Current Sensitivity Enhancement of a Quasi-One-Junction SQUID Comparator as an Input Circuit of SFQ Readout Circuit for a Superconducting Detector

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Acknowledgment

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The circuits were fabricated in the clean room for analog-digital superconductivity (CRAVITY) of National Institute of Advanced Industrial Science and Technology (AIST) with the Standard Process2 (STP2).

Outline

- Multiple superconductor detectors system using the single flux quantum (SFQ) signal processing

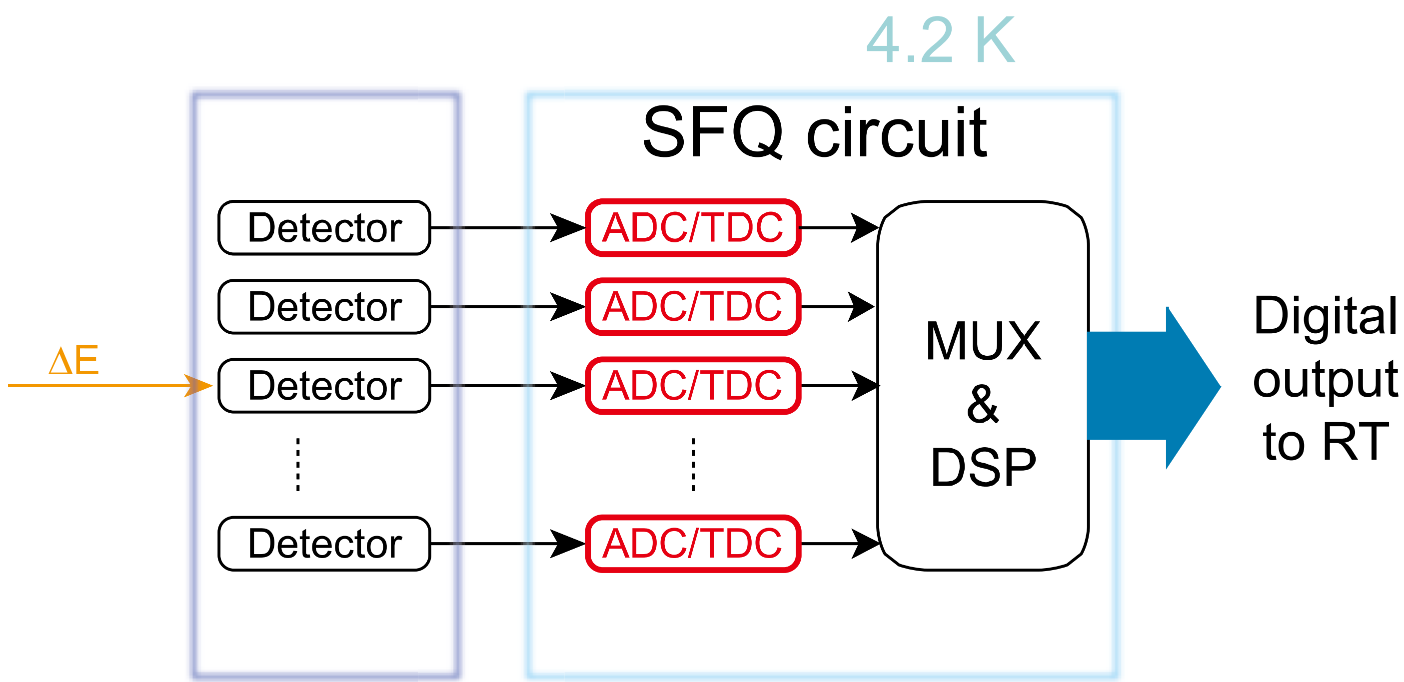
- 1-bit comparator with high-current sensitivity
  - Quasi-One-Junction SQUID

- Experiment
  - Gray zone width as current sensitivity

- Summary

Multiple superconductor detectors system

- Single flux quantum (SFQ) circuits
  - Superconductor digital circuits with high-speed operation (tens of GHz)
  - Analog-to-Digital converter (ADC), Time-to-Digital converter (TDC)
  - Intelligent signal processing
  - Large number of the input of a multiplexer by time division multiplexing



Multiple superconductor detectors system

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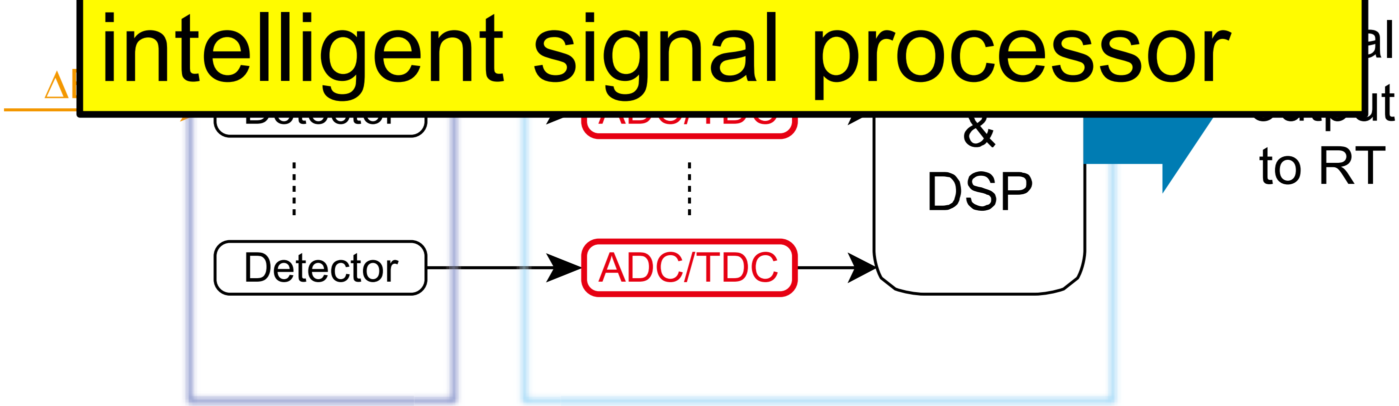
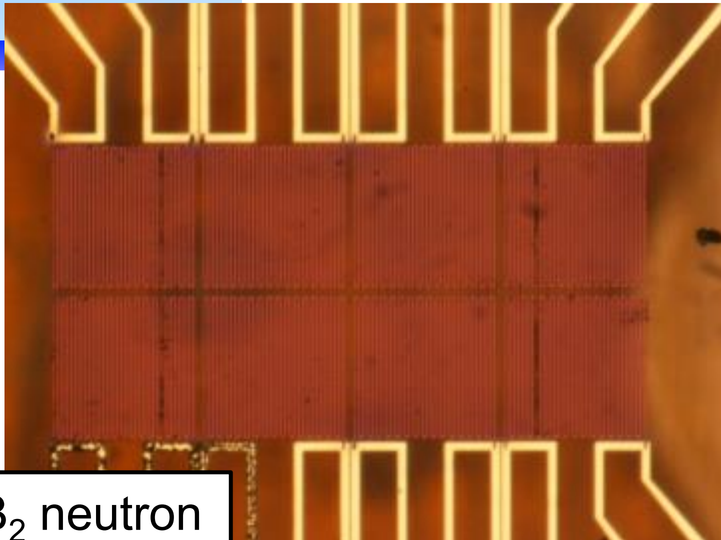
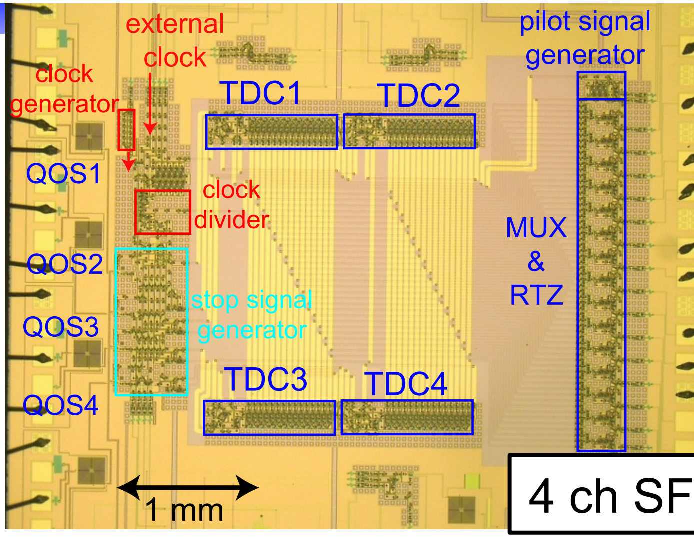
Multiple detectors system of 1000 – 10000 pixels with an intelligent signal processor



Demonstration of Neutron Diffraction System



MgB$_2$ neutron detectors

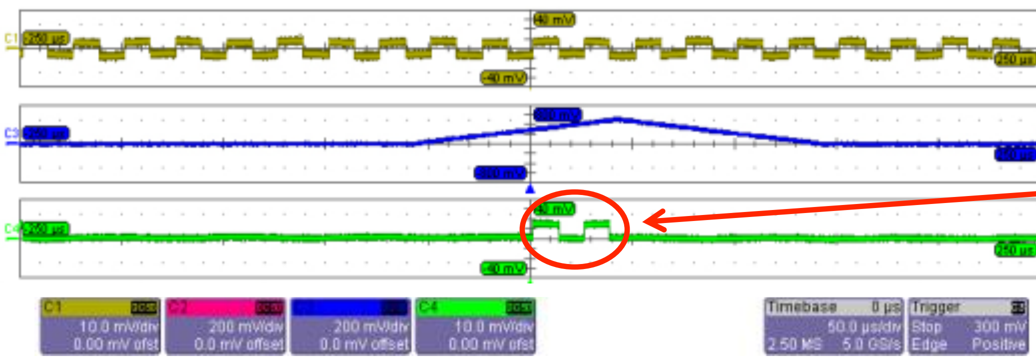


4 ch SFQ-TDC

clk_out

release for SFQ-TDC

bit 0

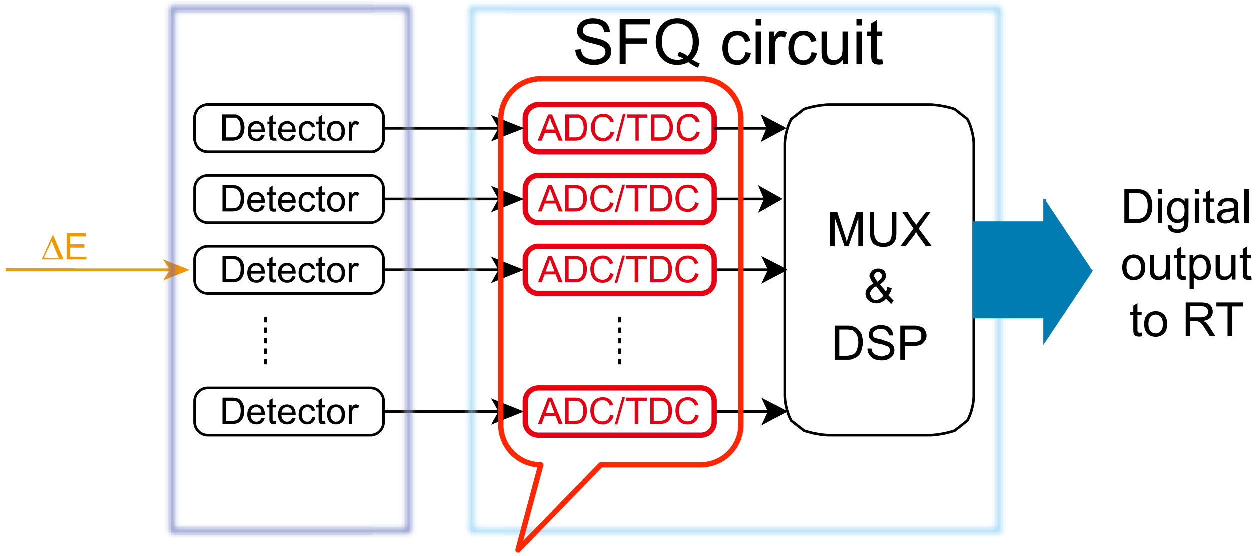


Multiplexed digital data

We have demonstrated the neutron diffraction system composed of an array of MgB$_2$ detectors and TDCs with a multiplexer based on the SFQ circuits with intelligence.

[1] S. Miyajima, *et al*., IEEE Trans. Appl. Supercond., Vol. 23, No. 3 (2013)

Purpose of this work



- Highly sensitive 1-bit comparator for currents to pick up the output signals of superconductor detectors
  - The obtained current sensitivity is 2-3 μA @ 4.2 K.
  - The magnitude of output signals of MgB_2 detectors is about 10 μA.

・The current sensitivity of less than 1μA is required for readout circuits for various superconductor detectors systems.
・Amplifier for currents using an input transformer

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- Multiple superconductor detectors system using the single flux quantum (SFQ) signal processing
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- Experiment
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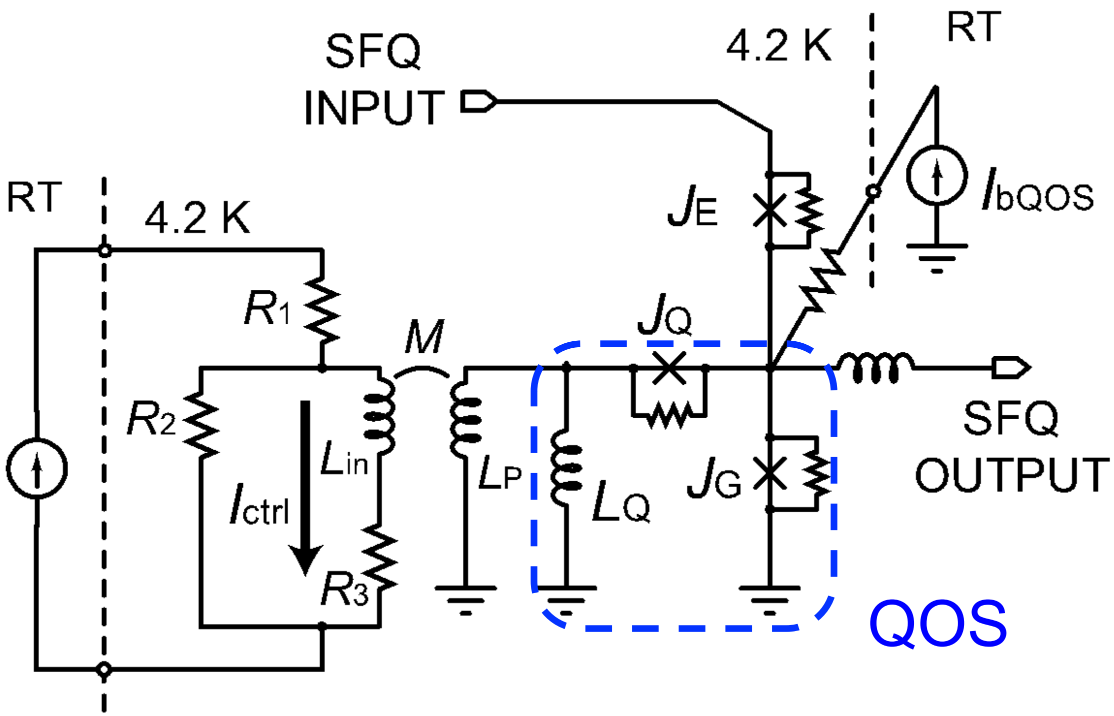
QOS comparator

- Quasi-one-junction SQUID (QOS)
  - A QOS is composed of the loop of J_G-J_Q-L_Q.
  - J_G and J_Q switch almost at the same time.
  - J_E works as an escape junction.
  - A detector is connected to a QOS comparator by inductive coupling.



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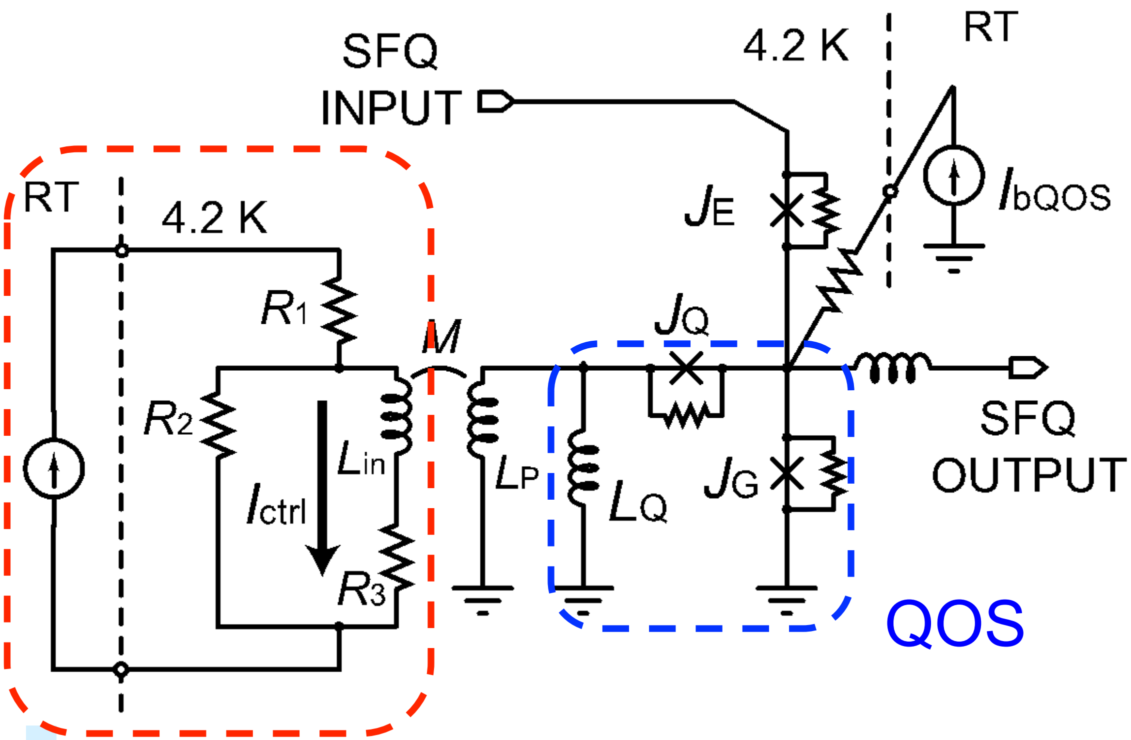
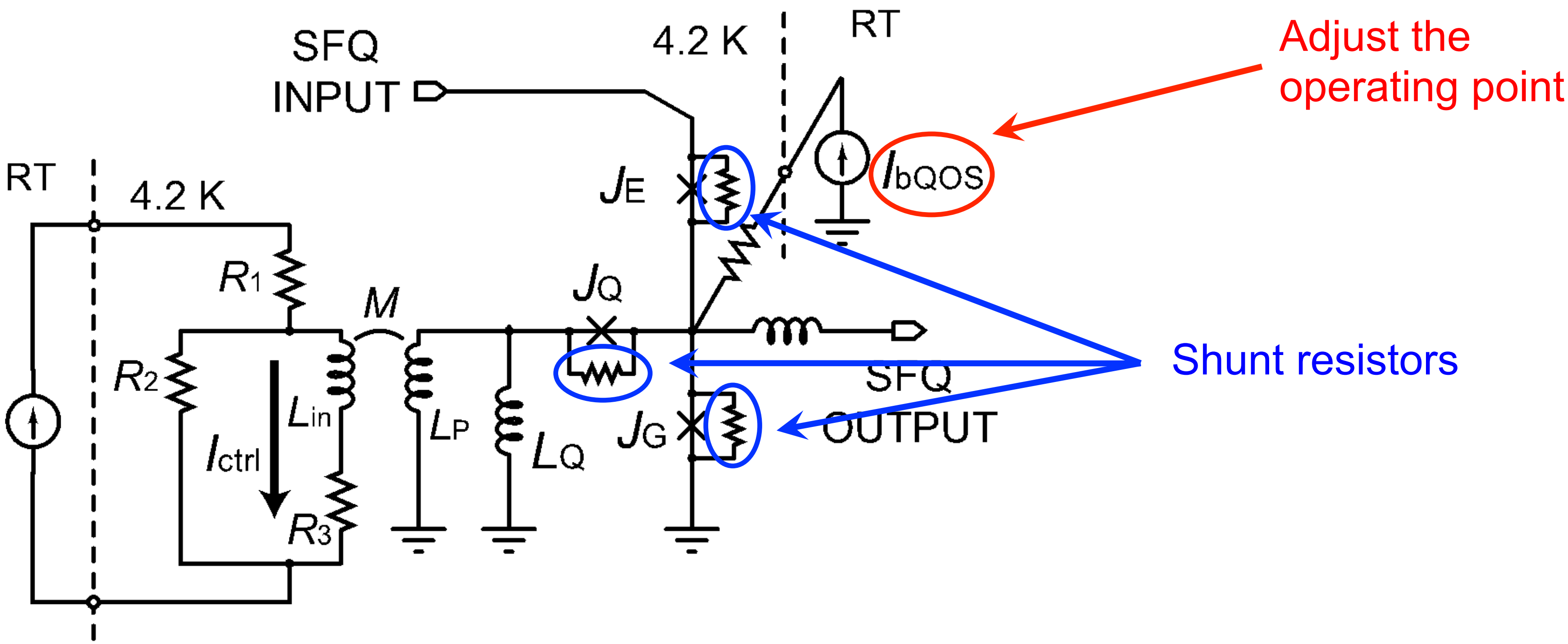


Input circuit for QOS (L_{in}:L_P = 20:1)

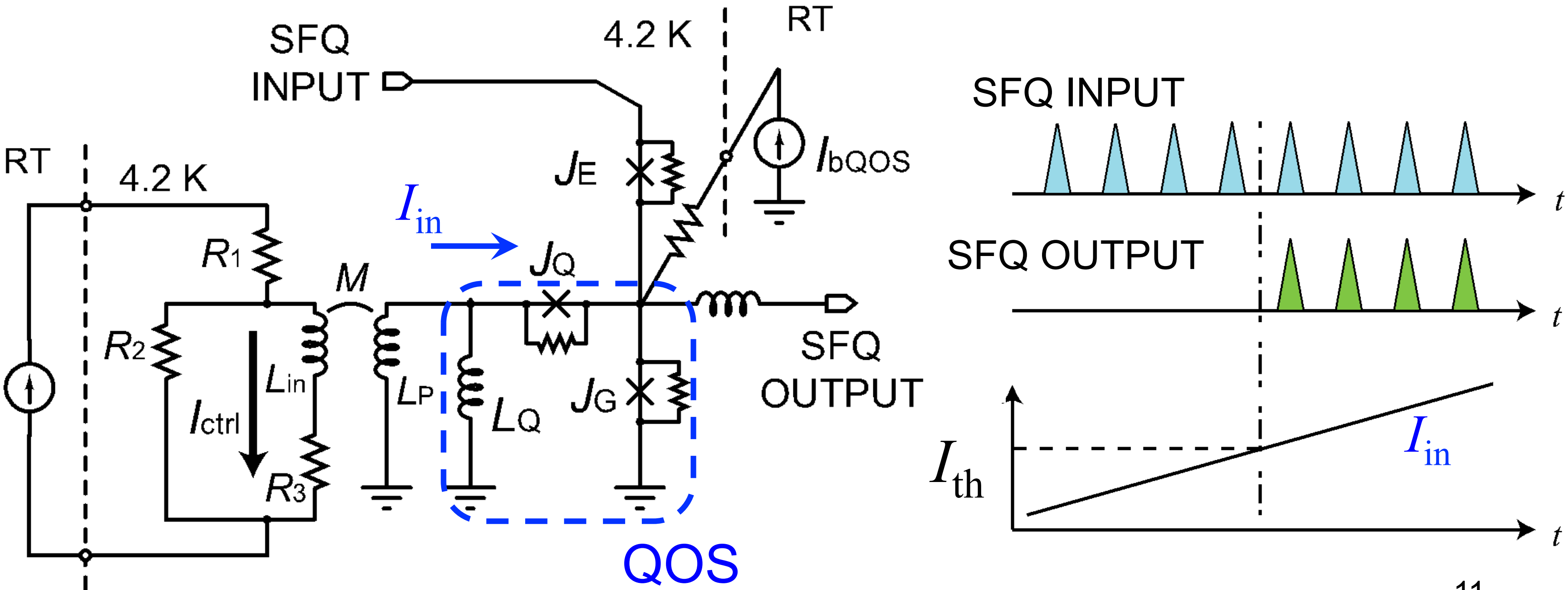
Design of QOS comparator

- An operating point is adjustable by an isolated bias line (I_{bQOS}).
- A shunt resistor is placed at parallel to each Josephson junction for the stable operation of the SFQ circuits.
  - Shunt resistors are the source of thermal noise.



Operation of QOS comparator

- Josephson junction generates the voltage pulse in switching.
  - SFQ pulse
  - Output signals of detectors supply the currents to QOS (I_{in}).
  - A QOS generates the SFQ pulses synchronized with SFQ INPUTs when the I_{in} is larger than the threshold current (I_{th}).



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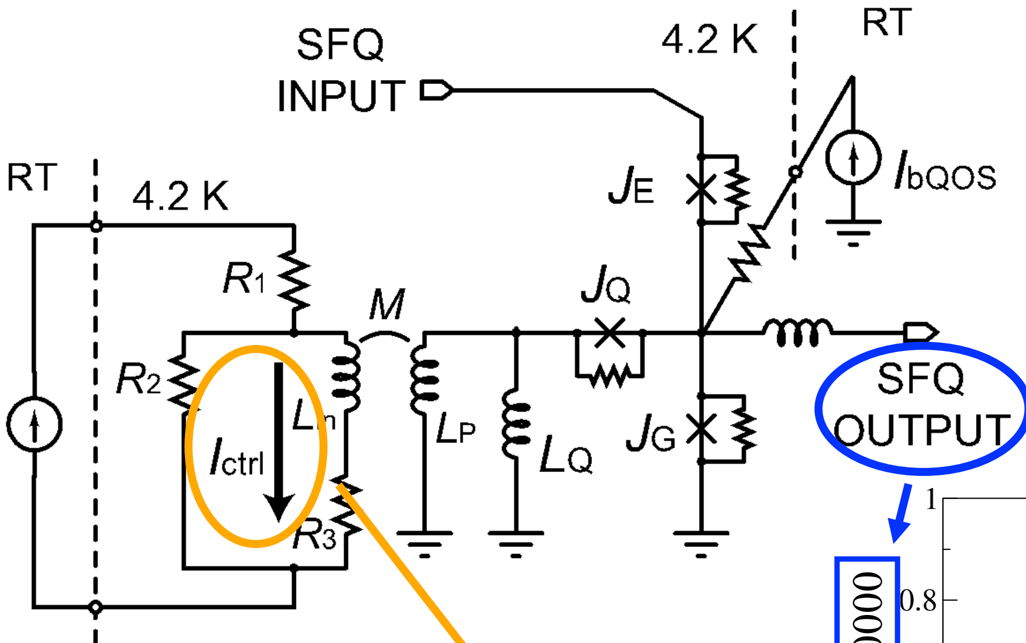
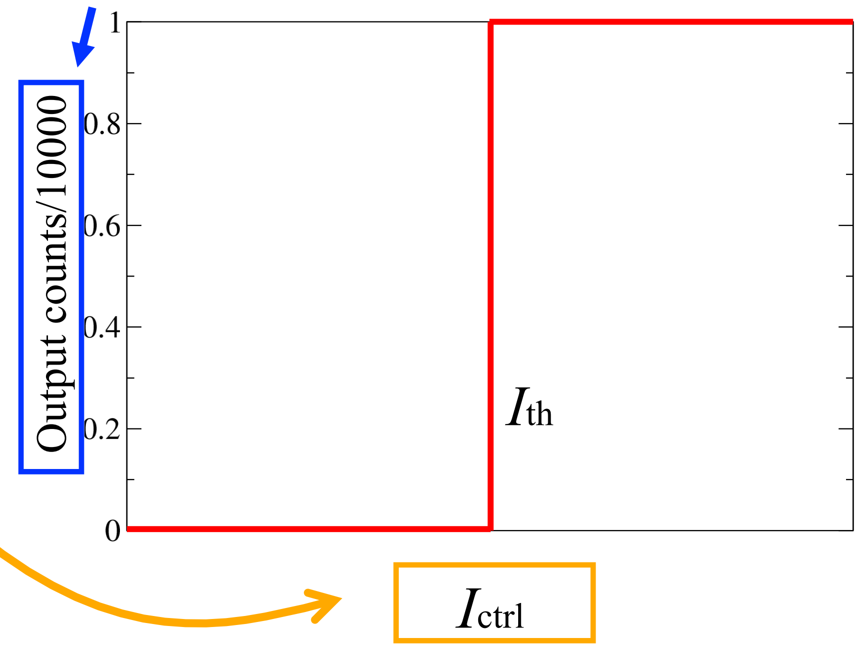
Estimation of the current sensitivity by gray zone





- The QOS generates the SFQ pulses with I_{ctrl} of larger than I_{th}.
- Thermal noise make the uncertain output region (gray zone).
- We supply I_{ctrl} by using a current source at RT.
- Trial number in each I_{ctrl} is 10000.

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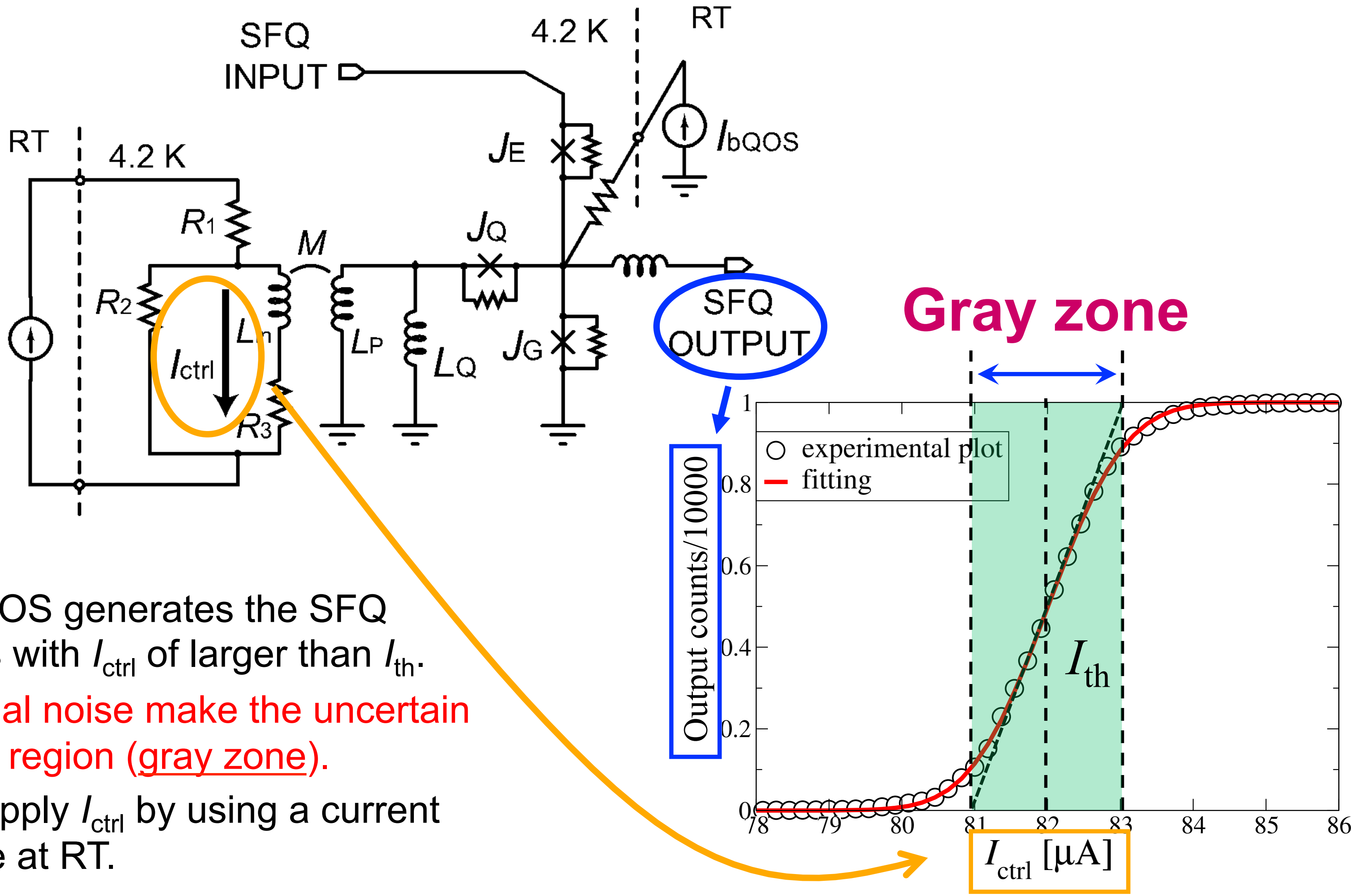

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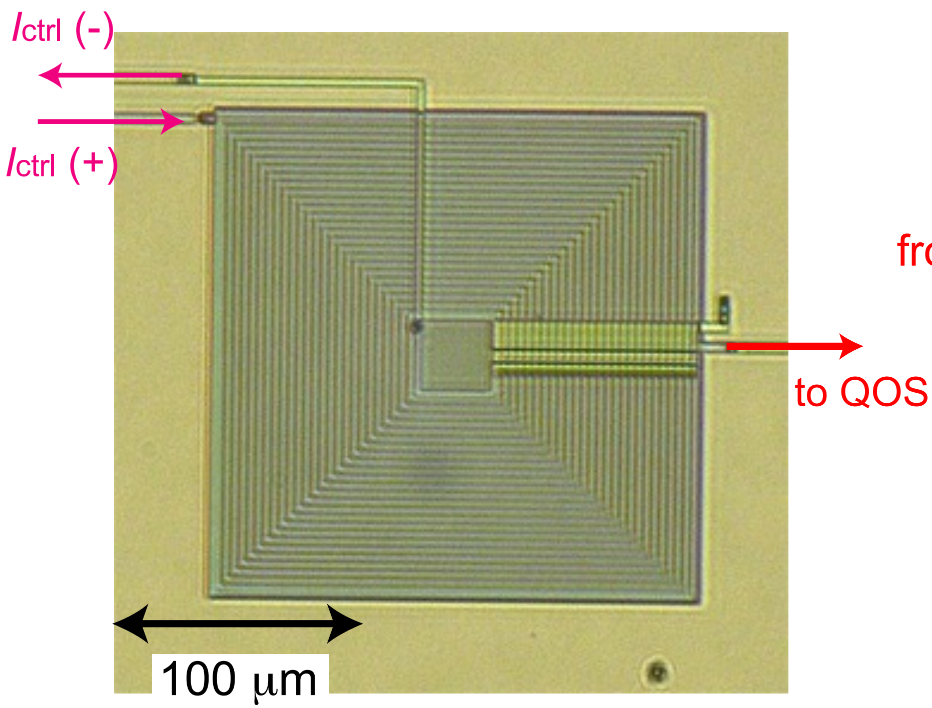
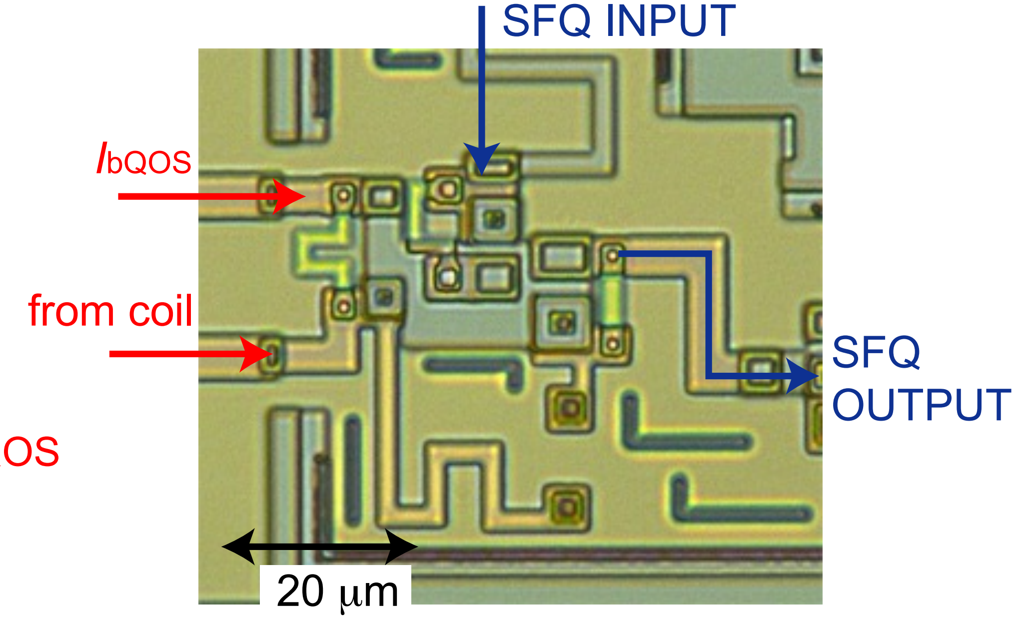
Photograph

- Input coil
  - Amplifier for currents
  - Turn ratio is 20:1

- QOS comparator

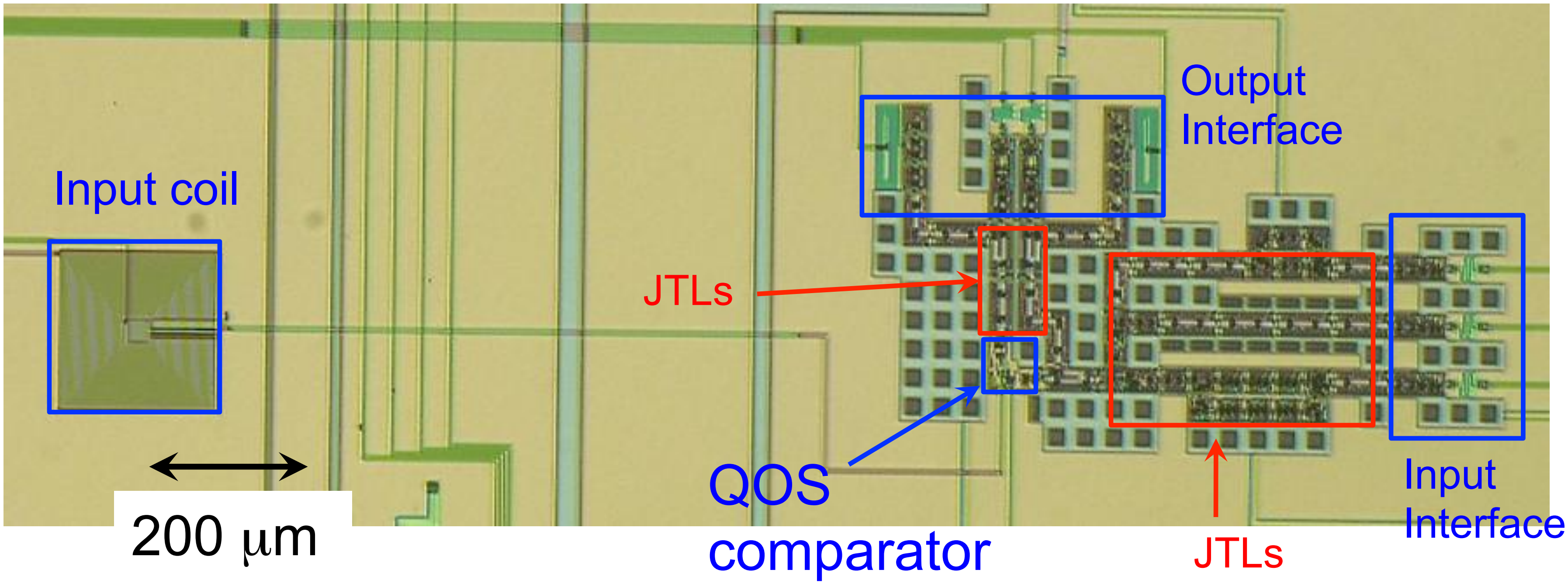




* Fabricated by AIST-STP2

Photograph

- The whole circuit of the QOS comparator including input/output interface circuits

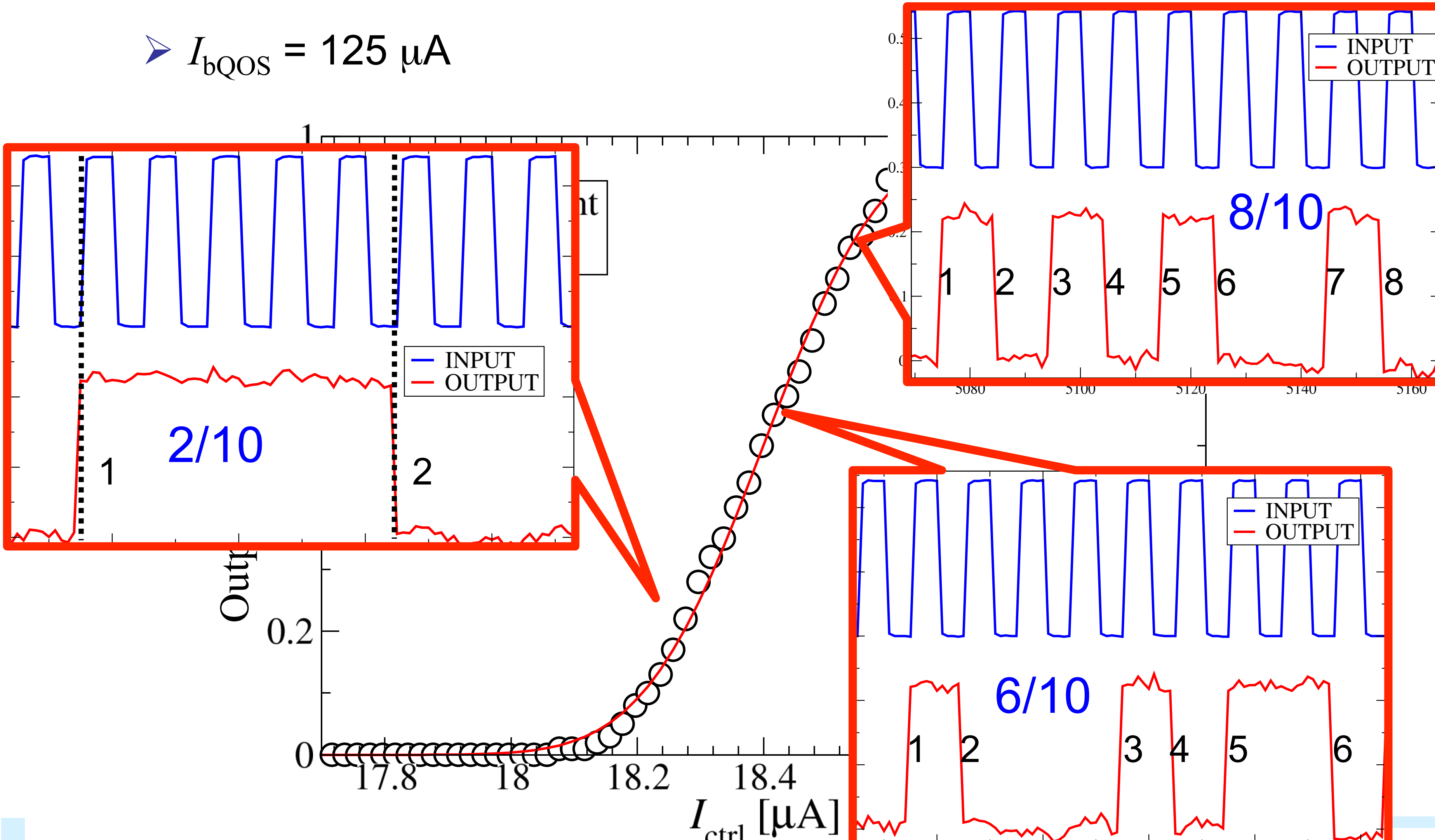


JTL: Josephson Transmission Line

* Fabricated by AIST-STP2

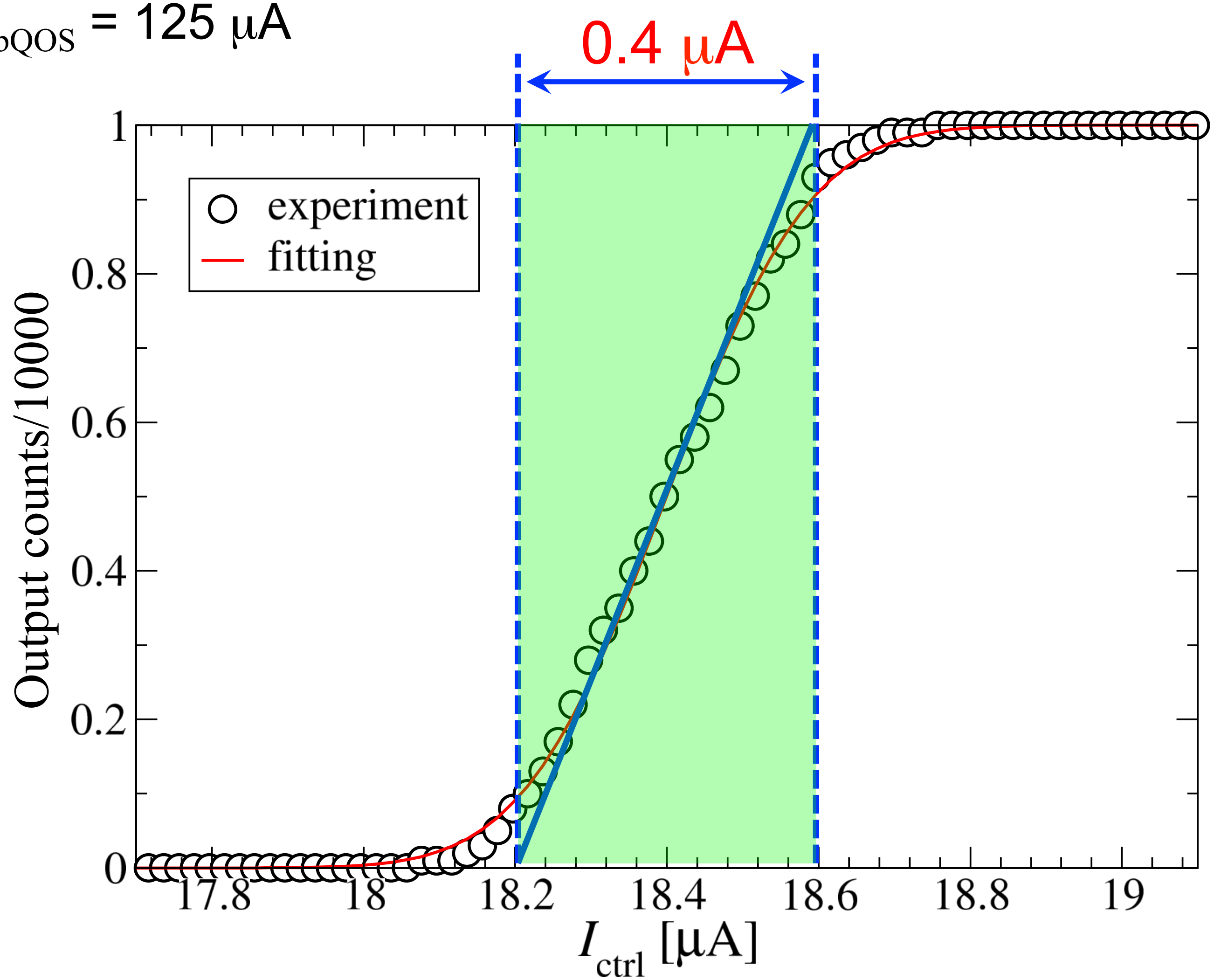
Experimental results

- I_{bQOS} = 125 μA



Experimental results

- The obtained gray zone width is about 0.4 μA @ 4.2 K.
  - I_{bQOS} = 125 μA

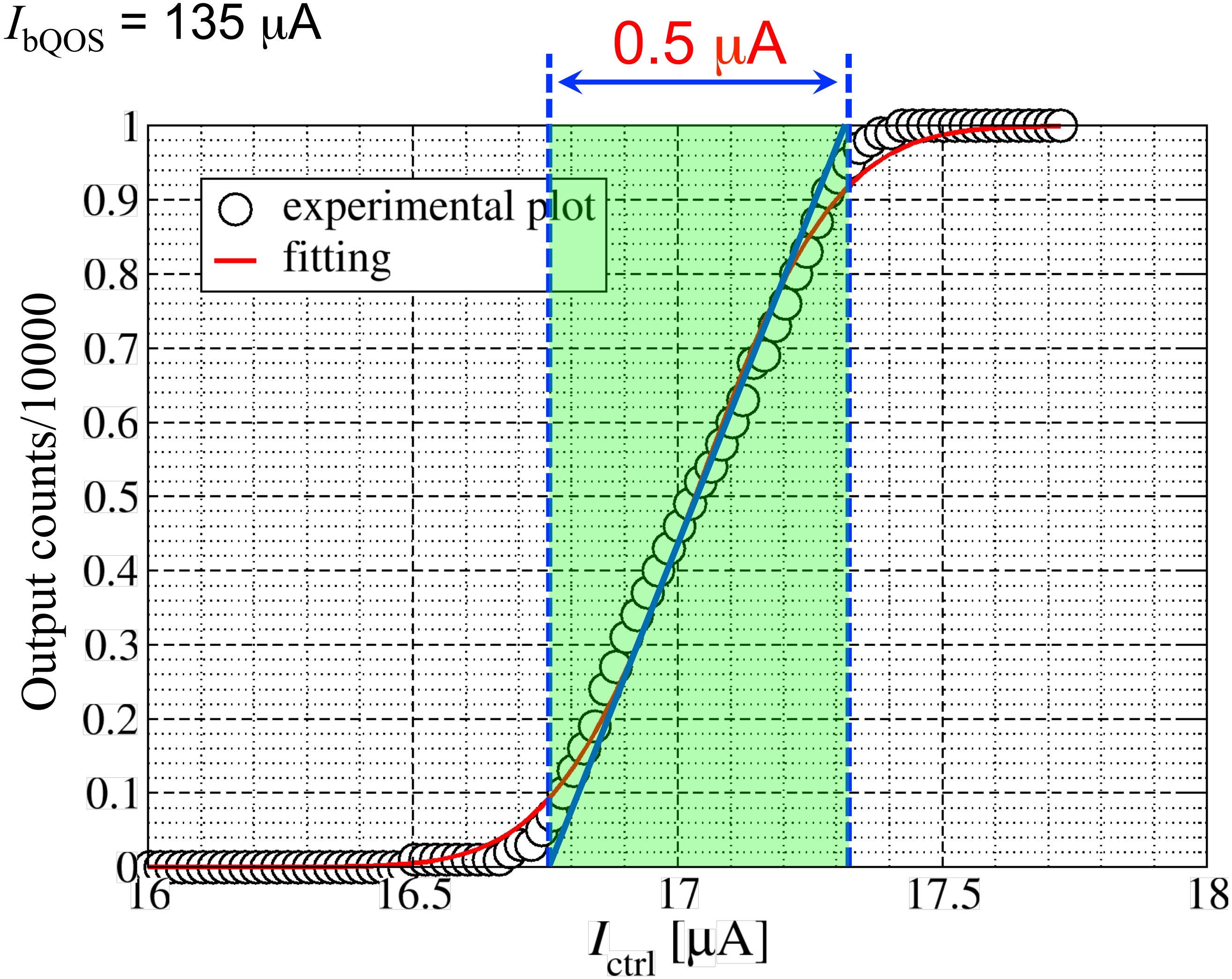


Summary

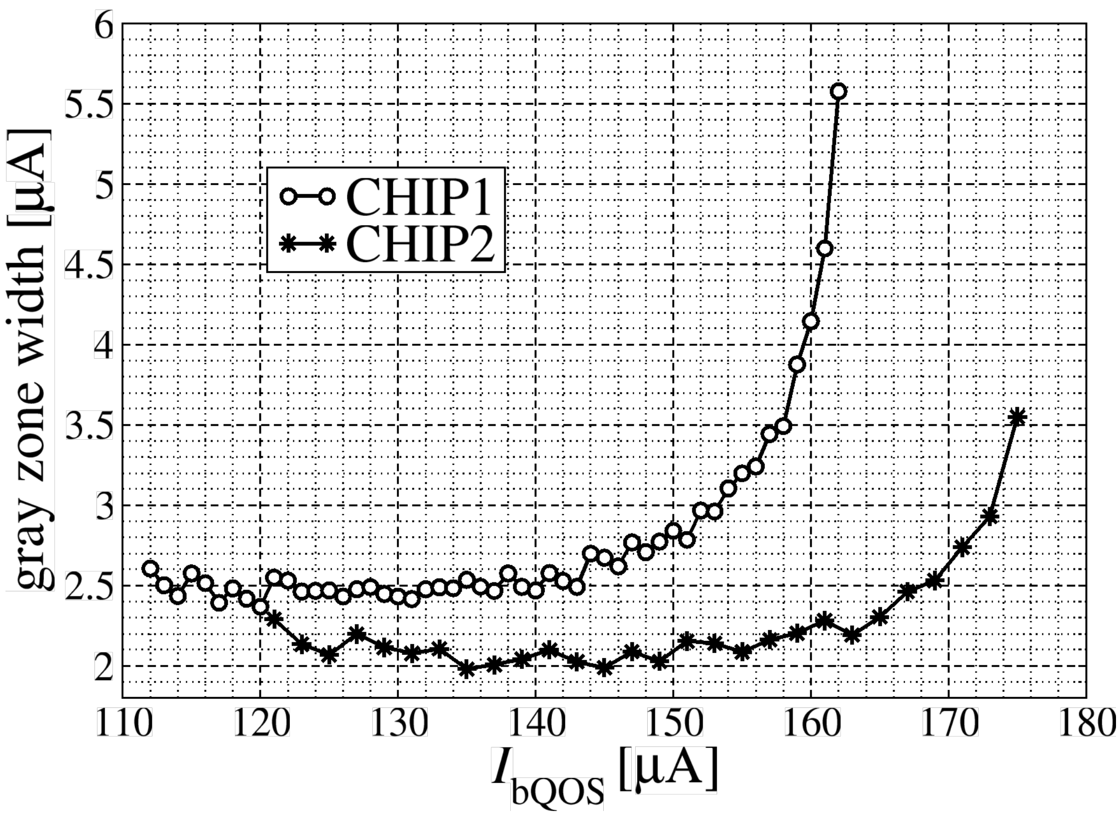
- We have developed the multiple superconductor detectors system using the SFQ signal processor.
- We designed the QOS comparator for improvement of the current sensitivity using an input transformer.
- The obtained current sensitivity is about 0.4 μA @ 4.2 K.
  - Enhancement of the current sensitivity
  - The decision time is tens of ps.
- The effective current sensitivity can be improved using the SFQ digital signal processor.
  - Likelihood discriminator (tens of nA @ 4.2 K)

Experimental results

- The obtained gray zone width is about 0.5 μA @ 4.2 K.
  - I_{bQOS} = 135 μA



Obtained Current Sensitivity

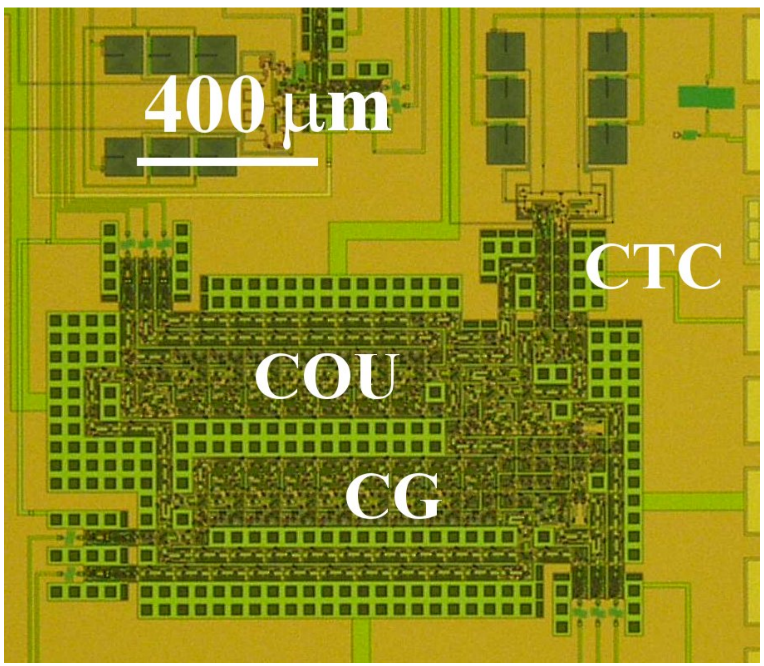


- ✓High-current sensitivity of 2-3 μA
- ✓High-speed operation of 20 GHz
- ✓Tuning free operation (wide bias current margin)

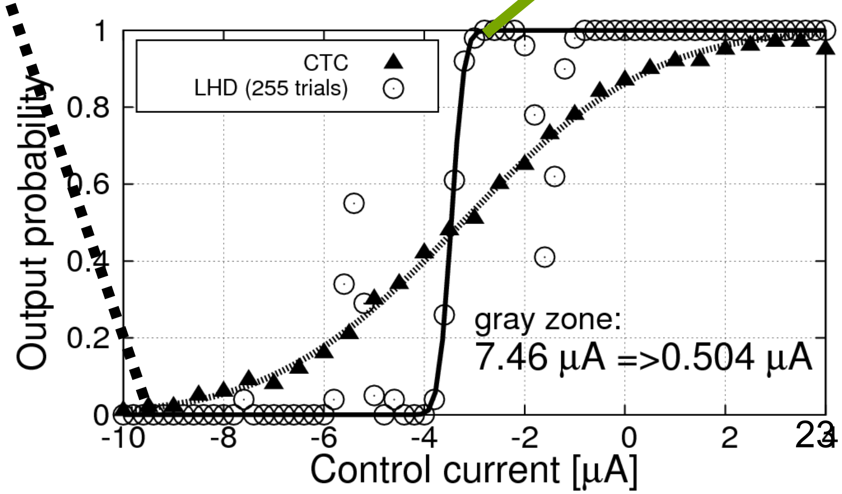
[2] S. Miyajima, *et al*., Jpn. J. Appl. Phys., Vol. 52, No. 3 (2013)

For higher current sensitivity

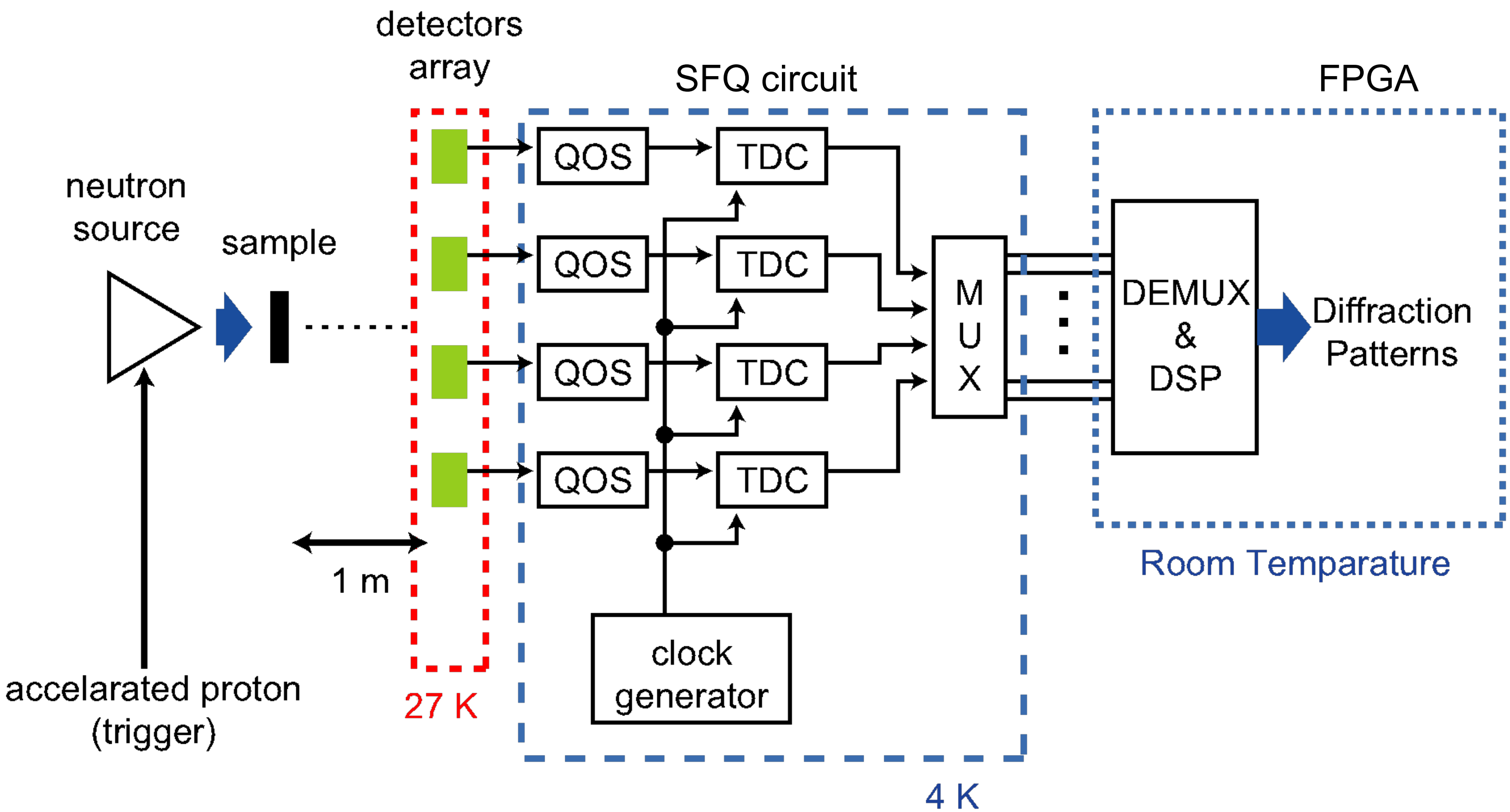
- The response time of the QOS comparators is about 50 ps.
  - Likelihood Discriminator based on the SFQ circuits can improve the effective current sensitivity with short acquisition time.



CTC 7.5 µA ⇒ **With LD** 0.5 µA



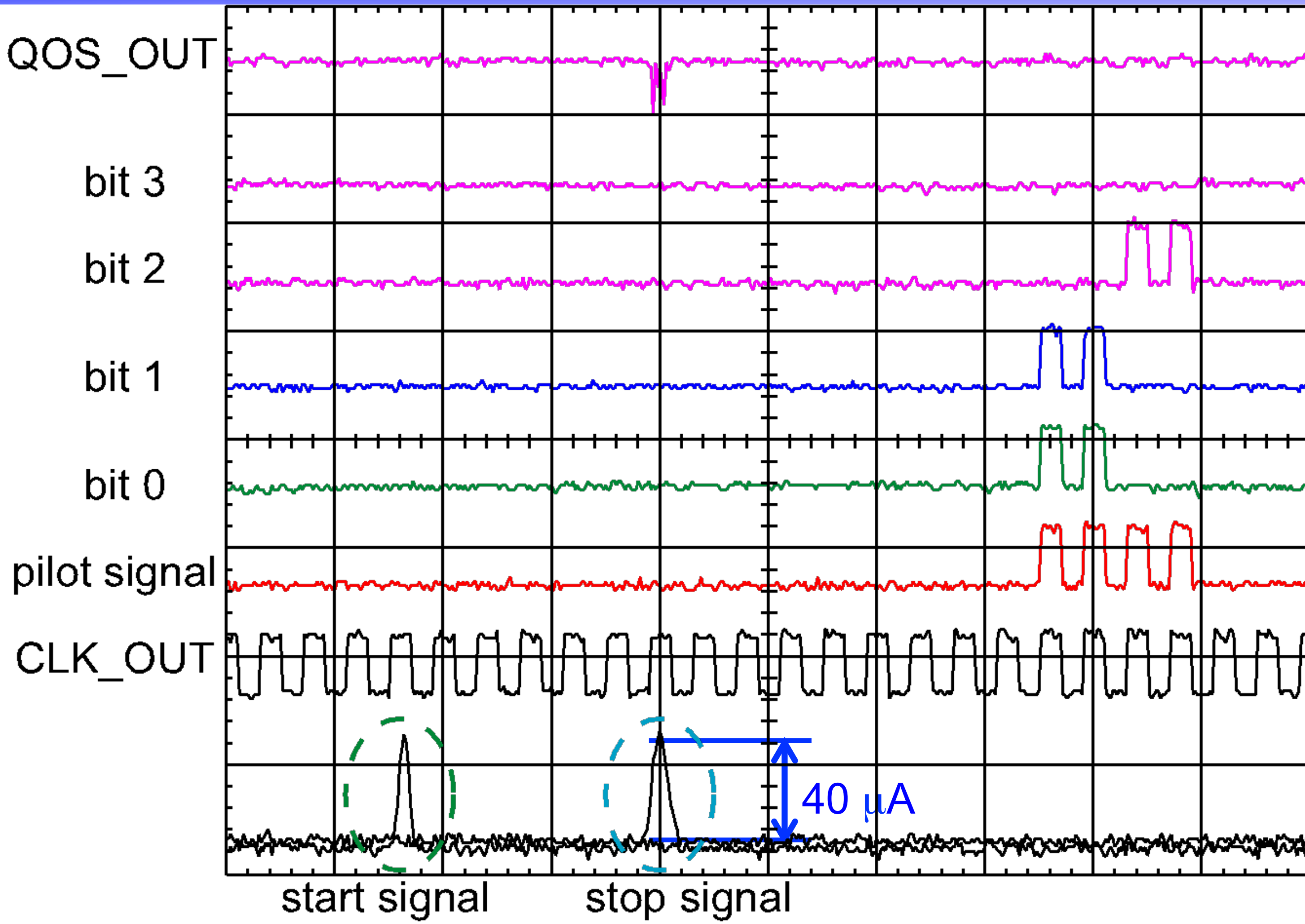
System using single-flux-quantum (SFQ) circuits



- Comparators with high sensitivity of a few μA and high-speed response
  - High sensitivity of a quasi-one-junction SQUID (QOS) meets the above.
- Time-to-digital converters (TDCs) can measure the TOF with time resolution of 10 ns.
  - High-speed nature of the SFQ circuit satisfies the above.
- Many signals should be multiplexed.
  - The SFQ circuits have potential of time-division-multiplexing of 10000 signals.

[3] A. Fujimaki, *et al.*, IEICE , vol. E94-C, No.3 (2011)

Example of observed waveform



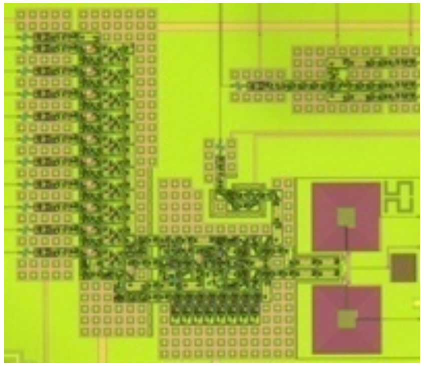
X : 500 s/div, start signal and stop signal : 50 mV/div, others : 500 mV/div

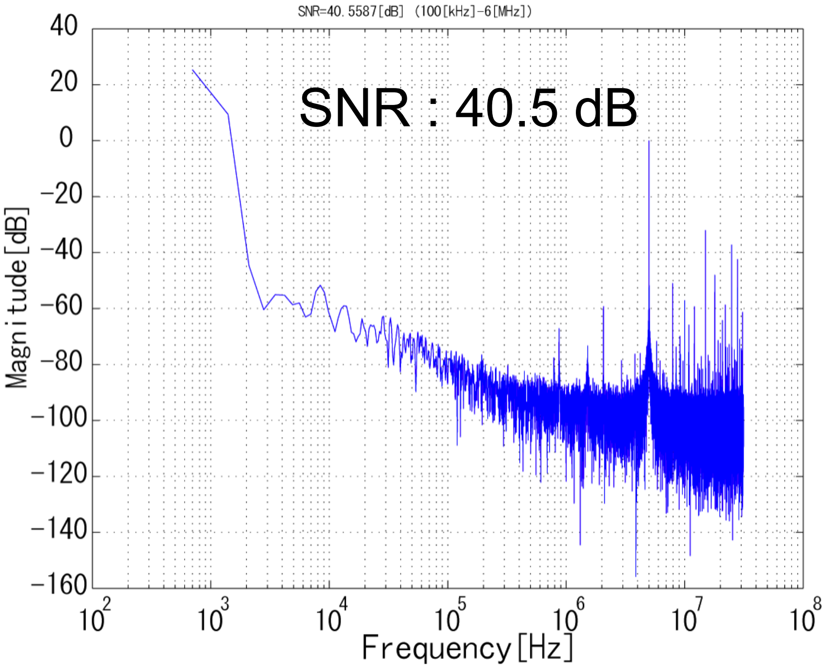
- Clock frequency is 10 kHz

Noise Power of the Prototype

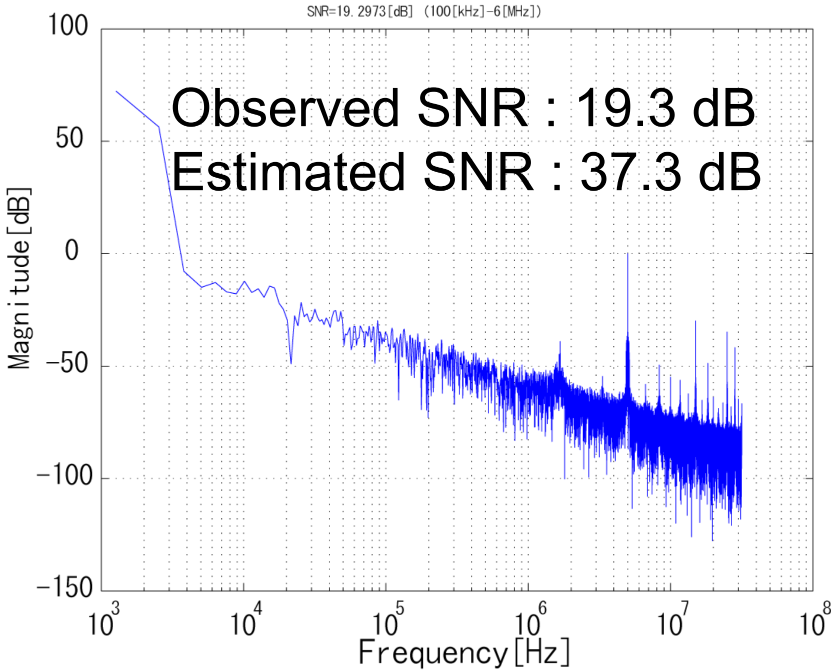
Prototype is more noisy by 40%.

Photo of ADC demonstrated here



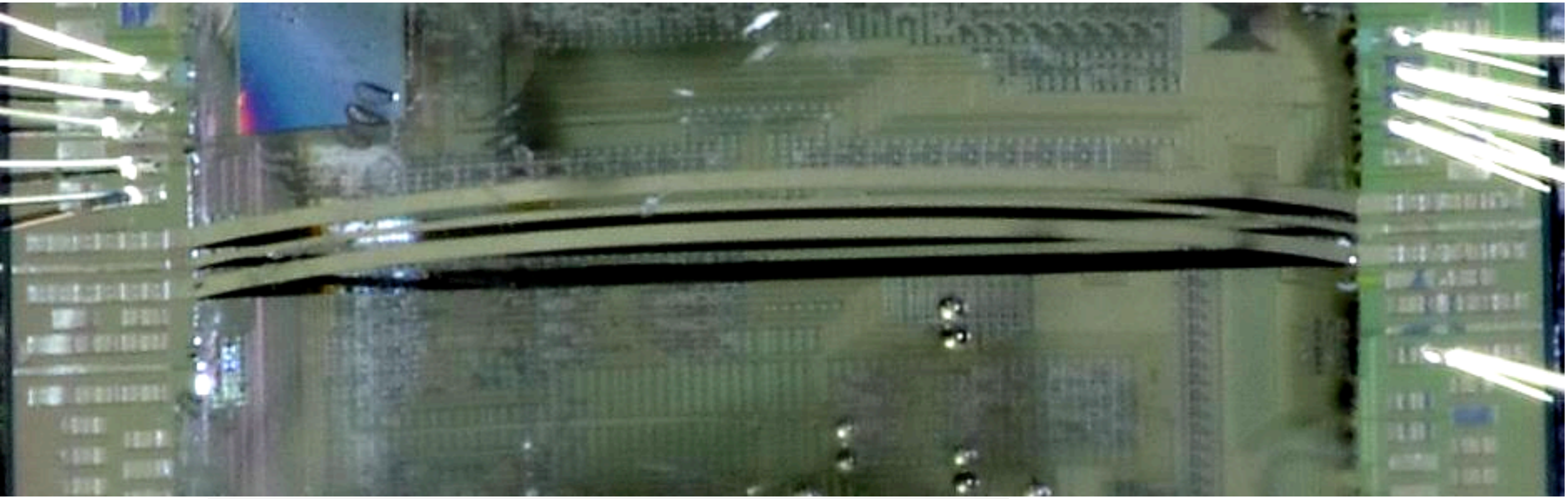


Power spectrum measured in the shielded room



Power spectrum in the cryocooler

Nb Coplanar lines

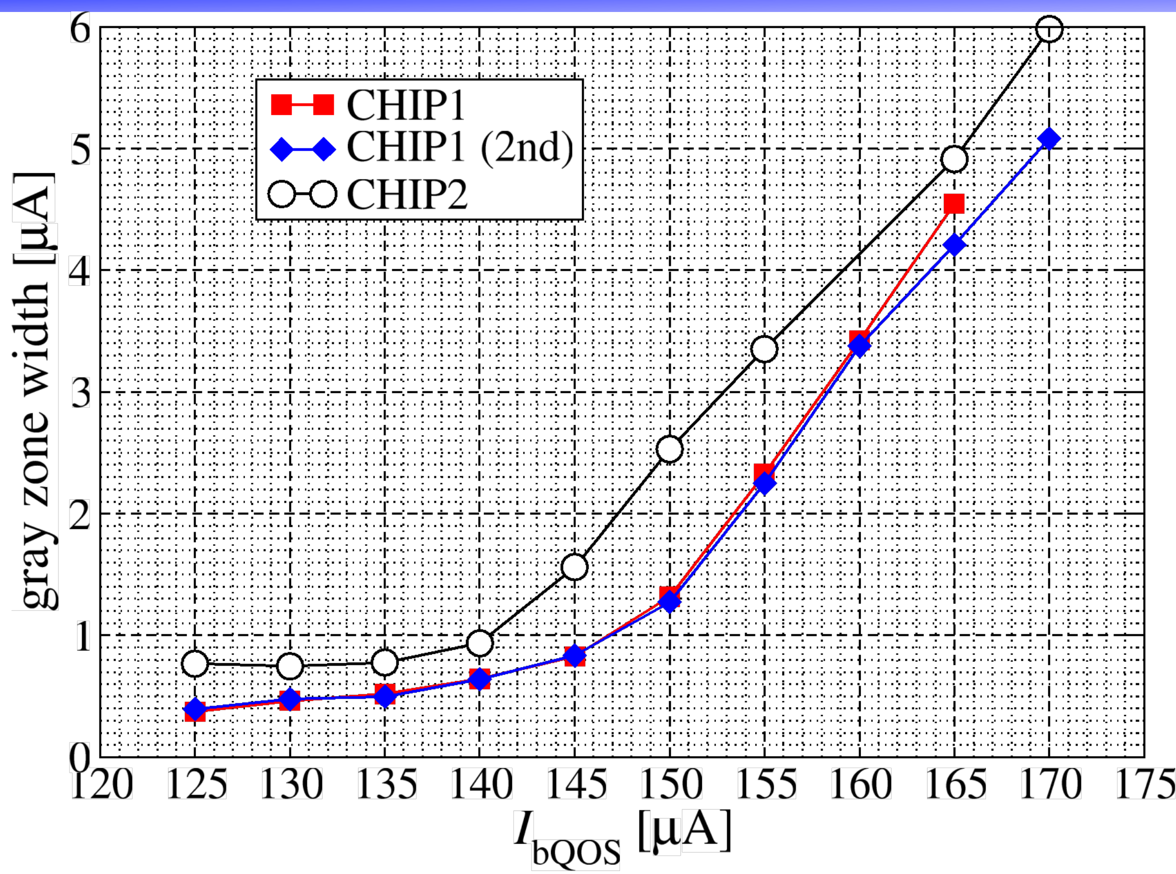


On-chip

5mm PTL

Off-chip 3cm PTL

Dependence of I_{bQOS}



- The results of 2 chips are almost same.
  - The spread of circuit parameters
- The bias current margin is not so wide.
  - The circuit parameters might not be optimized.