IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2016.
Slightly revised and annotated version of a presentation given at the QM 2016 held in Poznań, Poland, May 11 to 13, 1016.

High-precision pulse-driven AC Josephson voltage standard up to 1 V at PTB

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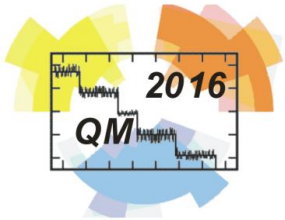

QM 2016 - 5th International Conference on Quantum Metrology

May 11-13, 2016

Poznan, POLAND

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outline

1. Principle PJVS and JAWS
2. 1 V JAWS @ PTB
   a) design
   b) fabrication
   c) setup
   d) overview : features
3. Precision of JAWS
   a) comparison JAWS vs. JAWS
   b) comparison JAWS vs. QVM
4. Summary

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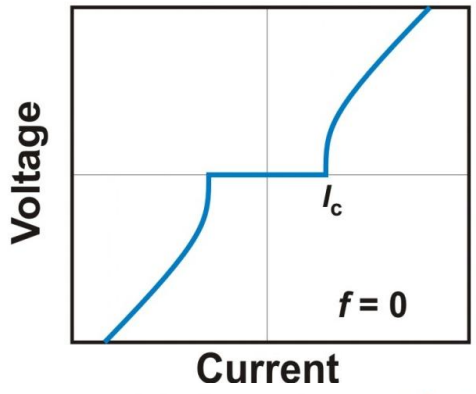
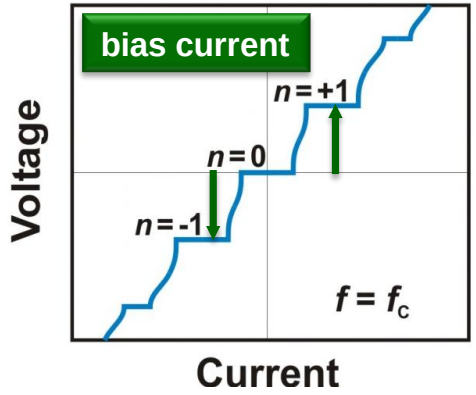
AC-QVM : Design of PJVS

SNS junctions :
non-hysteretic IVC

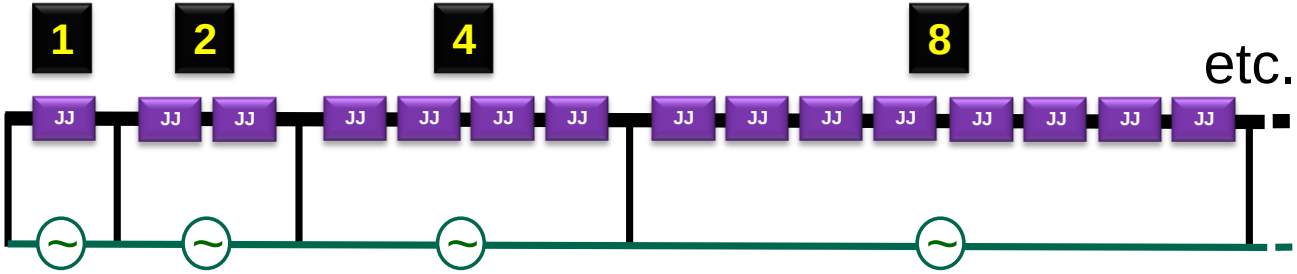




70 GHz : CW

AC-QVM : is based on
Programmable Josephson Voltage Standard

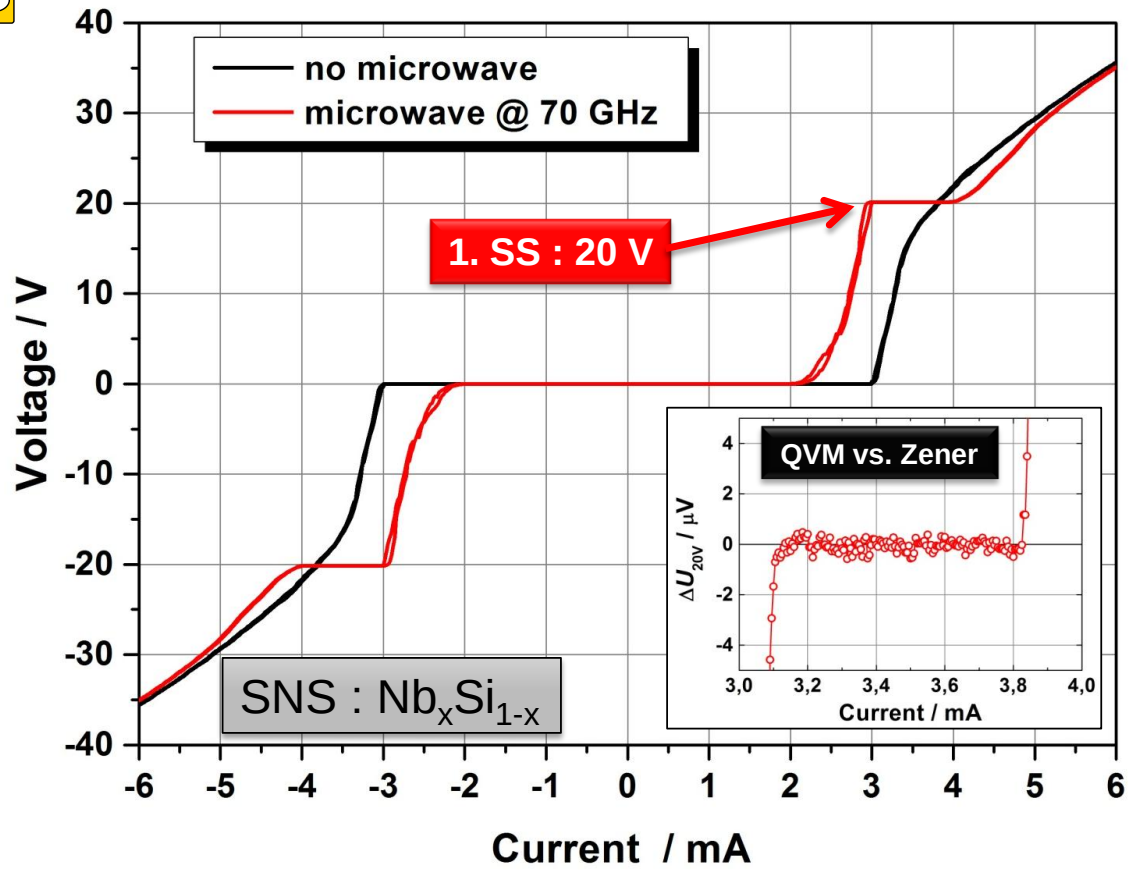
Josephson Junctions are arranged in a binary sequence



fast multi-channel current bias source

1 V PJVS : 8192 junctions : 1,2,4,…,4096
10 V PJVS : 69632 junctions : 1,2,4,….17,34…,34816

PJVS circuits : 10 V and 20 V



2008 worldwide first
10 V SNS @ 70 GHz

2012 worldwide first
20 V SNS @ 70 GHz

PTB circuits in more than 20 countries

10 V : 69 632 junctions
20 V : 139 264 double-stacked junctions

PJVS : AC-Quantum Voltmeter

- electronics : commercially available
- computer controlled

commercially availabe by SUPRACON

supracon
SQUID AND MICROFABRICATION TECHNOLOGIES

JAWS : principle of pulse-mode

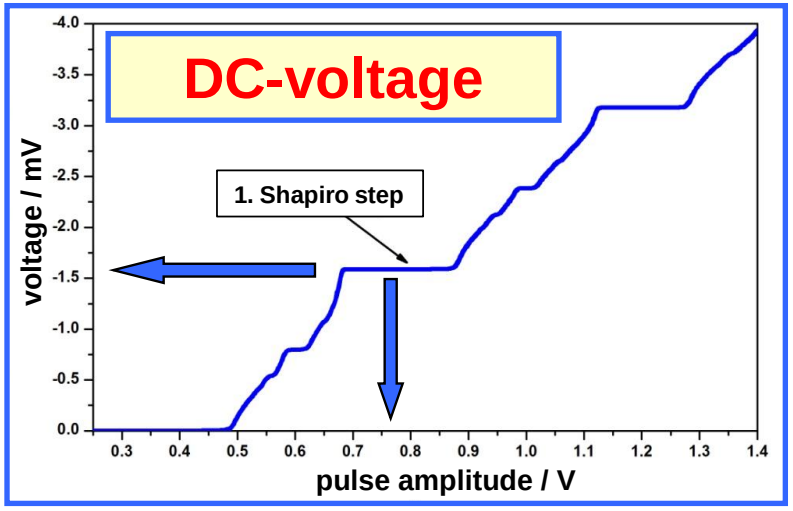
idea and first realization : S.P. Benz and C.A. Hamilton, *Appl. Phys. Lett.* 68 (1996) 3171

a current pulse (pulse repetition frequency f_p) transfers N flux-quanta $\Phi_0 = h/2e$ through a Josephson junction (number of junctions M).

pulse repet. freq. f_p = const.

Josephson-equation :

$$V_{DC} = M \cdot N \cdot \Phi_0 \cdot f_p$$



pulse repet. freq. $f_p \neq$ const.

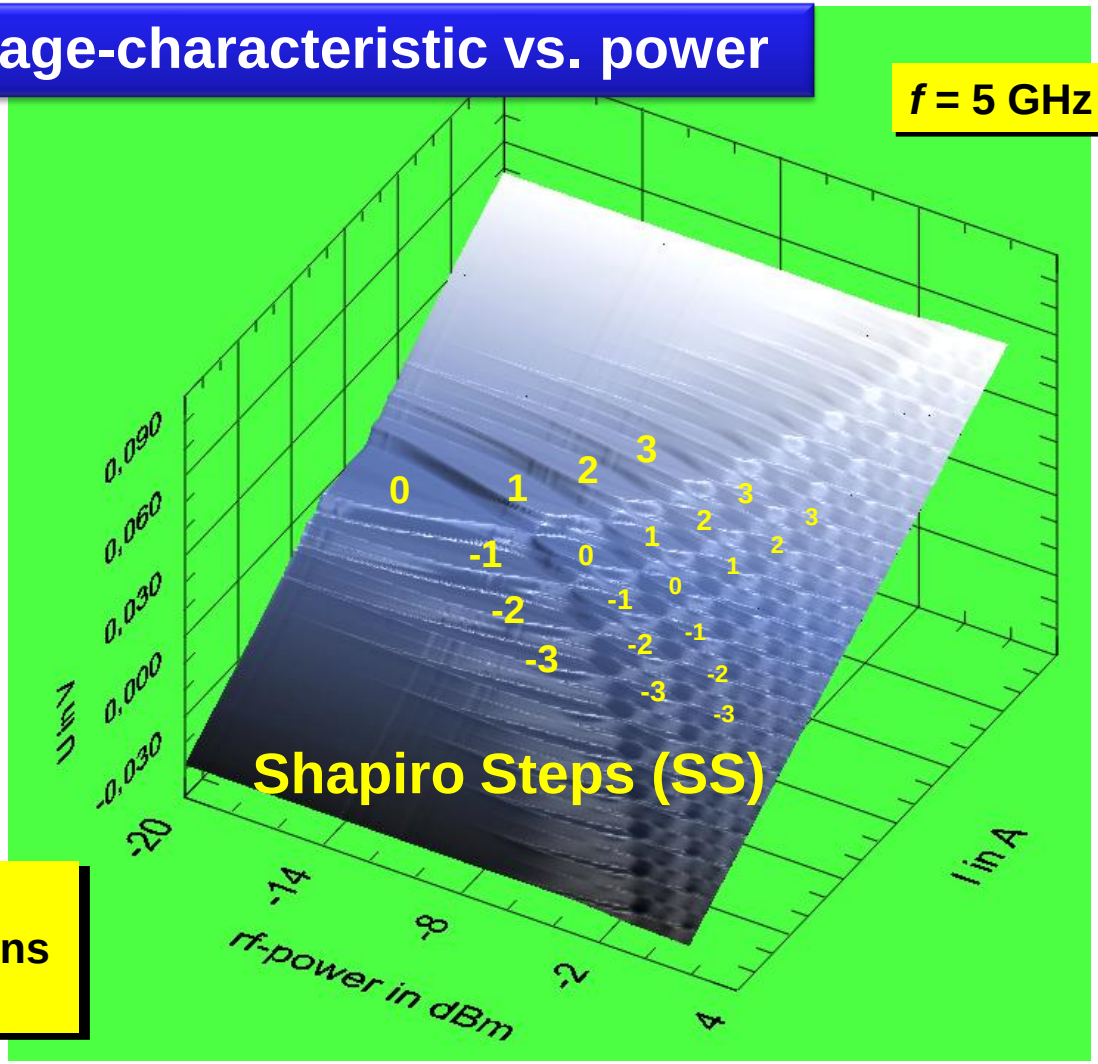
Josephson-equation in pulse-mode :

$$V_{AC}(t) = M \cdot N \cdot \Phi_0 \cdot f_p(t)$$

AC-voltage arbitrary waveform

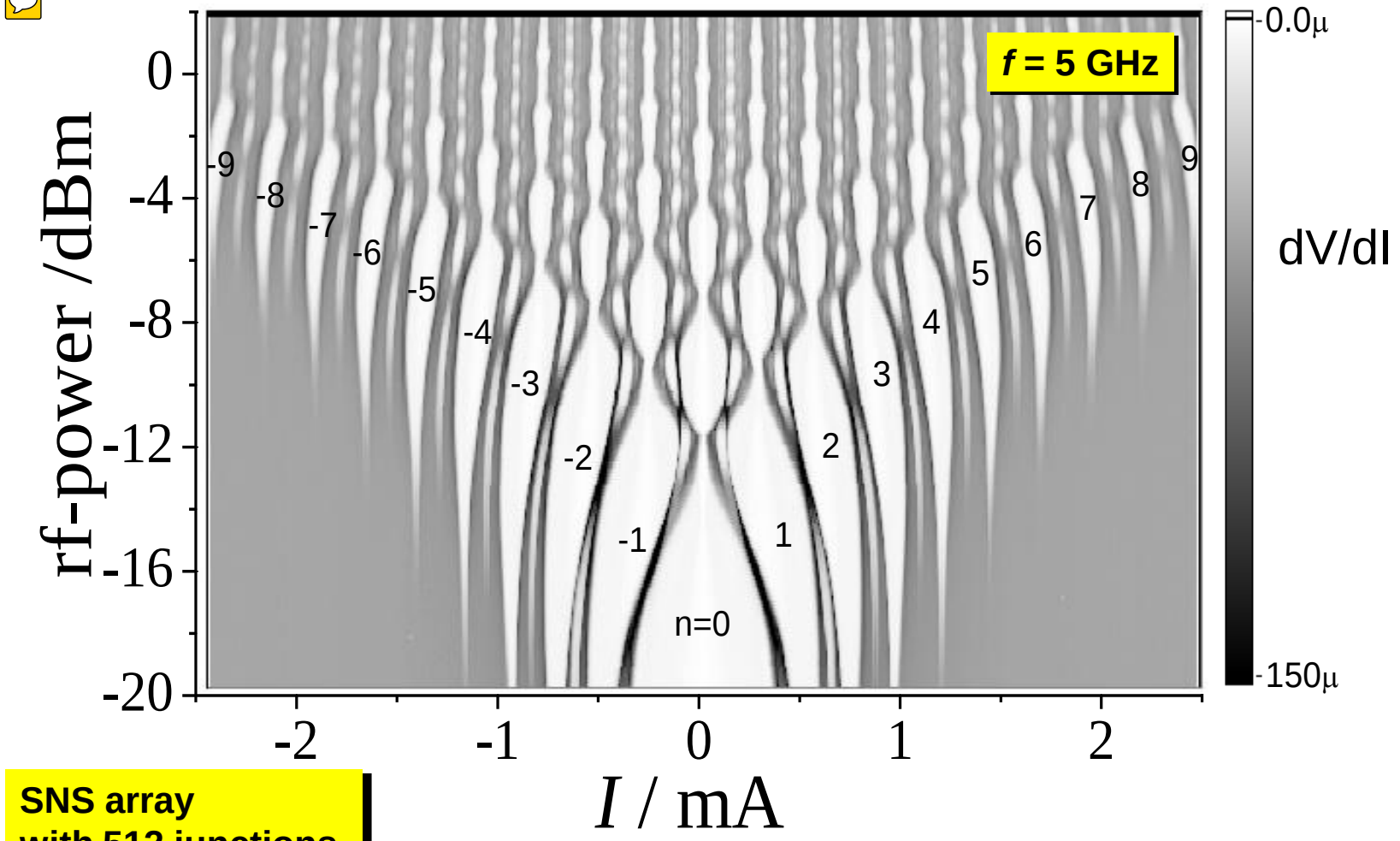
JAWS : Shapiro steps vs. power (I)

current-voltage-characteristic vs. power



SNS array with 512 junctions (0.7 x 0.7 µm²)

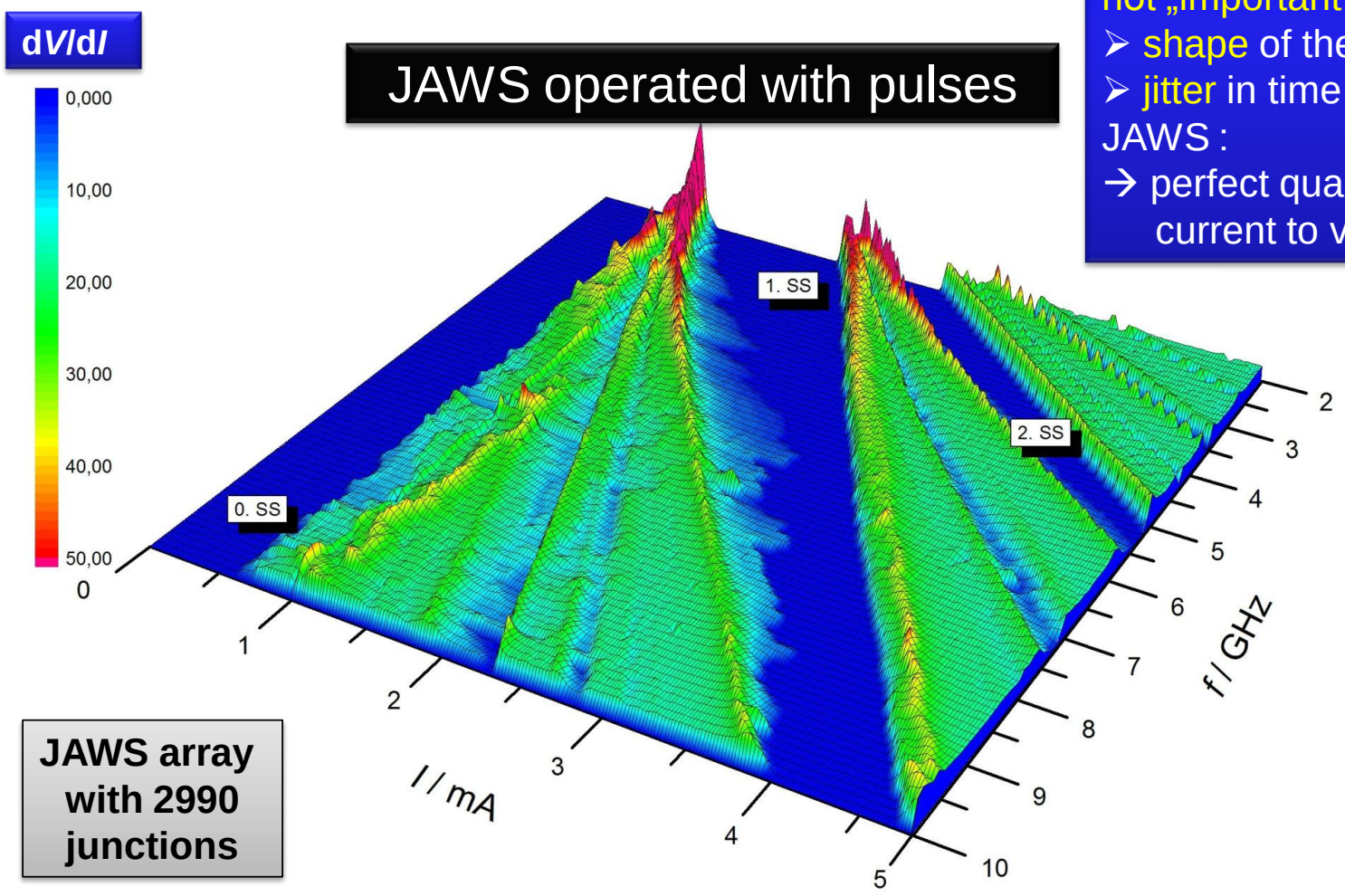
JAWS : Shapiro steps vs. power (II)



SNS array with 512 junctions (0.7 x 0.7 μm²)

Karpov, et al., *Journal Appl. Physics* 104, 2008

JAWS : Shapiro steps @ all frequencies



not „important“ :
- shape of the current pulses
- jitter in time & amplitude

JAWS :
→ perfect quantizer
current to voltage

JAWS array with 2990 junctions

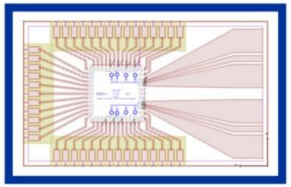
current-voltage-characteristic vs. frequency

JAWS : practical realization

computer

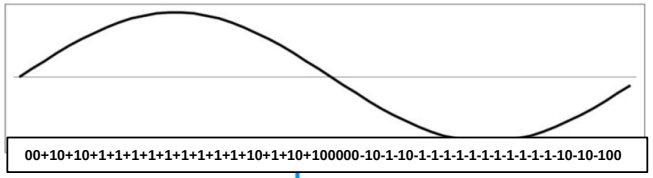
pulse-pattern-generator (PPG)

SNS JAWS chip @ LHe : 4.2 K



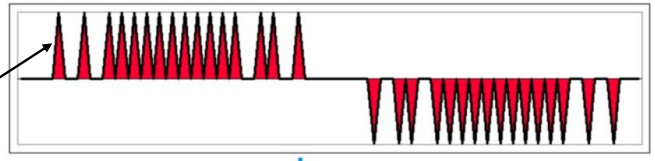
spectrum analyzer

arbitrary waveform

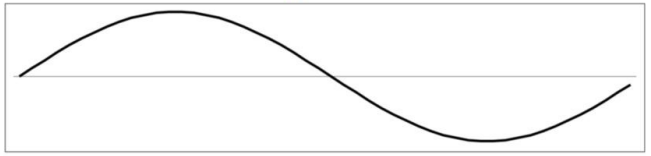


ΣΔ - modulation

current pulses



array output



quantized waveform

$$V(t) = M \cdot N \cdot \Phi_0 \cdot f_p(t)$$

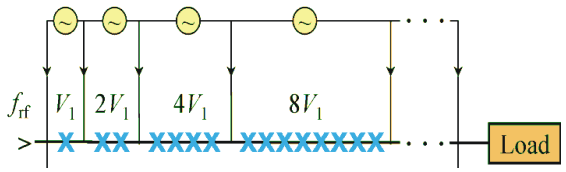
PJVS and JAWS : basic principle

AC-Programmable Josephson Voltage Standard

70 GHz

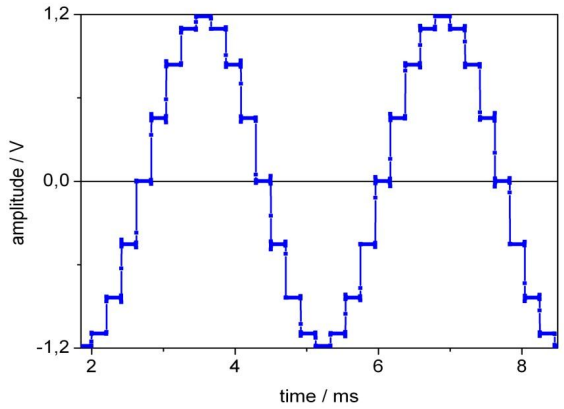
$V_{AC}(t) = M \cdot N \cdot \Phi_0 \cdot f$

binary



$M(t)$

number Josephson junctions

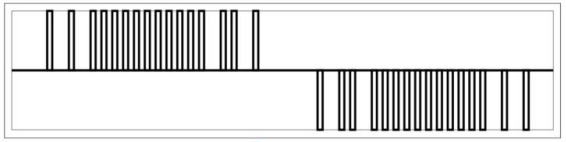


Josephson Arbitrary Waveform Synthesizer

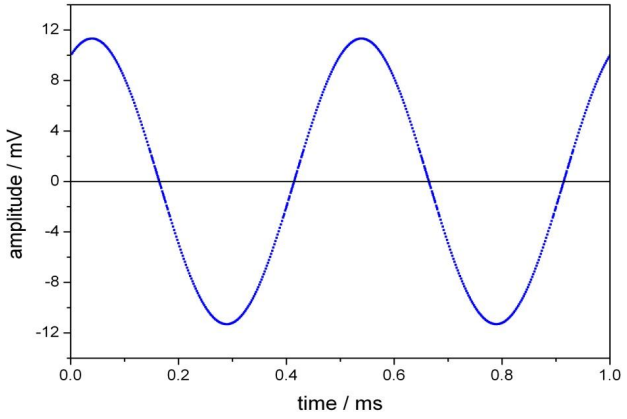
15 GHz

$f_p(t)$

pulse operation



pulse repetition frequency



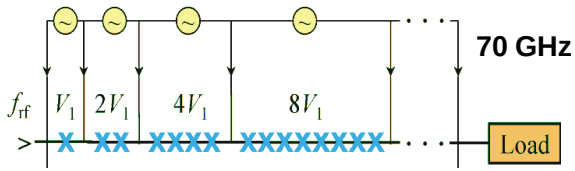
PJVS and JAWS : basic principle

AC-Programmable Josephson Voltage Standard

70 GHz

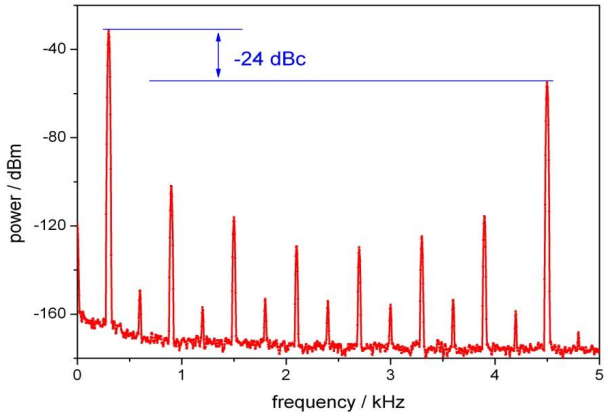
$V_{AC}(t) = M \cdot N \cdot \Phi_0 \cdot f$

binary



$M(t)$

number Josephson junctions

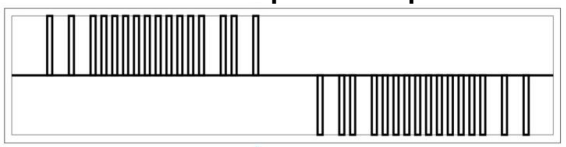


Josephson Arbitrary Waveform Synthesizer

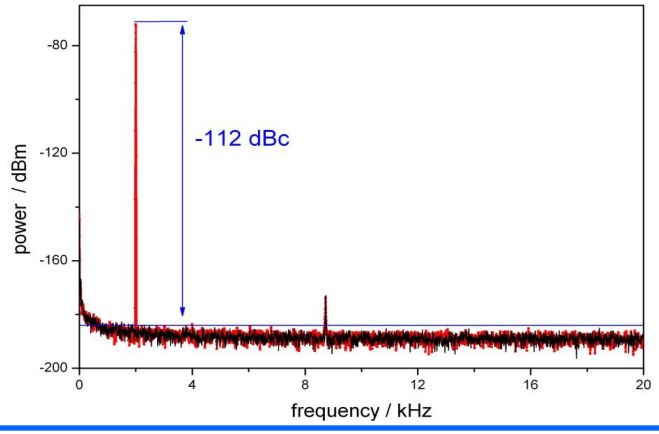
15 GHz

pulse operation

$f_p(t)$



pulse repetition frequency



PJVS and JAWS : basic principle

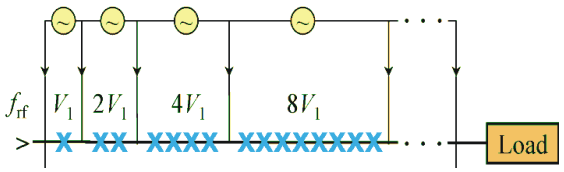
PTB

AC-Programmable Josephson Voltage Standard

70 GHz

$V_{AC}(t) = M \cdot N \cdot \Phi_0 \cdot f$

binary



$M(t)$

number Josephson junctions

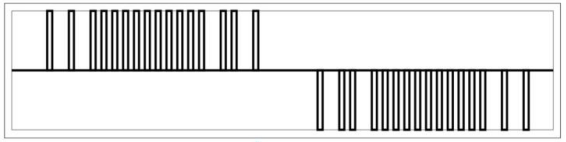
- output voltage : 20 V_p
- step approximated waveform
- spectrum : many harmonics
- not quantized between steps
- frequency range : DC…. < 10 kHz

Josephson Arbitrary Waveform Synthesizer

15 GHz

pulse operation

$f_p(t)$



pulse repetition frequency

- output voltage : 1 V_{RMS}
- real arbitrary waveform
- spectrum : no harmonics
- quantized at any time
- frequency range : DC…MHz

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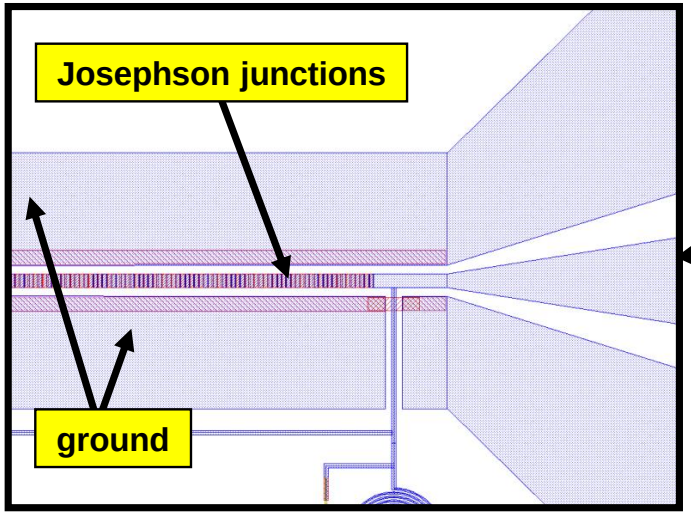
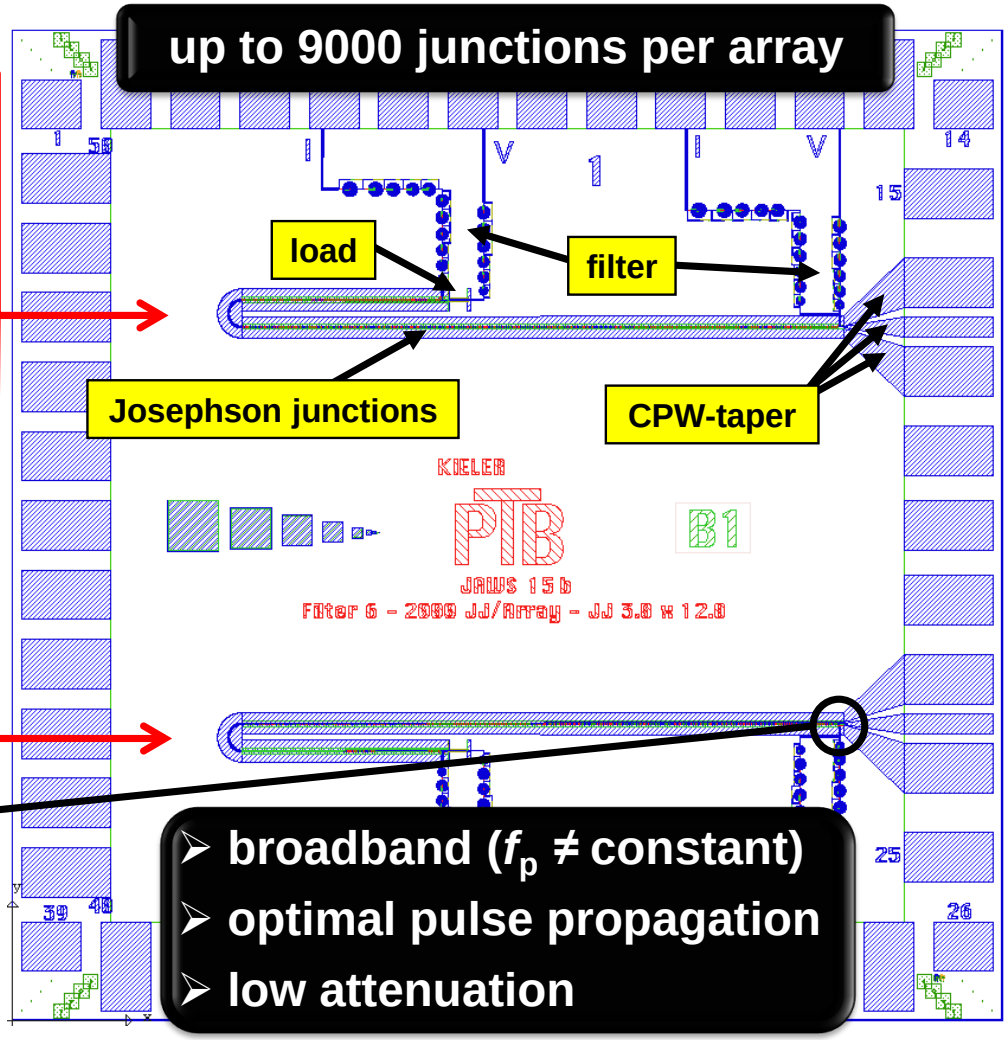
JAWS design : CPW

2 arrays @ chip :

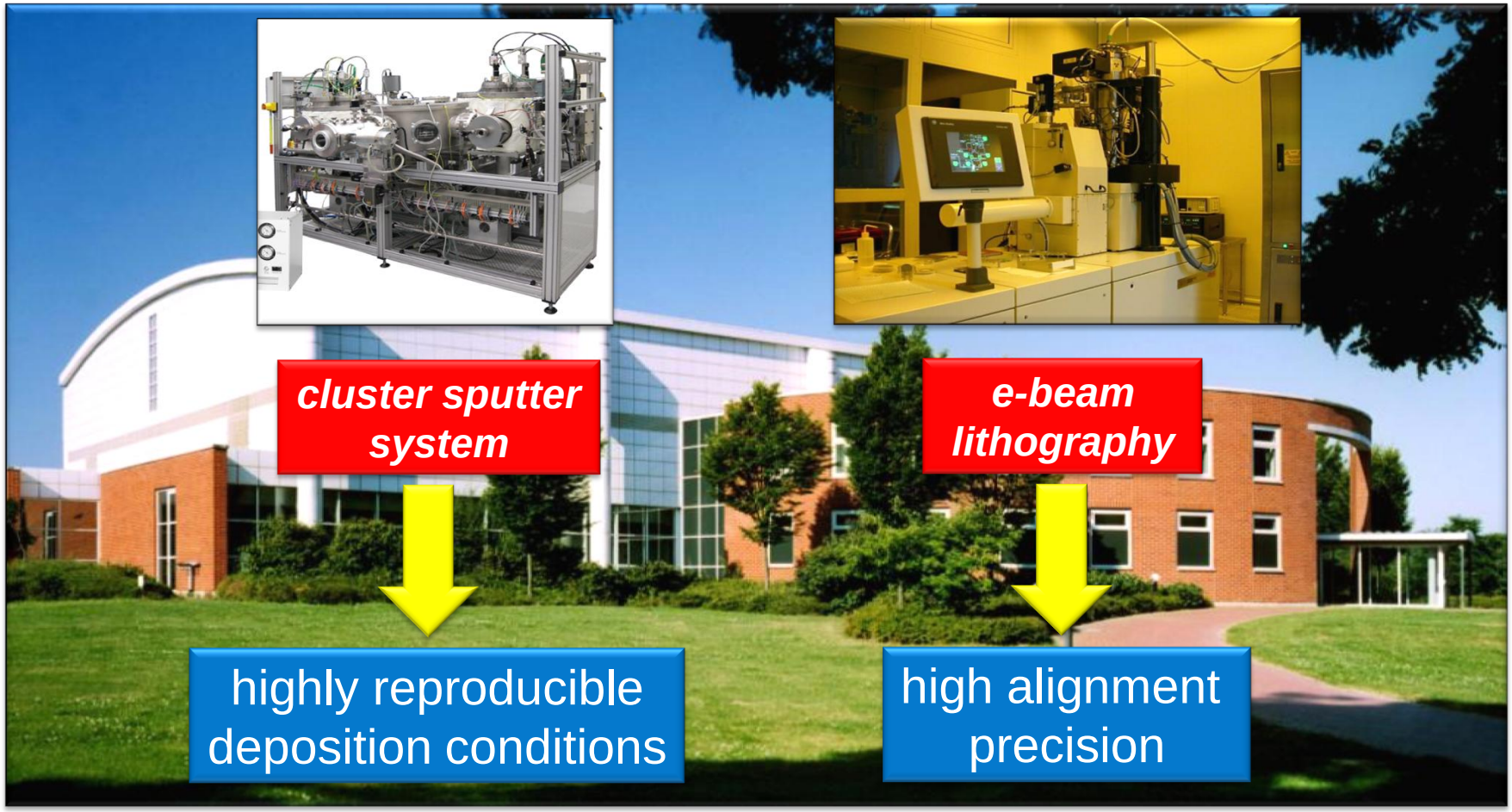
- size : 10 mm x 10 mm
- coplanar waveguide (CPW)
- CPW : 50 Ohm-taper
- Load : 50 Ohm
- on-chip LCR-filter





LCR-filter : M. Watanabe, et al., *IEEE Trans. Appl. Supercond.* 16, 2006
tapered CPW : P.D. Dresselhaus, et al., *IEEE Trans. Appl. Supercond.* 16, 2006

JAWS: major fabrication tools



UNIVEX 450C – Cluster - Sputter - System

Nb_xSi_{1-x} parameter for
70 GHz and 15 GHz

6 chambers

fully automatic

Nb, Si, AuPd,
HfTi, Al, Al_2O_3

SNS / SIS / SINIS

2 parameter to optimize :
JAWS : x ≈ 20%, d_{NbSi} ≈ 30 nm @ 15 GHz

SNS with NbSi : B. Baek, et al., *IEEE Trans. Appl. Supercond.* 16, 2006

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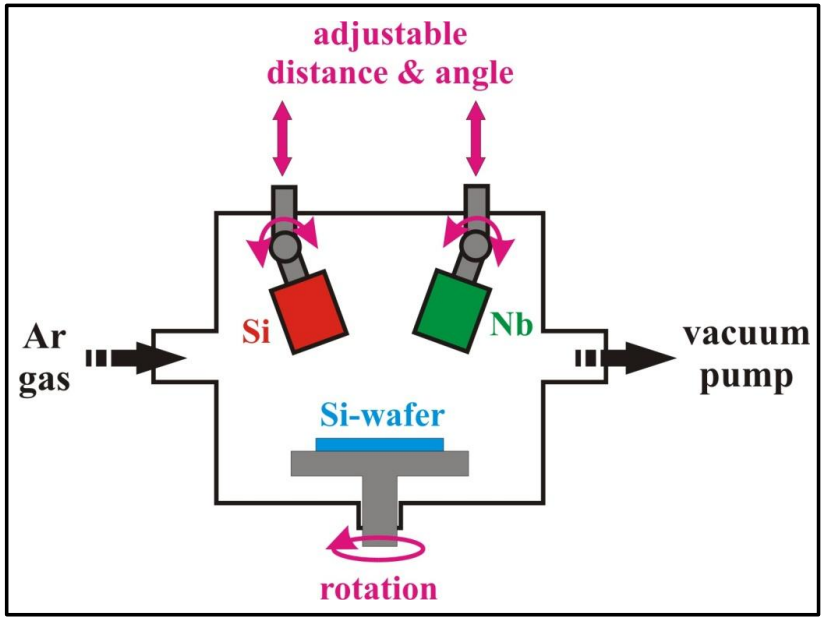
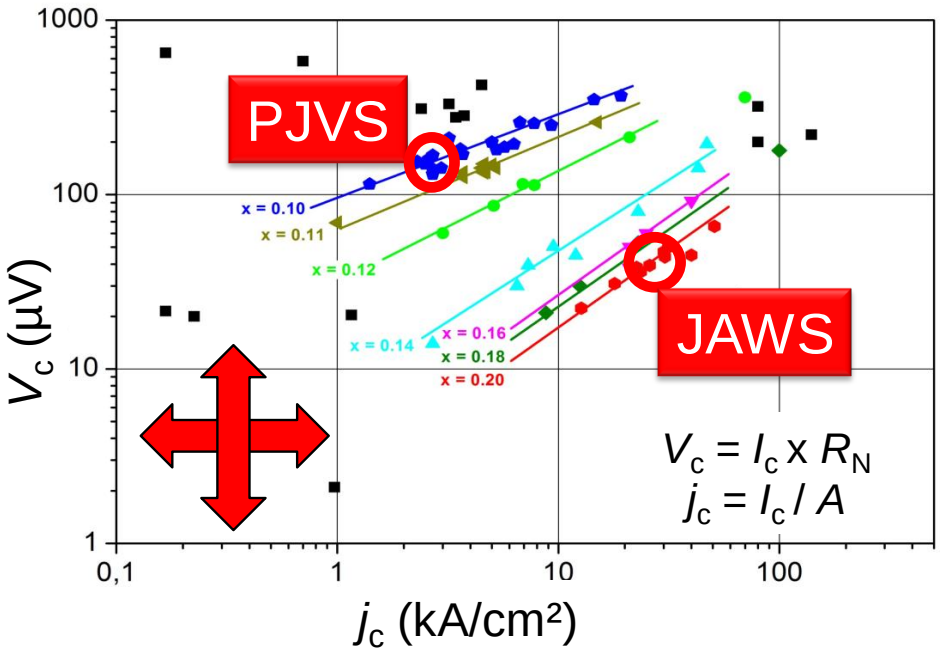
SNS junctions : Nb_xSi_{1-x}

Nb_xSi_{1-x} : co-sputter !

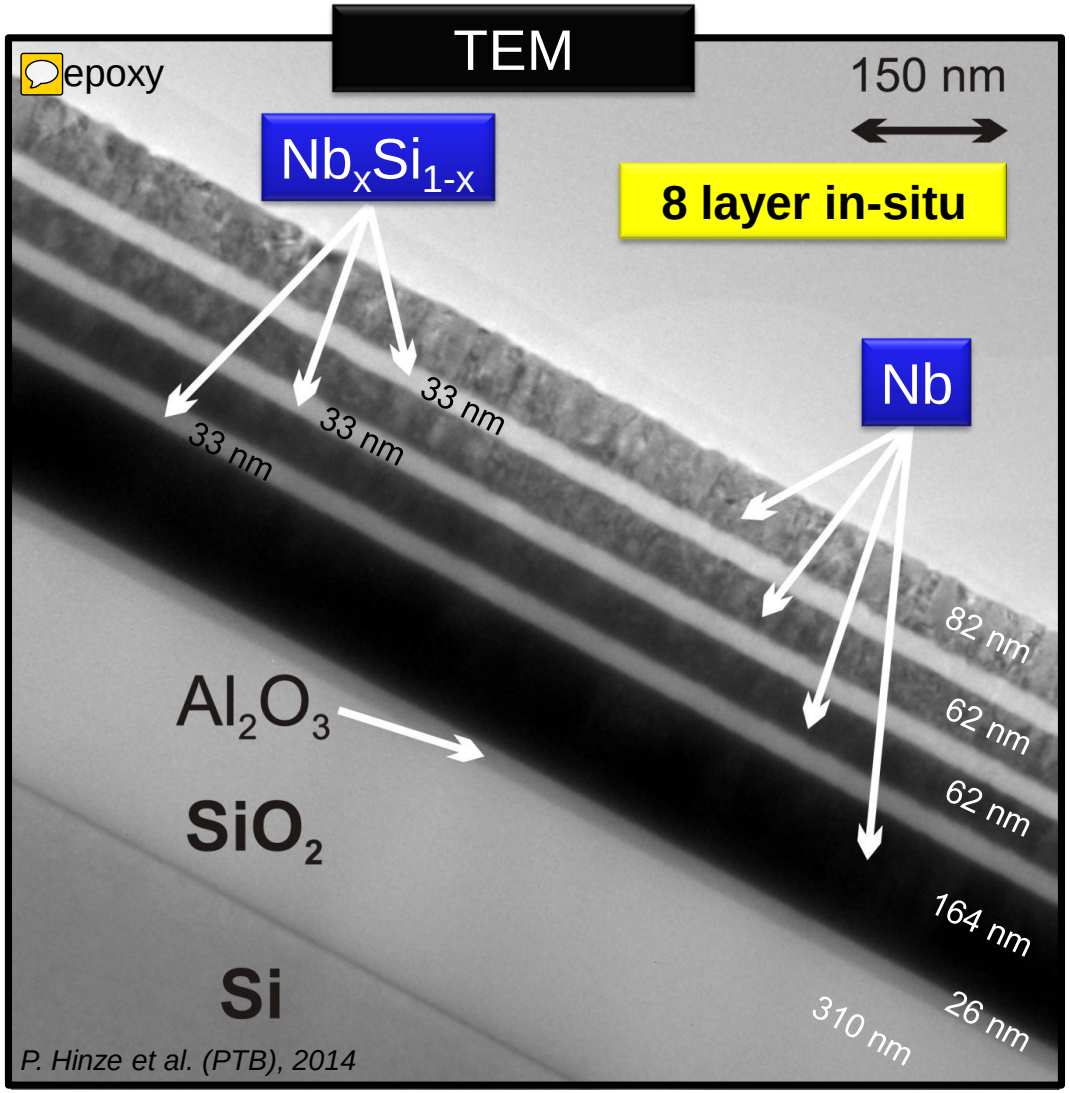
thickness *d* and Nb content *x*





j_c and V_c parameter adjustable in a wide range - nearly independent

SNSNSNS : triple-stacked junctions



UNIVEX 450C - system

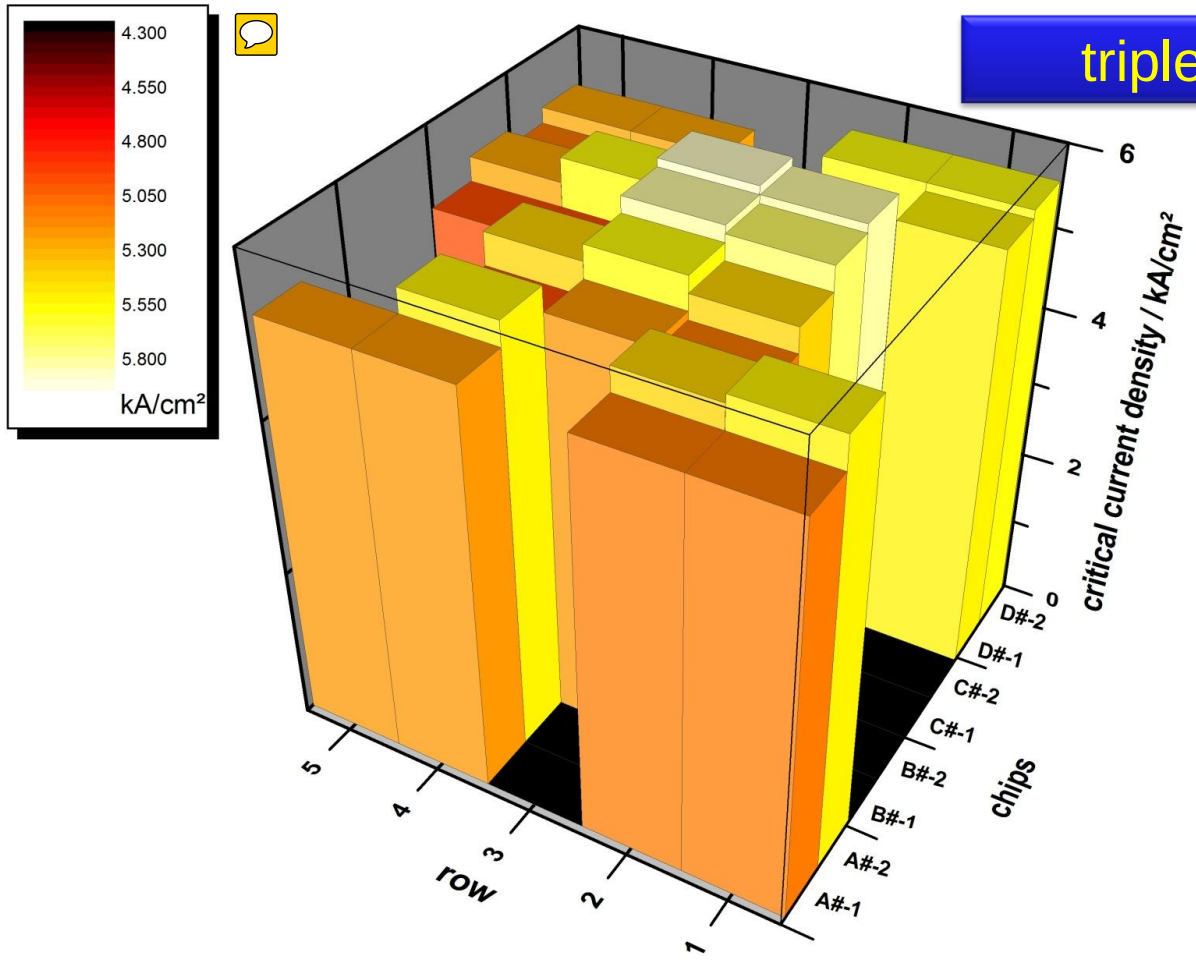
homogeneous & reproducible deposition conditions

for a given design :

3 x junction number

3 x output voltage

UNIVEX : low parameter spread



triple-stacked junctions

30 circuits measured (from 40)

228 000 junctions : 9 defect only

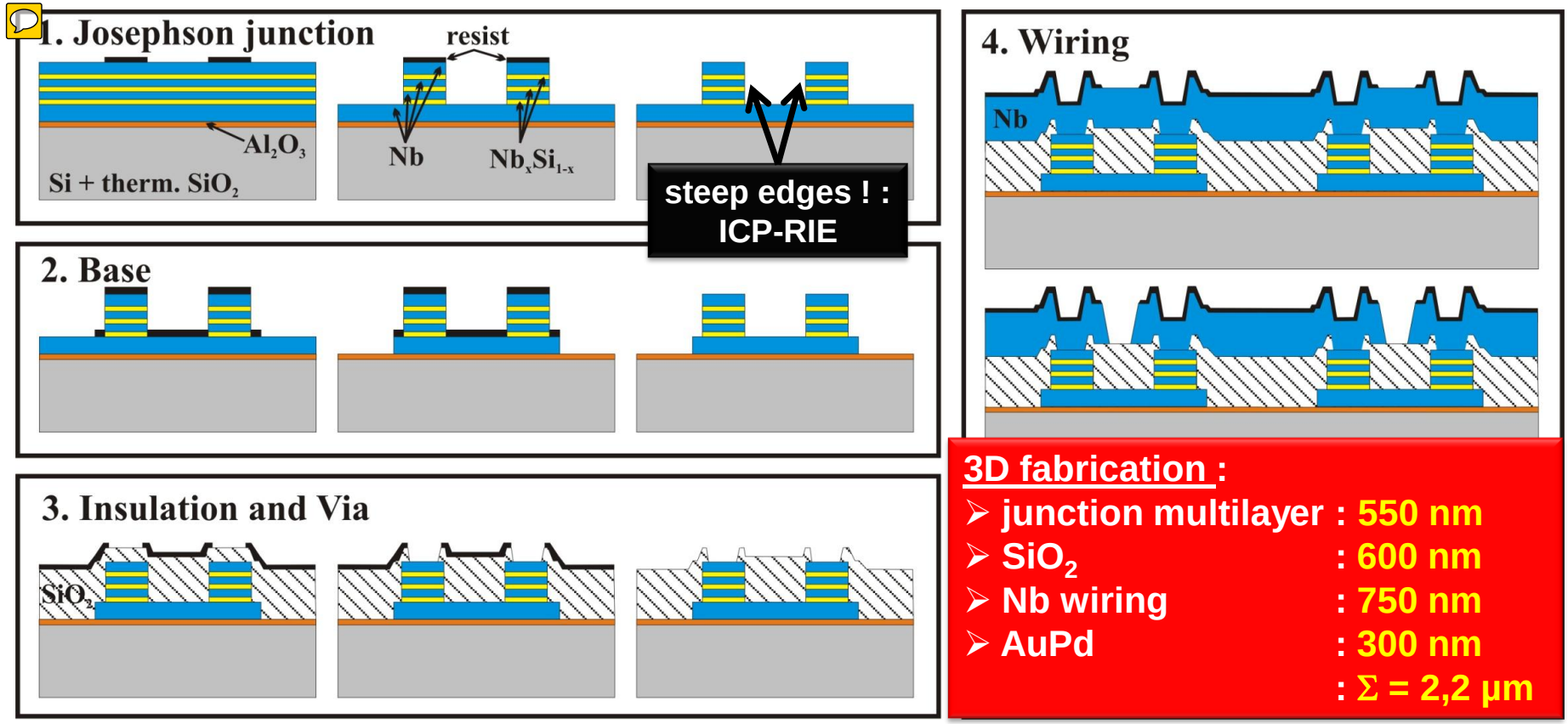
junction - yield : 99.996 %

deviation from mean value : 4.6 %

current density distribution @ wafer :

Window-process : JJ : SNSNSNS

PTB



3D fabrication :

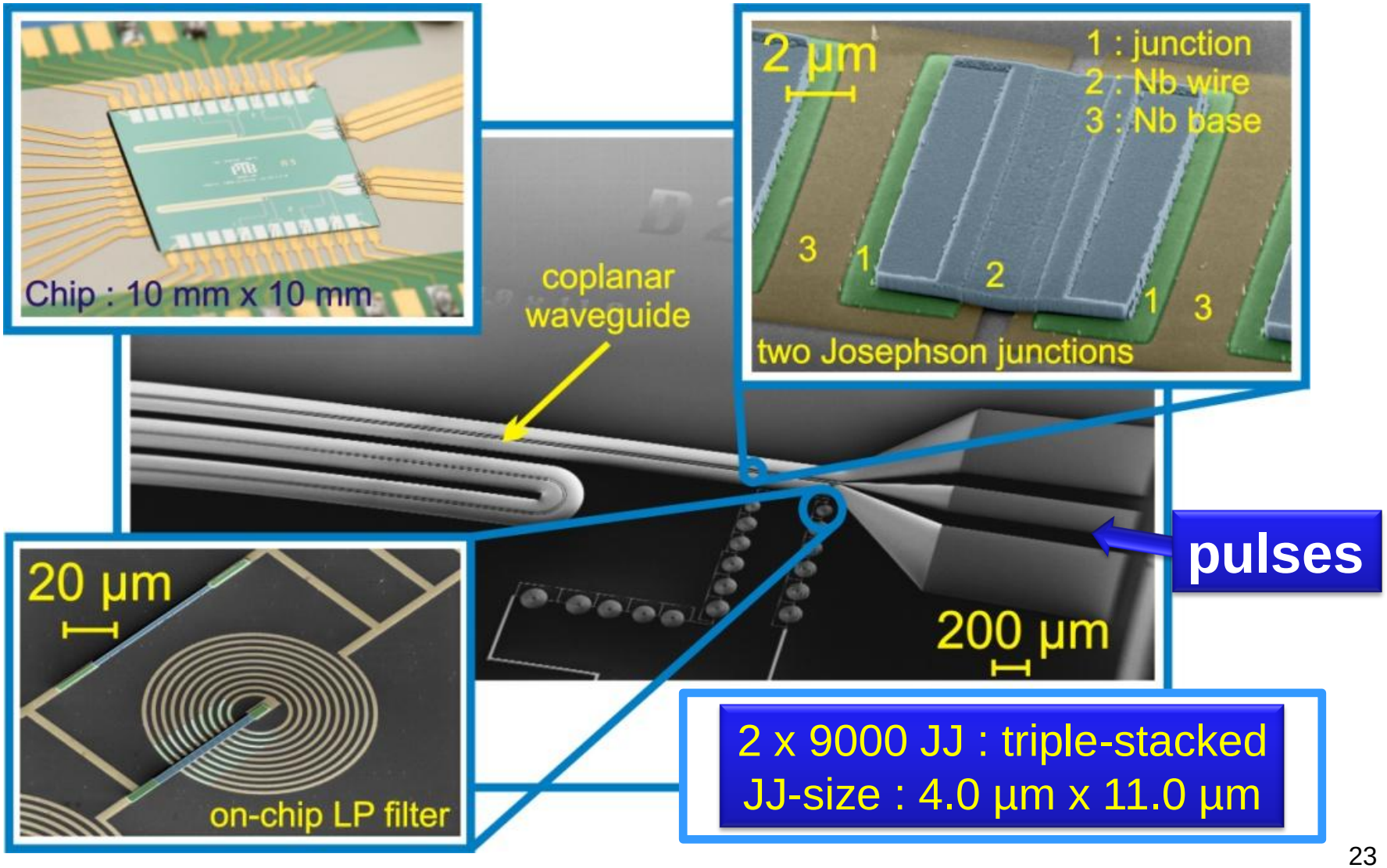
- junction multilayer : 550 nm
- SiO_2 : 600 nm
- Nb wiring : 750 nm
- AuPd : 300 nm
- : Σ = 2,2 µm

5. Load : AuPd resistors by lift-off; 6. Pads : remove SiO_2 by wet-etching

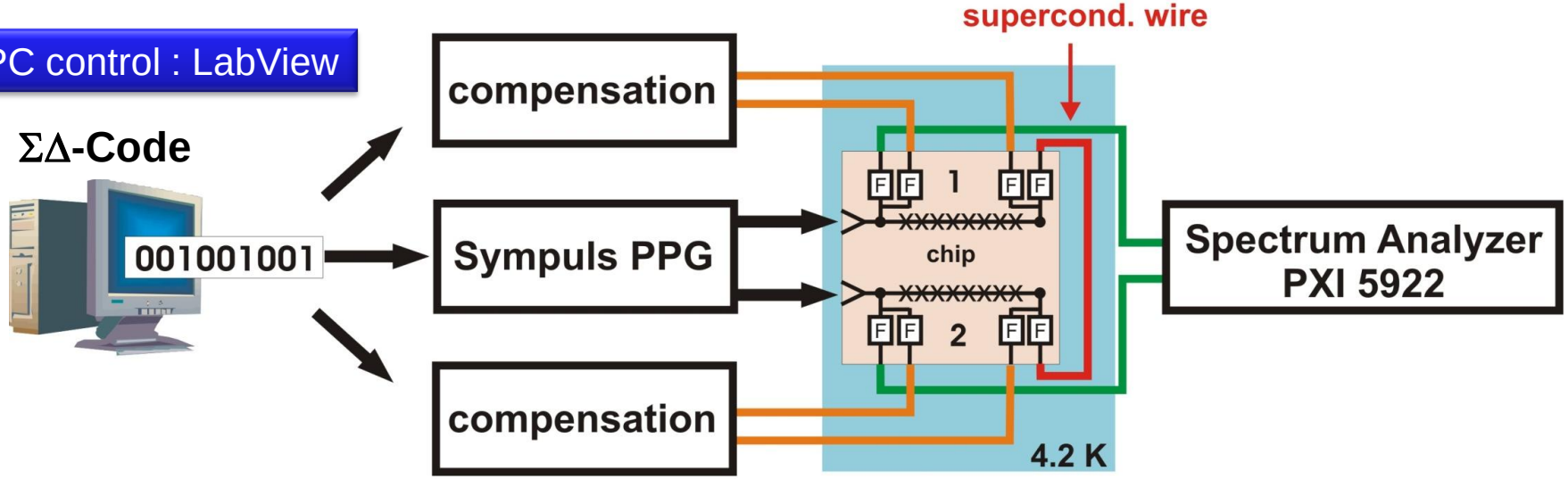
5 x deposition, 5 x etching, 5 x e-beam, 1 x lift off, 1 x opt. lithography

fabrication of large arrays with high yield !

Technology : large circuits



setup : 2 arrays in series @ 1 chip



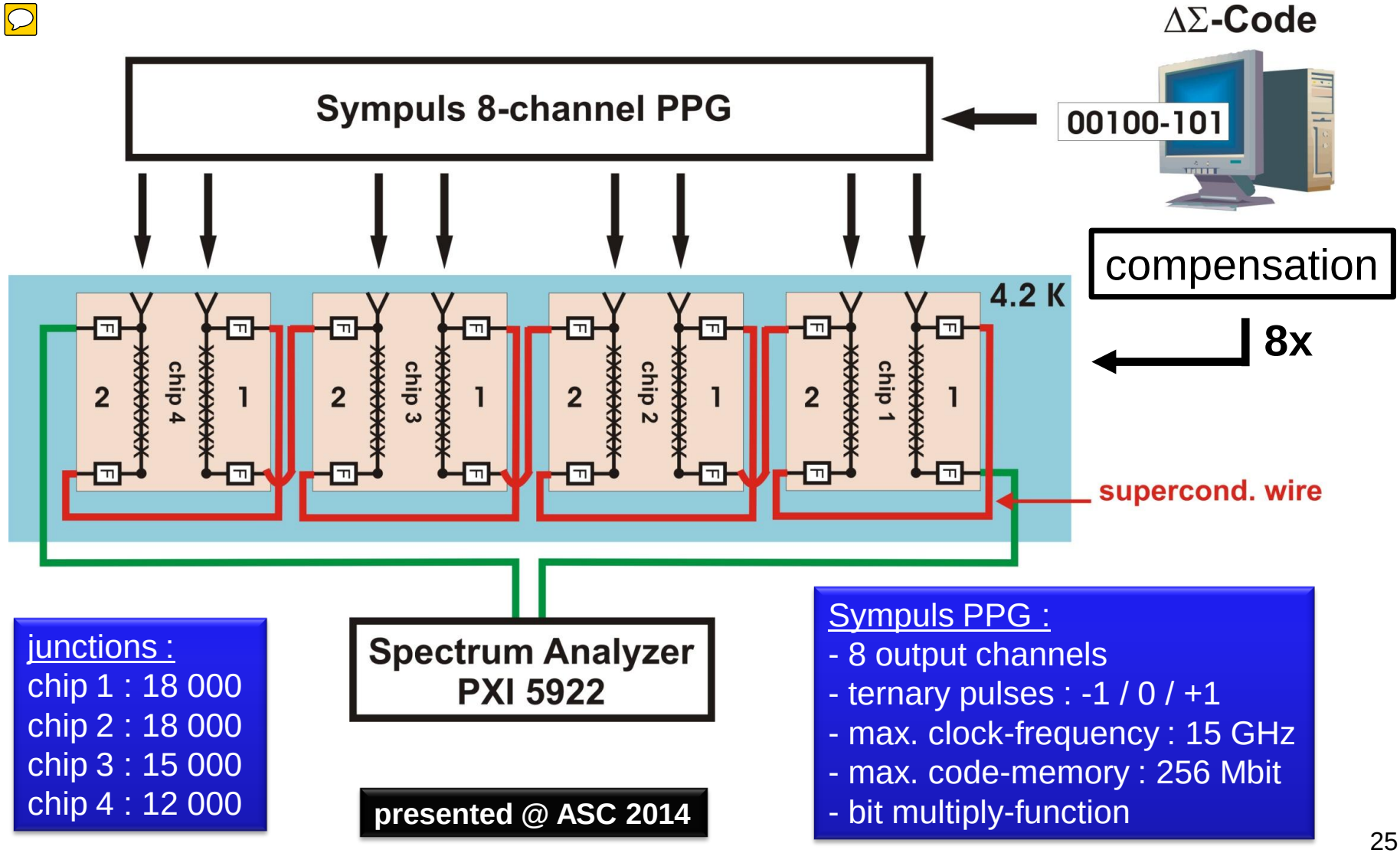
Sympuls PPG :
- ternary pulses : -1 / 0 / +1
- 2 output channels
- max. clock-frequency : 15 GHz
- max. code-memory : 256 Mbit

„pure“ spectra, if optimized :
- ΣΔ-codes
- experimental setup
- broadband Josephson arrays

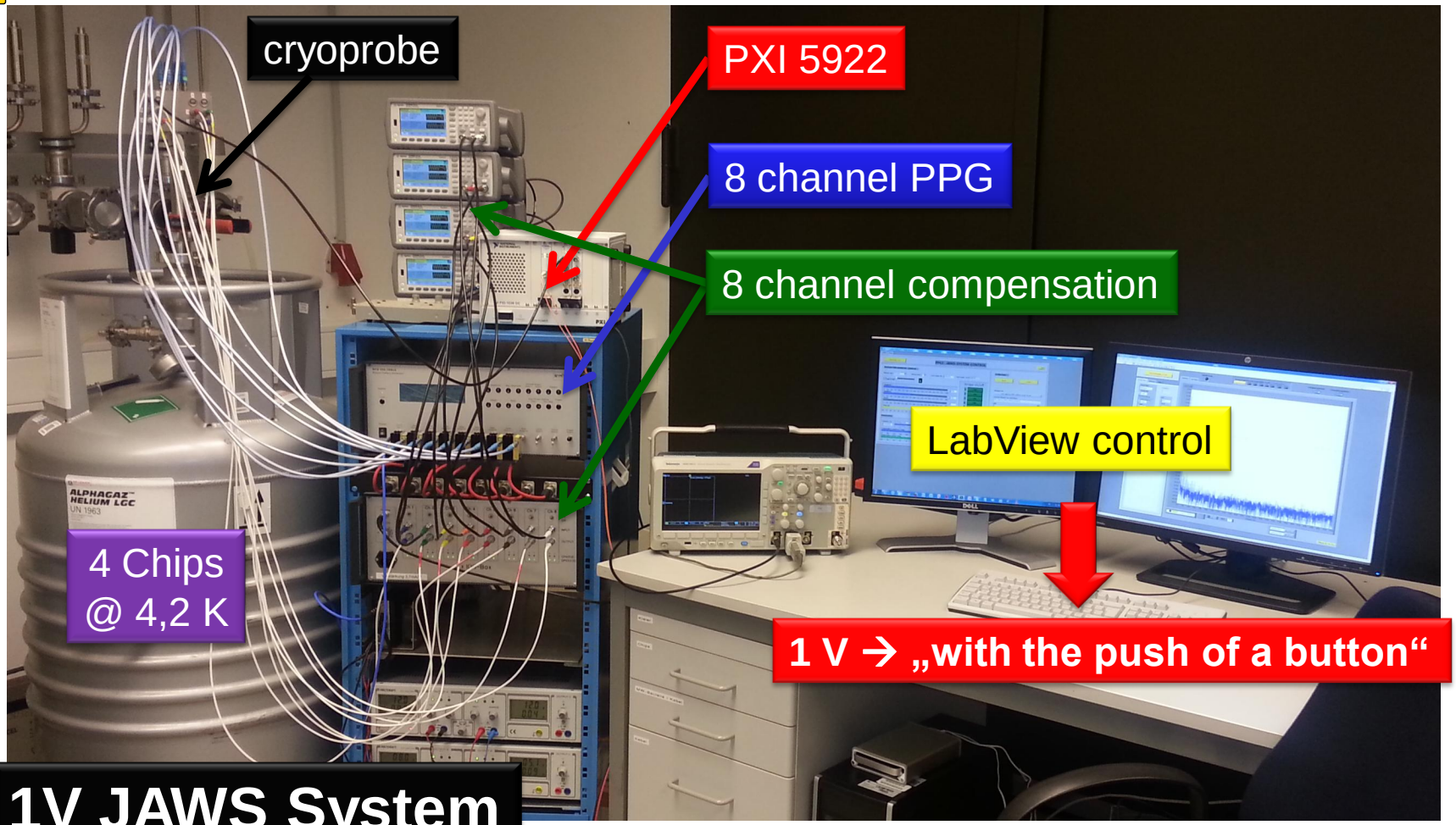
2 JAWS systems operational @ PTB

AC-coupling technique: S. P. Benz, et al., *IEEE Trans. Appl. Supercond.* 11, 2001

1 V-JAWS : 8 arrays @ 4 chips



optimized setup: 1V JAWS

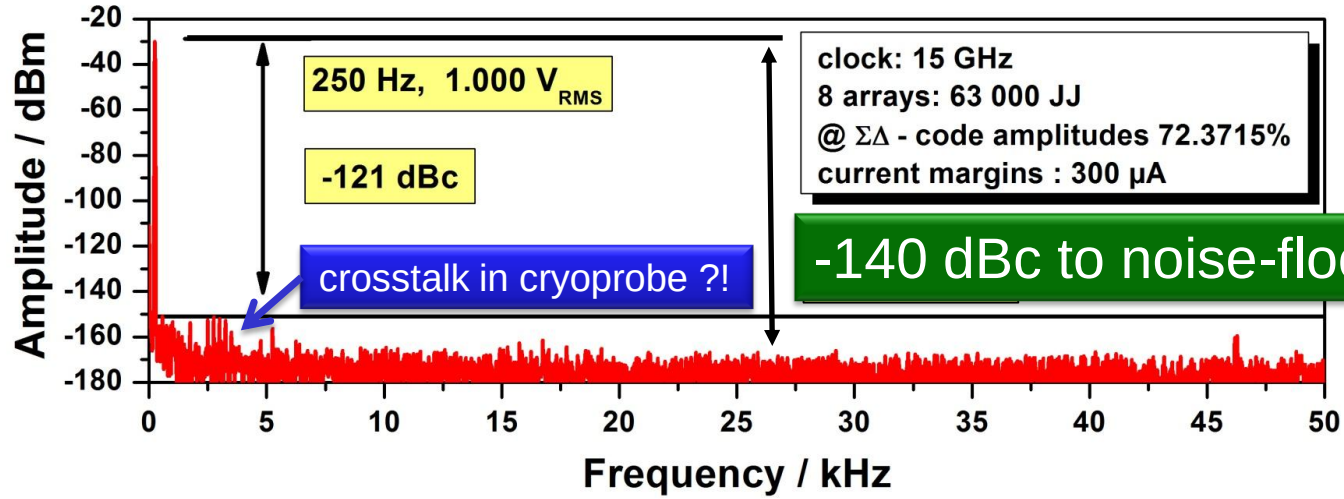


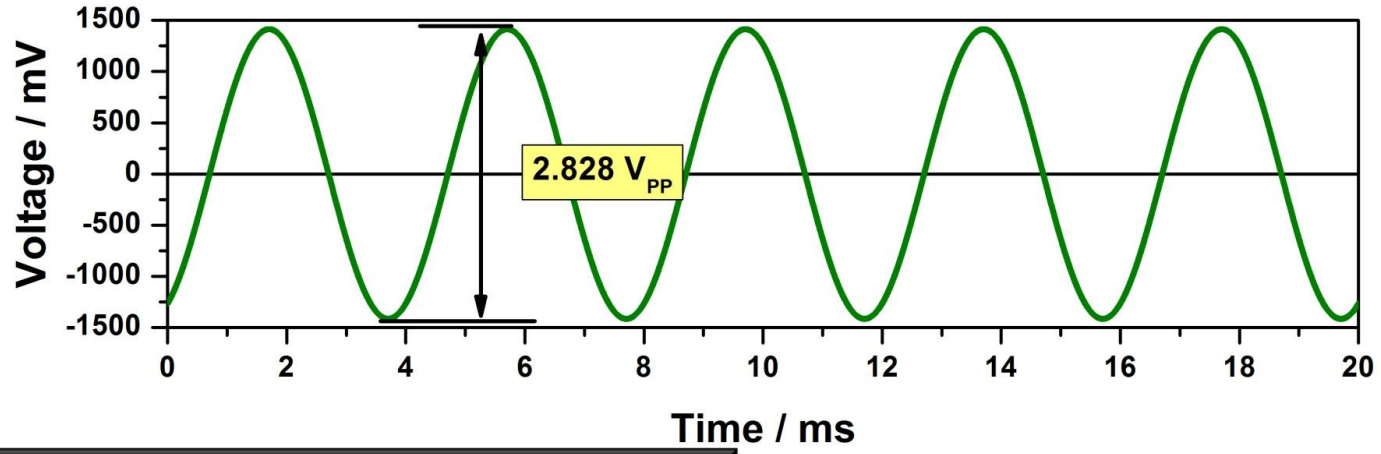
triple-stacked junctions : 8 array @ 4 chips

PTB

➢ spectra up to voltages of 1.0 V_{RMS} (2.8 V_{pp}) with 63 000 junctions

stable operation margins 300 µA





Kieler, et al., *IEEE Trans. Appl. Supercond.* 25, 2015

JAWS : features

- spectrally pure waveforms
- arbitrary waveforms
- large frequency bandwidth
- operation in cryocooler
- high time stability
- high precision
- 3 JAWS systems @ PTB
- first applications

already achieved !

JAWS : features

- spectrally pure waveforms
- arbitrary waveforms
- large frequency bandwidth
- operation in cryocooler
- high time stability
- high precision
- 3 JAWS systems @ PTB
- first applications

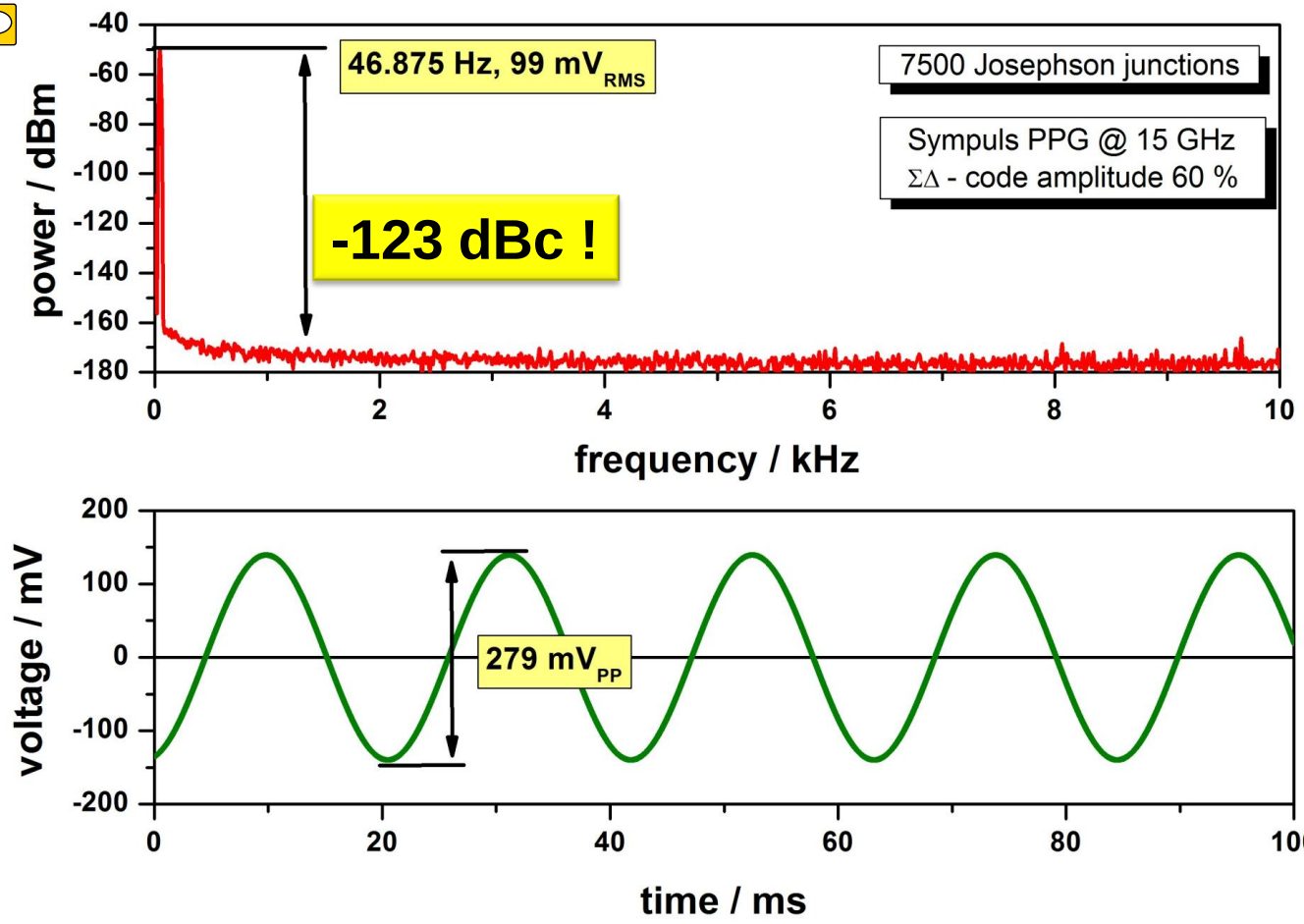
examples

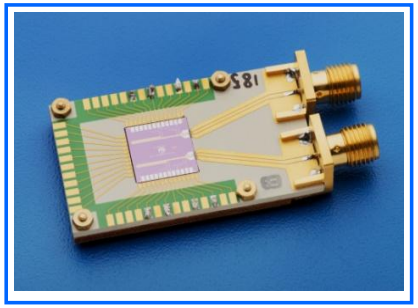
already achieved !

JAWS : spectrally pure waveforms !

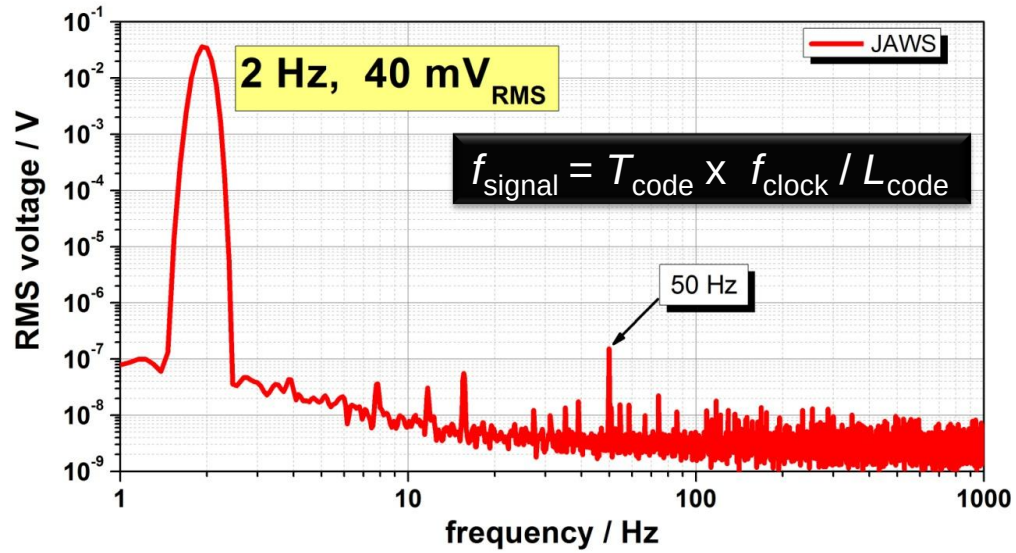
PTB

➢ spectra up to voltages of 279 mV_{pp} with 7 500 junctions with SNR of -123 dBc



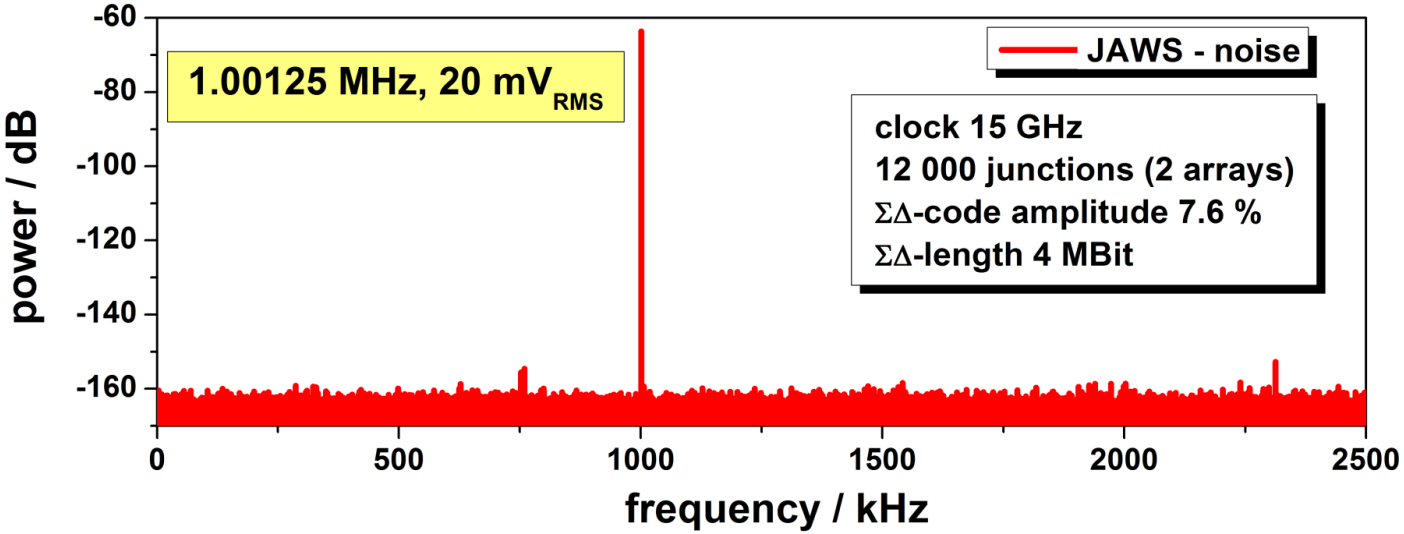


JAWS : large frequency range



bit-multiply option :
virtually increase
of ΣΔ-code memory
(up to 32 x 256 Mbit)

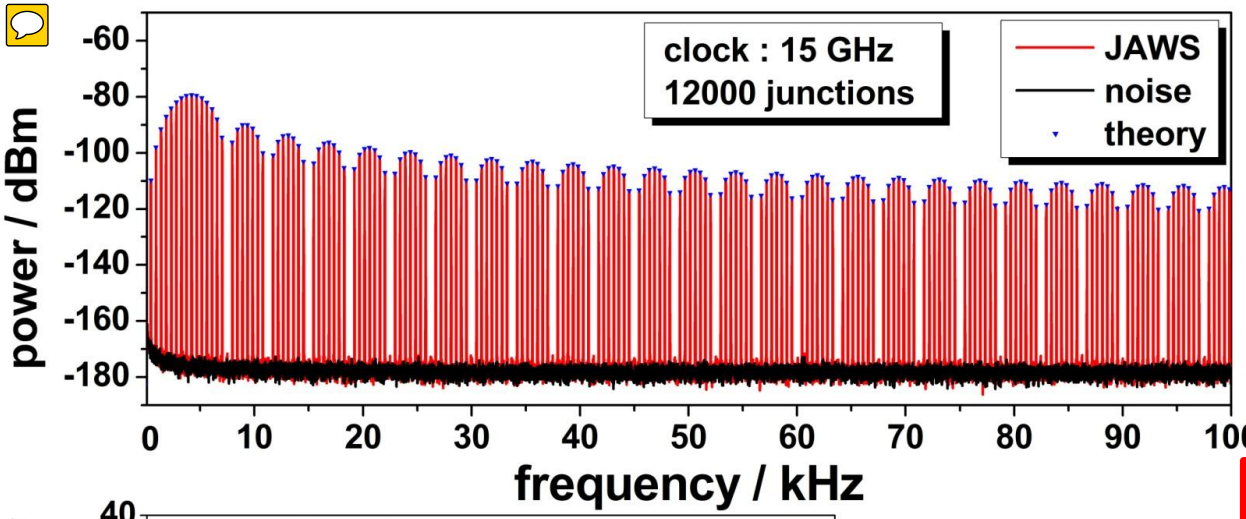
frequency range :
DC, 2 Hz … 1 MHz

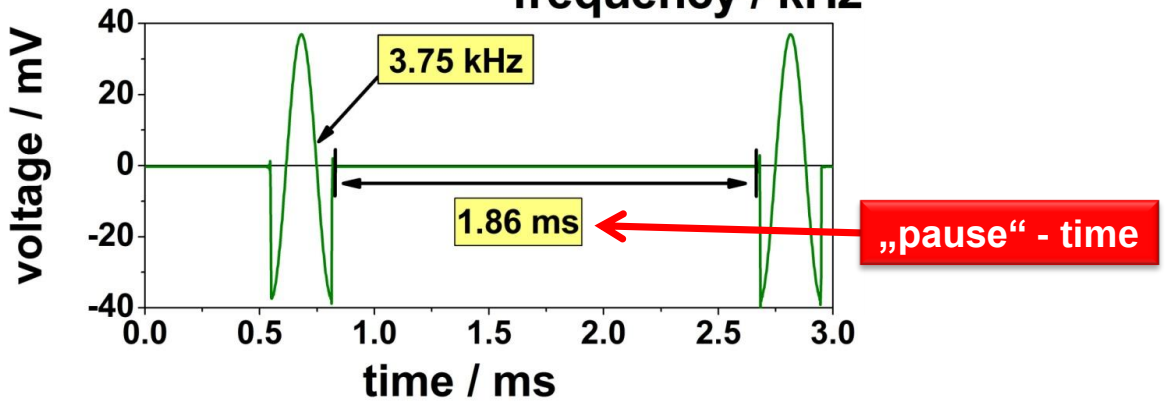


JAWS : arbitrary waveforms

application : characterization AD-converter (e.g. „single-shot“)

➢ non-continuous waveform : cosines with „pause“- time

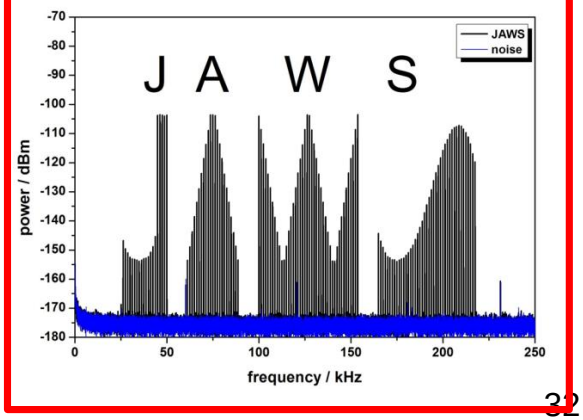




complex frequency comb

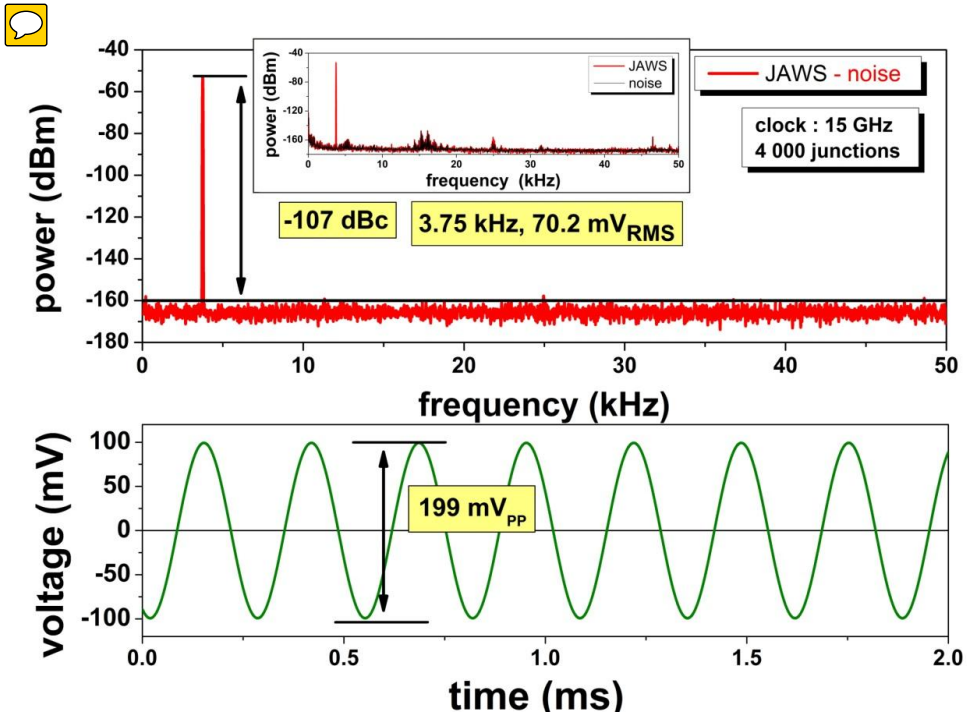
JAWS : most suitable

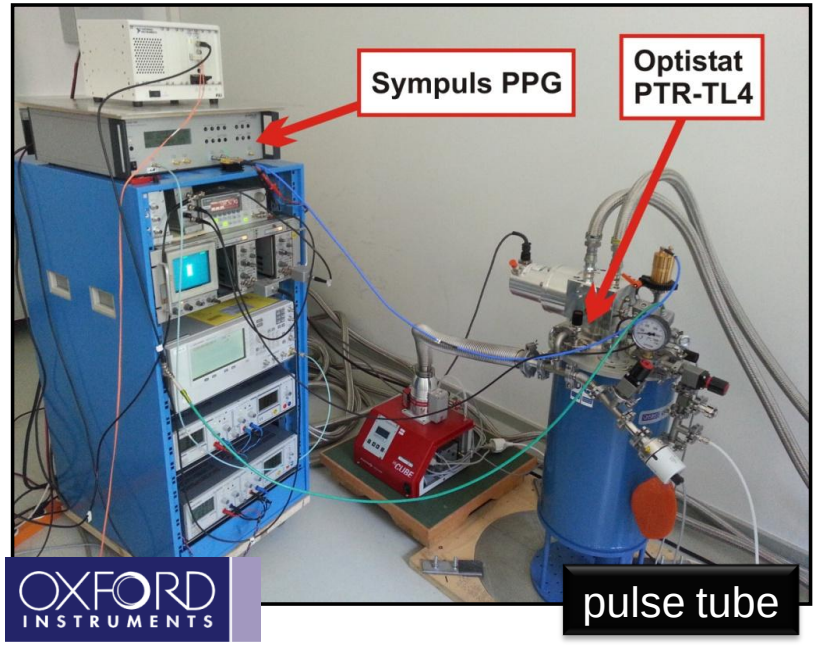
„any“ waveform !



JAWS : cryocooler operation

- spectra up to voltages of ≈ 200 mV_{pp} with 4 000 junctions
- temperature range : 4.2 K to 5.6 K





successful operation of JAWS in cryocooler

AIST :
2.6 mV_{pp} with 100 junctions,
SNR -80 dBc

Urano, et al., *SUST* 22, 2009

Kieler, et al., *W. Journal Cond. Matter Physics* 3, 2013

outline

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   a) design
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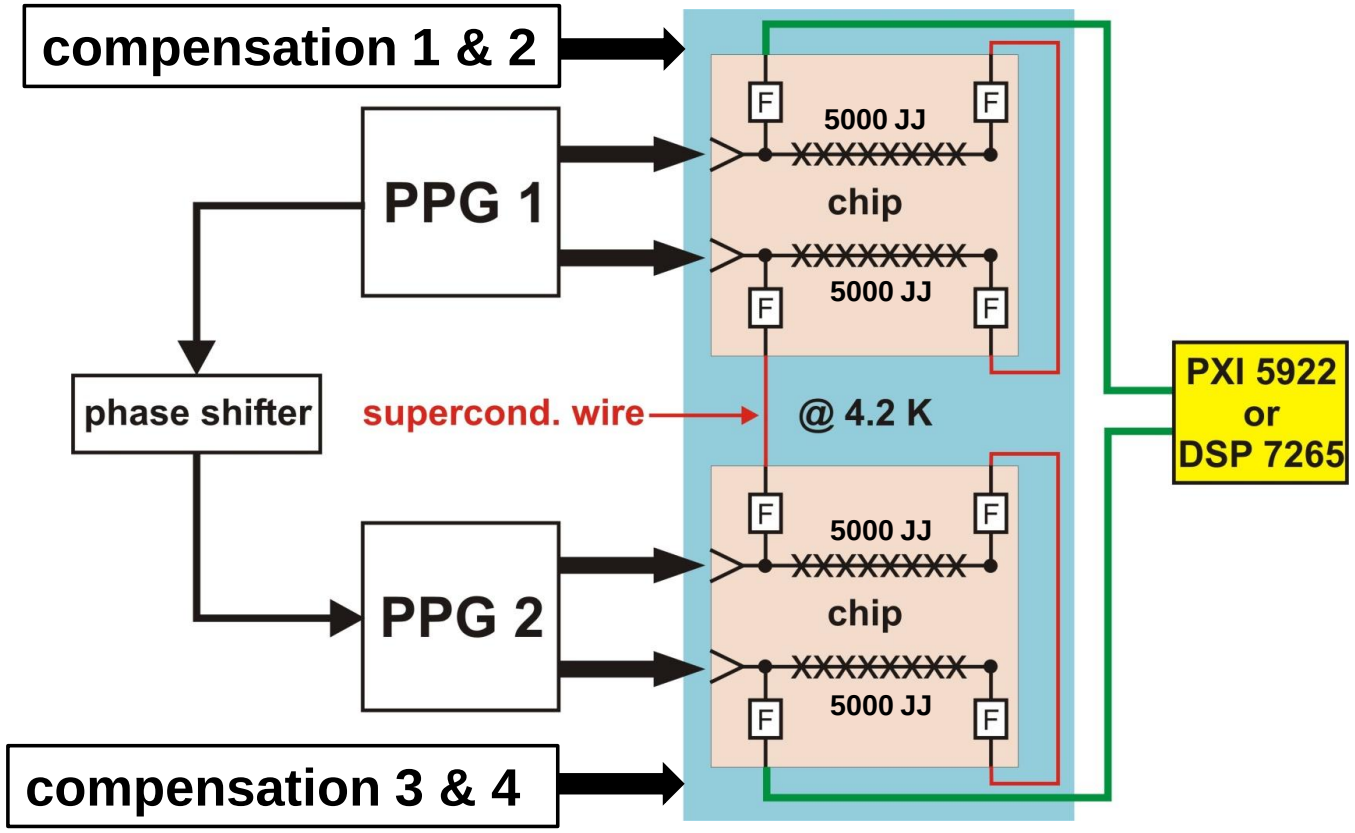
   a) comparison JAWS vs. JAWS
   b) comparison JAWS vs. QVM
4. Summary

direct comparison : JAWS vs. JAWS (I)

comparison : 10 000 junctions vs. 10 000 junctions

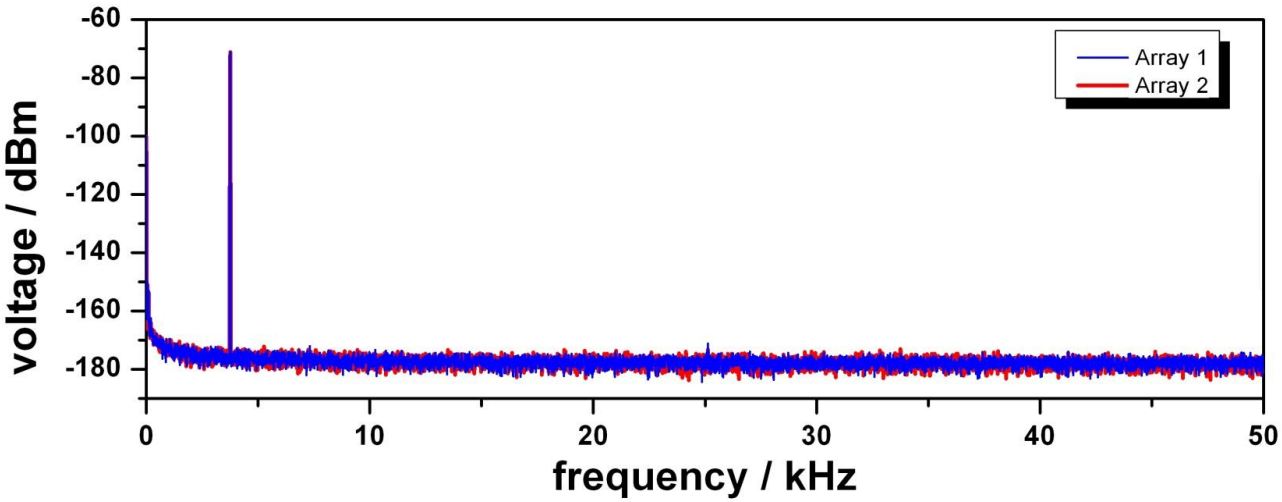


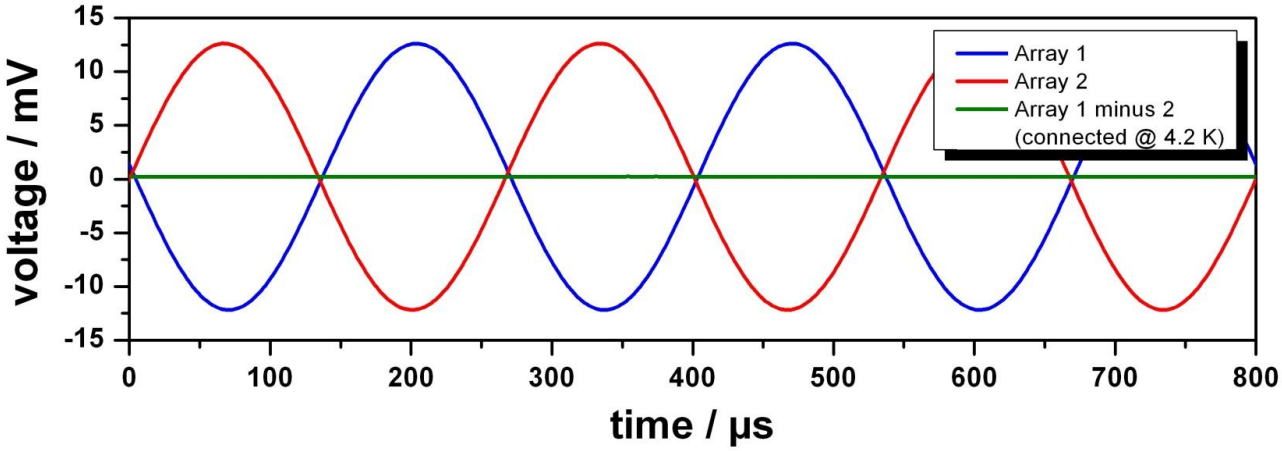
Kieler, et al., *IEEE Trans. Appl. Supercond.* 23, 2013

direct comparison : JAWS vs. JAWS (II)

if only one array switched on

PXI 5922 :
voltage difference already only 53 nV_{RMS}

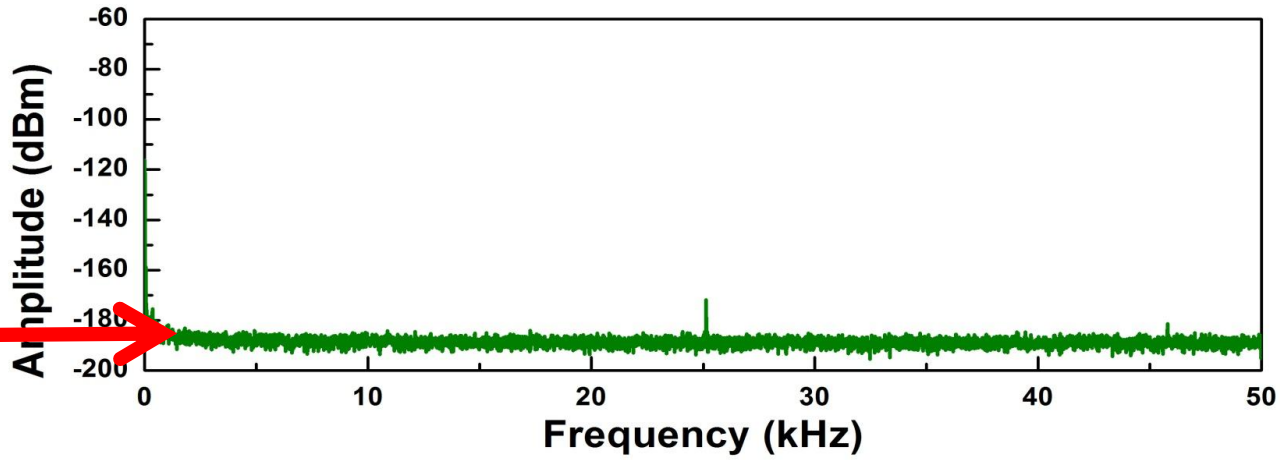


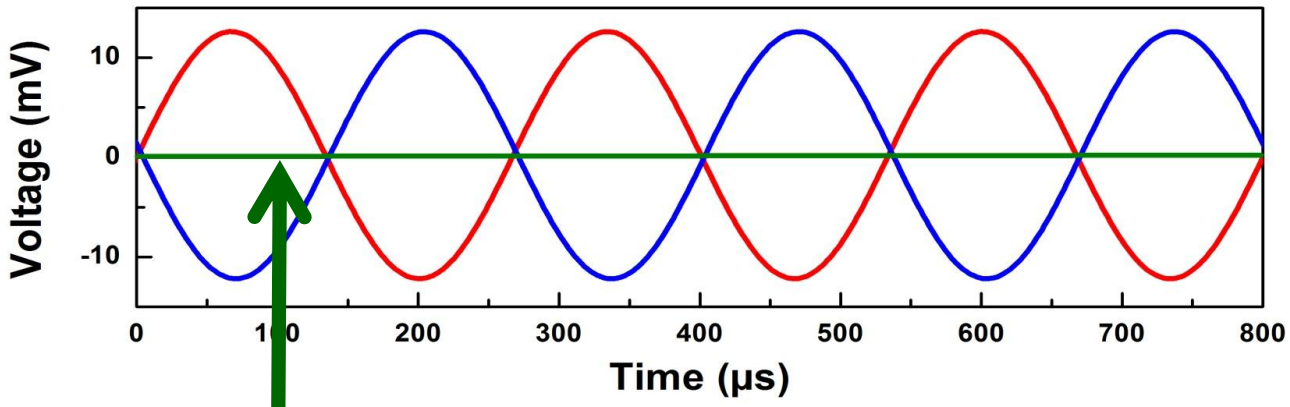


direct comparison : JAWS vs. JAWS (III)

both arrays switched on

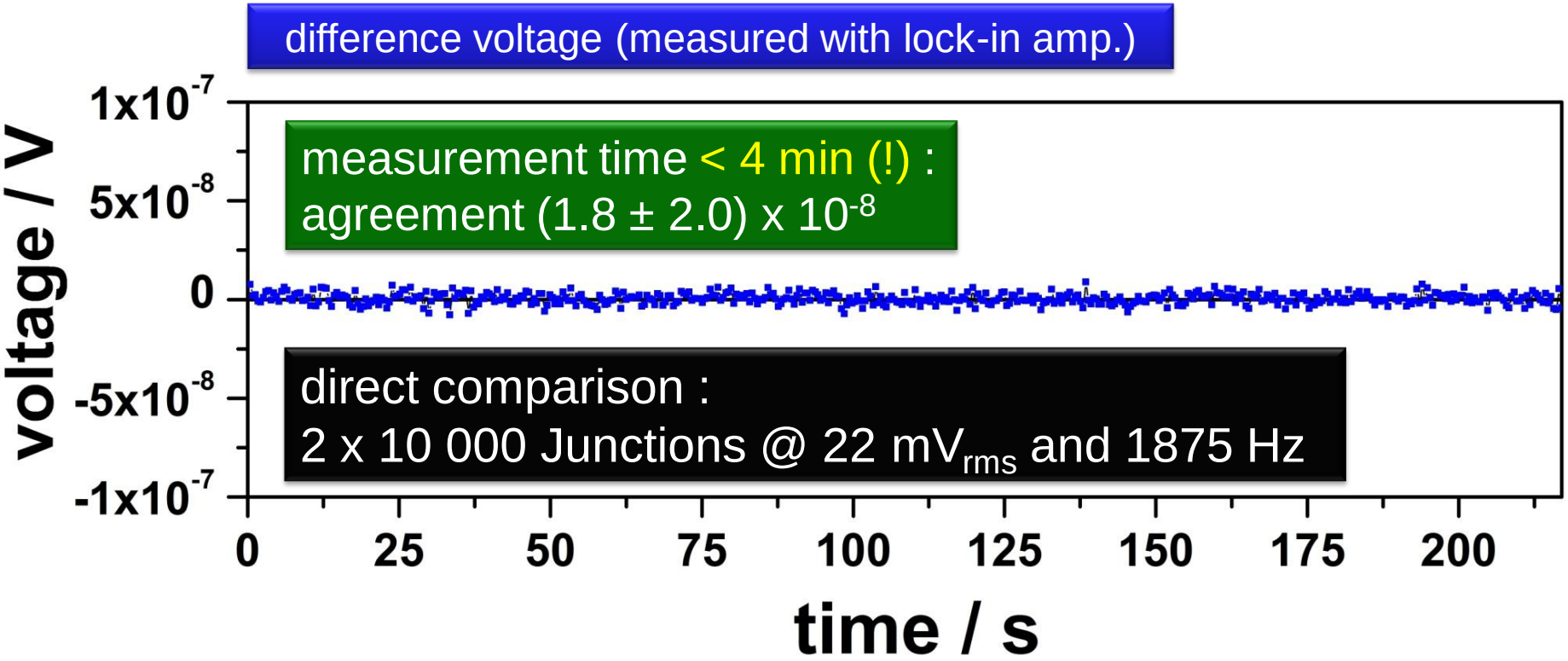
PXI 5922 :
voltage difference below noise floor
< 9 nV_{RMS}





cancellation of waveform, when both arrays are switched on

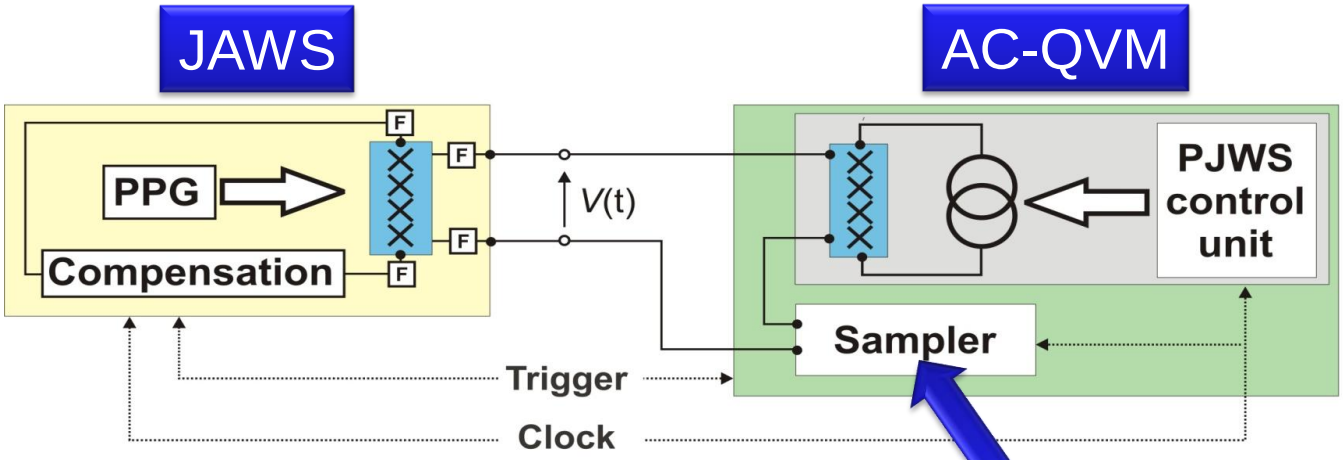
direct comparison : JAWS vs. JAWS (IV)



high precision of JAWS !

Kieler, et al., *IEEE Trans. Appl. Supercond.* 23, 2013

direct comparison : JAWS vs. QVM



- **problem :**

  no second 1 V-JAWS available

- **solution :**

  QVM demonstrated : 2 x 10^{-8}

  (J. Lee, CPEM 2014)

PXI 5922
(National Instruments)

direct comparison @ 1 V level
possible now !

JAWS vs. QVM : QVM with PXI 5922

PXI 5922 gain & offset are “not” stable

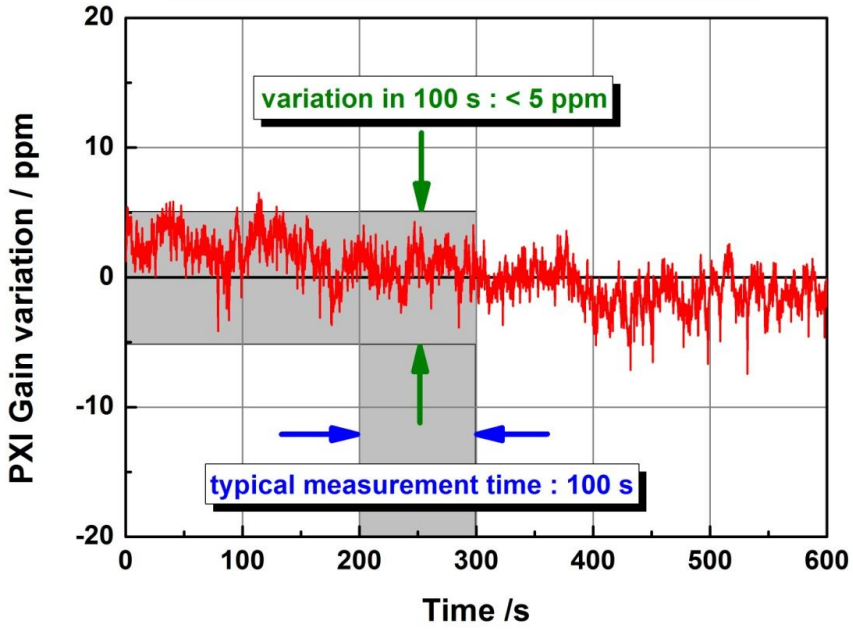
PXI 5922 : @ fixed sample rate of 4 MS/s or 10 MS/s

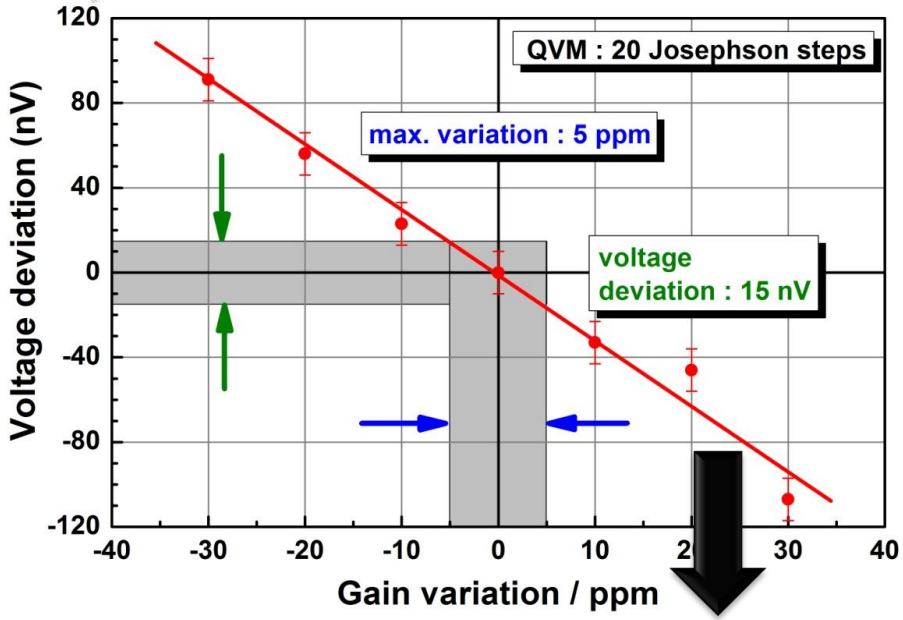
QVM : @ 150 mV_p for evaluation of gain/offset

gain error is small !

time window → gain variation

gain window → voltage variation

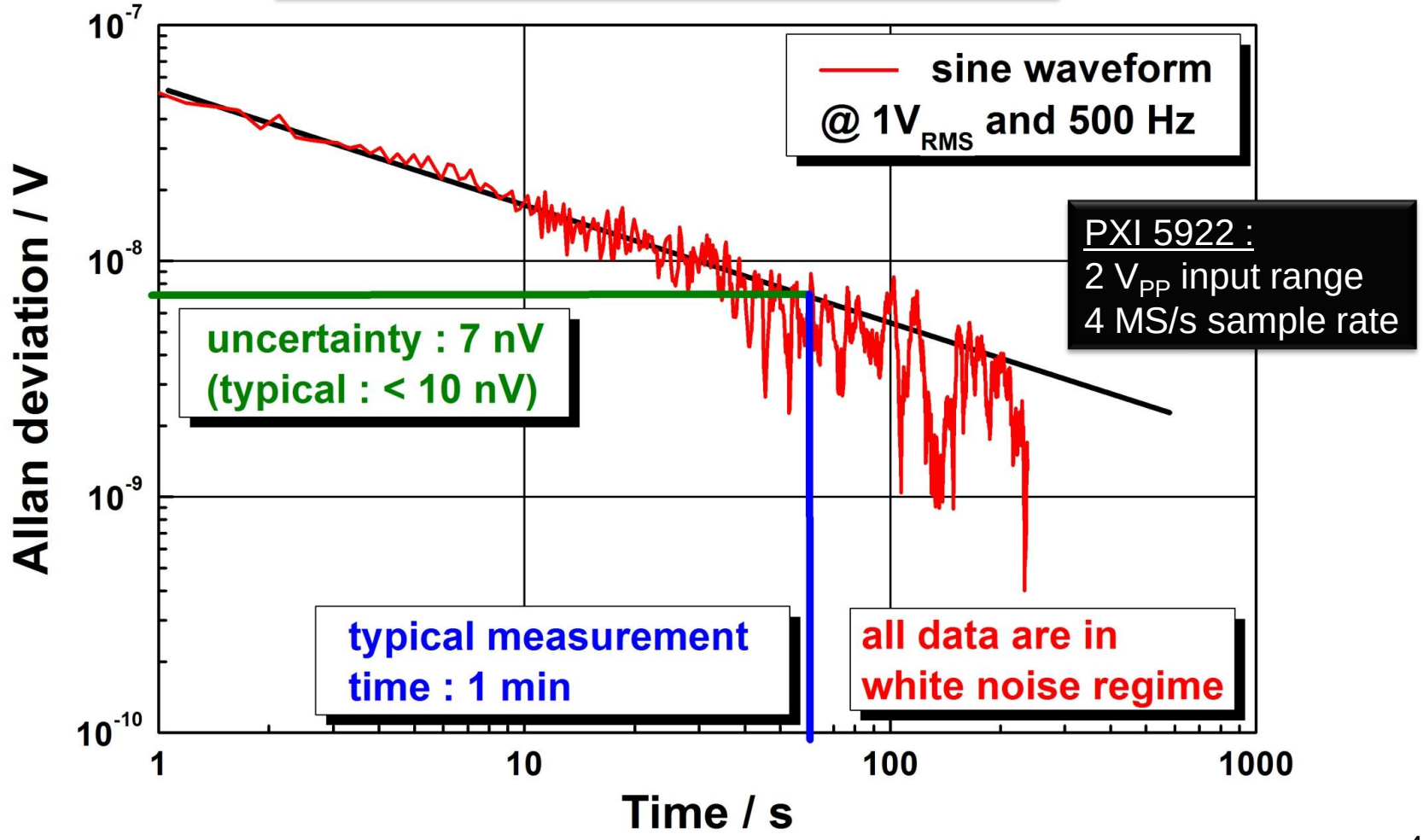




type-B uncertainty < 9 nV

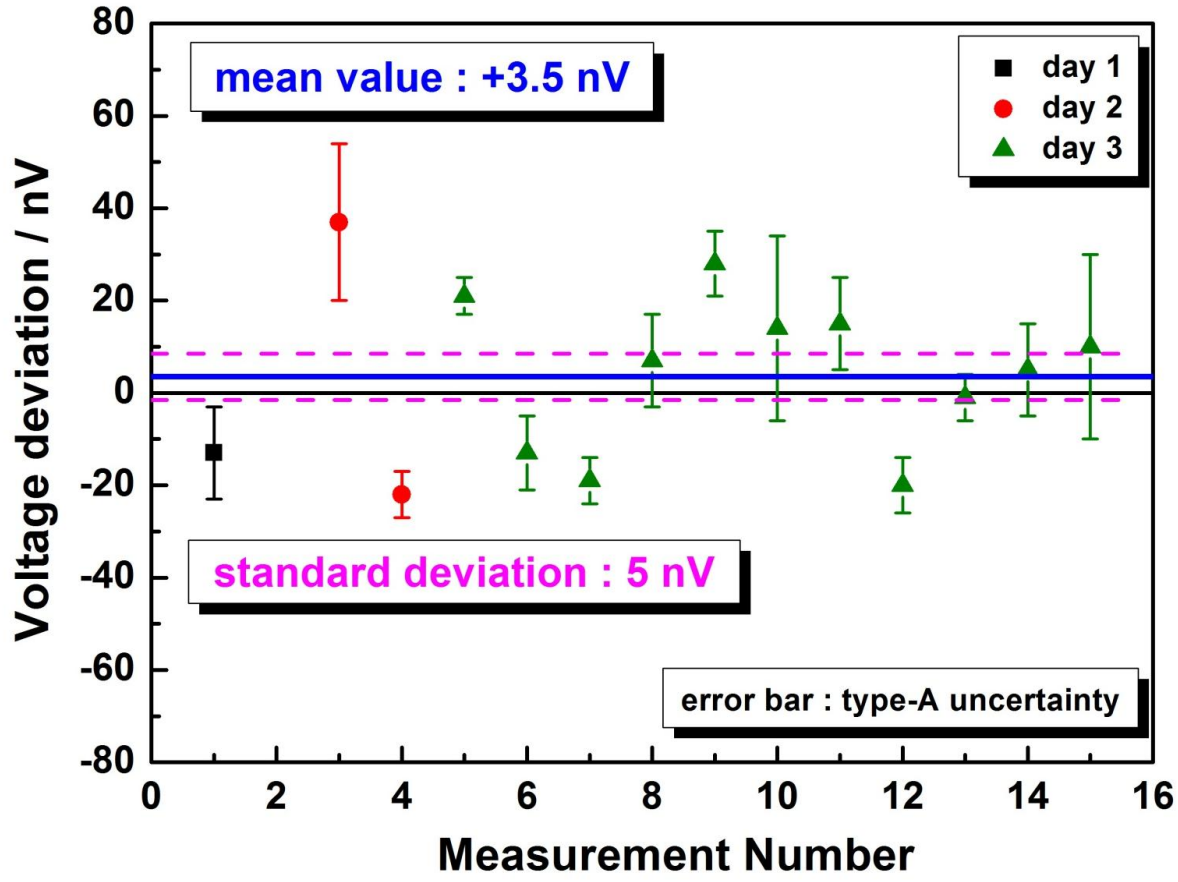
JAWS vs. QVM : measurement time

excellent Allan deviation !



JAWS vs. QVM : comparison @ 250 Hz

$V_{JAWS} - V_{QVM}$ = +3.5 nV ± 12 nV @ 250 Hz



comparison @ 1 V_{RMS}

excellent ppb agreement

Behr, et al., *Metrologia* 52, 2015

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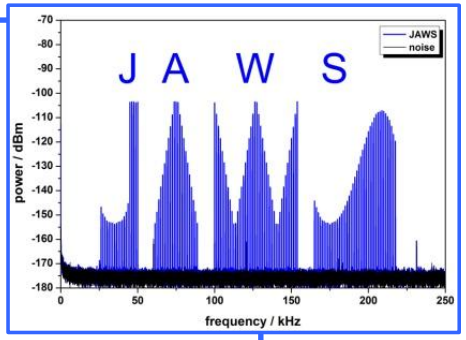
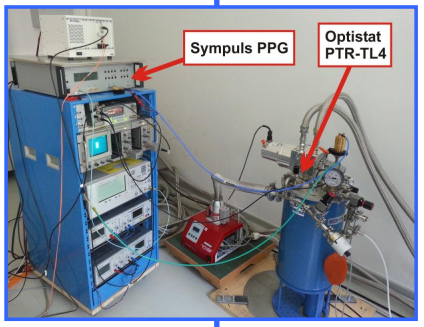
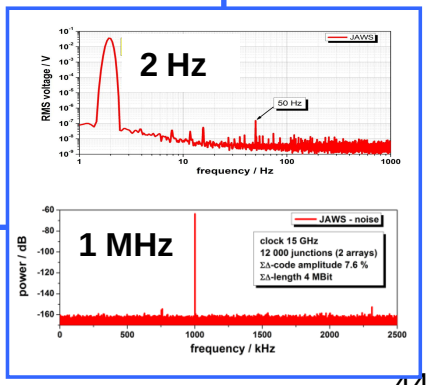
Summary (I)

high-quality AC-waveforms

- Nb_xSi_{1-x}- arrays with triple-stacked junctions
- up to 8 arrays in series : 63 000 junctions
- output voltage up to 1 V_{RMS} (2.83 V_{PP})
- high spectral purity : SNR better than -120 dBc
- high frequency range : DC, 2 Hz … 1 MHz
- high time stability : low noise and no drift
- arbitrary waveforms demonstrated
- JAWS successfully operated in cryocooler

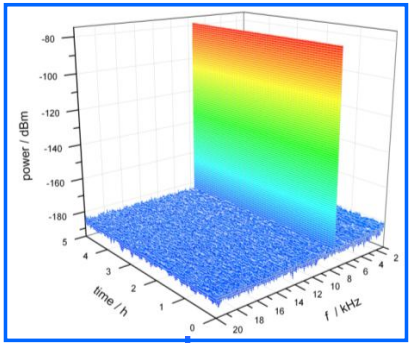




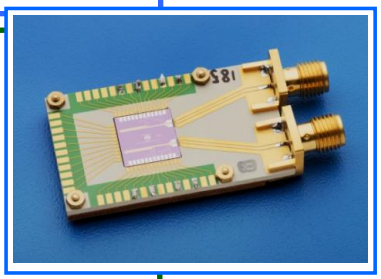


Summary (II)

high-quality AC-waveforms



- 3 JAWS systems operational :
  - JAWS 1 : 1 V_{RMS}
  - JAWS 2 : Impedance bridge with 2 x 100 mV_{RMS}
  - JAWS 3 : PJVS + JAWS : 1.18 V with SNR -125 dBc
- first applications : e.g. characterization of HF devices
- direct comparison JAWS - JAWS : (1.8 ± 2.0) x 10^{-8} @ 1875 Hz
- direct comparison JAWS - PJVS : (3.5 ± 11.7) x 10^{-9} @ 250 Hz & 1 V_{RMS}

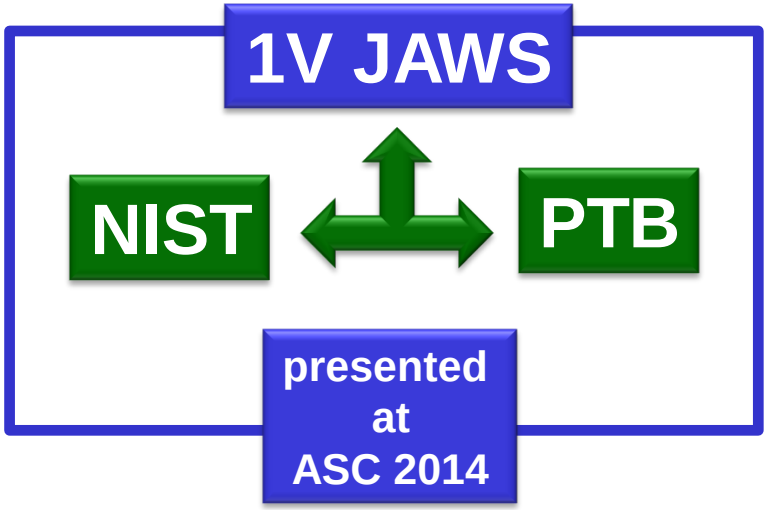


- next steps :
  - further reduction of crosstalk → new cryoprobe
  - more junctions per chip → less than 4 chips for 1 V

1 V JAWS: impact

fountain at castle Warberg, Germany

“Alles von dem sich der Mensch eine Vorstellung machen kann, ist machbar…”
(W.v.B.)



“all what a man can imagine, is possible…”
(W.v.B.)

„voltage source for arbitrary waveforms at the 1 V level with quantum precision and spectral purity“

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Thank you very much for your attention!

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