Physikalisch-Technische Bundesanstalt PTB

Euresco Conference "Future Perspectives of Superconducting Josephson Devices", Acquafredda di Maratea, 1-6 July 2000

Recent Progress on Quantum Voltage Metrology

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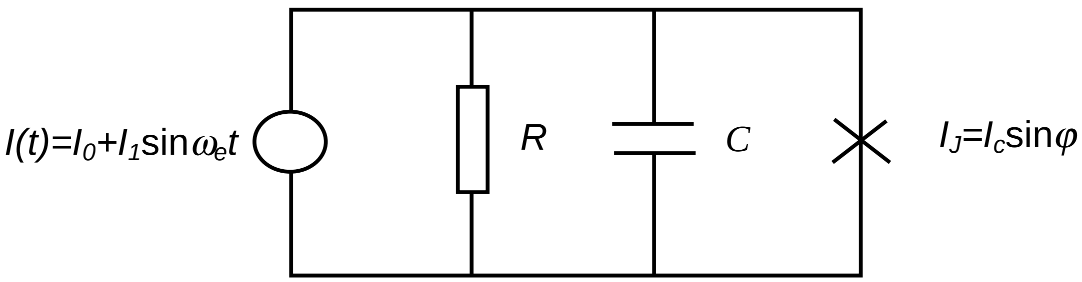
Josephson Junction: Real Case

Parallel connection of the external current source $I(t) = I_o + I_1 \sin\omega_e t$, the junction normal-state resistance R_n, the junction capacitance C, and the ideal Josephson inductance $I = I_c \sin\varphi$.



$$I_0 + I_1 \sin\omega_e t = I_c \sin\varphi + V(t)/R_n + C dV(t)/dt$$

Dimensionless with
$V(t) = (\hbar/2e)\, d\varphi/dt$
$i_0 = I_0/I_c, \quad i_1 = I_1/I_c,$
$\Omega = \hbar\omega_e/2eI_cR_n, \quad t' = \hbar t/2eI_cR_n$
$\beta = 2eI_cR_n^2C/\hbar$

$$\beta d^2\varphi/dt^2 + d\varphi/dt + \sin\varphi = i_0 + i_1 \sin(\Omega t')$$

$(\beta)^{1/2}$ is the quality factor for the LC Josephson resonator and characterises the damping of the Josephson oscillator.

Typical junction parameter for SIS, SNS, and SINIS junctions

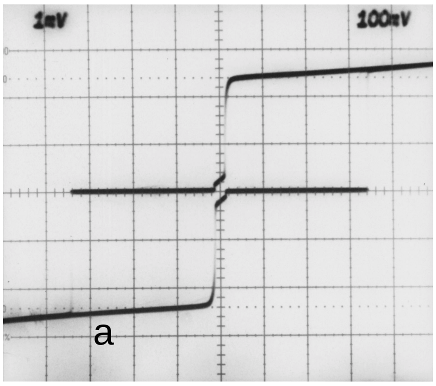
SIS: Superconductor-Insulator-Superconductor

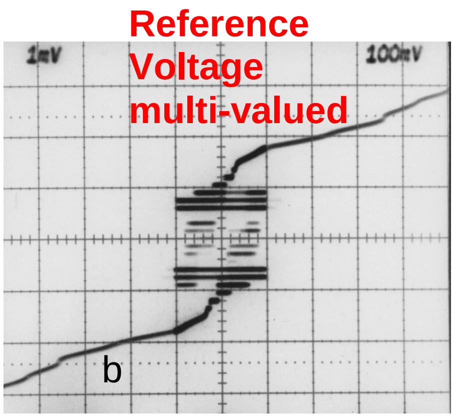
SINIS: Superconductor-Insulator-Normal Metal-Insulator-Superconductor

SNS: Superconductor-Normal Metal-Superconductor

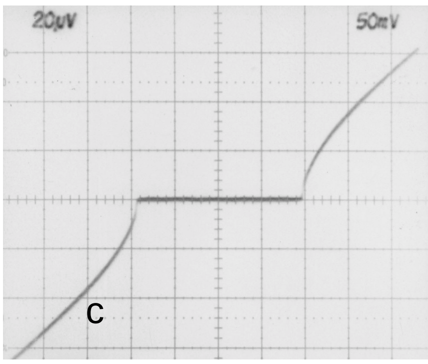
	SIS	**SNS**	**SINIS**
β	10^5	$\rightarrow 0$	1
I_cR_n	1 mV	20 μV	100 μV
$\omega_e/2\pi$	70 GHz	10 GHz	70 GHz
R_n	100 Ω	0,003 Ω	0,1 Ω
$(\omega_e C)^{-1}$	0,06 Ω	$\rightarrow \infty$	0,06 Ω
A	20x50 μm^2	2x2 μm^2	20x50 μm^2

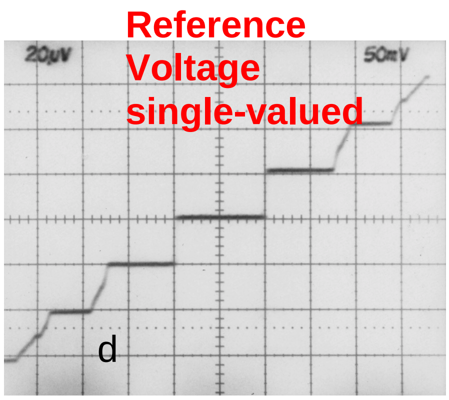
a) DC characteristic of a Nb-Al_2O_3-Nb tunnel junction. Vertical: 1 mV/div, Horizontal: 0.125 mA/div.
b) DC characteristic of a Nb-Al_2O_3-Nb tunnel junction under 70 GHz microwave radiation.





c) DC characteristic of a Nb-PdAu-Nb junction. Vertical: 20μV/div, horizontal: 0.4 mA/div.
d) DC characteristic of a Nb-PdAu-Nb junction under 10 GHz microwave radiation. Vertical: 20μV/div, Horizontal: 0.4 mA/div.





Josephson reference voltages > 1mV require large series arrays!

Josephson Series Arrays for Voltage Metrology

Stable phase-lock of the Josephson junctions to the external oscillator is essential

1. Chaos-free coupling of the Josephson oscillators to the external microwave source

- $\omega_p < \omega_e$

$\omega_p = (2eI_c/\hbar C)^{1/2} = (\beta)^{1/2}/R_nC$ (Plasma frequency)
$\beta = 2eI_cR_n^2C/\hbar$

- $\omega_p \approx \omega_c$ (for SNS and SINIS junctions)

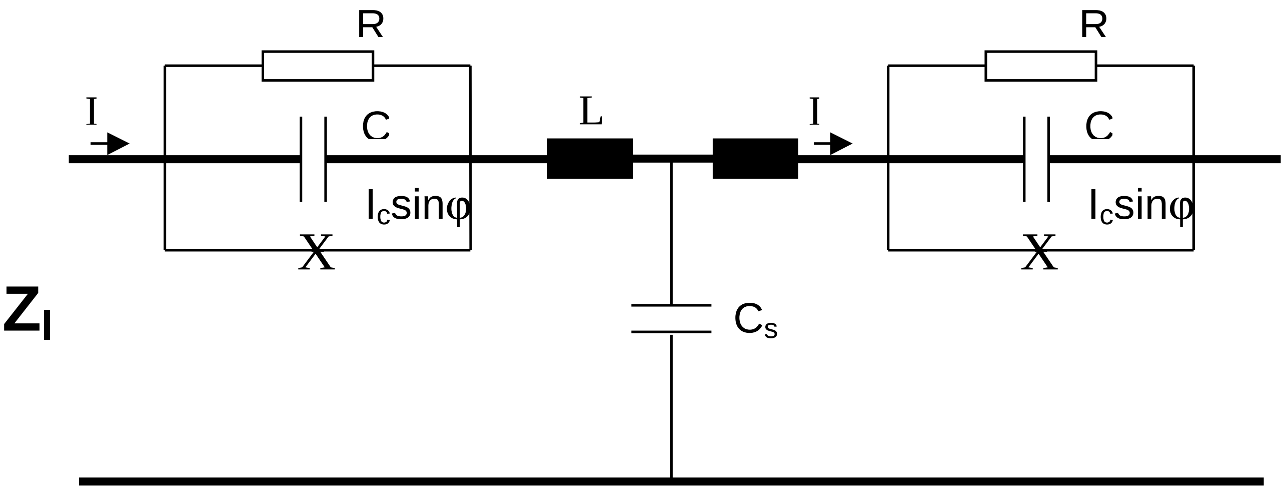
$\omega_c = 2eI_cR_n/\hbar$ (characteristic frequency)

- No phase variation across the junction area (small junctions)

2. Homogenous microwave distribution

- Arrays must be an integrated part of microwave transmission lines

Section of the periodic stripline



The **amplitudes of the current components** may be estimated to:

$I_n \approx V/R_n$ $\qquad$ $I_C \approx V\omega C$ $\qquad$ $I_J \approx V/\omega L_J$

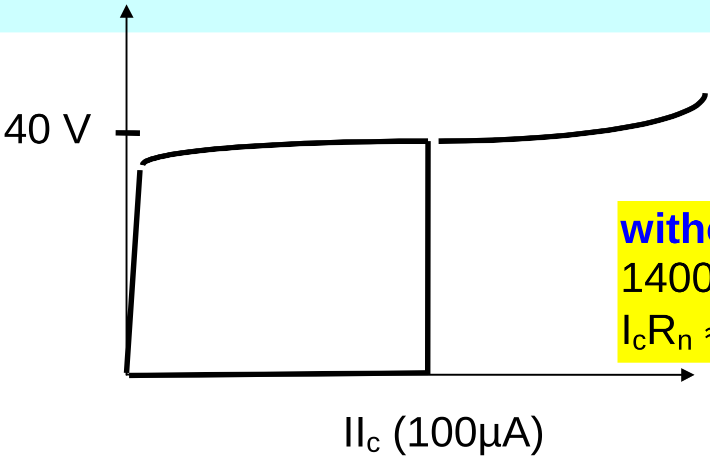
The **degree of matching the stripline impedance Z_l to R_n** and the **size of the RF current component** flowing through R_n determines how much microwave power is coupled to the junction and by this the **stripline attenuation α**

Typical data (microstripline):

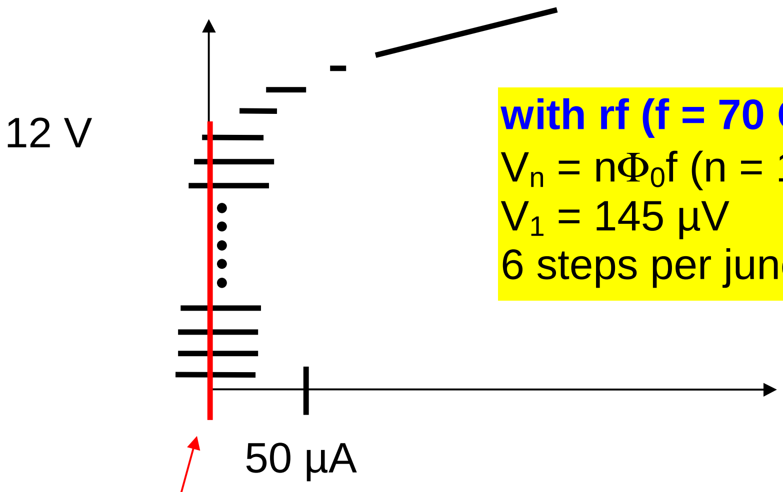
	SIS	*SNS*	*SINIS*
β_c	10^5	0	1
A	20x50 μm^2	2x2 μm^2	20x50 μm^2
I_cR_n	10 mV (subgap)	20 µV	100 µV
$\omega_e/2\pi$	70 GHz	10 GHz	70 GHz
$\omega_p/2\pi$	15 GHz	----------	50 GHz
$\omega_c/2\pi$	------------	10 GHz	50 GHz
R_n	**100 Ω (subgap)**	**0,003 Ω**	**0,1 Ω**
$(\omega C)^{-1}$	**0,06 Ω**	$\rightarrow \infty$	**0,06 Ω**
ωL_J	**1,3 Ω**	**0,03 Ω**	**0,15 Ω**
Z_l	5Ω	150Ω	5Ω
w/d	50µm/2µm	3µm/365µm	(50µm/2µm)
$L;C_s$	1,5 pH; 0,2 fF	4 pH; 0,3 fF	1,5 pH; 0,2 fF
α	**0,00012 dB/period or 0,002 dB/mm**	**0,0015 dB/period or 0,25 dB/mm**	**0,05 dB/period or 1 dB/mm**

Conventional Josephson Voltage Standard

SIS- arrays (underdamped junctions):
output voltage 10V
Uncertainty: ± $5x10^{-11}$



without rf
14000 junctions
$I_cR_n \approx$ 2 mV



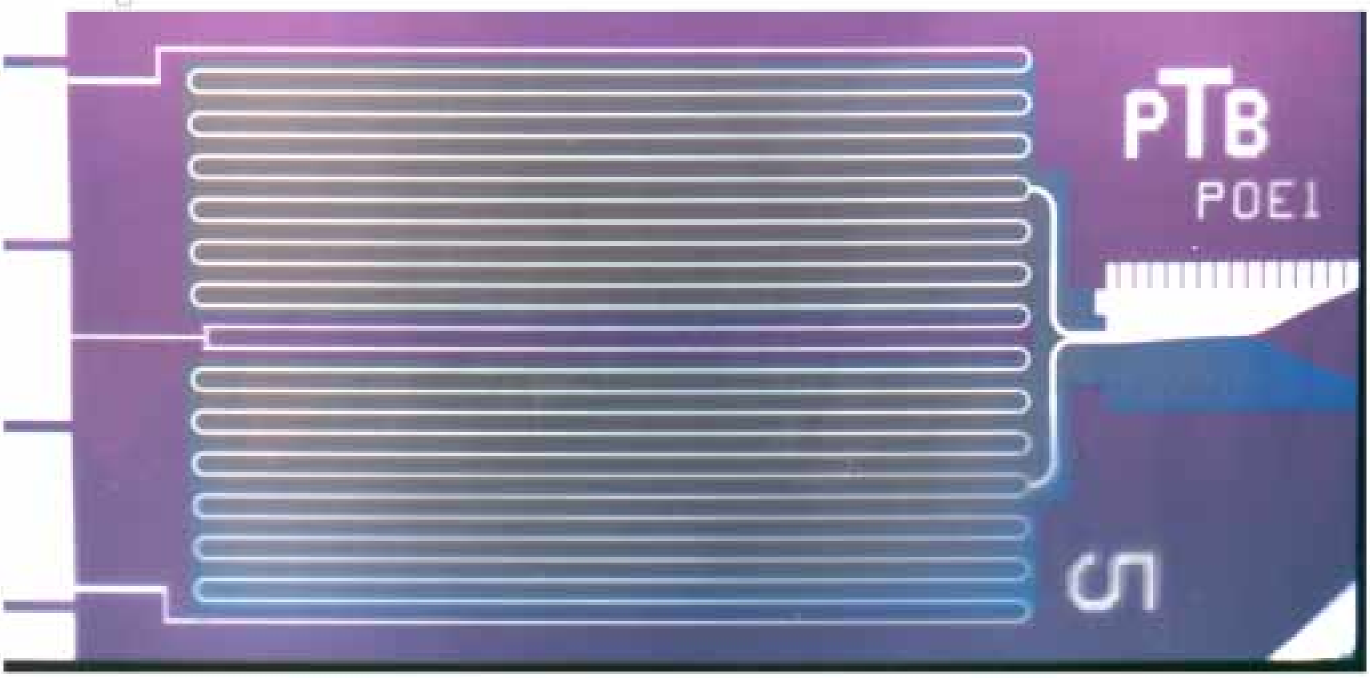
with rf (f = 70 GHz)
$V_n = n\Phi_0 f$ (n = 1,2,....,82000)
V_1 = 145 µV
6 steps per junction

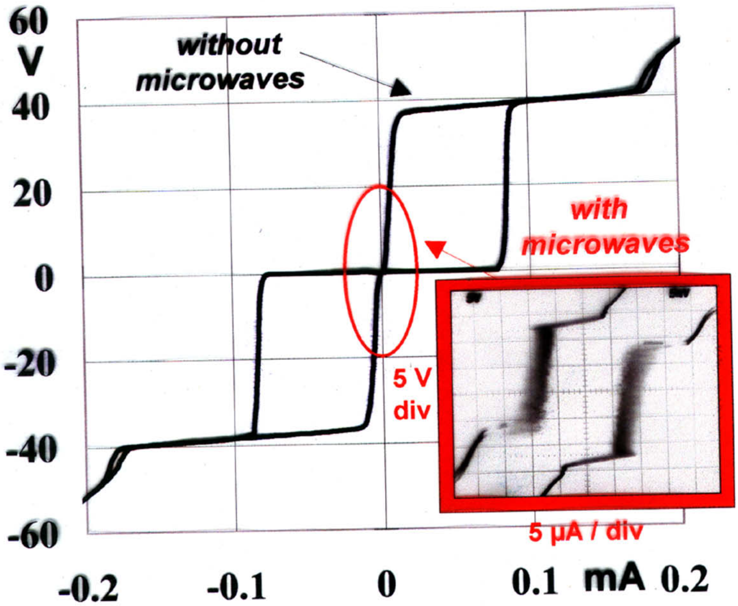
Bias I = 0
V multi-valued but precisely quantized into fundamental voltage steps: 82000 for 12 V

Series Array of 14 000 Nb-Al2O3-Nb Josephson Junctions

Junction area: 20x50 µm2

Size of the Si-Chip: 1x2 cm2

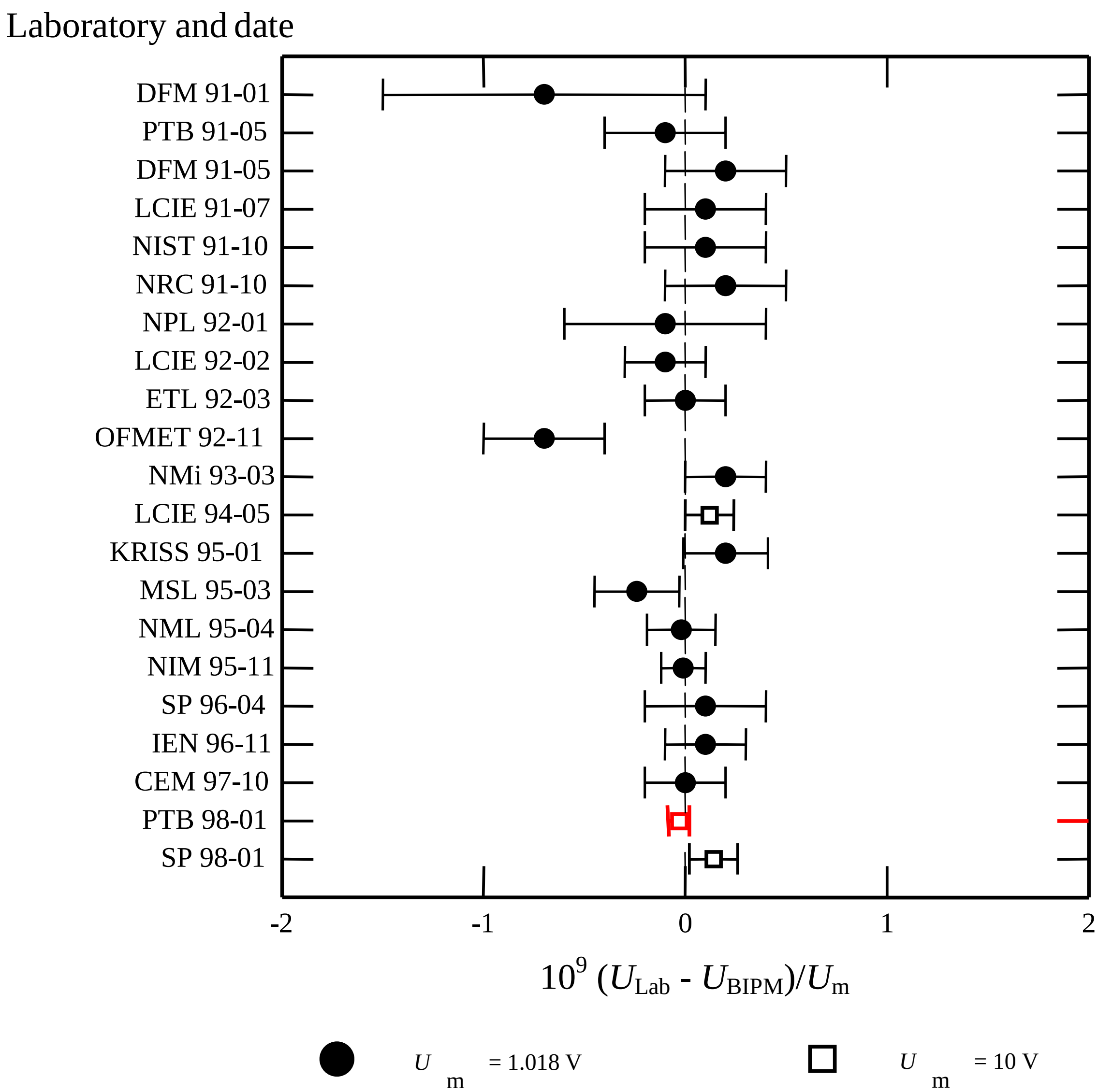




***I-V* characteristic of a 10 V circuit**

- jc = 10 A/cm^2, i.e. f/f_p = 6
- 10 mW at antenna / 70 GHz
- zero-current steps from -12 V to +12 V
- current-width at 10 V : 25 μA
  (more than 1 hour stable)
- each step can be selected
  without changing the rf-power

Results of BIPM on-site key comparisons of Josephson standards
(BIPM.EM-K10.a and BIPM.EM-K10.b)



$U_{PTB} – U_{BIPM}$ = - 3 · 10^{-11} V with a relative uncertainty of 5 · 10^{-11} V

Weighted means of direct and indirect (via transfer voltage device)
with combined type-A and type-B uncertainties from both

Conventional Josephson Voltage Standard

Advantages:

- established technology
  - relatively large linewidths
  - no shunts
- large output voltages per junction
  - high order steps (7)
  - high drive frequency
- tolerates series resistances at zero current bias
- tolerates shorts
- tolerates large parameter spread

Consequences:
⇒large DC output voltages
⇒moderate fabrication effort

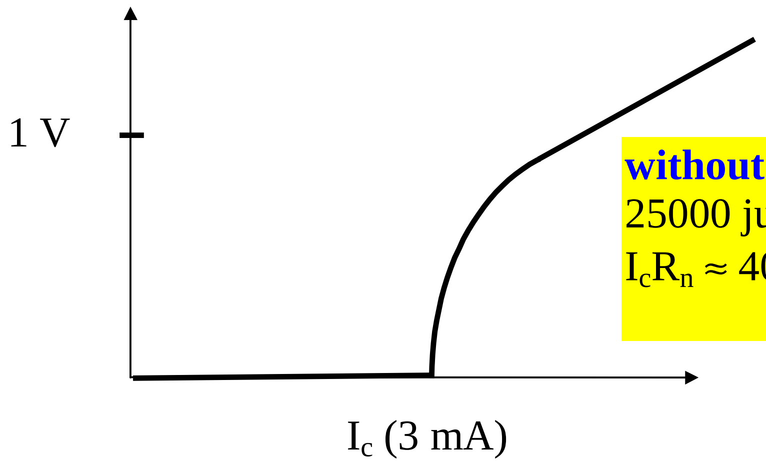
Disadvantages:

- HTS technology not available (hysteretic tunnel junctions!!!)
- DC output voltage not single-valued
  - difficult to adjust
  - after bias lost no automatic return
  - readjustment time consuming
  - voltage step of the individual junction not adjustable
- DC output voltage instabilities (chaos??)

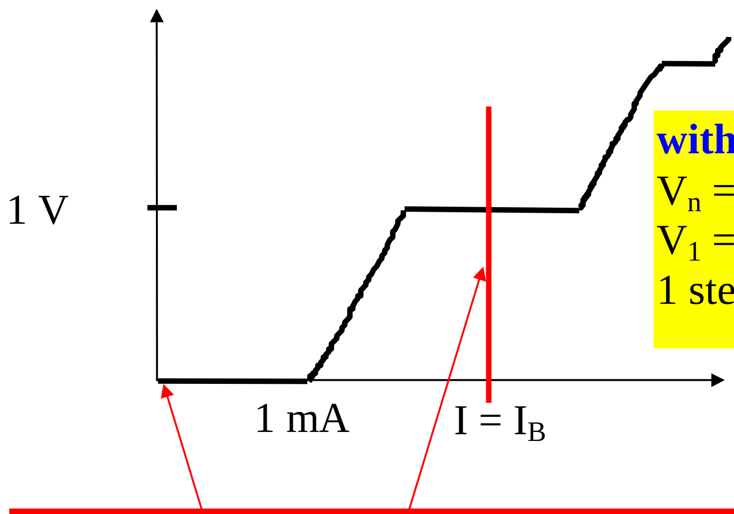
Consequences:
⇒no high operation temperatures
⇒no AC synthesis?
⇒no AC voltage measurements?

Programmable Josephson Voltage Standard (D/A converter)

SNS- or SINIS- arrays (highly damped junctions):
output voltage 1V
Uncertainty: ± 2×10^{-10} V



without rf
25000 junctions
$I_c R_n \approx 40\ \mu V$



with rf (f = 20 GHz)
$V_n = n\Phi_0 f$ (n = 25000)
$V_1 = 40\ \mu V$
1 step per junction

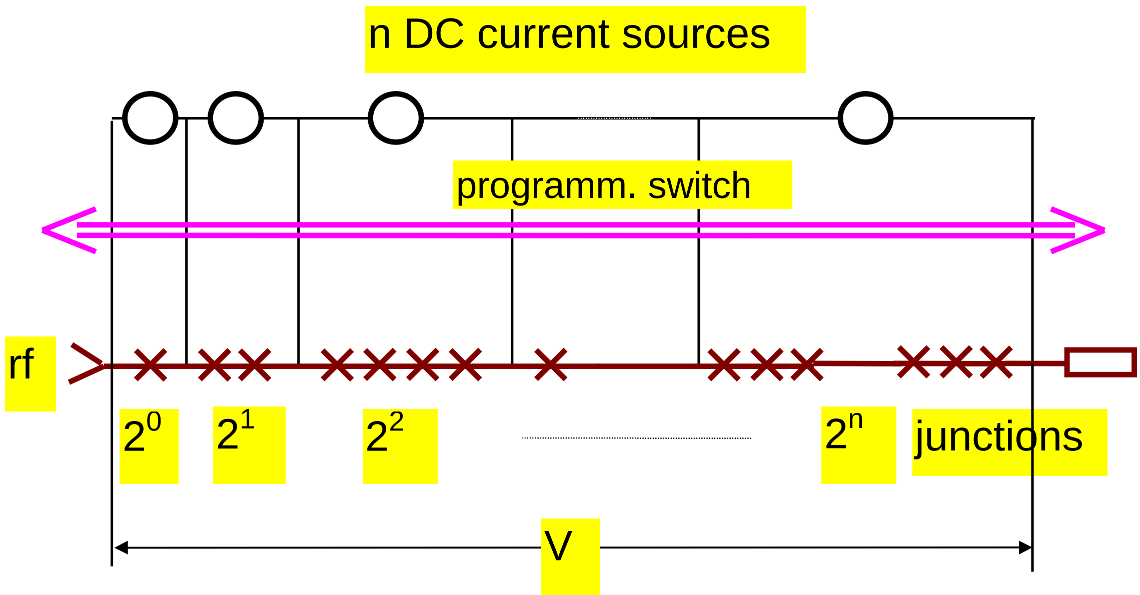
Bias I = 0 or I = I_B
Output voltage V, single valued: V = 0 or
$V_B = 25000\ V_1 = 1V$
$0 < V < V_B$ = ?????

Programmable voltage standards

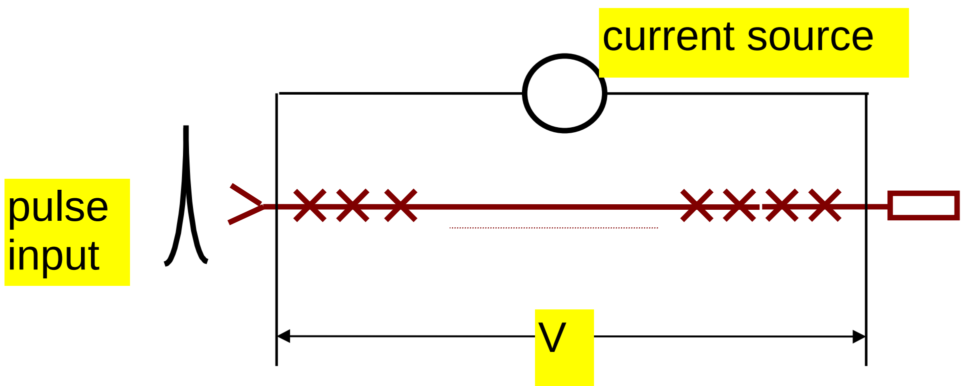
Rapid adjustment of the DC Josephson voltage allows synthesis of arbitrary AC waveforms with the fundamental precision of the DC Josephson voltage standard ⇒ Digital to Analog (D/A) converter

Two types on the basis of series arrays of highly damped Josephson junctions:

Binary sequence of subarrays combined by a programmable switch (Hamilton et al 1995, Benz et al 1996)



Arrays driven by rapidly tunable rf sources (pulse and bipolar drive) (Benz and Hamilton 1996, Maggi 1996, Benz et al 1998, 1999)



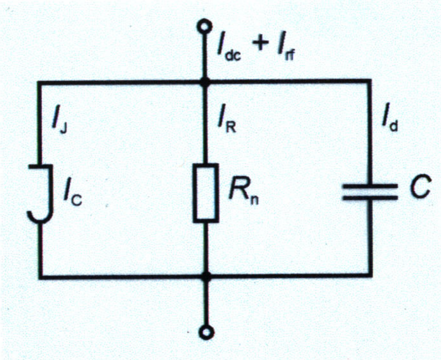
Microwave attenuation of the array stripline

SIS-junctions

$R_n = 50\ \Omega$

$C = 50$ pF => $Z_c = (2\pi f C)^{-1} = 0{,}05\ \Omega$ bei $f = 70$ GHz

=> Microwave attenuation per 1000 SIS junctions:
0,1 dB bei $Z_0 = 5\ \Omega$



SINIS-junctions

$R_n = 0{,}1\ \Omega$

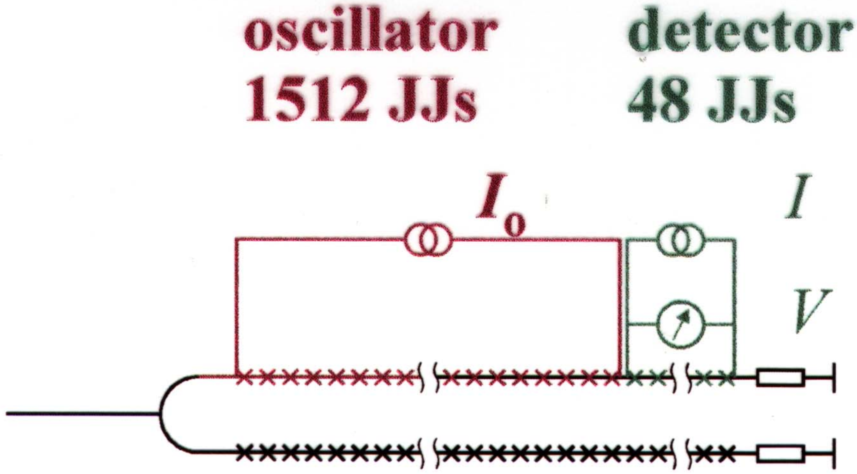
$C = 50$ pF => $Z_c = (2\pi f C)^{-1} = 0{,}05\ \Omega$ bei $f = 70$ GHz

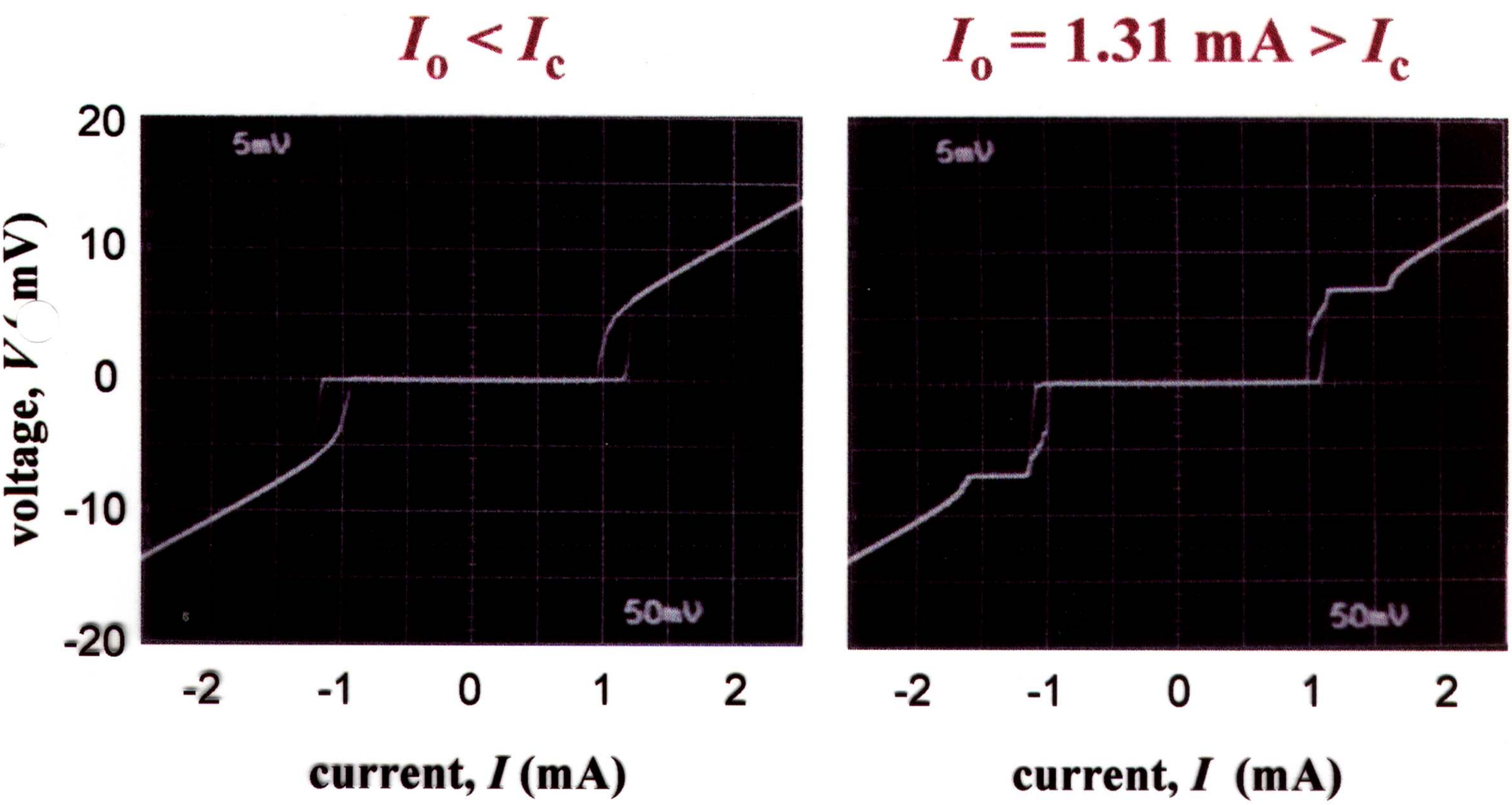
Microwave attenuation per 1000 SINIS junctions:
50 dB bei $Z_0 = 5\ \Omega$

How is it possible to generate a Shapiro-step at 1 V in a 5-Ω stripline with more than 1700 SINIS junctions?

Josephson junction series array in SINIS technology

stimulated emission of microwave





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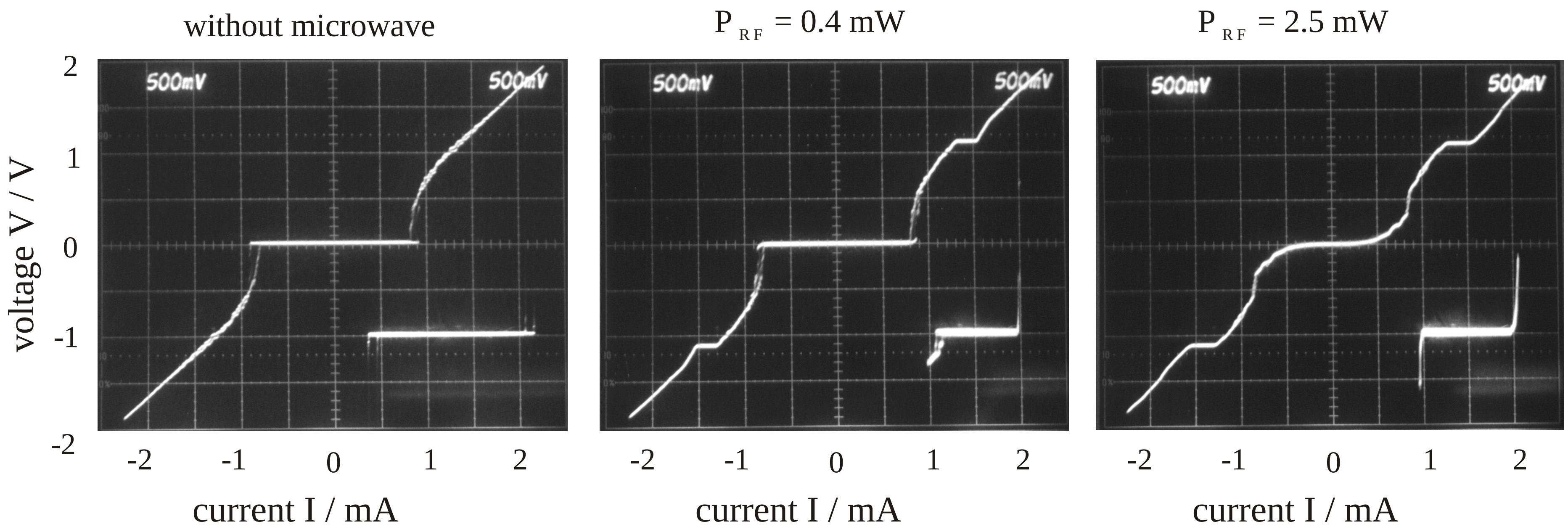
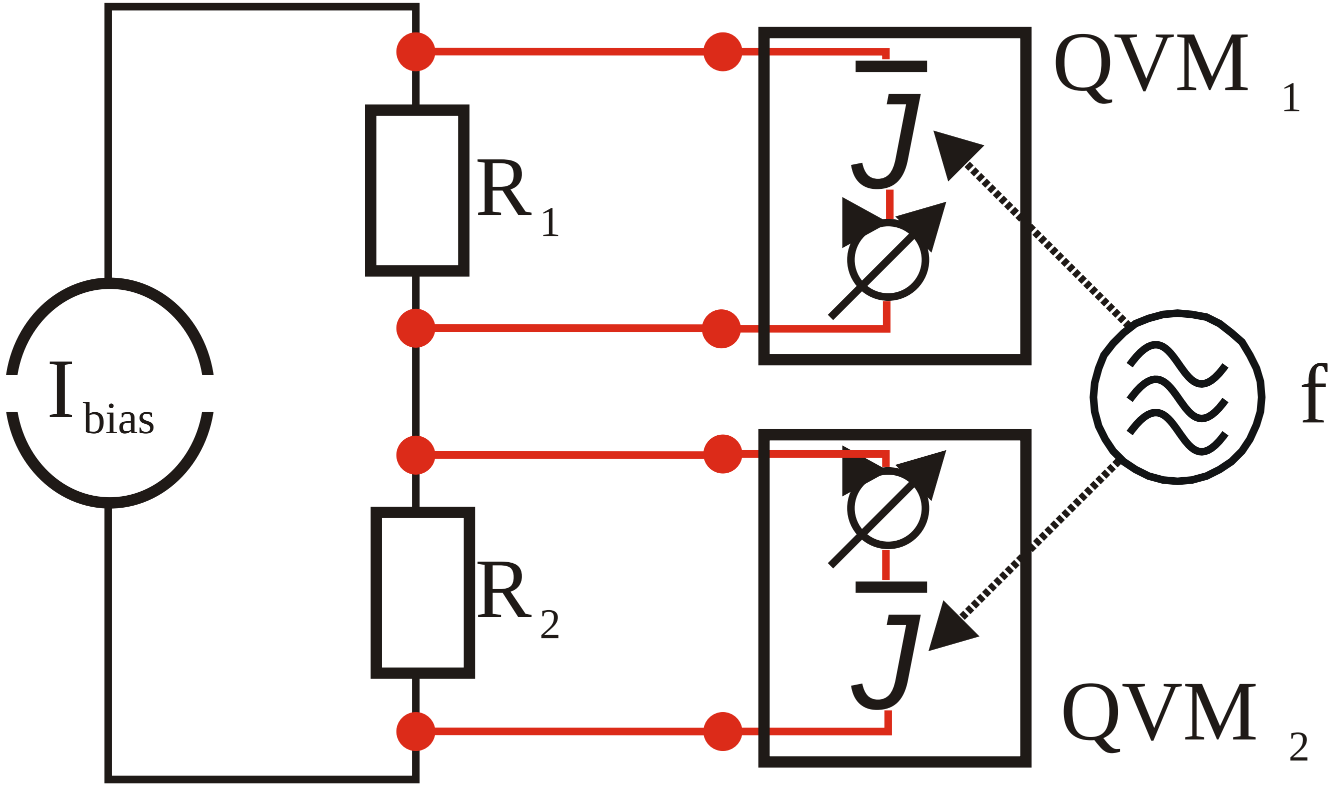
Application of Josephson series arrays to a DC quantum voltmeter

Current-voltage characteristics of a binary divided 8192 SINIS Josephson series array



Measurement set-up for the RVD measurements



Application of Josephson series arrays to a DC quantum voltmeter

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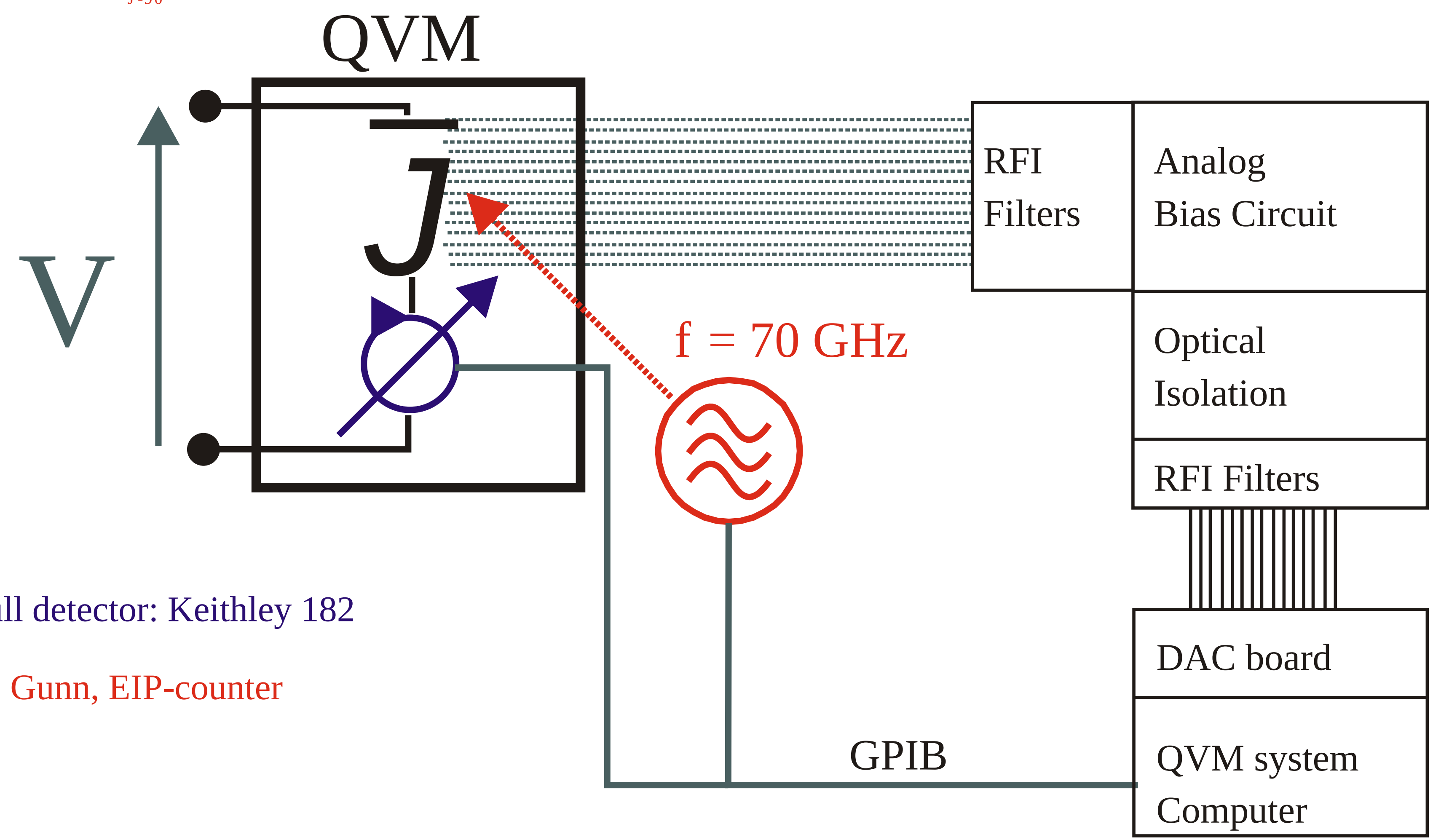
Technical Data QVM equipment

$V = nf/K_{J\text{-}90}$

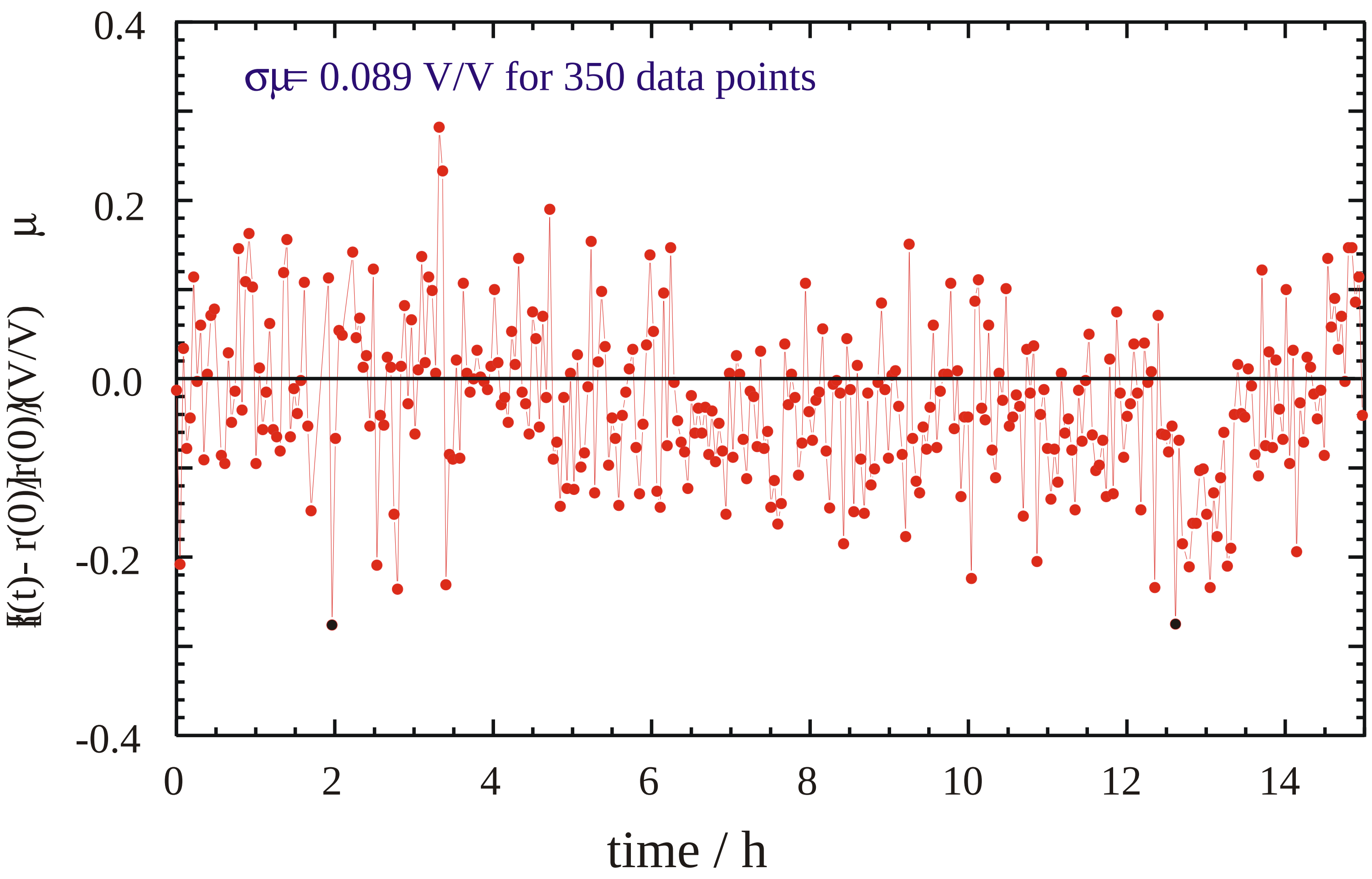


null detector: Keithley 182

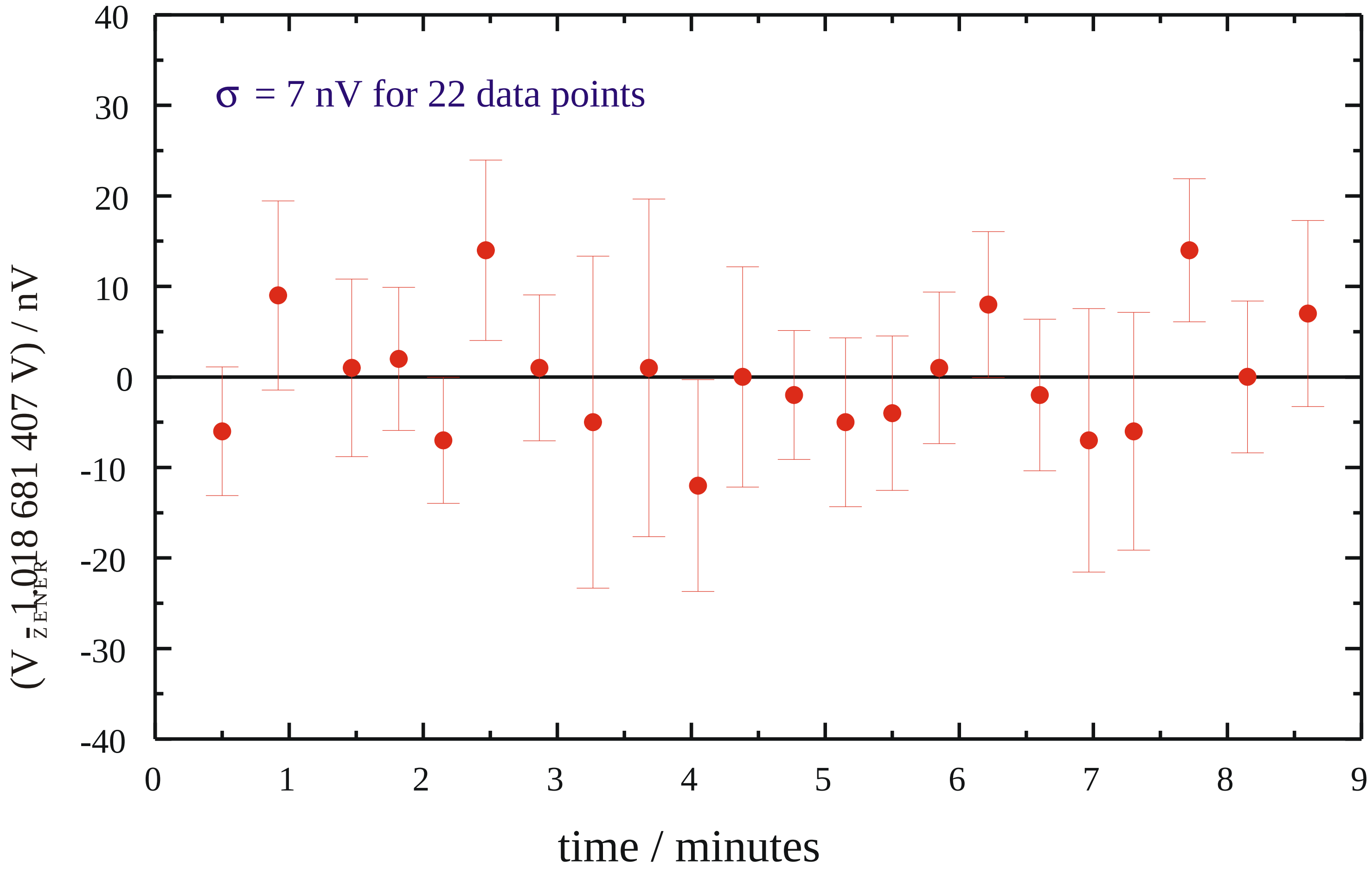
f : Gunn, EIP-counter

Measurements of the relative change [r(t) - r(0)]/r(0) of the ratio r = 10:1 dividers,

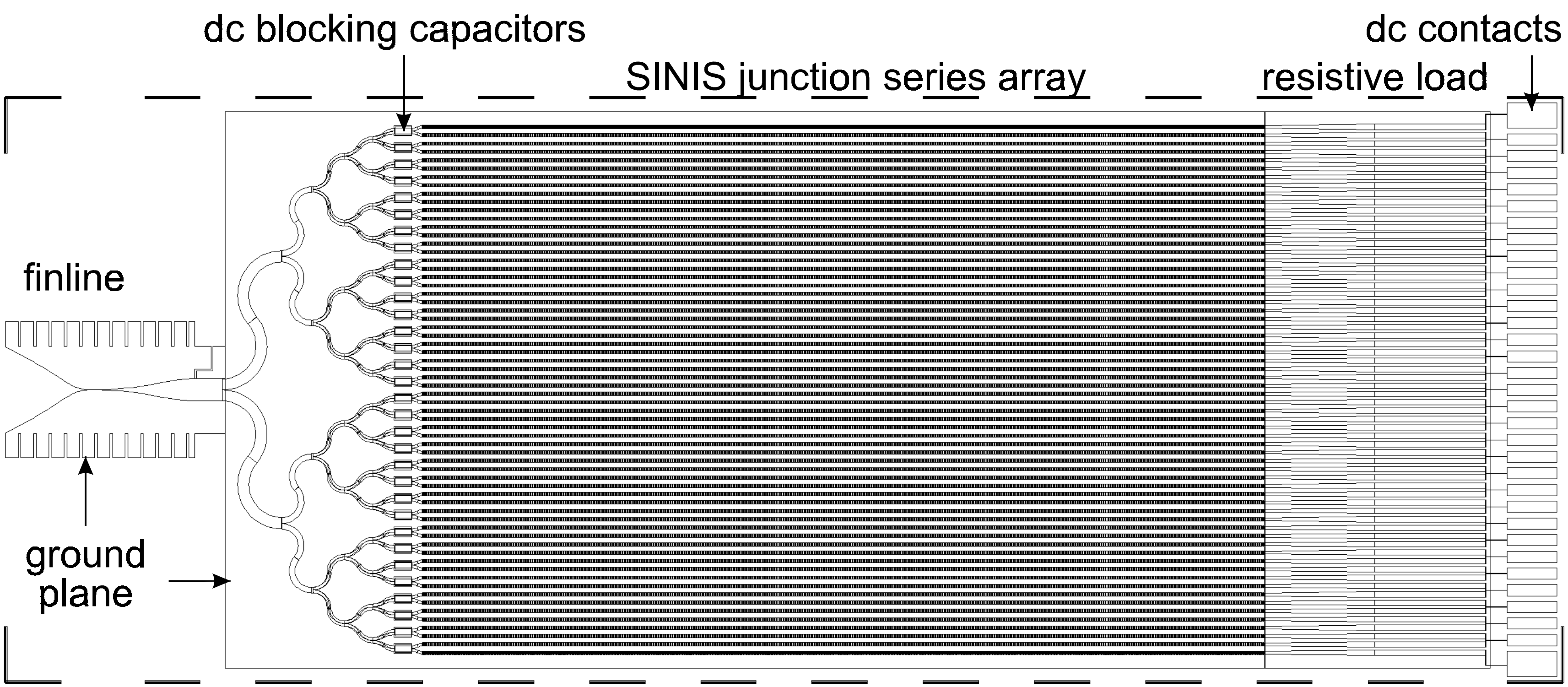
r = R_1/R_2, R_1 = 10 Ω, R_2 = 1 Ω



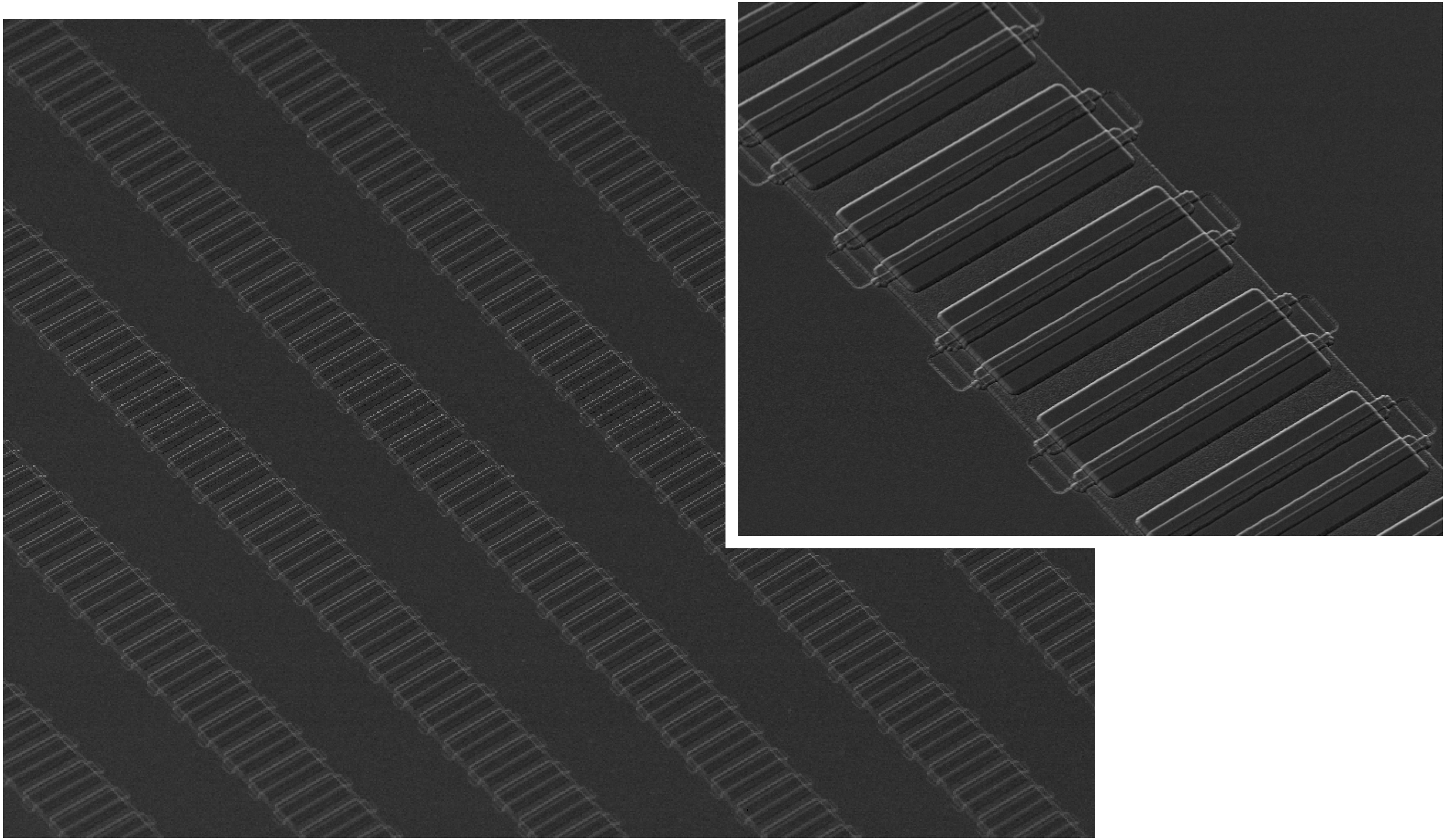
Calibration of a Zener reference standard at 1.018 V with the QVM

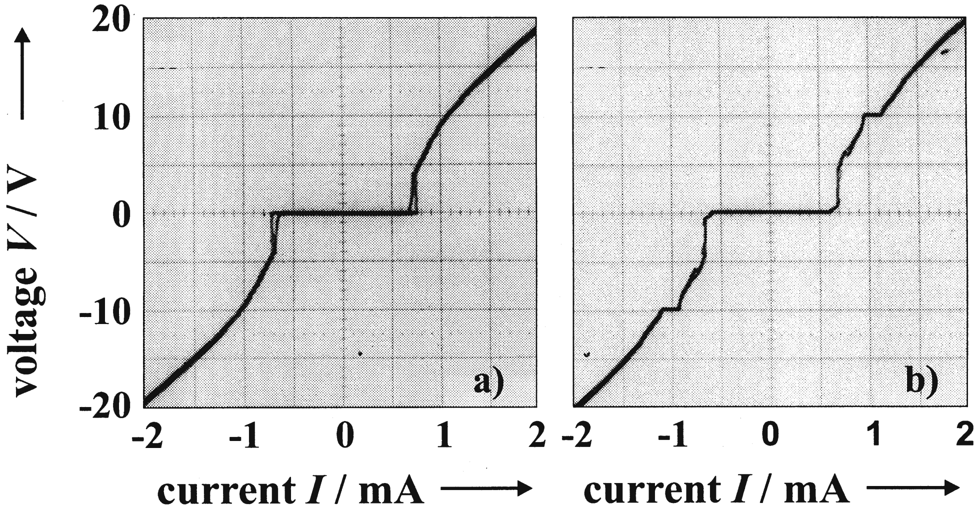


Design of a 10 V SINIS series array of about 70 000 junctions

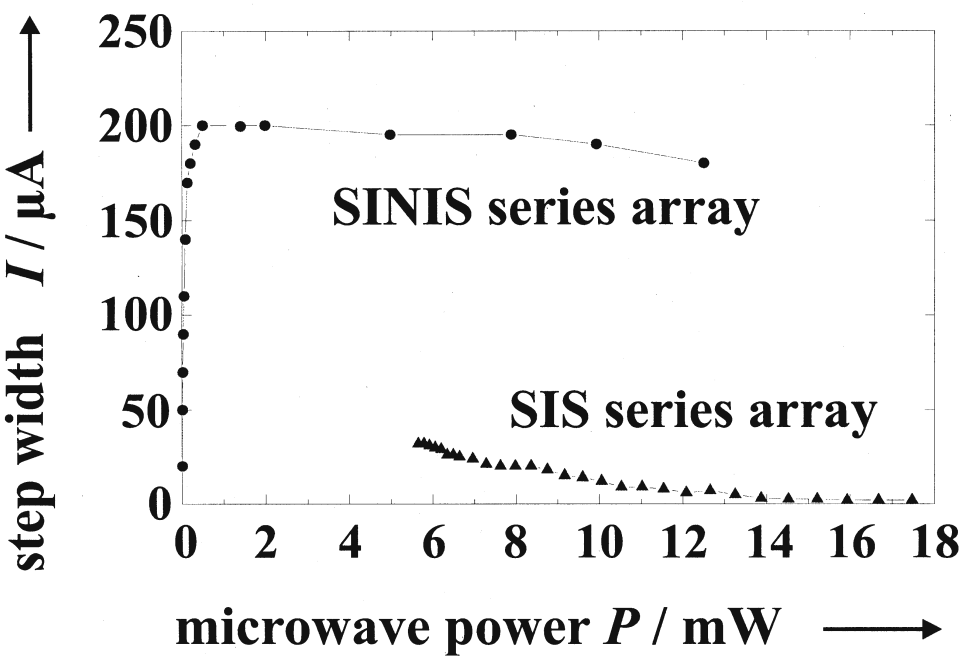


SINIS array for a 10-V Josephson voltage standard



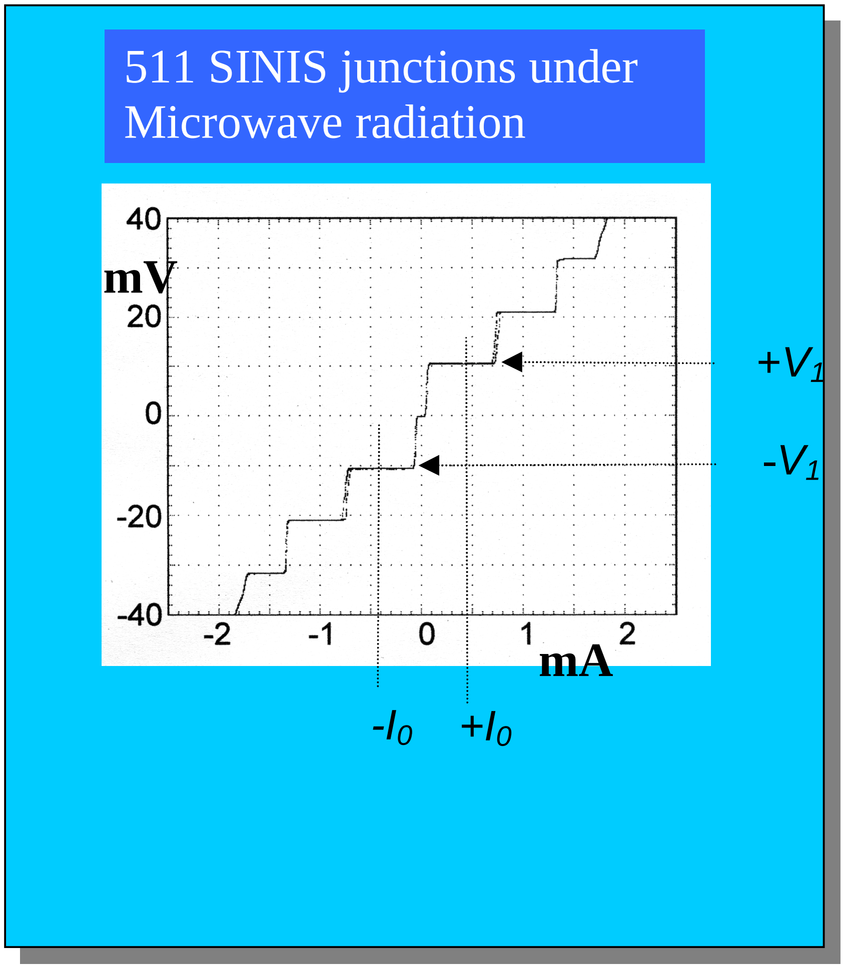


Current-Voltage characteristic of a series array of 69120 SINIS junctions
a) without microwave
b) with microwave (70 GHz, < 1mW)

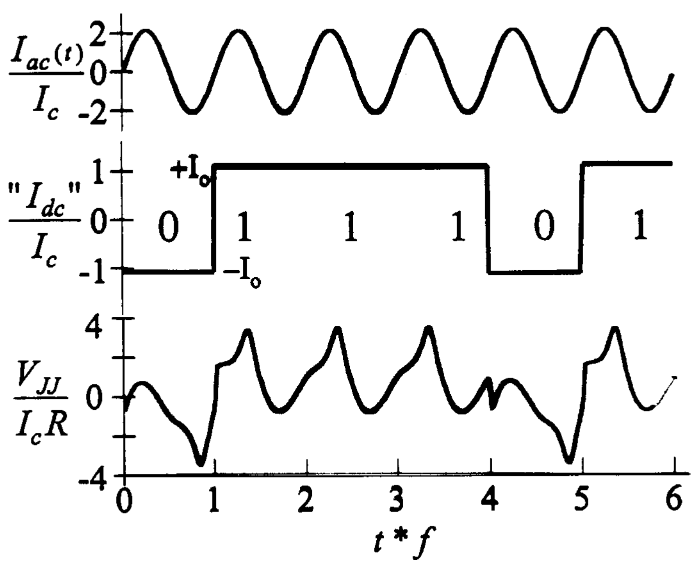


Upper curve: current width of a constant voltage step of 2 microwave paths (2160 junctions) of a 10 V SINIS array
Lower curve: current width of the 10V step of an SIS array

Bipolar voltage source



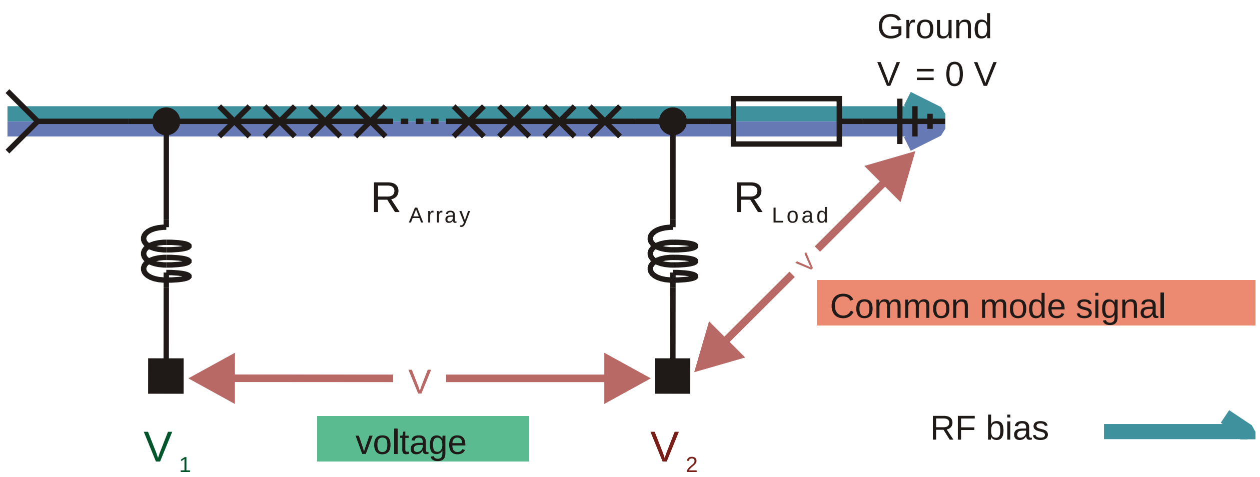
Junction input and output



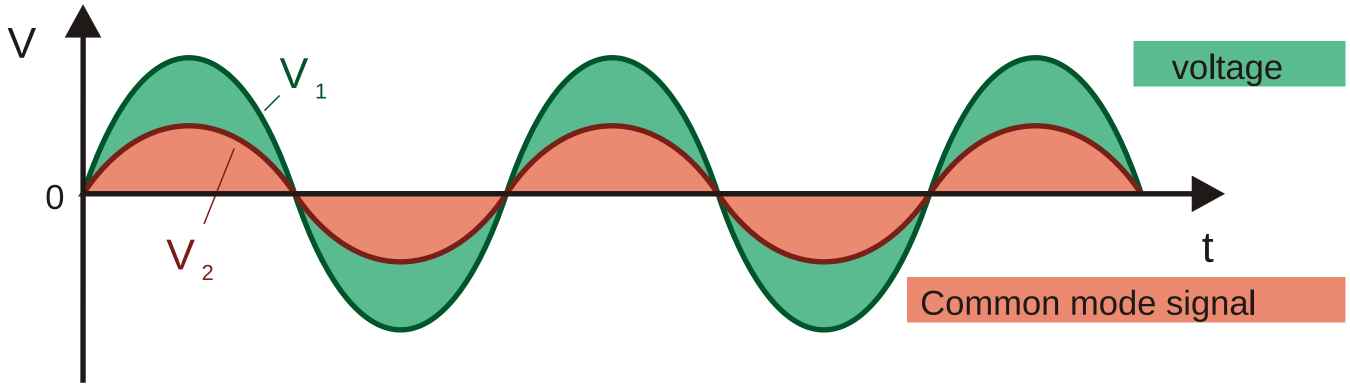
Benz, S. et al IEEE Trans. Instr. Meas. 48, 266 (1999)

AC bipolar Josephson voltage standard

AC bipolar voltage source
broadband current line for DC and RF bias

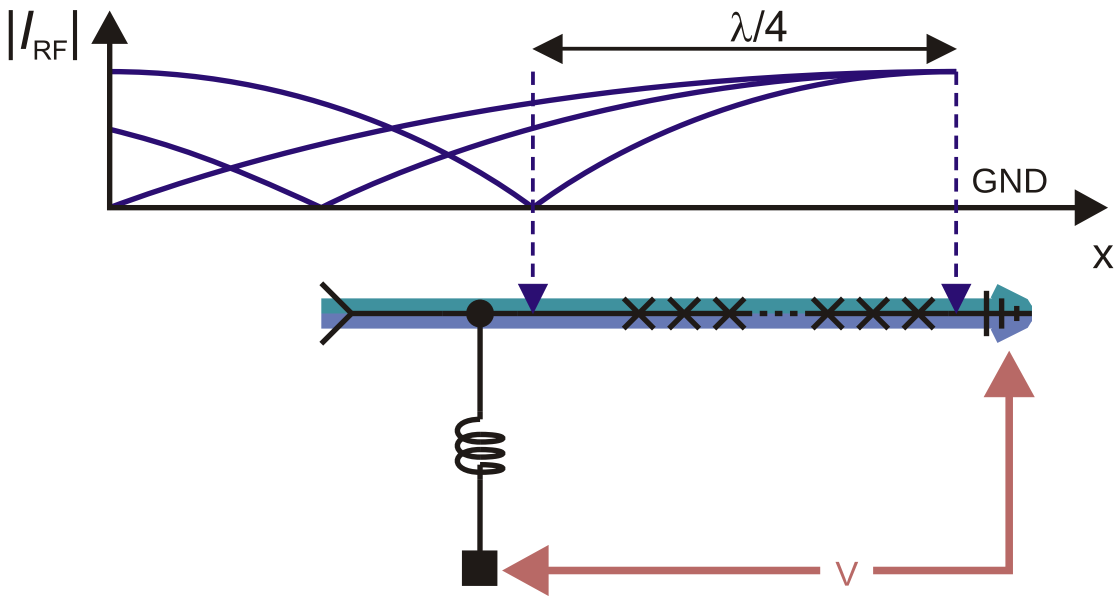


Common mode signal
offset voltage drop at the load



AC bipolarJosephson voltage standard

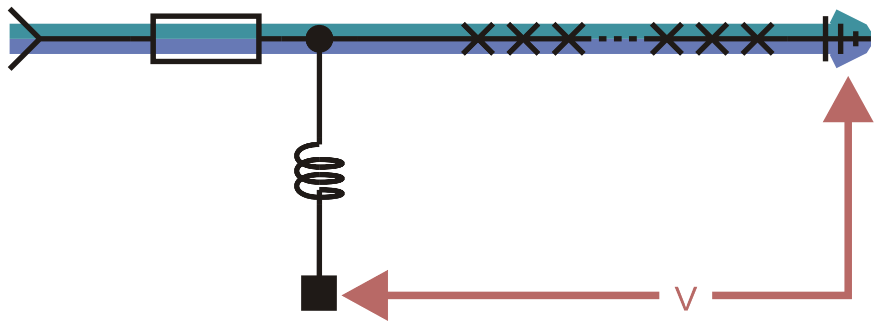
Possible solution to
avoid common
mode voltages



a rray grounded
without load

condition:
array length ∢L/4

for suppression of modes:
load before the array



RF bias

DC bias

Programmable Josephson Voltage Standard

Advantages:

- absolutely stable DC output voltage
- DC output voltage per junction determined
- wide step current widths
- HTS junction technology available in principle

Consequences:
⇒fast switching possible
⇒precise AC operation possible; max. frequency dependent on the type
⇒high operation temperatures in principle

Disadvantages:

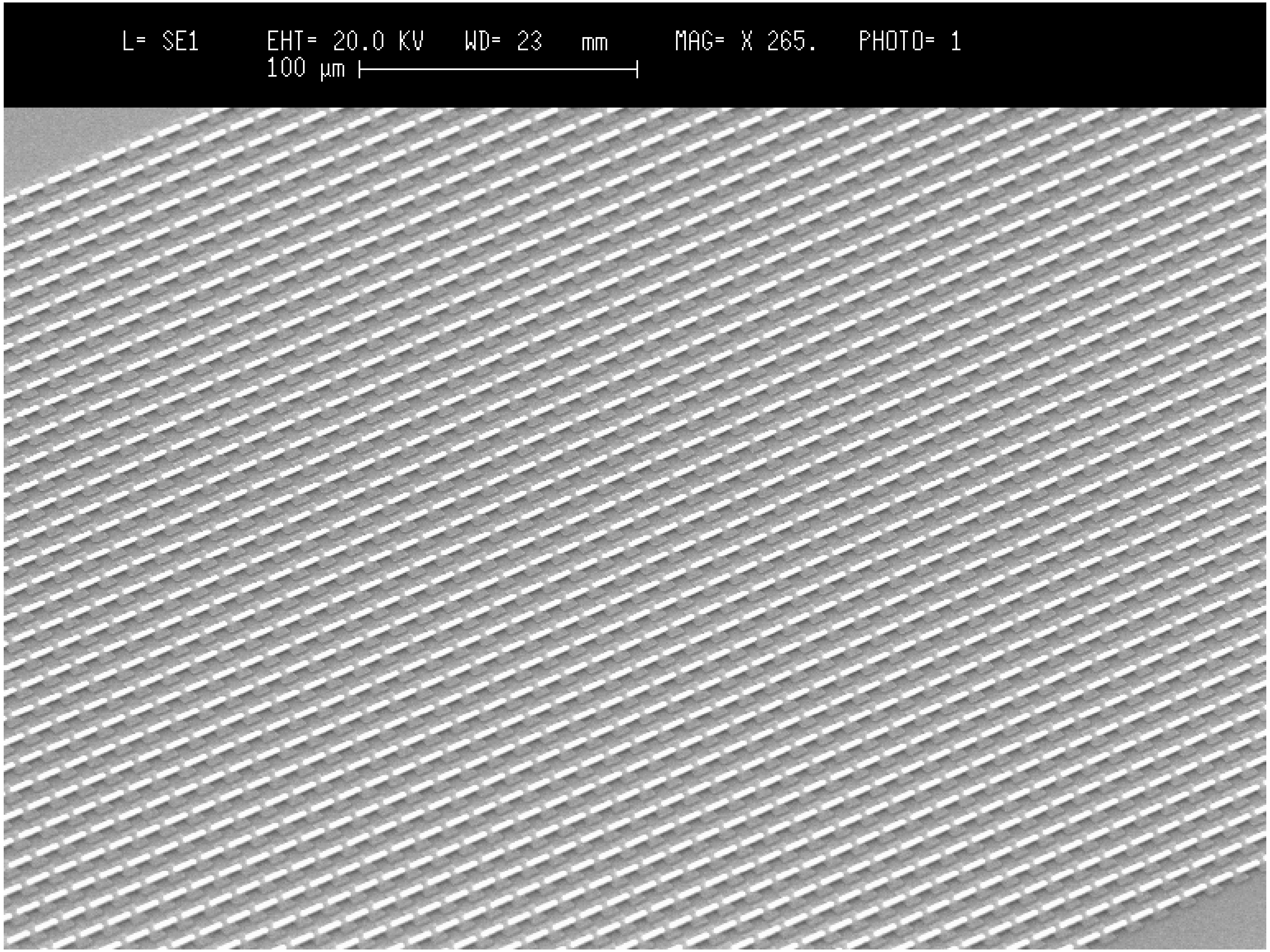
- does not tolerate shorts
- does not tolerate series resistances
- small linewidths and low drive frequencies for high DC output voltages
- low DC output voltage per junction
- transients influence accuracy

Consequences:
⇒more complex circuit fabrication
⇒high junction number: complex microwave distribution
⇒ max.AC operation frequency depends on the transients

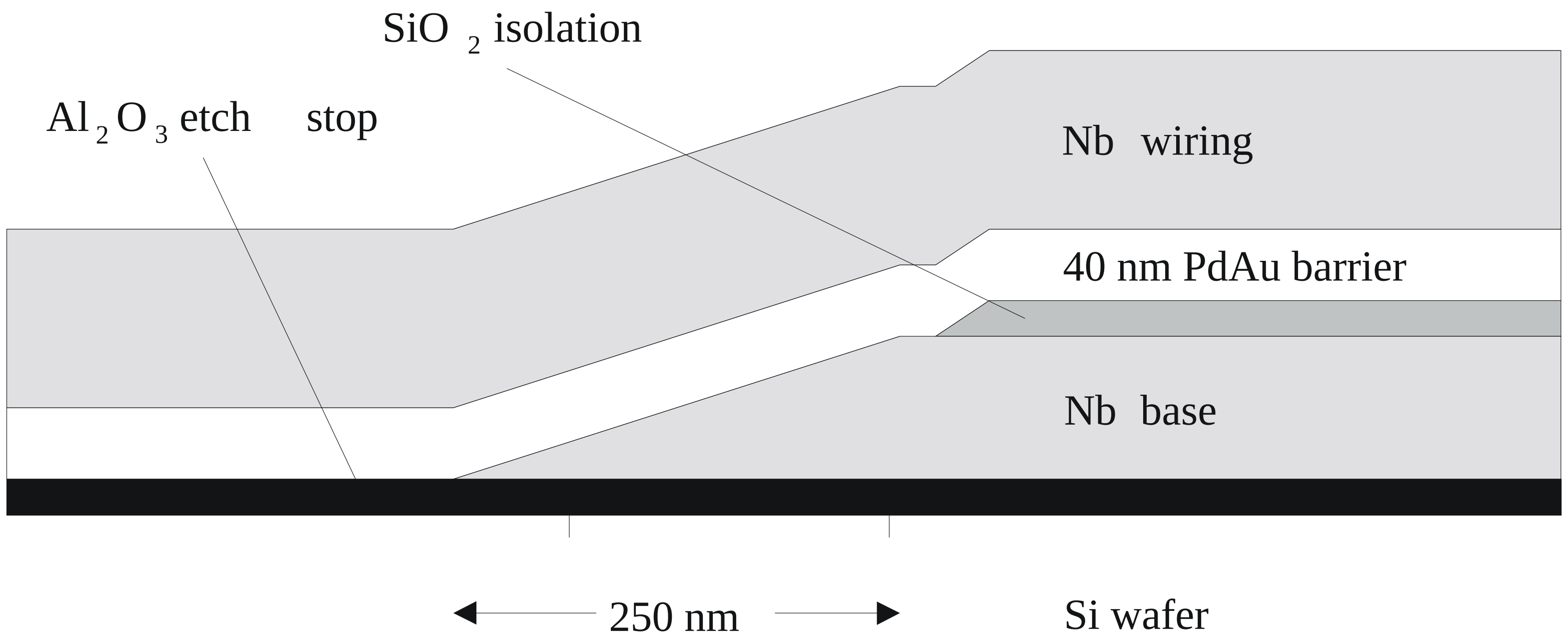
Outlook

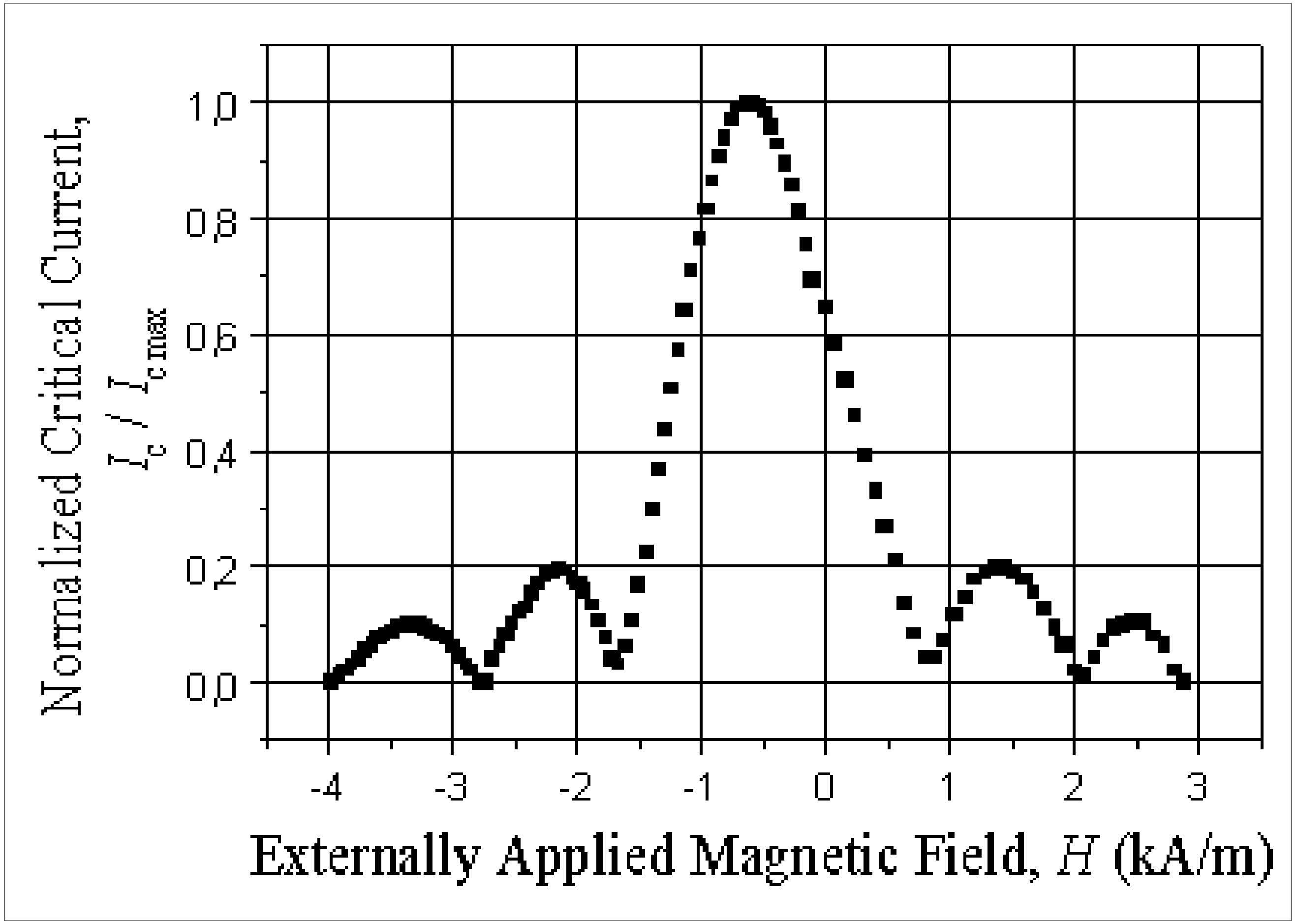
- LTS technology development of arrays of moderately and highly damped Josephson junctions for programmable voltage standards and RSFQ circuits
  - No shorted junctions
  - Smaller junctions
  - Higher critical current densities
  - Reduction of the parameter spread
- Standard circuits with integrated RSFQ circuits for low cost frequency control
- RSFQ voltage multipliers (Semenov, SUNY)
- HTS circuits with low resistance shunting (Klushin, Forschungszentrum Jülich)

Series array of 10 000 SNS ramp-type junctions (Nb/PdAu/Nb)



Cross-section of a ramp-type junction

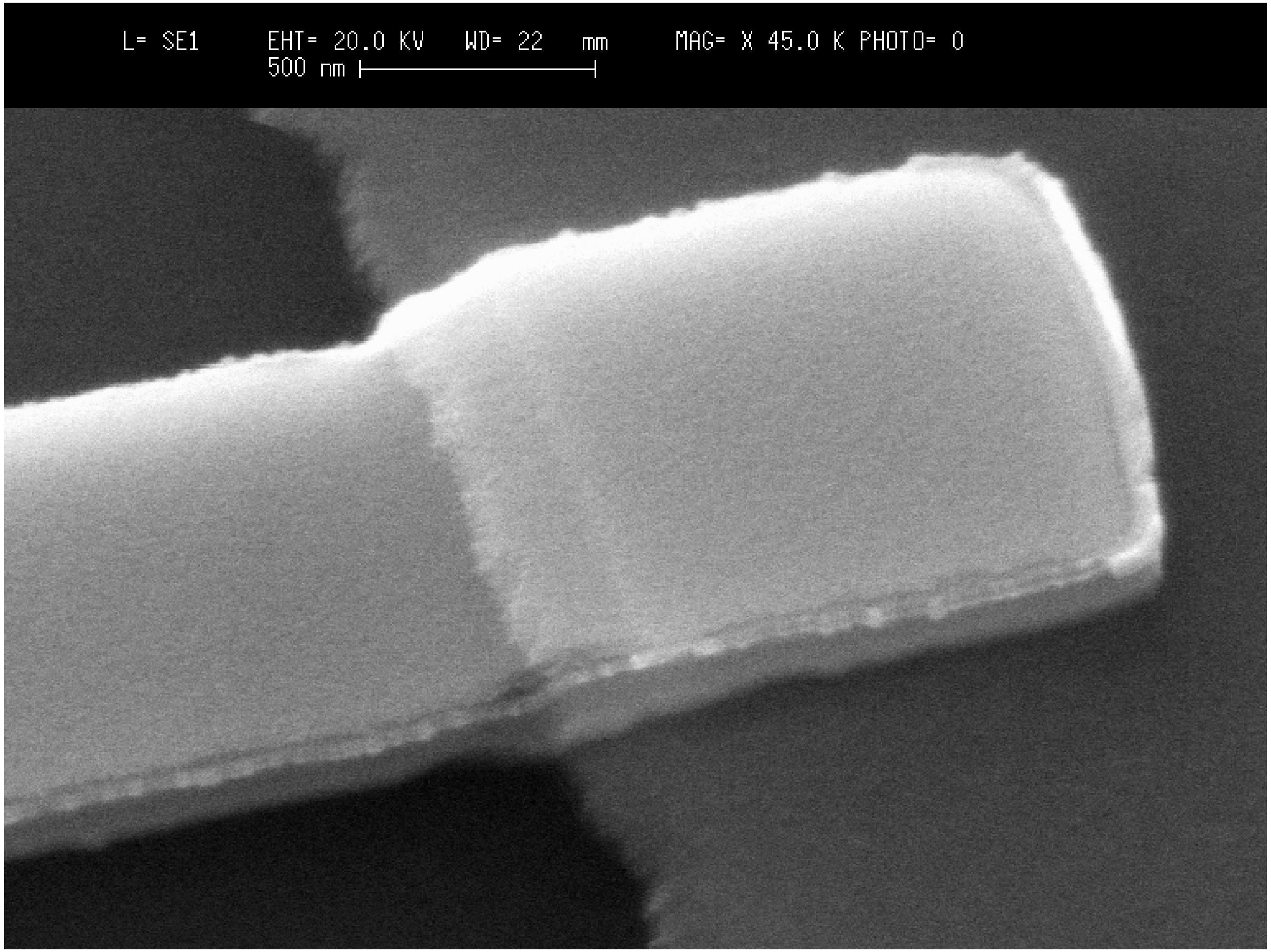


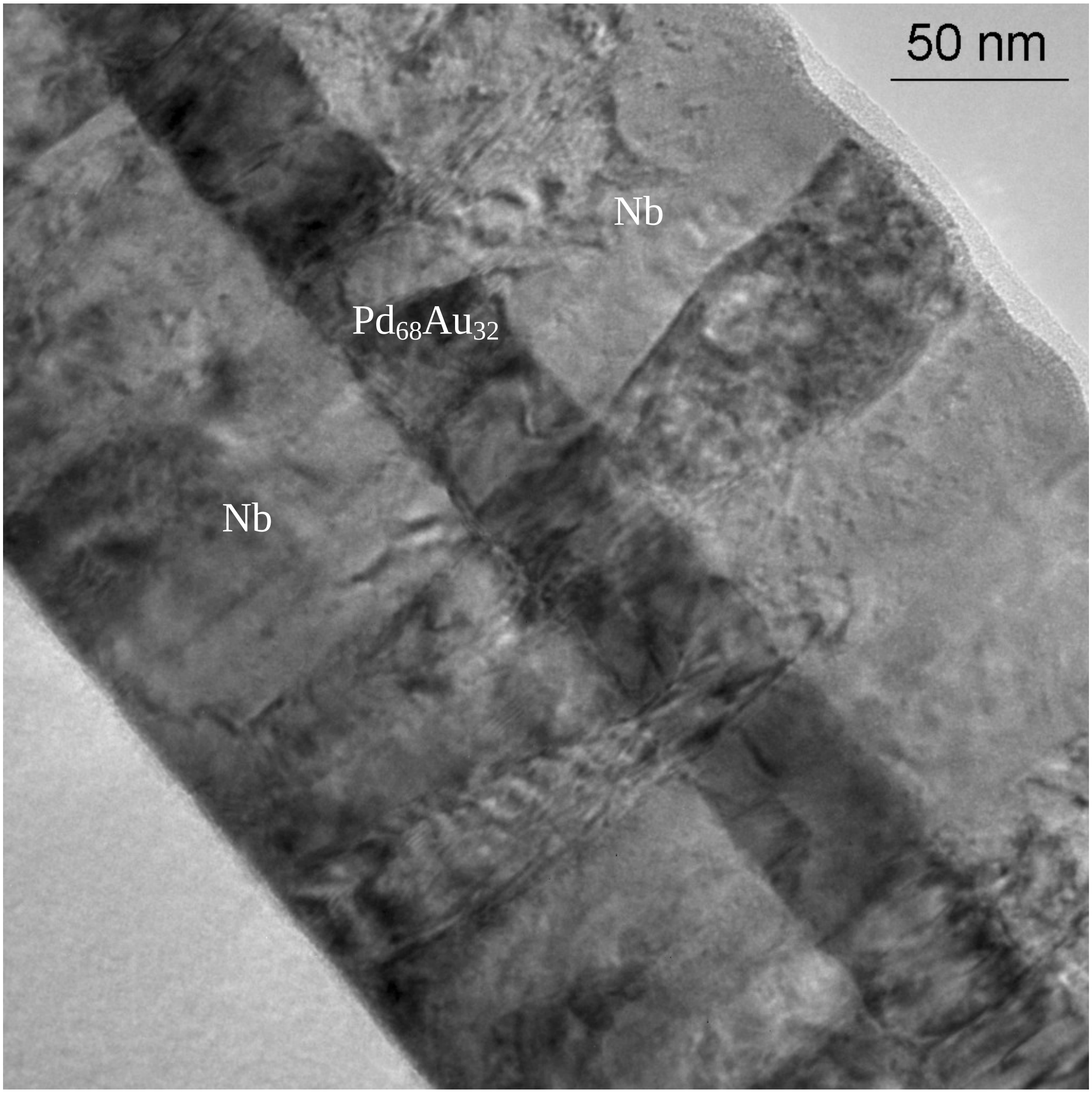


Magnetic field dependence of the critical current of an SNS ramp-type junction

Single SNS (Nb/PdAu/Pd) ramp-type junction

junction area: 0.25x1.3 μm^2, N-layer: 40nm





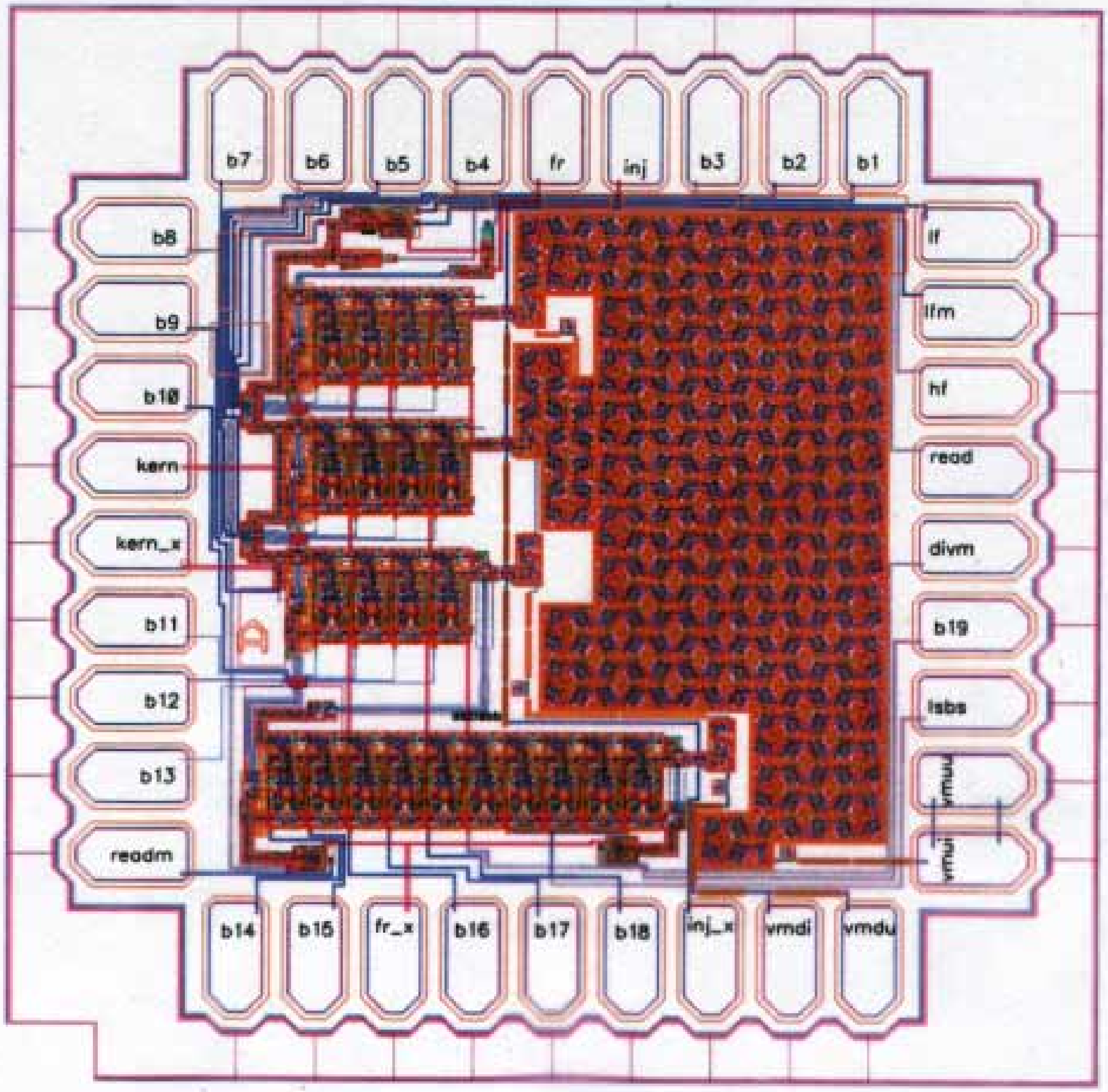
cross-section of an SNS-sandwich

RSFQ D/A-converter
maximum DC output voltage: about 5 mV

Stony Brook

Digital to Analog Converter

2397 Josephson junctions
2^{19} quantization levels



designed by V. Semenov

A. Klushin, FZ Jülich

I-V-Characterisic of a series array of 154 shunted YBCO junctions

(a) without microwave

(b) with microwave

Insert: constant voltage step of the array