Business from technology

Progress in (Hadamard-coded) multiplexing of Transition Edge Sensors

Mikko Kiviranta, Nikolai Beev

VTT Technical Research Centre of Finland

Jan van der Kuur, Marcel Bruijn

SRON, the Netherlands

Oliver Brandel, Sven Linzen, Ludwig Fritzsch

IPHT Jena, Germany

Jussi Ahoranta

University of Helsinki, Finland

Jari Penttilä, Leif Roschier

Aivon Oy, Finland

Stuff covered:

- Hadamard coding with current steering switches

  Still in progress: difficulties with switch operation
- TD multiplexer using 3-junction interferometers as switches, for pixel characterization

  Multiplexer works, experiment with real TESes in progress
- Binary addressing utilizing Hadamard codes and periodicity of the SQUID response

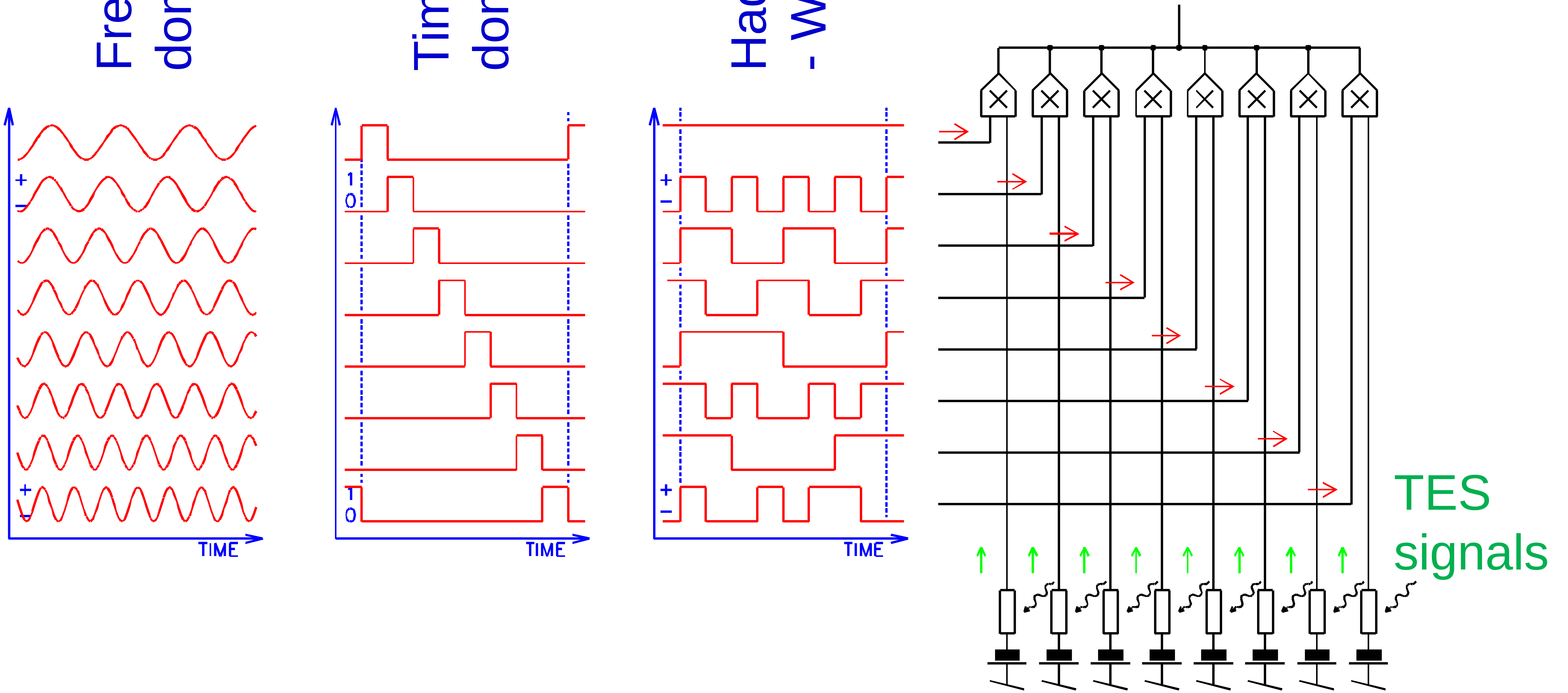
  Demonstrated by slope-switching SQUIDs and test loads

Orthogonal basis sets for multiplexing

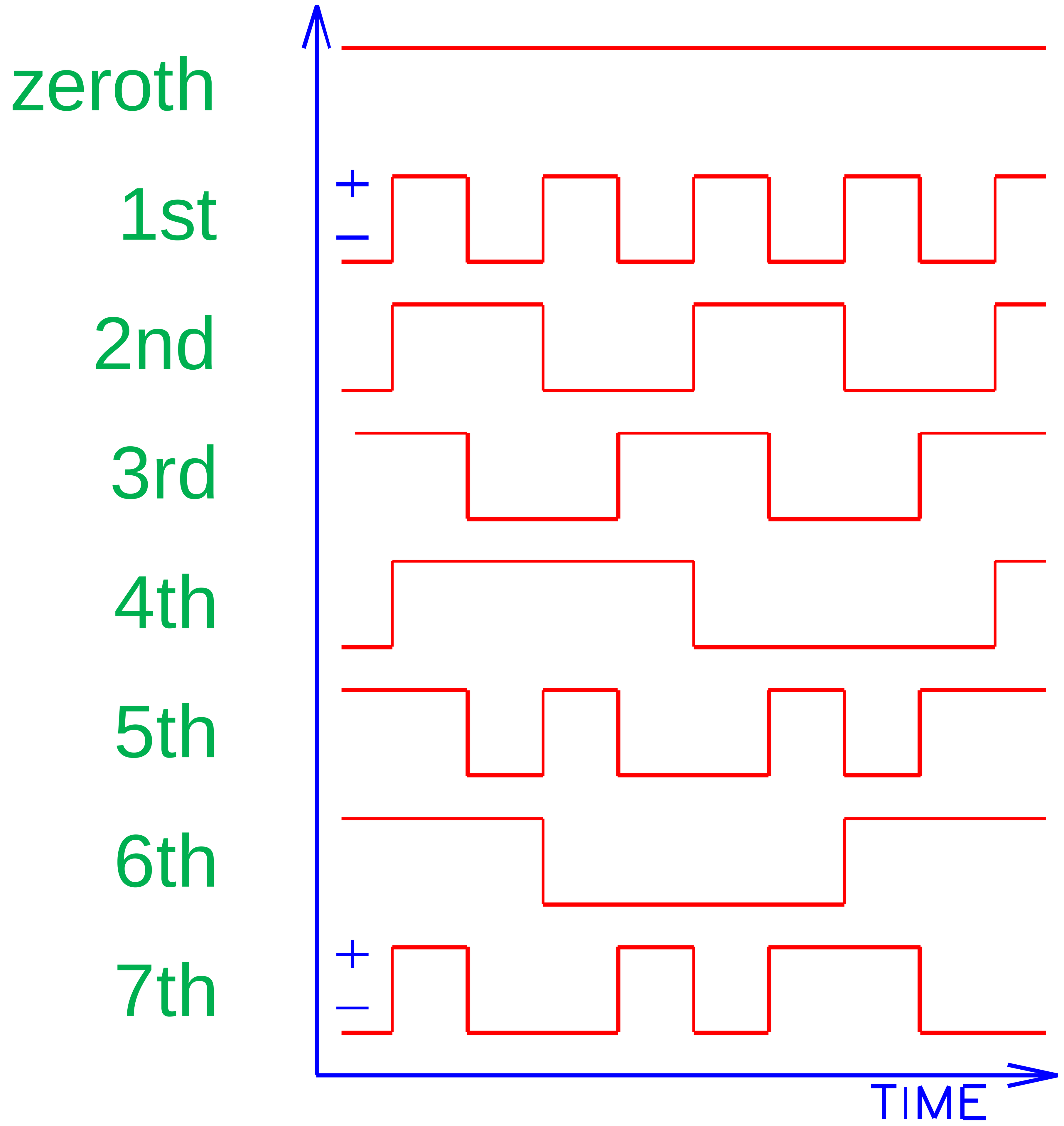
Frequency domain

Time domain

Hadamard - Walsh

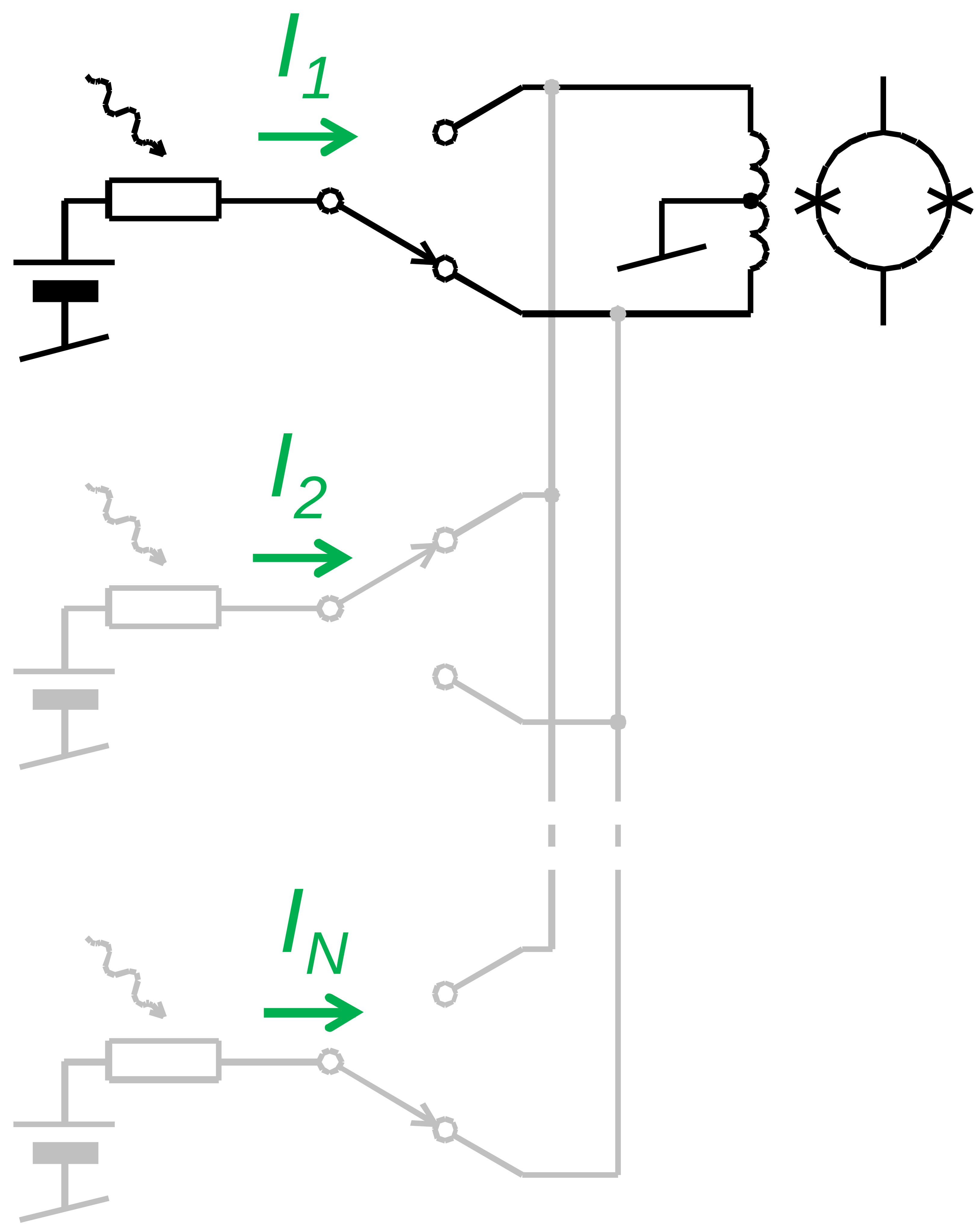


Hadamard (Walsh) codes



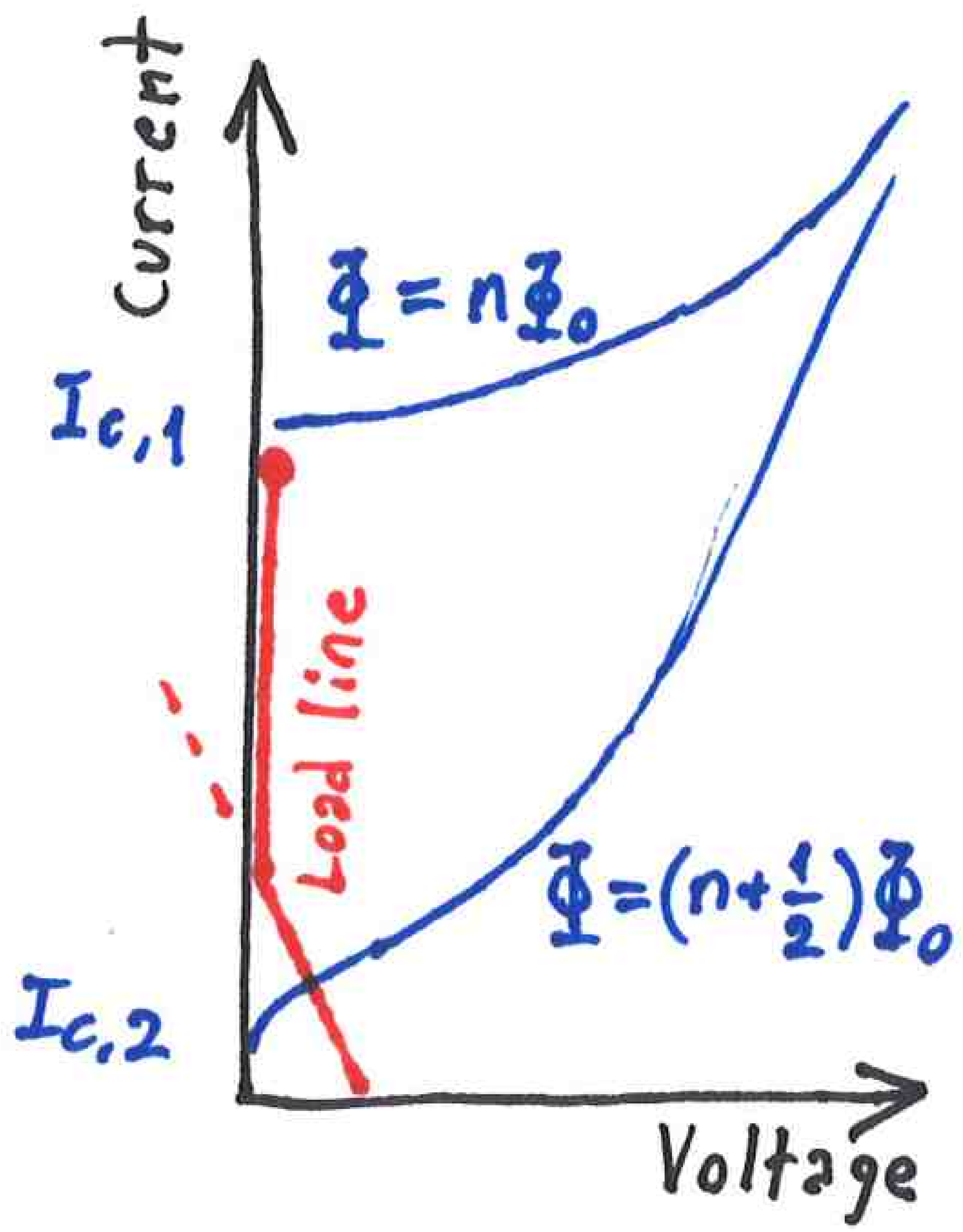
Codes are **bipolar two-level**

$\Rightarrow$ multiplication by a **commutating switch**

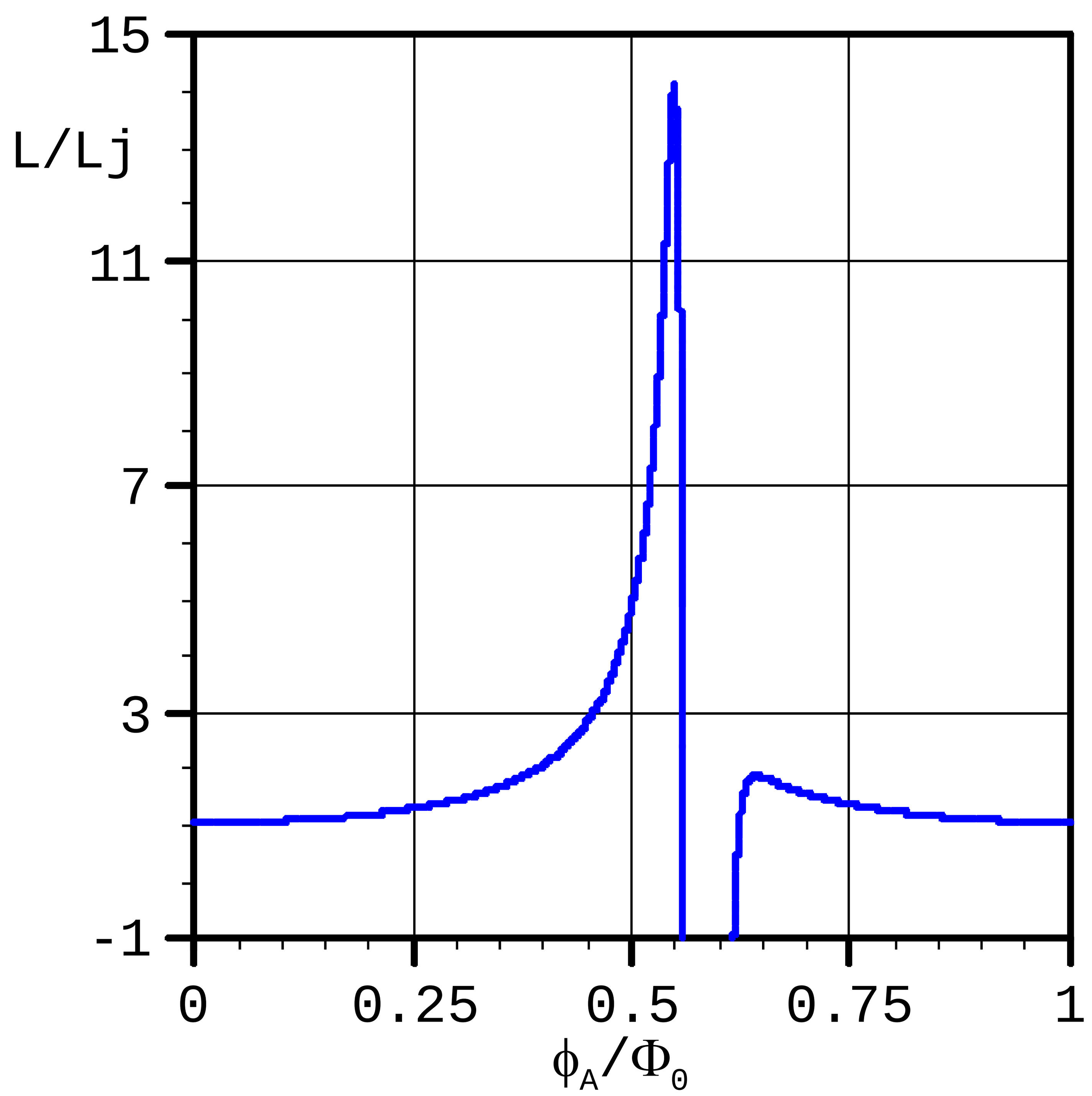


JJ based current steering switches

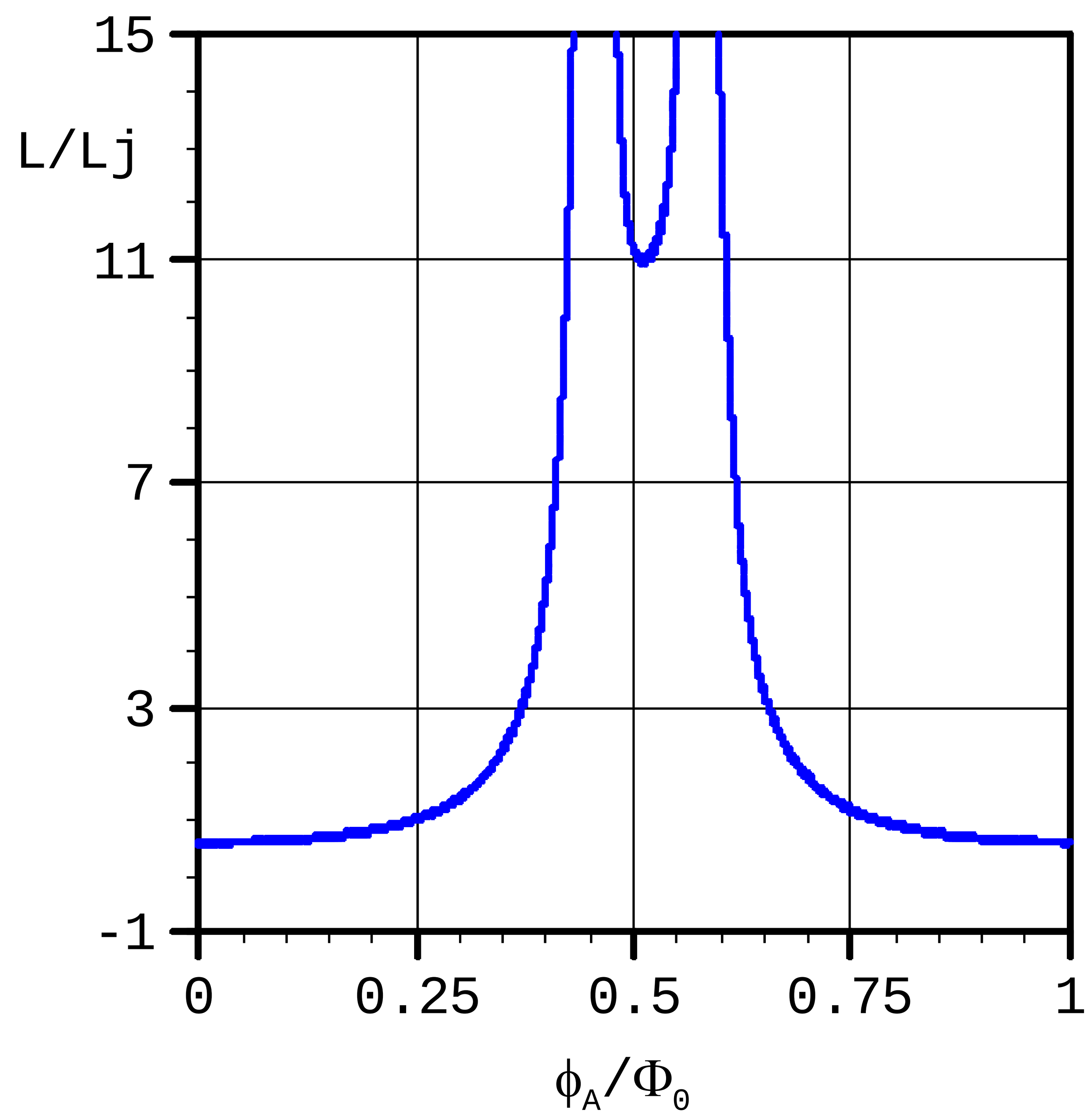
Low-β_L SQUID, voltage state
(J.Beyer, SuST 2008)



Low-β_L SQUID, as controlled inductance



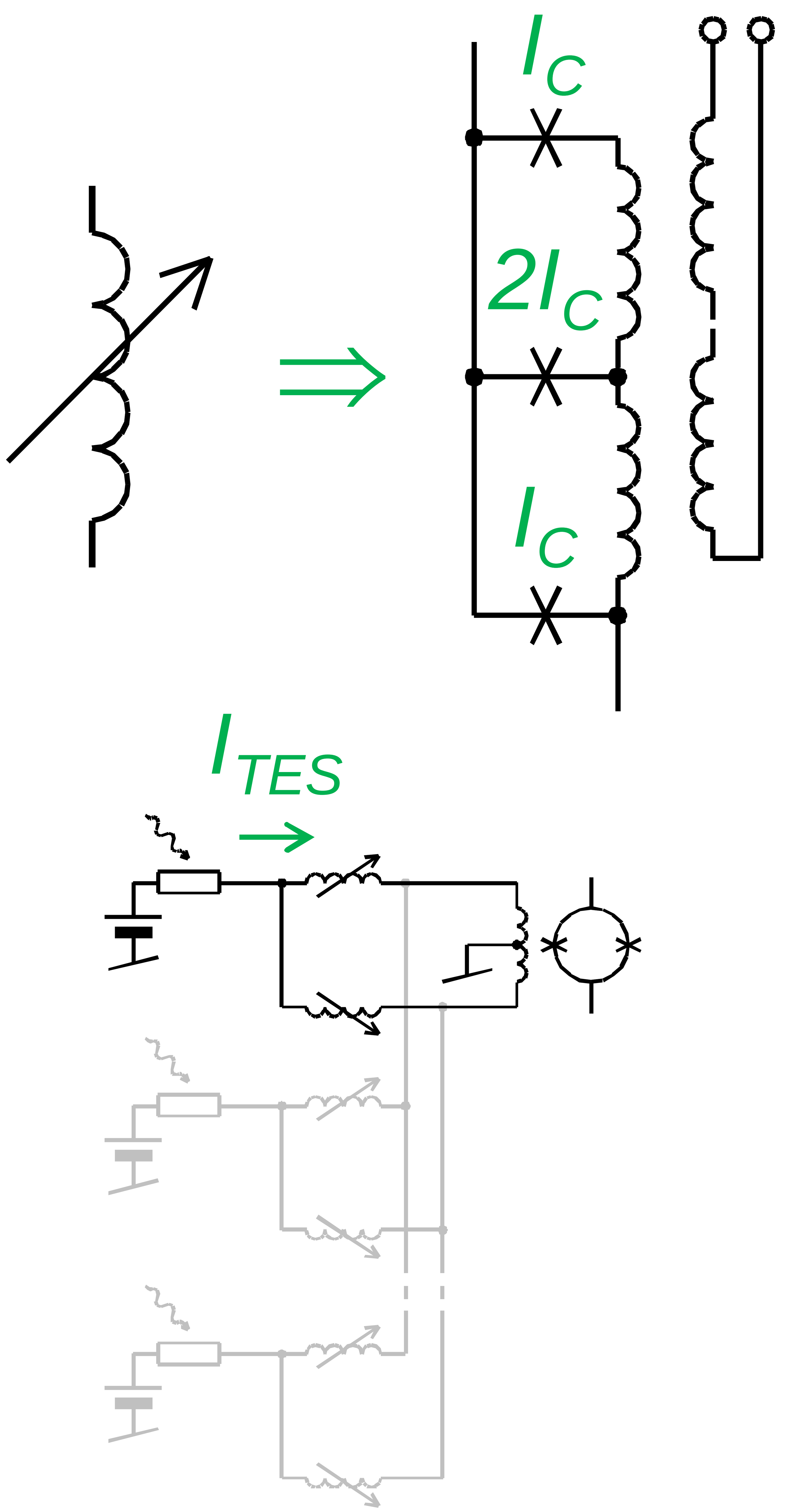
Zappe interferometer, controlled inductance
(J.Ullom, LT26 presentation, 2011
H. Zappe, IEEE Trans. Magn. 1977))

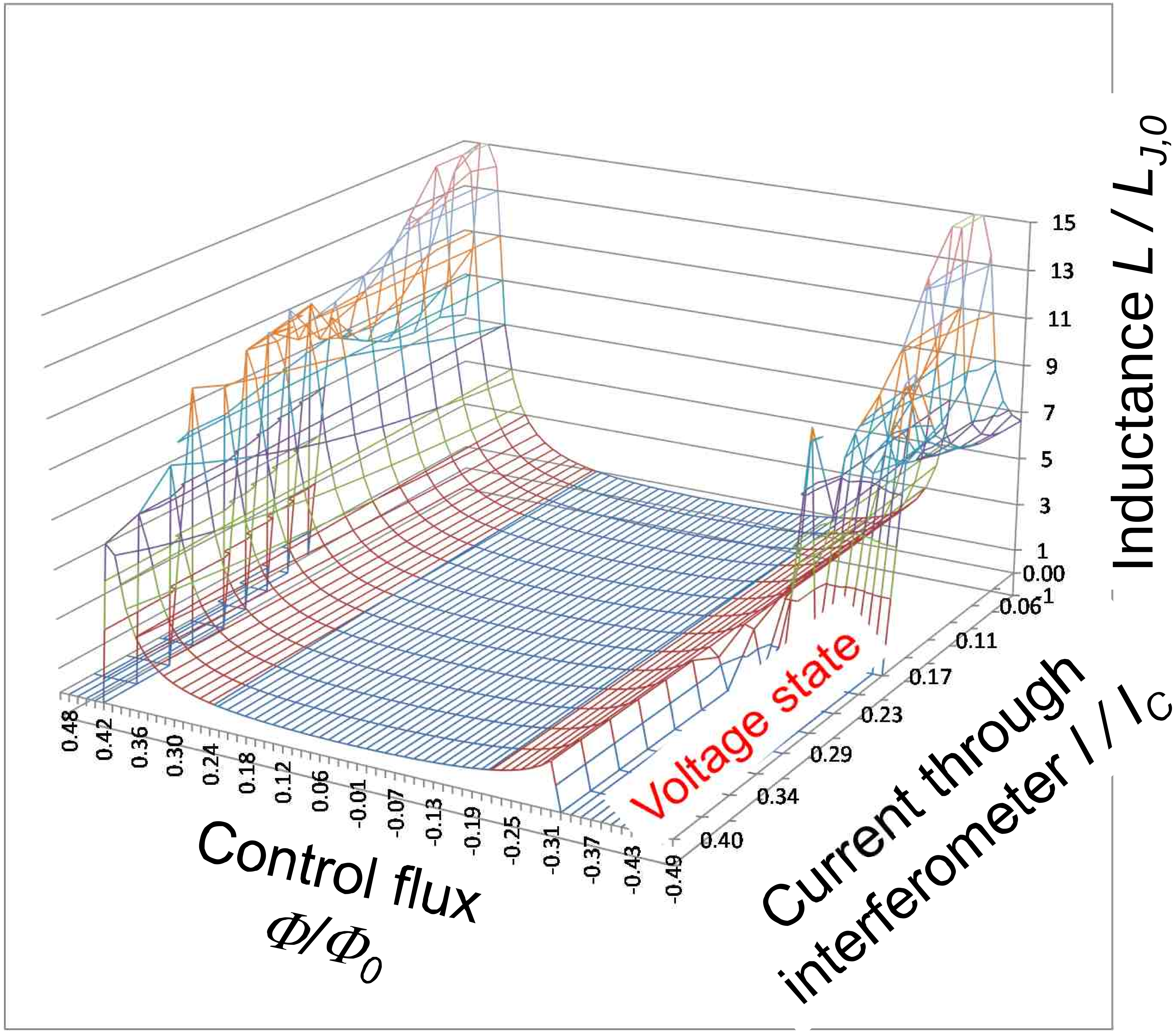


$$\boxed{L_J = \frac{\Phi_0}{2\pi I_C \cos\phi_A}}$$

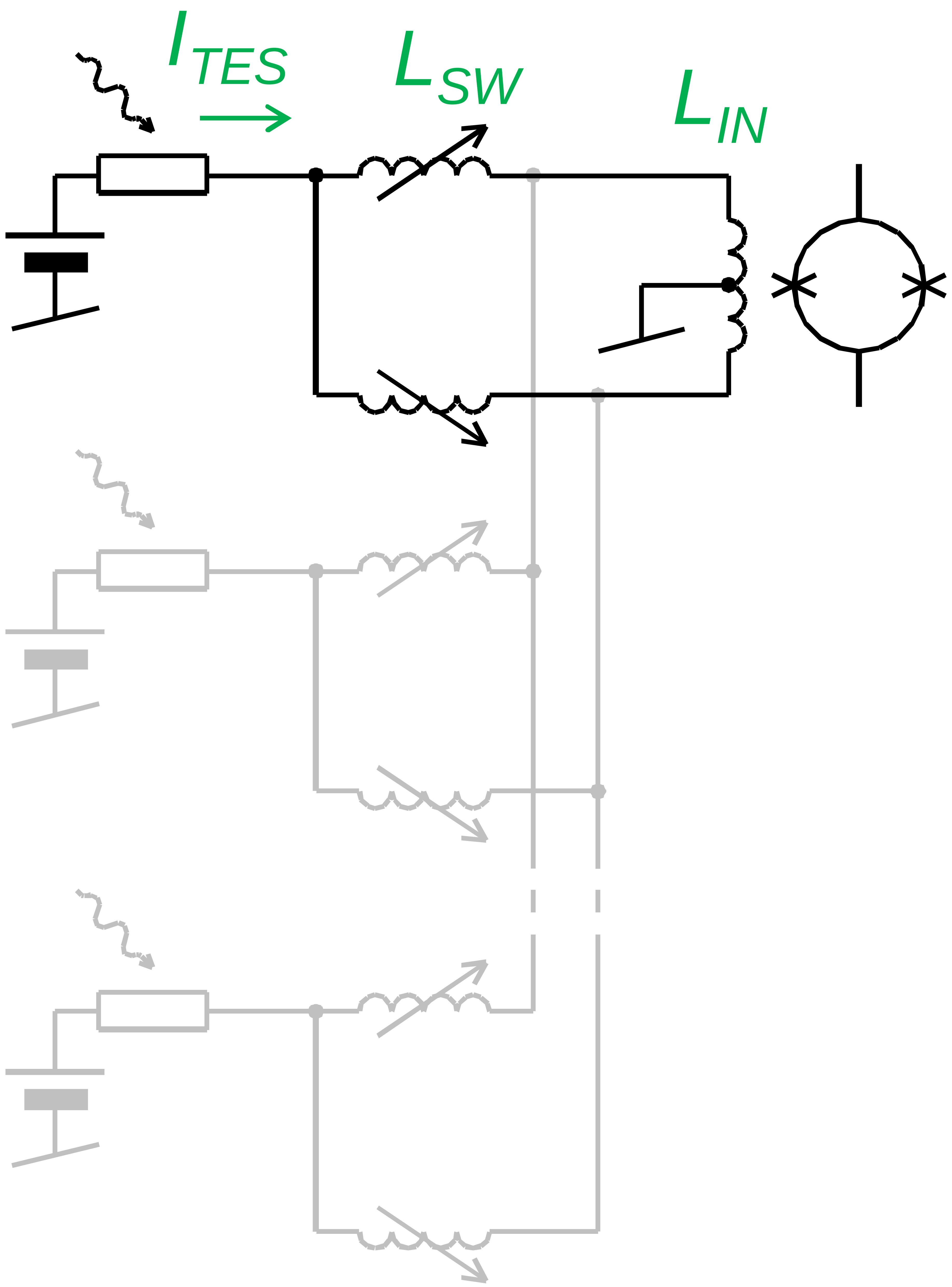
Josephson inductance

Inductive CS switch: dynamic range





Inductive CS switch: dynamic range



Current noise ↔ SQUID energy resol.

$$I_{N,SQ} = \sqrt{\frac{\varepsilon}{2\,L_{IN}}}$$

L_{SW} and max. current are related

$$I_{MAX,SW} \sim \frac{\Phi_0}{2\pi\, L_{SW}}$$

Must be dominated by controlled-*L*

$$L_{SW} >> L_{IN}$$

L_{SW} becomes small, lets use ***N*** in series

$$D \equiv \frac{I_{MAX}}{I_N} \sim \sqrt{N}$$

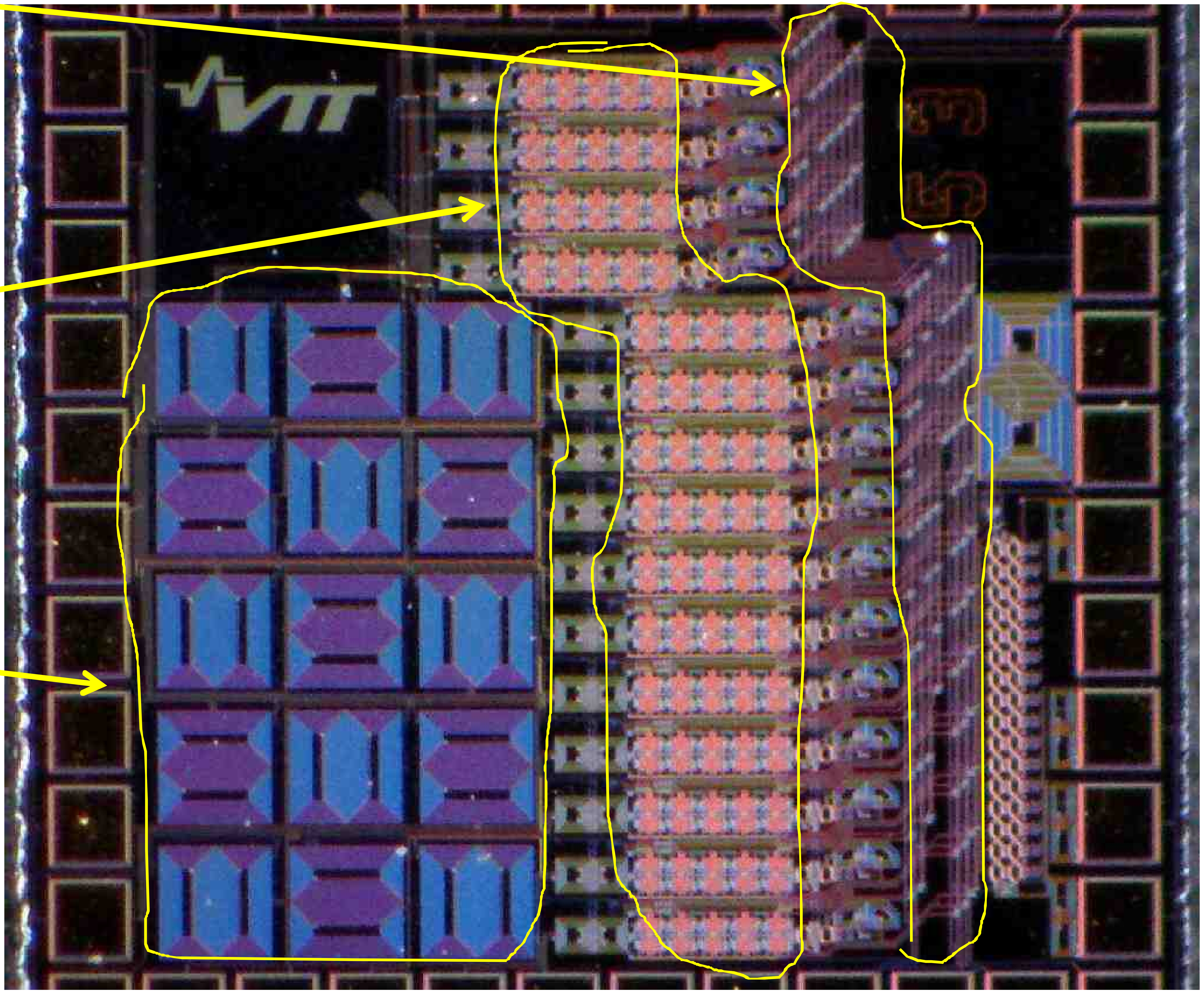
Switch = array of interferometers

15-channel CDM MUX chip

Binary-to-Hadamard coding matrix (explained soon)

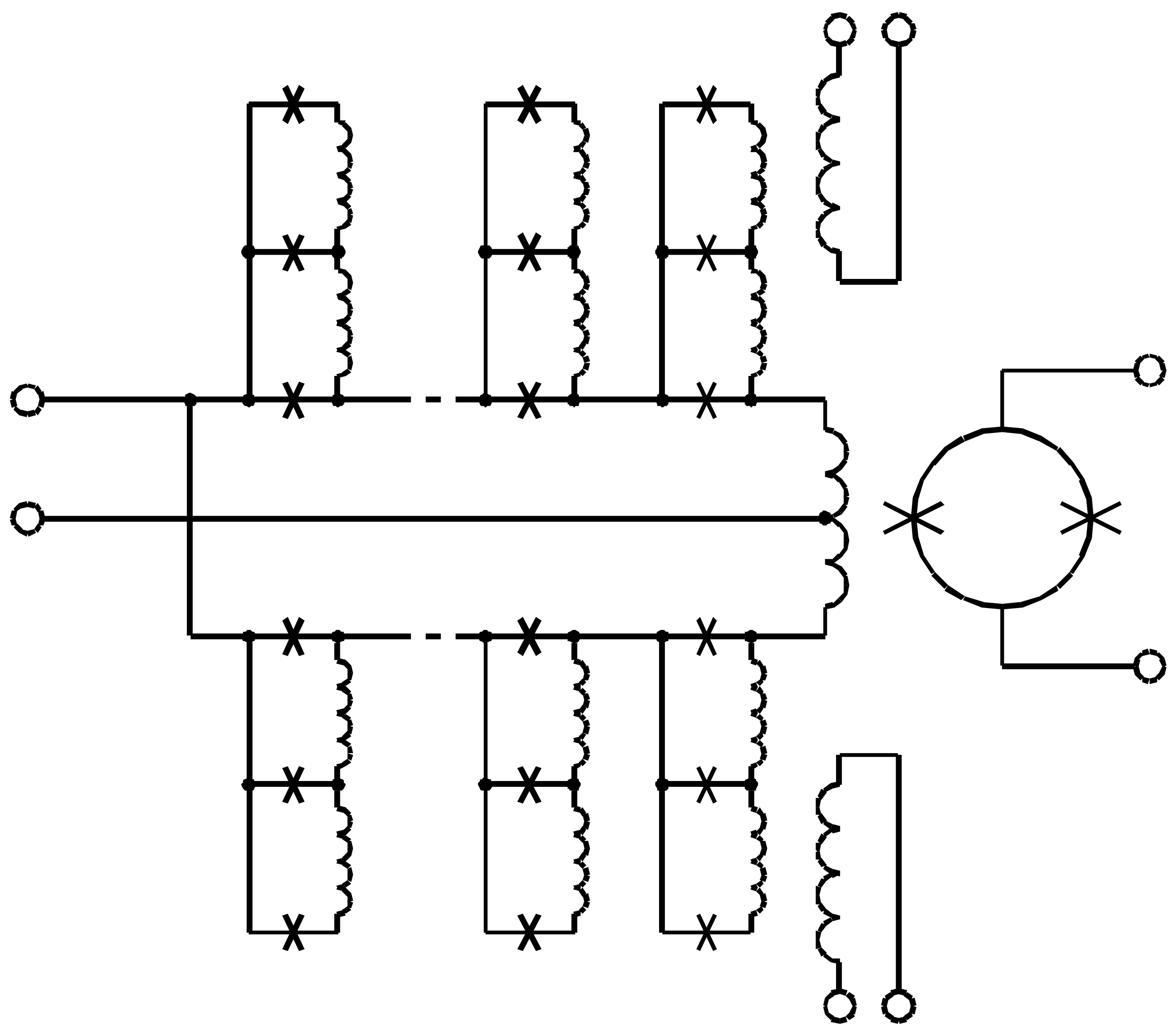
Current steering switches: **10** Zappe interferometers **in series**

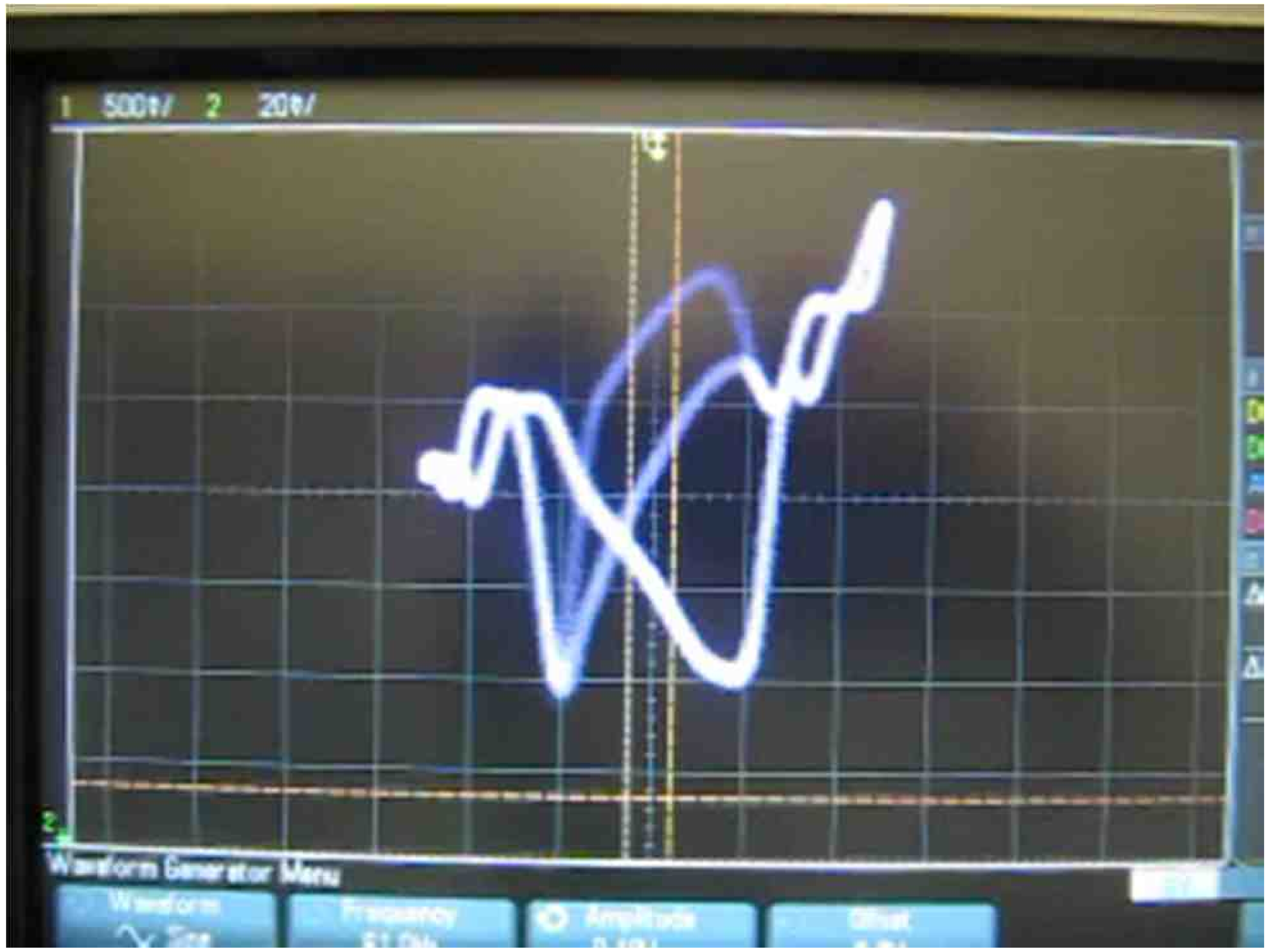
Antialias filters



Functions in a strange way!

Current steering test switch, inductive mode

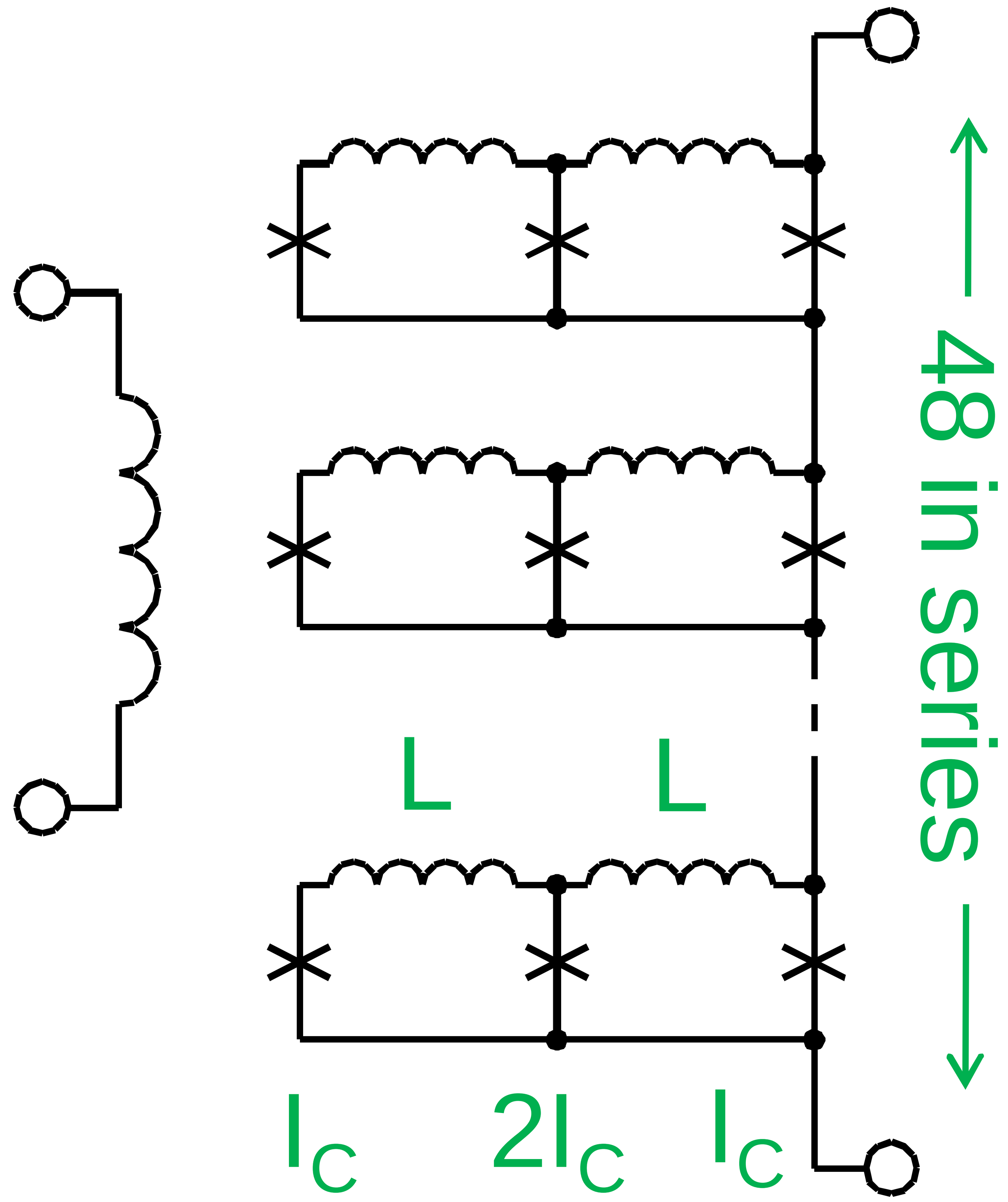


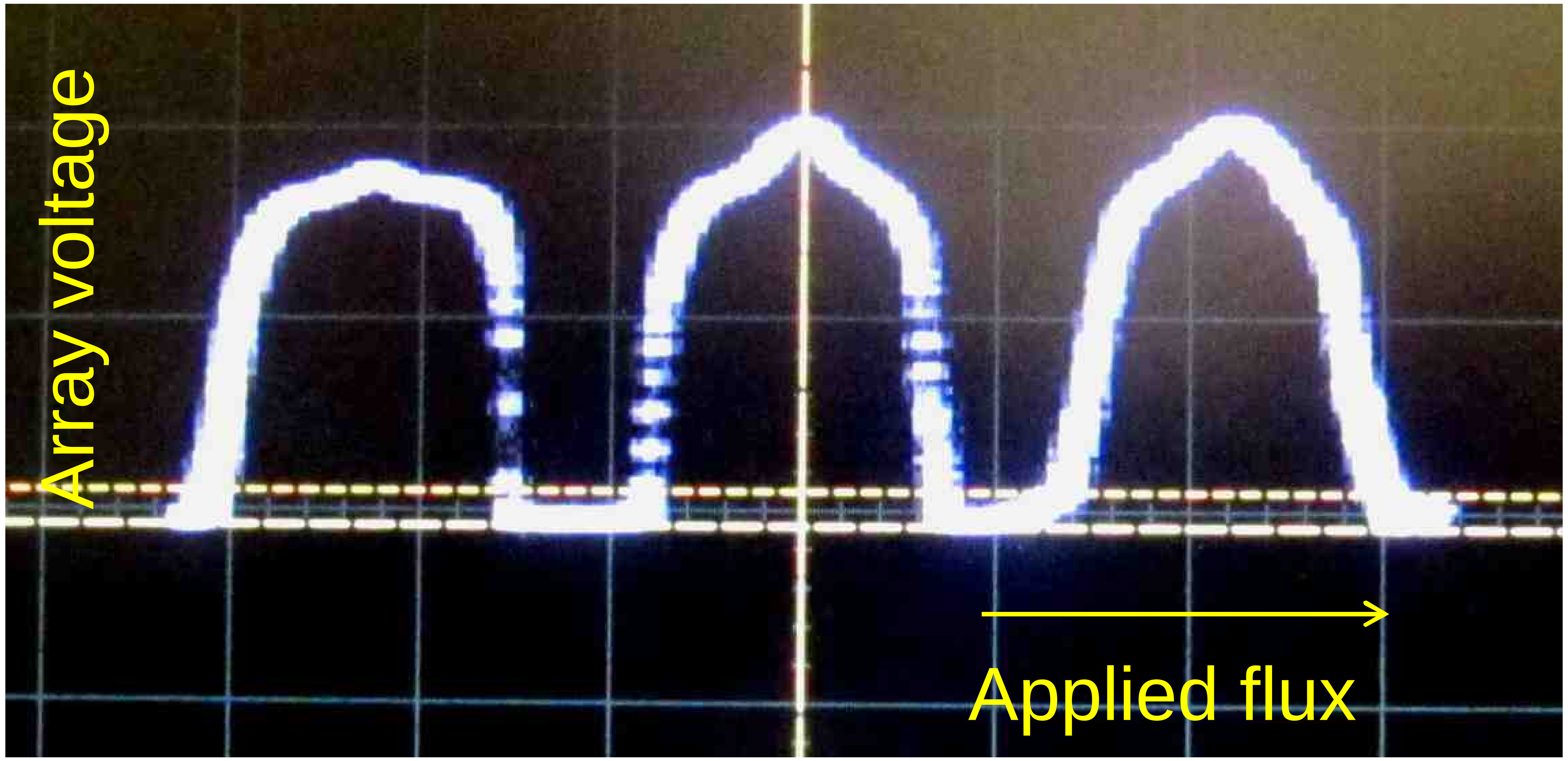


Response not exactly what we anticipated!

- Flux trapping in inductive mode (not in voltage mode)?
- Back-action from readout SQUID?
- Strong envelope in interference pattern?

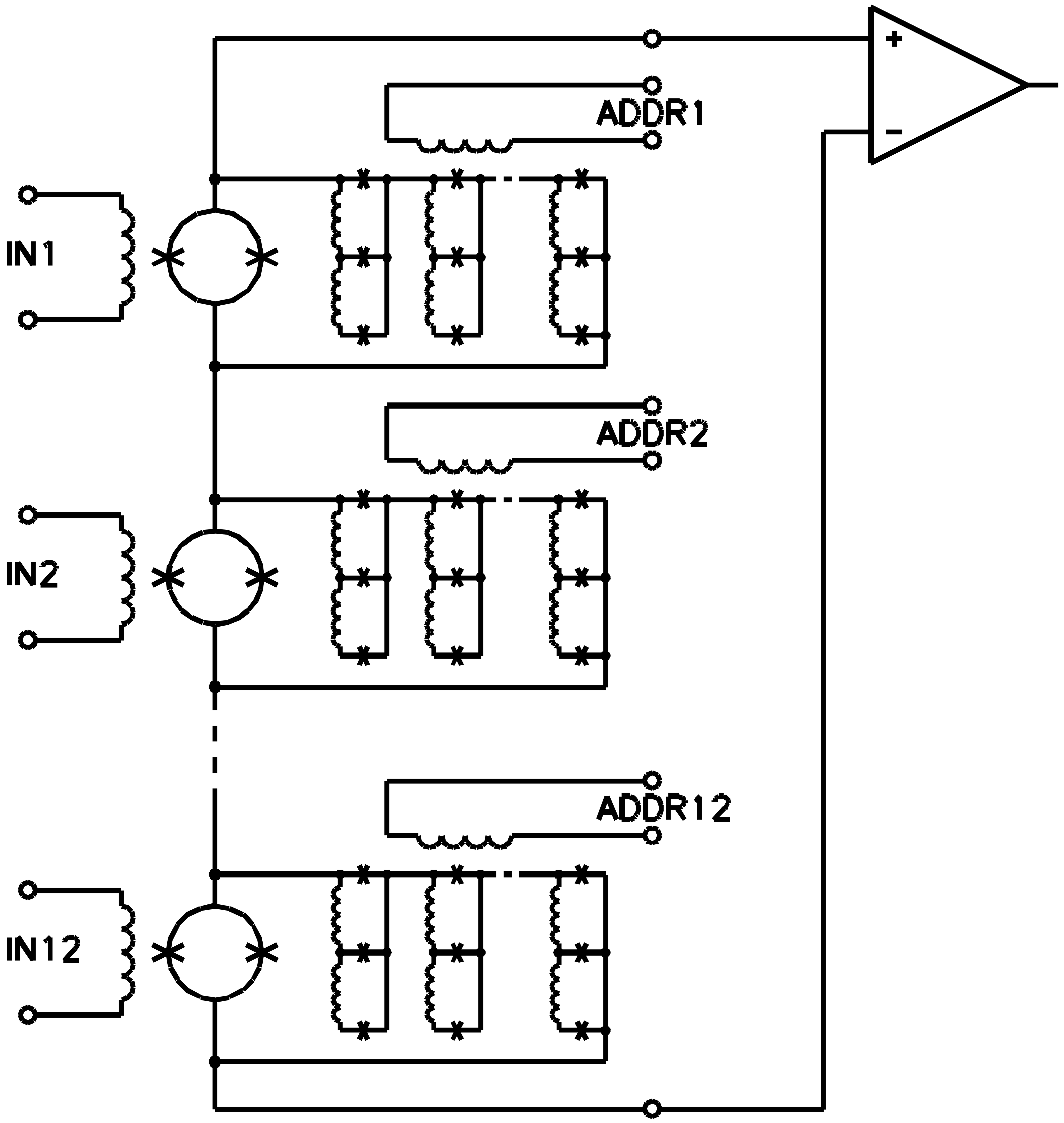
Zappe interferometer arrays in voltage state

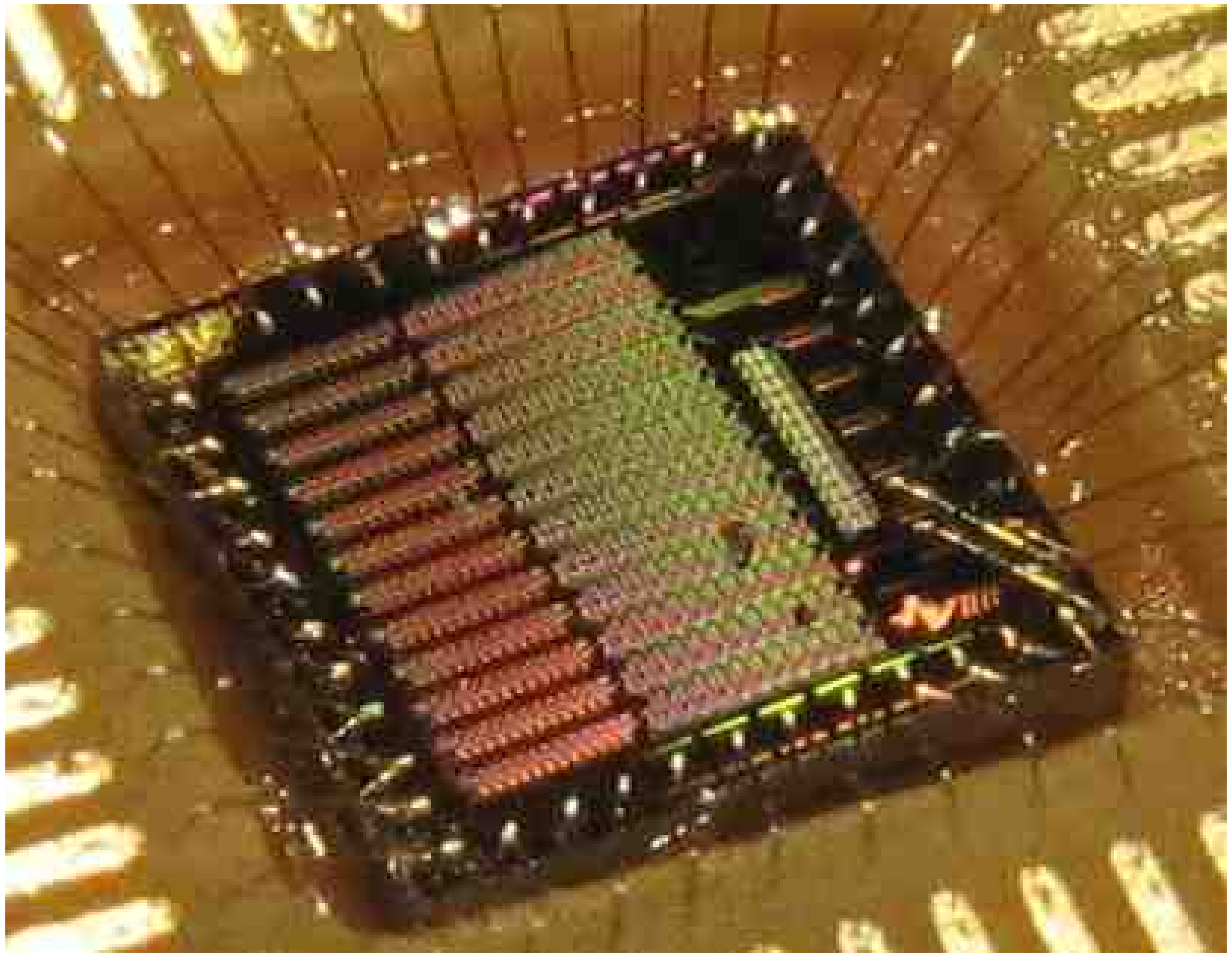




They function nicely as expected!

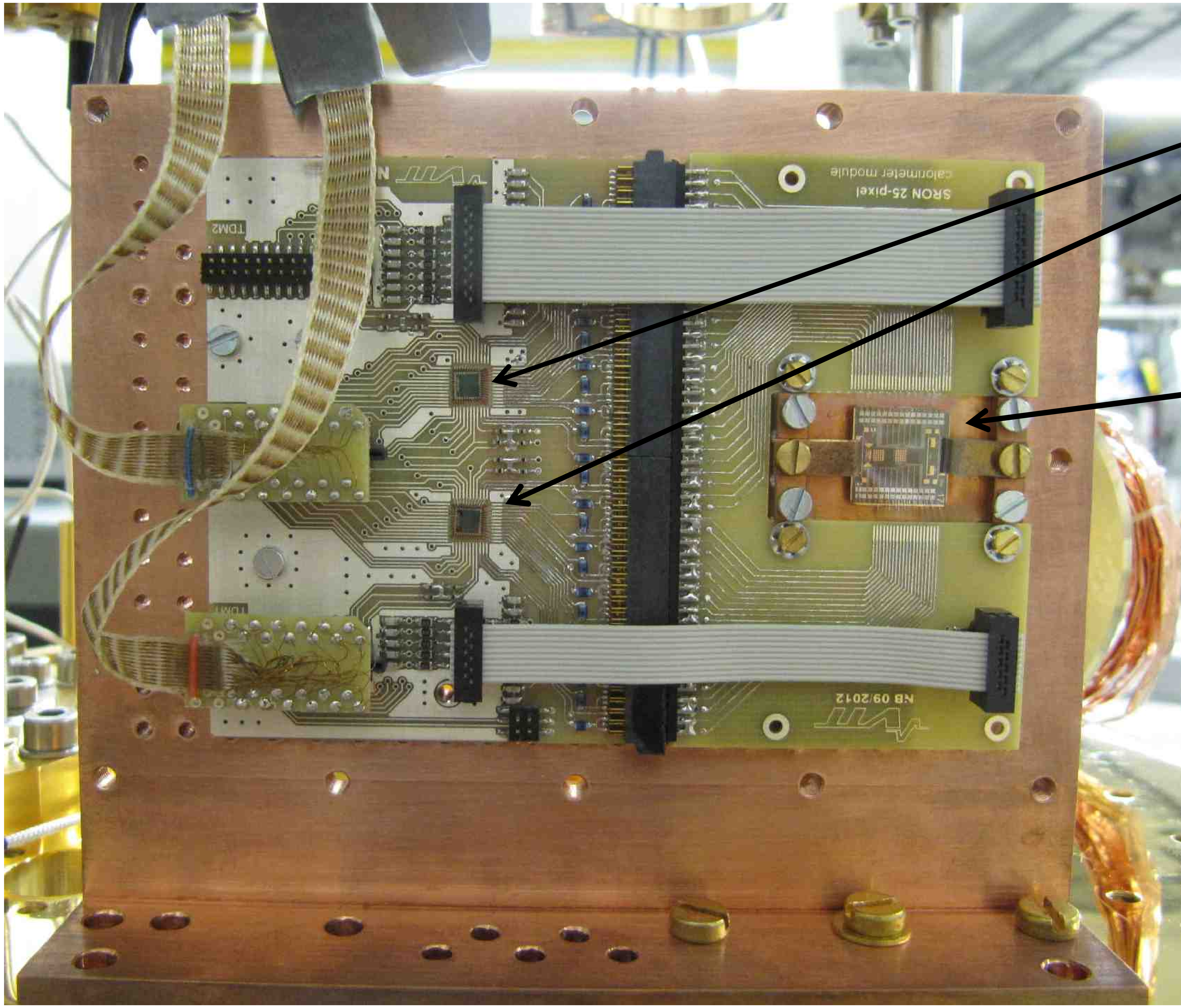
12-channel Beyer-style time domain MUX using voltage-state Zappe switches





Works nicely at 4.2K with test loads

Experimental 100mK TDM calorimeter setup



1:12 TDM MUX chips

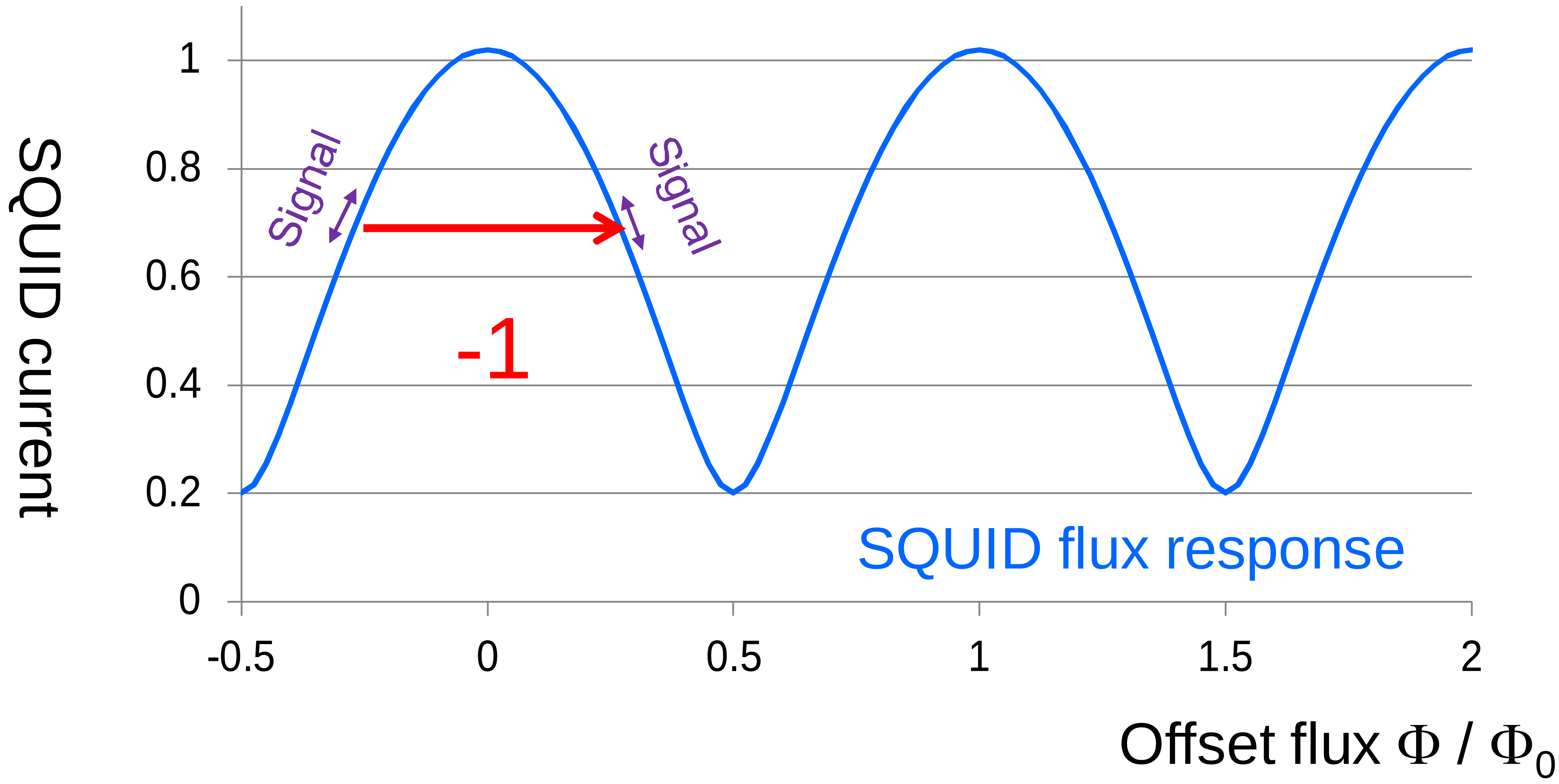
5 x 5 X-ray calorimeter array (SRON)

So far suffers from heat leakage through the Faraday cage structure ⇒ **no data yet**

Binary-to-Hadamard coding

(orginally K. Irwin, SuST 2010)

SQUID slope change as the commutating switch

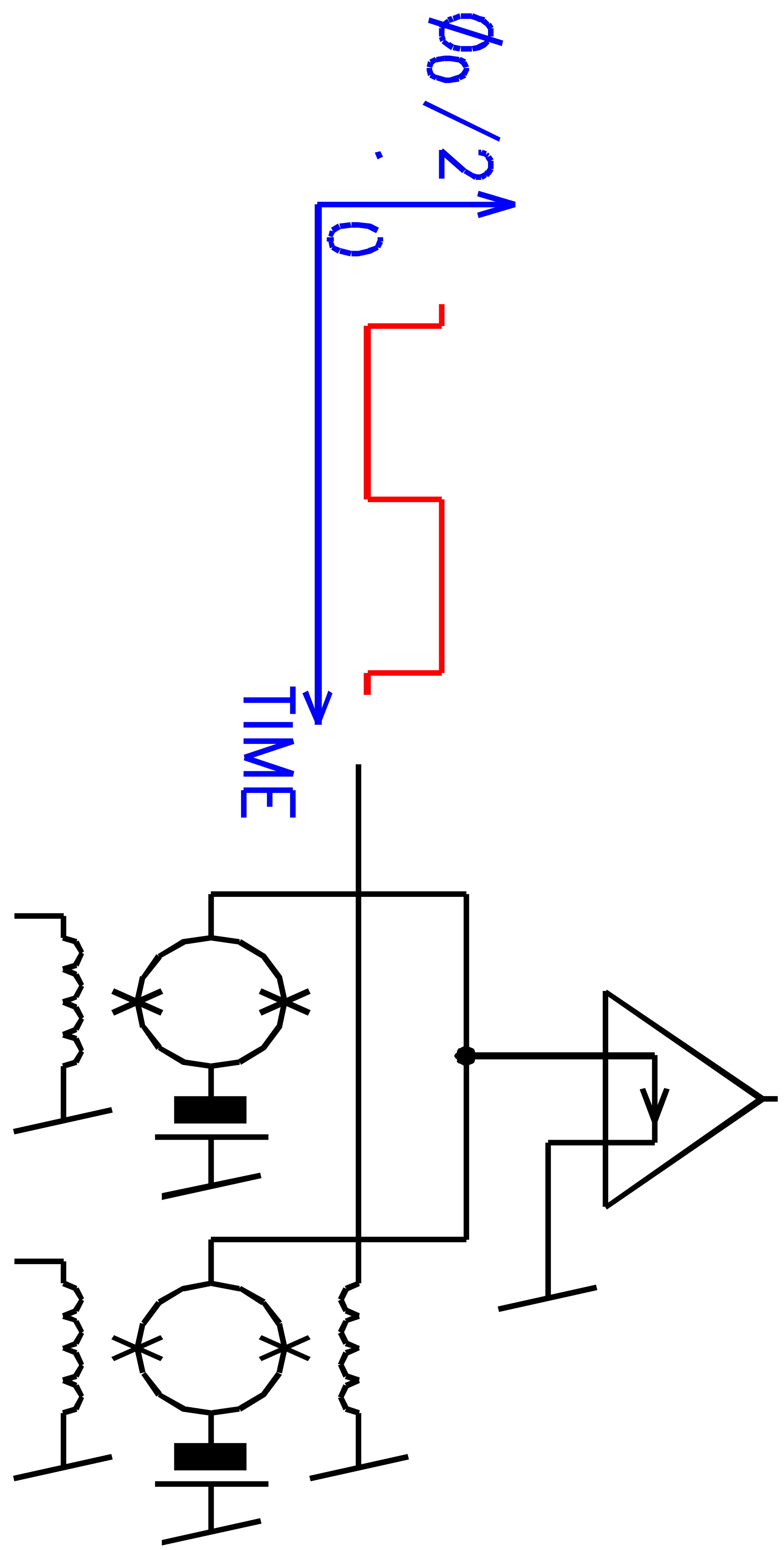


The primitive Hadamard matrix

Time evolution

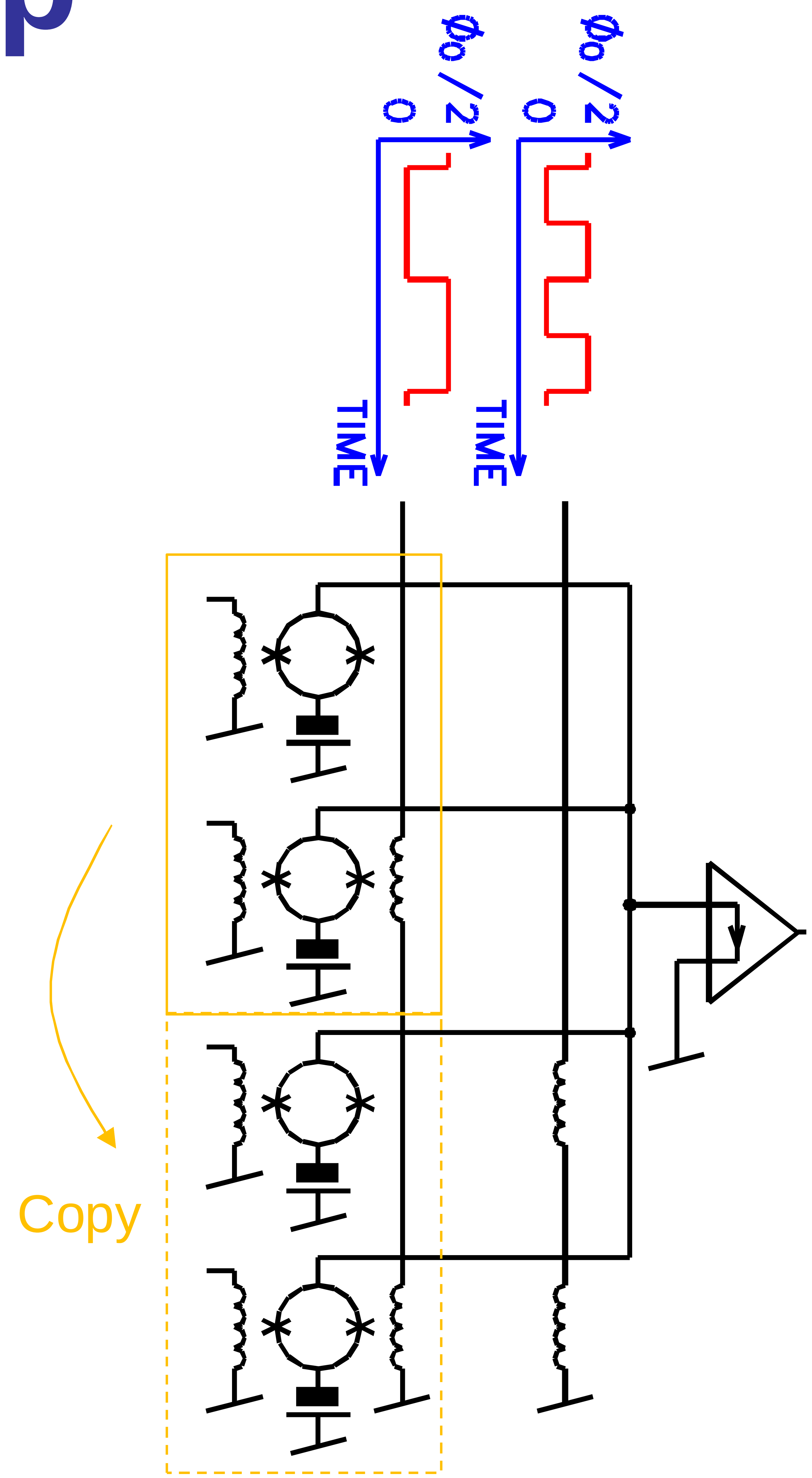
Channels, orthogonal codes

$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

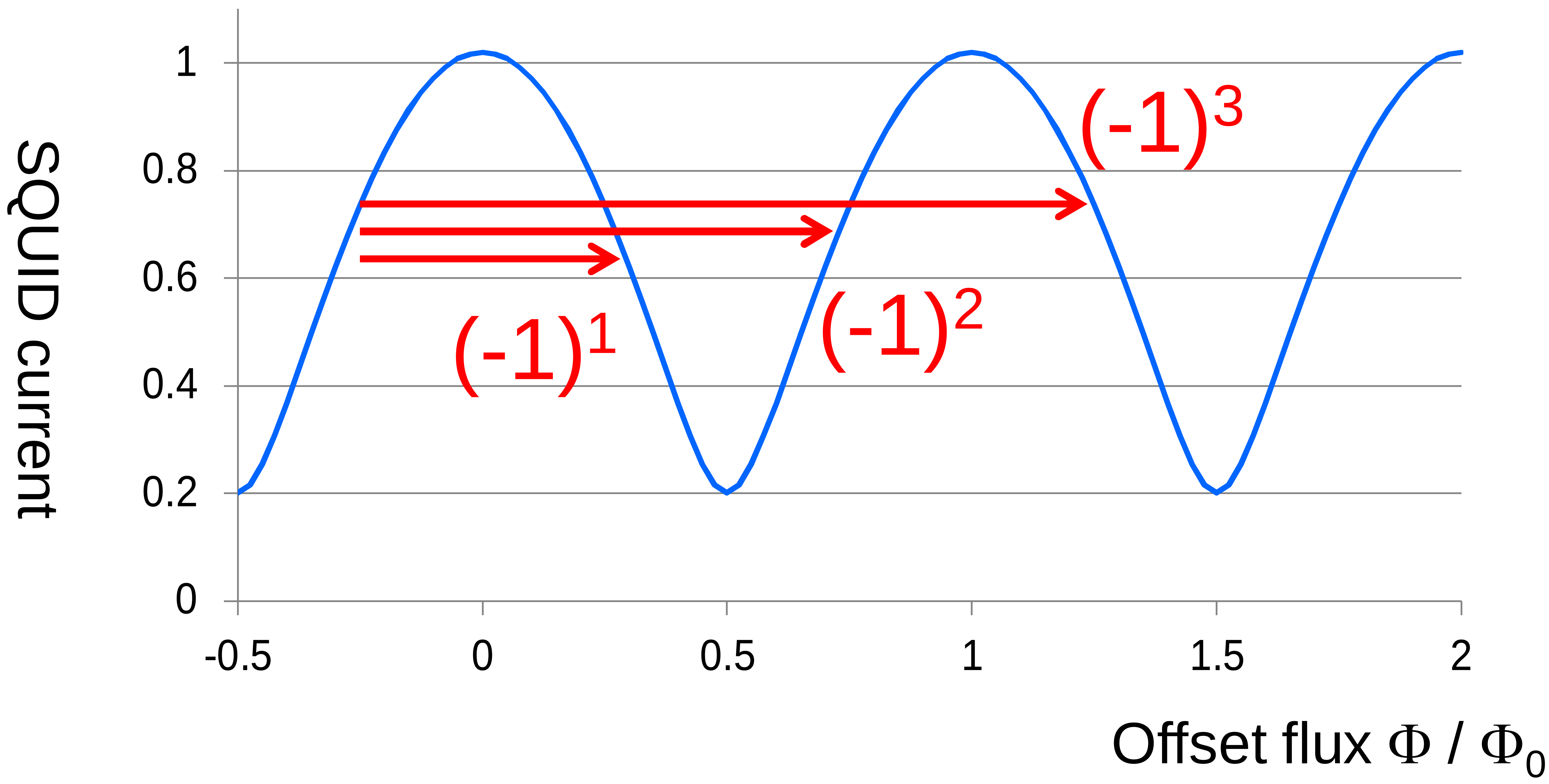


First recursive step

$$\begin{bmatrix} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} & \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \\ \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} & -\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \end{bmatrix}$$

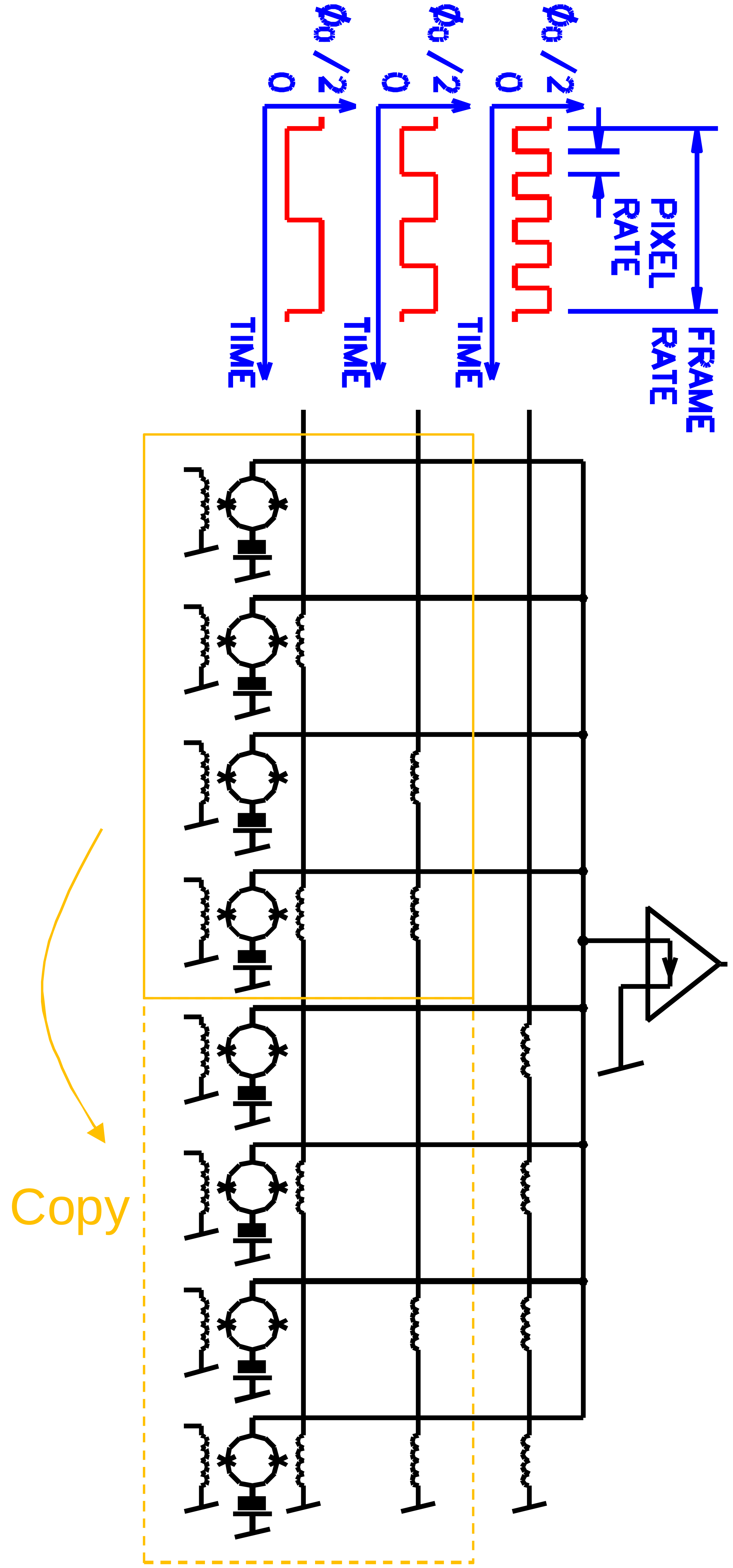


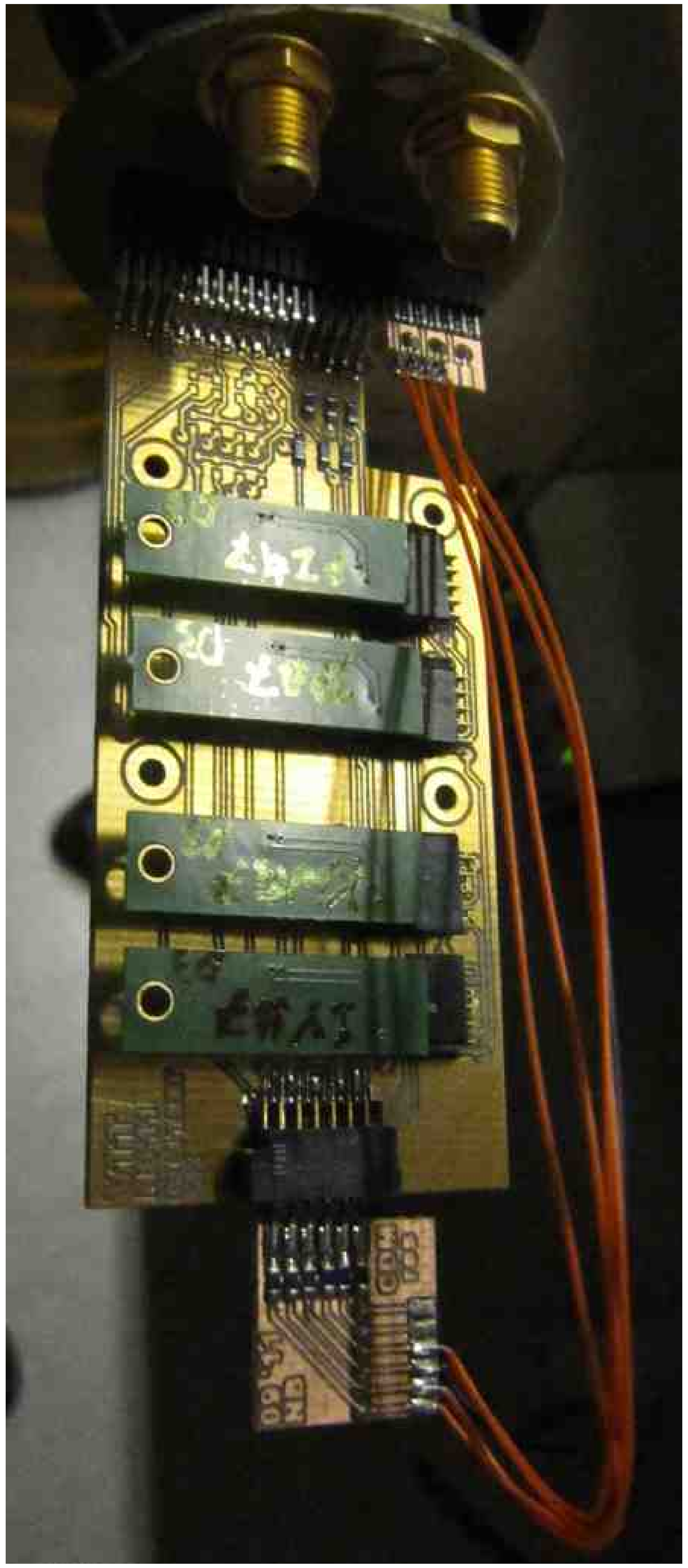
Successive multiplications by -1
$\Leftrightarrow$ Successive Φ_0 / 2 flux shifts

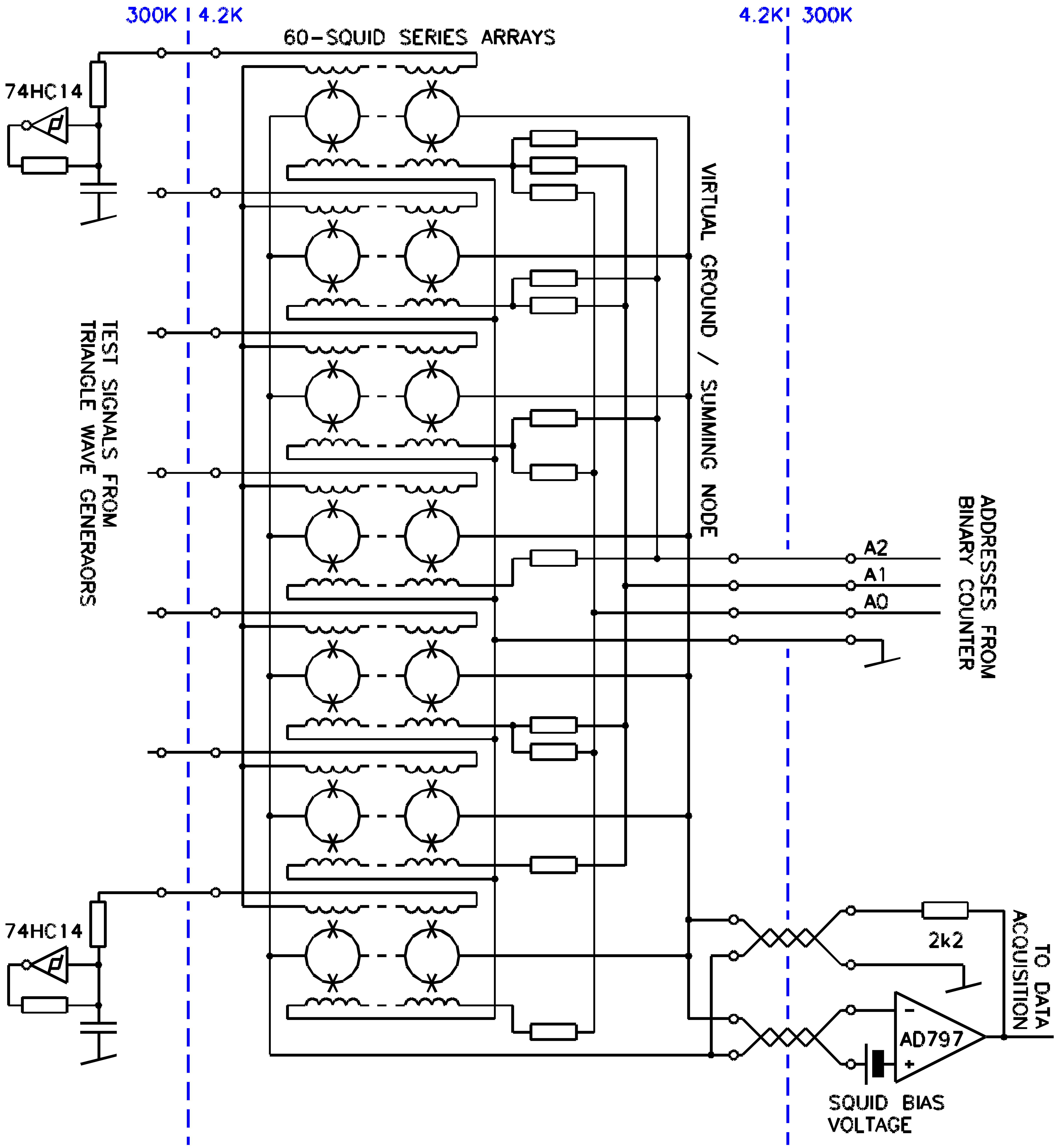


Second recursive step

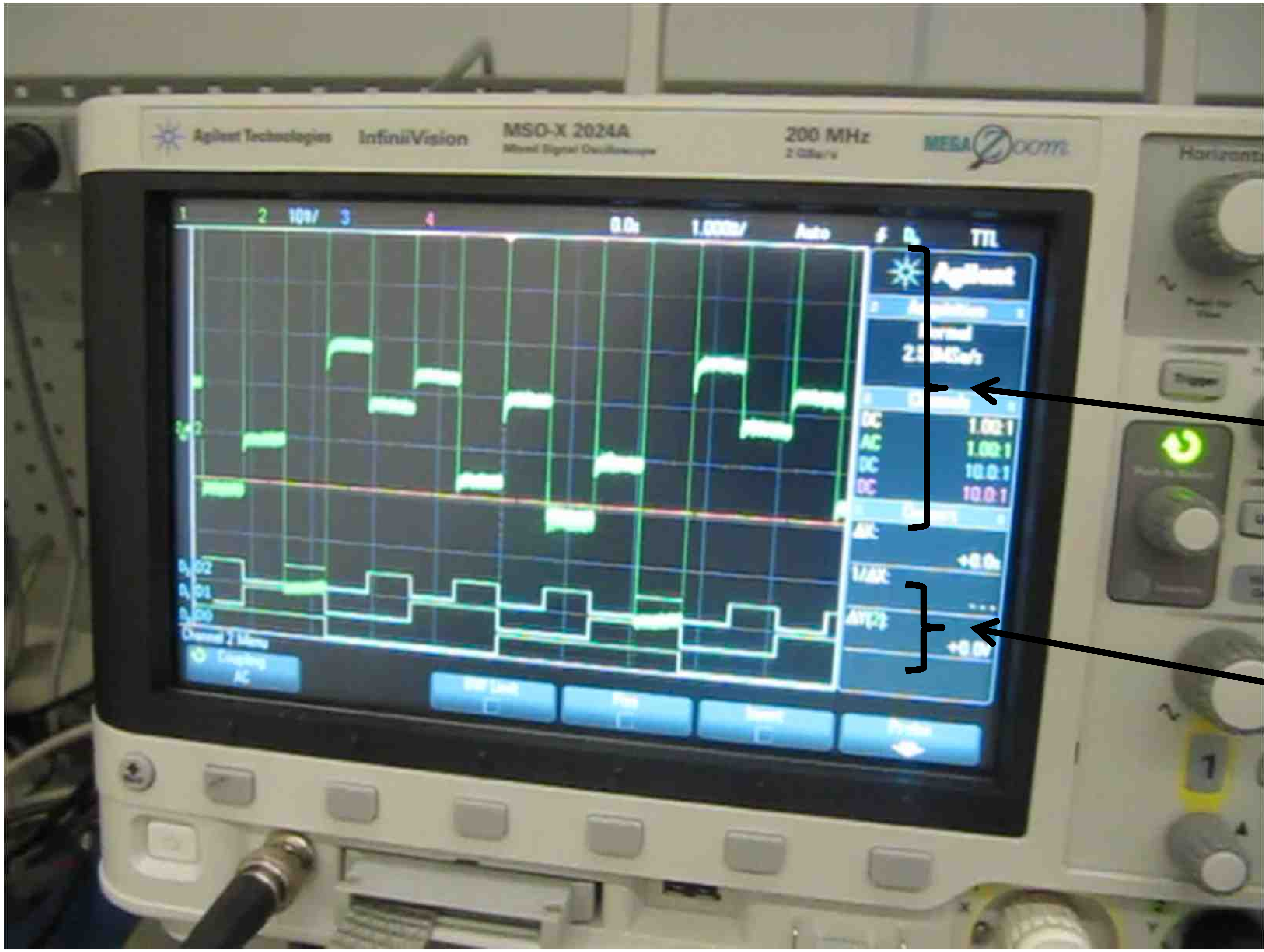
$$
\begin{bmatrix}
\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & \begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & \begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & \begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}\\
\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & -\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & \begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & -\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}\\
\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & \begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & -\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & -\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}\\
\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & -\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & -\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} & \begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}
\end{bmatrix}
$$






300K
4.2K
4.2K
300K
60-SQUID SERIES ARRAYS
74HC14
74HC14
TEST SIGNALS FROM
TRIANGLE WAVE GENERAORS
VIRTUAL GROUND / SUMMING NODE
A2
A1
A0
ADDRESSES FROM
BINARY COUNTER
2k2
AD797
TO DATA
ACQUISITION
SQUID BIAS
VOLTAGE

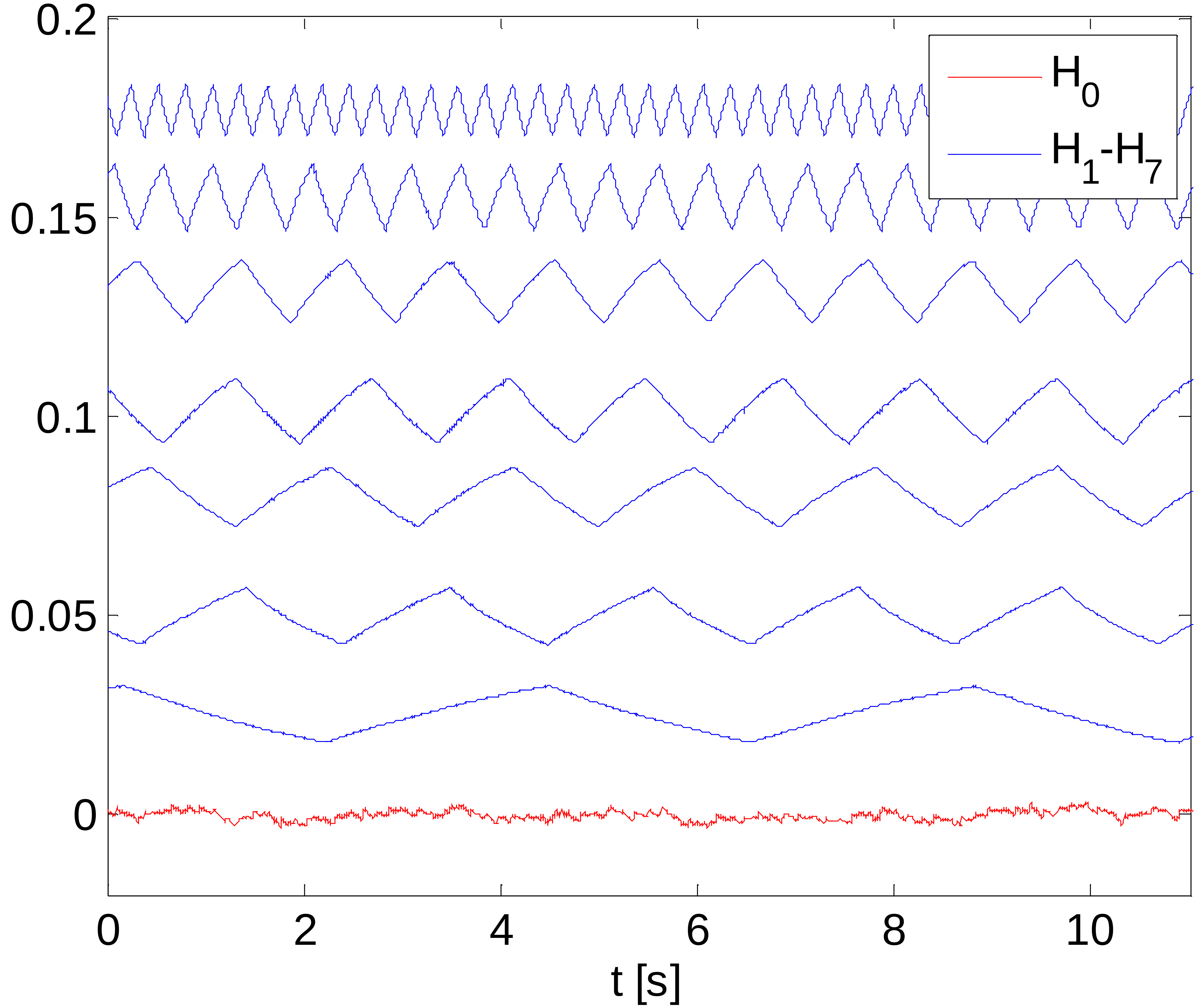
7-ch Hadamard coded output, one input driven by sawtooth



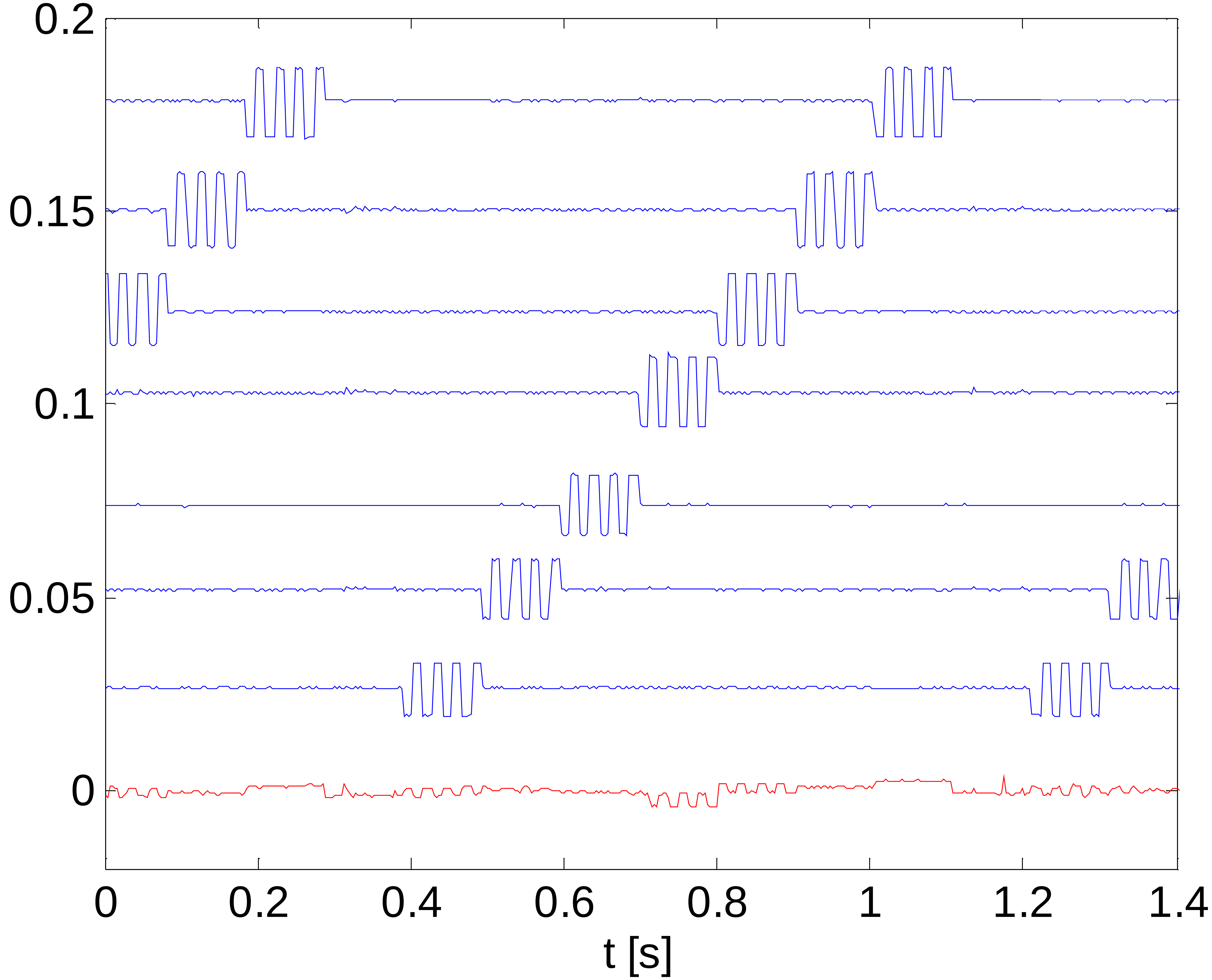
Summed output from SQUIDs

3-bit binary address at 2500 pix/s

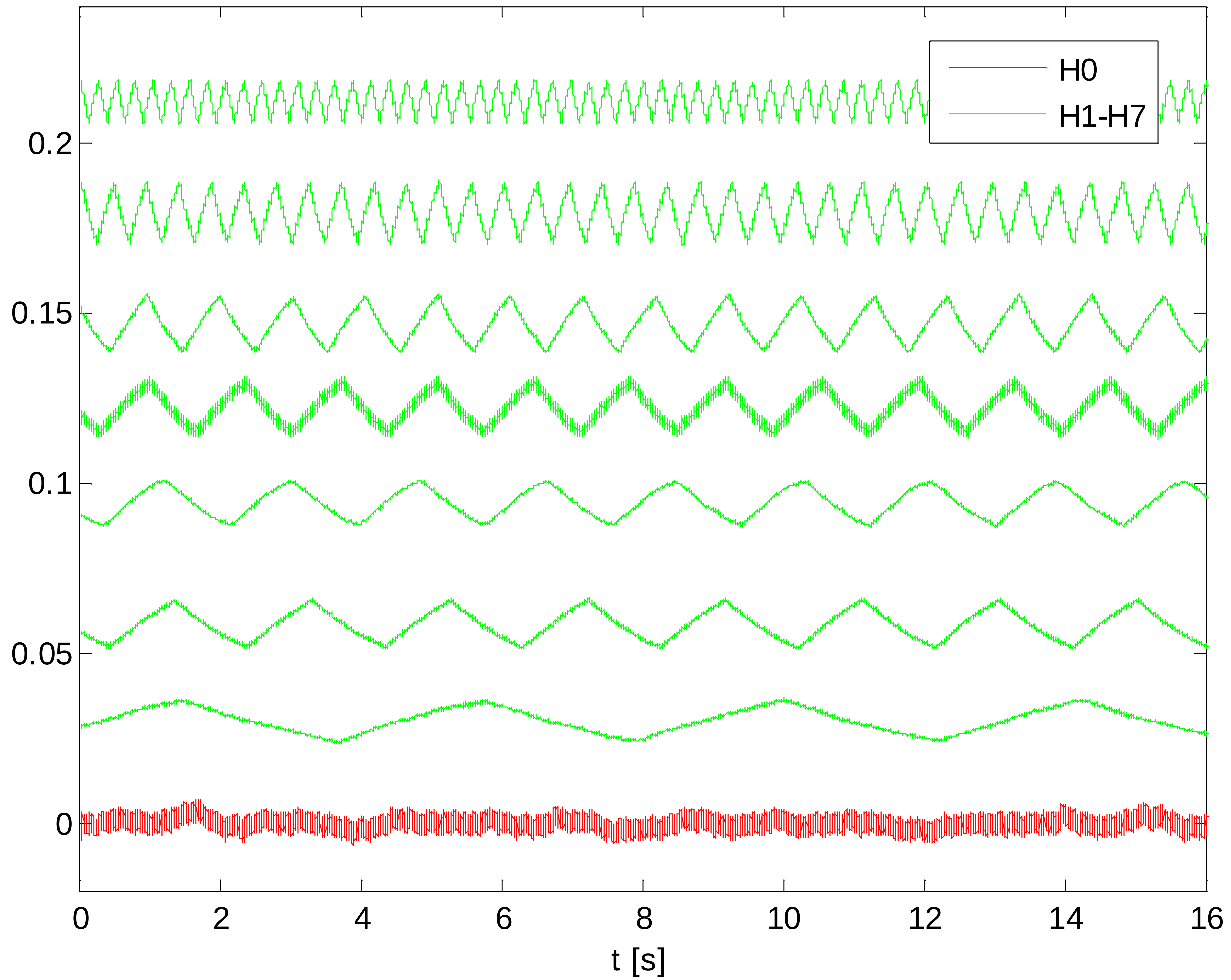
Seven test signals multiplexed and demultiplexed at 2.5 kpix/s



Seven calibration signals multiplexed and demultiplexed at 2.5 kpix/s



Seven test signals multiplexed and demultiplexed at 30 kpix/s



What have we learned, achieved?

- Log N scaling (binary addressing) is much more efficient than $N^{1/2}$ scaling, inherent in NIST-style TDM.
  - Example: 16 384 pixels require 128 address lines via TDM, 14 address lines via binary-addressed CDM.
- Slope-switching adds SQUID noise ~$N^{1/2}$.
  - Unattractive, but no worse than the noise penalty in TDM.
- Our design of current-steering switches may be misguided.
  - More complicated than the NIST design, complexity offers many paths for faulty operation.
- Cryogenic setup with X-ray calorimeters is almost ready
  - Thermalization problem must be solved
- Cross-compatible fab process, IPHT Jena ⇔ VTT Espoo

We have received support from the grant no. 262947 of the European Community's seventh framework programme (FP7/2007-2013) , and from the Center of Excellence in Low Temperature Quantum Phenomena and Devices by the Finnish Academy of Sciences.

Thank You!