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KRISS NTT UNSW AUSTRALIA PTB

Universality of the tunable-barrier electron pump at the part-per-million level

Stephen Giblin

CPEM 2016

13th July 2016

"REUNIAM" 2008-2011

iMERA PLUS

EURAMET European Association of National Metrology Institutes

"QU-AMPERE" 2012-2015

EMRP European Metrology Research Programme ▸ Programme of EURAMET

"E-SI-AMP" 2016-2019

e-SI-Amp

EMPIR EURAMET

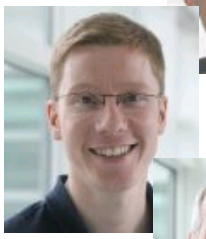
NPL single electron group

National Physical Laboratory | Quantum Metrology Institute

Stephen Giblin

Patrick See

Jonathan Fletcher



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Geb Jones

John Griffiths

Ian Farrer

David Ritchie

Collaborators

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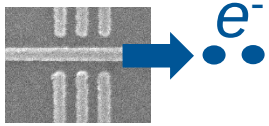
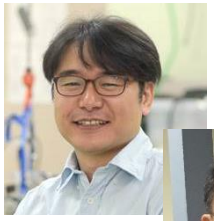
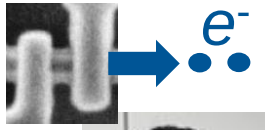


Myung-Ho Bae

Nam Kim



NTT



Gento Yamahata

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Dietmar Drung

Christian Krause

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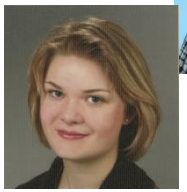
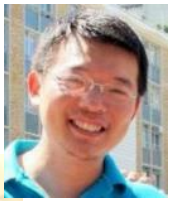


UNSW AUSTRALIA

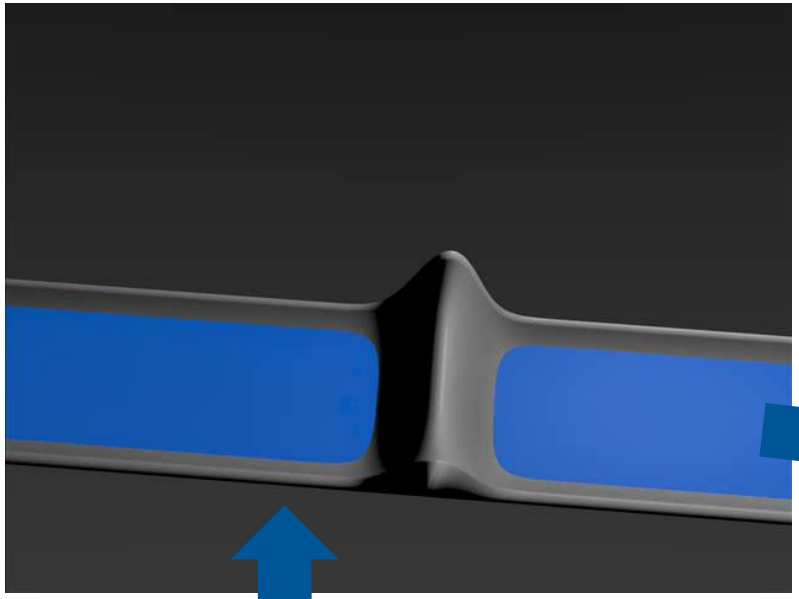


Ruichen Zao

Alessandro Rossi

Andrew Dzurak

The tunable-barrier pump



Current I_P

$V_G(t)$
Frequency f

One-electron plateau:
$I_P = ef$
Experimentally, we measure ΔI_P:

$$\Delta I_P = \frac{I_P - ef}{ef}$$

f = 1 GHz ⟶ I_P = 160 pA

Device images

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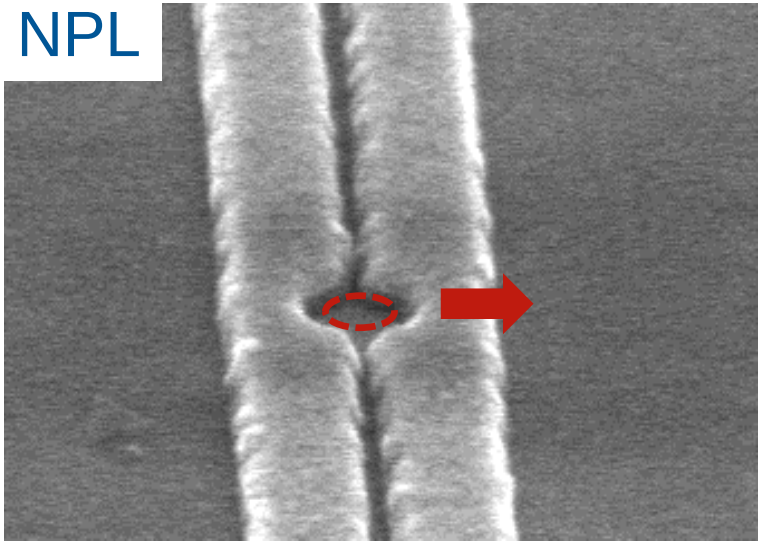
500 nm

Gallium Arsenide

NPL



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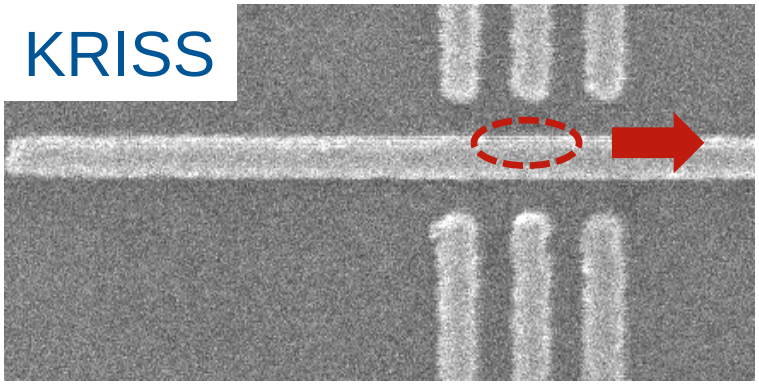
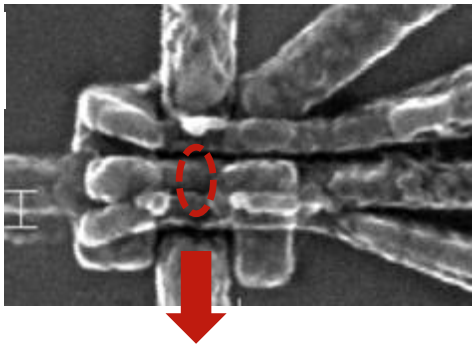
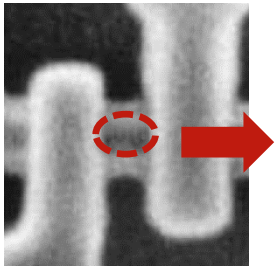


Silicon

UNSW



NTT

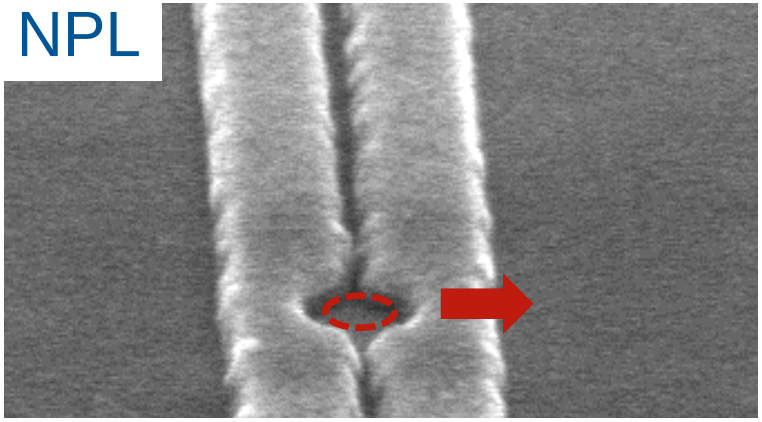


Device images

500 nm

Gallium Arsenide

NPL



Giblin et al, *Nature Communications* **3**, 930 (2012)

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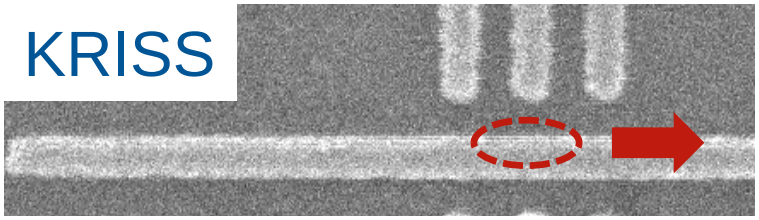


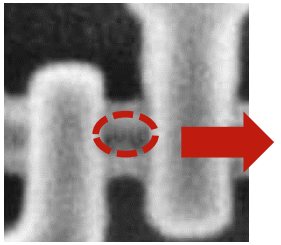
Ahn et al, *Phys. Rev. B*. **90,** 085307 (2014)
Bae et al, *Metrologia* **52**, 195 (2015)

Silicon

UNSW

Rossi et al, *Nano Letters* **14**, 3405 (2014)

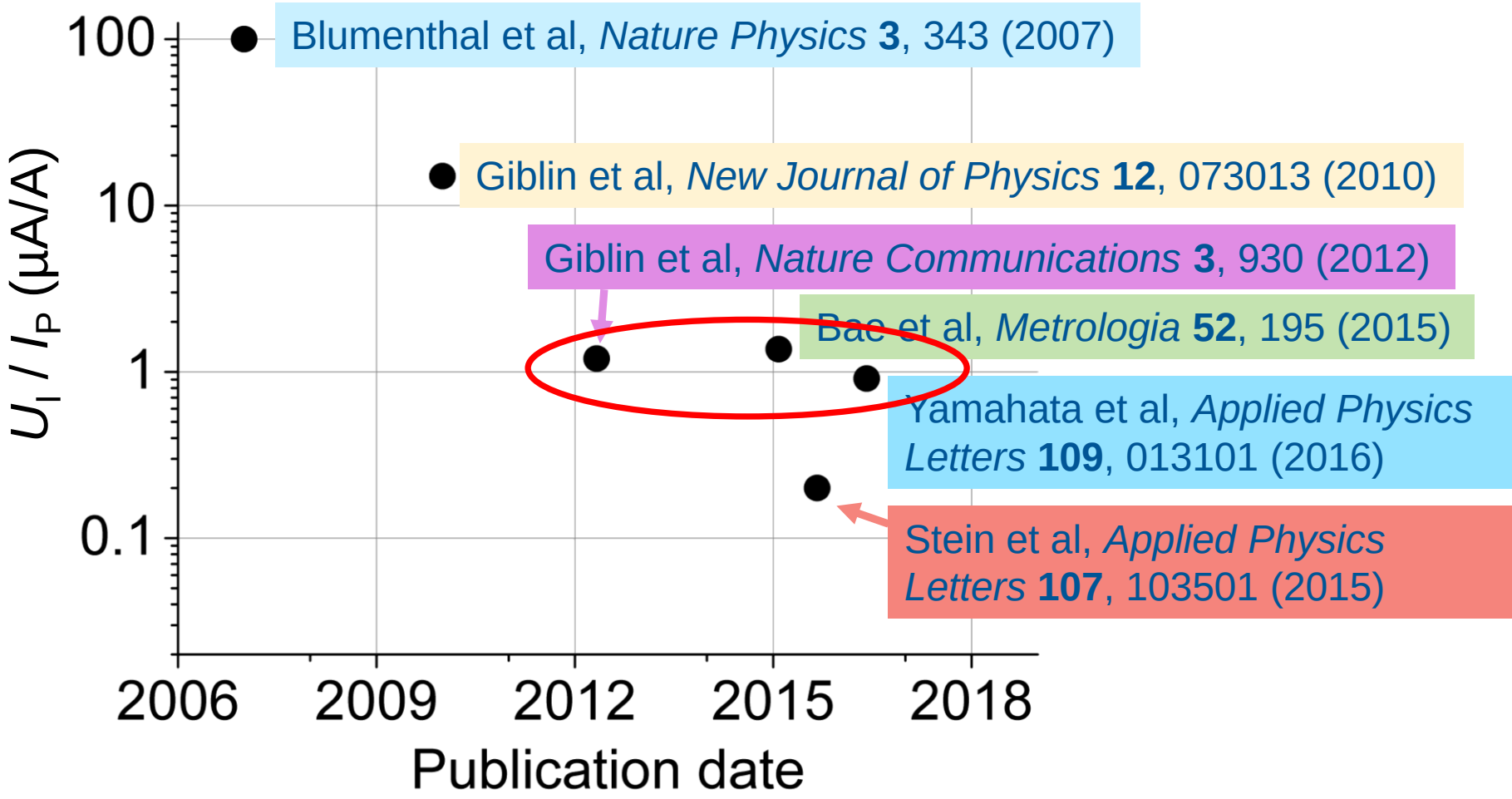
NTT



Fujiwara et al, *Appl. Phys. Lett.* **92**, 042102 (2008)
Yamahata et al, *APL* **109**, 013101 (2016)

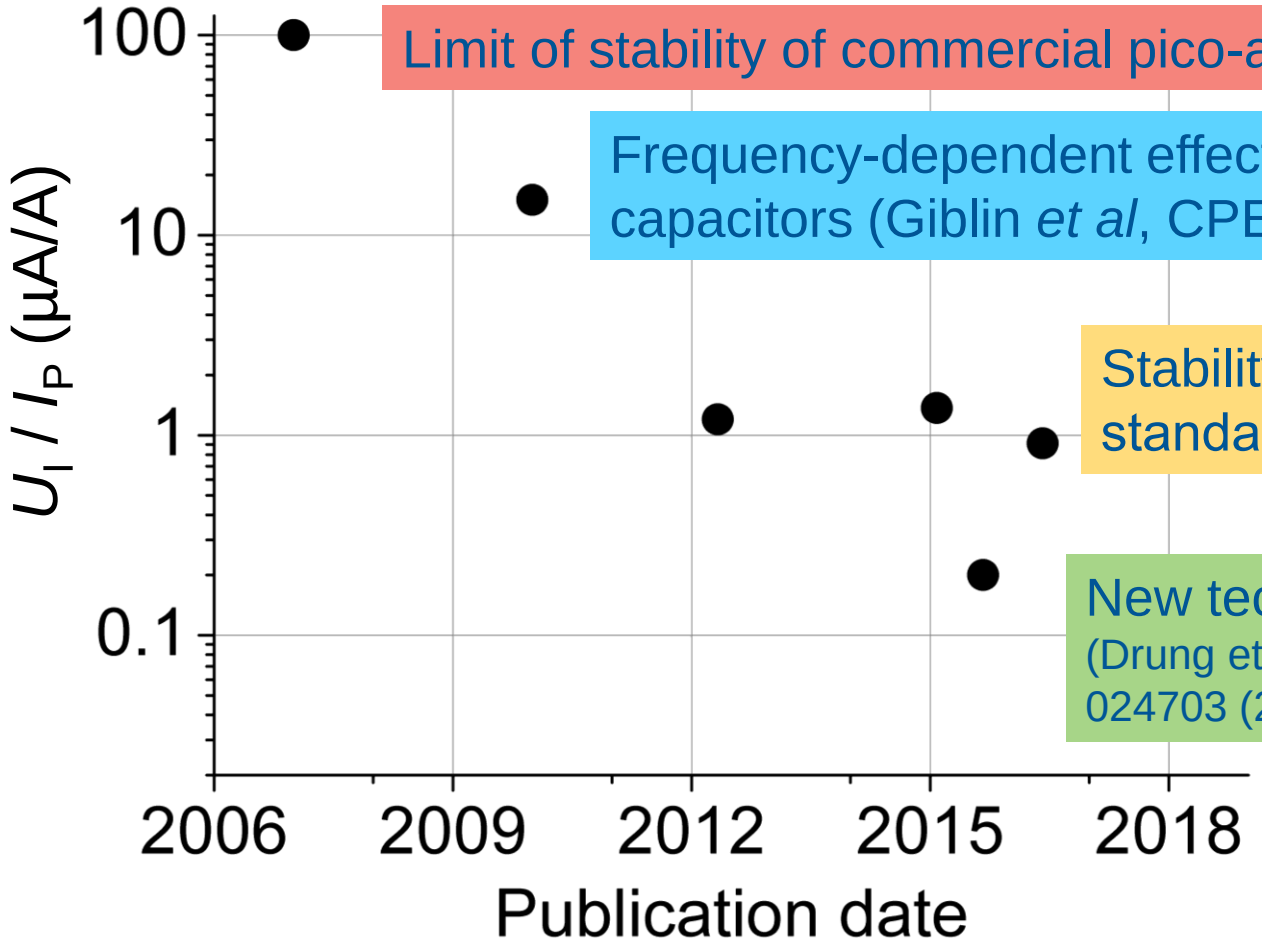
Historical overview

Accuracy of pump current measurements, 0.3 GHz ≤ f ≤ 1 GHz
$\Delta I_P < U_I / I_P$ in all cases



Historical overview

Requirement to measure pump current has pushed limits of existing small-current metrology



Limit of stability of commercial pico-ammeter

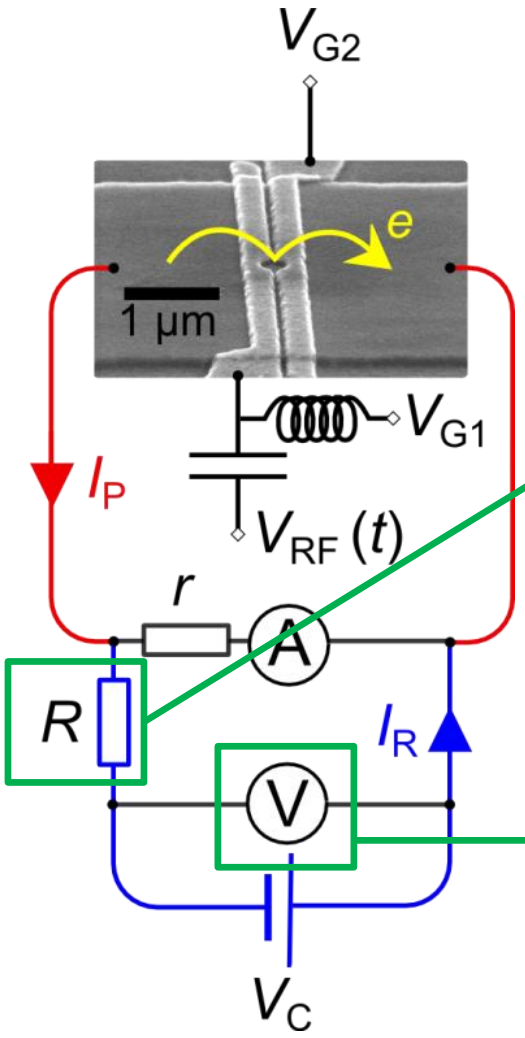
Frequency-dependent effects in gas-dielectric capacitors (Giblin *et al*, CPEM 2010)

Stability of commercial standard resistors ≥ 100 MΩ

New technology – ULCA
(Drung et al, Rev. Sci. Instr. **84**, 024703 (2015).

Pump current measurement I

Colin Porter
Clinton Kelly



0.8 ppm

Guildline 9336 (thick-film) Standard @ ±0.005 C

NPL "Mk. 4" CCC

1 MΩ	0.12
10 MΩ	0.20
100 MΩ	0.40
1 GΩ	1.60

CMC (2-σ)

0.6 ppm

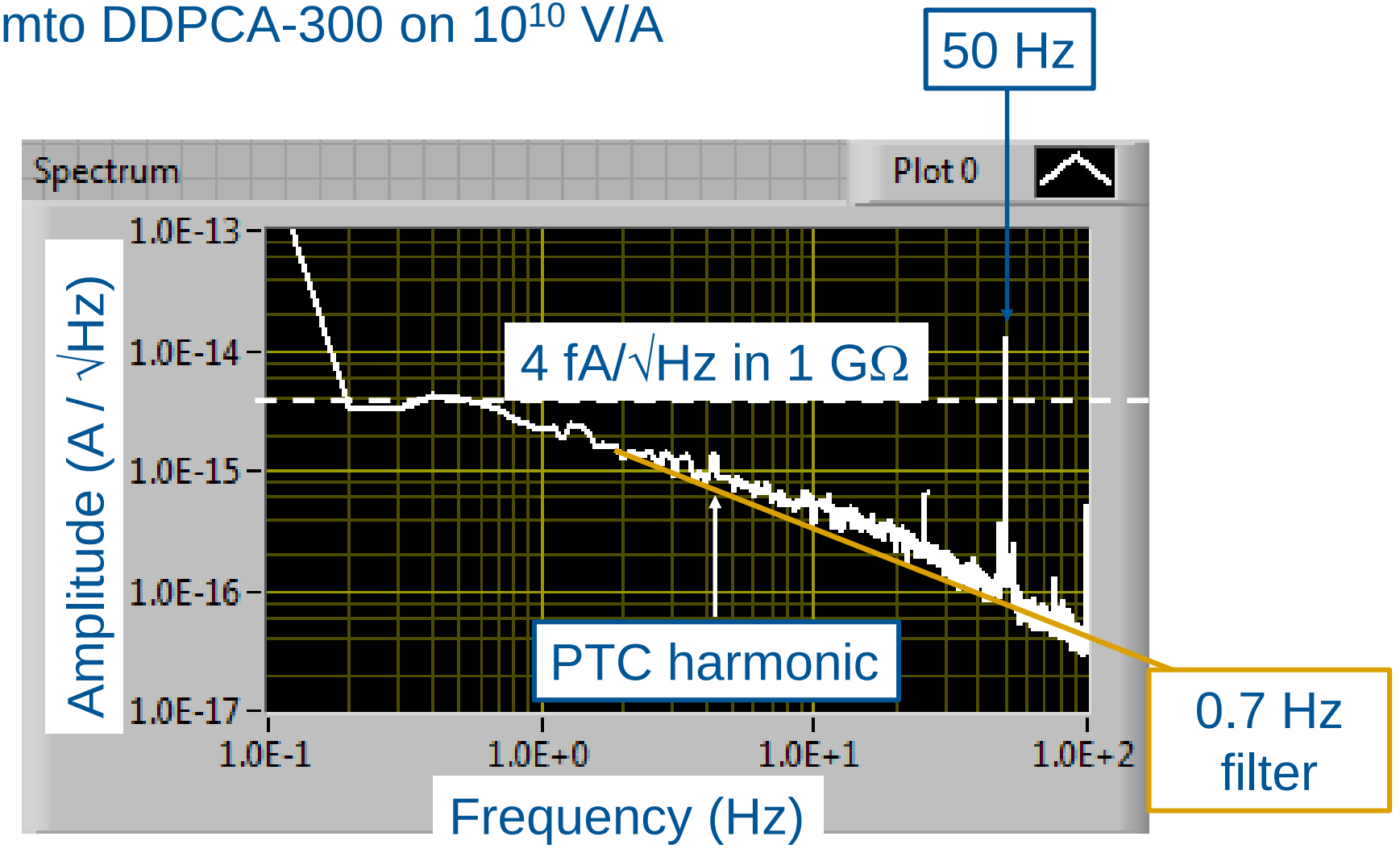
1 V transportable Zener standard

Josephson effect primary voltage std.

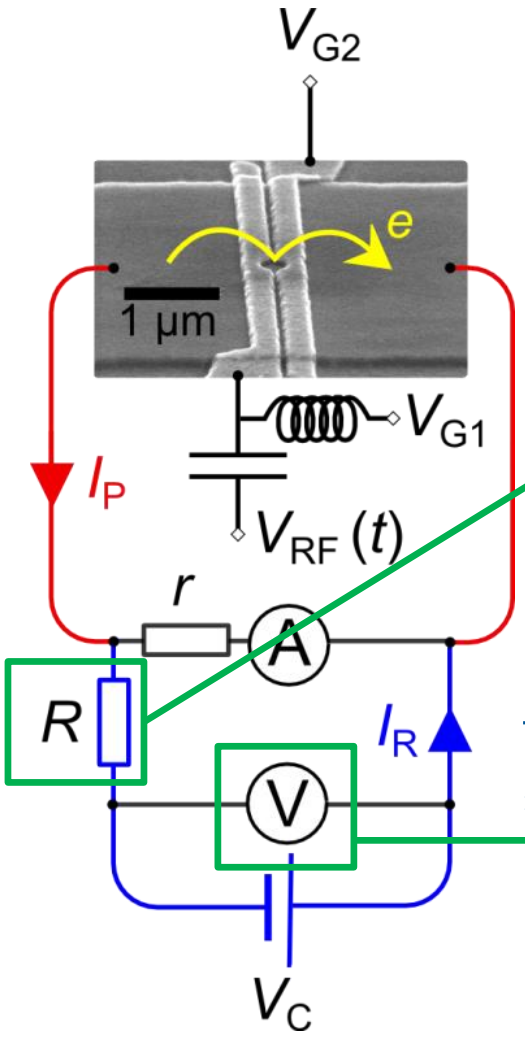
HP3458A

Ammeter noise spectrum

Femto DDPCA-300 on 10^{10} V/A



Pump current measurement II



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1 MΩ	0.12
10 MΩ	0.20
100 MΩ	0.40
1 GΩ	1.60

CMC (2-σ)

~~0.6 ppm~~
≈0.1 ppm

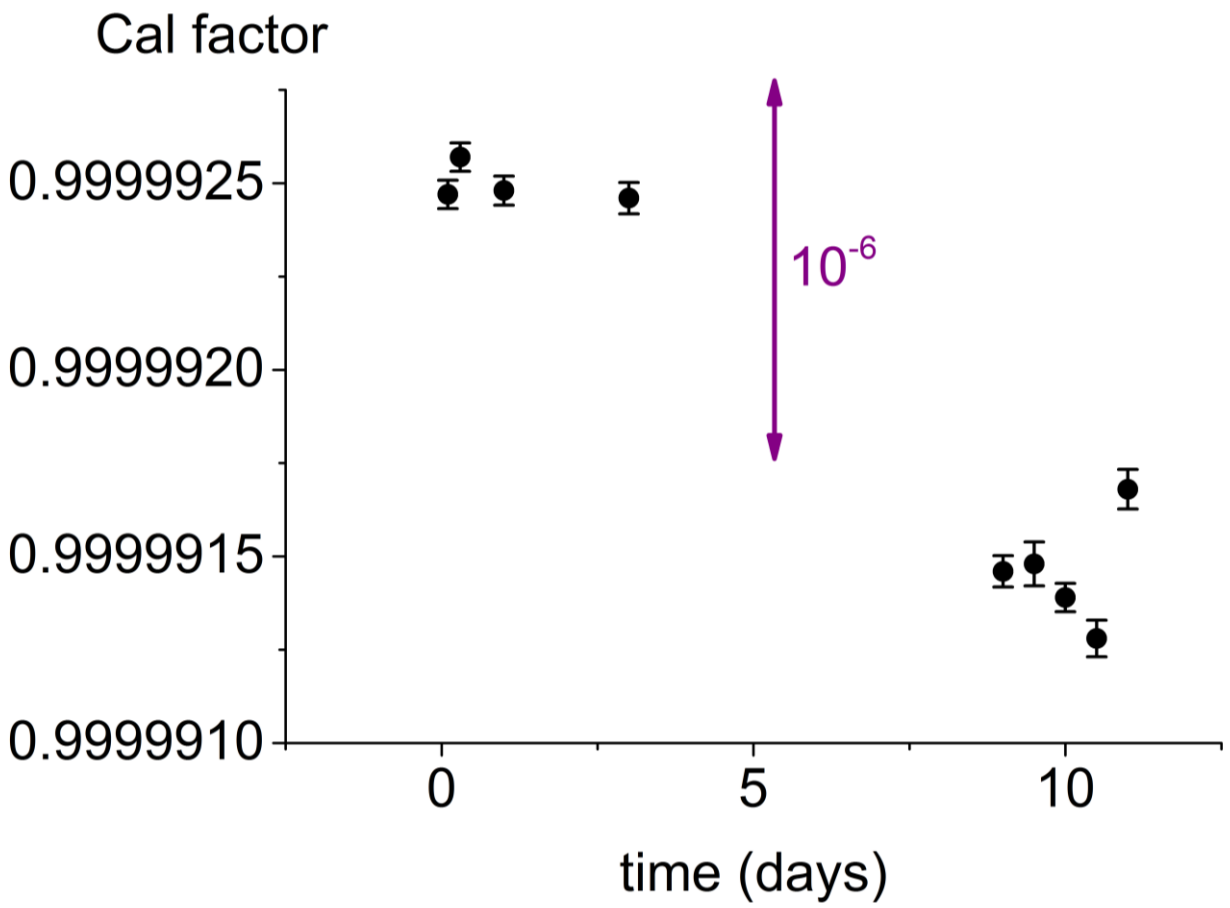
Automated scanner

Josephson effect primary voltage std.

Direct calibration on ≈ 30 – m cable

HP3458A

Typical stability of 3458A cal factor



Pump current measurement III

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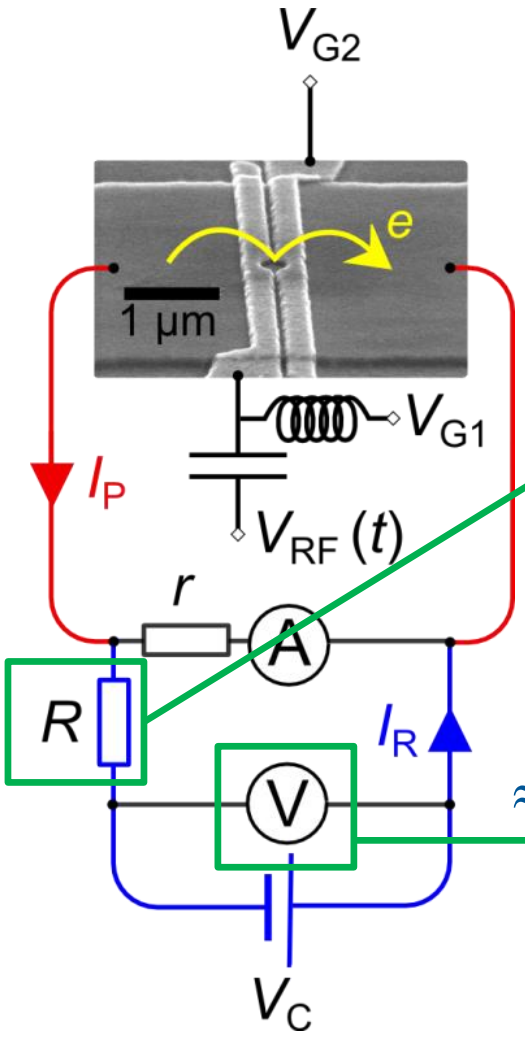
Error budgets are flawed -J. Faller



~~0.8 ppm~~
≈0.2 ppm

≈0.1 ppm

Guildline 9336 (thick-film) Standard @ ±0.005 C

NPL "Mk. 4" CCC

Re-evaluate uncertainty budget
Ratio type B < 0.01 ppm
Type A ≈ 0.2 ppm
(to be published)

Automated scanner

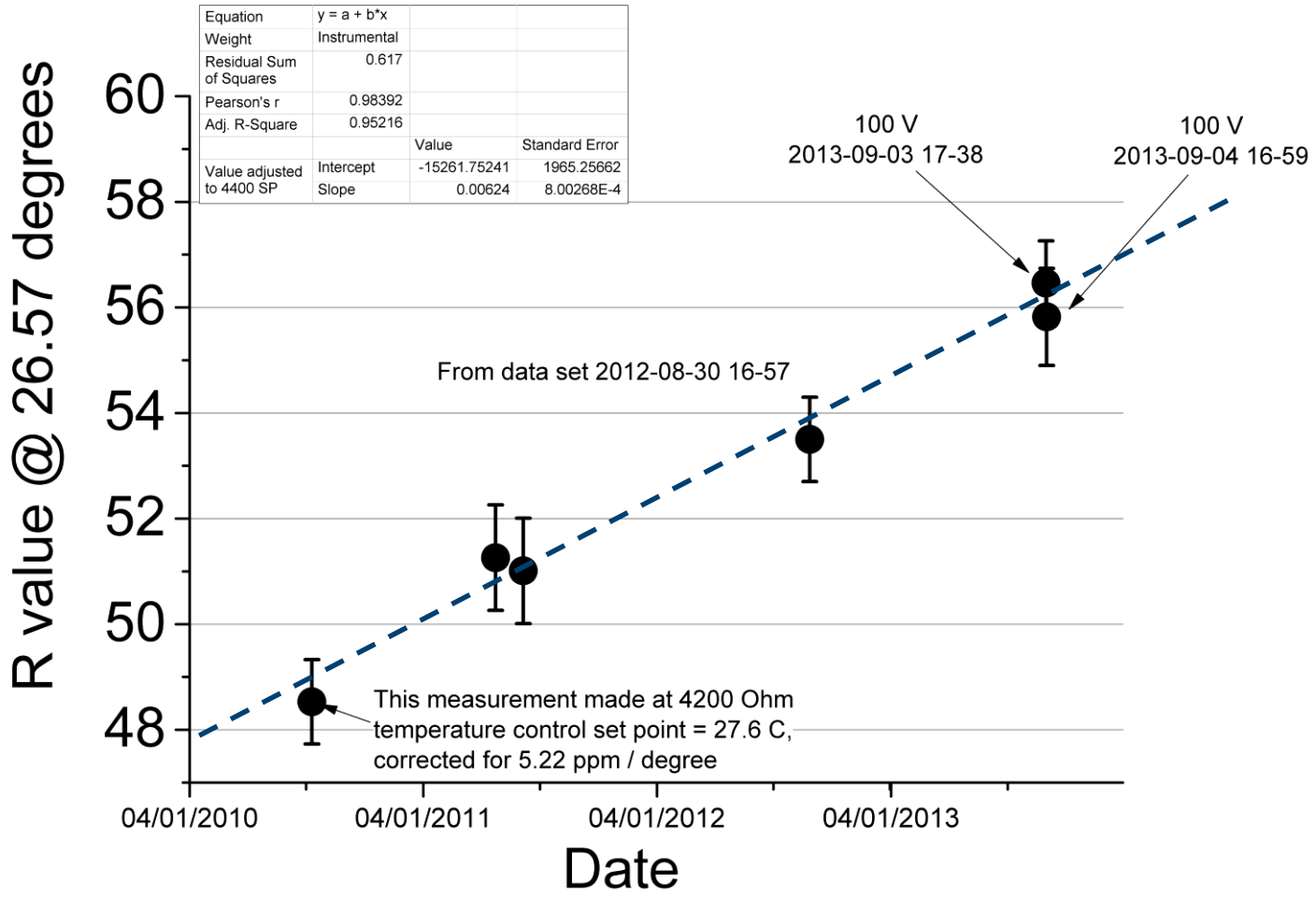
Josephson effect primary voltage std.

Direct calibration on ≈30 – m cable

HP3458A

Resistor stability I

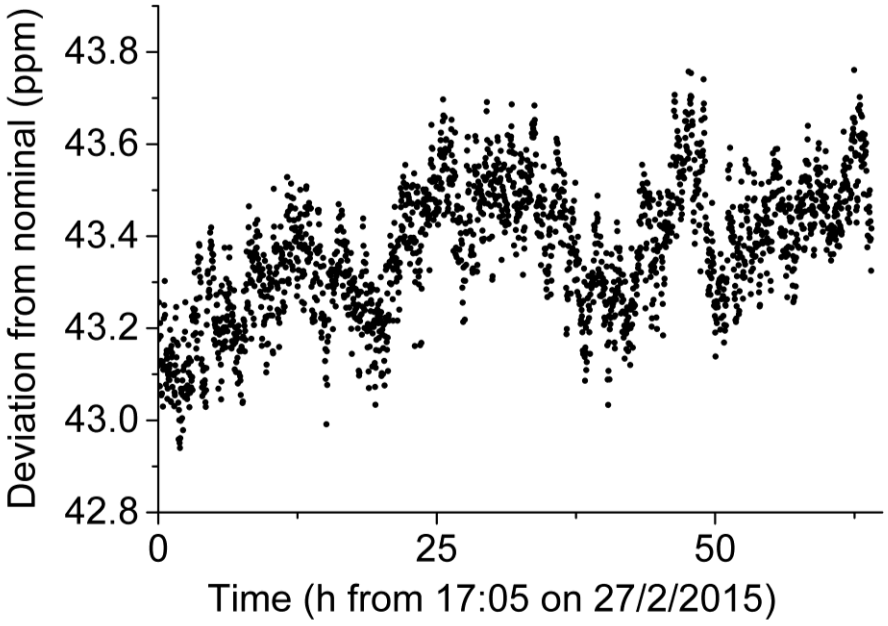
Pump measurements 2011-2015 based on long-term drift of resistor



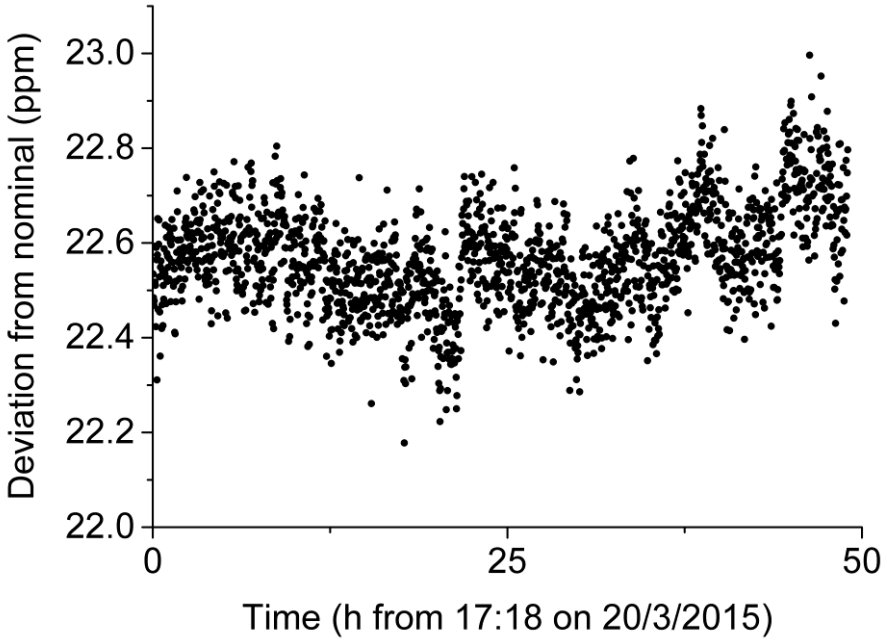
Resistor stability II

Evidence for short-term instability of thick-film standard resistors. These plots are both 100 MΩ measured at 100 V

Guildline 9336

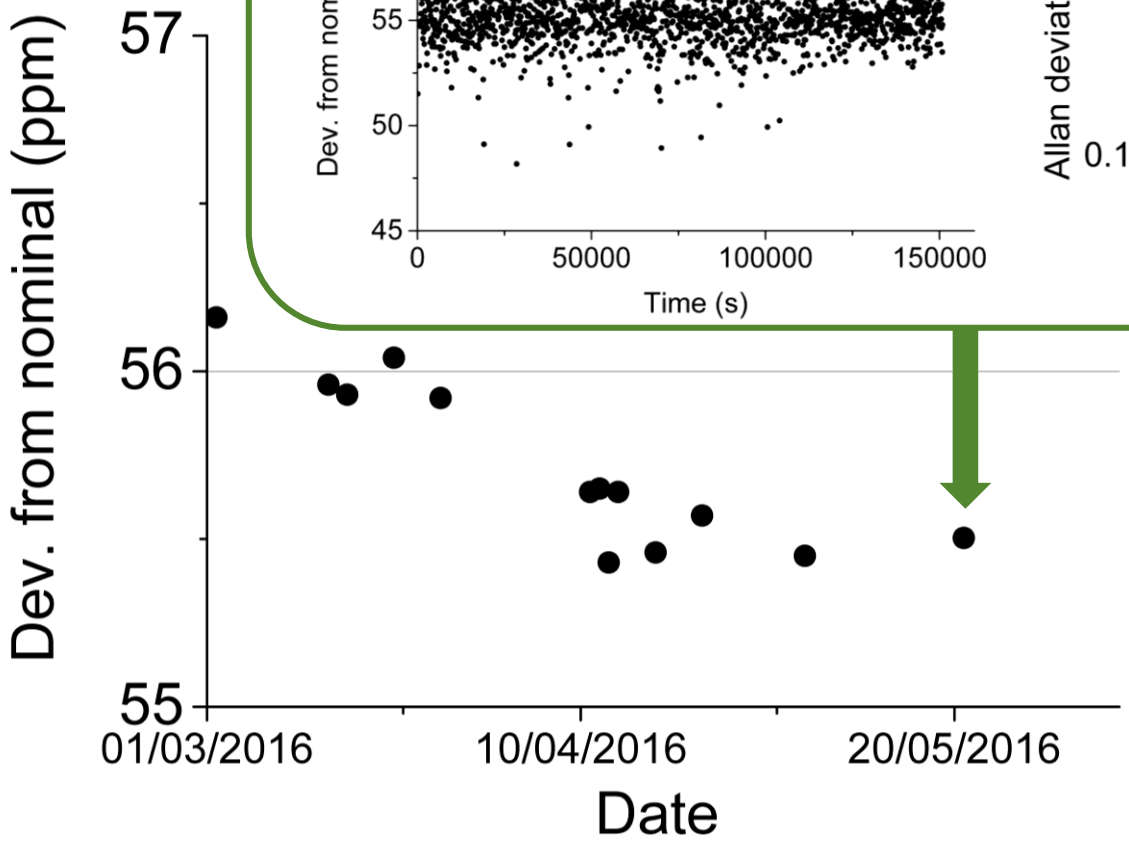


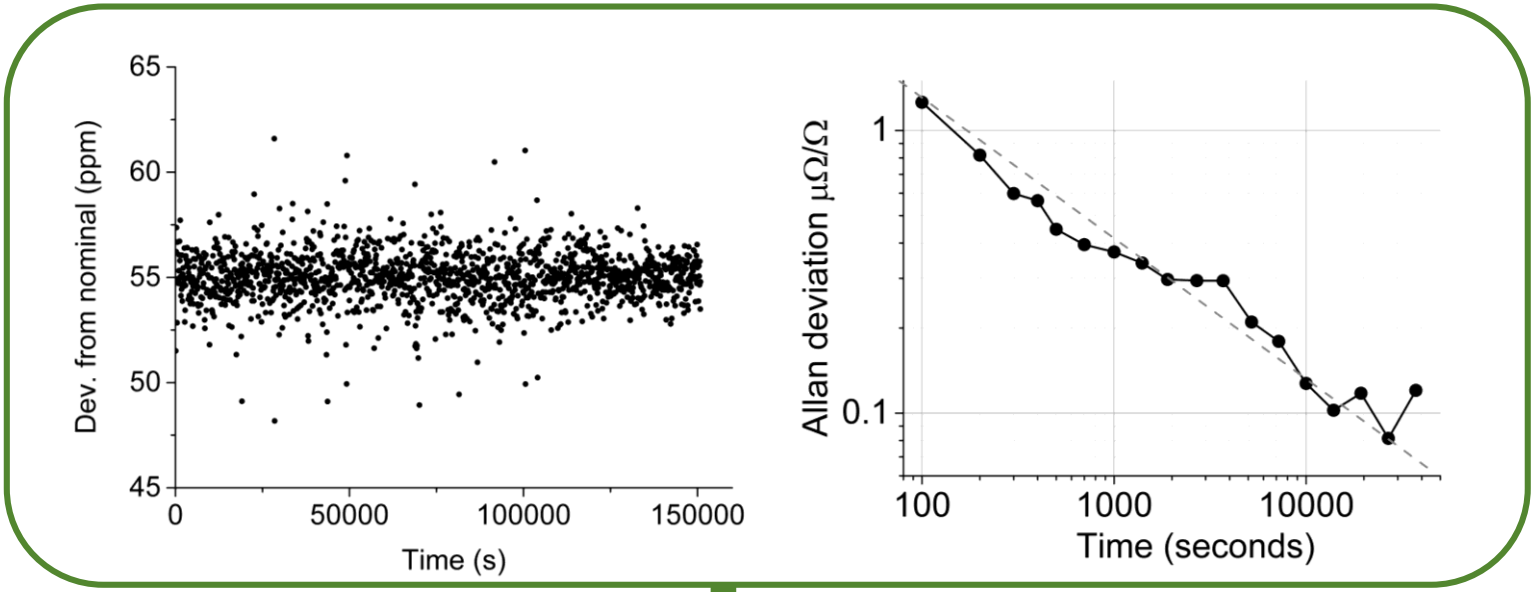
MI 9331 G



Resistor stability III

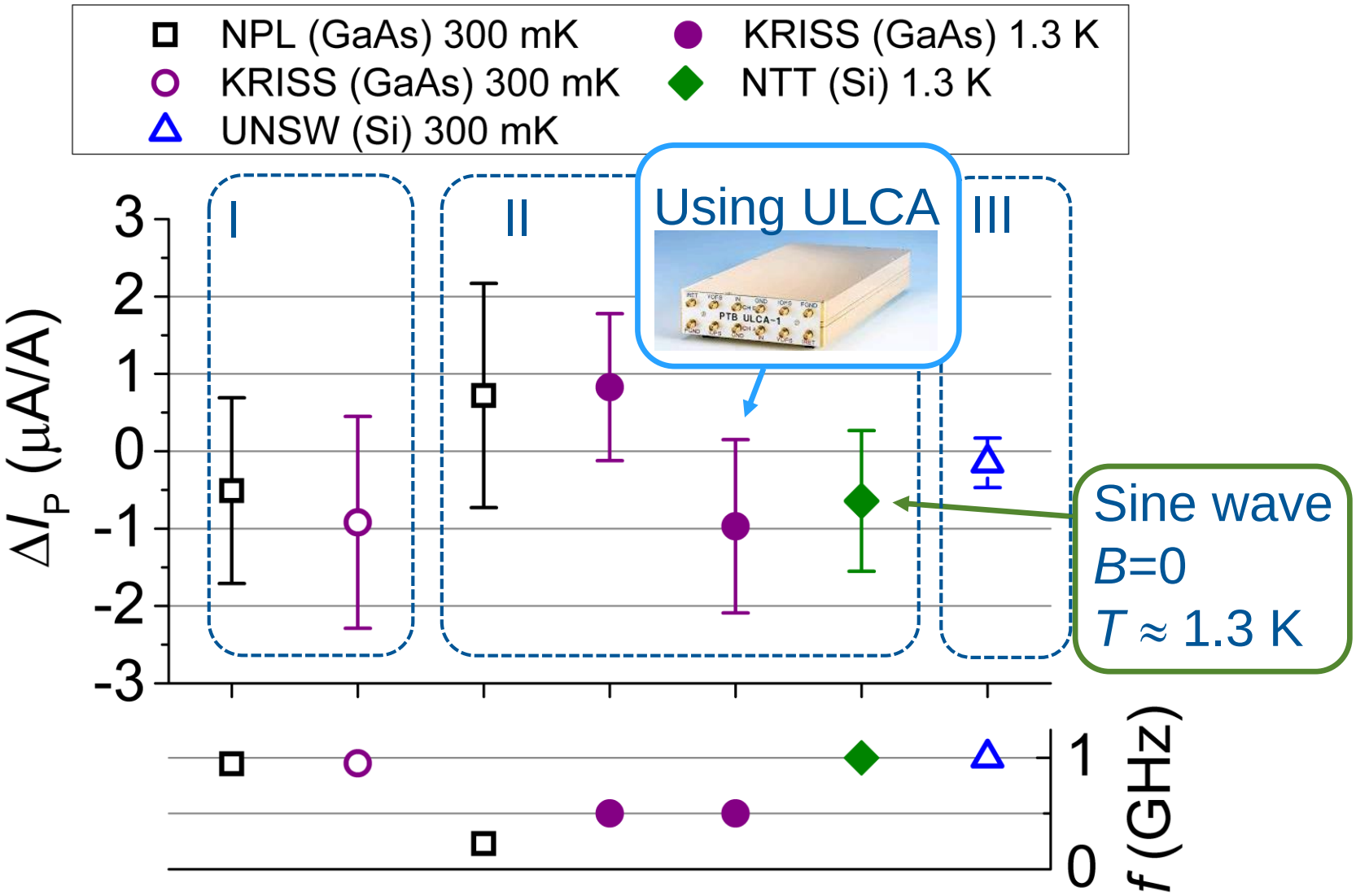
1 GΩ





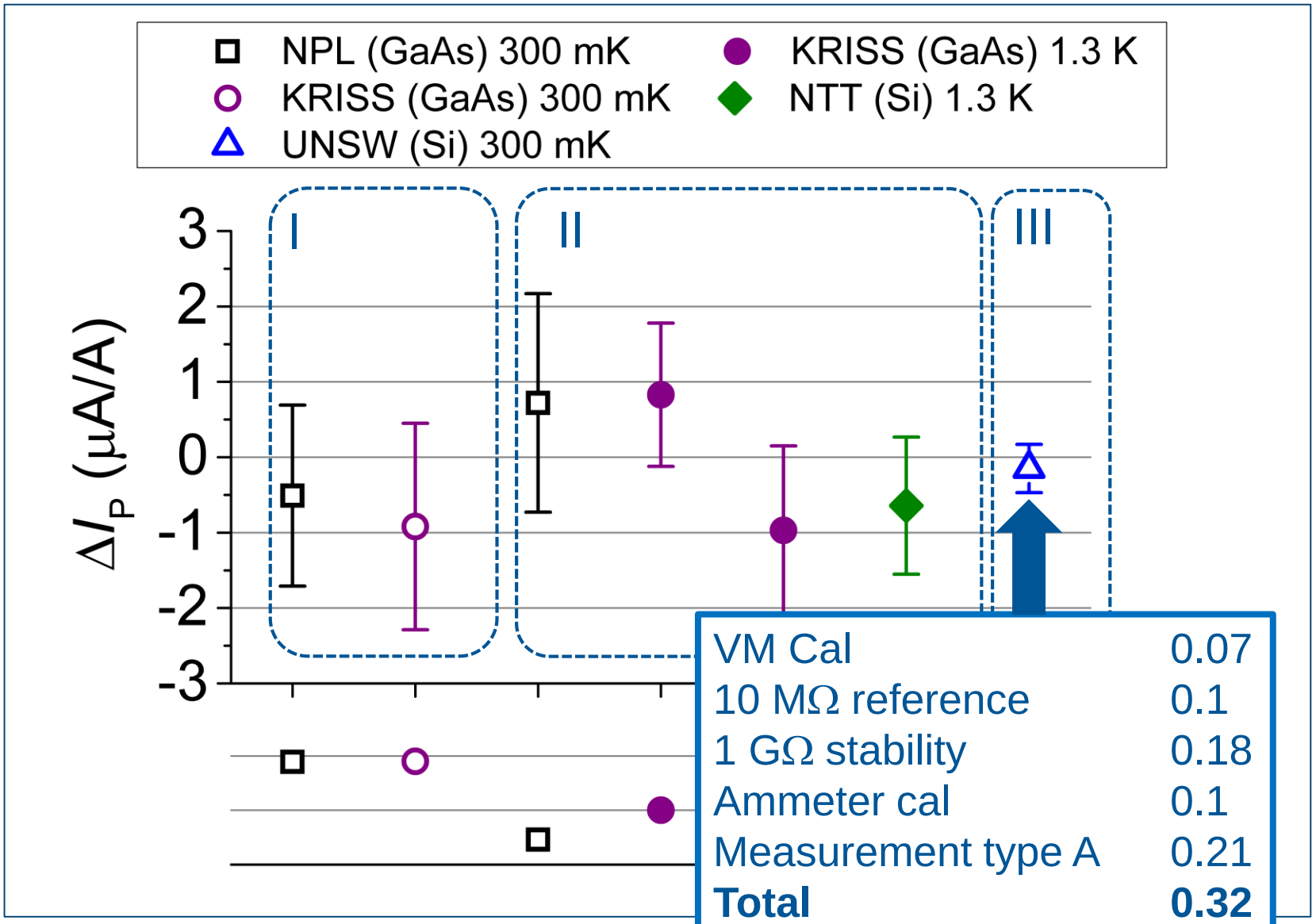
Calibrations at ±33 V, 10^2:10^4 turns ratio against 10 MΩ reference on NPL "Mk. 4" CCC

Results summary

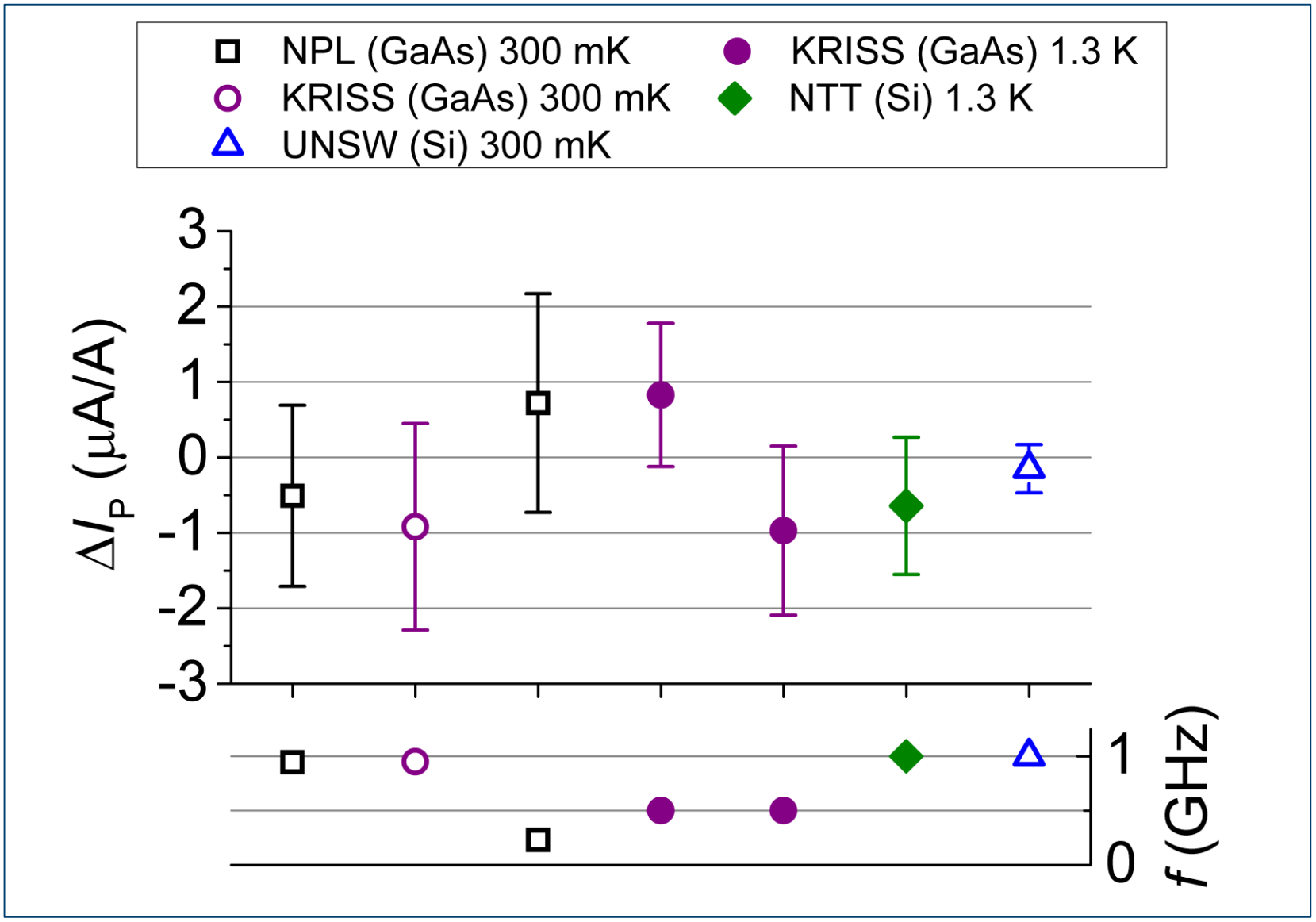


ULCA comparison: Drung et al, *Metrologia* **52**, 756 (2015)

Results summary



Results summary



Question: what determines upper frequency limit?

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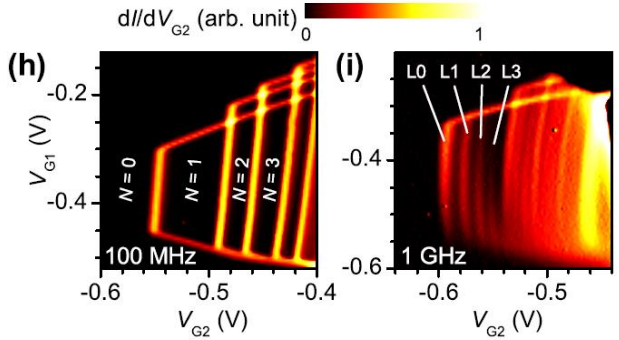
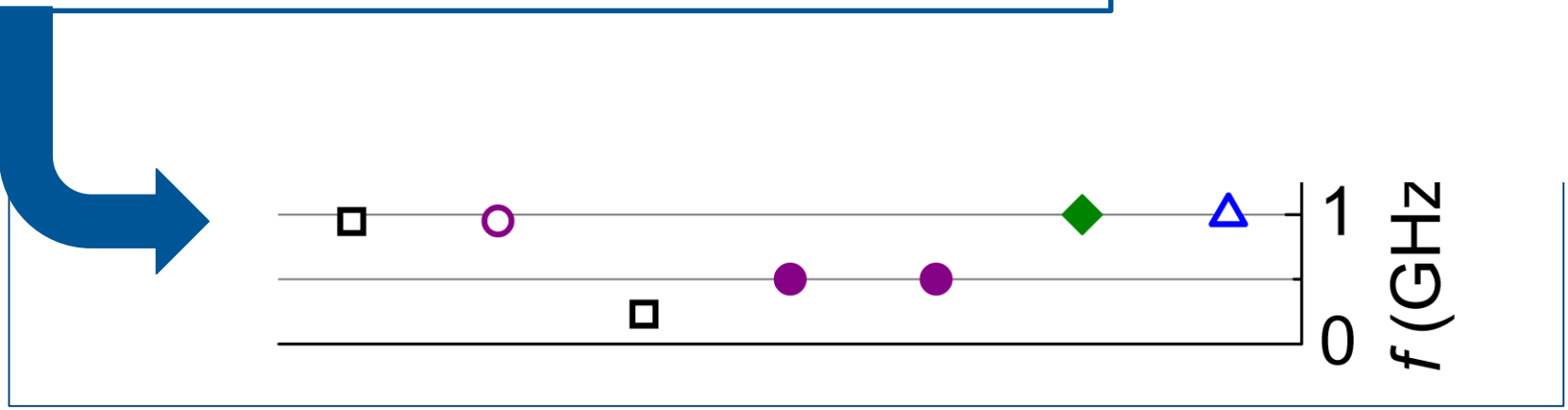
Non-adiabatic excitations?

Kataoka et al, *PRL* **106**, 126801 (2011)



Circuit effects?

Difficult to get flat plateaus above 1 GHz



How stable is the pump?

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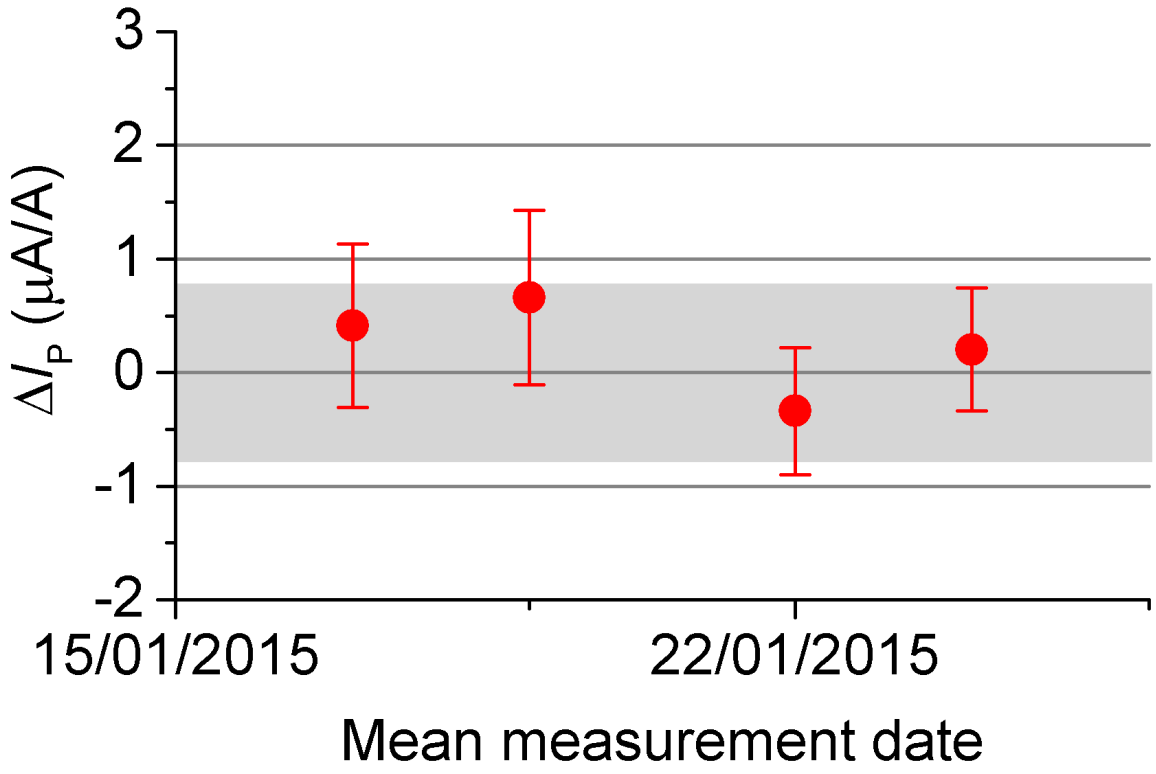
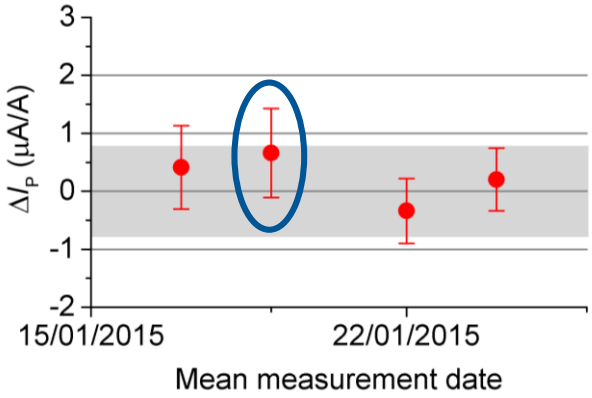
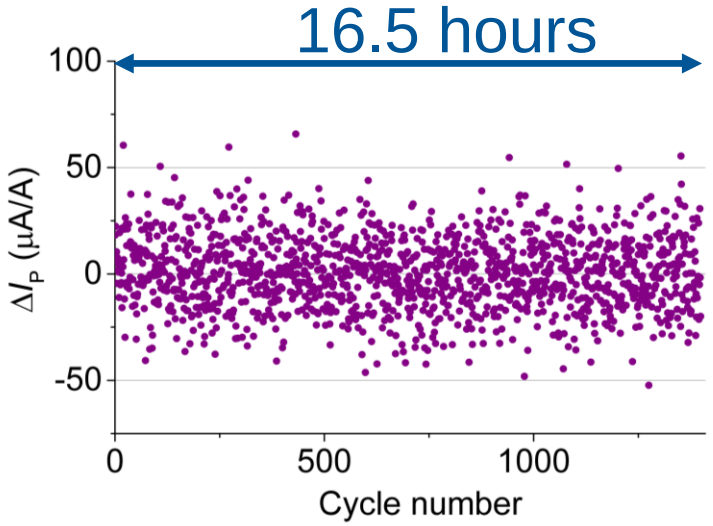
Measurements at fixed operating point

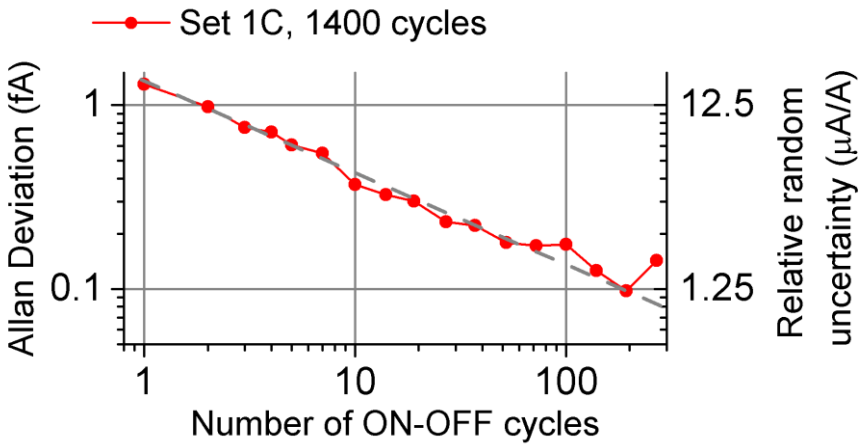


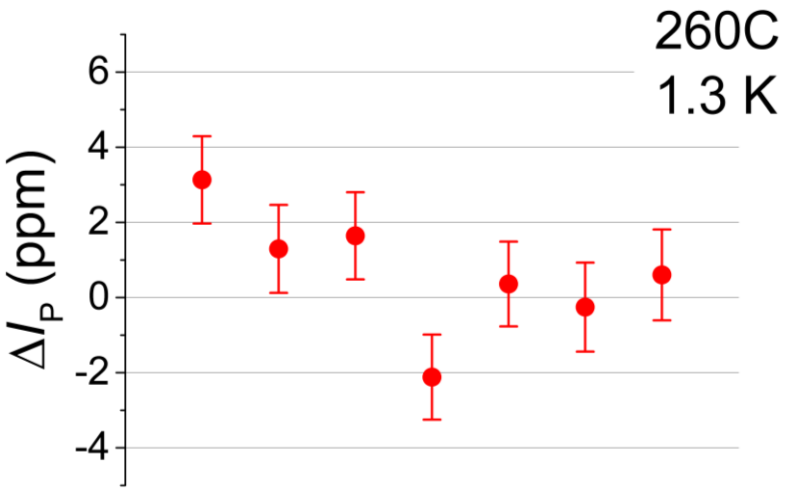
How stable is the pump?

Longest continuous measurement to date:
KRISS pump, 1400 cycles









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Universal mechanism

PRL 104, 186805 (2010) PHYSICAL REVIEW LETTERS week ending 7 MAY 2010

Universal Decay Cascade Model for Dynamic Quantum Dot Initialization

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[1]Faculty of Computing, University of Latvia, Riga LV-1586, Latvia
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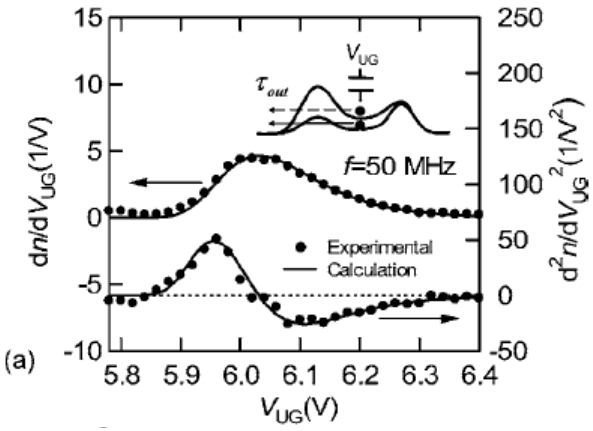
[3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
(Received 26 January 2009; revised manuscript received 22 February 2010; published 7 May 2010)



Fujiwara et al, *Appl. Phys. Lett.* **92**, 042102 (2008)