Perspective of development of superconducting detectors and electronics in Poland

Krzysztof Pomorski

AGH

kdvpomorski@gmail.com

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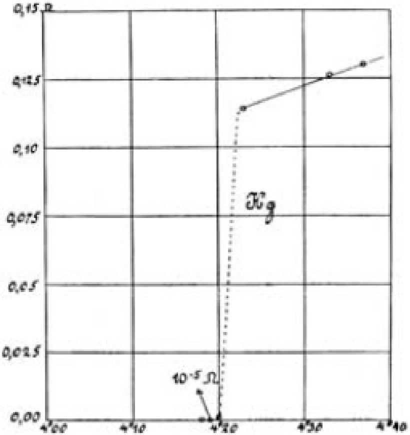
Overview

1. Short introduction to superconductors

2. Josephson effect

Discovery of superconductivity



: Fig. 1. Kamerlingh Onnes' measurement of the resistance of a mercury sample denotes the detection of superconductivity in the year 1911.

Meissner effect

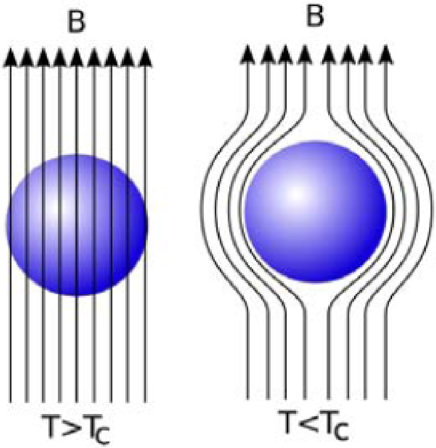


Fig. 2 . A superconductive ball, cooled down in an external magnetic field. For T < Tc the magnetic field B is expelled from the sample.

From Drude semiconductor model to superconductivity

In case of semiconductors we use Drude model given as $j = c_1 E$.

We introduce vector potential as $B = \nabla \times A$.

In such case $E = \frac{dA}{dt} - \nabla V$, where V is scalar electrostatic potential.

In case of superconductors in London limit we have $j = c_2 A$.
London model can be obtained when relaxation constant goes to infinity so $\tau \to +\infty$.

Usually the higher is the τ there is less defects occur in material. Electrons or holes are scattered on those defects.

High relaxation constant means the existence of order in the system!!!. It is the order due to existence of Cooper pairs when two electrons with opposite spin create boson.

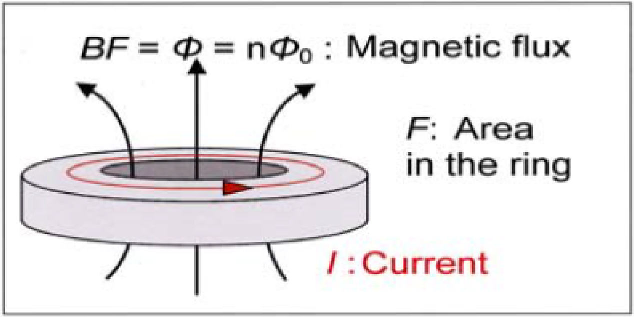
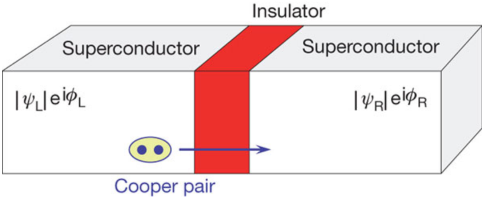


Fig. 3. In a current carrying superconductive ring the magnetic flux as product the magnetic field and the ring area is quantized in integer multiples of $\Phi_0 = h/2e$.

Josephson effect



wavefunctions $\Psi_{1,2}$ of both superconductors couple in such a way that the current $I(t)$ and the voltage $V(t)$ across the weak link are dependent on the phase difference $\varphi_2 - \varphi_1 = \varphi$ between the phases of the two wavefunctions in the following way:

$$V(t) = (\Phi_0/2\pi)\partial\varphi/\partial t \quad \text{and} \quad I(t) = I_c \sin\varphi.$$

I_c is the junction-critical current.

Figure: Tunneling Josephson junction.

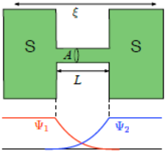


Figure: Weak link Josephson junction.

Current-voltage characteristic of Josephson junction

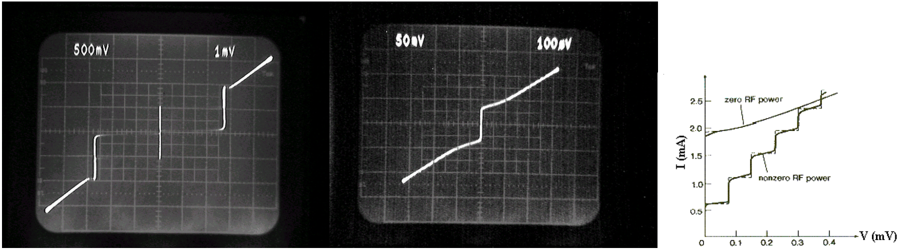
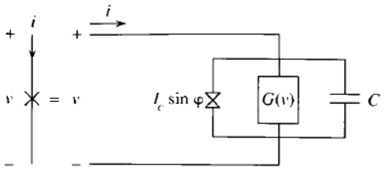


Figure: Current-voltage characteristics of tunneling and weak-link Josephson junction (without and in microwave field).

RCSJ model of Josephson junction

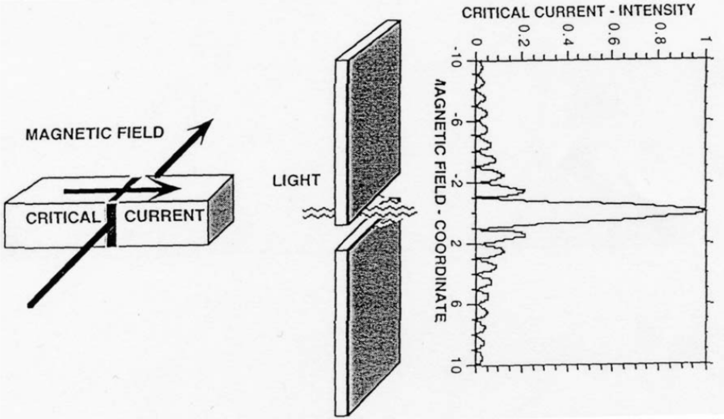


$$i = I_c \sin \varphi + vG(v) + C\frac{dv}{dt} \qquad \text{and} \qquad v = \frac{\Phi_o}{2\pi}\frac{d\varphi}{dt}$$

Therefore,

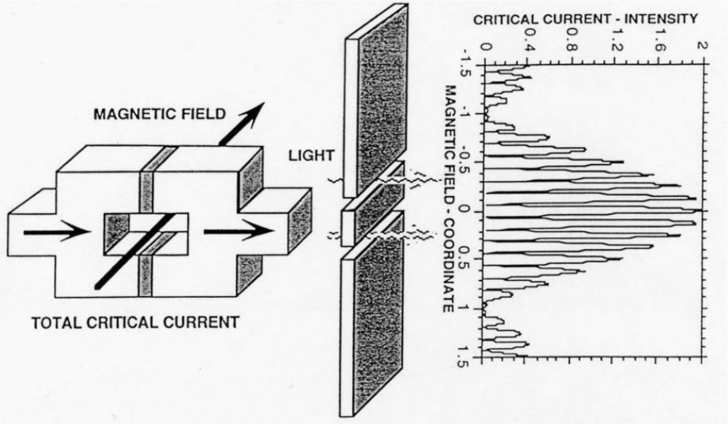
$$i = I_c \sin \varphi + G(v)\frac{\Phi_o}{2\pi}\frac{d\varphi}{dt} + C\frac{\Phi_o}{2\pi}\frac{d^2\varphi}{dt^2}$$

Josephson junction in magnetic fields

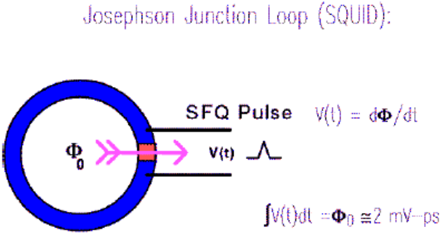


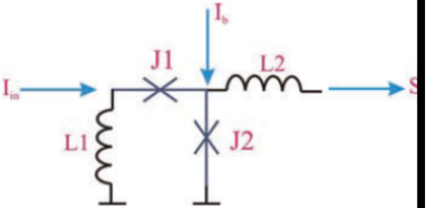
Analogy of a Josephson junction in a magnetic field and light diffracted in a single slit.

SQUID in magnetic field



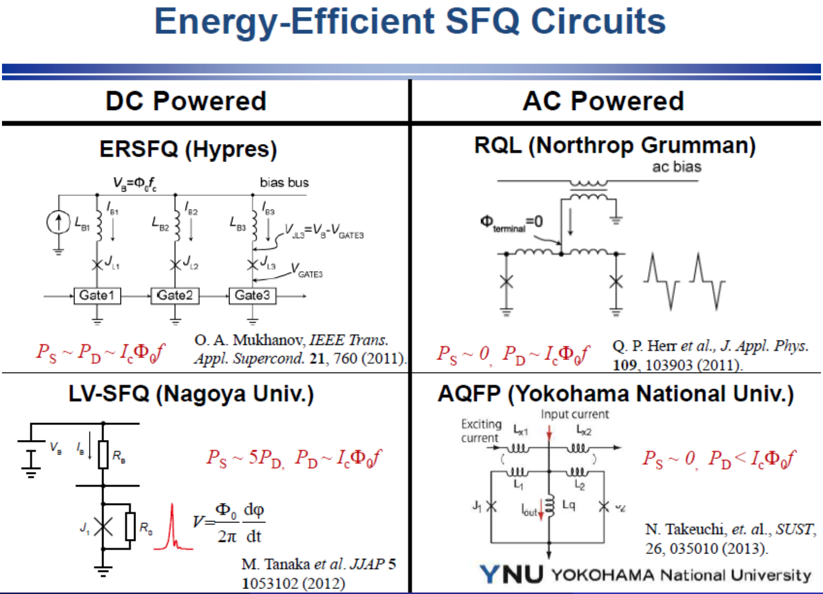
Analogy of a SQUID in a magnetic field and light interfering through two slits.

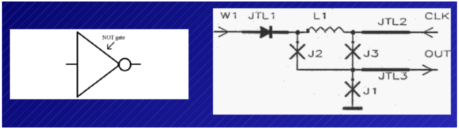




Dysypacja poniżej aJ (10^{-18} J) na operację logiczną!!! Grancia Landauera osiągnięta doświadczalnie dla obwodów o wyskiej skali integracji ($>$ 10000 JJs)!!!

Basic variants of SQF

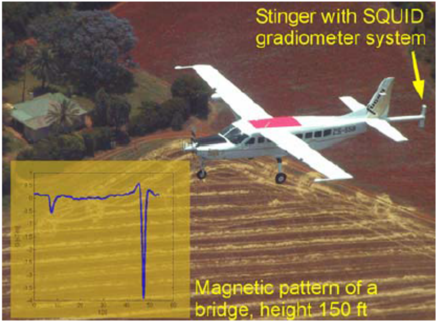



NOT gate
W1
JTL1
L1
JTL2
CLK
J2
J3
OUT
JTL3
J1

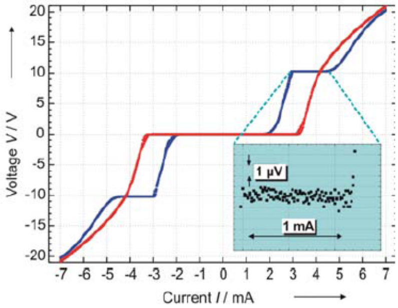
Cooling requirements for superconducting electronics

temperature	cooling power	SE application
70 - 80 K	10 - 100 mW	small HTS SQUIDs (mm^2) 10 - 20 mW; larger SQUIDs (cm^2) 50 - 100 mW;
	2-10 W	HTS filters for telecom
30 - 40 K	10 – 20 mW	digital HTS circuits with small complexity and failure tolerant, e.g. sampler and DigiSQUID
20 K	?	MgB_2 devices, however, junction technology not yet available
8 - 10 K	0.1 – 0.2 W	NbN, ADC, voltage standards, perhaps detectors
4 – 5 K	0.1 – 0.2 W	Nb-based RSFQ and voltage standards*
3 – 5 K	0.3 - 3 mW	LTS SQUIDs, SIS mixers, hot-electron bolometers, single-photon detectors.
0.1 -0.3 K	20-100 µW	transition edge sensors
50 mK	10 µW	micro bolometers
10 mK	µW	qubits (quantum computing)

* The cooling power required for RSFQ may be reduced by more advanced circuit design, see text.



. Air borne SQUID system for geophysical sounding (IPHT Jena).

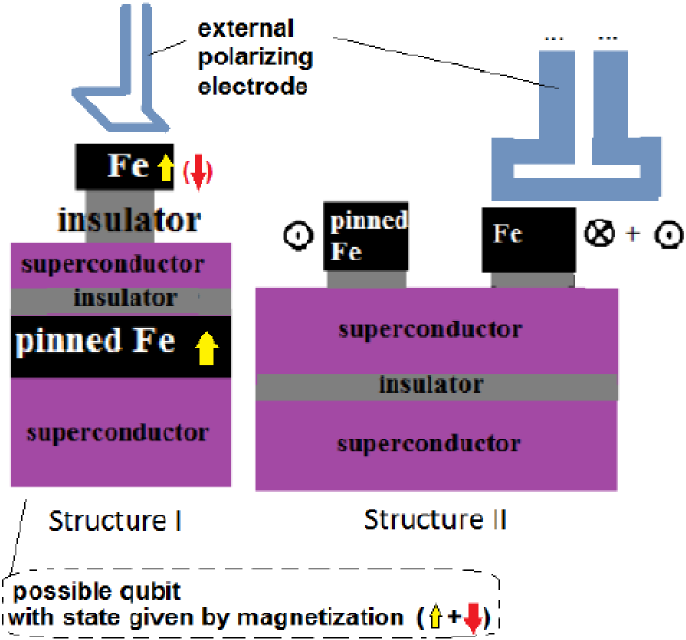


Current-voltage characteristic of a 10-V series array consisting of 69,632 SNS Josephson junctions under 70-GHz microwave irradiation. The width of the constant-voltage step is above 1 mA, which guarantees correct AC operations

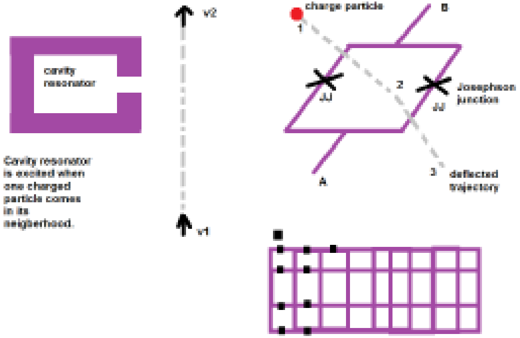
Superconducting vs semiconductor detectors

Comparison of photon counting SSPD and semiconducting APD

	Semiconducting APD		Superconducting SPD	
Detectors	Si	InGaAs	SSPD	TES
Temperature (K)	300	200	2 – 4.2	0.1
Wavelength (μm)	0.4 – 1.1	0.9 – 1.7	0.4 – 5.6	0.1 - 5
Time resolution	300 ps	300 ps	18 ps	300 ns
Quantum efficiency	70% @ 630 nm	25% @ 1.55 μm	>10% @ 1.55 μm	>92% @ 1.55 μm
Dark-count rate (Hz)	< 100	< 104	< 0.1	< 0.001
Maximum count rate	10 MHz	4 MHz	250 MHz	20 kHz
Photon number resolution	Very limited	No	Yes (limited)	Yes

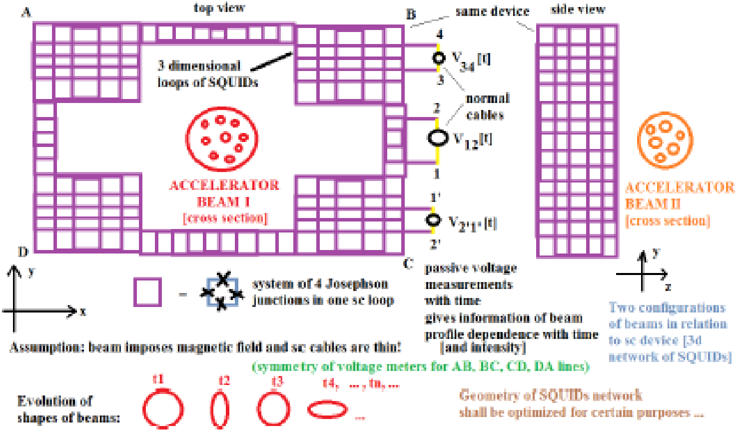

external
polarizing
electrode
...
...
Fe
insulator
superconductor
insulator
pinned Fe
superconductor
pinned
Fe
Fe
+
superconductor
insulator
superconductor
Structure I
Structure II
possible qubit
with state given by magnetization (+)

Superconducting non-invasive detector of charged particles



Principle of excitation of resonant cavity by charged particle.

Beam diagnostic tool



Possible institutions on Polish side

- Instytut Fizyki Jadrowej, PAN, Krakow
- Instytut Ceramiki i Materialow Budowlanych w Warszawie
- Instytut Technik Elektronowych w Warszawie (?) i Krakowie
- AGH, Wydzial Fizyki i Informatyki Stosowanej
- AGH, Wydzial Elektroniki, Informatyki i Telekomunikacji
- Instytut Niskich Temperatur PAN, Wroclaw
- Wydzial Fizyki UW (?)
- Wydzial Fizyki, Astronomii i Informatyki Stosowanej UJ (?)
- Technical University of Ilmenau (?)
- Politechnika Lodzka (?)

Operational targets [to be chosen ...]

- Superconducting single photon detectors (M+I)
- Superconducting neutron detectors (M + I)
- Basic logical gates in Rapid Single Quantum Flux electronics (M+I)
- High temperature SQUIDs for Geology (M+I)
- Low temperature SQUIDs for Geology (M+I)
- Superconducting RAM for RSQF electronics (M+I)
- Superconducting non-invasive detectors of charged particles (M+I)
- Scheme of superconducting satellite (M)
- High temperature superconducting sensors of Electromagnetic Radiation (I)
- Superconducting antennas and receivers (M+I)

M-modeling , I-implementation

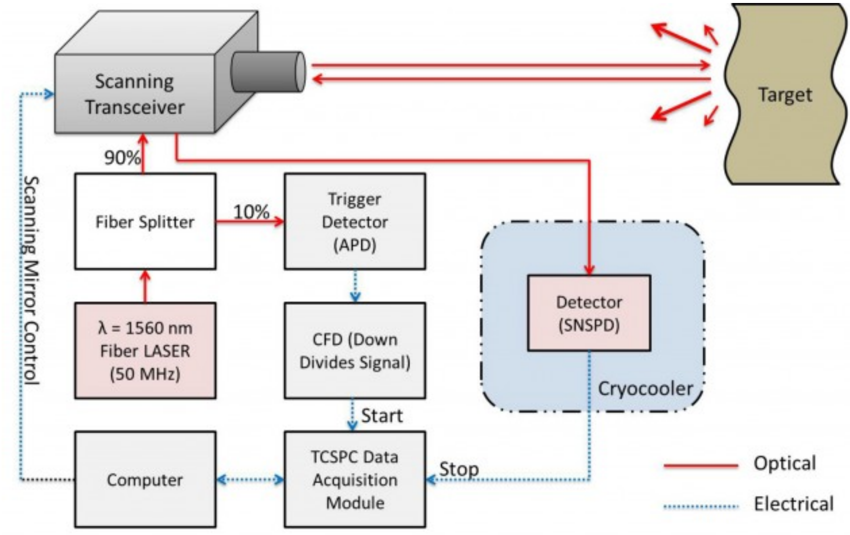
Product to be delivered

- Hardware and software platform for processing signals from superconducting detectors as in astronomy.
- Creating software for development of superconducting electronics
- Equipment and software for improvement of work of Geophysicists

Key technical aims

- Usage of lithography at ITE in Warsaw or at UW
- Integrating electronic elements
- Creation of Josephson junctions in integrated manner

Superconducting camera



References

[1]. European Roadmap on Superconductor Electronics Status and Perspectives, 2010:
http://cordis.europa.eu/docs/projects/cnect/7/215297/080/deliverables/001-SPULSE215297D1321roadmapjune2010.pdf
[2]. Applied superconductivity conference, Denver, 2016
[3]. N.Yoshikawa talk 2016
[4] A.Fujimaki, Development of superconducting processors
[5]. K.Pomorski ideas...
[6]. Superconducting RAM ...
[7]. https://www.extremetech.com/extreme/152922-superconducting-camera-can-snap-3d-photos-from-1100-ya
[8]. http://www.asiaa.sinica.edu.tw/~mingjye/dir-3/result-f.htm

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