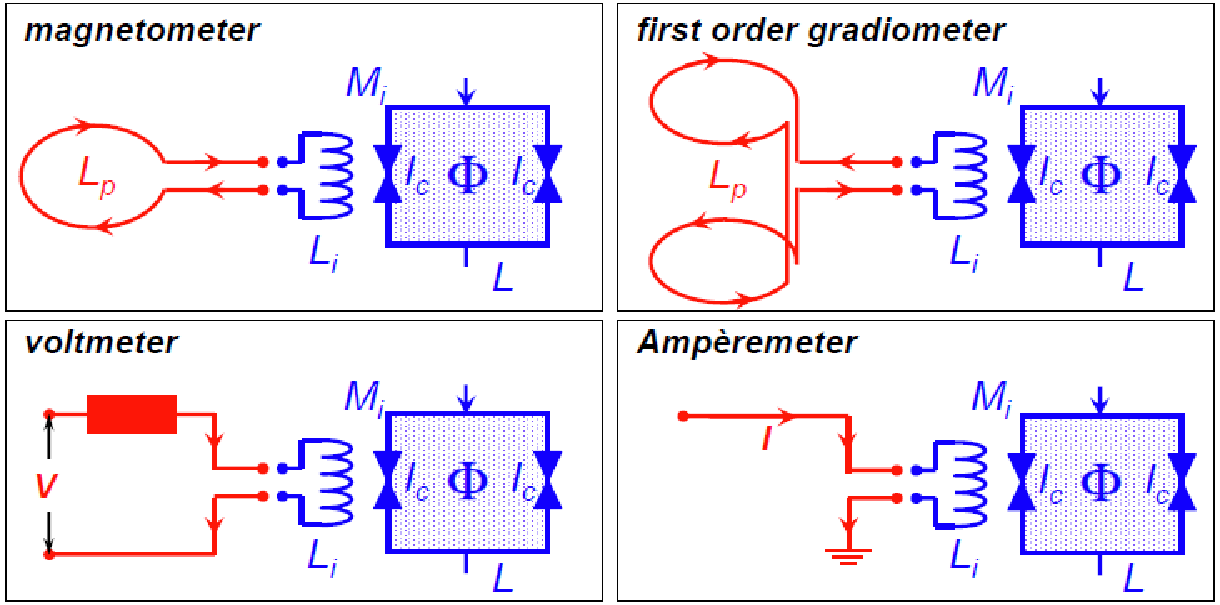


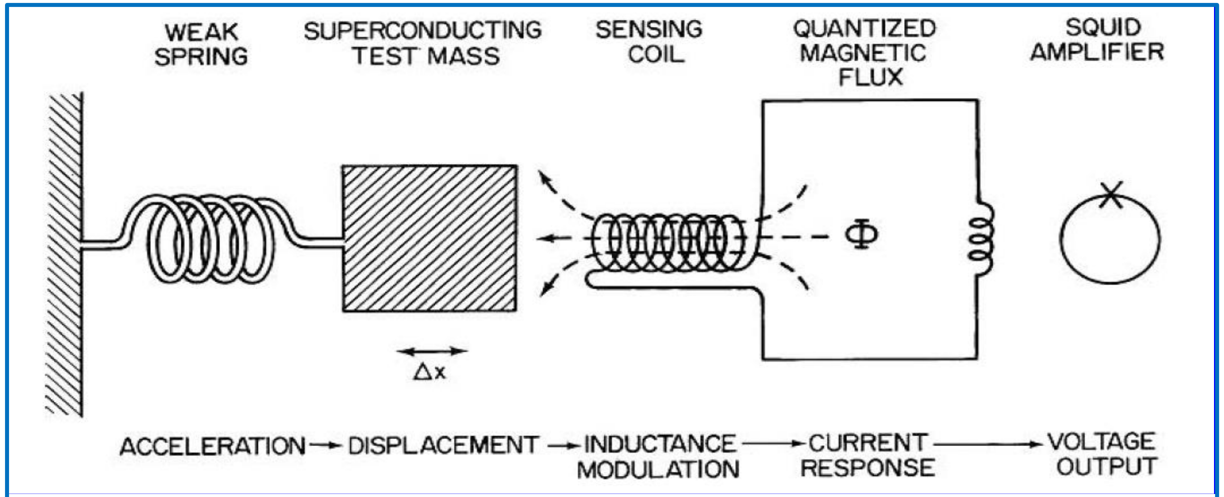
$\Delta V_{out} \propto \Delta\Phi$

Enlarged dynamic range

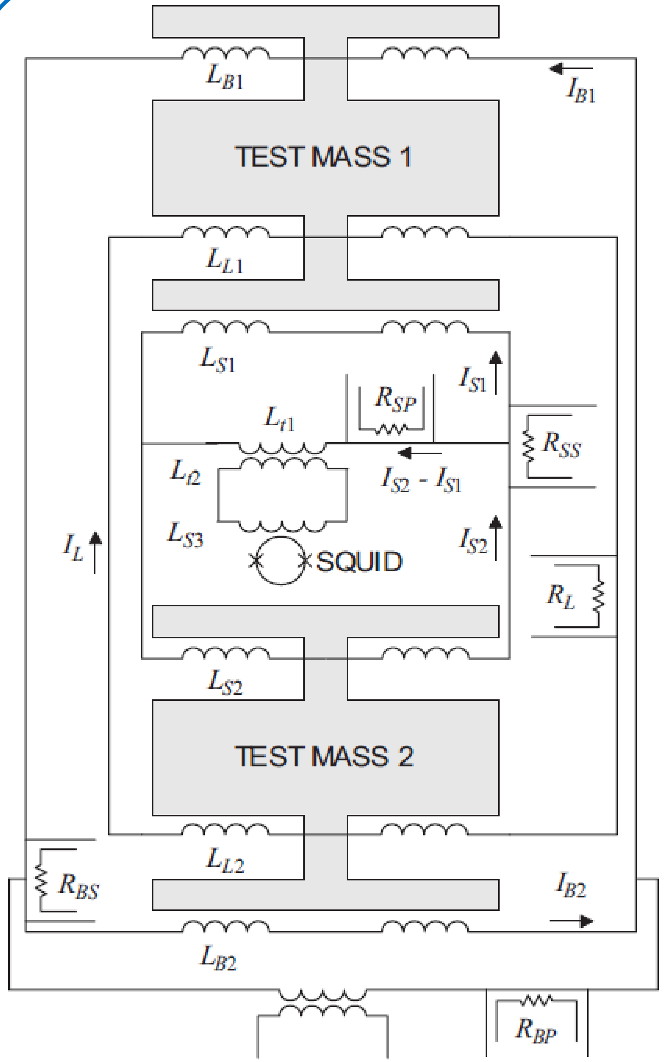


Flux Transformers





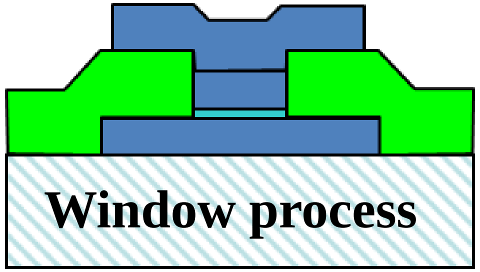
Acceleration/Displacement/Gravity

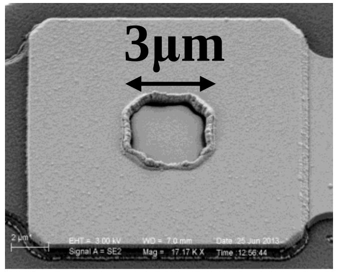


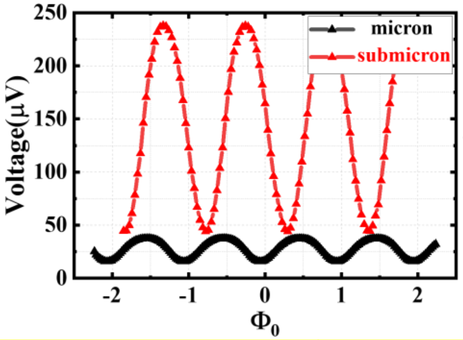
Gravity gradient

SQUID Applications

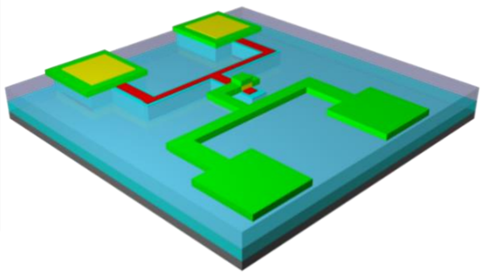
SQUID Design & Fabrication

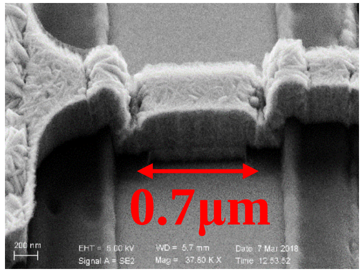




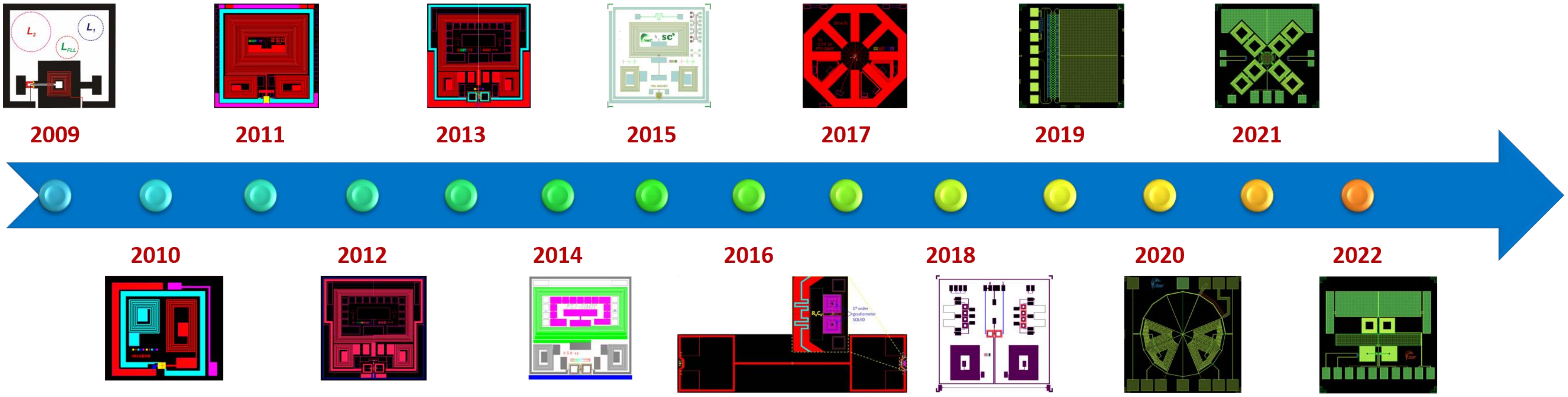


Cross process

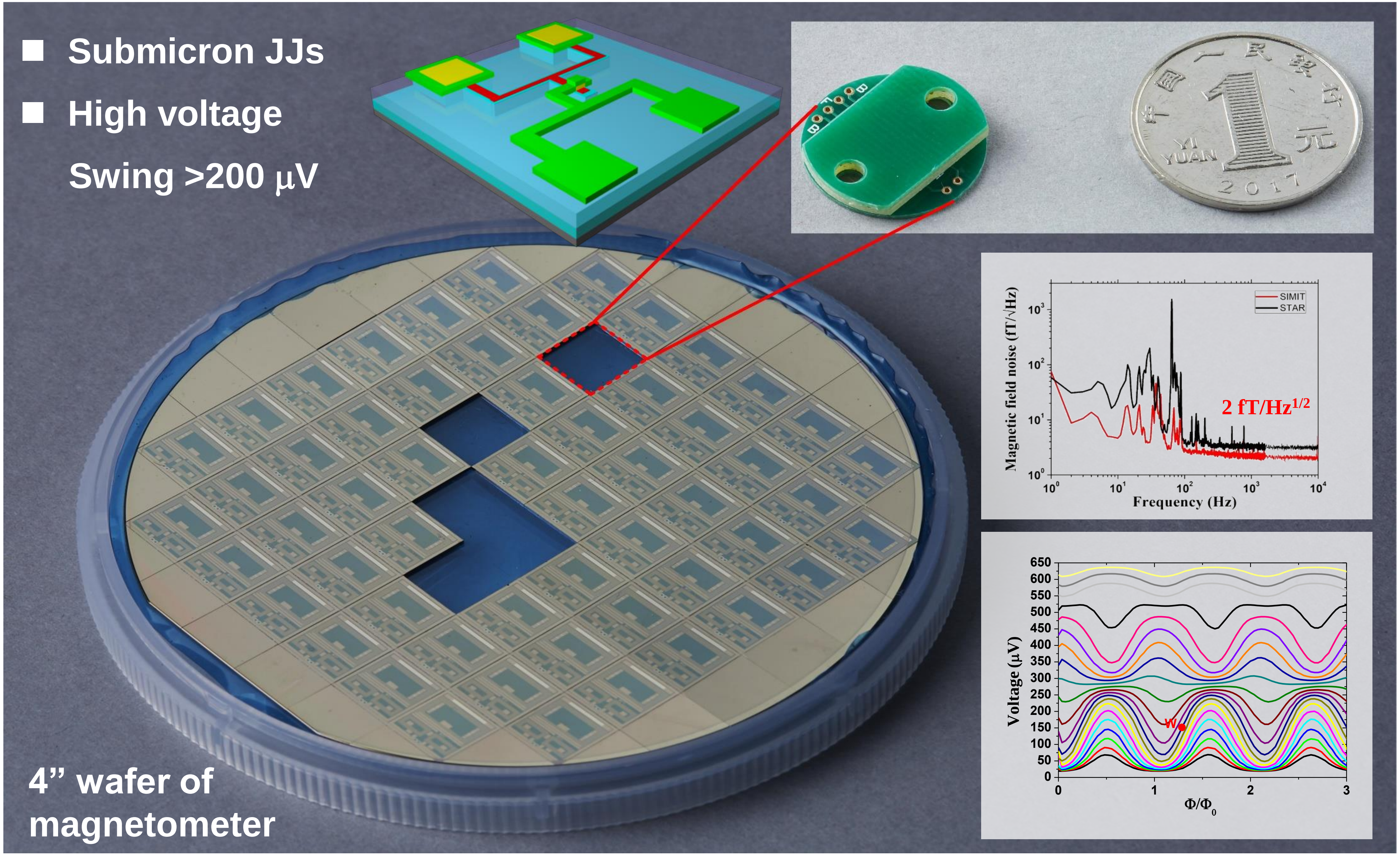




SQUIDs with micron JJs | SQUIDs with submicron JJs

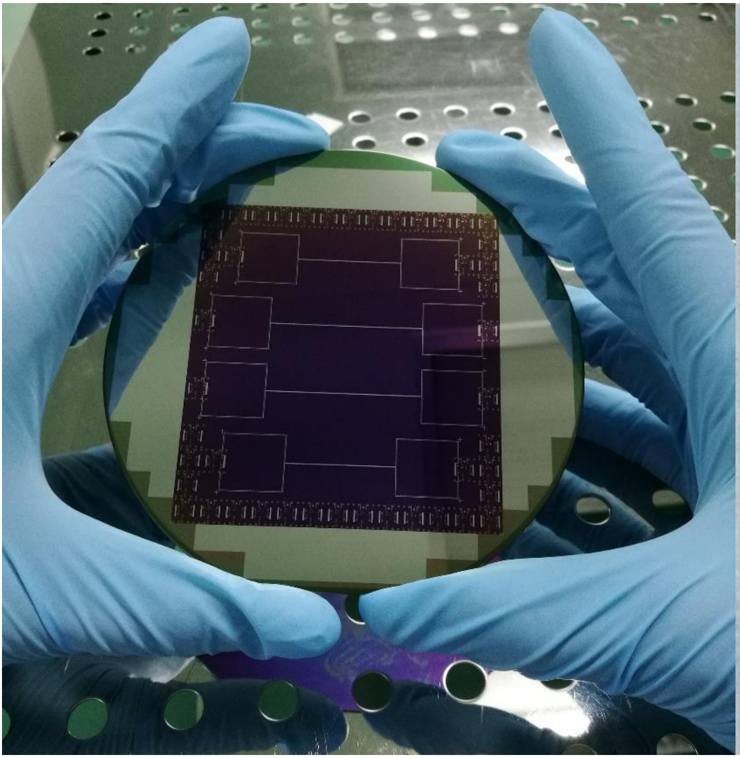


High Performance SQUID Magnetometer

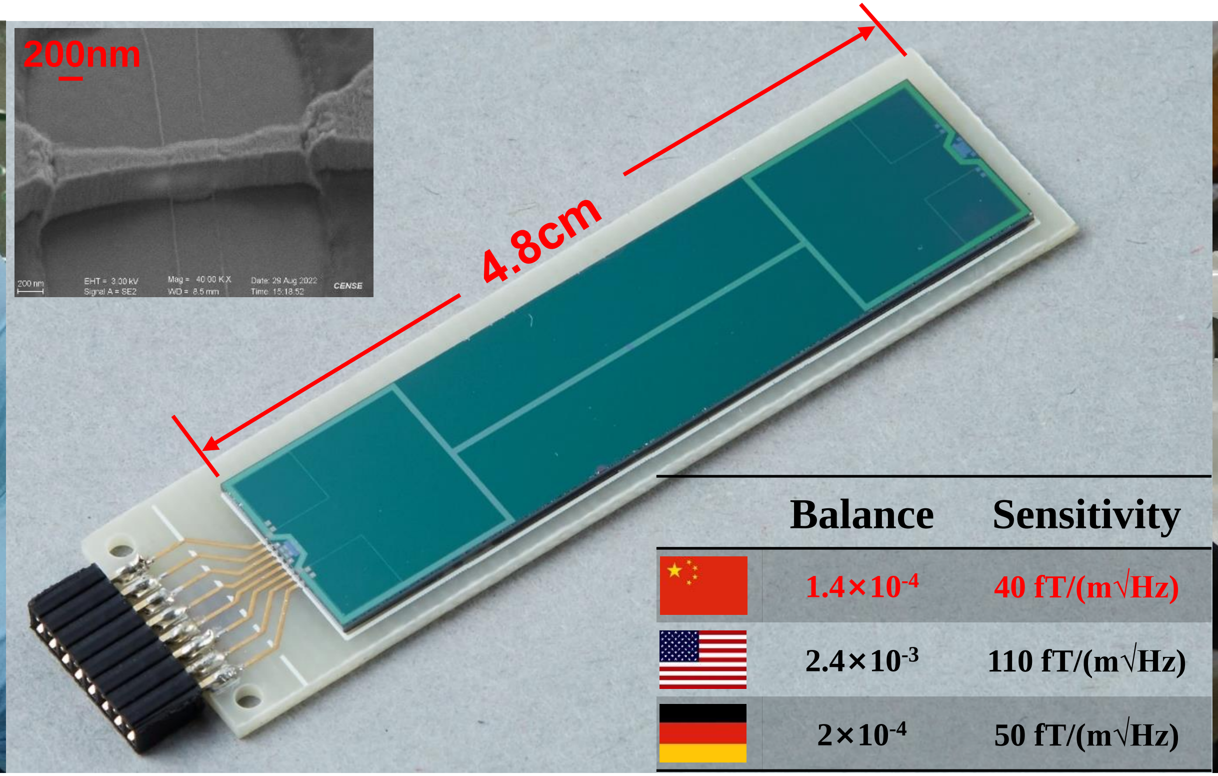


High Performance SQUID Gradiometer

SQUID gradiometer wafer

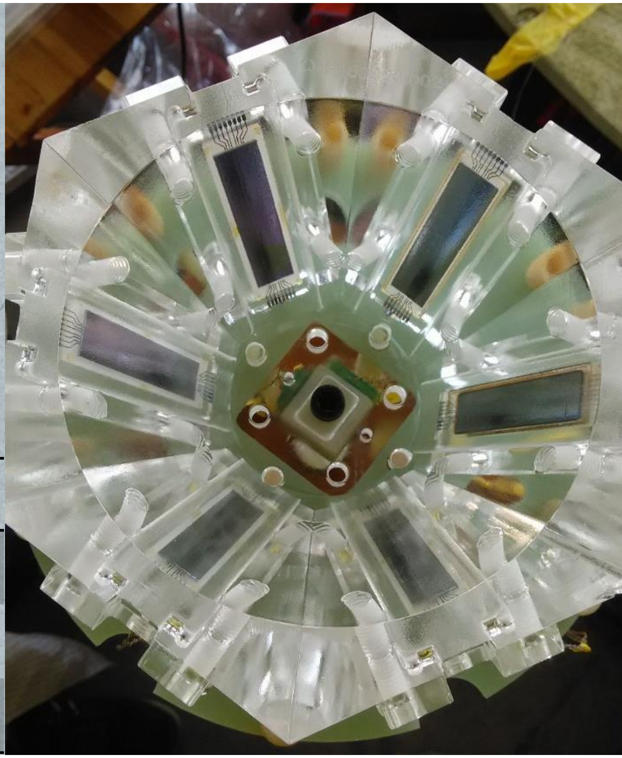


SQUID gradiometer module



	Balance	Sensitivity
	1.4×10-4	40 fT/(m√Hz)
	2.4×10-3	110 fT/(m√Hz)
	2×10-4	50 fT/(m√Hz)

Full tensor probe



SQUID gradiometer with submicron JJs and centimeter-sized input coil for geophysical prospection

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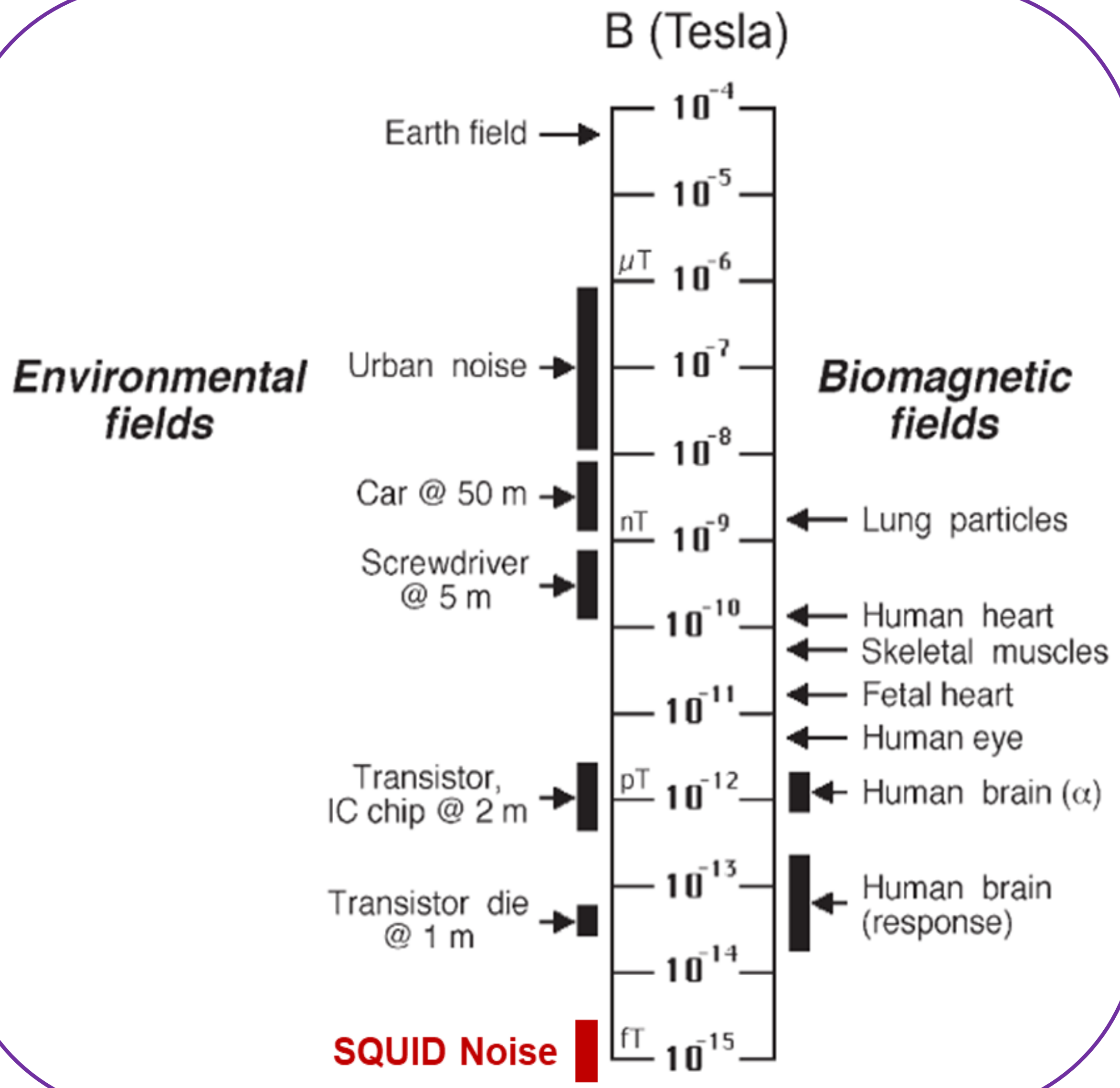
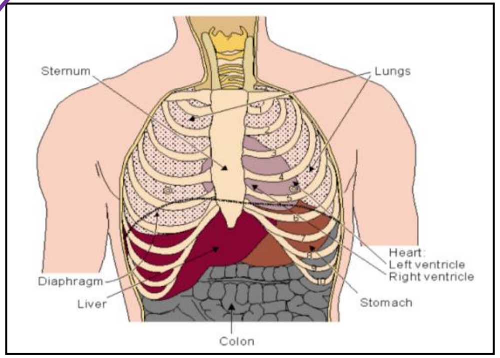
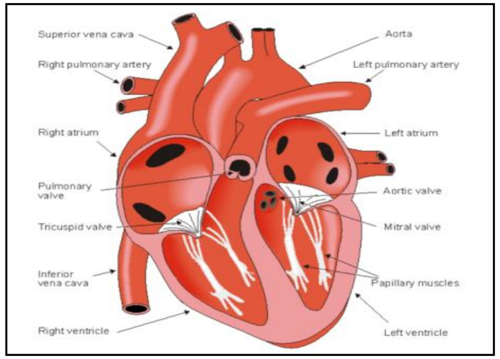
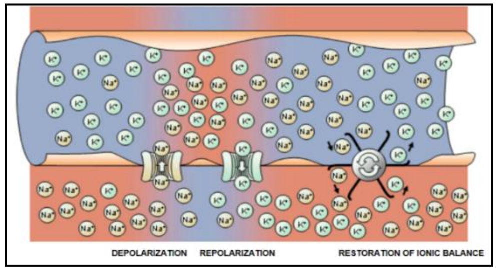
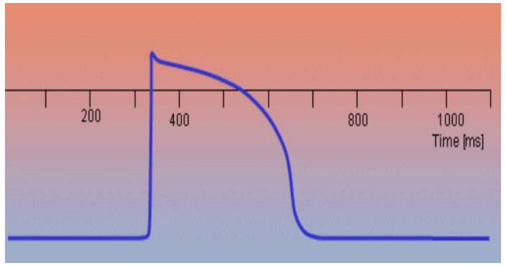
Detection of Magnetic Fields of our Body











SQUID Based Sensing Units

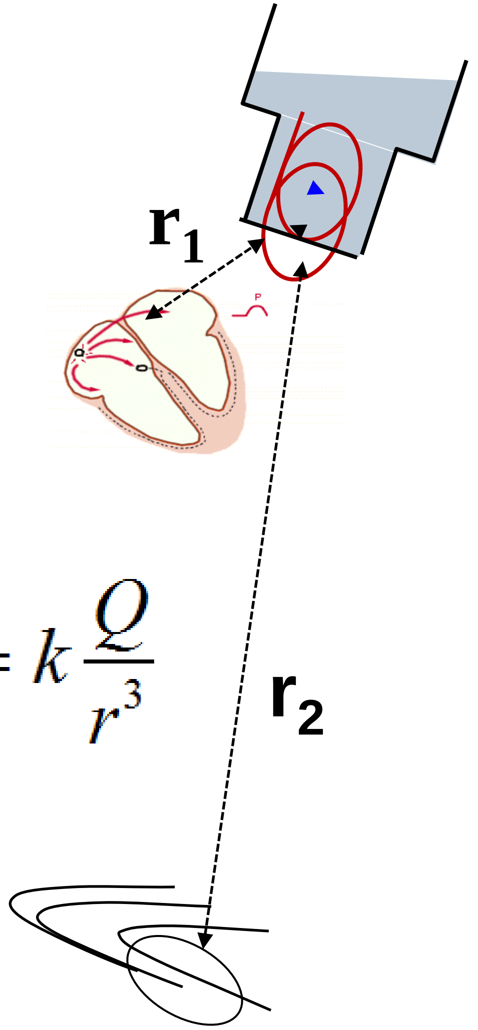
+ Noise Suppression Algorithms

+ MSR (Optional)

Detection of Magnetic Fields of our Body

$$G_{out} = \sum_{i=1}^{3}(C_{Bi}B_i) + \sum_{j=1}^{5}(C_{Gj}b_jG_j) + C_{G2}b_6b_7G^{(2)}$$

Reference sensor output ***Signal sensor output***



$$B = k\frac{Q}{r^3}$$

B_i (i=1 to 3), G_j (j=1 to 5) are outputs of the hardware reference sensors

$G^{(2)}$ is the output of the hardware signal sensor

C_{Bi} (i=1 to 3), C_{Gj} (j=1 to 5) and C_{G2} are coefficients to be optimized

The task is to maximize the signal to noise ratio of the systems by optimize the design of signal and reference sensors and the coefficients in the equation (software gradiometer)

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MCG System for Unshielded Environment

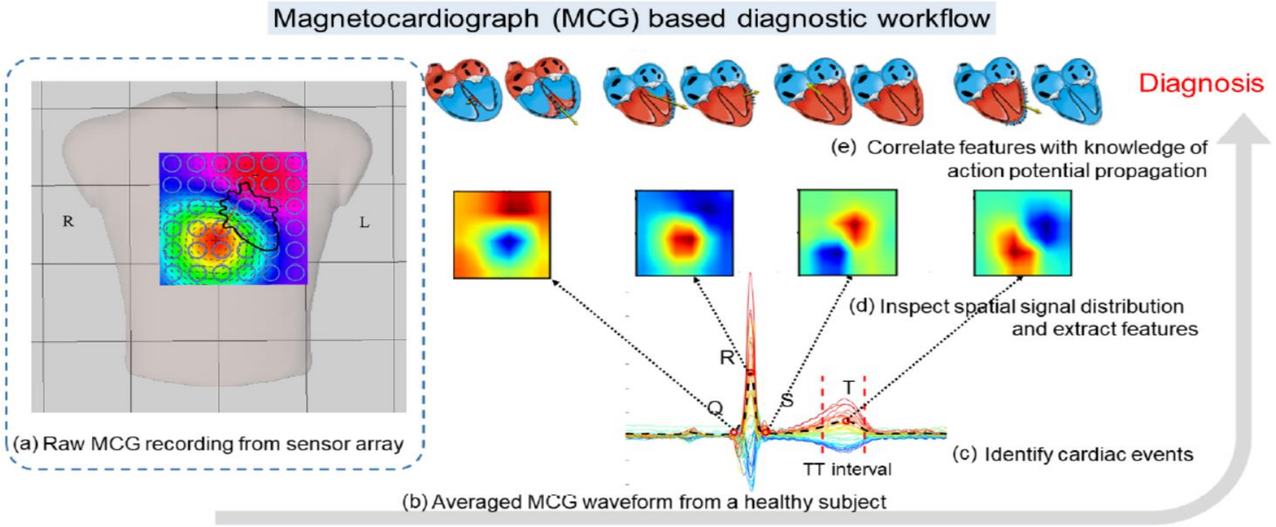
NMPA approved MCG system

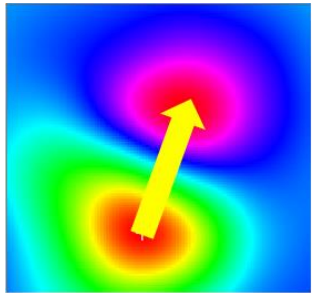
Potential clinical applications:

1. Early screening for ischemia heart diseases (IHD)
2. Diagnosis of IHD, such as obstructive coronary heart disease, non-obstructive coronary heart disease
3. Cardiac prognostic monitoring
4. Arrhythmogenic risk assessment

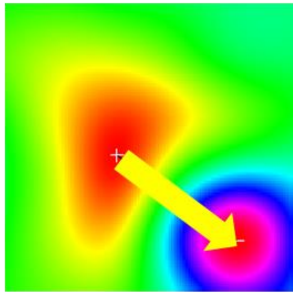
$$G_{out} = \sum_{i=1}^{3}(C_{Bi}B_i) + \sum_{j=1}^{5}(C_{Gj}b_jG_j) + C_{G2}b_6b_7G^{(2)}$$

3 B sensors and 5 gradient sensors for noise suppression





Normal MCG



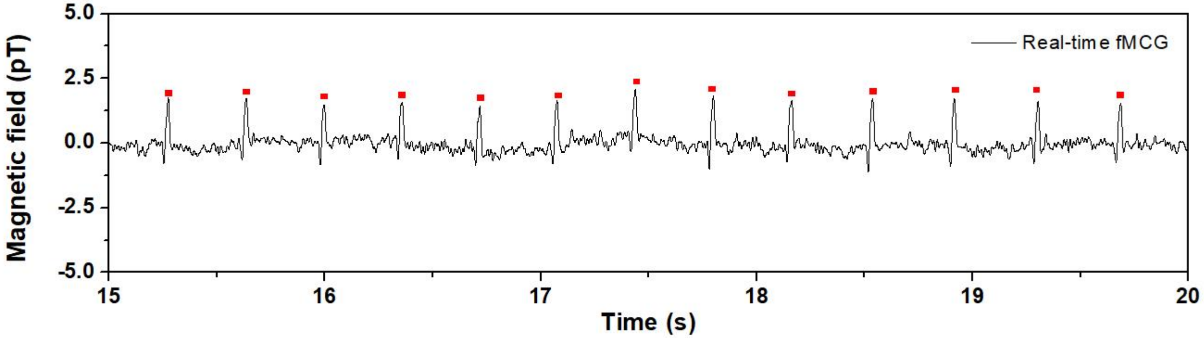
IHD

Prototype of Fetal MCG system

$$\mathbf{G}_{out} = \sum_{i=1}^{3}(C_{Bi}B_i) + \sum_{j=1}^{5}(C_{Gj}b_jG_j) + \mathbf{C}_{G2}b_6b_7\mathbf{G}^{(2)}$$

3 B sensors and 5 gradient sensors for noise suppression + local shielding

Noise level: ≤0.8pTpp @1-90Hz

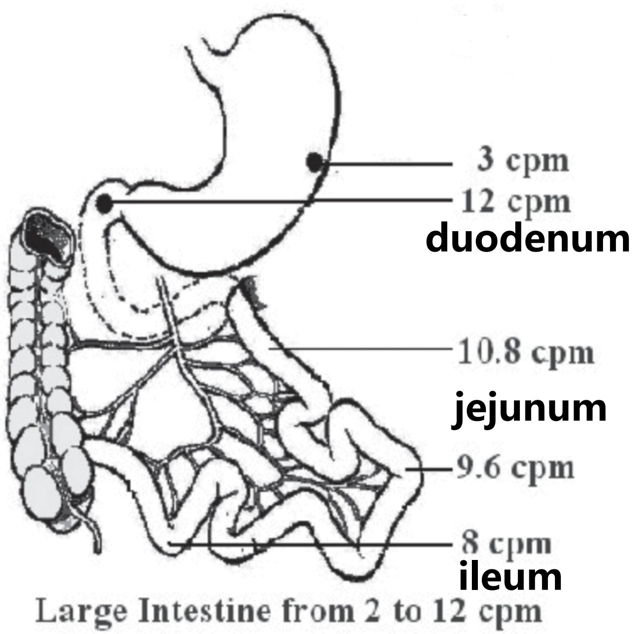


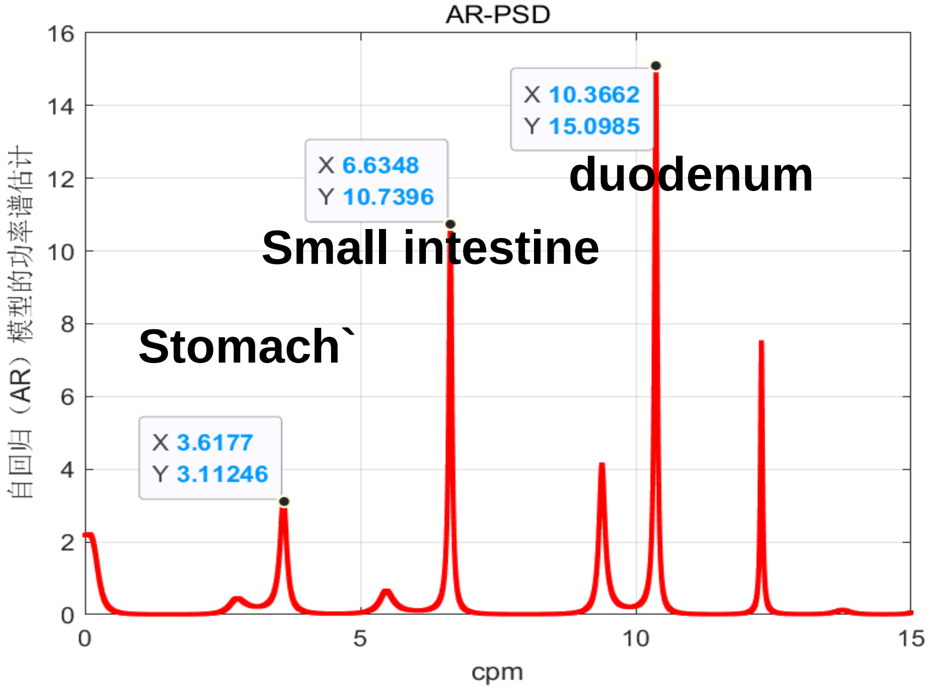
Real-time fetal MCG recordings at 28 weeks of gestation (cooperated with Shanghai Xinhua hospital)

Preclinical trials to be started:

1. **Evaluation of fetal arrhythmias, known or suspected conduction disorders, sinus/atrioventricular node disease**
2. **Diagnosis of a long QT syndrome**
3. **Monitoring fetal development, such as fetal autonomic nervous system activity, fetal movement**

Magnetoenterogram (MENG) & Magnetogastrogram (MGG)





Challenges

Very low freq.: 3 to 12 cpm (< 0.2 Hz)

Very low magnitude: several pT

Averaging not applicable

Solution

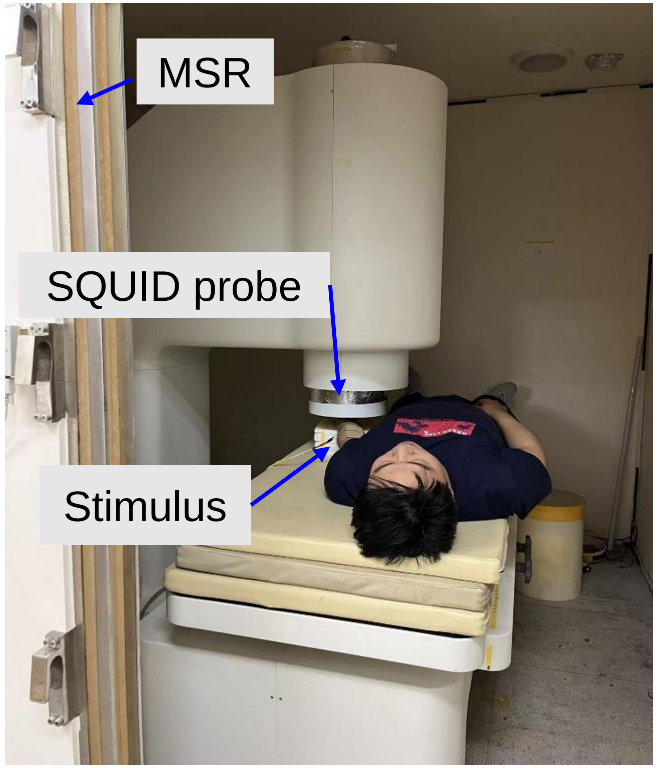
Advanced noise rejection algorithms

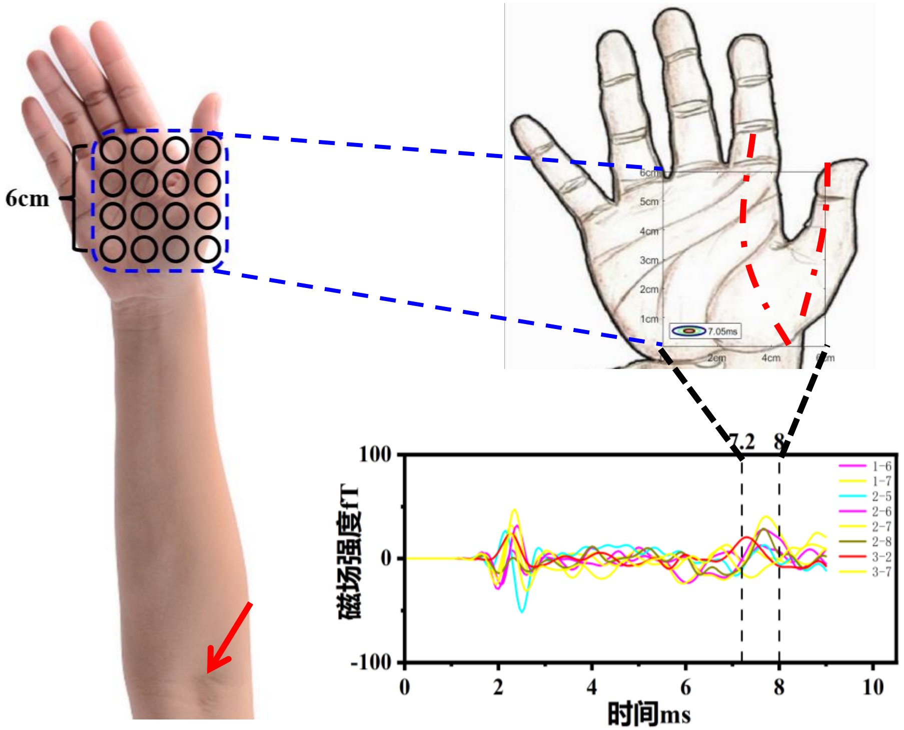
Outlook

Modernization of Chinese Traditional Medicine

Health Research

Magnetoneurography (MNG) System under Development





stimulus point

Challenges

Optimization of stimulating profile

Interference of the stimulating device

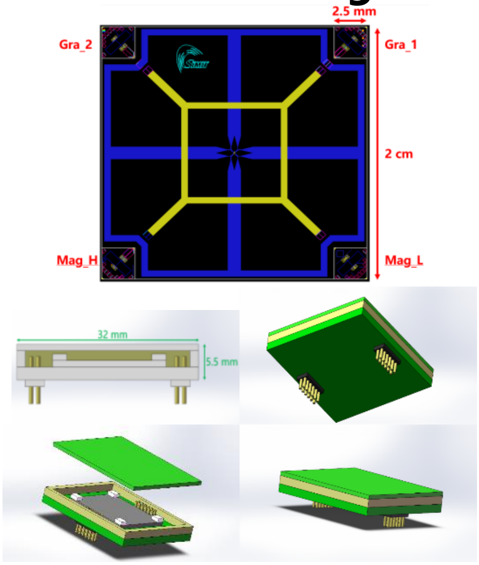
Outlook

Acupuncture research

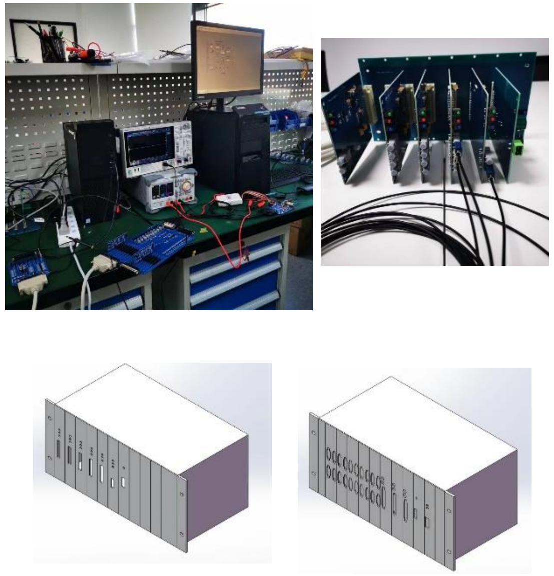
Modernization of Traditional Chinese Medicine

Magnetoencephalography (MEG) System

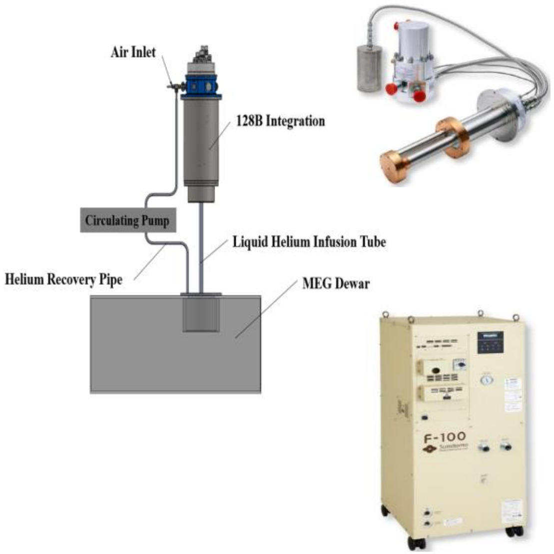
SQUID Design



Readout circuit

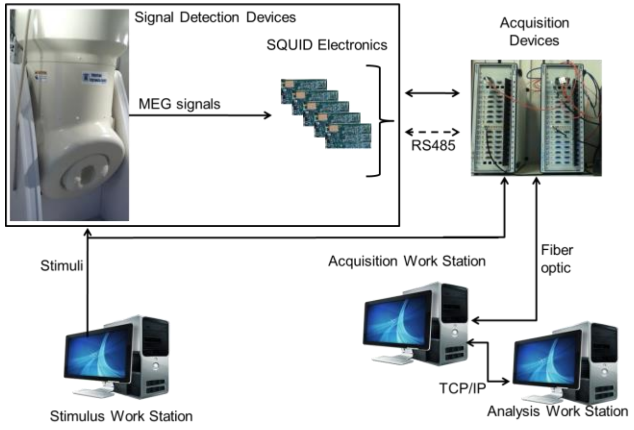


Helium Liquefier- Recycler

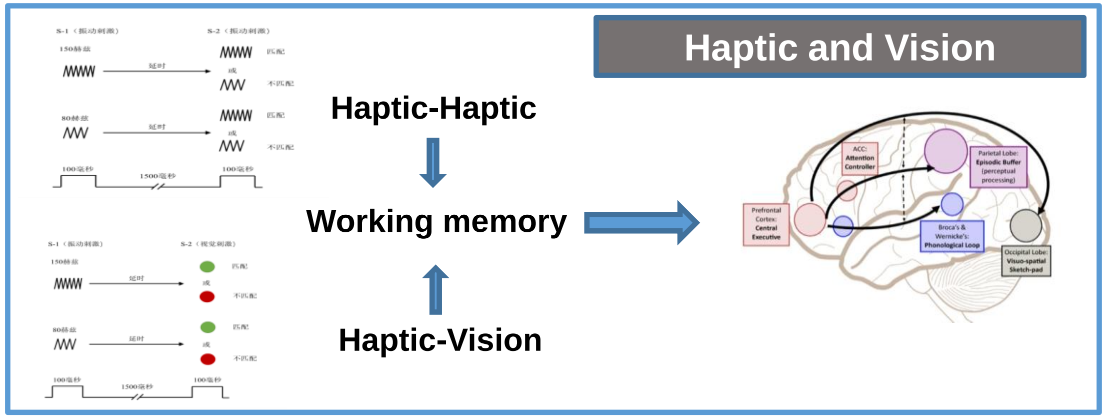


MEG data acquisition

MEG system



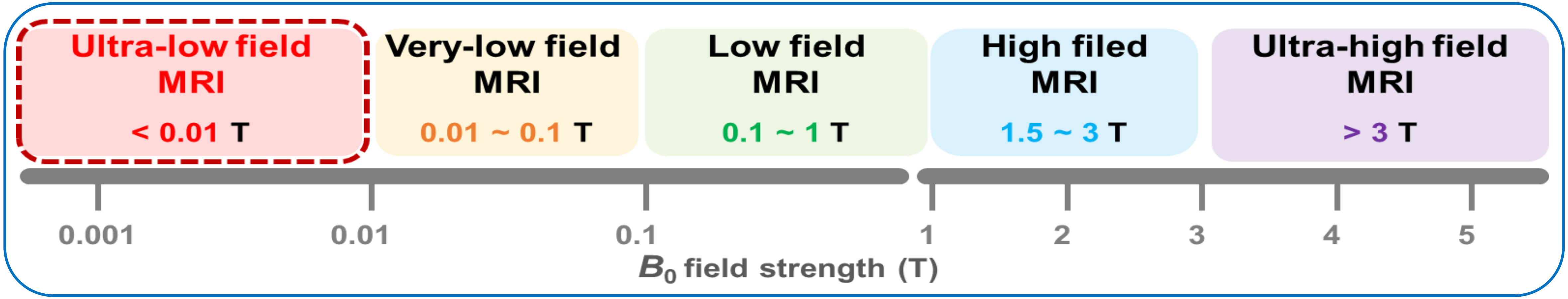
MEG applications



Magnetic Resonance Imaging (MRI)

✓Advantages

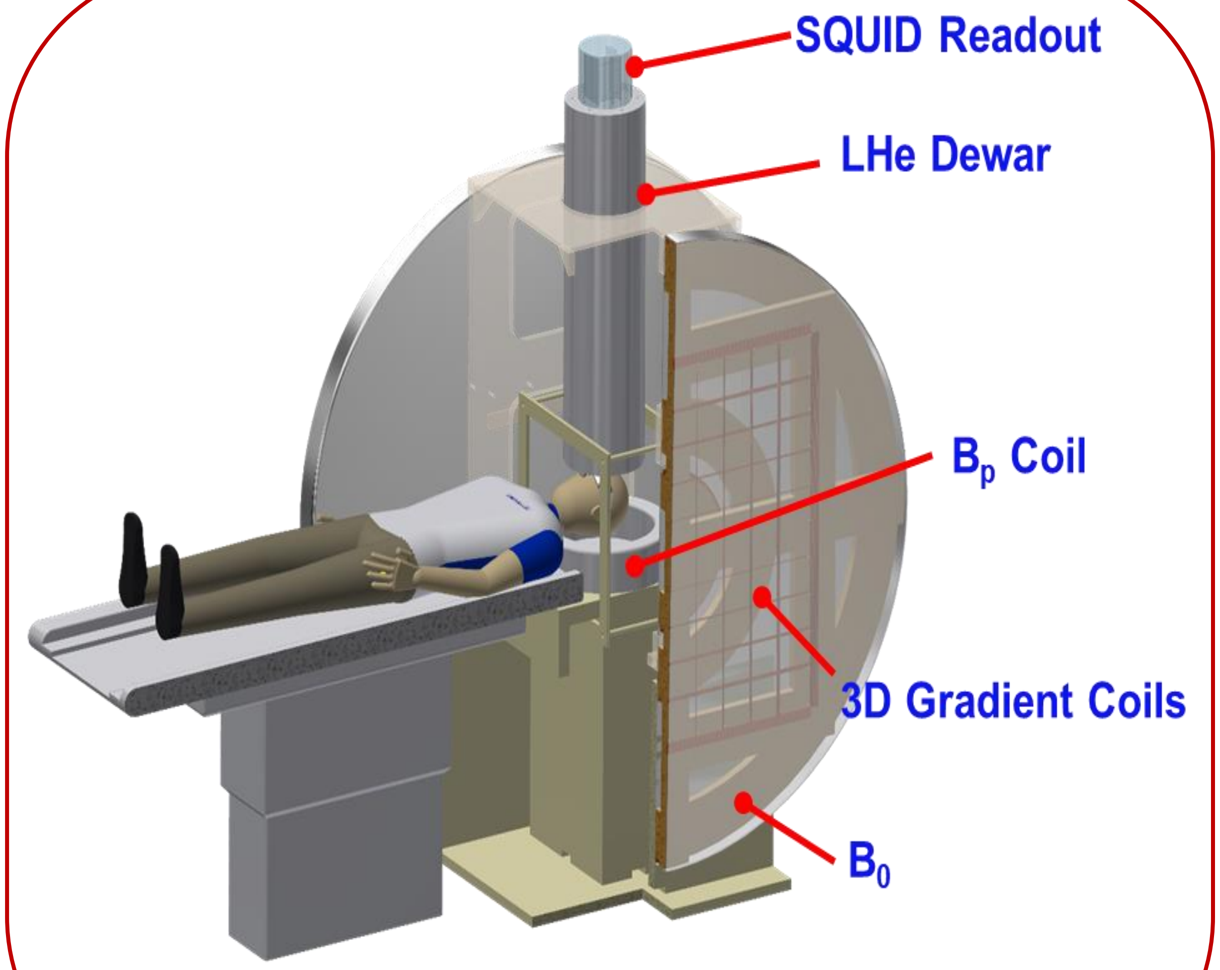
- ☺ No ionizing radiation, non-invasive
- ☺ Image acquisition from any direction and in any orientation
- ☺ Excellent contrast on abnormalities in soft tissues/organs
- ☺ ….



Two trends

- ❑ Higher field (11.7 T, 132 tons @ Europe)
- ❑ Lower field: portable、specific applications

ULF MRI System



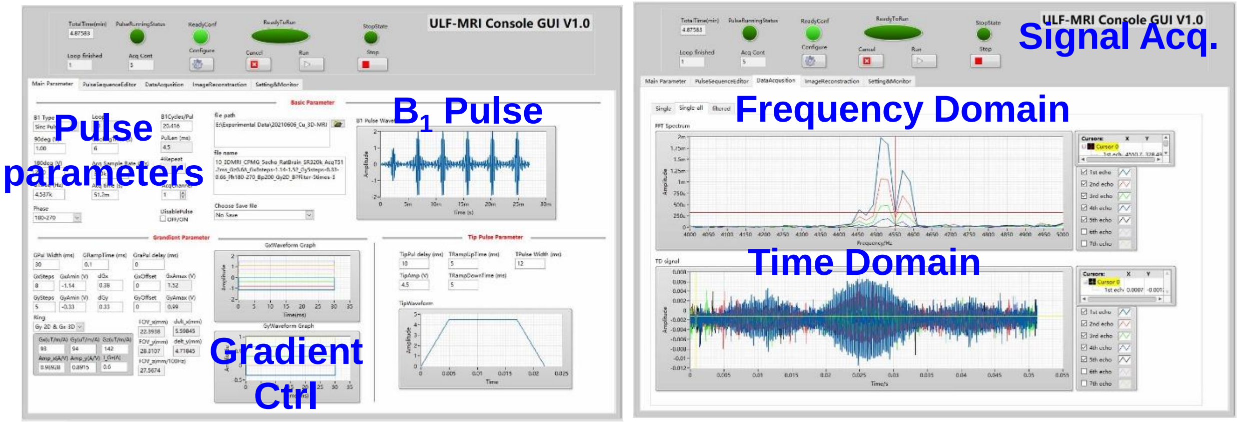
System Schematic

- B_p = 87 mT; B_0 = 0.11 mT (f_L~4.7 kHz)
- G_{max} = 230 μT/m
- 5 channels; noise: 1.5 ~ 3 fT/√Hz

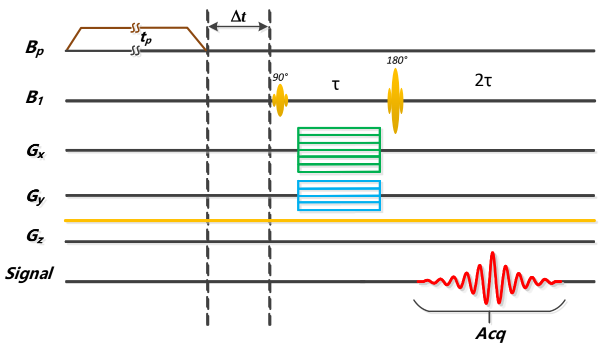
FPGA-based MRI Console

Parameter Setting, Sequence Generation, Signal Acq. & Pre-processing

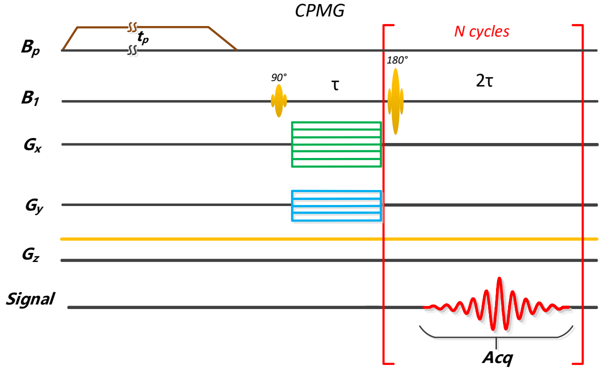
User Interfaces



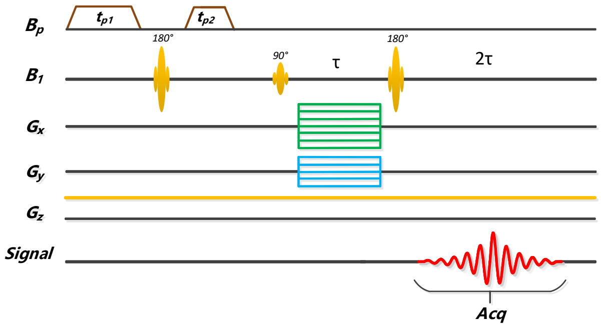
MRI Pulse Sequence Generation



T_1-mapping sequence



T_2-mapping sequence

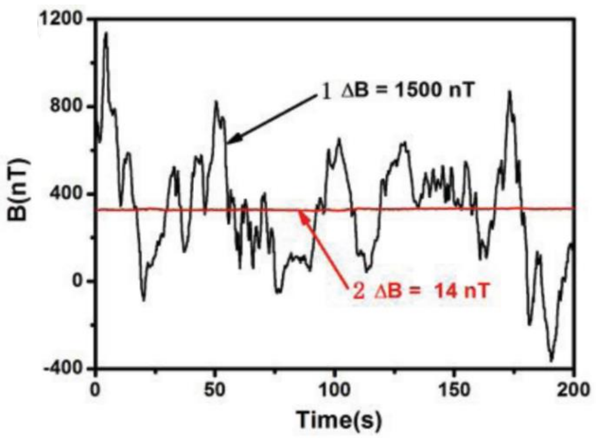


Inversion recovery sequence

Price	< 7k USD
Size	18.5×17.3×6 cm^3
Weight	1 kg
Transmitter Channels	8
Receiver Channels	8
EMC	Good

Environmental Interference Suppression Techniques

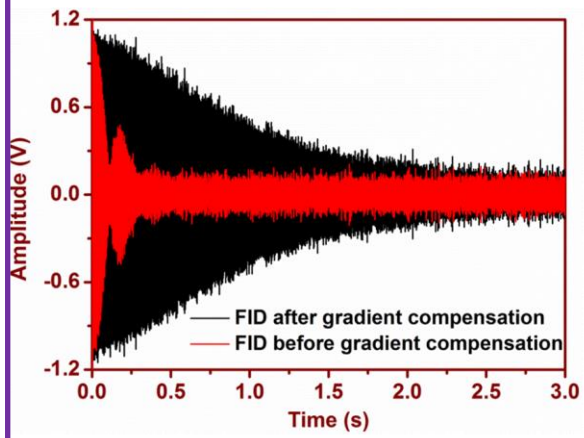
✓Environmental field fluctuation suppression



Suppression factor: >100

✓ *J. Magn. Reson.* 257 (2015) 8-14

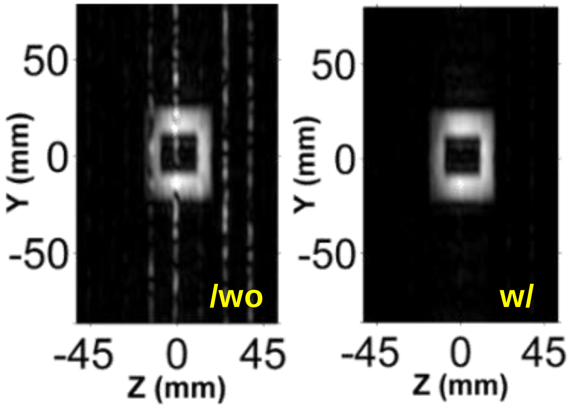
✓Environmental gradient field compensation



SNR enhanced by a factor of 10

✓ *Appl. Phys. Lett.* 102 (2013) 102602

✓Power-line harmonics suppression



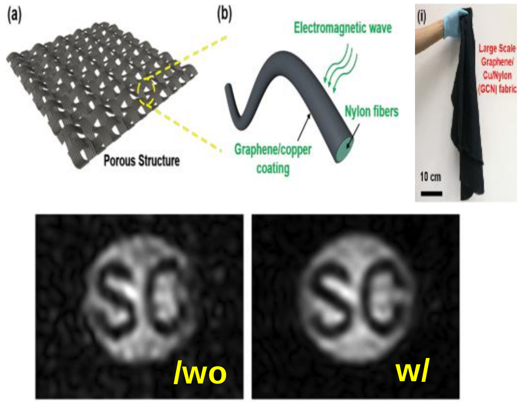
Suppression factor: 86%

✓ *J. Magn. Reson.* 286 (2018) 52

✓ *Sensors* 19 (2019) 3566

✓ *IEEE TAS* 32 (2022) 1600705

✓RF frequency interference shielding

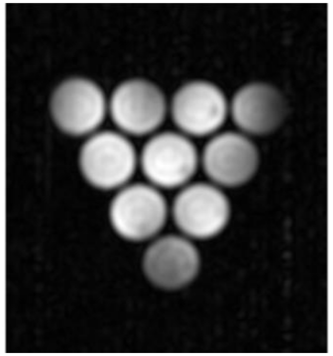


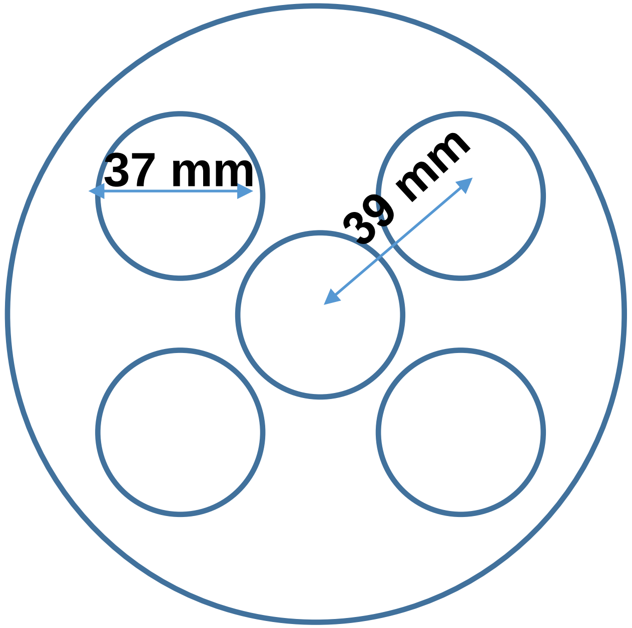
SNR enhanced by a factor of 4.3

✓ *J. Magn. Reson.* 317 (2020) 106775

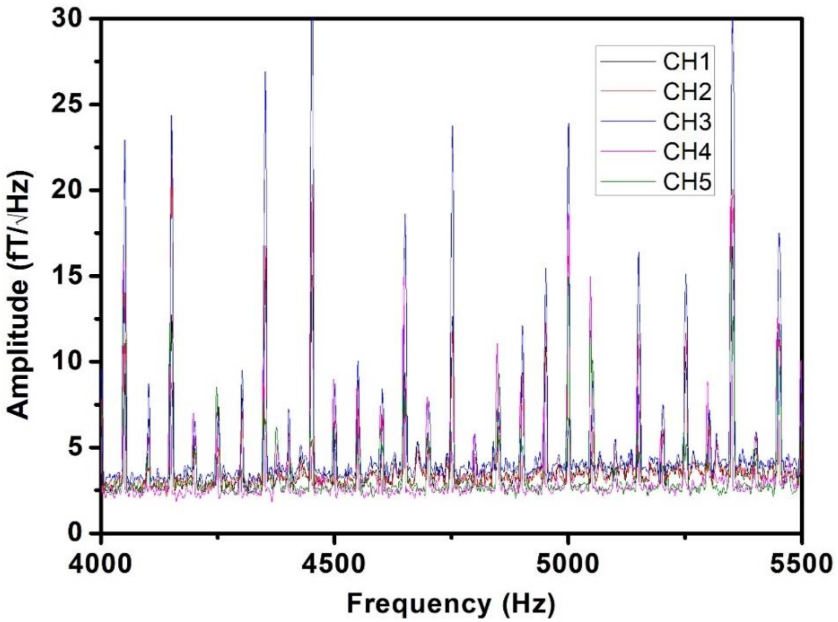
Five-Channel Imaging and Reconstruction

- 2nd-order gradiometer array to enlarge FOV
- Geometry optimization to increase SNR & reduce external interference
- Realization of SENSE & GRAPPA parallel imaging

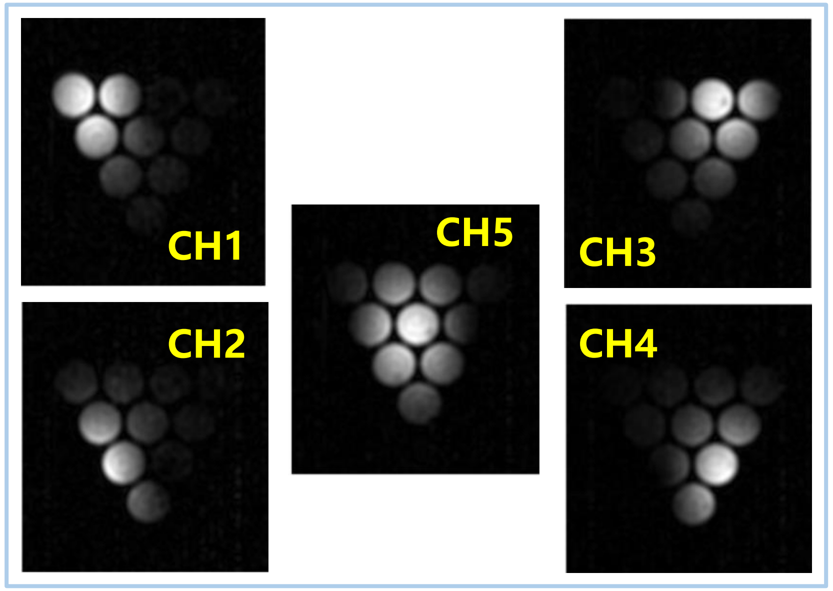




Geometry of signal channels



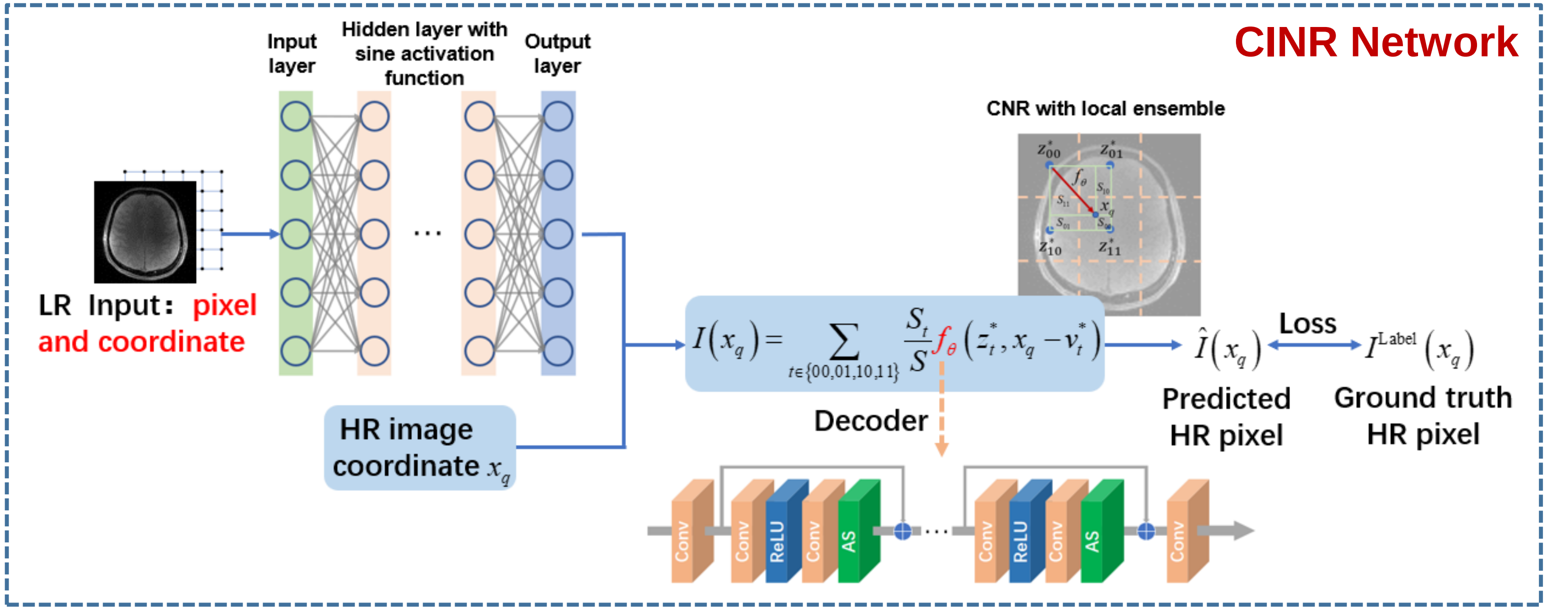
Noise spectra of 5 signal channels

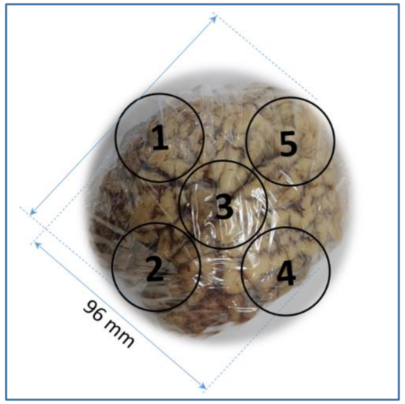


Deep-learning Based Post-processing

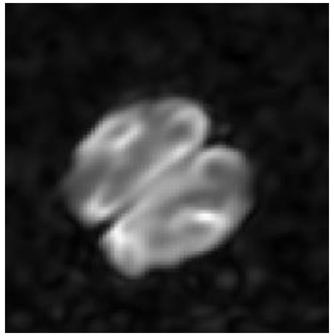
➢ **Main challenges: low spatial resolution & Gibbs artifacts**

Continuous image neural representation (CINR)

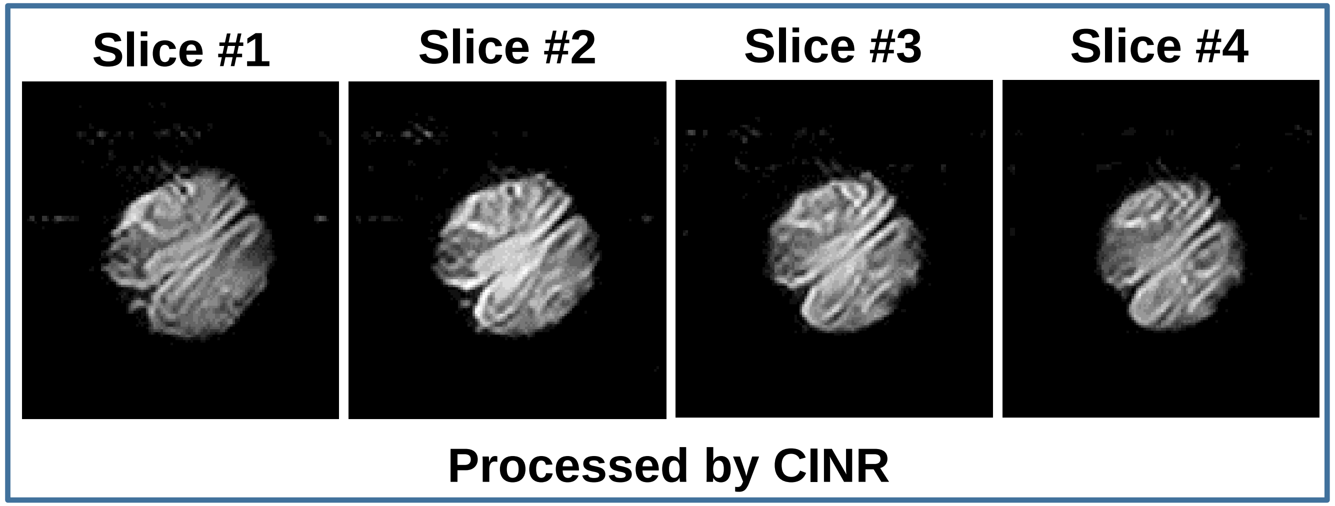




FFT recon.



FFT recon.

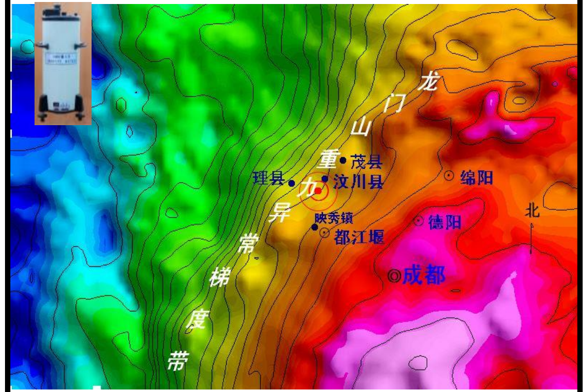


Processed by CINR

Geophysical Methods for Mine Prospecting

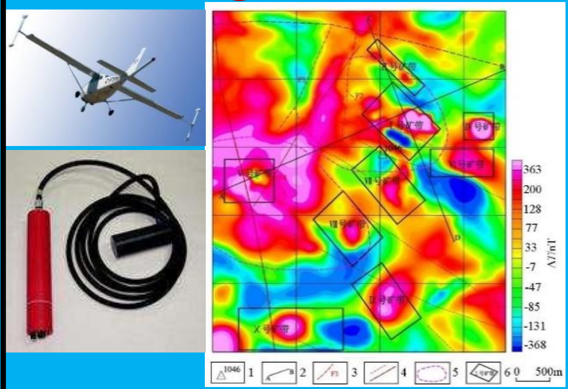
Searching for mine by detecting and analyzing the underground spatial variation of physical properties of the target areas (density, magnetic permeability, resistivity, acoustic impedance etc)

Gravity



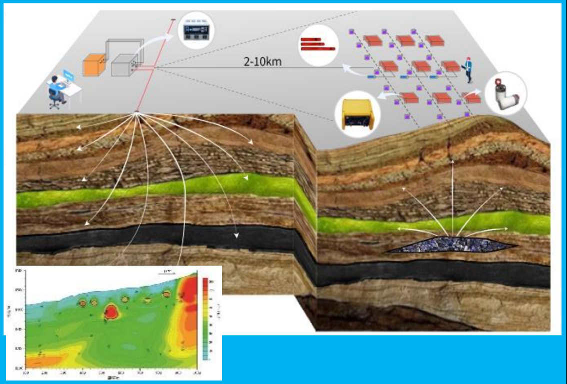
Metal, Oil, Gas

Magnetics



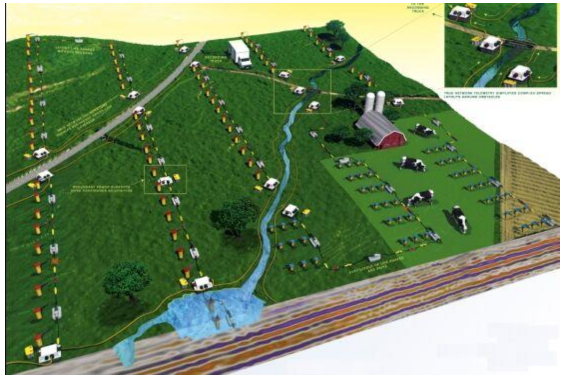
Metal

Electric



Metal, Coal

Seismic



Oil, Gas

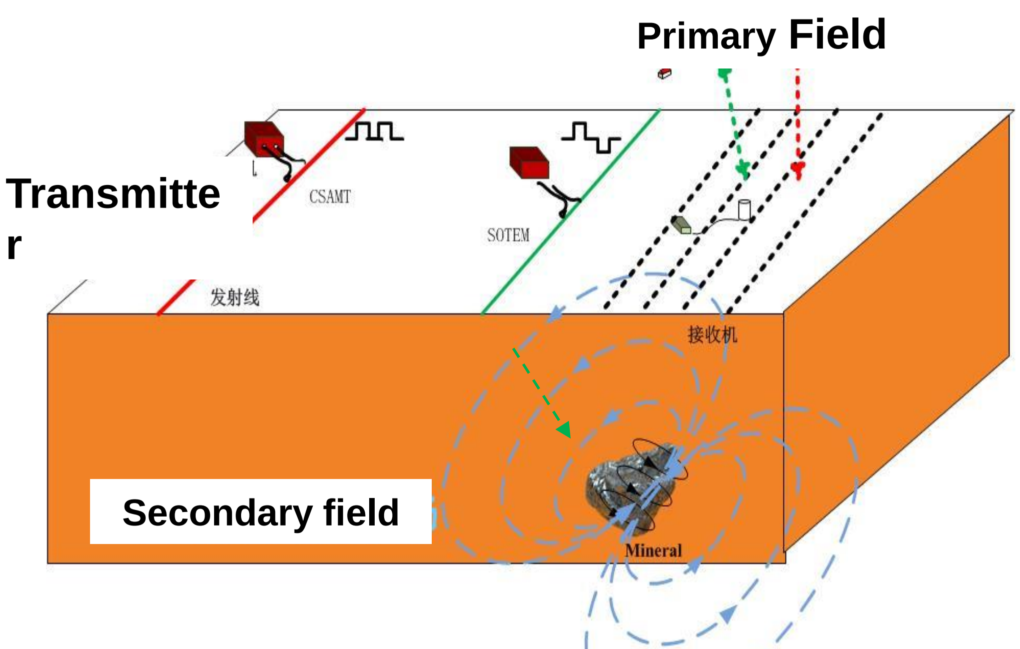
Superconducting sensors provide extreme sensitivity to gravity, magnetic & electromagnetic measurements

SIMIT sets its focus on magnetic and electromagnetic methods

Ground Based SQUID TEM System

Transient Electromagnetic Method (TEM)

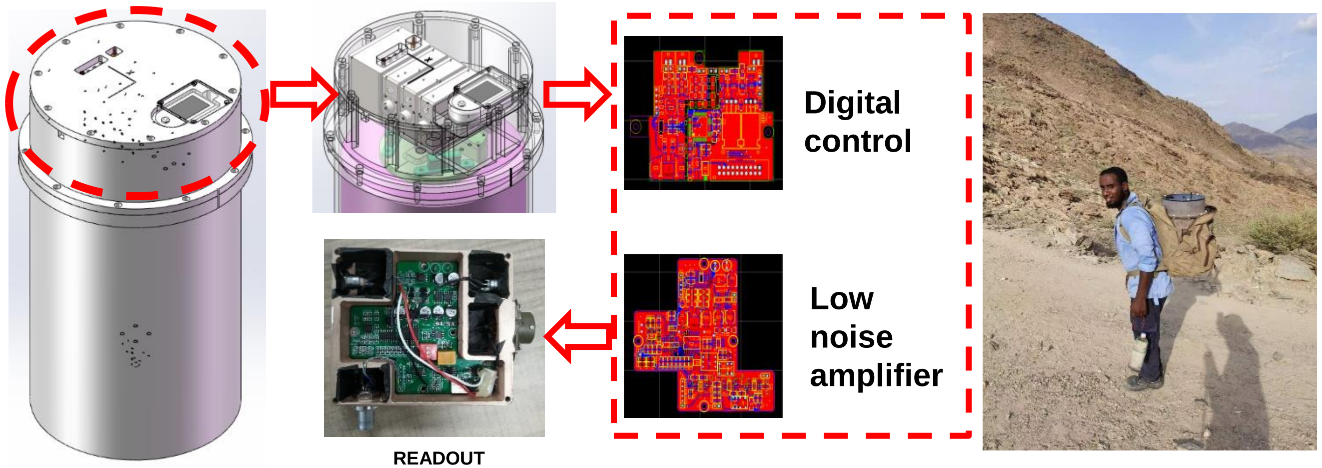
- ✓ Effective for metal mine exploration
- ✓ Traditional coil system: 500m depth



SQUID based TEM

More than 3000m exploration depth

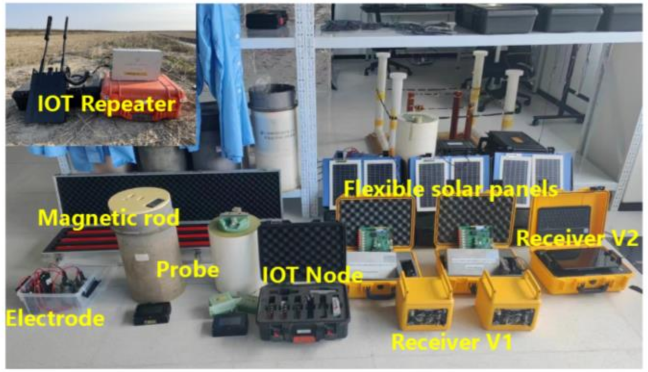
SQUID based TEM system @ SIMIT



Transimitter

40KW / 60KW

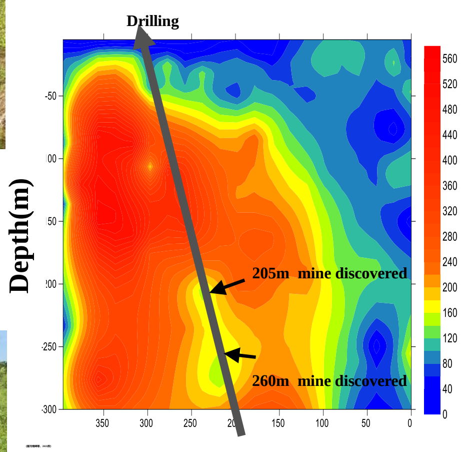
Sensor & receiver



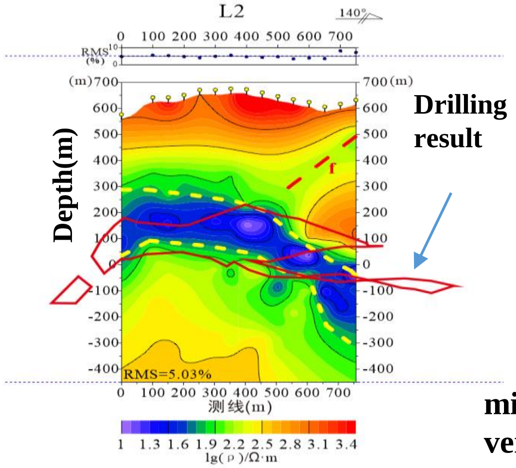
Different sensors and receivers

Typical Results Obtained

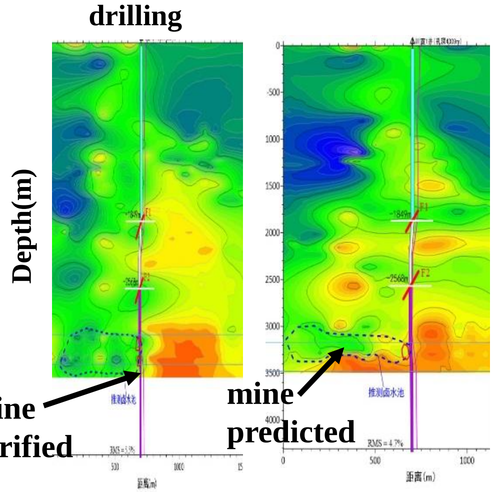
Tungsten and tin mine



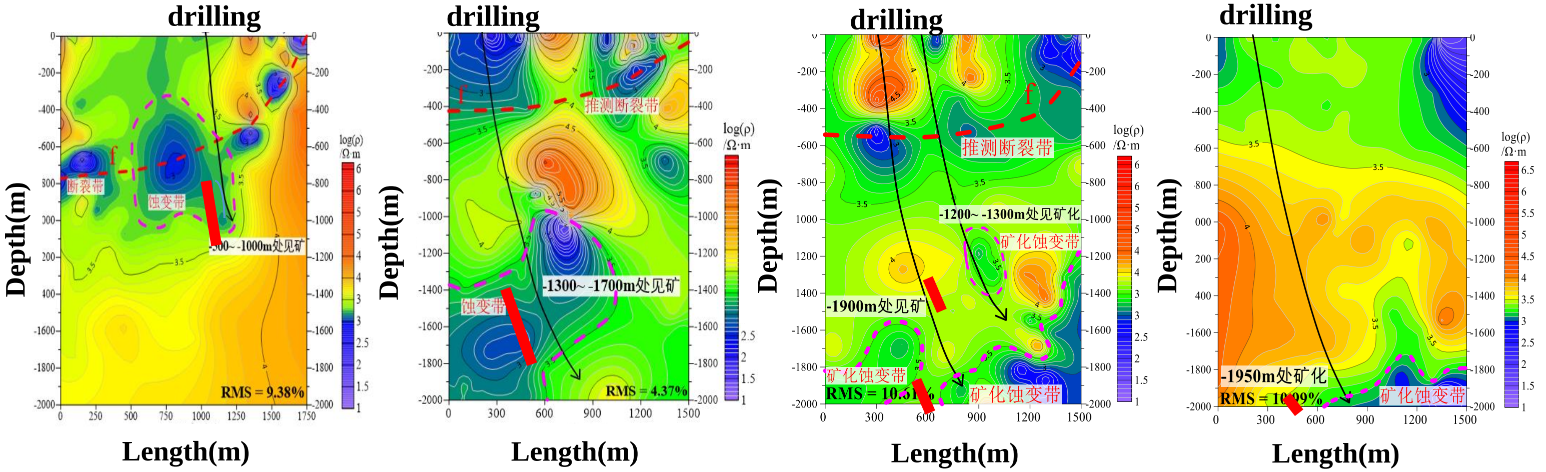
Copper mine discovered



>3000m Lithium surveying



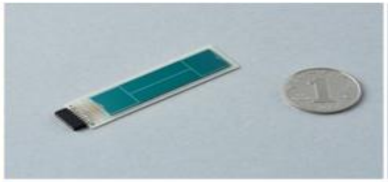
Deep copper mine discovered buried @2000m underground

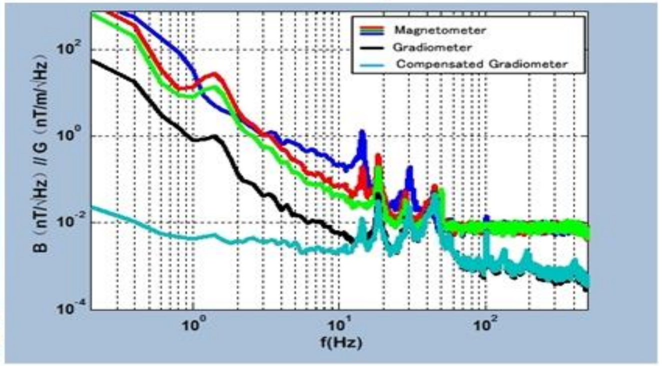


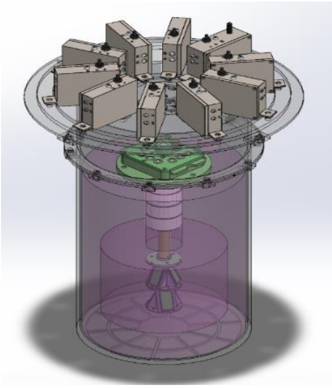
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56, March 2024. Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China

SQUID Full-Tensor Aeromagnetic System

✓ **Helicopter based SQUID full-tensor system developed @SIMIT**







Parameters	Best Others	SIMIT
Total field	/	1nT
Noise level	40fT/m/√Hz	90 fT/m/√Hz
Resolution	10pT/m	20pT/m
1/f corner	/	10
Bandwidth	1kHz	1kHz
Chanell	9	9
Weight	/	50kg
Refilling time	2 days	2 days

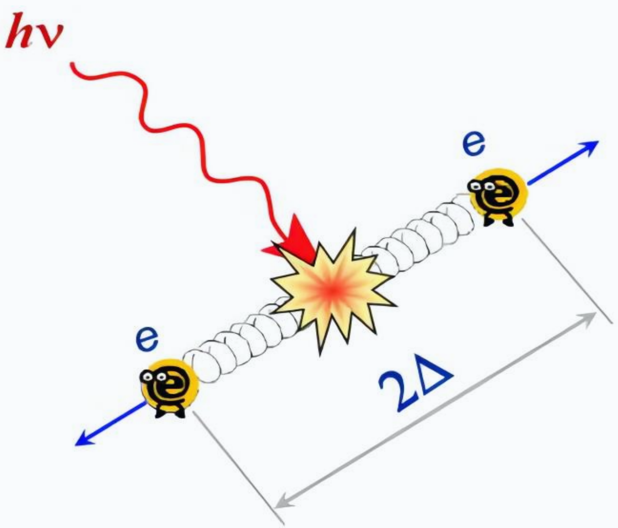
UAV based system is being tested for more economical exploration

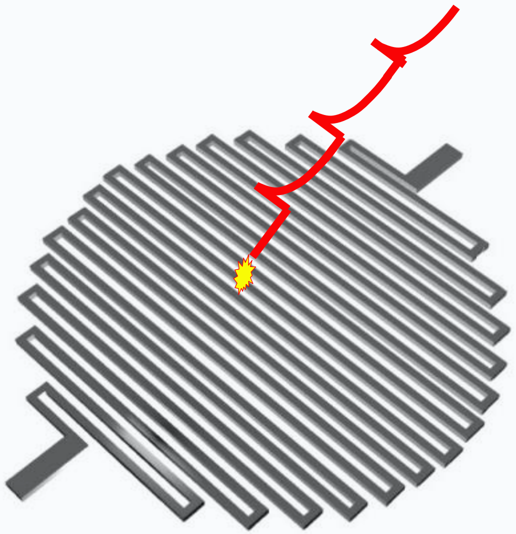
Outlines

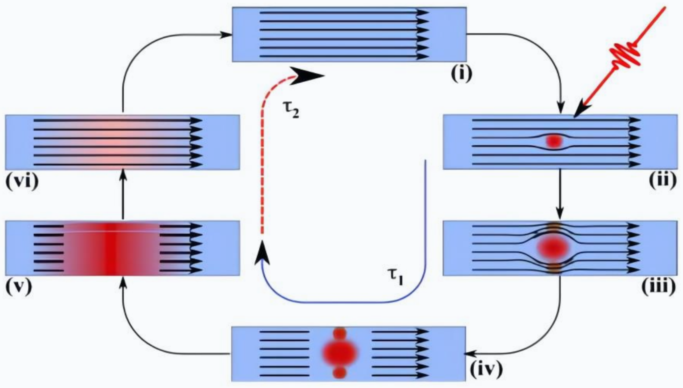
- General introduction to superconducting electronics
- SQUID sensor development and applications
- SNSPD detector development and applications

Working Principles of SNSPD

SNSPD = Superconducting Nanowire Single Photon Detector







Photon energy VS. Cooper Pair energy
h ν (1eV) VS. 2Δ (~meV)

Material: ultra-thin NbN thin film (~ 5 nm);
Structure: nanowire (width <= 100nm)

Electro-thermal model
self-recovery detection process

Advantages of SNSPD

SPD	SDE (%)	CR (Hz)	DCR (s^{-1})	TJ (ps)	Temp (K)
SNSPD (NbN)	≥ 95	≥ 100 M	≤ 1	≤ 20	~ 2.1 K
STJ (Al)	60	5 K	N/A	N/A	< 1K
TES (W)	95	100 K	~ 0	100 ns	0.1 K
InGaAs APD	20	100 M	16K	55	200 K
IR PMT	2	10 M	200 K	300	RT

@ 1550 nm

SNSPD show superior performance advantages compared to other detectors

Cooling is no longer a bottleneck of superconductive devices (down to ~ 2K in several hours at an expense of 1.5 KW)

Applications of SNSPD

Quantum communication

Quantum key distribution

Quantum teleportation

Laser communication

Deep space, moon and other long distance laser communication

quantum information

Quantum computing

Optical quantum computing

Ion-trap quantum computing

Lidar

Single-photon lidar

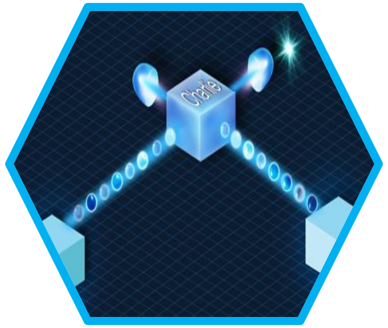
Quantum lidar

faint light detection

Quantum measurement

Quantum time synchronization

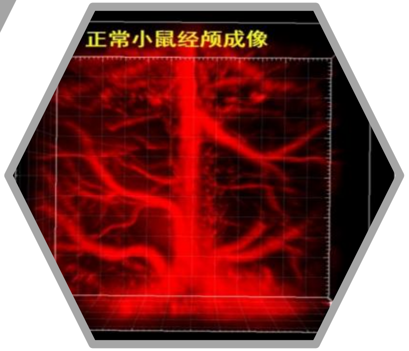
Super resolution imaging



Biofluorescence detection

Bioluminescence detection in the near-red region II

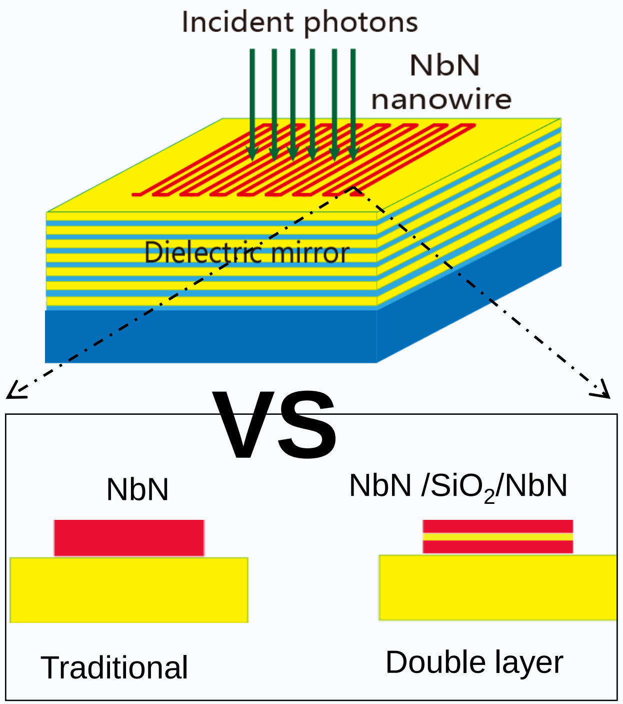
No afterpulse fluorescence detection

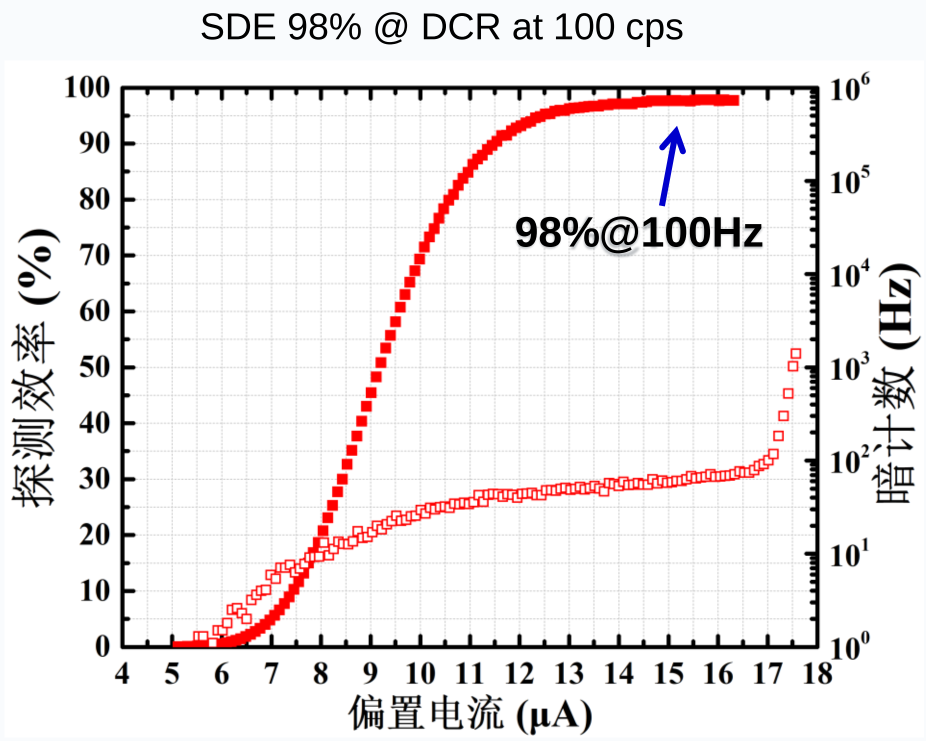


IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56, March 2024. Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China

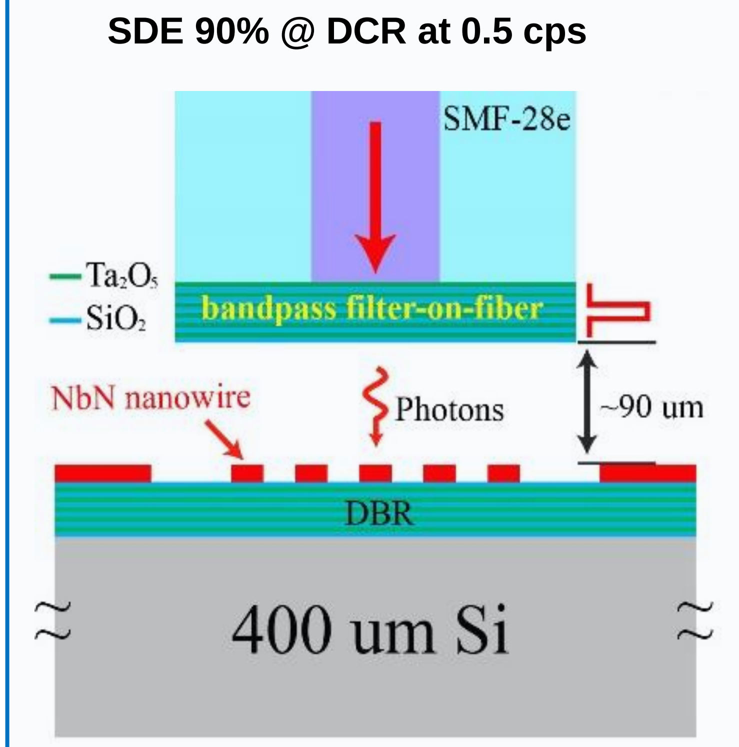
Design of SNSPDs

High SDE SNSPD





Low DCR SNSPD



Decoupling of light absorption and light response

Compared to the conventional single-layer devices:

- **The optimal detection efficiency was increased from 90% to 98%**
- **Efficiency greater than 80% device yield increased from 10% to 74%**
- **Opt.Express, 2020 ; Patent :202010837660.0**

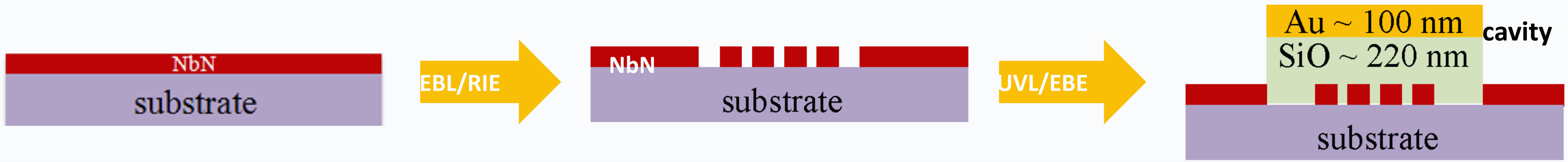
Patent: ZL201710207615.5

SUST 31, 035012(2018)

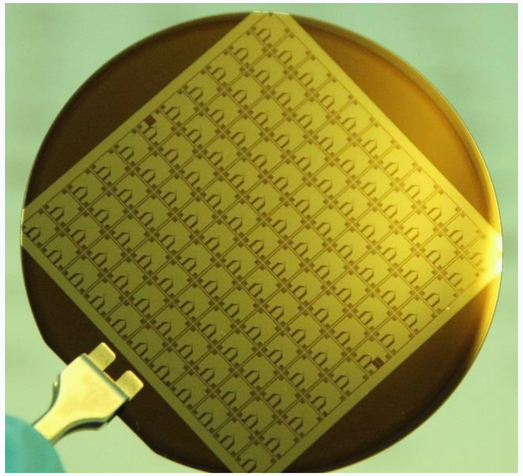
SNSPD Fabrication Process Development

Main Fabrication process

Electrode Fabrication → Define nanowire → Define active area → Opical cavity fabrication → Dicing



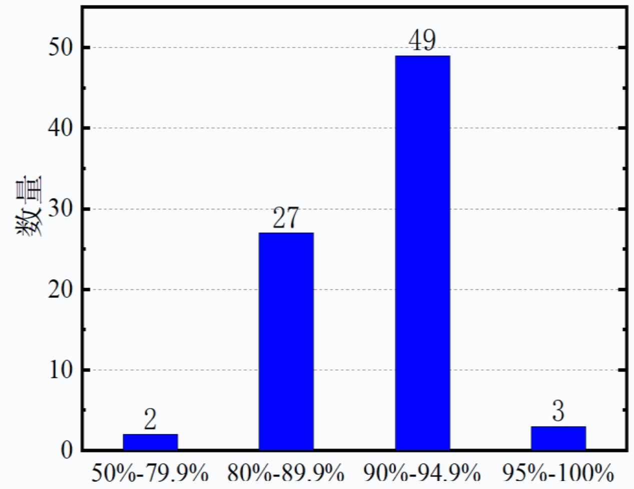
High fabrication yield



Image@2inch wafer

92	不饱和	89	不饱和	88	88	x	94	x	x
82	77	73	不饱和	90	86	93	90	x	86
不饱和	84	不饱和	91	87	91	87	87	92	x
多模	93	90	92	87	92	90	94	87	91
93	90	92	93	90	89	95	91	88	94
92	90	x	95	88	92	94	92	88	93
93	91	86	93	87	x	退化	89	88	91
多模	91	94	91	93	90	90	90	89	91
不饱和	91	x	91	82	89	93	91	89	93
88	多模	91	84	90	89	x	91	91	95

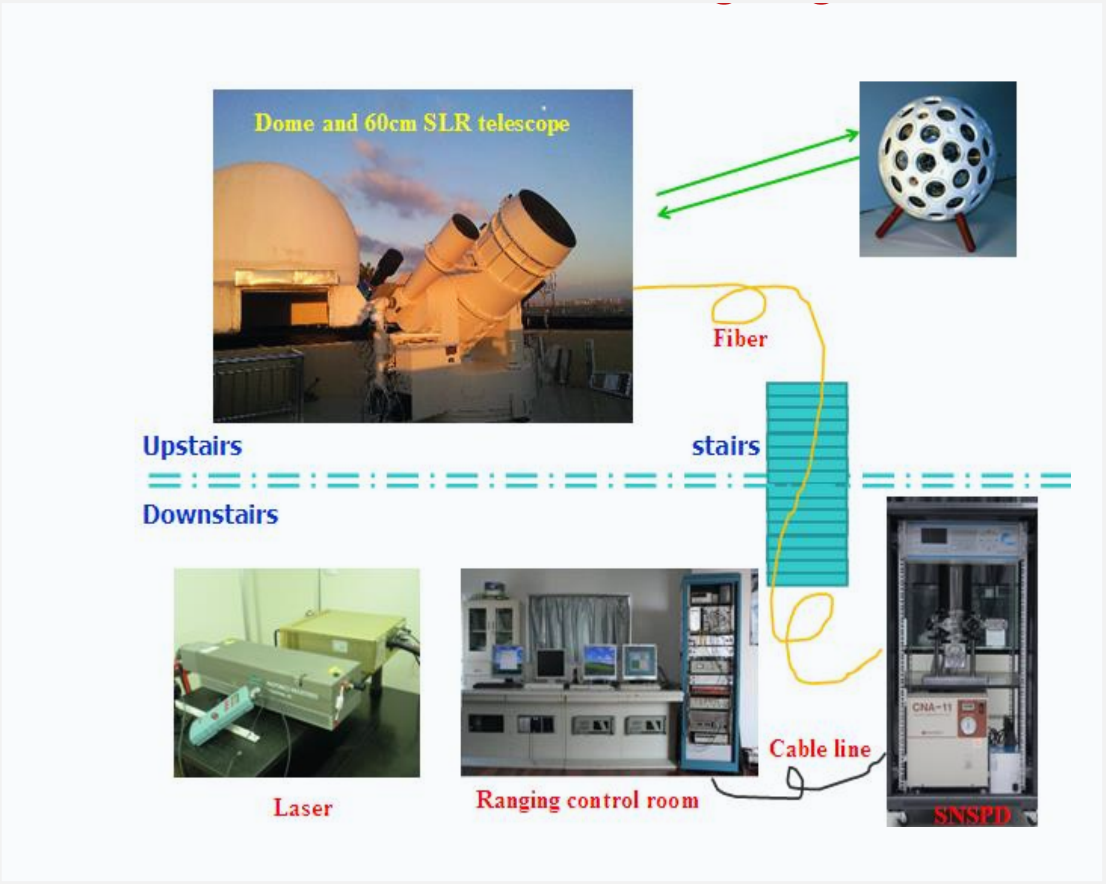
SDE@2inch wafer



SDE distribution

SNSPD Applications: LIDAR

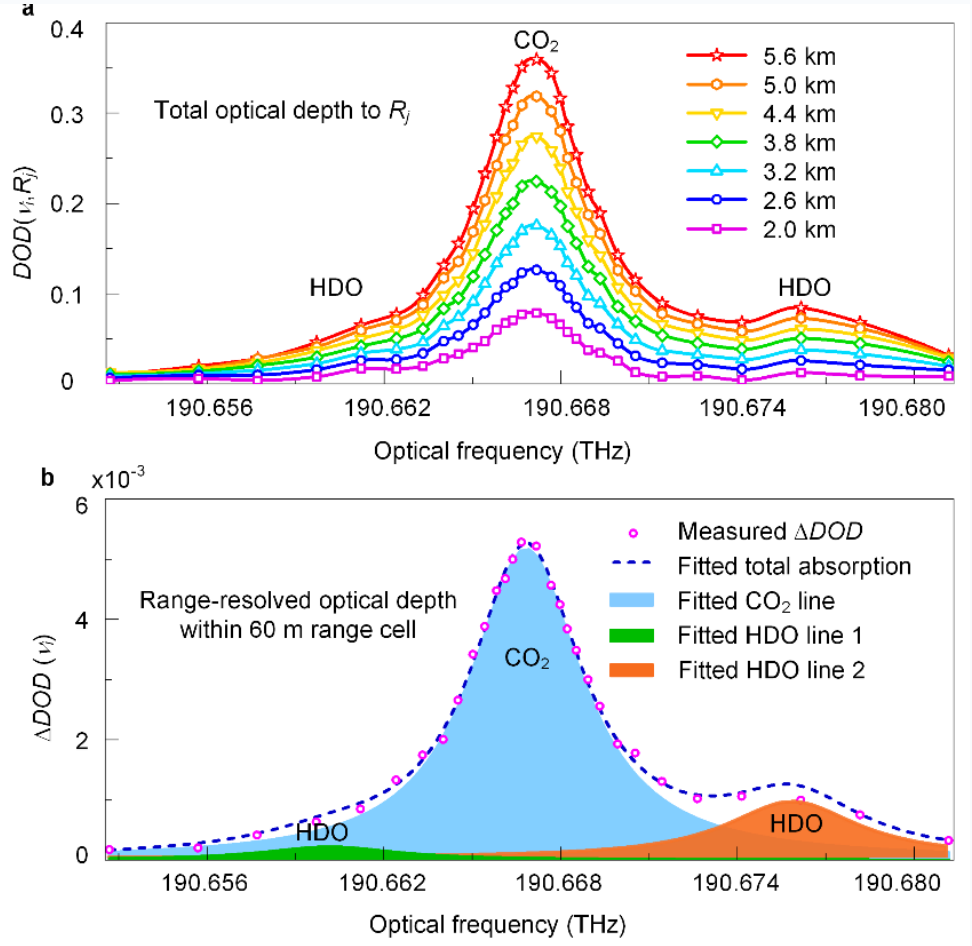
Satellite laser ranging



OE 24 3535 (2016)

1. 2016：3000 km, LARES SLR，Resolution of 8mm。
2. 2017：20,000km,Glonass SLR，Resolution of 2cm。

Free-space spectroscopy based on lidar



Range-resolved optical spectrum analysis（CO2...)

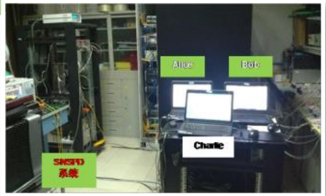
Light Sci App 10(1): 212. (2021)

Applications: Quantum Communication

2011
1. Lab based 100km QKD experiments in the chambers
2. DE (4%, NICT)

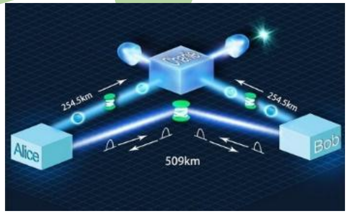
2012
1. The 100-km intercity QKD network experiment
2. DE （4%， NICT)

2013
1. 4-SNSPD ~50%, SIMIT
2. The QC experiments between Beijing and Hefei

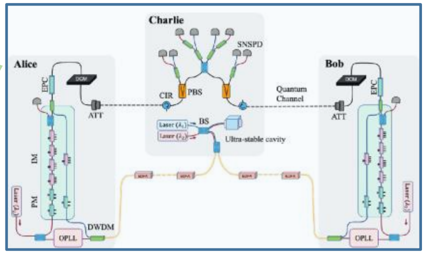


2013-14
1. 200 km MDI-QKD
2. "China's Top ten Scientific and technological Progress" in 2014

2015-16:
1. 200 km^2 MDI-QKD network
2. 400 km MDI-QKD



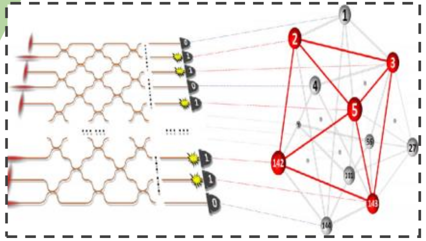
20-22 years
1. > 600 km TF QKD
2. Free-space MDI QKD



2023
1. > 1000 km QKD,
2. > 100Mcps QKD
3. Free-space MDI QKD

Collaborated with JW Pan
- PRL 113: 190501. (2014)
- PRX 6, 011024 (2016).
- PRL 117: 190501. (2016)
- PRL 123: 100505. (2019)
- PRL 124: 070501. (2020)
- PRL 125: 260503. (2020)
- Nat Photon 14: 422. (2020)
- PRL 126: 250502. (2021)
- Nat Photon 15: 570. (2021)
- PRL 128: 180502. (2022)
- PRL 130, 210801 (2023);
- PRL 131, 100802 (2023)
- Nat Photon.17,416-421 (2023)

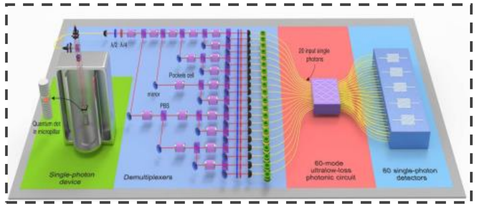
Applications: Quantum Computing



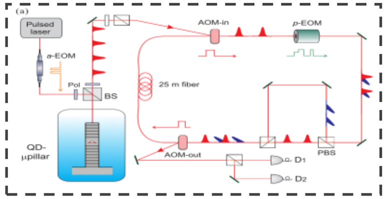
2022-23:
JIUZANG v2- v3
255 photons
Solving Graph Problems Using Gaussian Boson Sampling

2019:
20-photon Boson Sampling
(~48 qubits) (60 SNSPDs)

2020-21:
JIUZANG: 76/113 qubits
Boson Sampling
100/144 SNSPDs in 7/10 cryostats, SDE ~0.81/0.83



2018:
Scalable Boson Sampling with photon loss (13 SNSPDs)
12-Photon Entanglement and Boson Sampling (24 SNSPDs)



2017:
1st Boson Sampling using SNSPD

Collaborated with CY Lu & JW Pan
- ☐ PRL 118: 190501 (2017)
- ☐ PRL 120: 230502 (2018)
- ☐ PRL 121: 250505 (2018)
- ☐ PRL 123: 250503 (2019)
- ☐ Science 4: 070501 (2020)
- ☐ PRL 127: 180502 (2021)
- ☐ PRL 130, 190601 (2023)
- ☐ PRL 131, 150601 (2023)

Spin-off Companies

漫迪医疗
CSHMEDI

Key Products

MCG，fMCG

CFDA approved

赋同量子
—PHOTEC—

Key Products

SNSPD systems
No.1 market share
in China

上 海 赋 同
Micro Magnetic

Key Products

Geophysical
prospection services

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 56, March 2024. Plenary presentation given at ACASC 2023, 31 Oct. 2023, Shanghai, China

Summary

- Superconductive sensors/detectors have played indispensable roles in many applications requiring extremely high sensitivity.
- SIMIT has developed a series of SNSPDs which have demonstrated superior performance advantages in quantum efficiency, dark count rate etc. The detectors have been successfully used in photon based quantum key distribution and quantum computation etc.
- SIMIT has developed a series of SQUID sensors which are successfully used in bio-imaging, ultra low field magnetic resonance imaging and geophysical prospection.
- SIMIT has developed China's first superconductive VLSI fabricating lines, which is used for developing superconductive sensor/detectors, digital circuits and quantum circuits. We welcome colleagues from home and abroad for scientific collaborations.

Acknowledge

XIE Xiaoming
Team Founder

WANG Zheng
Chief Scientist

YOU Lixing
Dean
SNSPD

REN Jie
Vice Dean
SFQ design

LIN Zhirong
Quantum
Computation

PENG Wei
Fab Manager

Thanks for your attention.