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Modern AC Josephson voltage standards at PTB

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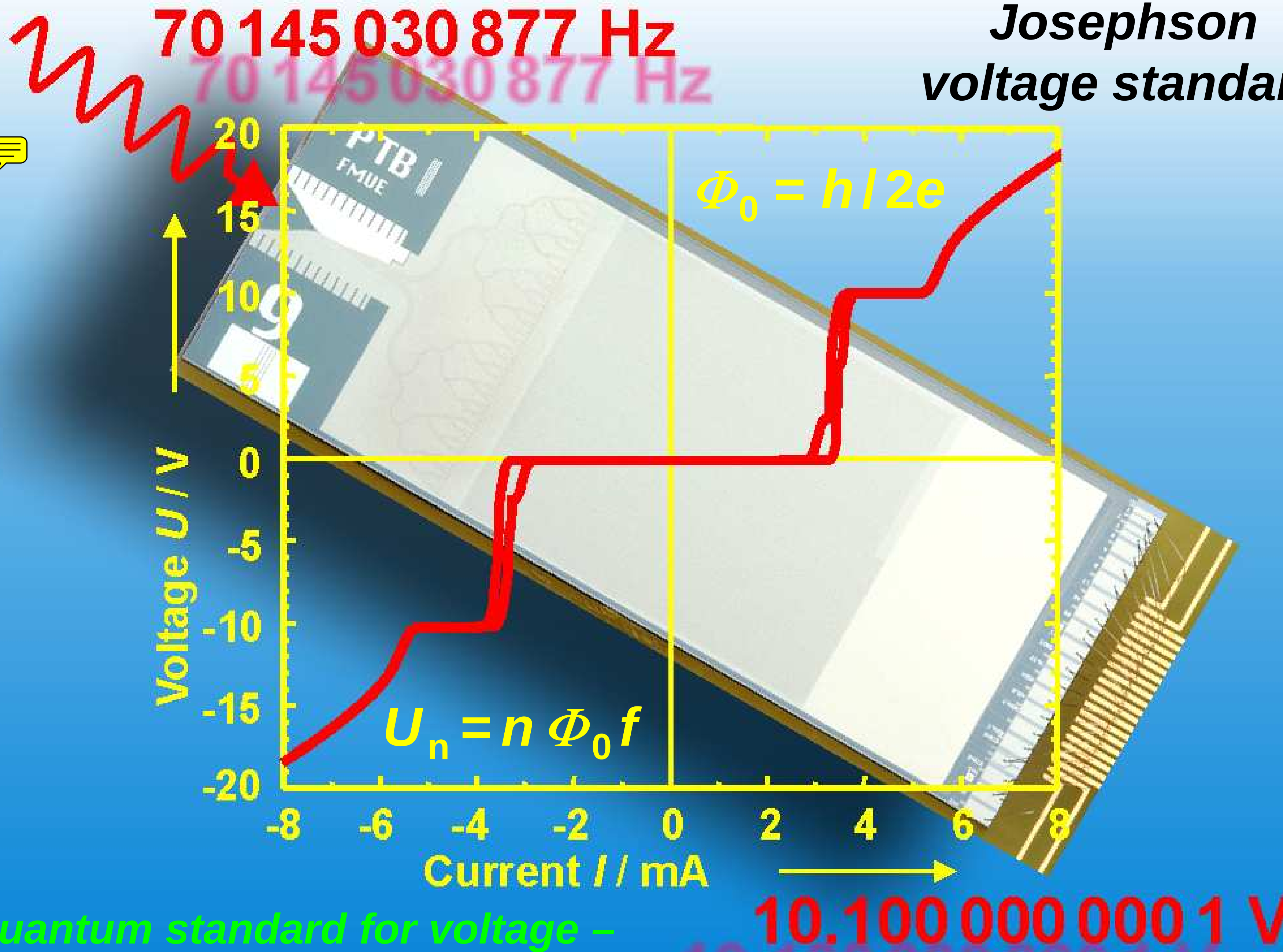
Josephson voltage standard



Quantum standard for voltage – reference to physical constants

70 145 030 877 Hz

Josephson voltage standards

- important application of Superconductor Electronics
- unique characteristics for precision measurements (*due to superconductivity: magnetic flux quanta*)
- niche market
- DC applications: commercial suppliers, up to 10 V
- AC applications: under development
  motivation: extension of high accuracy from DC to AC
  goals: 1 V, 10 V, pure waveforms (achieved in part)

- Requirements
  * large series arrays of Josephson junctions

10.100 000 000 1 V

Outline

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- Fundamentals: AC Josephson voltage standards
- Technology: Nb_xSi_{1-x} Josephson junctions
- Josephson voltage standards for AC applications:
  * binary-divided JJ series arrays (70 GHz drive)
  * pulse-driven JJ series arrays
- Combing binary-divided array + pulse-driven array
- Conclusions and outlook

Work supported in part by the EU within EMRP JRP SIB59 'Q-WAVE'

EURAMET
European Association of National Metrology Institutes

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

AC Josephson voltage standards

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How to make an AC Josephson voltage standard?

$$V_n = n \cdot m \cdot \Phi_0 \cdot f$$

→ pulse-driven arrays

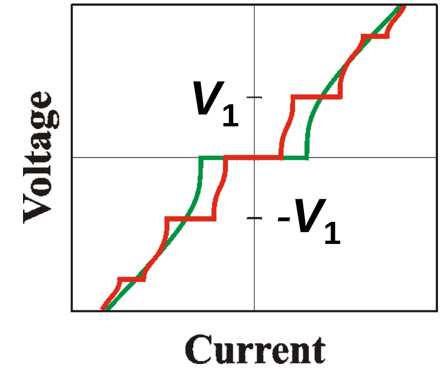
→ binary-divided arrays

(m = number of junctions)

f / GHz	15	70
V_1 / µV	30	145
No. JJ (10 V)	330 000	70 000

Both versions need overdamped JJs:

- SNS junctions
- SINIS junctions
- shunted SIS junctions
- S-Sc-S junctions



Robust & reliable technology required

Technological requirements

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- **overdamped JJs**
- **robust, reliable, reproducible (*10 V array: 70,000 JJs*)**
- **different operation ranges:**
  $V_C \approx 150\ \mu V$ (70 GHz), $j_C \leq 10\ kA/cm^2$ (binary-divided)
  $V_C \approx 30\ \mu V$ (15 GHz), $j_C \approx 50\ kA/cm^2$ (pulse-driven)

=> high-resistance material for barrier required (*binary metallic alloys not suitable*):

material near metal-insulator transition

Nb_xSi_{1-x}: electrical junction parameters tunable by Nb content *x* from SNS-like ($x > 0.12$) to SIS ($x < 0.08$)

Co-sputtered Nb_xSi_{1-x} barrier JJs

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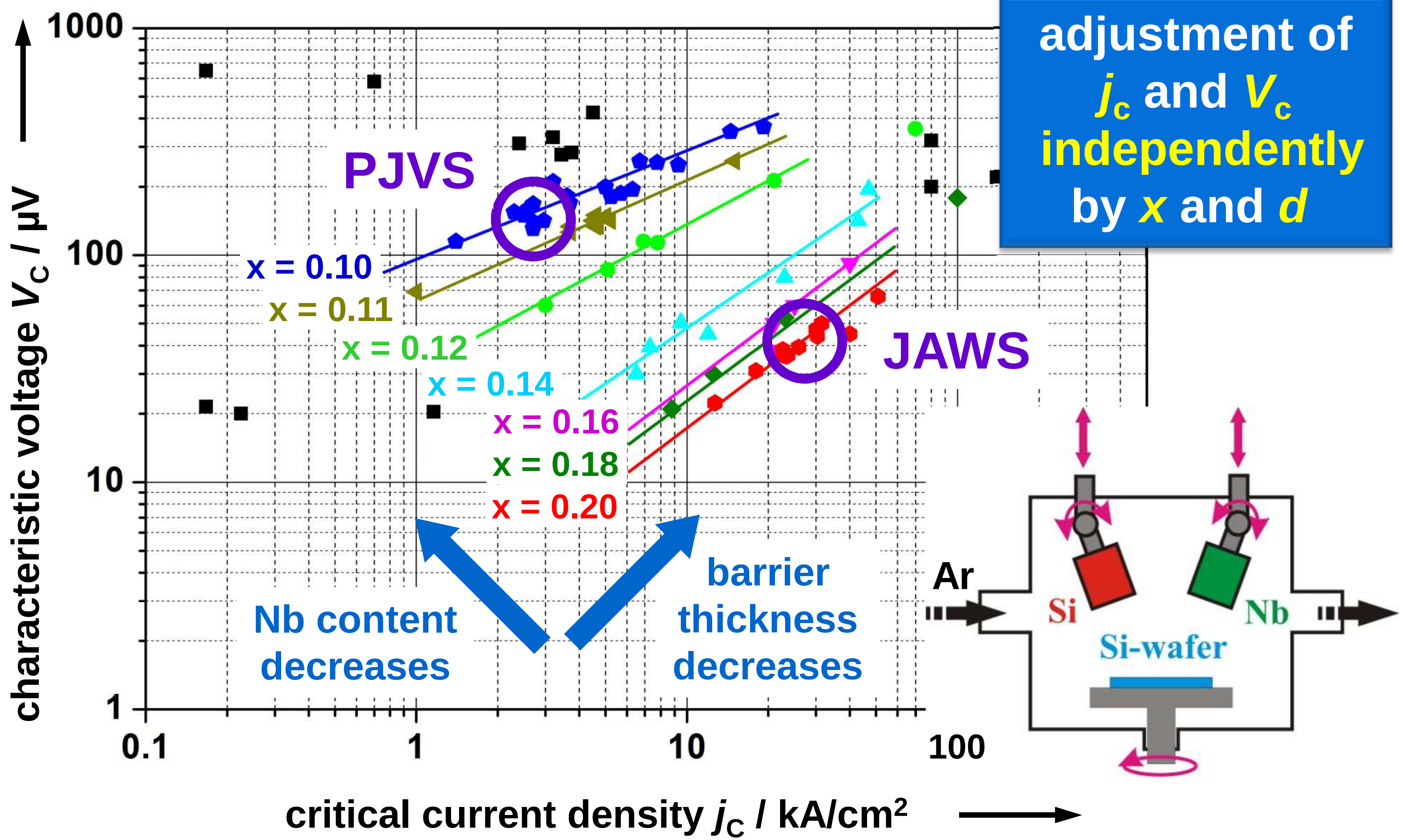

adjustment of j_c and V_c independently by x and d

Nb_xSi_{1-x} double-stacked JJs

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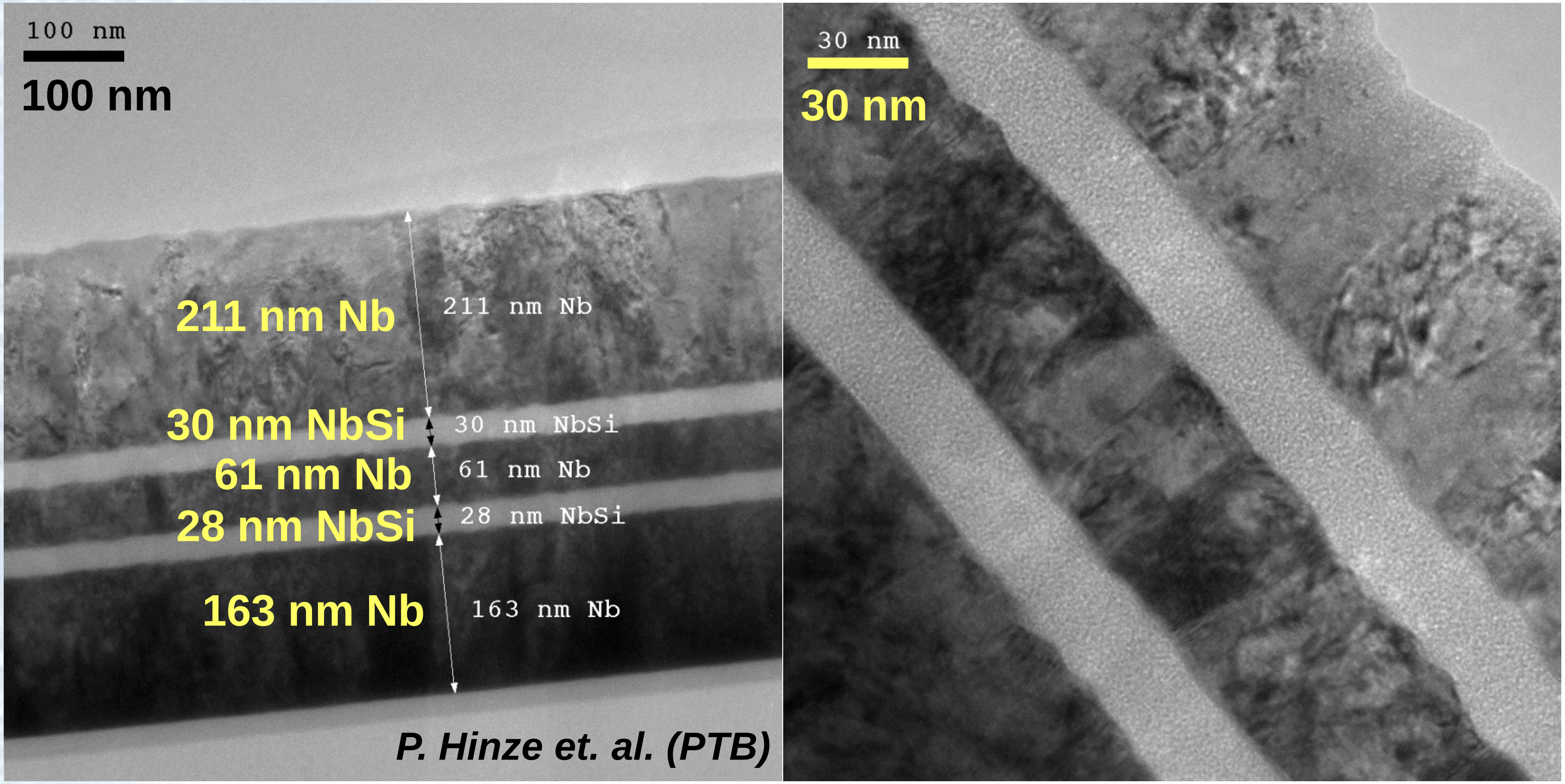
- **Stacked junctions for higher integration**



- **Barrier: homogeneous, amorphous (TEM)**

Programmable voltage standards (PJVS)

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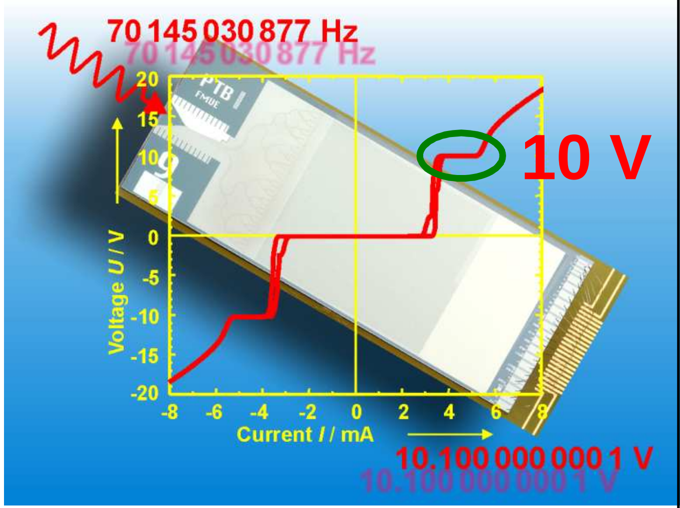
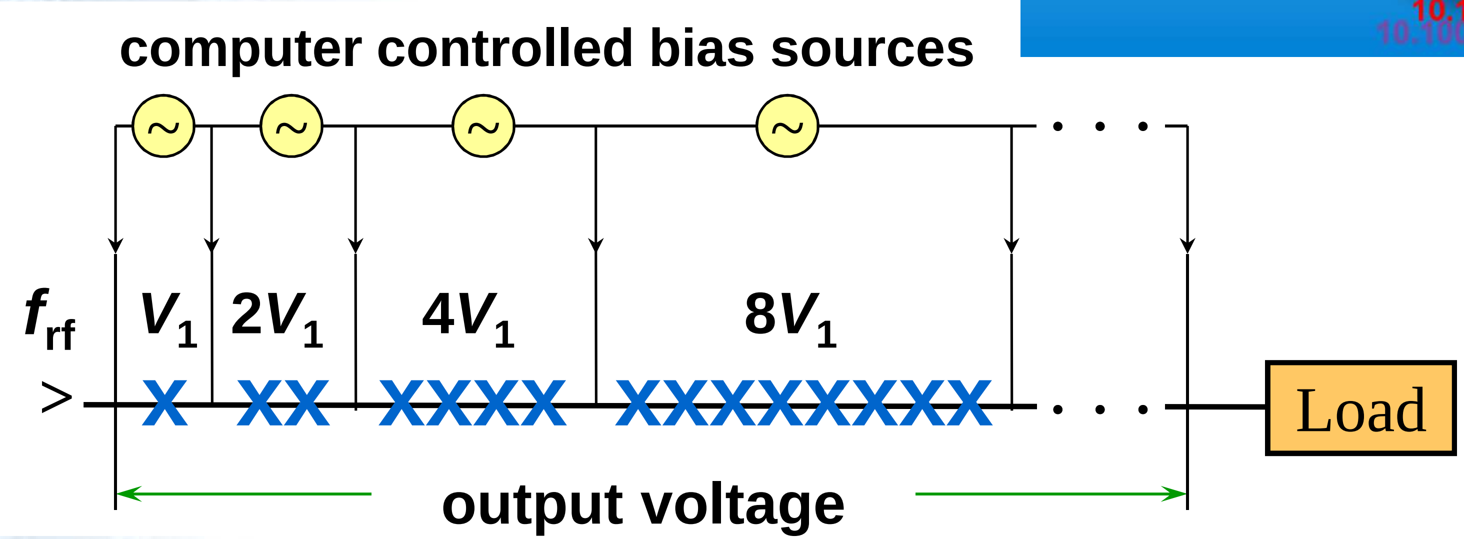
- $V_n = n \cdot m \cdot \Phi_0 \cdot f$
- **overdamped Jos. junctions**
- **binary-divided series array**





- **D/A converter with fundamental accuracy**

PJVS: 10 V SNS arrays – design

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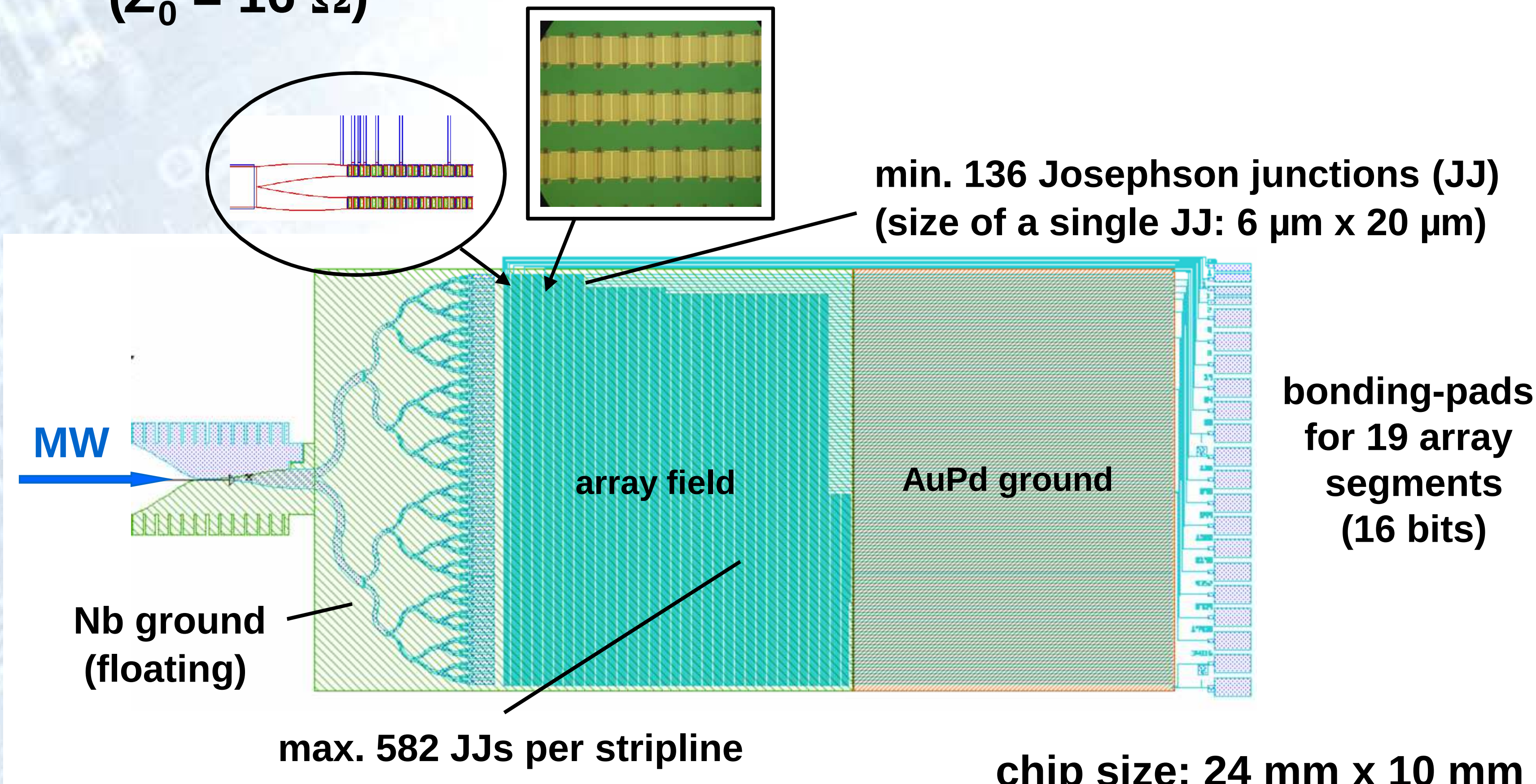
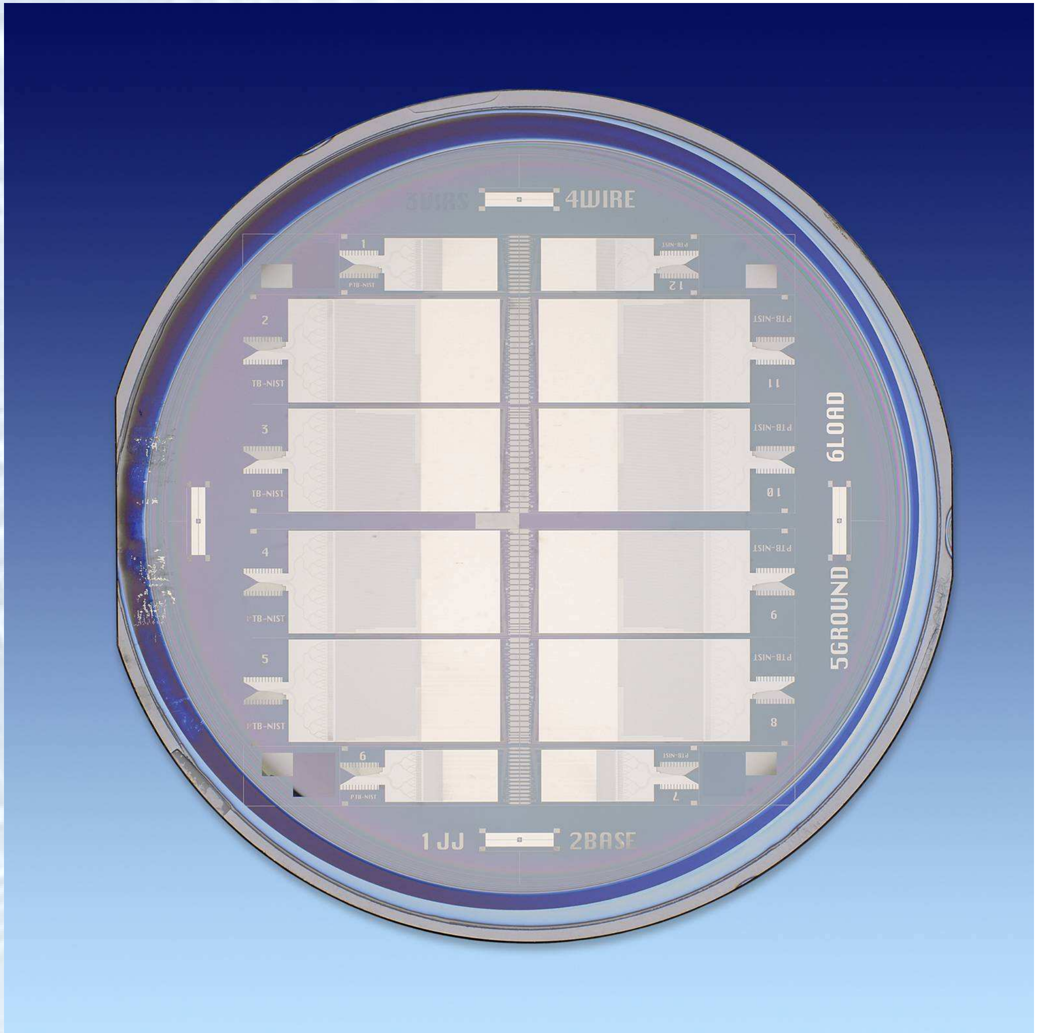
- **69,632 JJs embedded in 128 parallel microstriplines (Z_0 = 16 Ω)**



chip size: 24 mm x 10 mm

PJVS: 10 V SNS arrays – fabrication



PTB process similar to fundamental SNEP (7 levels)

e-beam lithography until wiring level (DC circuit)

ground and load are deposited on top of the circuit (1.5 µm SiO_2 as dielectric layer)

→ **JJs embedded in microstrip lines**

PJVS: 20 V SNS arrays – measurement

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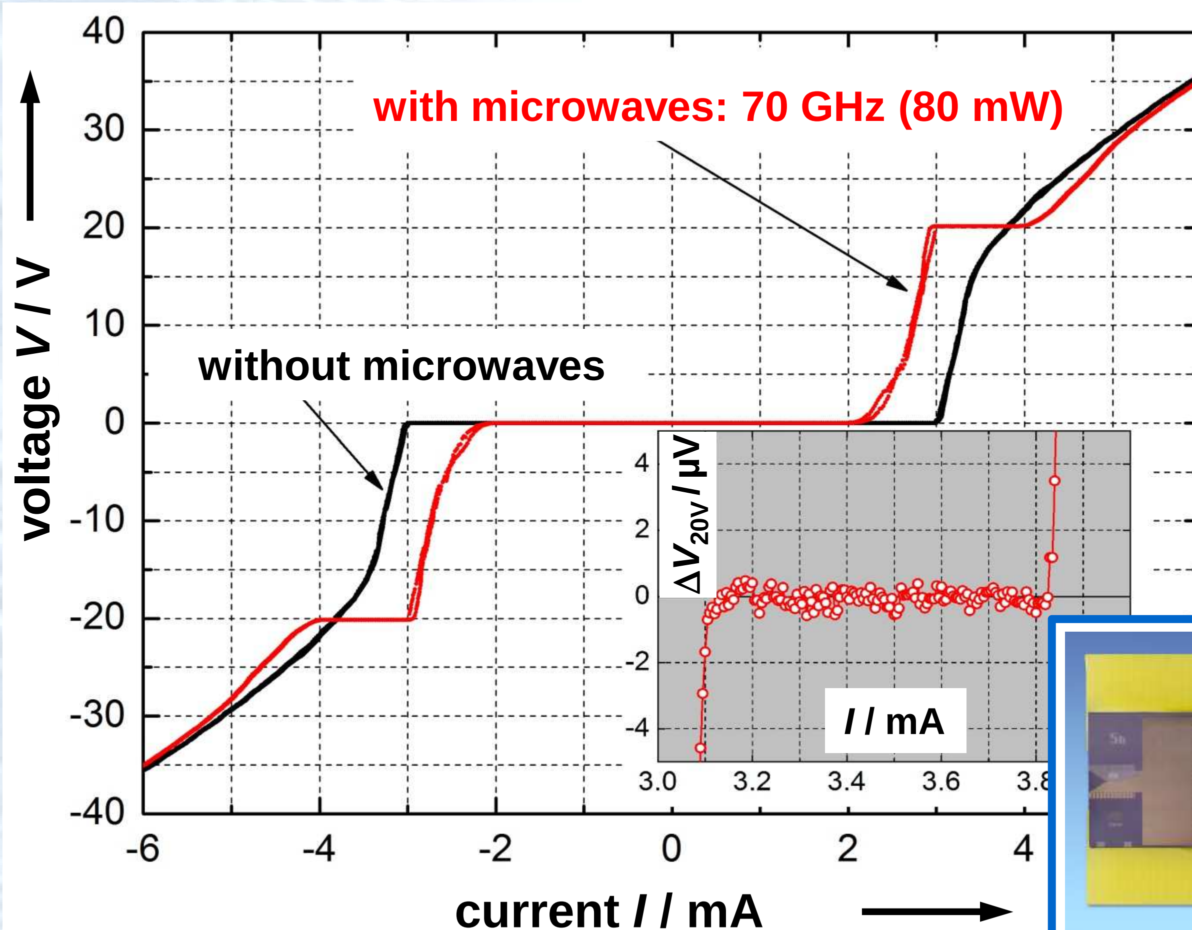

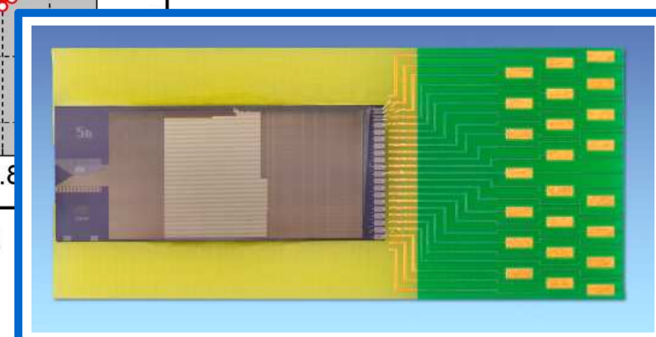

Nb_xSi_{1-x} JJ for operation at 70 GHz:

139,624 SNS JJs (69,632 double stacks)

F. Mueller et al., *IEEE Trans. Appl. Supercond.* 23 (2013) 1101005

Pulse-driven Josephson arrays

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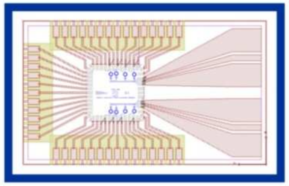
$V_n = n \cdot m \cdot \Phi_0 \cdot f_p$

computer

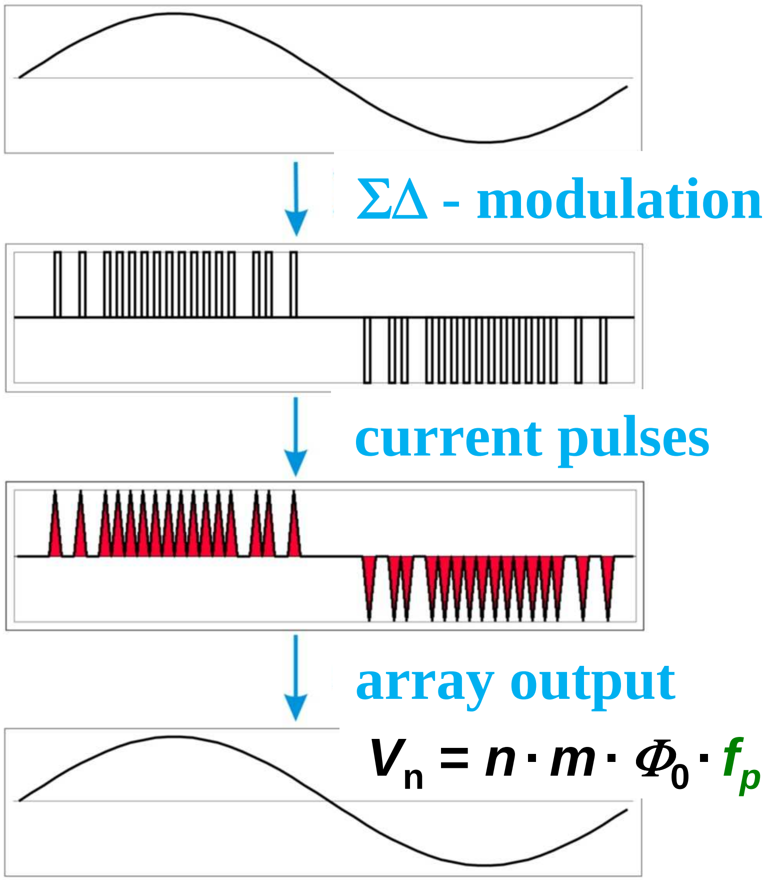
pulse-pattern-generator (PPG)

SNS **JAWS** chip @ 4,2 K



spectrum analyzer

arbitrary waveform



$V_n = n \cdot m \cdot \Phi_0 \cdot f_p$

quantized waveform

Pulse-driven Josephson arrays

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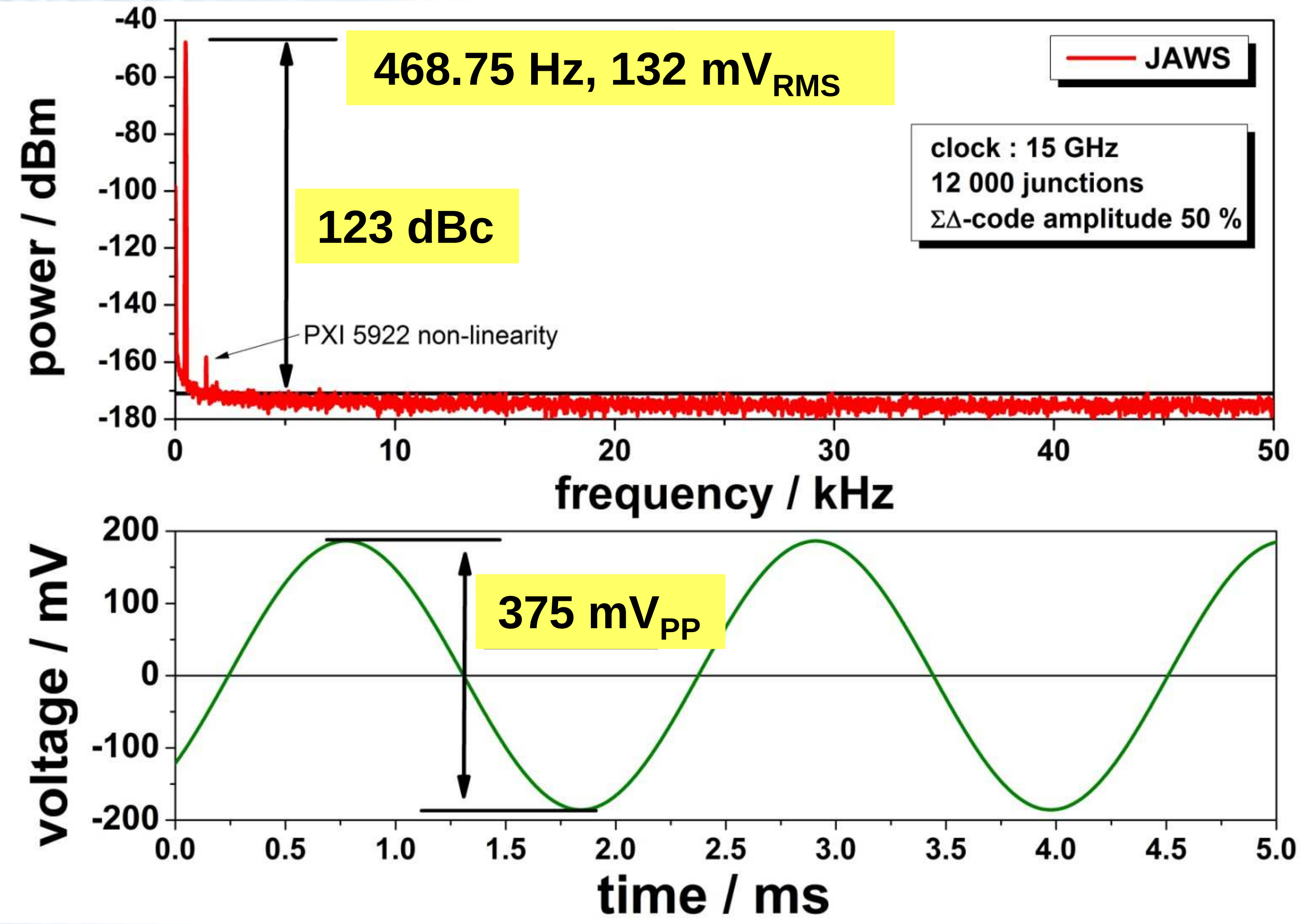
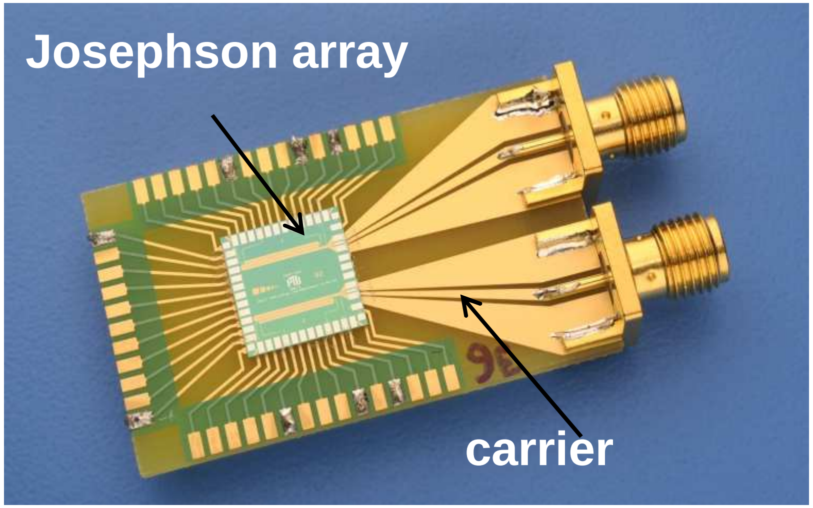
- Josephson Arbitrary Waveform Synthesiser (JAWS)

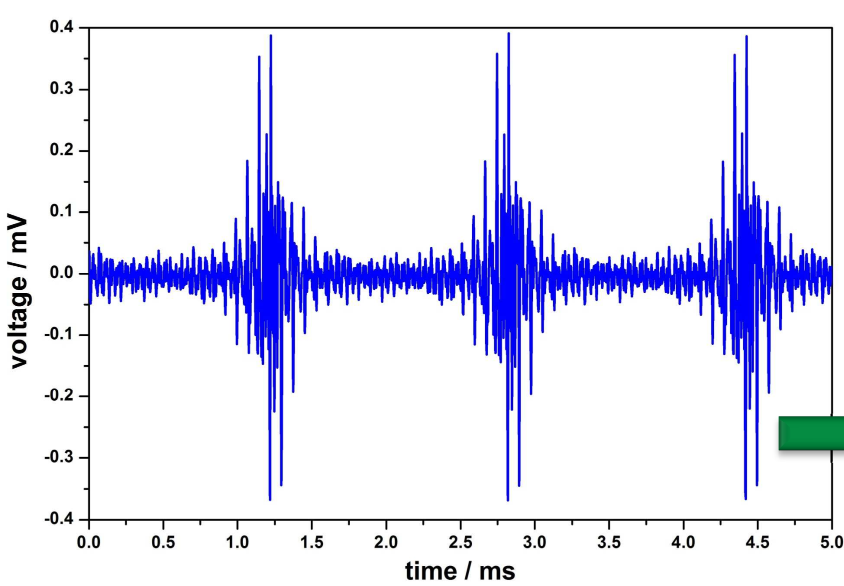


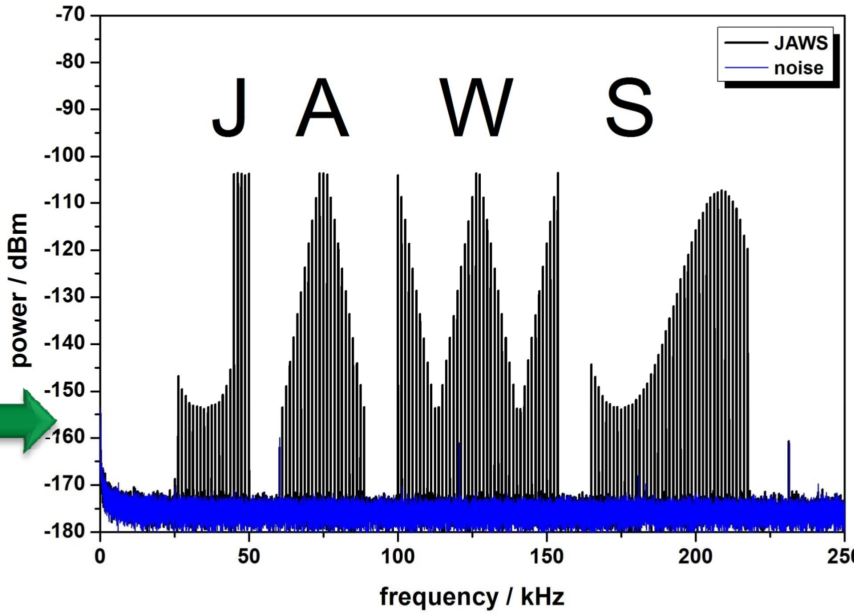
synthesis of arbitrary waveforms with pure spectra

Pulse-driven Josephson arrays

- **Josephson Arbitrary Wave-form Synthesiser (JAWS)**

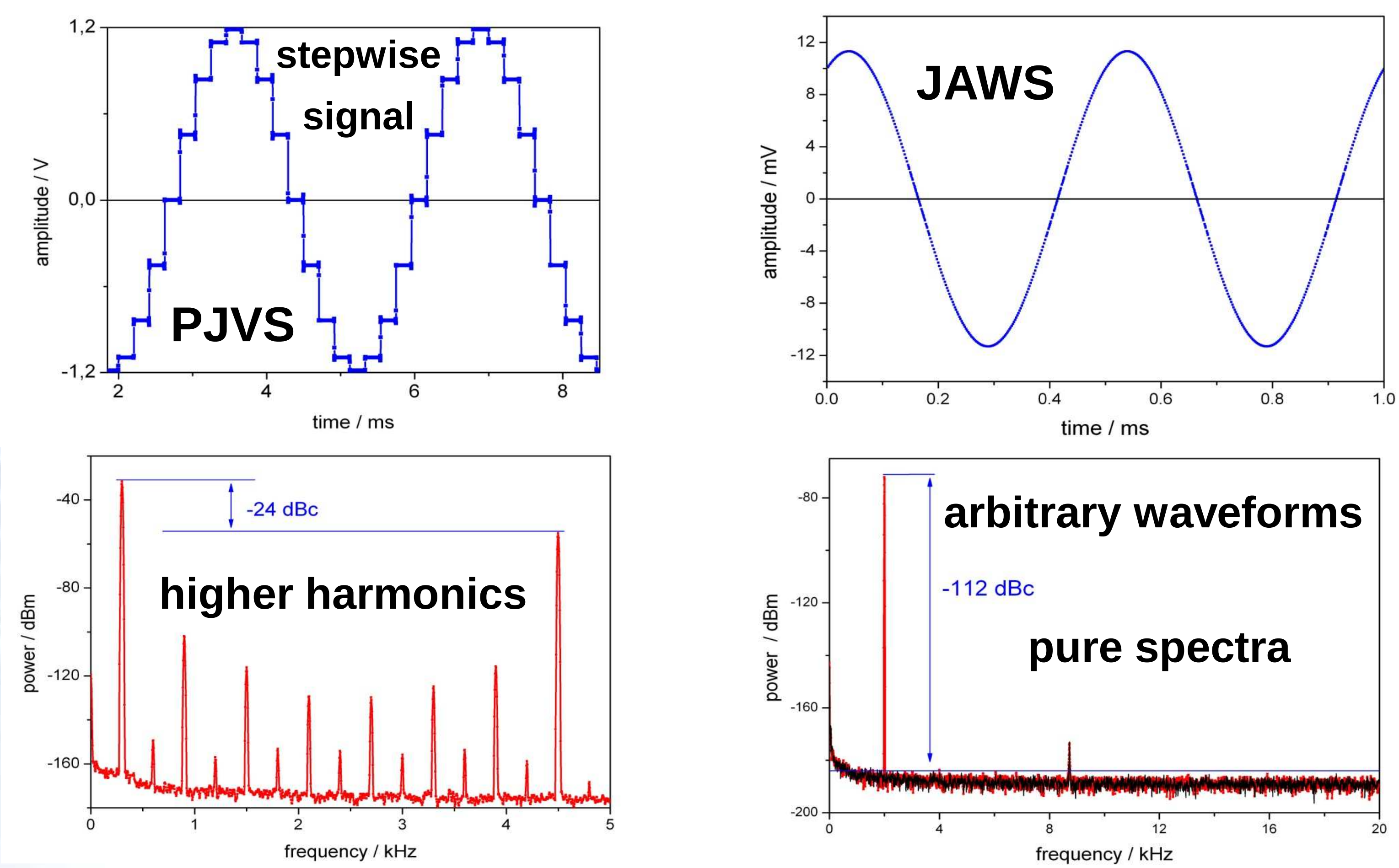






Combination of PJVS and JAWS?

- **pure waveforms and higher voltages?**



PJVS + JAWS: principle

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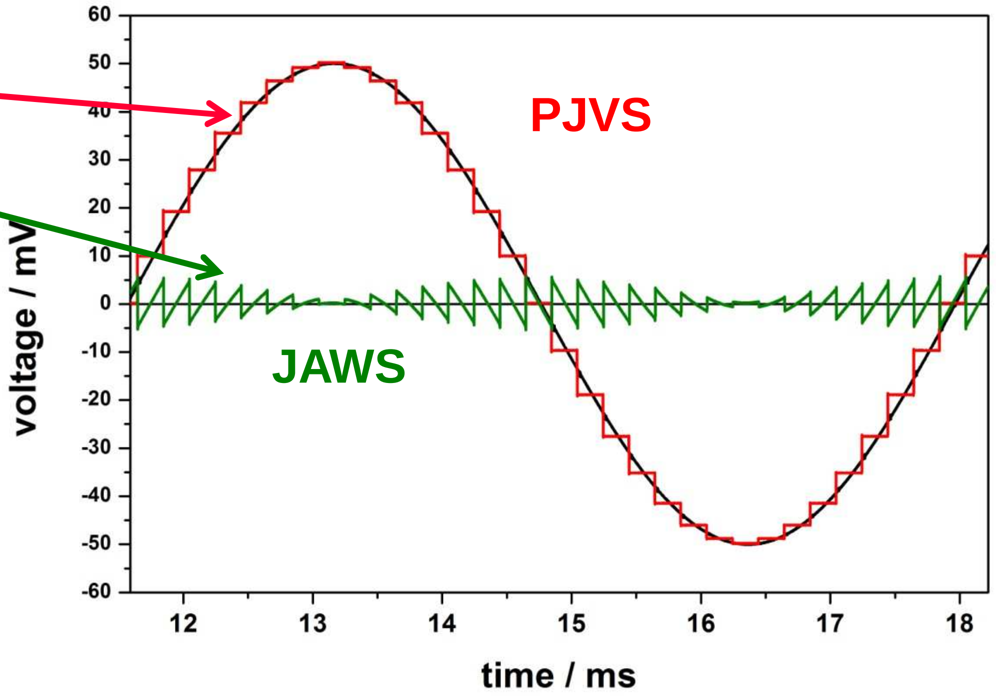
Goal: spectrally pure signals of 1 V (10 V)

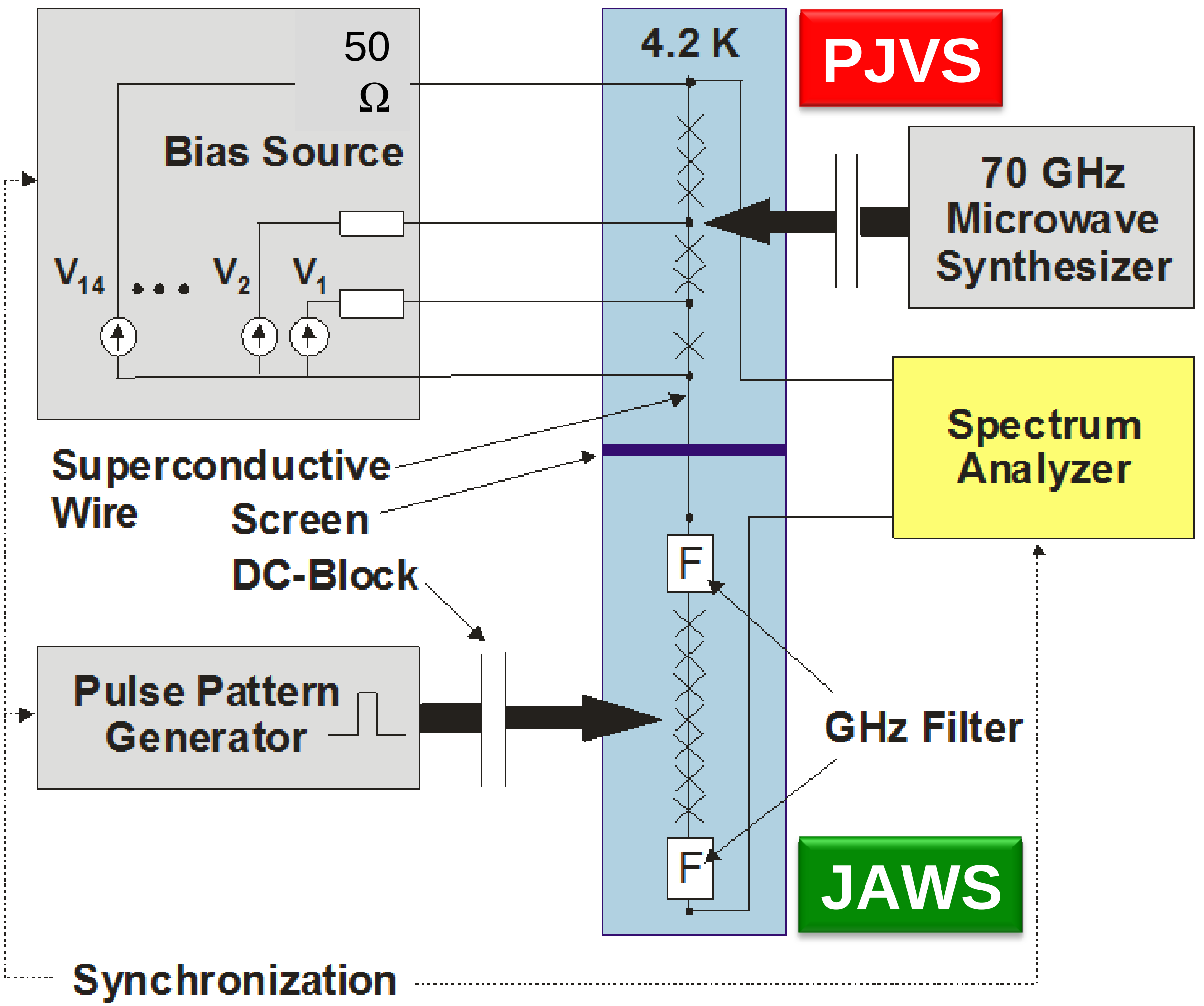
- **PJVS:** stepwise signal, higher harmonics; transients
- **JAWS:** harmonics of PJVS signal are compensated

=> PJVS
+ JAWS
= sine wave



(idea: J. Kohlmann et al, *IEEE Trans. Instrum. Meas.* 56 (2007) 472)

PJVS + JAWS: setup



PJVS + JAWS: measurement

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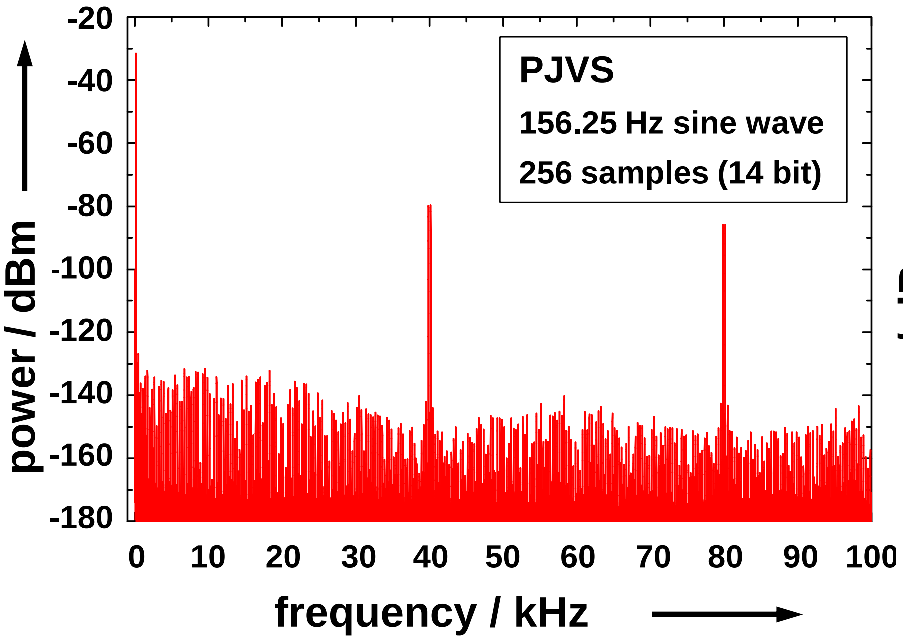
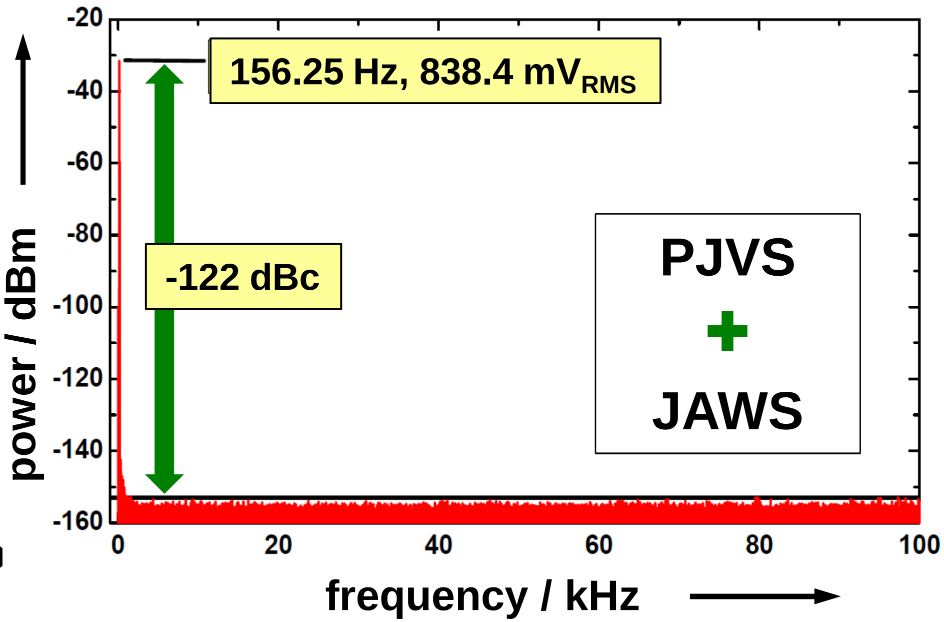
- **PJVS: binary-divided 1 V array (8,192 JJs: 1.18 V)**
- **JAWS: pulse-driven array (4,795 JJs: 47 mV) (compensation of about 4,000 harmonics up to 1 MHz)**





R. Behr et al, *IEEE Trans. Instrum. Meas.* 62 (2013) 1634

Conclusions and outlook

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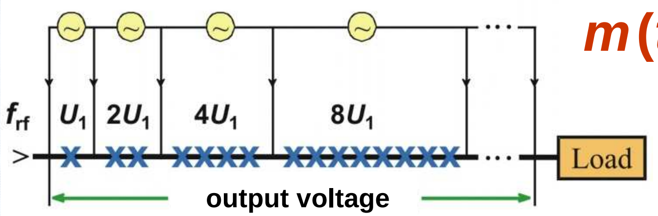
$$U_n(t) = n \cdot m \cdot \Phi_0 \cdot f$$

Binary-divided arrays

70 GHz



$m(t)$

number of Joseph. junctions

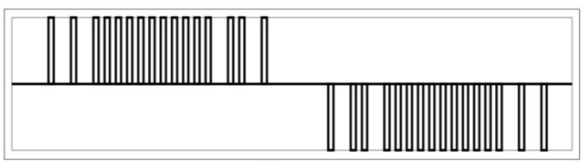
- \+ 1 V and 10 V (also 20 V)
- \+ high accuracy (sampling mode)
- \- transients limit accuracy
- \- spectra: many higher harmonics

Pulse-driven arrays

15 GHz

$f_p(t)$

pulse drive



pulse repetition frequency

- \+ pure spectra
- \+ high accuracy
- \- output voltage < 1 V

The PTB is a member of FLUXONICS e.V. (www.fluxonics.org)

Conclusions and outlook

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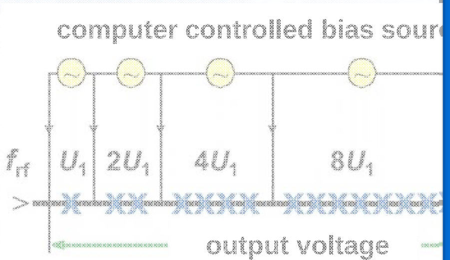
Binary-divided arrays

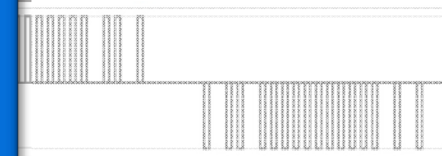
70 GHz



Pulse-driven arrays

15 GHz

pulse drive



$$U_n(t) = n \cdot m \cdot \Phi_0 \cdot f$$

Combination:

PJVS + JAWS

pure spectrum at 1 V

number of Joseph. junctions

pulse repetition frequency

Binary-divided arrays:

+ 1 V and 10 V (also 20 V)
+ high accuracy (sampling mode)
- transients limit accuracy
- spectra: many higher harmonics

Pulse-driven arrays:

+ pure spectra
+ high accuracy
- output voltage < 1 V

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