



# *Theory and Experimental Analysis of the sensitivity of an Adiabatic Quantum Flux Parametron*

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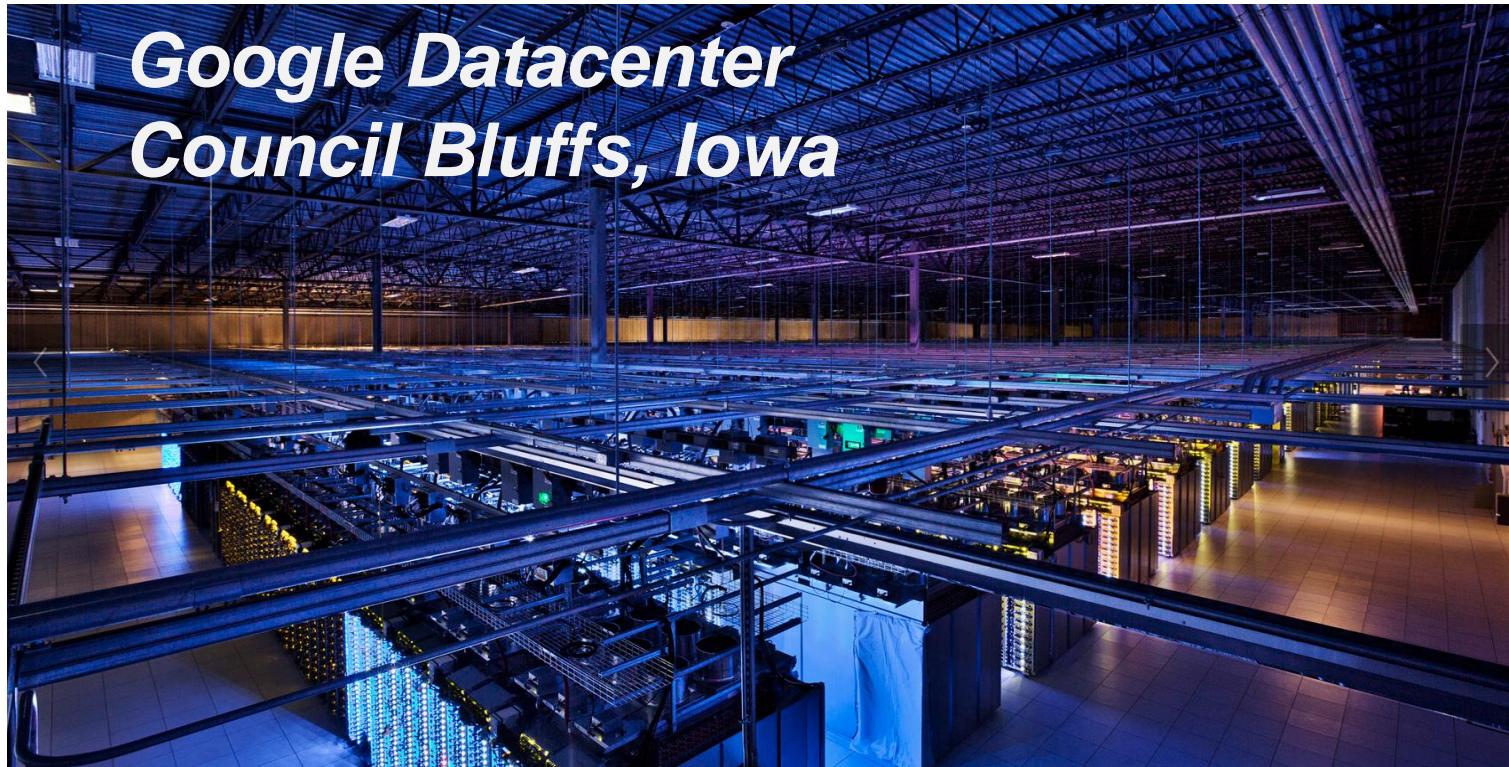


### ***Outline***

- 1. Motivation***
- 2. Energy dissipation in computing***
- 3. Sensitivity of Josephson comparator***
- 4. AQFP comparator analysis***
- 5. Conclusion***



Energy efficiency is the key performance measure today.



**Originally 115,000 square feet, \$600M**

<http://www.google.com/about/datacenters/gallery/#/locations/council-bluffs/2>

# Energy dissipation of shift registers



What matters in computation today?

Energy dissipation per operation

Logic	Shift register circuit	Energy Dissipation [aJ/bit-op]	Operation Frequency [GHz]
RSFQ	DFF based	840	50
LV-RSFQ [1]	DFF based	4.0	18
eSFQ [2]	Modified DFF	0.3 - 0.8	20
<b>AQFP [3]</b>	<b>QFL</b> (QFLs includes 20 cells)	<b>0.12</b>	<b>5</b>

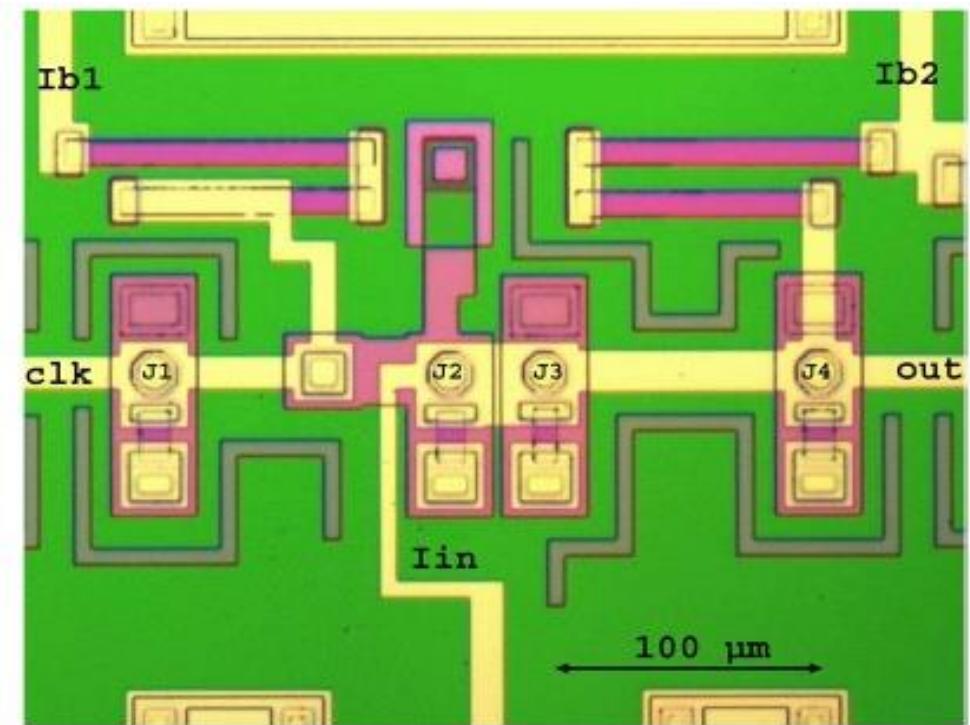
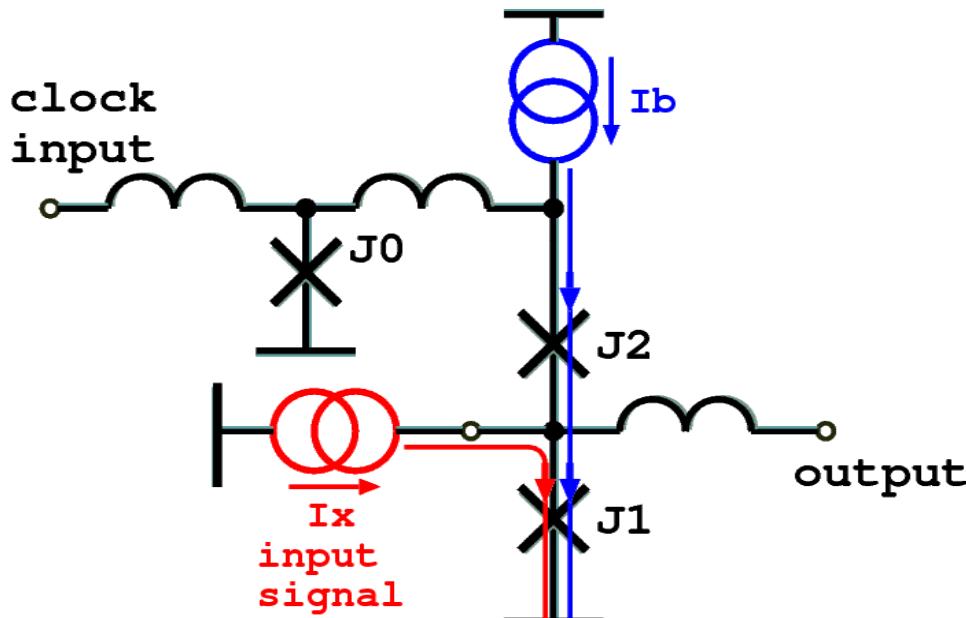
[1] M. Tanaka et al., *Jpn. J. Appl. Phys.* 51, 053102 (2012)

[2] M. H. Volkmann et al., *Supercond. Sci. Tech.* 26, 015002 (2013), I. Vernik et al. SuST 2014

[3] N. Takeuchi et al., *JOURNAL OF APPLIED PHYSICS*, Vol. 115, No. 10, 103910, 2014

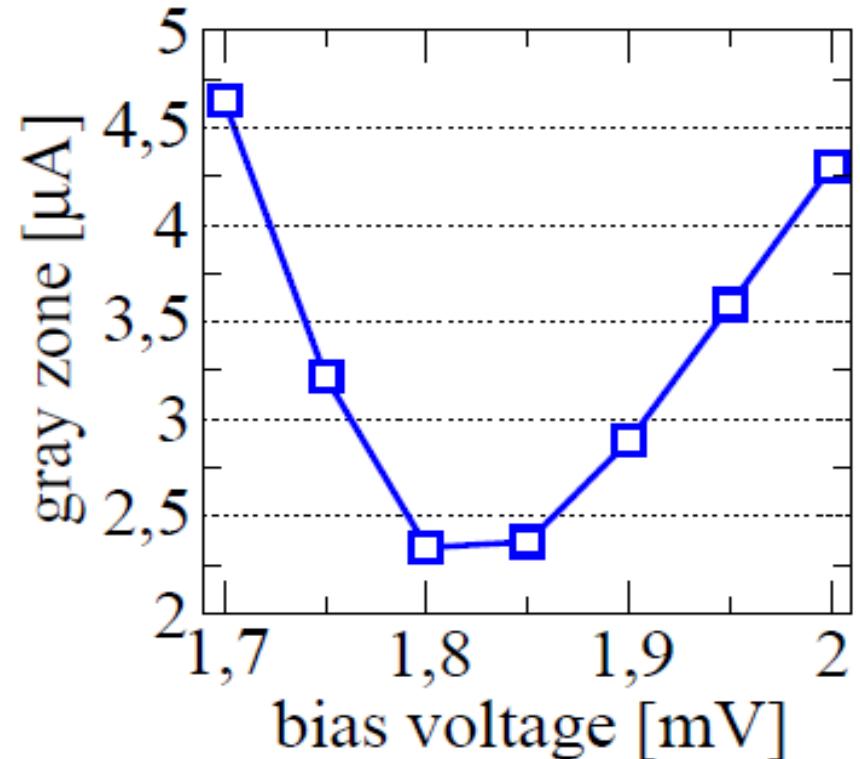
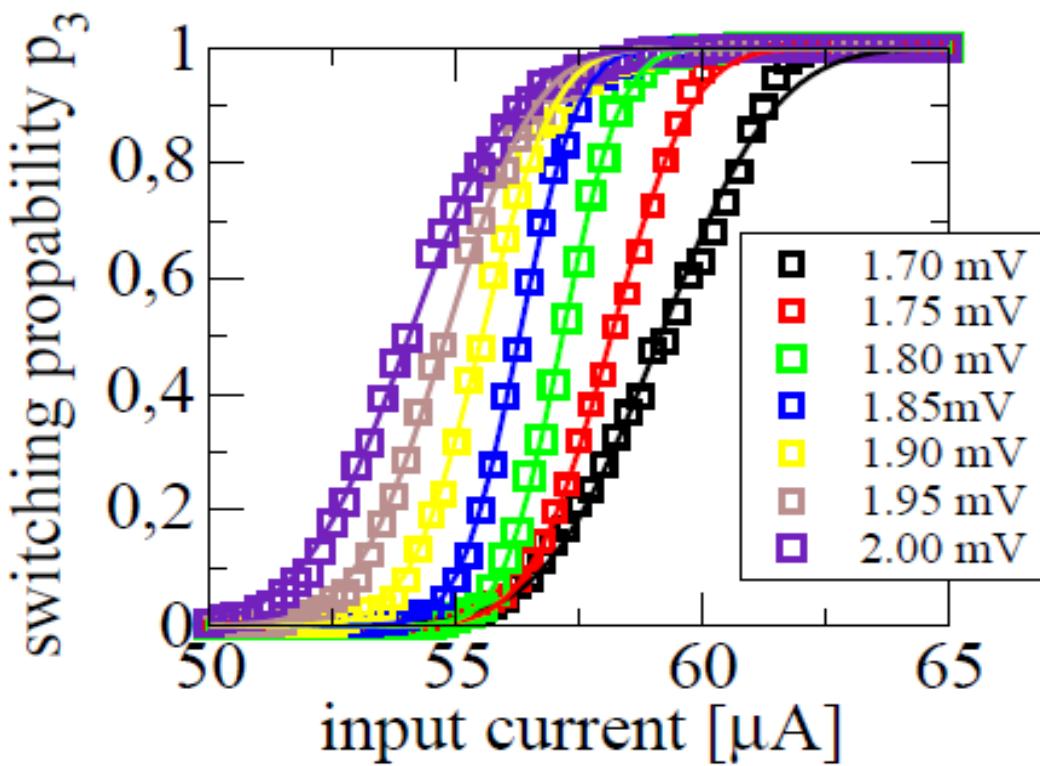
# Josephson comparator

- two equal Josephson junction are driven by a clock pulse
- the direction of the input current determines the decision
- if the input current is above a certain threshold, an output pulse is generated



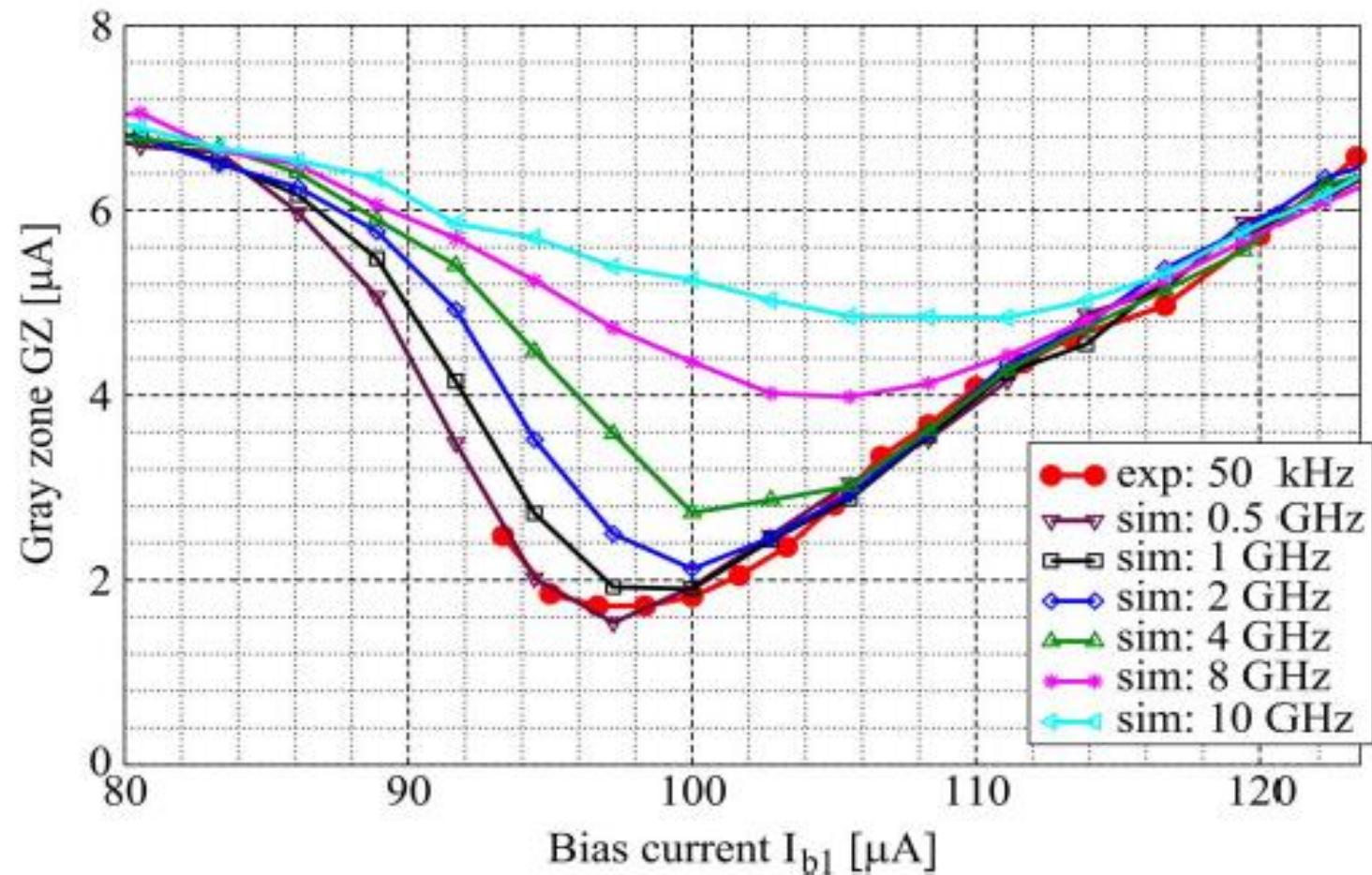
# Experimental results

- at very low bias voltage, the comparator grayzone reaches a minimum point



- to understand the reason for the unique operation point, we need to understand the transient switching cycle

# Frequency dependence of grey zone

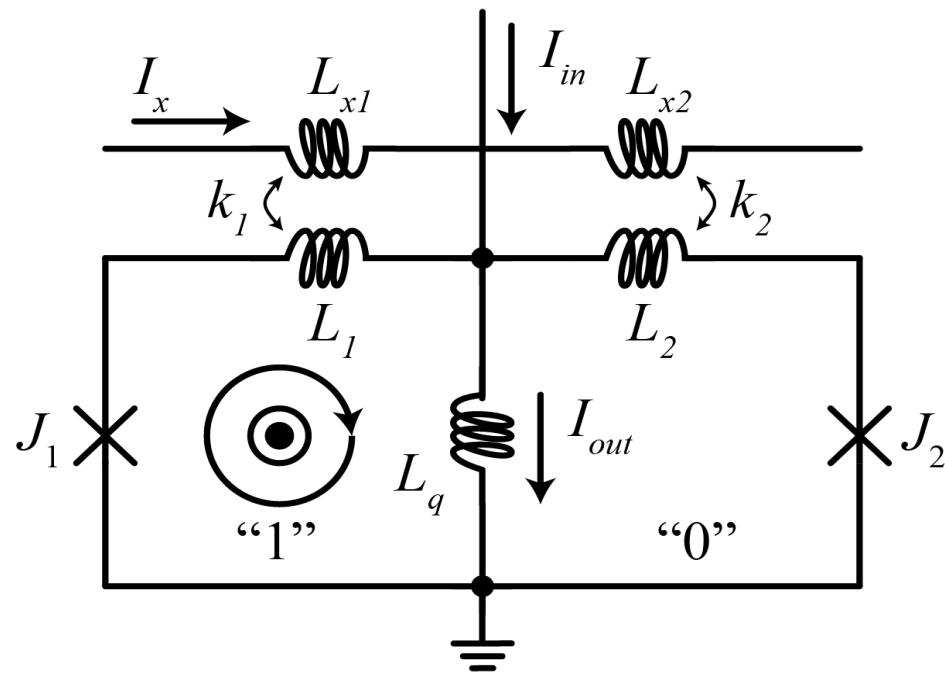


The minimum grey zone depends on clock frequency and bias current.

T. Haddad et al., "Experimental analysis of the bias dependent sensitivity of a Josephson comparator",  
IEEE Transactions on Applied Superconductivity, Vol. 25, No. 3, pp. 1301804 (4pp), 2015

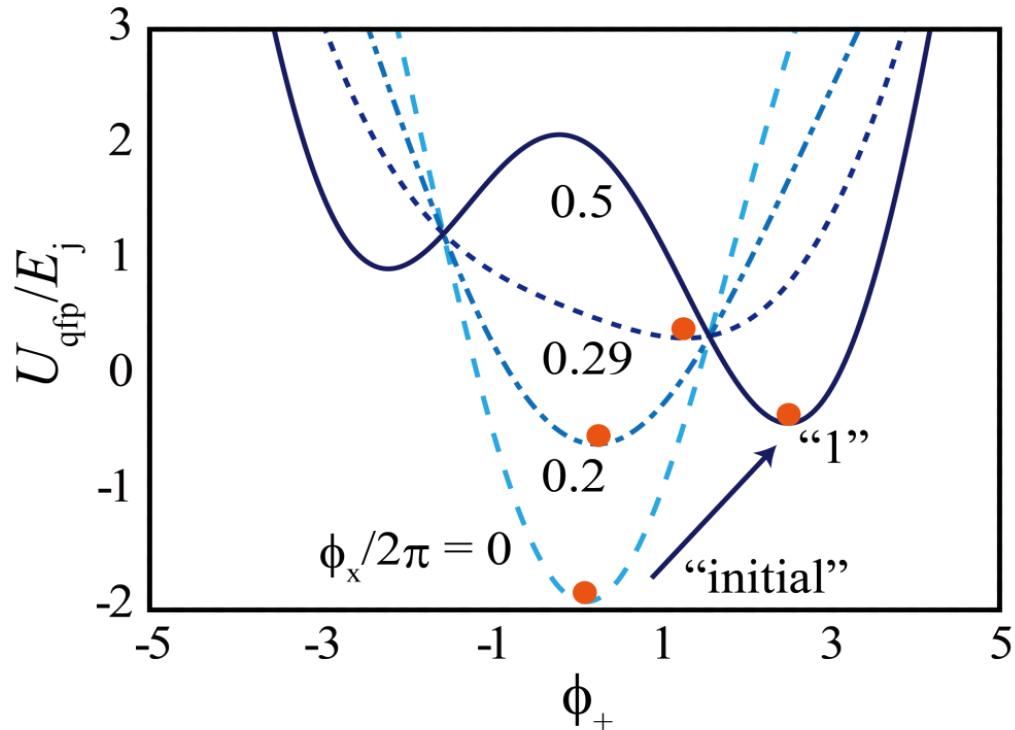
# Principle AQFP operation

## AQFP gate



An SFQ is stored in the right or left loop depending on  $I_{in}$ .

## Potential energy of the gate



Potential energy changes adiabatically during a switching event.

[1] N. Takeuchi, Y. Yamanashi, N. Yoshikawa, *Appl. Phys. Lett.* 102, 052602 (2013).

# Circuit example 16-word register file



- **Circuit area :**

**$2.34 \times 4.71 \text{ mm}^2$**

- **Junction number :**

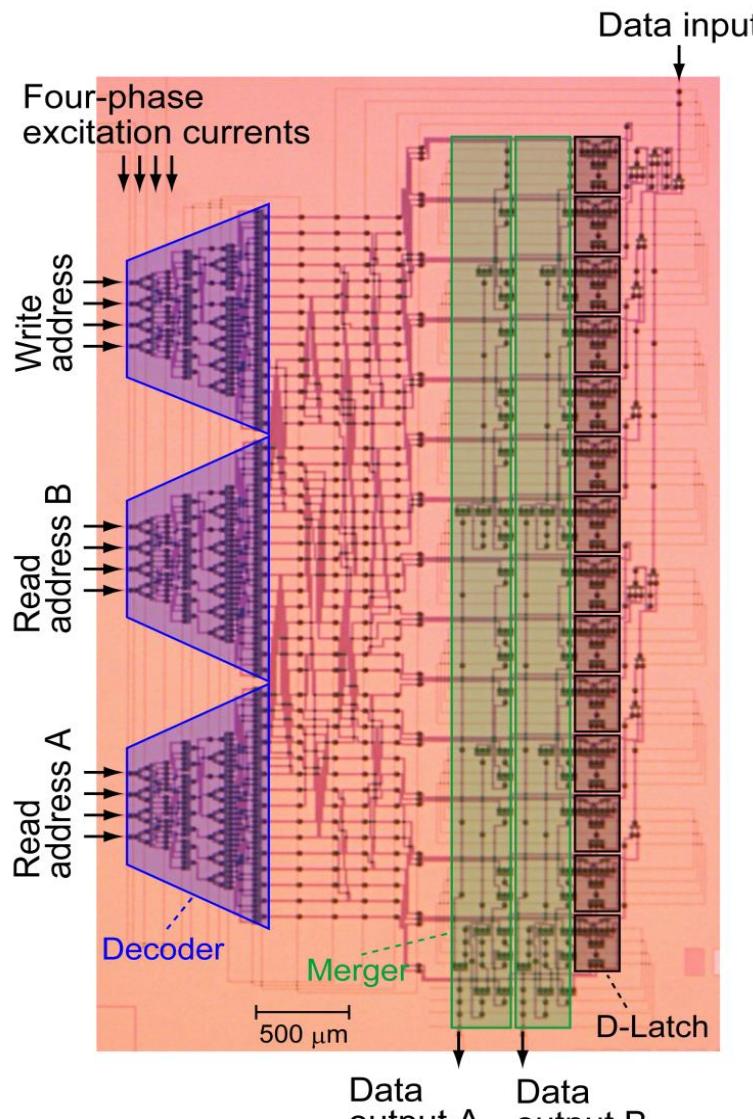
**2260 JJs**

- **Latency :**

**1600 ps for 5 GHz  
(8 clock cycles)**

- **Power consumption :**

**7.1 aJ/clock cycle for 5 GHz**



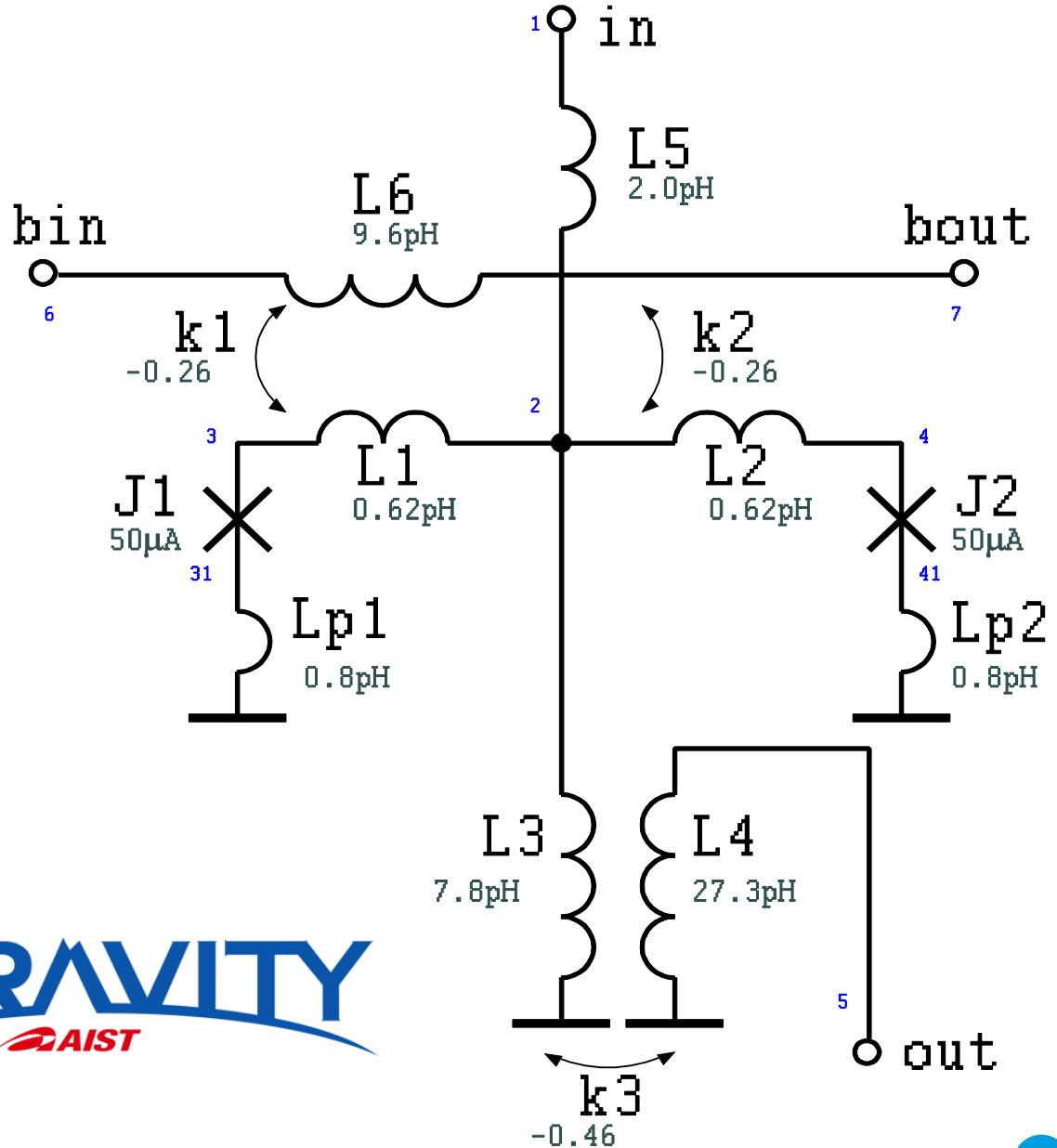
**AIST 10 kA/cm<sup>2</sup> Nb  
High-speed Standard Process**



# AQFP fundamental circuit

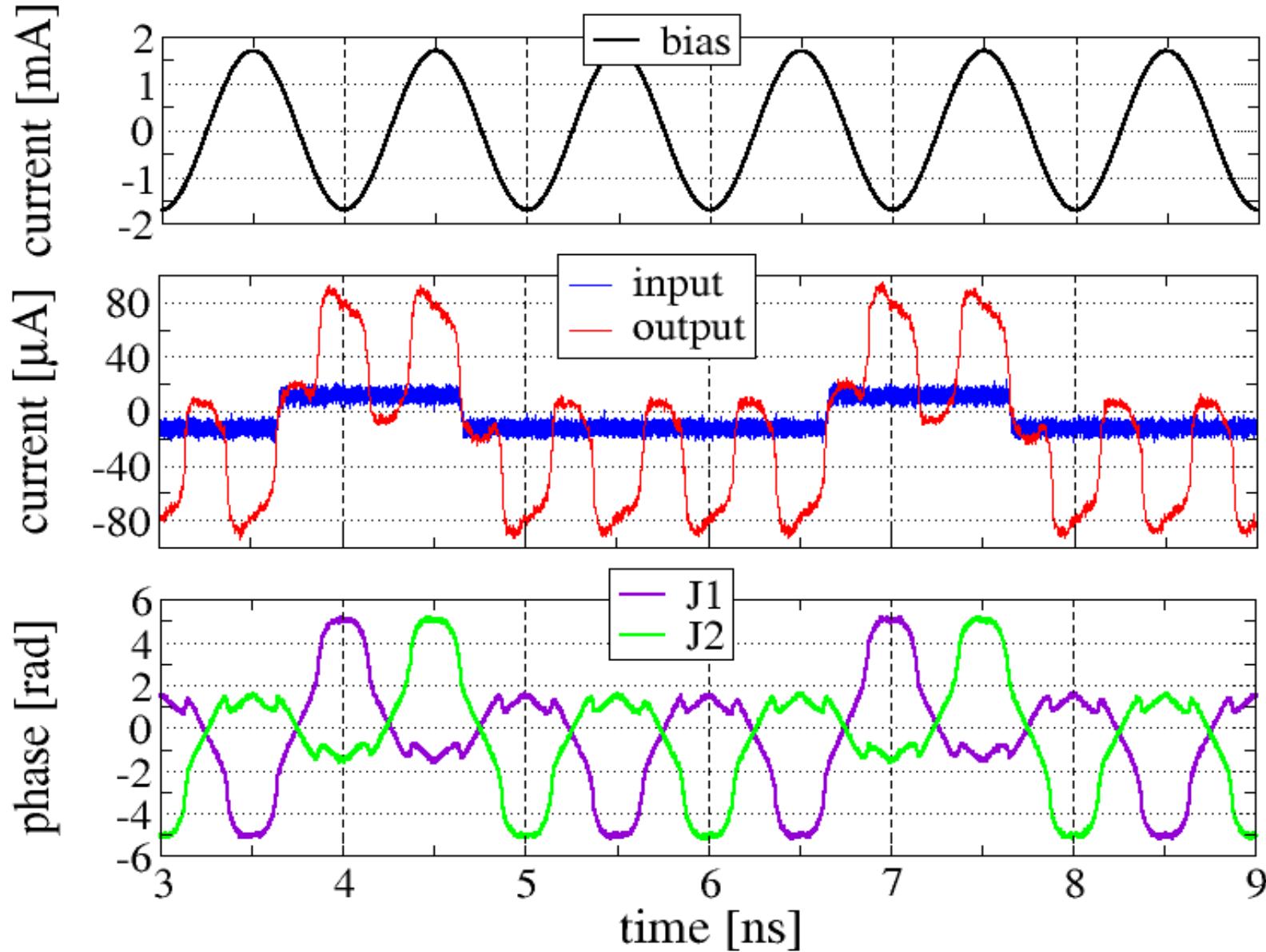


- two symmetric branches
- all Josephson junctions have the same size
- depending on input current  $J_1$  or  $J_2$  will make a  $2\pi$ -phase increase
- circuit fabrication is based on CRAVITY  $2.5 \text{ kA/cm}^2$  process



<https://unit.aist.go.jp/riif/openi/cravity/en/index.html>

# Circuit simulation result of AQFP comparator

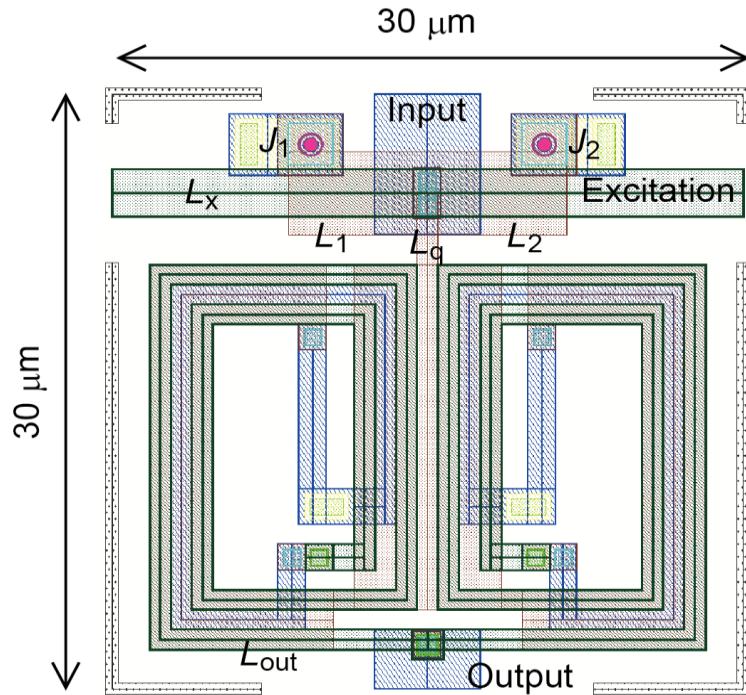
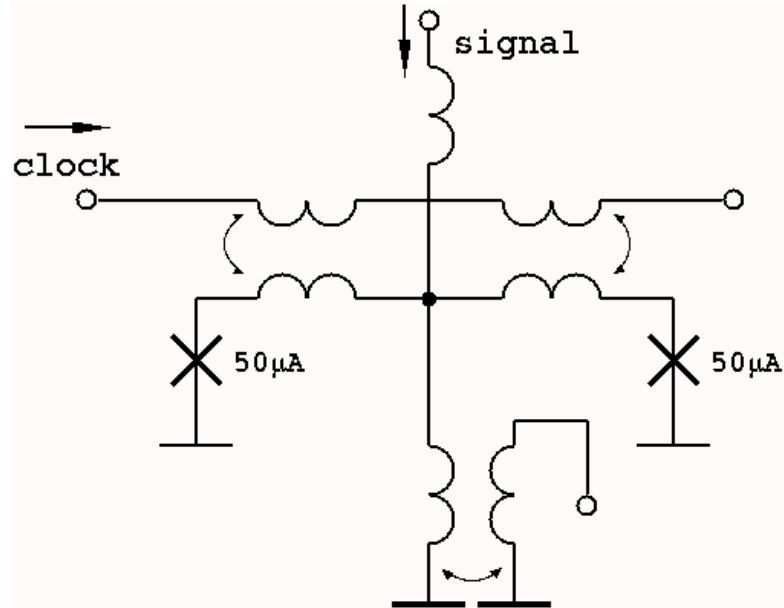


Input current  
(blue)

Output current  
(red)

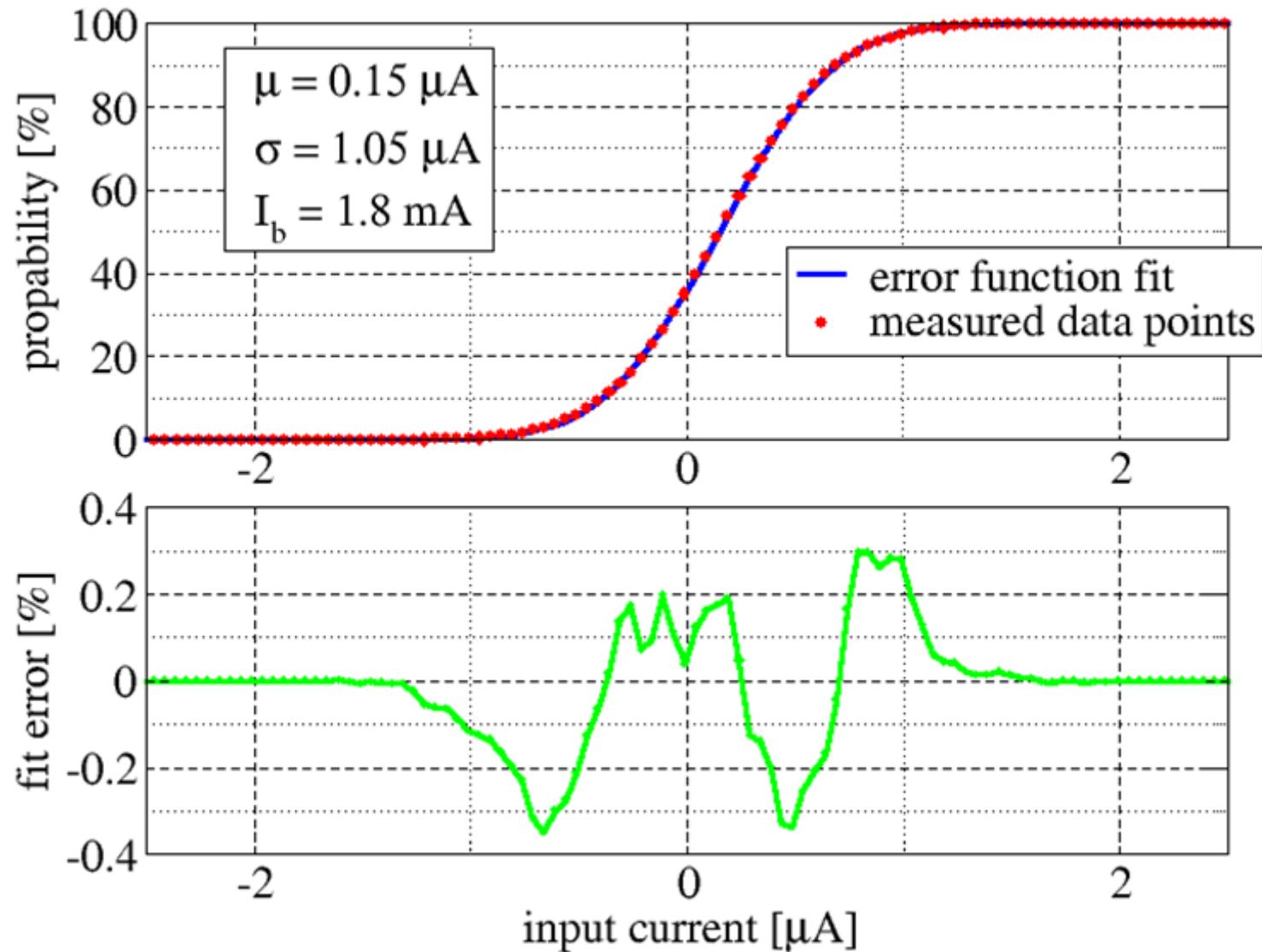
AQFP consists of

- two Josephson junctions with  $I_c=50 \mu\text{A}$  and
- two transformers.



Large circuits require **fan-out** and **low BER**.

# Experimental investigation of AQFP

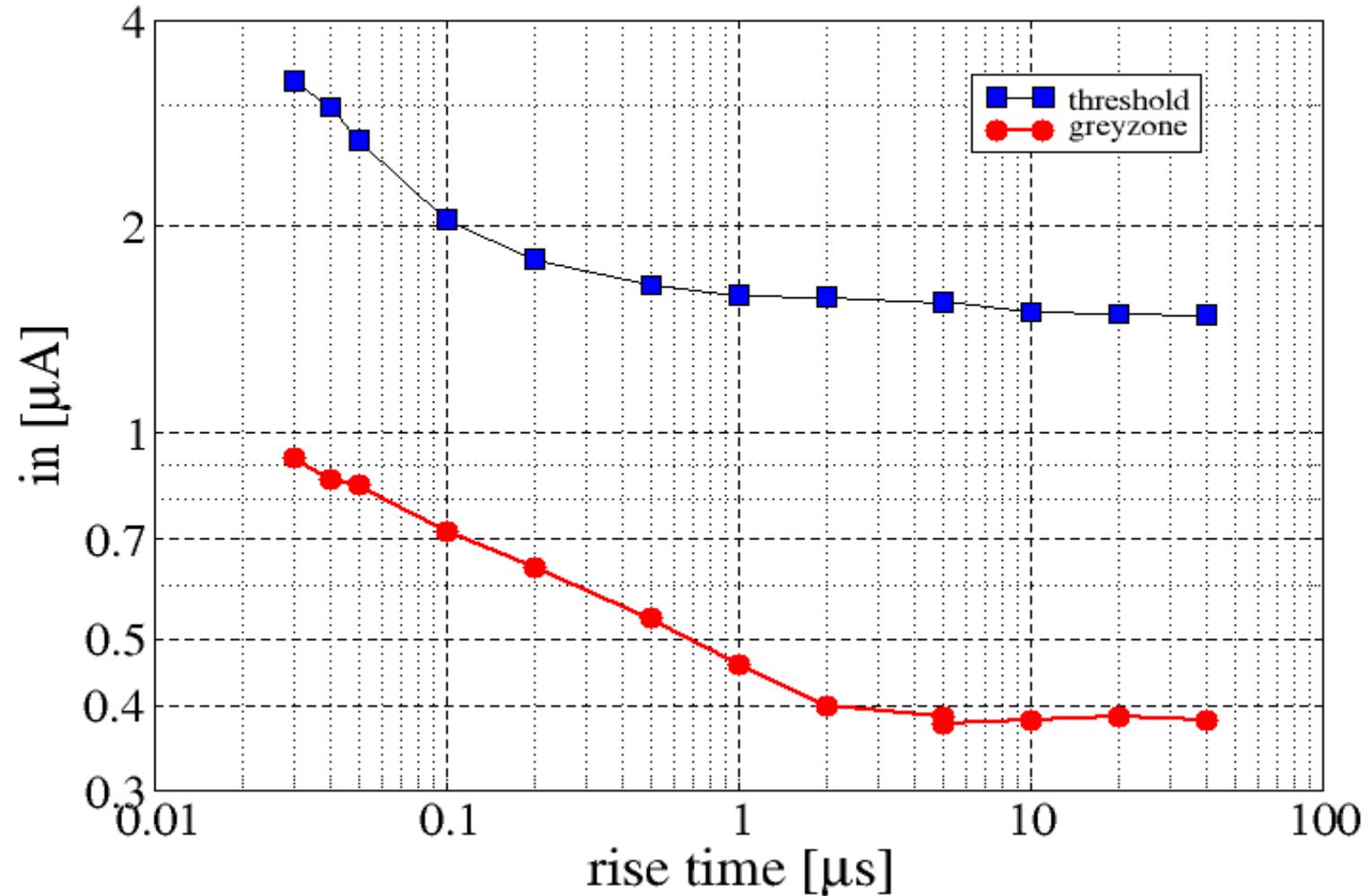


**Very good agreement and deviation of less than 1 %**

# Measured AQFP sensitivity versus rise time

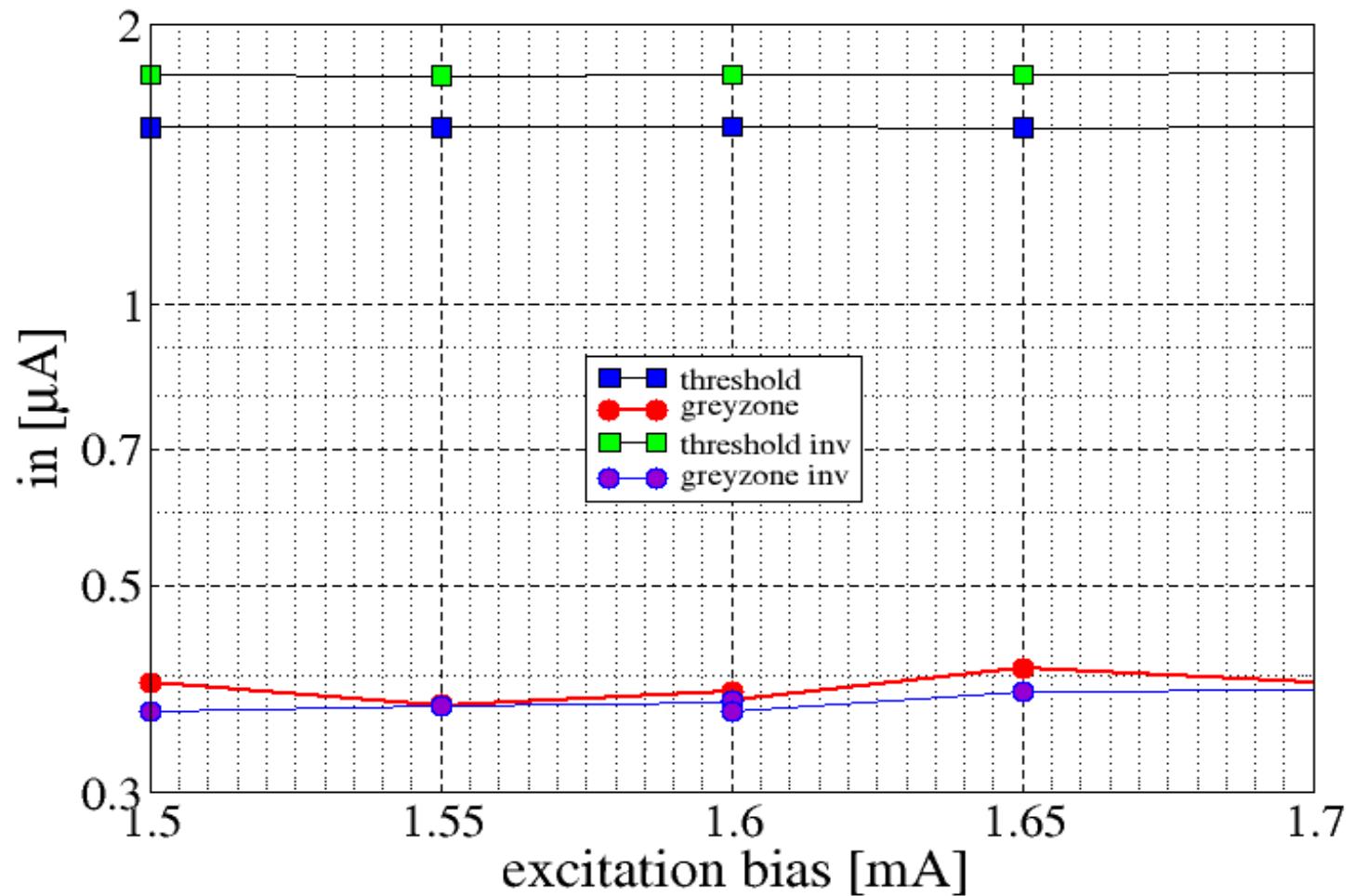
$20 \text{ ns} \rightarrow GZ = 1\mu\text{A}$

slope  $a = 1.56$



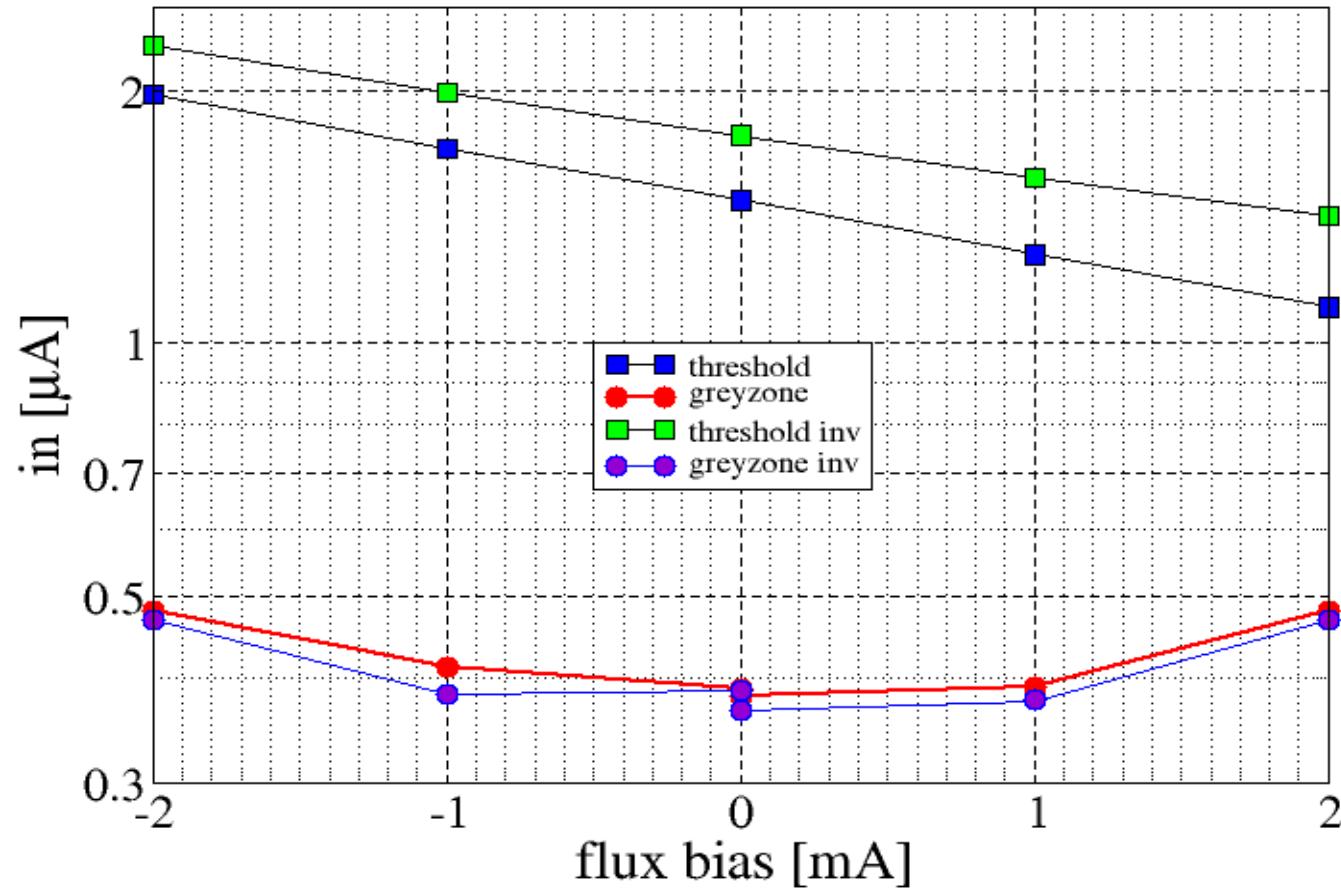
# Parameter vs. Excitation current

The greyzone in independent on excitation bias current.

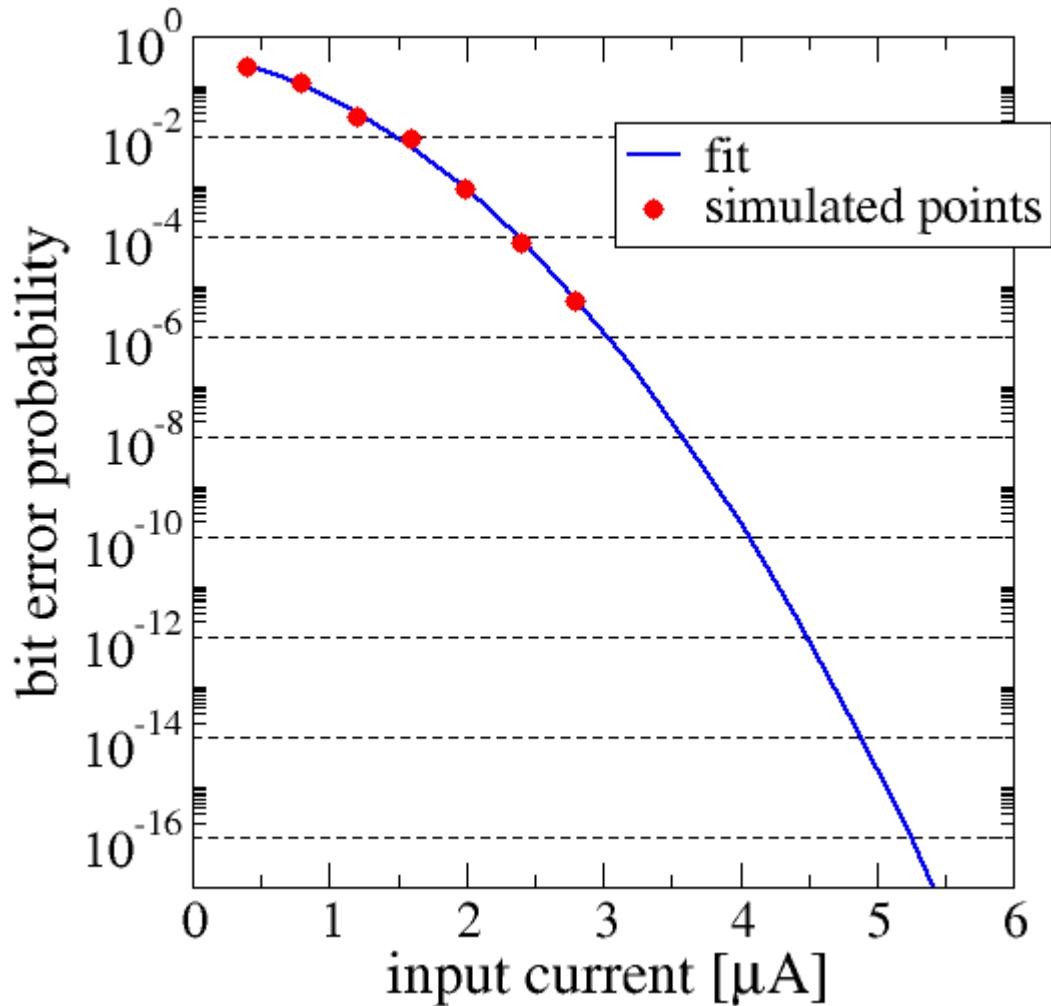


# Parameter vs. magnetic bias

The greyzone is independent on some ambient magnetic field current.



# Extrapolation of BER



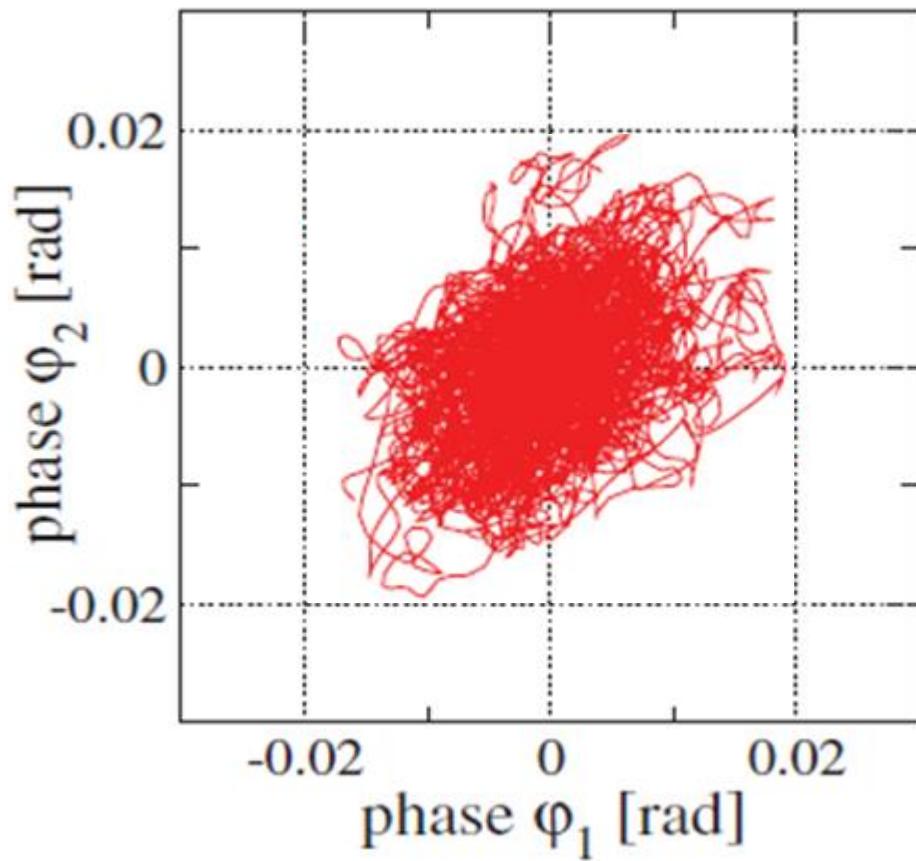
- JJ critical current 50  $\mu\text{A}$
- Input sensitivity @ 4K (greyzone) is 0.4  $\mu\text{A}$  @ low speed and 3.0  $\mu\text{A}$  @ 5 GHz
- input current of 5  $\mu\text{A}$  enables  $\text{BER} < 10^{-15}$

# Simulations of the JJ phase noise

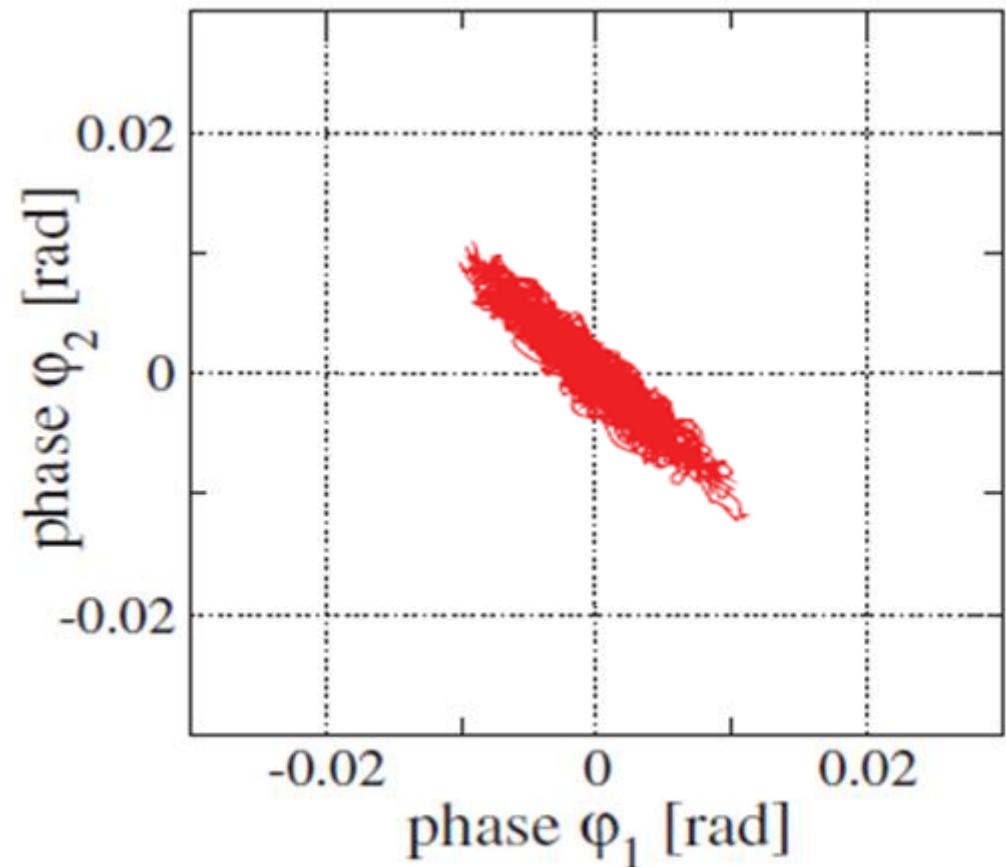


Noise driven phase variations depend on the circuit topology.

Josephson comparator



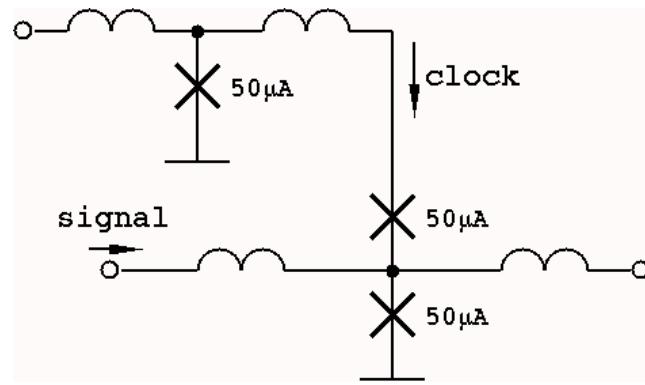
AQFP comparator



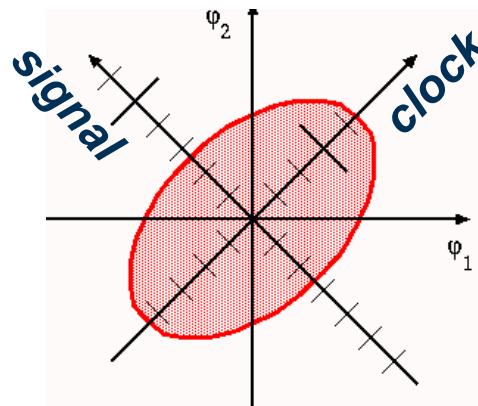
T. Ortlepp, S. Miyajima, H. Toepfer, A. Fujimaki, „Josephson comparator with modified dynamic behaviour for improved sensitivity“, Journal of Applied Physics, Vol. 111, No. 12, 123901 (5pp), 2012

# Comparison of comparators

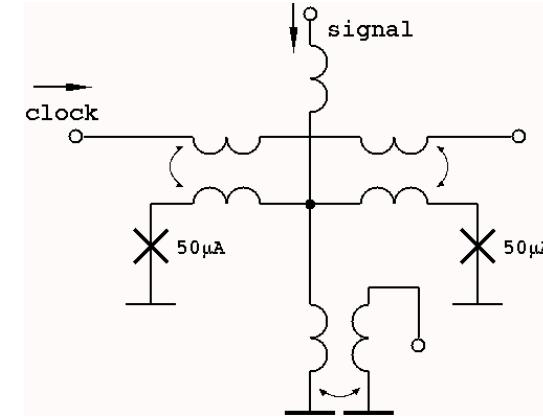
## Josephson comparator



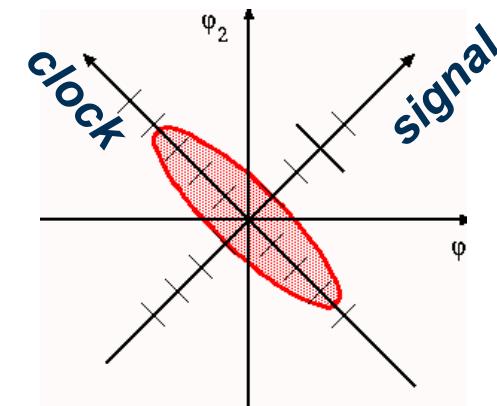
1. **clock current** has same direction for both JJs
2. **input current** is positive for J1 and negative for J2



## AQFP comparator



1. **input current** has same direction for both JJs
2. **clock current** is positive for J1 and negative for J2



# **Conclusion AQFP greyzone experiments**

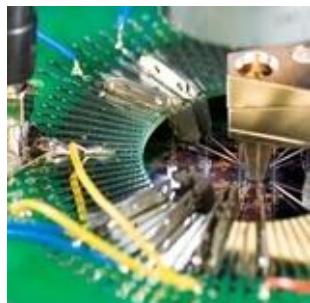


- 1. The minimum measured grey zone is about  $0.38 \mu\text{A}$  @ LHe.**
- 2. The greyzone is not influenced by the excitation bias.**
- 3. The greyzone is not influenced by the flux bias.**
- 4. Experimental data enables excellent error function fit.**
- 5. The dependence on the rise time is confirmed by simulation. Same slope is obtained.  
This is a typical white noise dependence on effective bandwidth.**
- 6. very robust operation for  $I_c=50 \mu\text{A}$**
- 7. extrapolated  $\text{BER} < 10^{-15}$  for maximum fan-out of four**

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*End*



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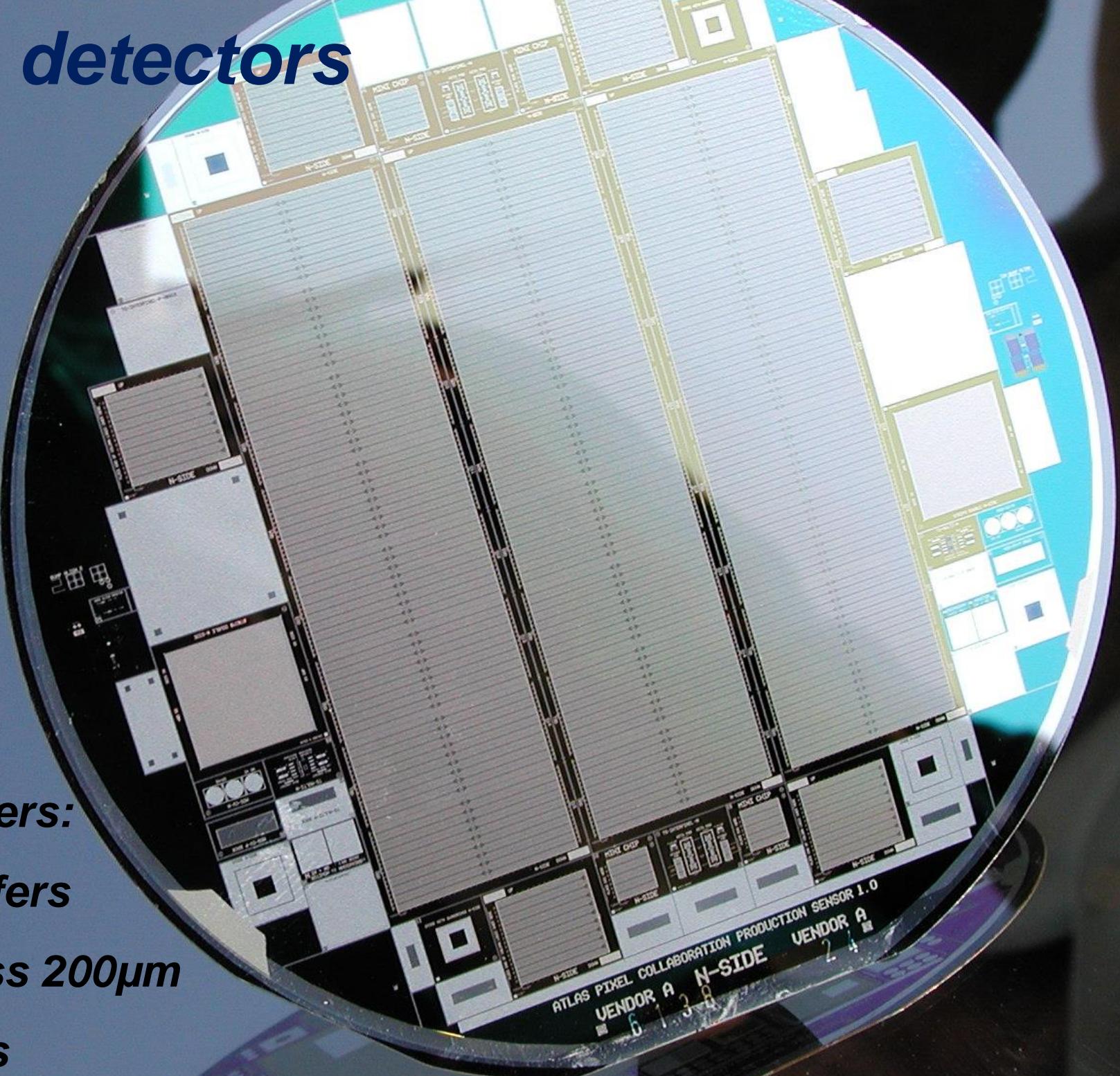


# *Location on the "Semiconductor-Hill" of Erfurt*



CiS is located next to X-FAB Foundry and to Melexis.

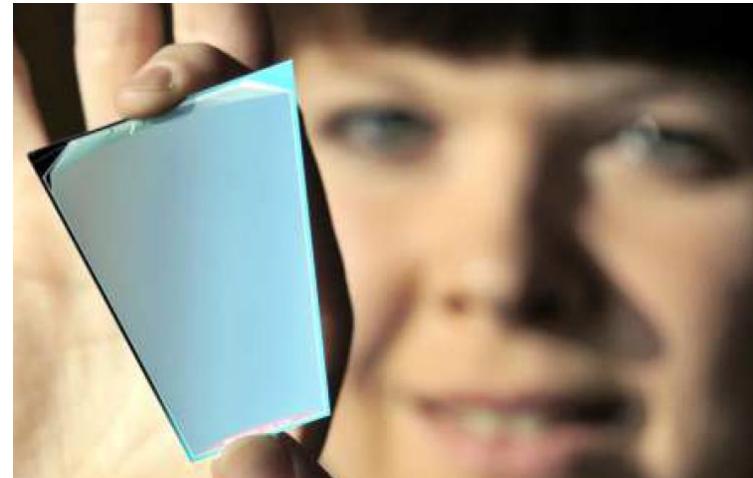
# Radiation detectors



*Typical parameters:*

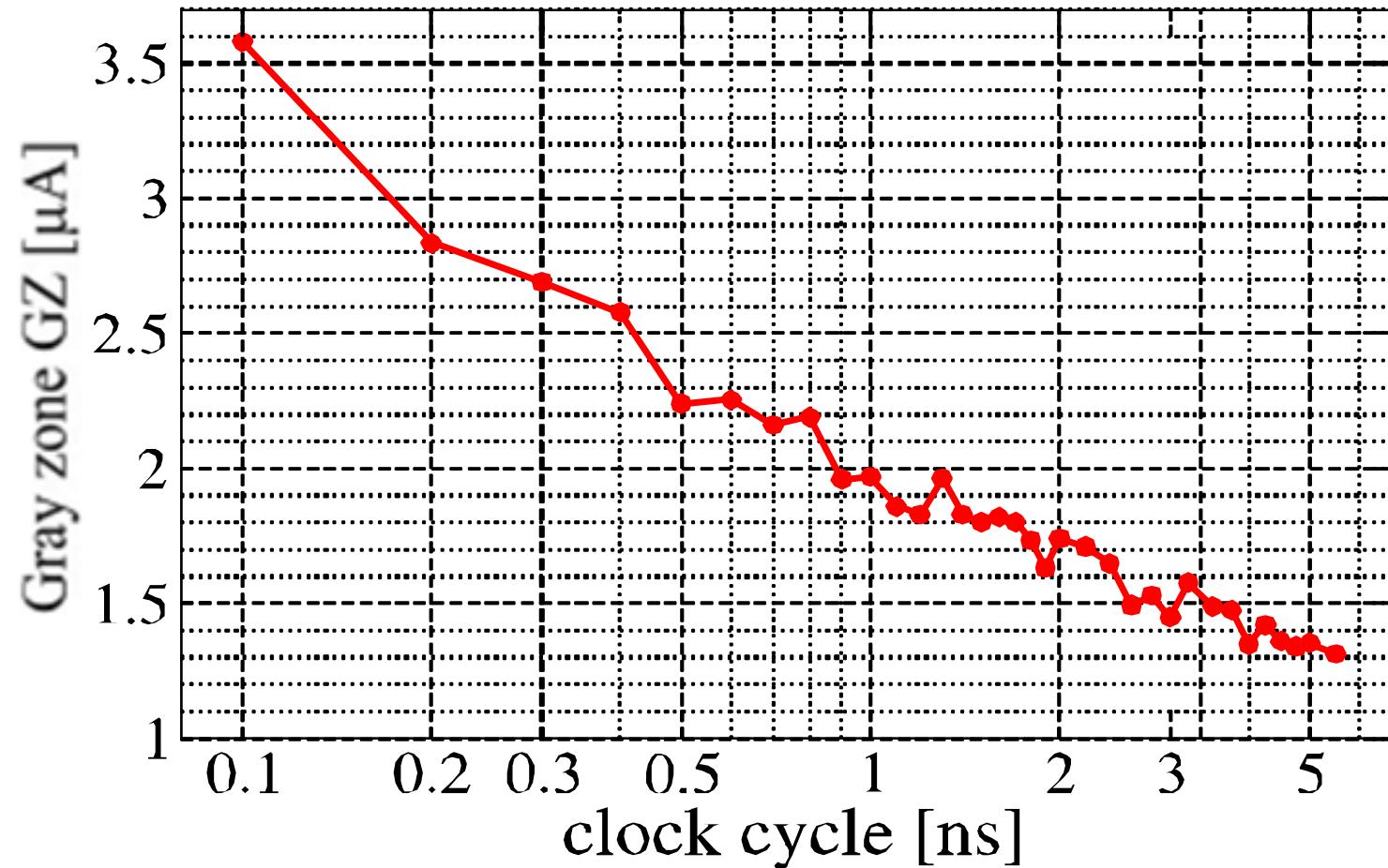
- double side wafers**
- wafers thickness 200 $\mu$ m**
- large area chips**

*In total CiS delivered  
8470 fully functional wafers  
to different large physics experiments.*



**CiS received the „Industrial supplier award“  
for high-quality fabrication of radiation detectors for CERN.**

# Simulated AQFP sensitivity



***20 ns estimation -> 1.08 μA greyzone***

***slope a = 1.59***