ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Fabrication, response and stability of miniature piezoresistive force-sensing thick-film cantilevers

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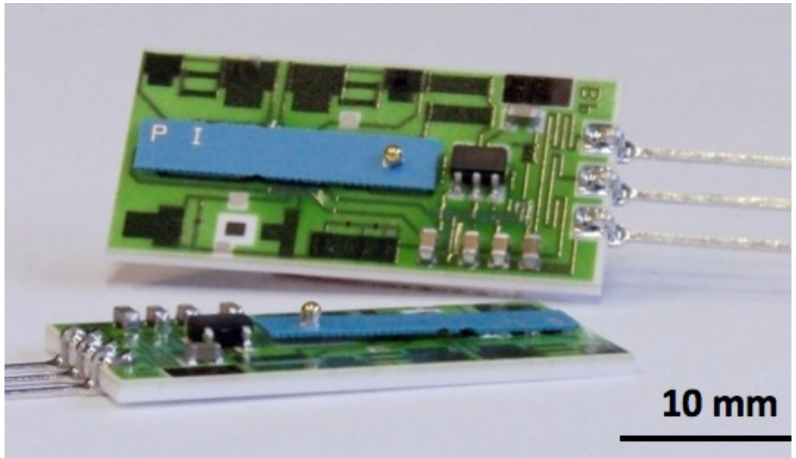

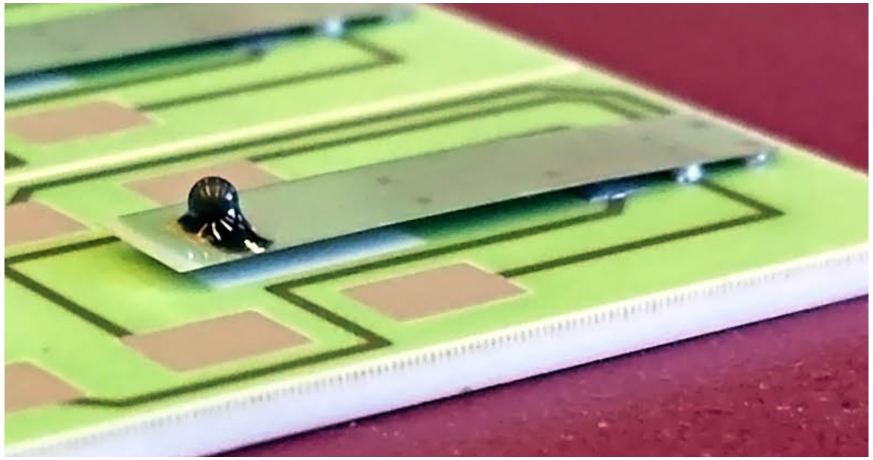

Outline

1. Introduction
2. Manufacturing
3. Thermal drift
4. Force response & signal stability
5. Conclusions & outlook

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Typical thick-film piezoresistive sensor

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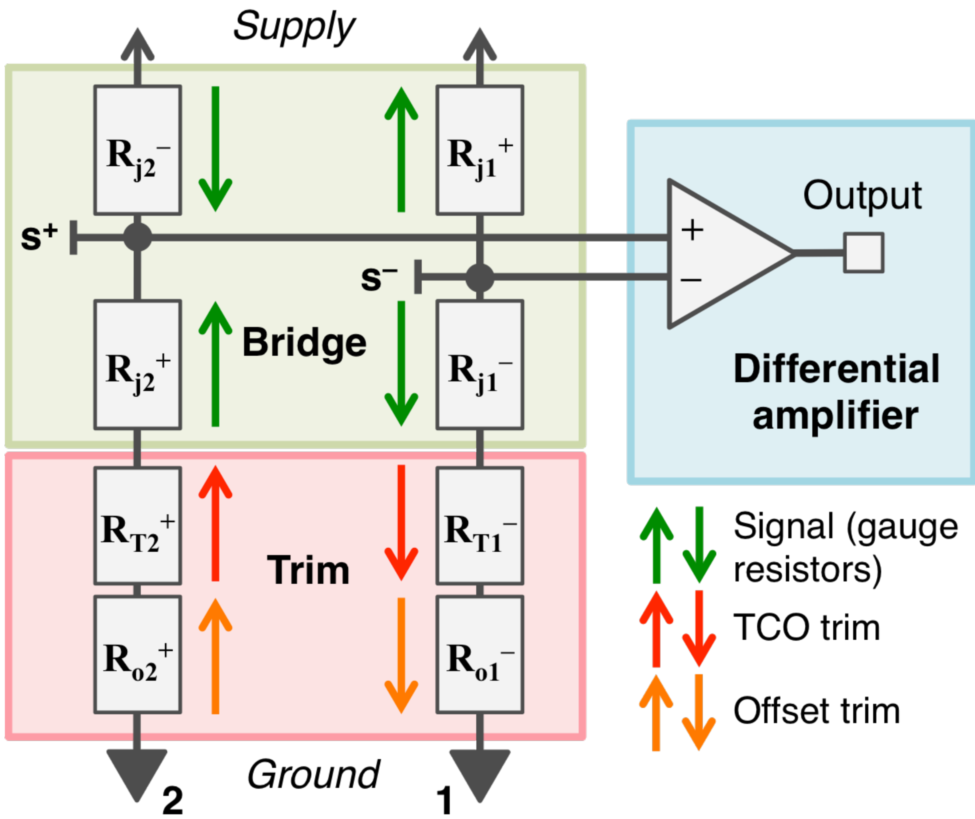
- **Typical elements**
  - Sensing bridge
  - Offset trim
  - TCO trim
  - Differential amplifier



- **Typical values (±)**
  - **Offset ~30 mV/V**
  - **Response ~2-3 mV/V**
  - TCO ~1 μV/V/K
    (50 K : ~0.05 mV/V, ~2% F.S.)

- **For 0.1% F.S.:**
  - Offset reduction ~10'000×
  - Stability (bridge) ~2-3 ppm

Cantilever force cell – principle

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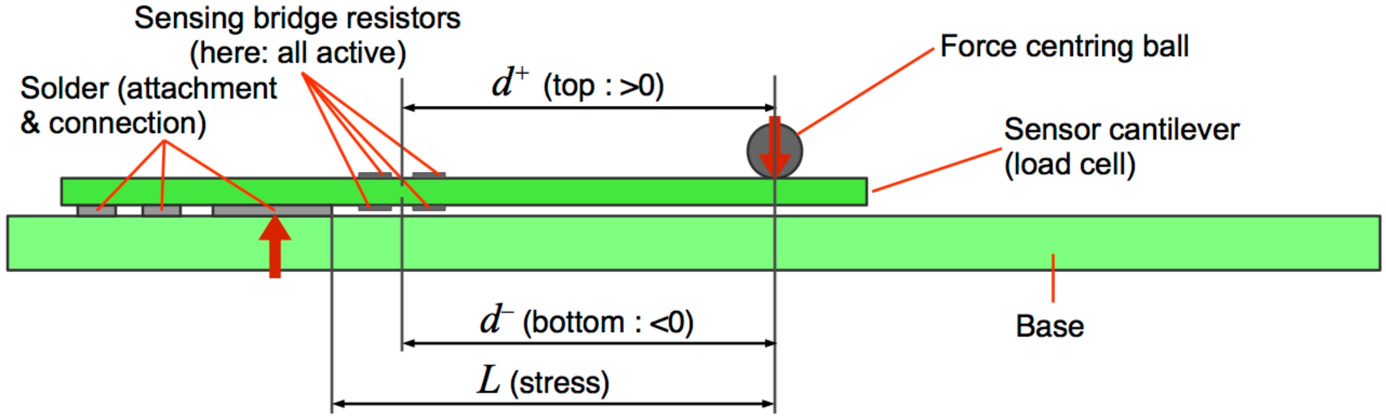
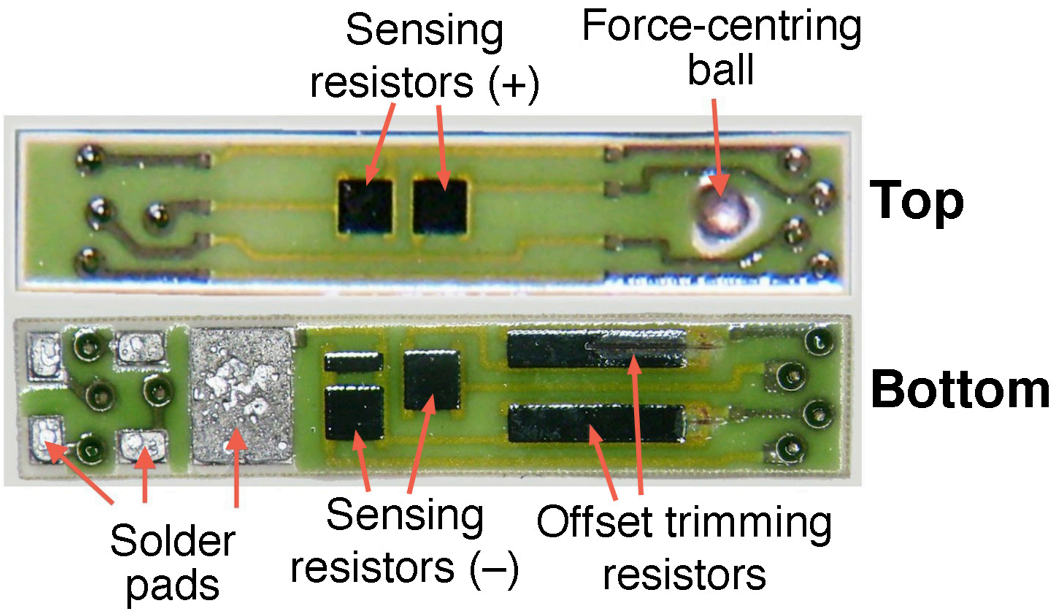
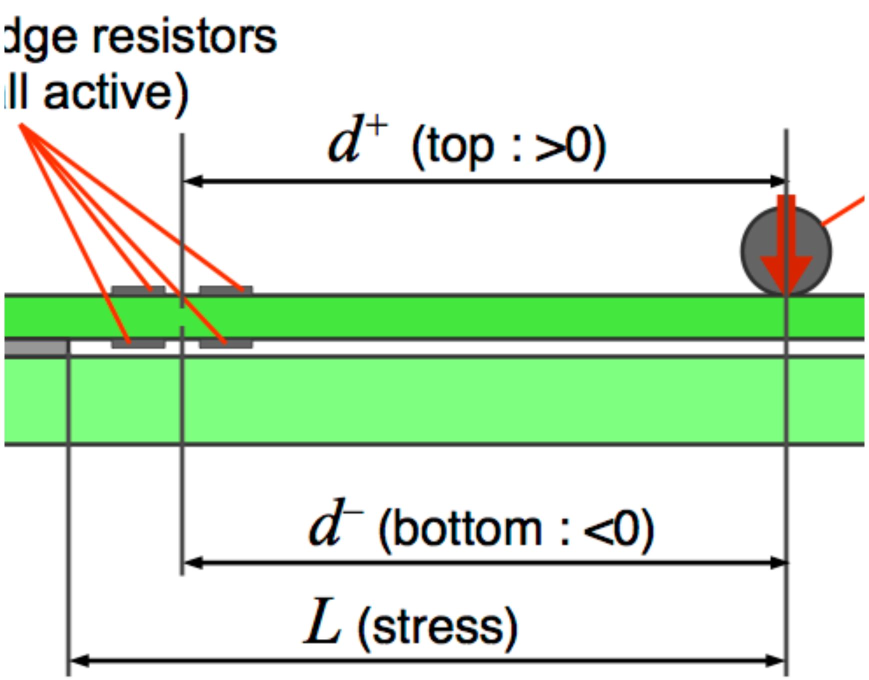




- Piezoresistive bridge
- Thick-film resistors
- Gauge factor K_L ~12

Cantilever force cell – distances



Geometry

- L : for stress
- d^+ : positive signal (avg.)
- d^- : positive signal (avg.)
- d : signal (overall)
- b : cantilever width
- h : cantilever thickness

$$d = \tfrac{1}{2}\left(d^+ - d^-\right)$$

Nominal stress:

$$\sigma = \frac{6}{b \cdot h^2} \cdot L \cdot F$$

Effective sensor strain:

$$\varepsilon_r = \frac{6}{b \cdot h^2 \cdot E} \cdot d \cdot F$$

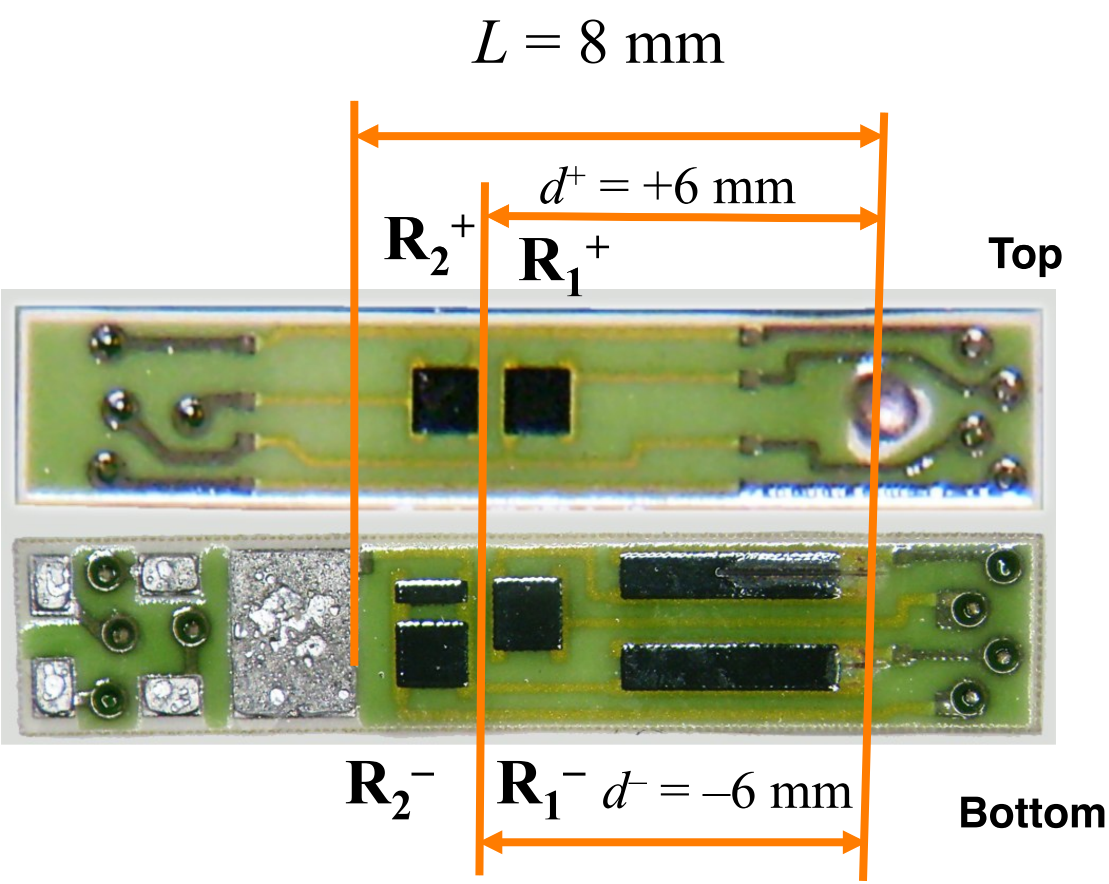
Response (signal / supply):

$$r = K_L \cdot \varepsilon_r$$

(E = substrate elastic modulus; K_L = piezoresistive longitudinal gauge factor)

Classical cantilever

$$d/L = 75\%$$



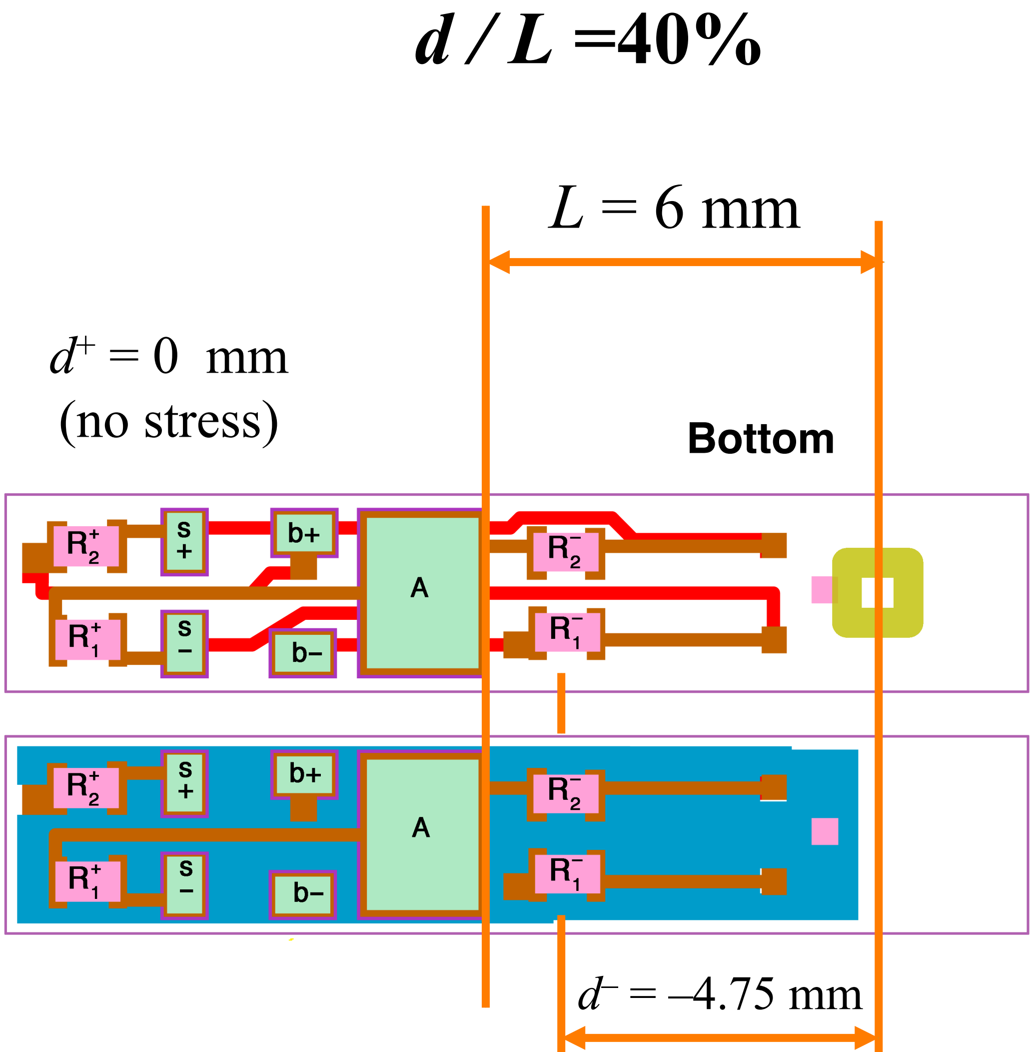
Pros

- Full active bridge
- Little thermal drift

Cons

- Double-side, complex fabrication
- More difficult resistor matching (separate prints)
- Layers on top side
- Sensitive to horizontal forces

Single-side cantilever (type 1)



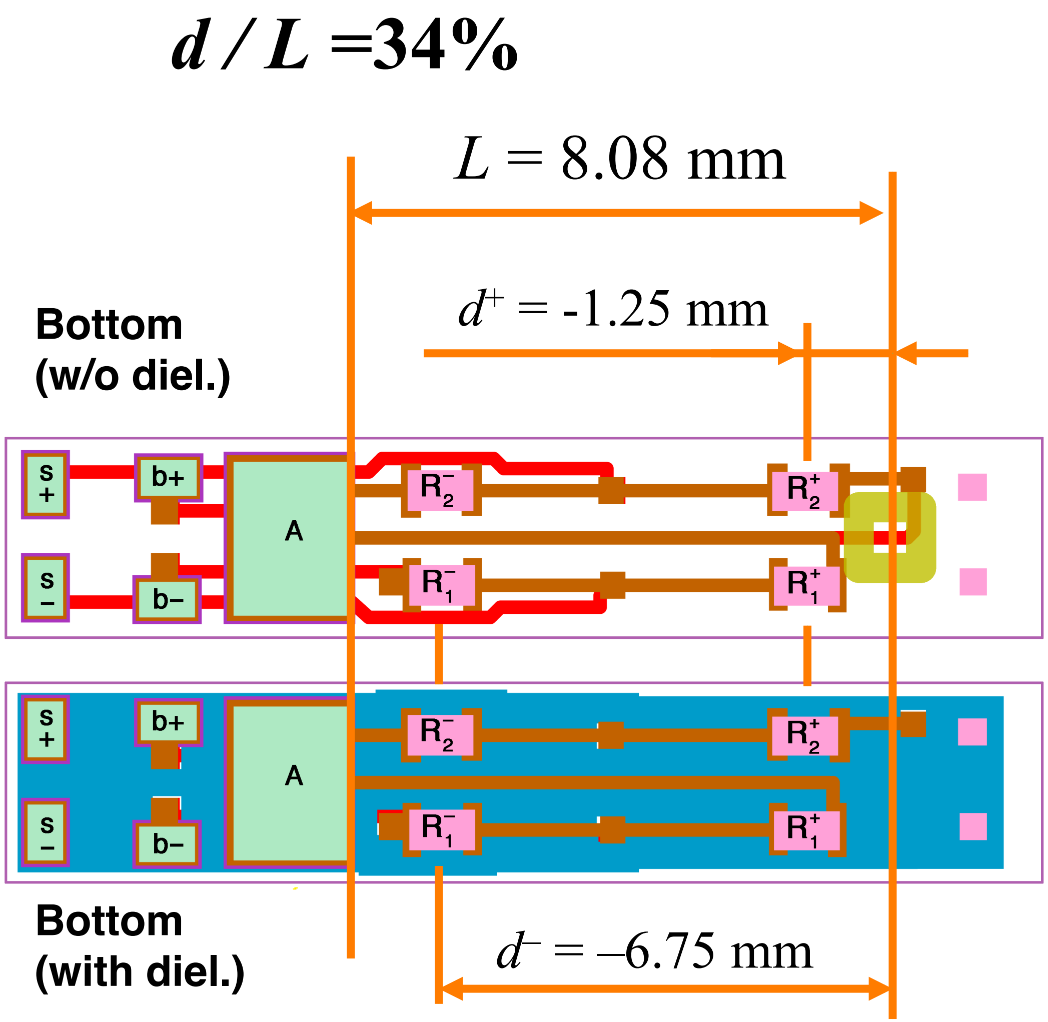
Pros

- Single-side, simple
- Good resistor matching (single print)
- Blank top side
- Little thermal drift

Cons

- Half bridge, less sensitive
- Sensitive to horizontal forces

Single-side cantilever (types 2/3)



Pros

- Single-side, simple
- Good resistor matching (single print)
- Blank top side
- Horizontal force compensation

Cons

- Half bridge, sensitivity further reduced by "retrograde" resistors
- Buried conductors?

Substrates (blank) – static fatigue

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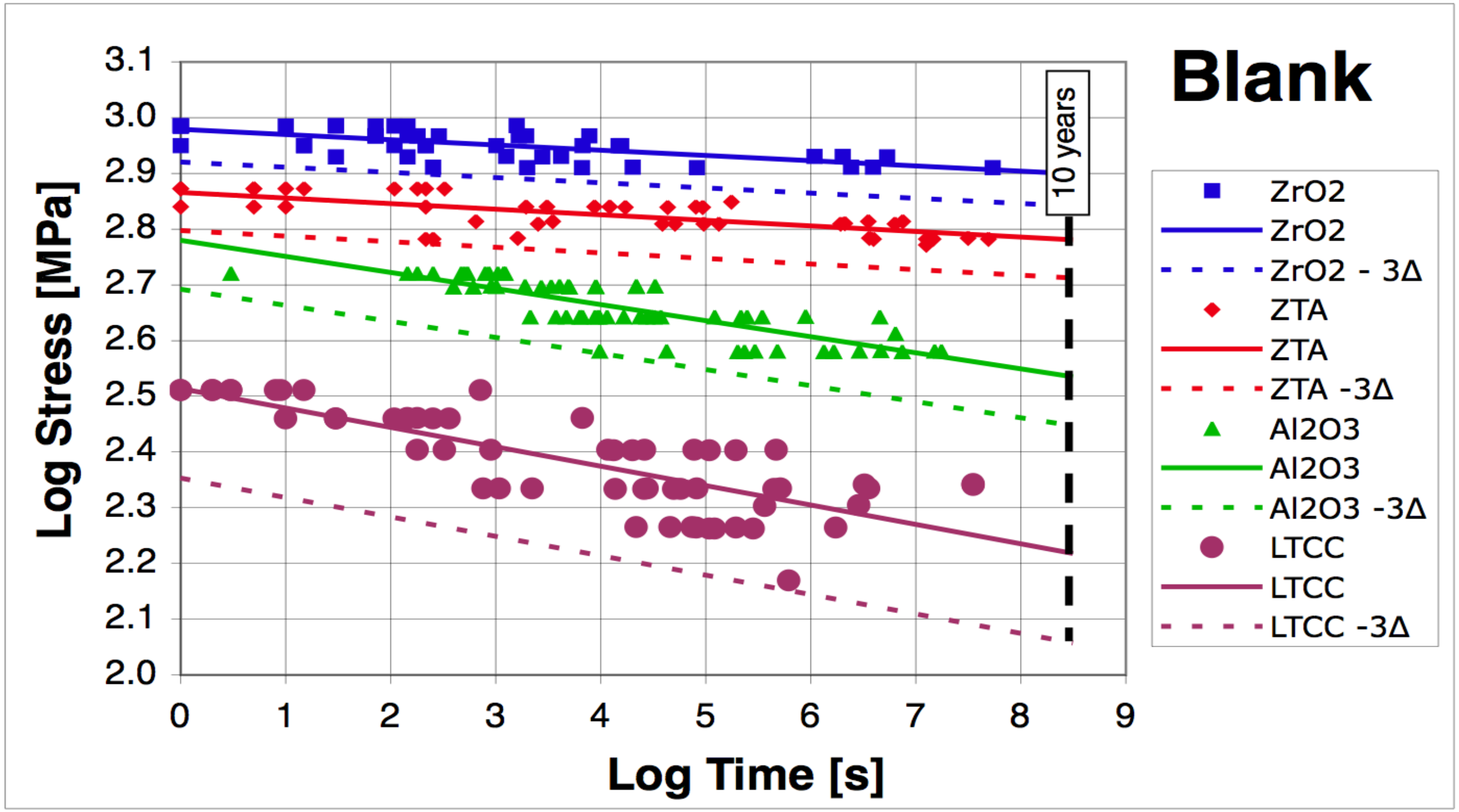
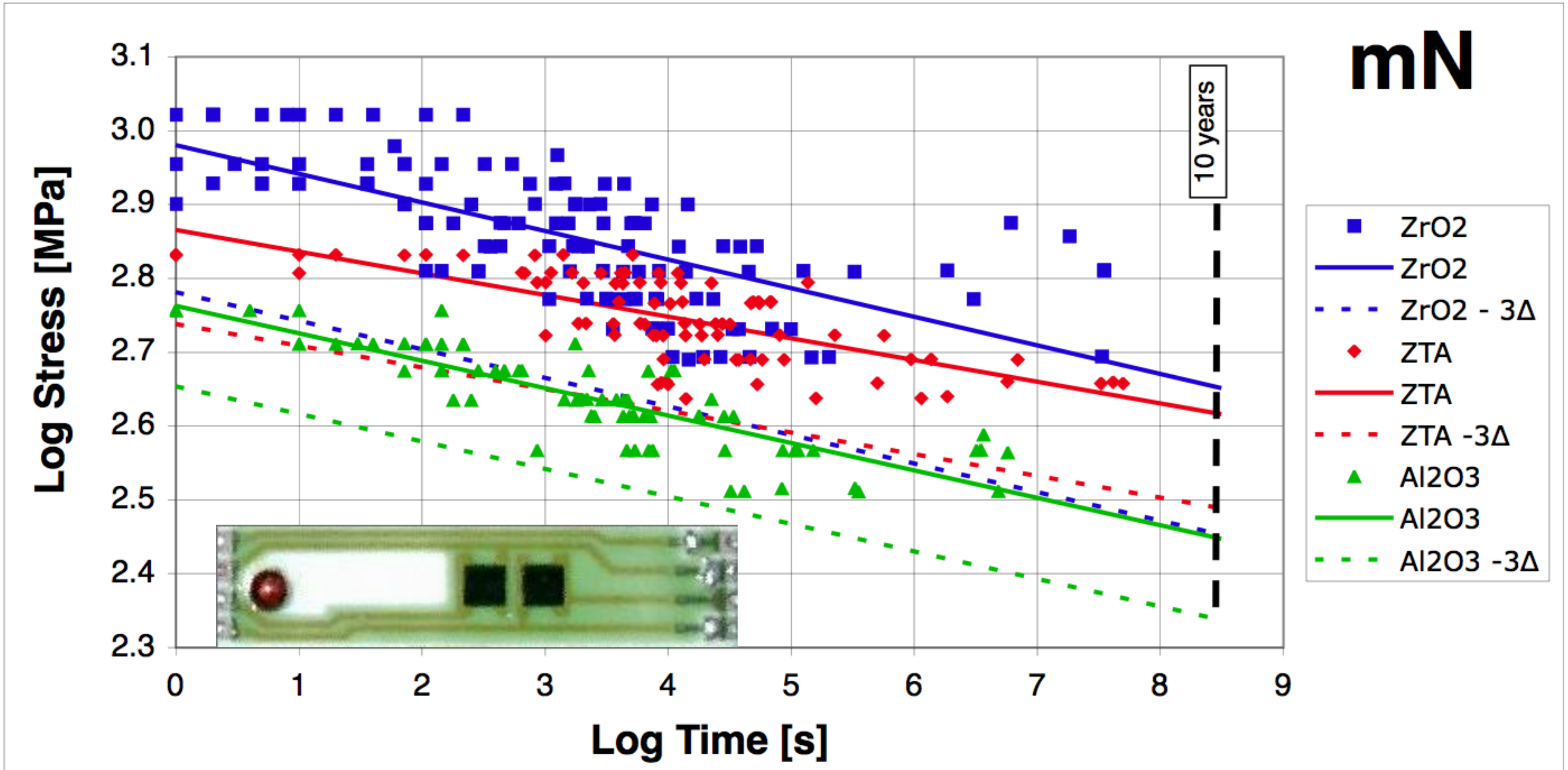


- Very good performance for ZrO2:Y (YSZ) & ZTA
- Glassy (Al2O3 96% & LTCC) : poorer

Substrates (load cell) – static fatigue



- Strong degradation of high-strength substrates (ZrO_2 & ZTA)
- *ZrO_2 & ZTA better with single-side cantilevers (blank top side)*

Substrates (load cell) – static fatigue

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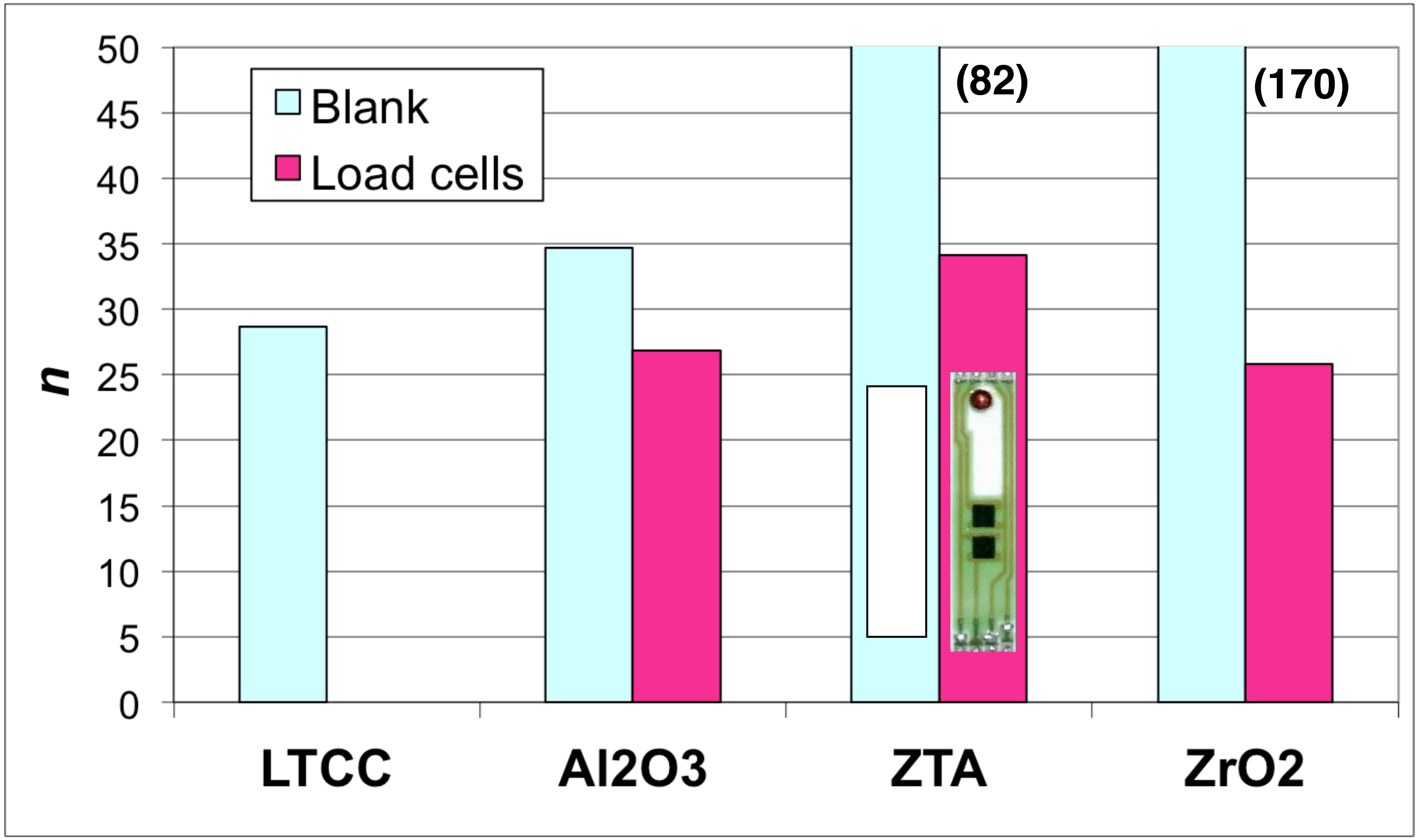

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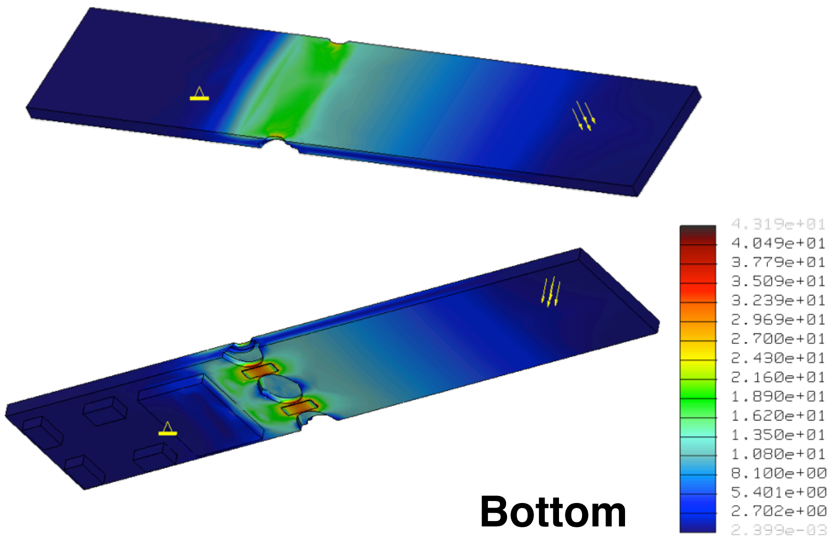
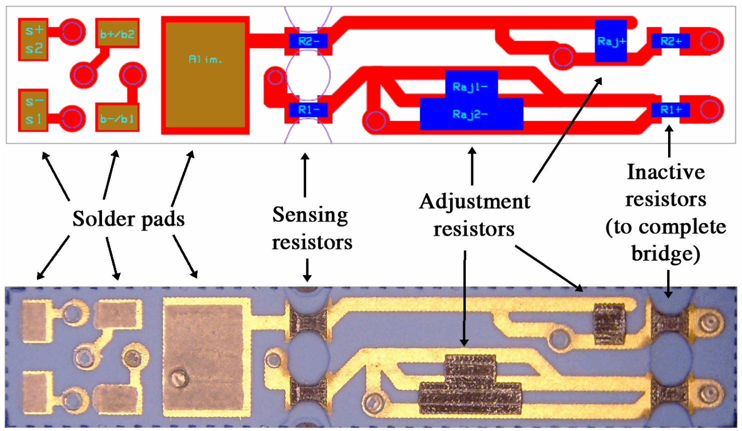
- *ZrO_2 & ZTA better with single-side cantilevers (blank top side)*

LTCC structured cantilever





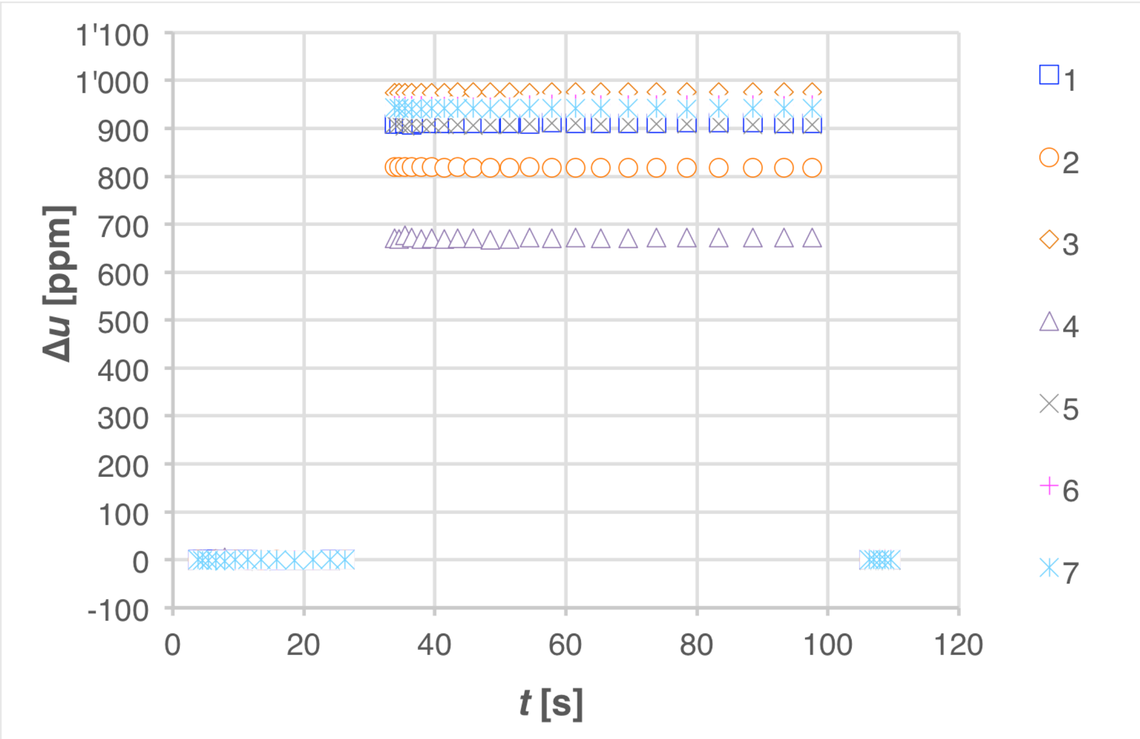
Pros

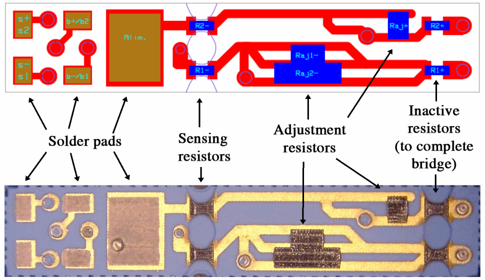
- Single-side
- Good resistor matching
- **Higher signal by structuration**
  - **Concentration of compression**
  - **In practice ~2x**
- Horizontal force compensation

Cons

- LTCC process critical for thin, sensitive cantilevers (shrinkage matching, warpage)
- Resistor compatibility
- **Drift???**

LTCC cantilever – drift ?





- Moderate, consistent signal
- No apparent drift

LTCC cantilever – drift ?

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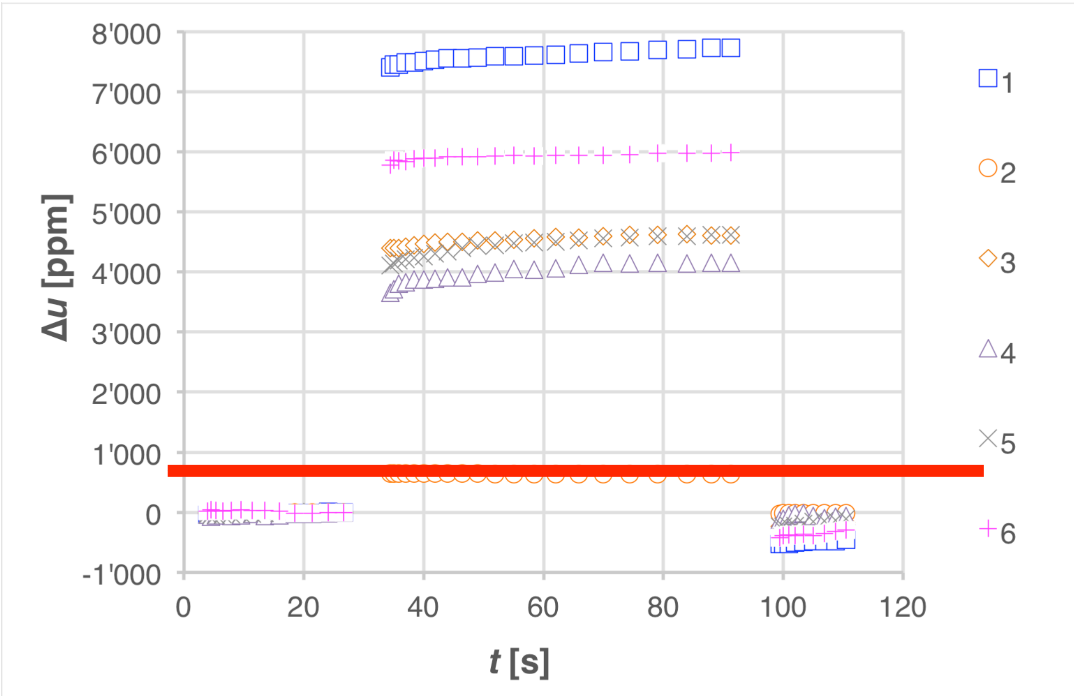
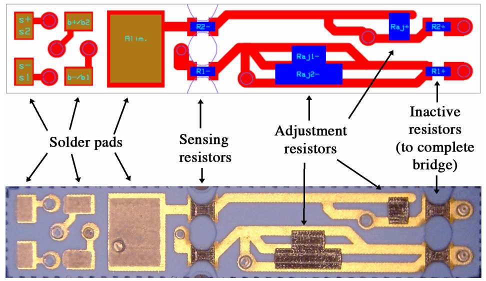
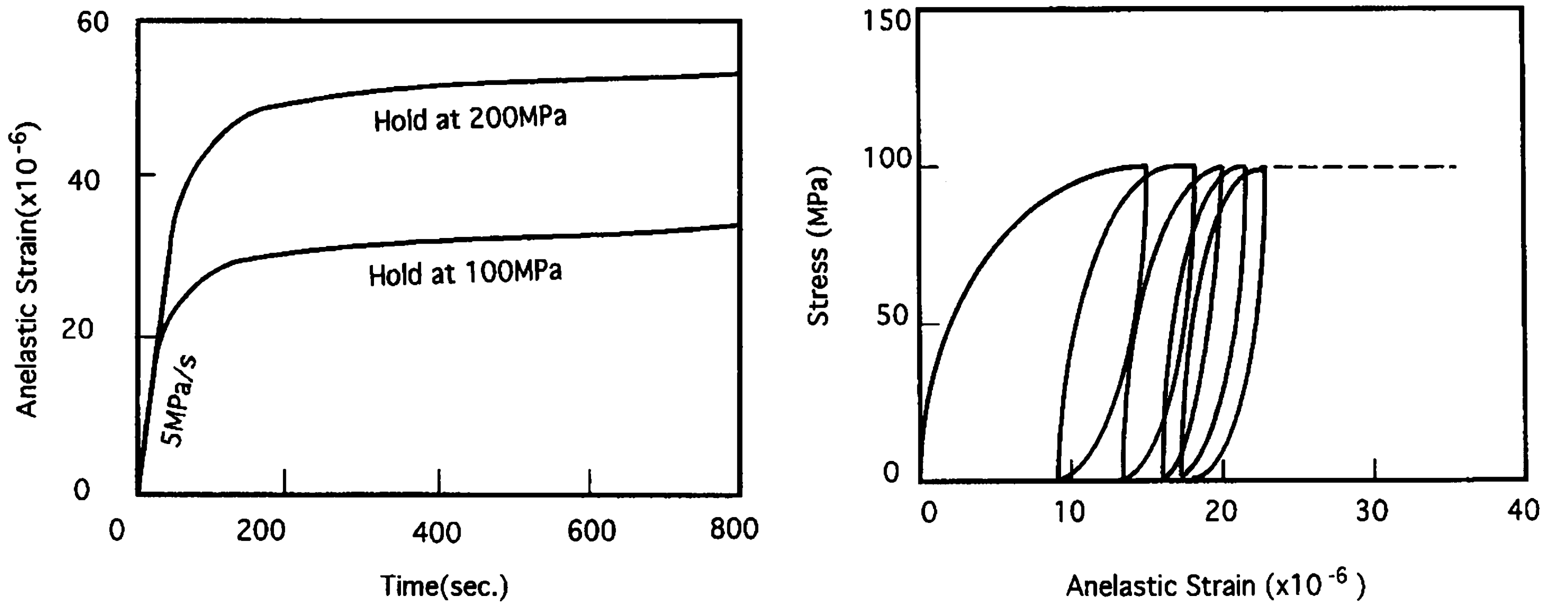




- Abnormally high signal
- Strong variations between samples
- Significant drift

YSZ cantilevers – drift?



Pan & Horibe, Acta Mater. 1997

Anelasticity in YSZ

- Ferroelasticity
- Problematic for elastic substrate…

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Substrates

Code	Substrate material	Thickness [μm]
A	3YSZ (Kerafol)	45
B	3YSZ (Kerafol)	90
C	Al_2O_3 96% (Kyocera A-476)	400
D	Al_2O_3 96% (CeramTec Rubalit 708S)	150
E	ZTA (CeramTec Rubalit HSS 2-14-02-004)	250
F	ZTA (CeramTec Rubalit HSS4-38/3 S2)	320
G	LTCC (Heraeus CT700)	470 / 710
H	LTCC (Heraeus Heralock HL2000)	180 / 270
I	LTCC (DuPont 951)	270 / 410

Tested substrates

- All pre-fired
- Not structured, same layout

Layouts

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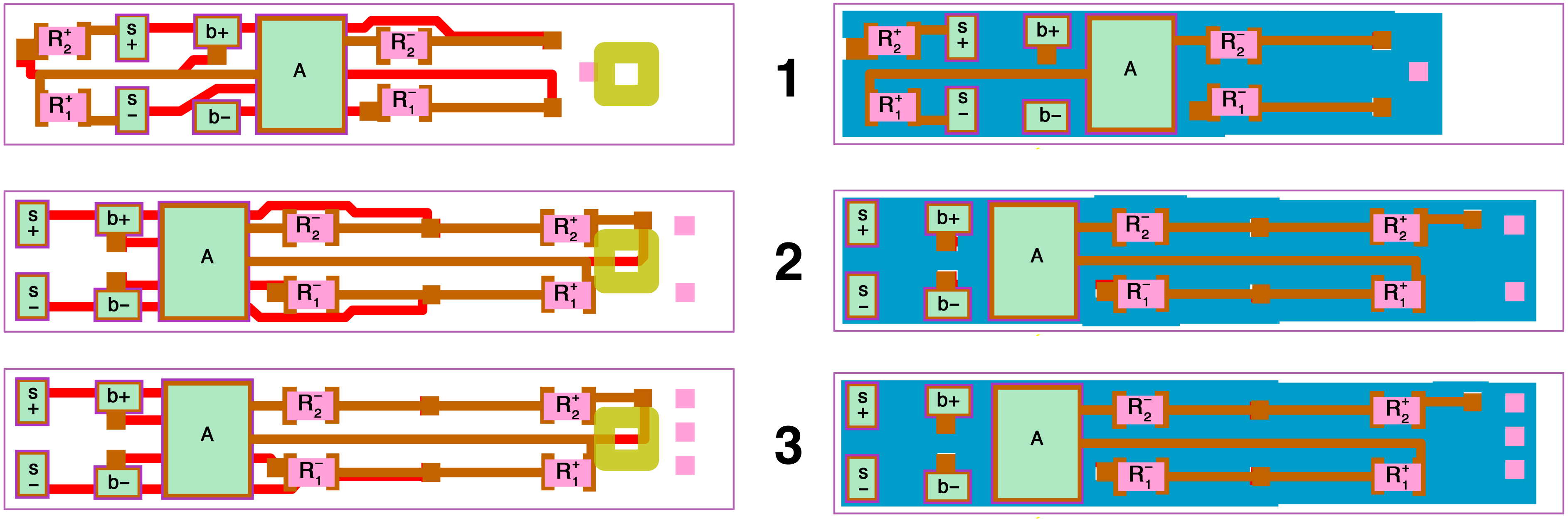

Tested layouts

1) Short cantilever, half-bridge
2) Long cantilever (no tracks under resistors)
3) Long cantilever (tracks under resistors)

Fabrication

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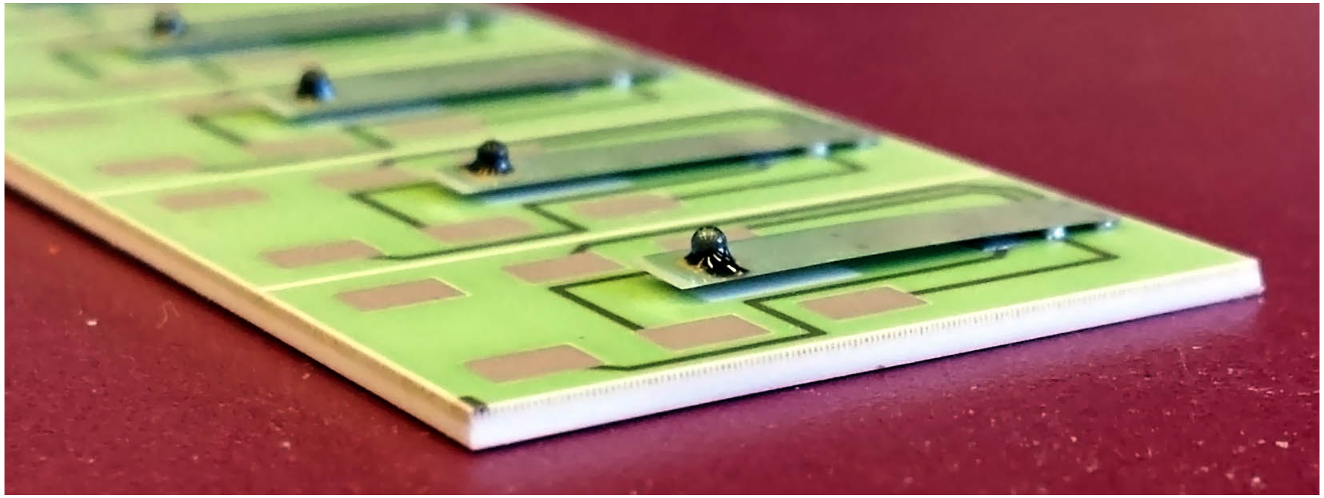

- Resistors (DP 2041) on dielectric:
  - 3YSZ : ESL 4931 (for steel -> CTE ~ YSZ)
  - Others : ESL 4913 + 4917 (low CTE)
- 3YSZ : 45 μm critical, 90 μm OK
- Al_2O_3 / ZTA : OK down to 150 μm (ZTA recommended)
- LTCC : flatness critical (DP951 $\gtrsim$ HL2000 > CT700)

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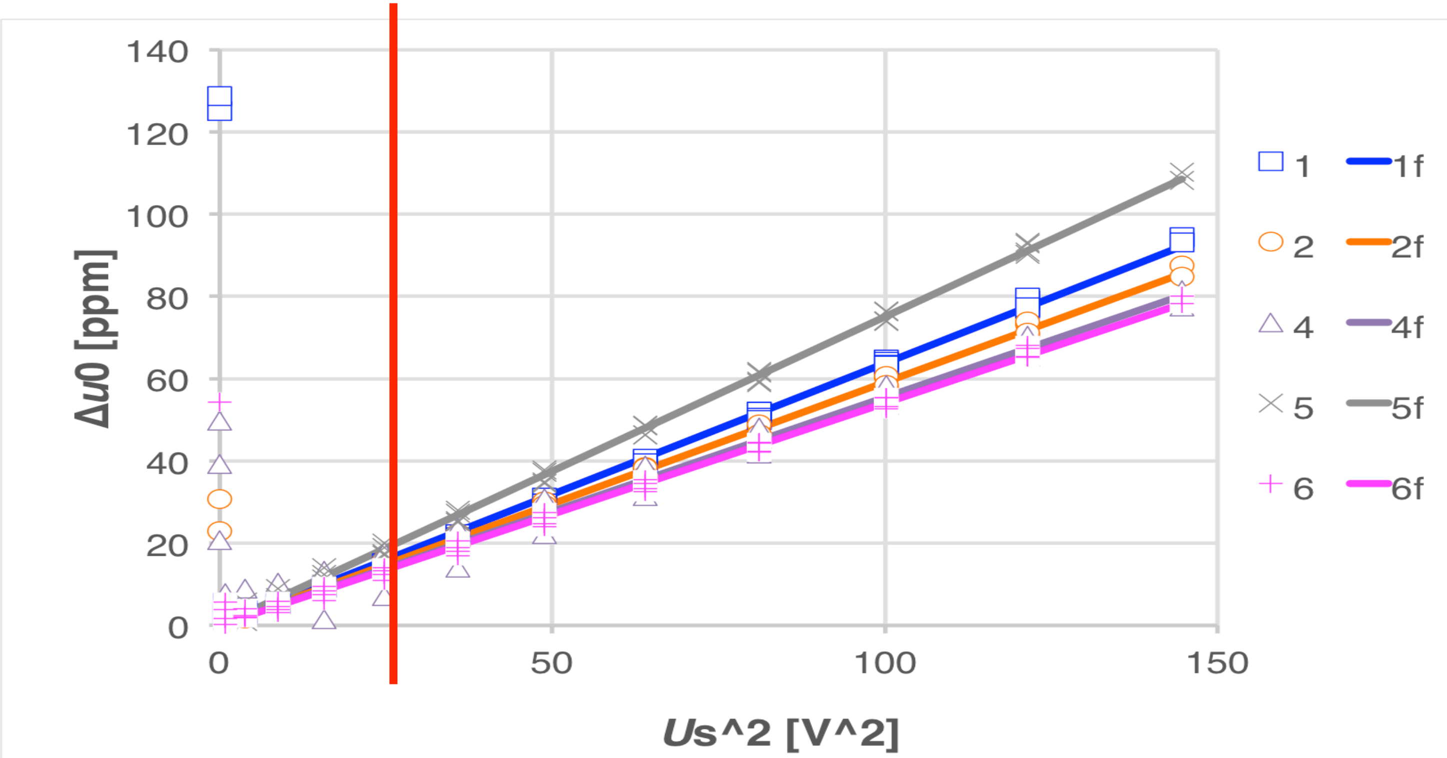
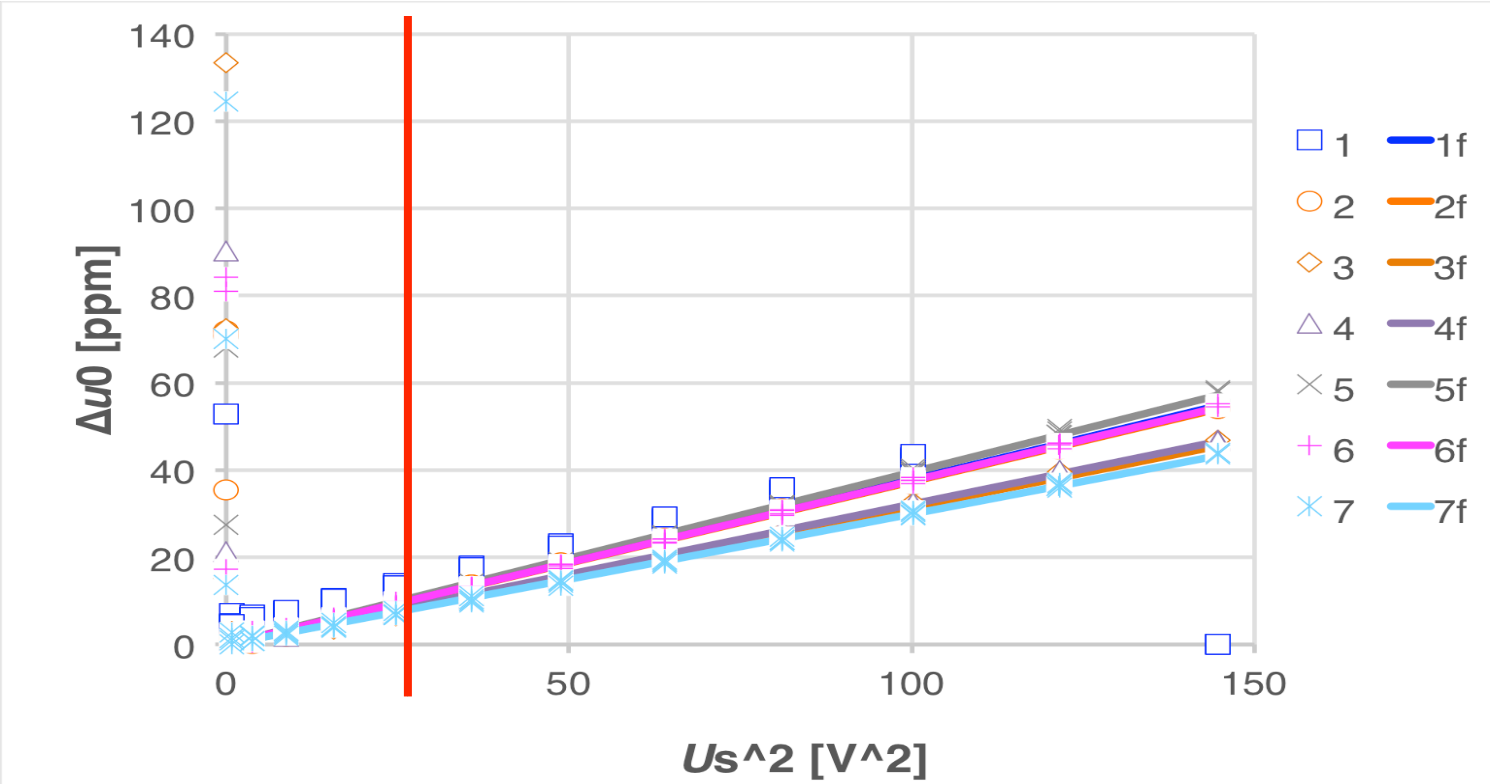
A – 45 μm 3YSZ – layout 3



- Very low heat conductance (45 μm thick, $k \sim$ 2-3 W/m/K)
- Thermal drift max ~1% (for 2'000 ppm F.S.)

B – 90 μm 3YSZ – layout 2



- Same material, 2x thickness
- ½ thermal drift

D – 150 μm alumina – layout 2

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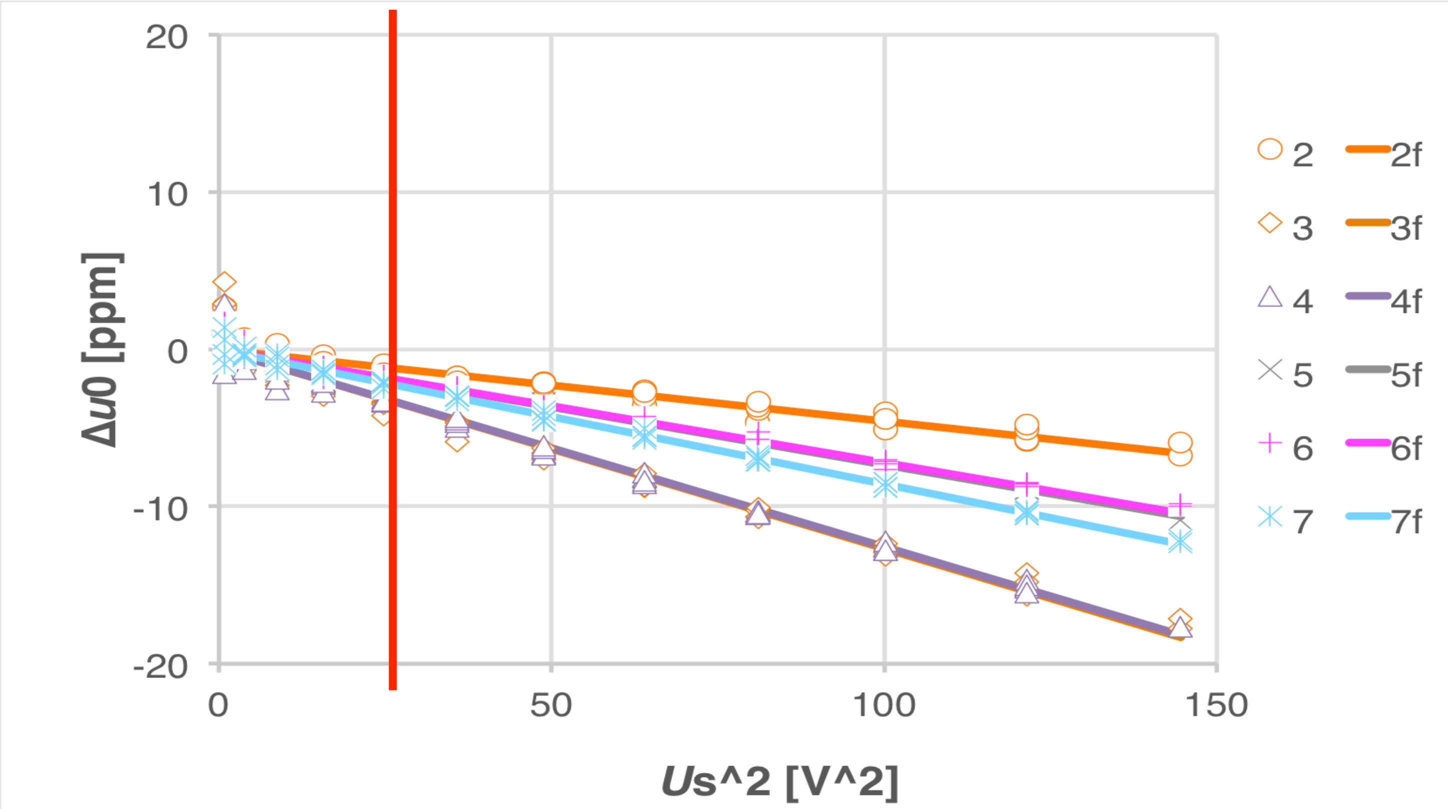

- Very low thermal drift even for thinnest Al_2O_3

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A – 45 μm 3YSZ – layout 3

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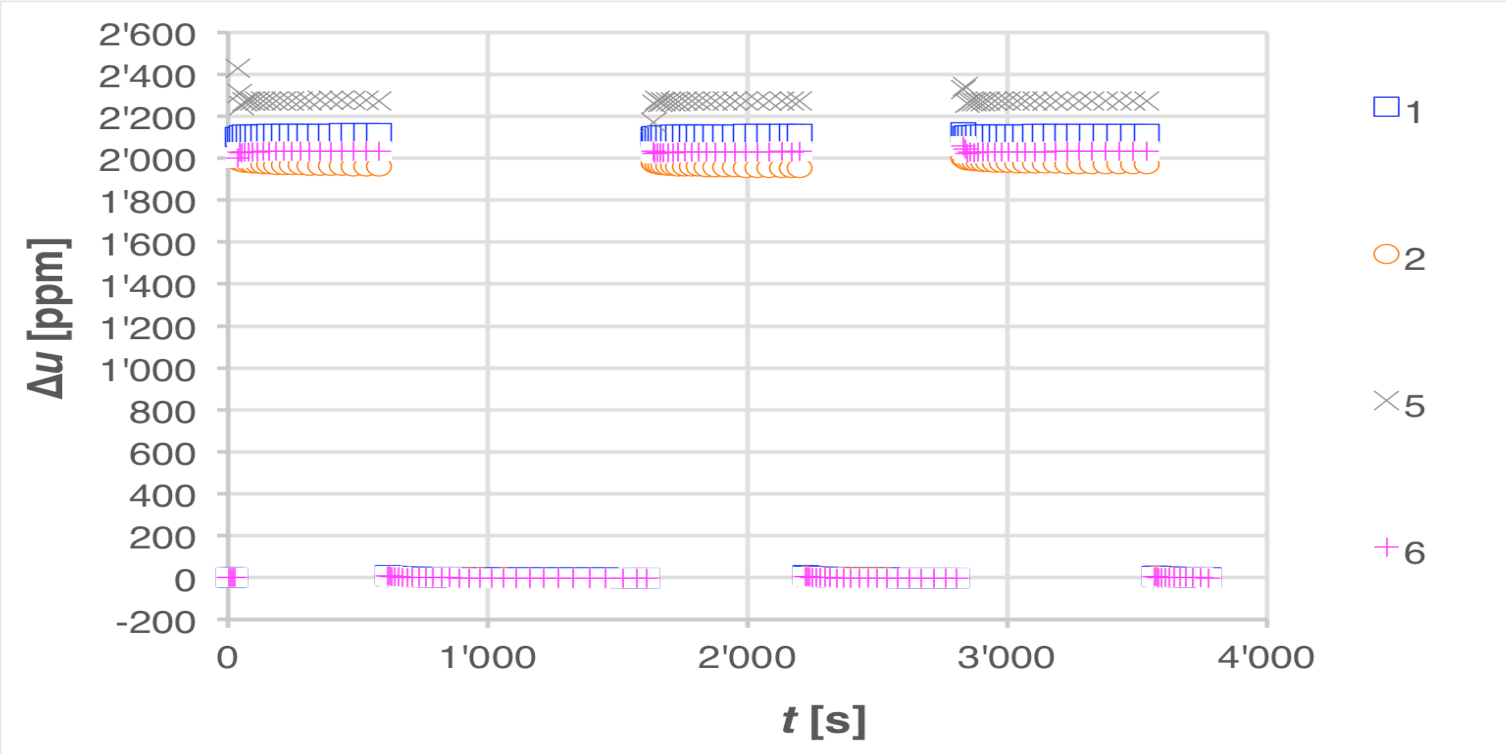

- High signal level, consistent
- No visible drift (<±5 ppm)
- Linear signal, ~43 ppm/mN

B – 90 μm 3YSZ – layout 2

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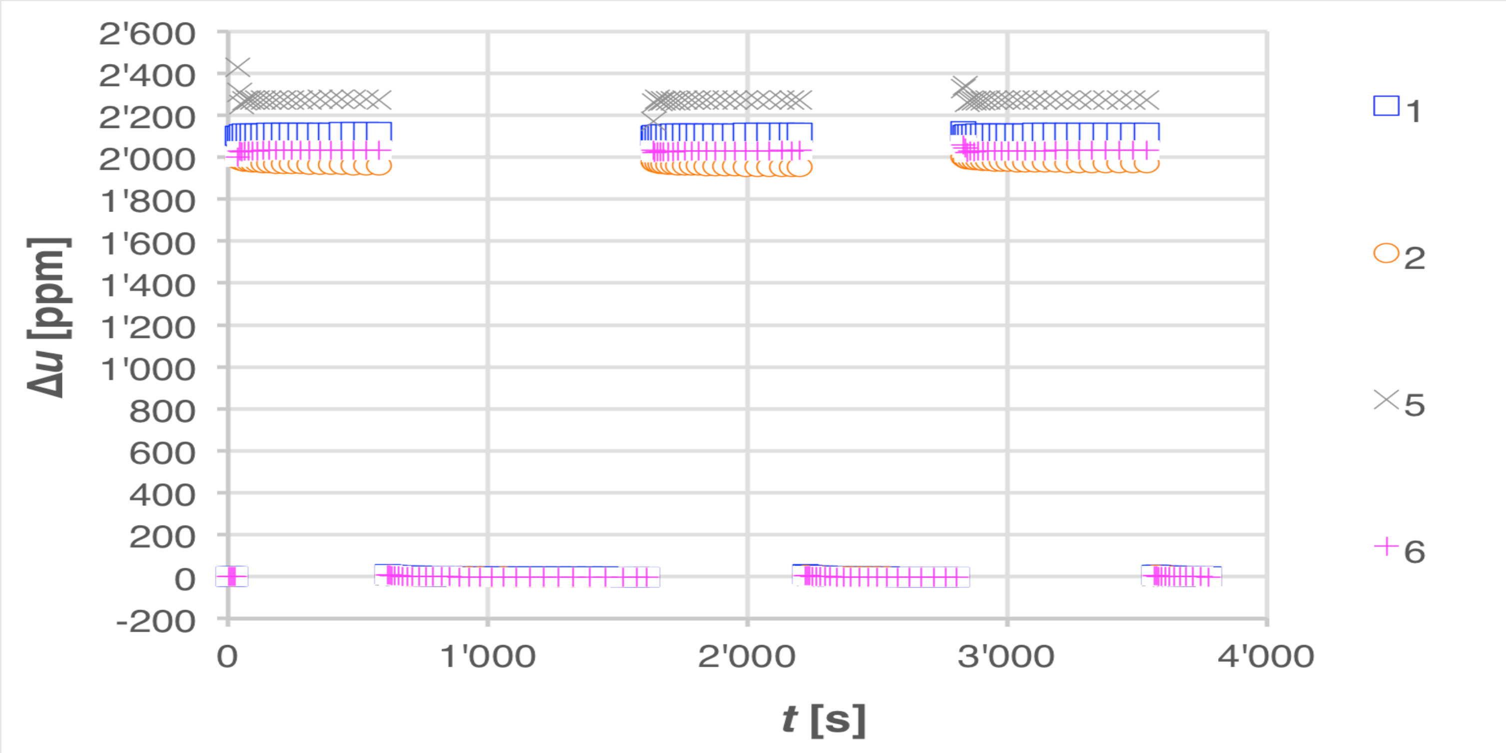
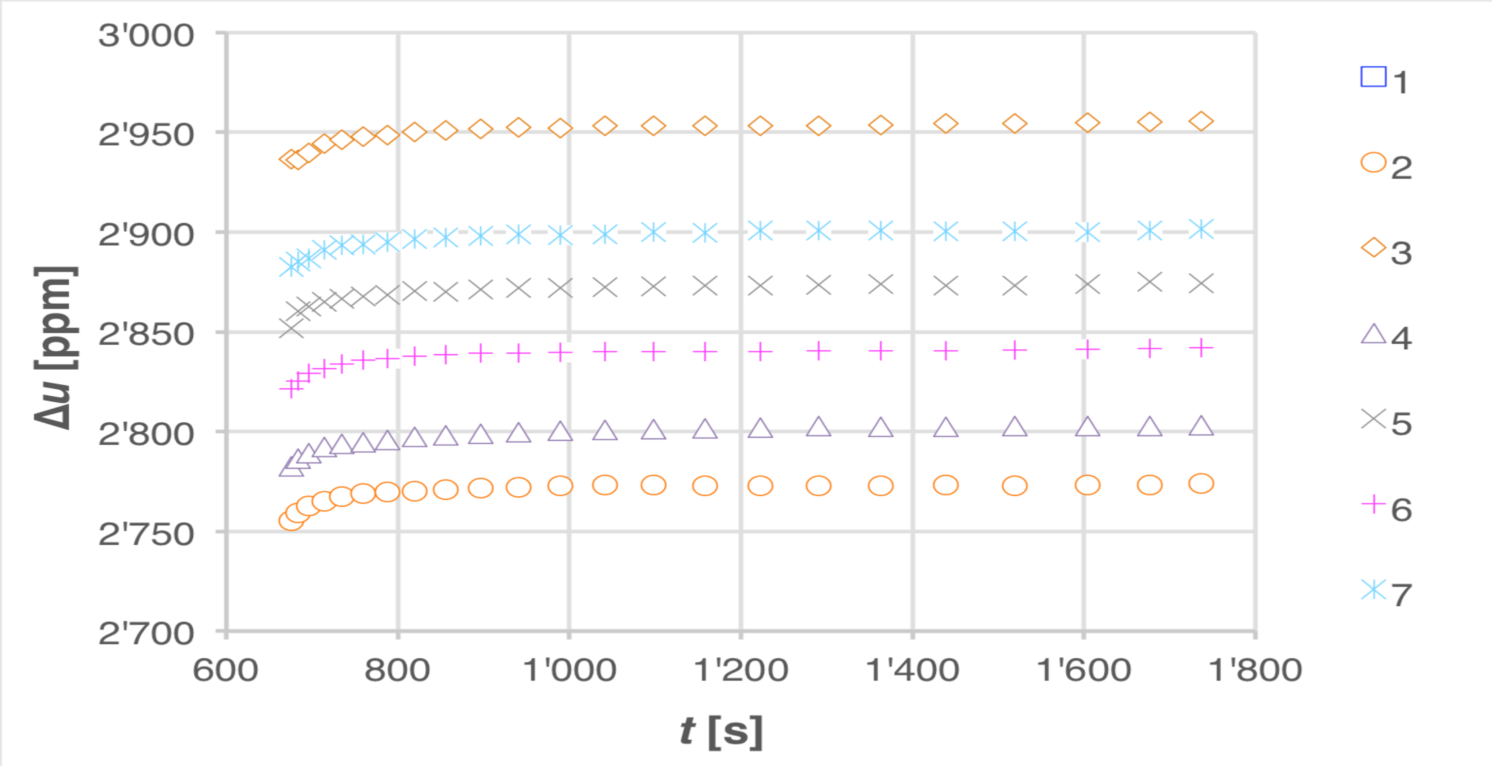


- High signal level, quite consistent
- Linear signal, ~20 ppm/mN
- Slight drift?

B – 90 μm 3YSZ – layout 2 (loading)



- High signal level, quite consistent
- Linear signal, ~20 ppm/mN
- Slight drift?

B – 90 μm 3YSZ – layout 2 (unloading)

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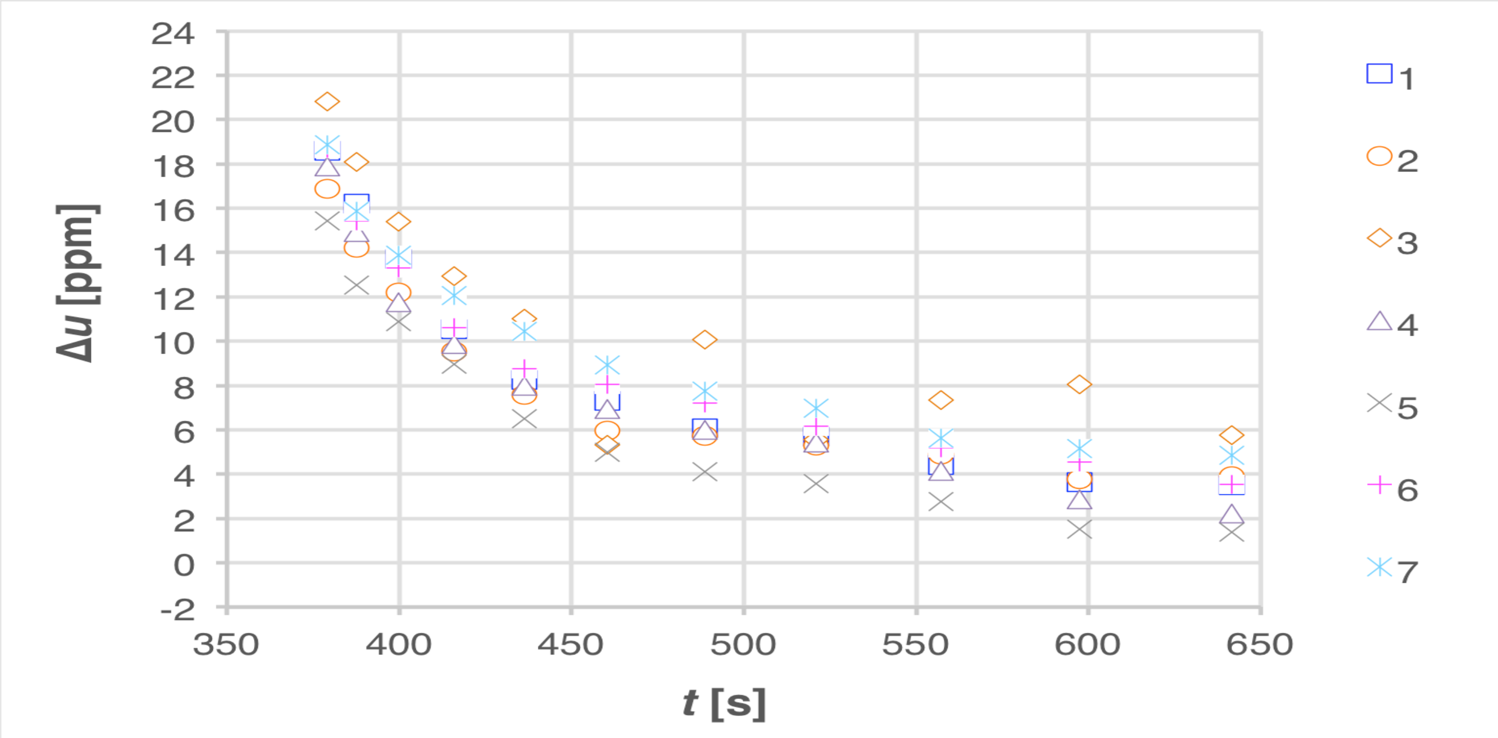

- High signal level, quite consistent
- Linear signal, ~20 ppm/mN
- Slight drift?

B – 90 μm 3YSZ – layout 3 (unloading)

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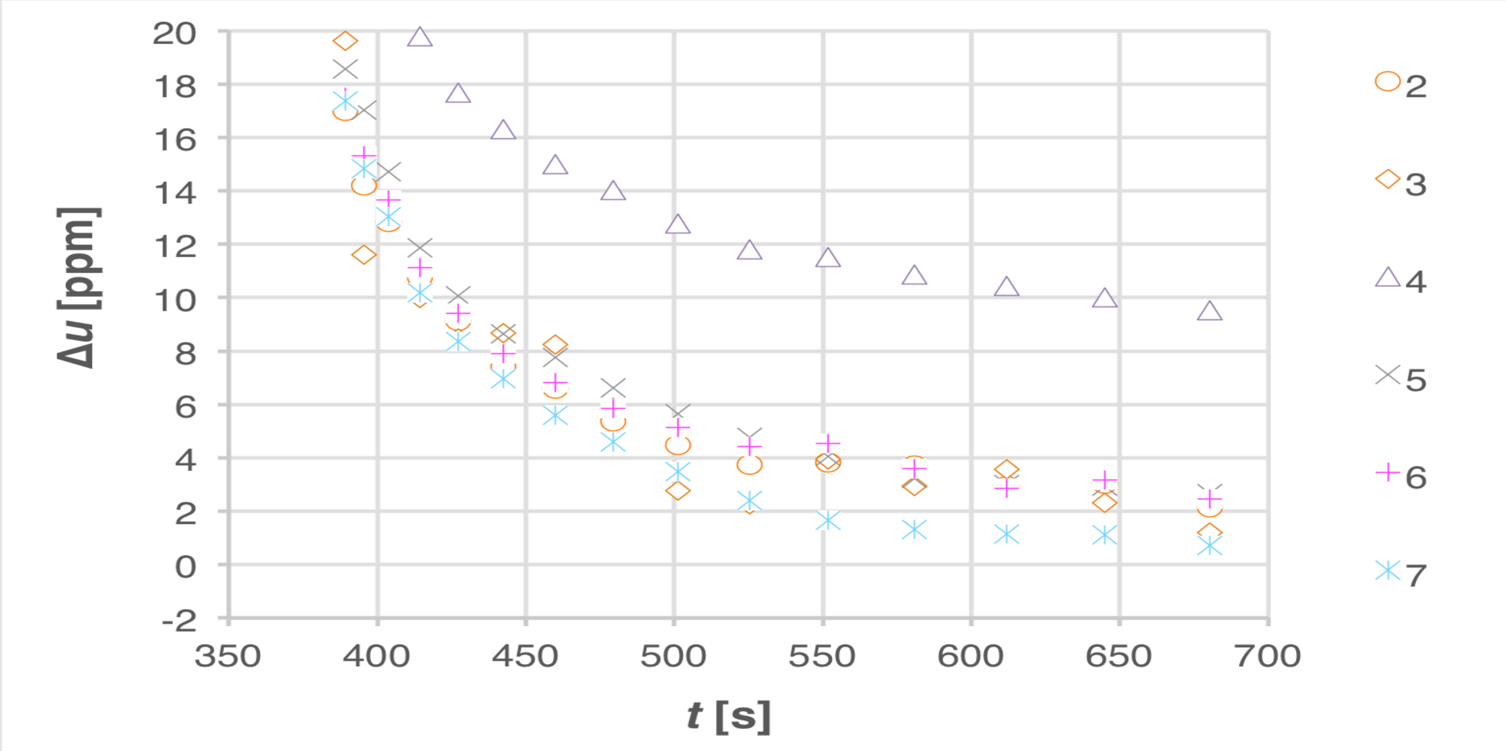
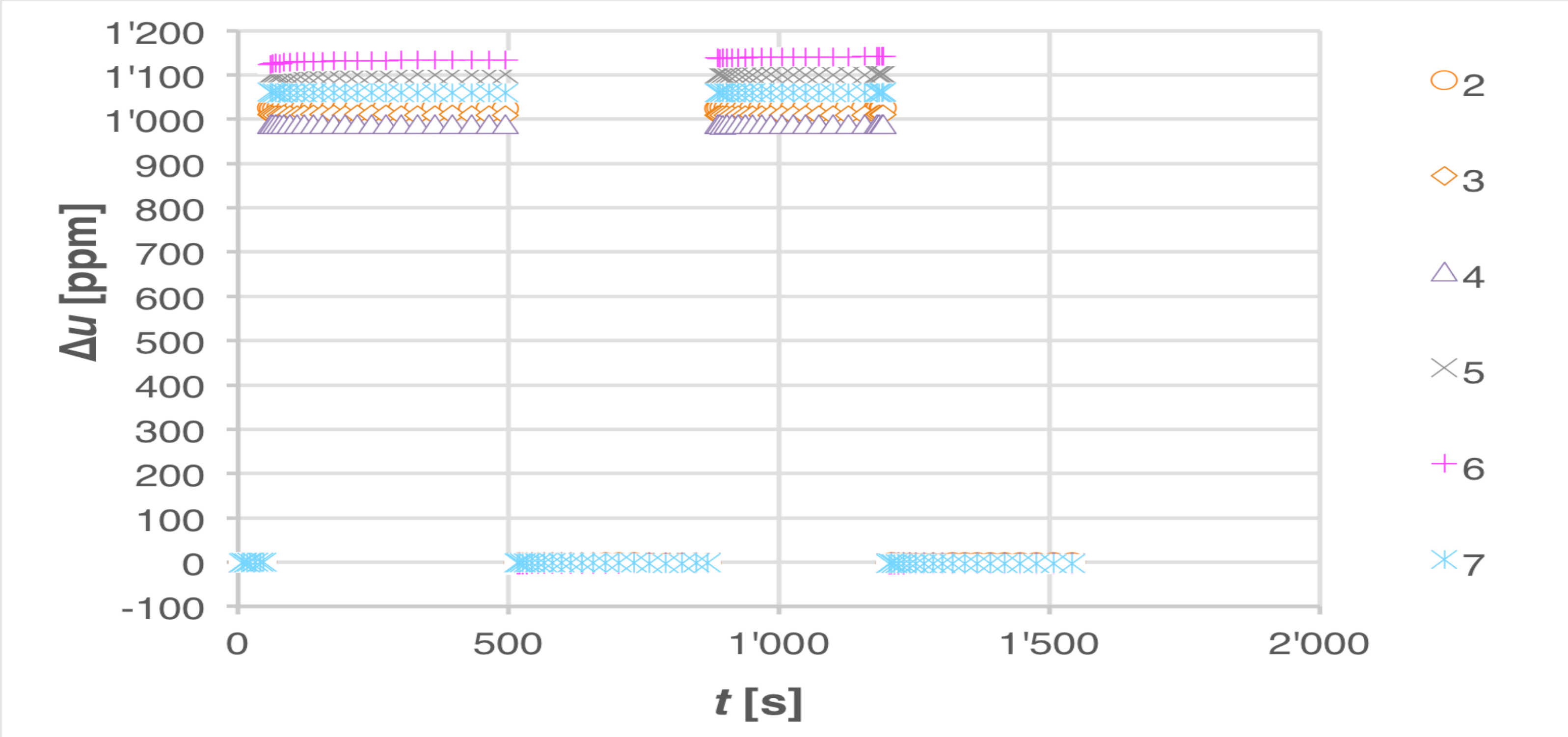


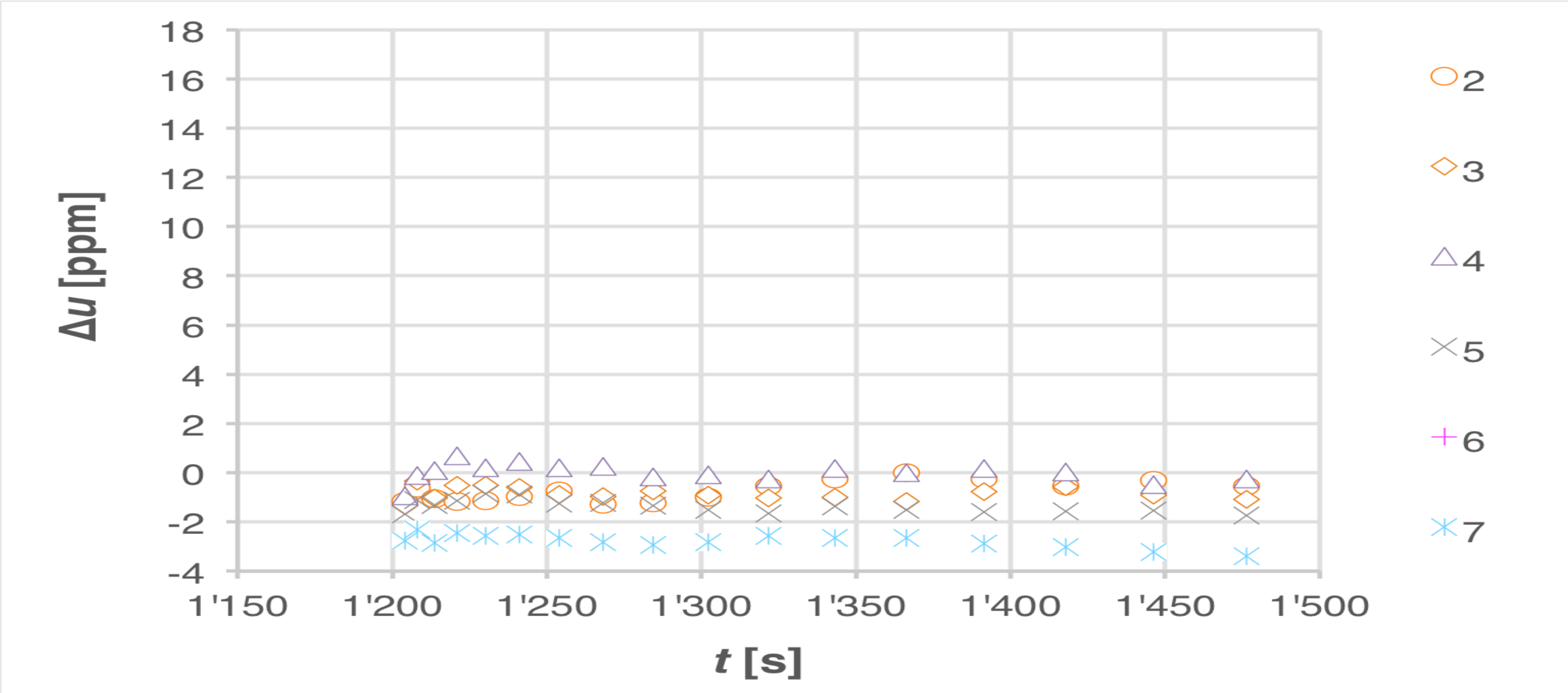
- Apparent drift similar for both layouts

D – 150 μm Al_2O3 – layout 2



- Expected magnitude vs 90 μm YSZ (B) & 400 μm Al_2O_3 (C)
- Very clean signal

D – 150 μm Al_2O3 – layout 2 (unloading)



- Expected magnitude vs 90 μm YSZ (B) & 400 μm Al_2O_3 (C)
- Very clean signal

H2 – 180 μm LTCC HL2000 – layout 3

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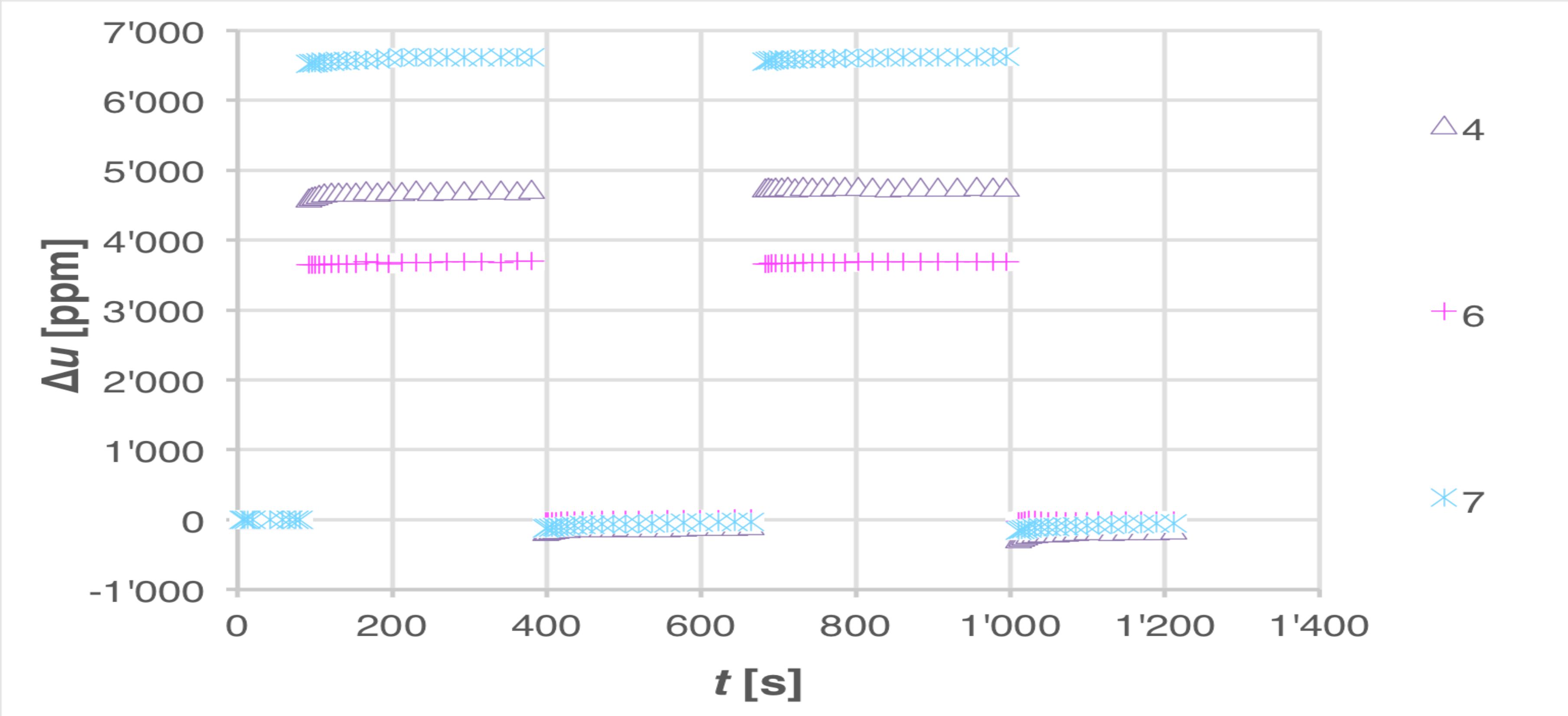
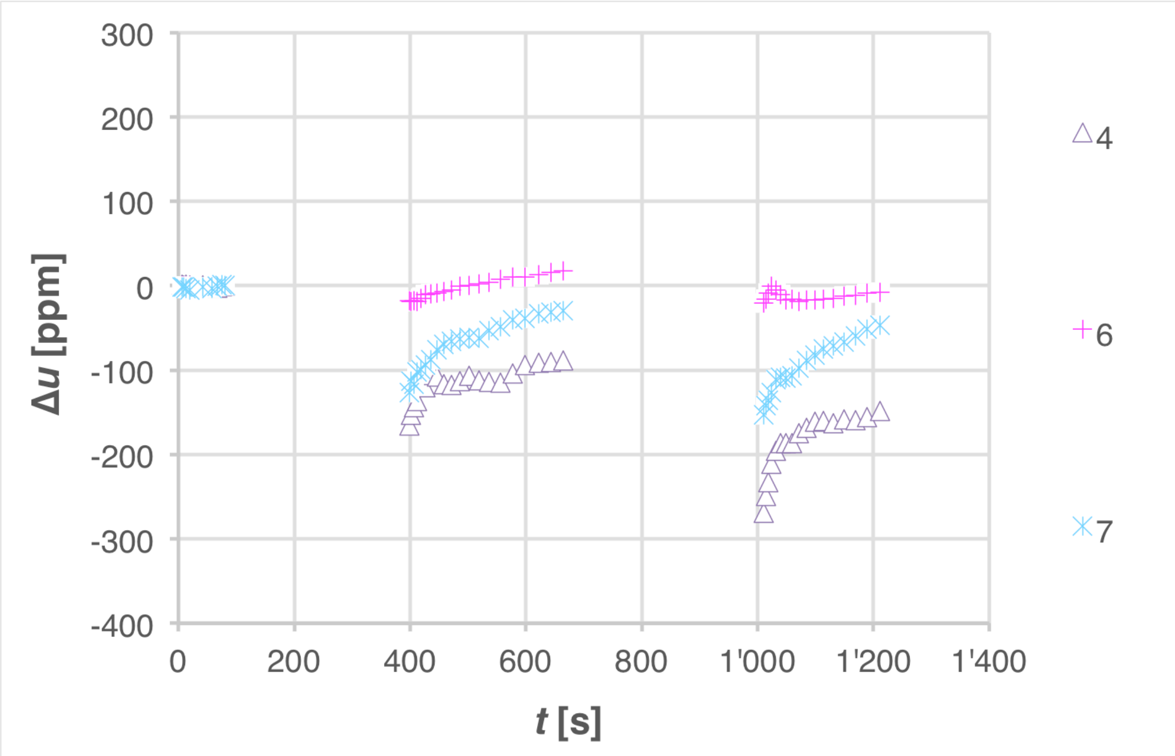


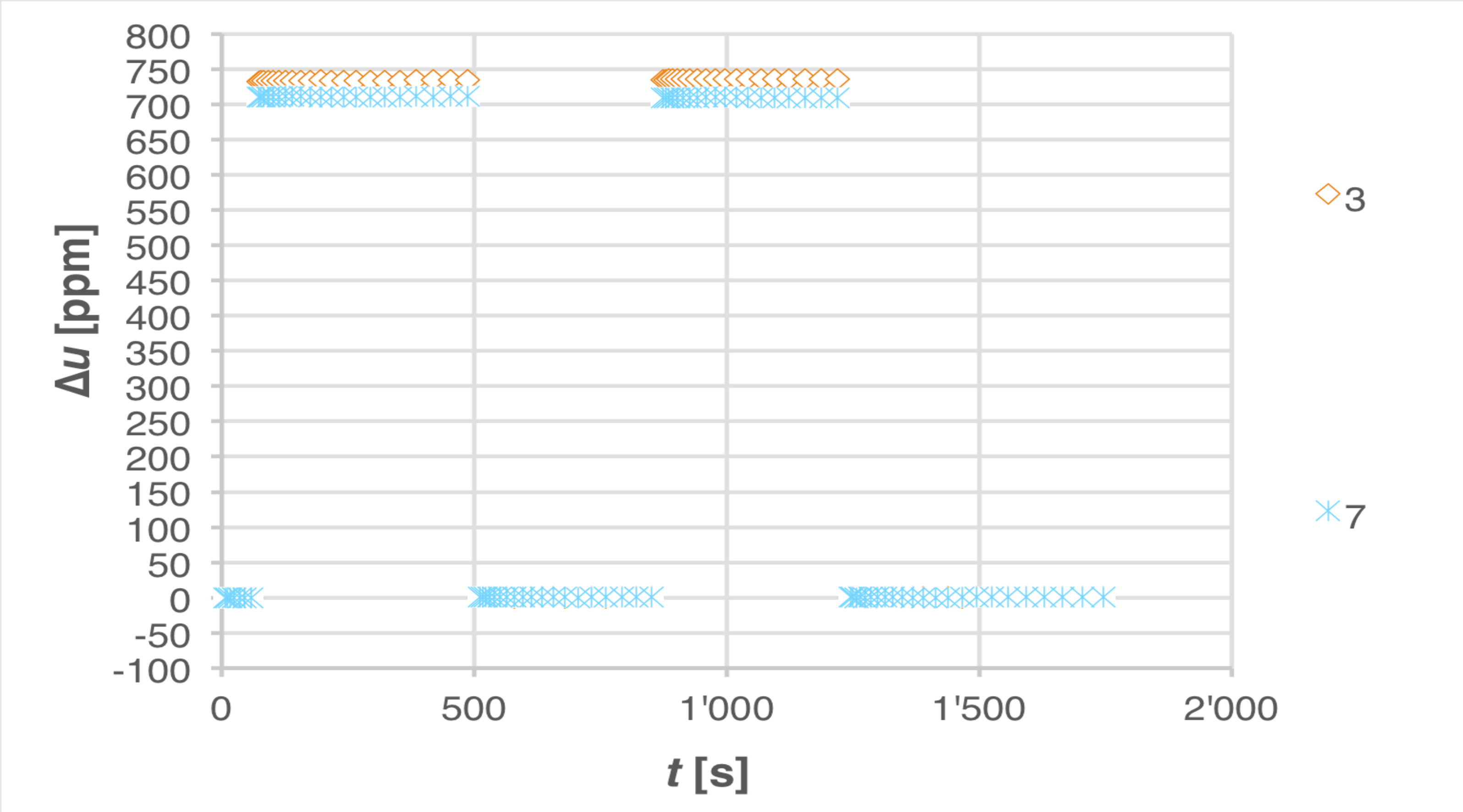
- High signal, large variations
- Visible zero drift (not anelastic) – damage ?
- No apparent dependence on layout

H2 – 180 μm LTCC HL2000 – layout 3



- High signal, large variations
- Visible zero drift (not anelastic) – damage ?
- No apparent dependence on layout

H3 – 270 μm LTCC HL2000 – layout 2



- Thicker: mostly similar behaviour
- Some "clean" samples

H3 – 270 μm LTCC HL2000 – layout 2

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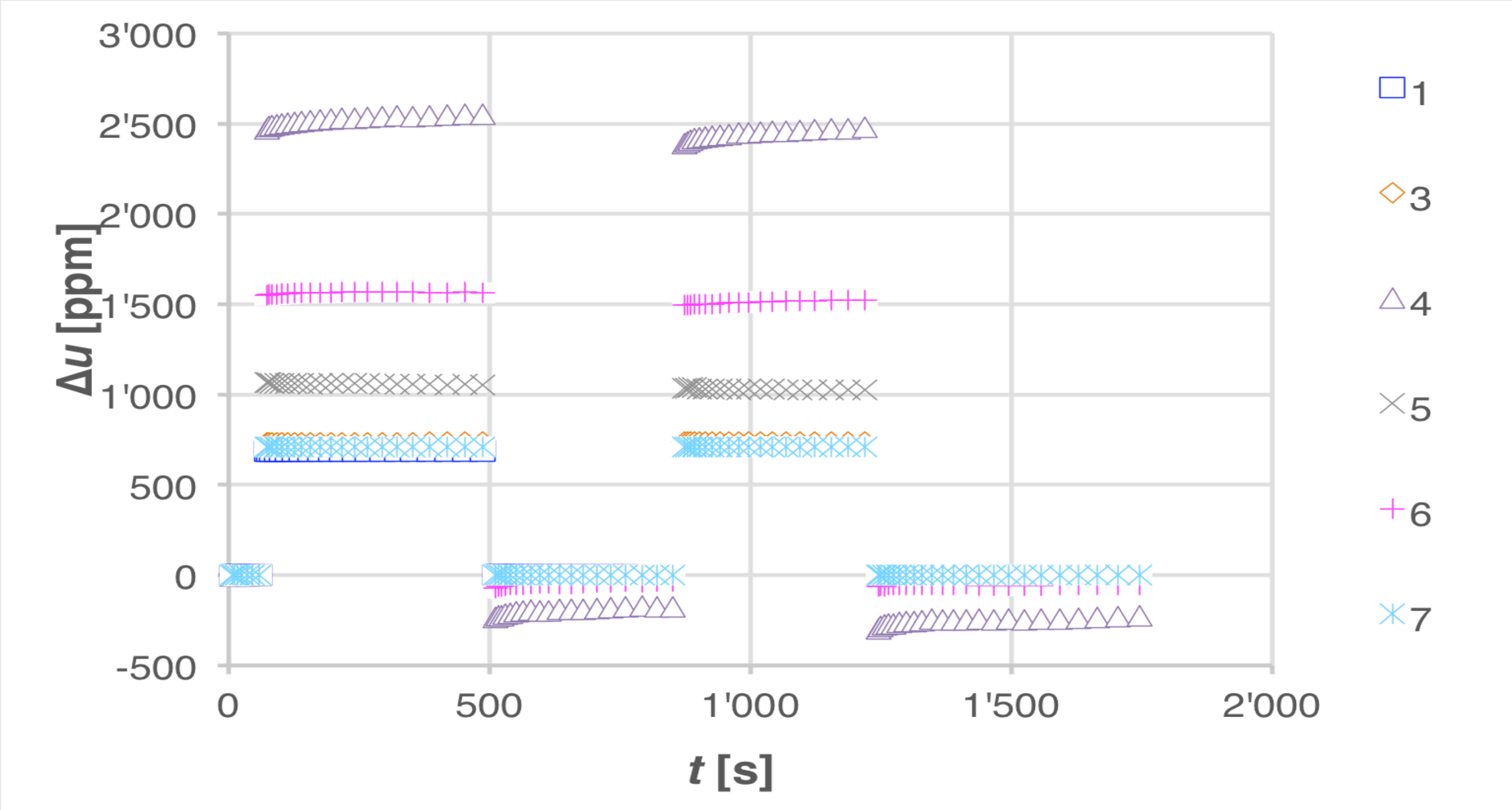
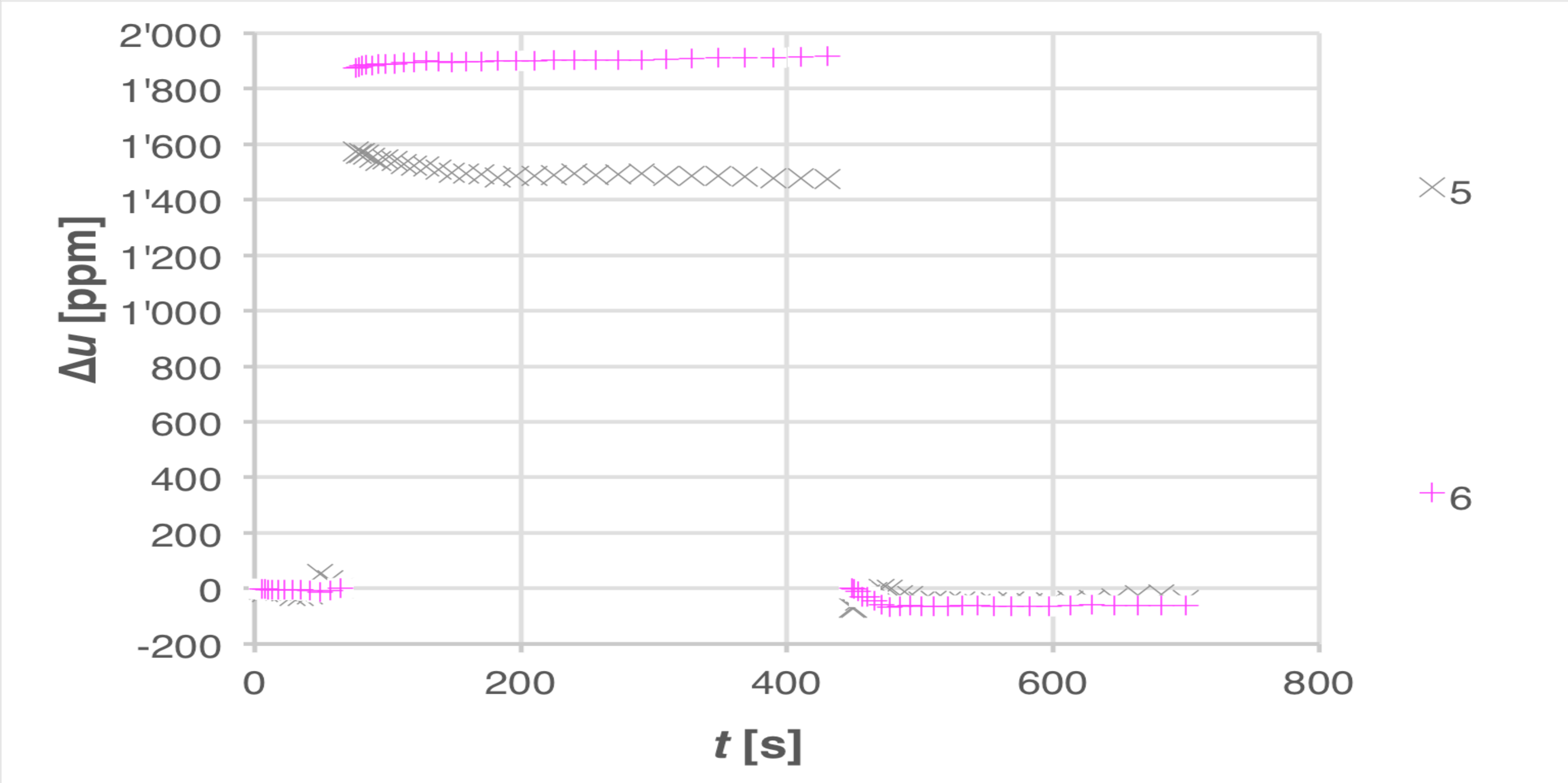


- Thicker: mostly similar behaviour
- Some "clean" samples

I2 – 270 μm LTCC DP951 – layout 2



- Different LTCC : similar behaviour

I2 – 270 μm LTCC DP951 – layout 2

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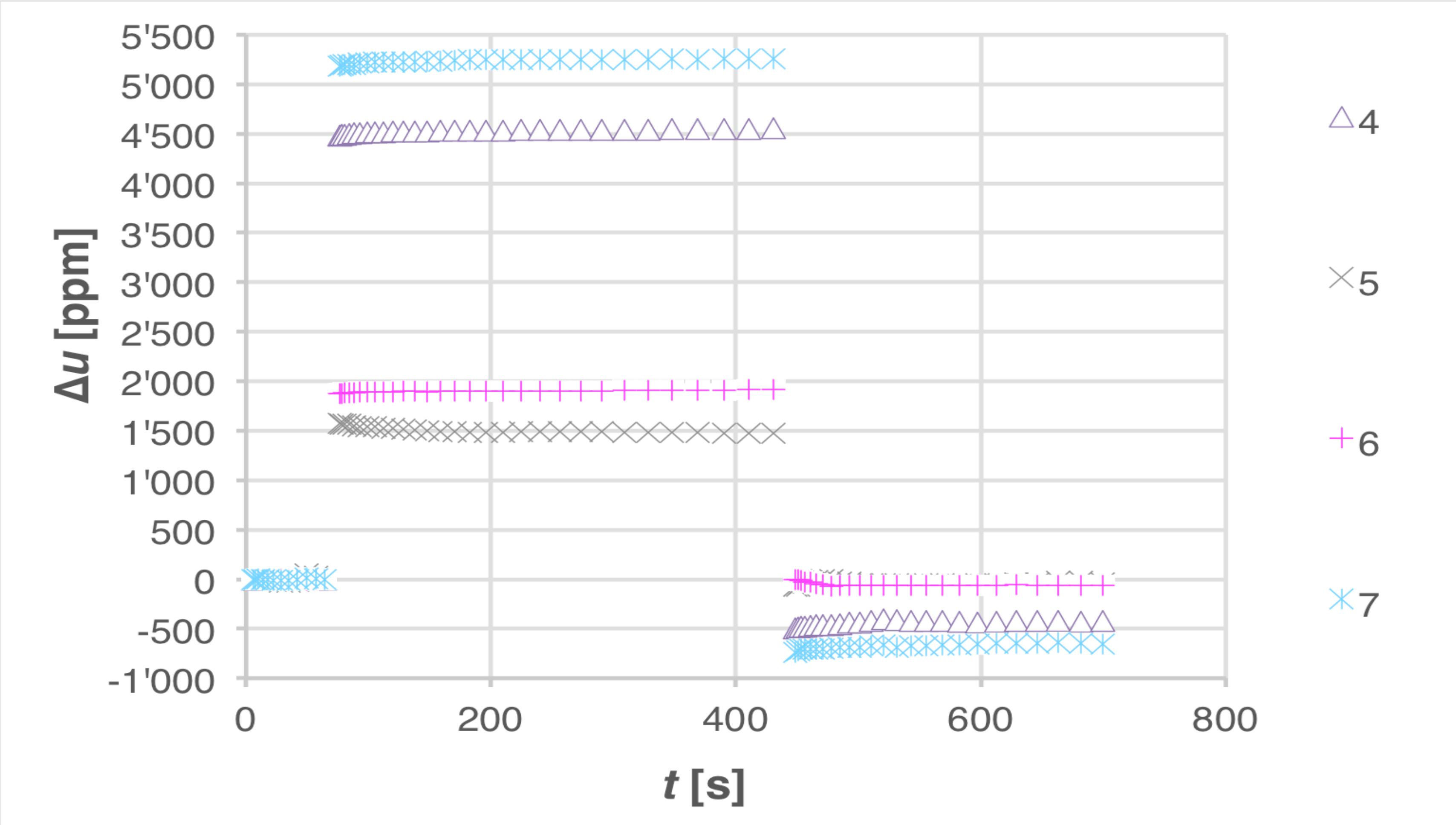
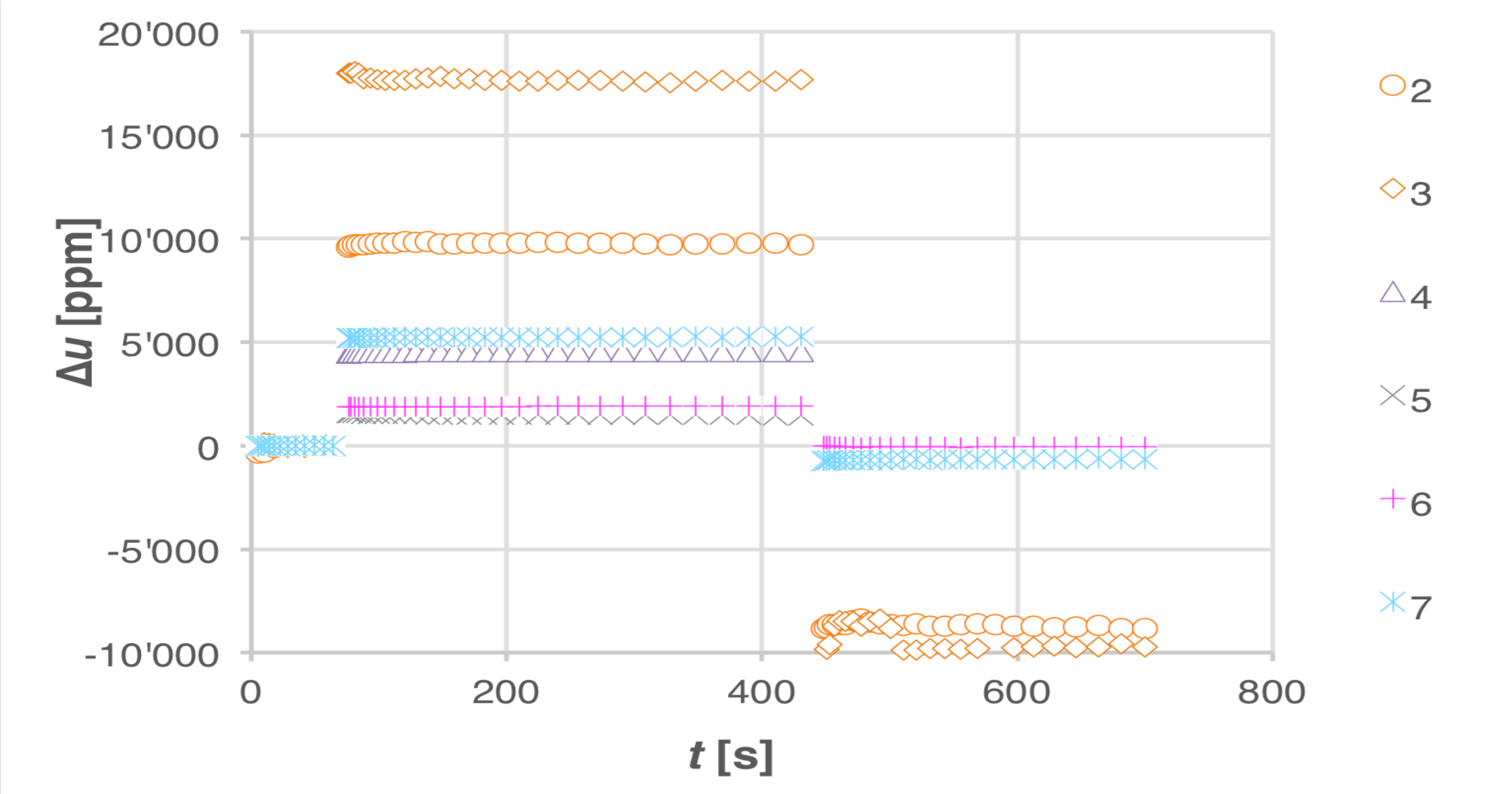


- Different LTCC : similar behaviour

I2 – 270 μm LTCC DP951 – layout 2



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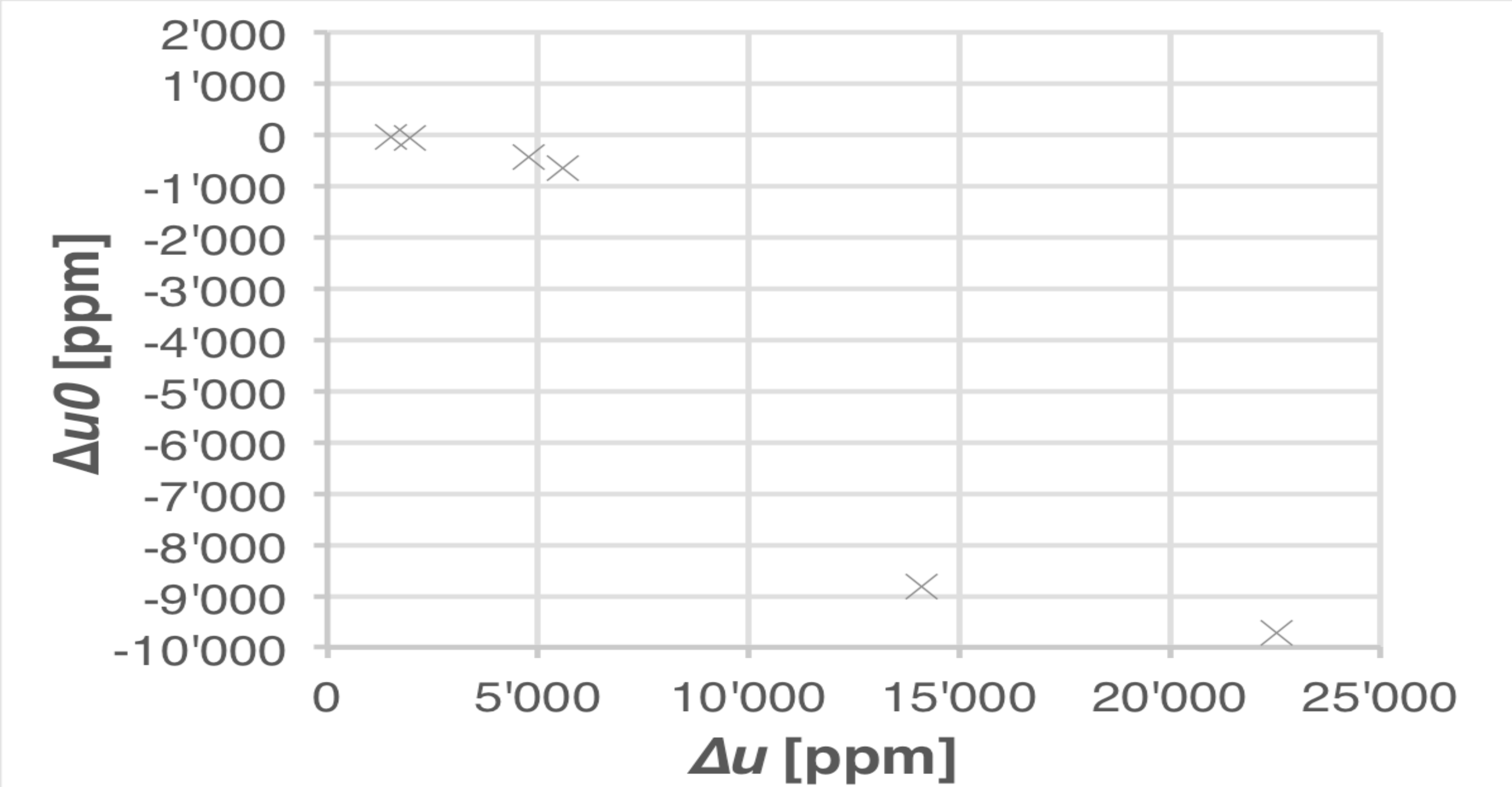
I2 – 270 µm LTCC DP951 – layout 2



- Increase of drift with apparent signal -> anomaleous

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Conclusions

- Thin cantilevers on many substrates, including LTCC
- Same manufacturing process:
  - Post-fired, single-side
  - Two-layer, piezoresistors on thick-film dielectric
  - Resistors allowed above buried tracks (variant 3) or not (variant 2)
- Results:
  - Al_2O_3 / ZTA : clean signal, thermal drift not a problem
  - 3YSZ : possibly slight anelastic drift & thermal effects due to very low thermal conductance of cantilever
  - LTCC : signal mostly unstable (some clean samples)
    - **Cause ? Low thermal expansion ?**

Outlook

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- Elucidate drift mechanism on LTCC
  - Perform progressive loading tests
  - Check for resistor damage
  - Try on LTCC with high CTE – should avoid instabilities

- Extended analysis of new design
  - Performance & economics vs existing cantilever
  - Sensitivity to side loads
  - Lowest practical force ranges (deflection, manufacturing…)

The end

Thank you for your attention !