Instituto de Química

EQCM · 6-HOUR SHORT COURSE

MODULE 2

Instrumentation and Experimental Practice

From the EQCM cell to a calibrated, interpretable dataset

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M2 MODULE 2 · LEARNING OBJECTIVES

What you will master in this module

By the end of these two hours, you will be able to:

01

Set up an EQCM experiment — pick the right crystal, electrodes and cell geometry.

02

Calibrate the sensitivity factor C_p experimentally using Faraday's law as the reference.

03

Recognise artifacts (drift, stress, bubbles, temperature) and tell them apart from real signal.

04

Read a combined CV + Δf + ΔD dataset and extract mass-per-electron (M/z) information.

05

Decide when Sauerbrey is enough, and when a viscoelastic model is mandatory.

M2 MODULE 2 · AGENDA

Two hours, five sections

Theory → practice → real data → hands-on

2.1 — 25 min

The EQCM cell

Crystal, electrodes, geometry, cleaning

2.2 — 25 min

Instrumentation

Oscillator vs. impedance, QCM-D, overtones

2.3 — 25 min

Calibration & validation

C_p from Faraday, artifacts, sanity checks

2.4 — 30 min

Data analysis & live demo

CV + Δf + ΔD, M/z, viscoelastic models

2.5 — 15 min

Hands-on exercise

Read a real EQCM trace in small groups

SECTION

The EQCM cell

2.1

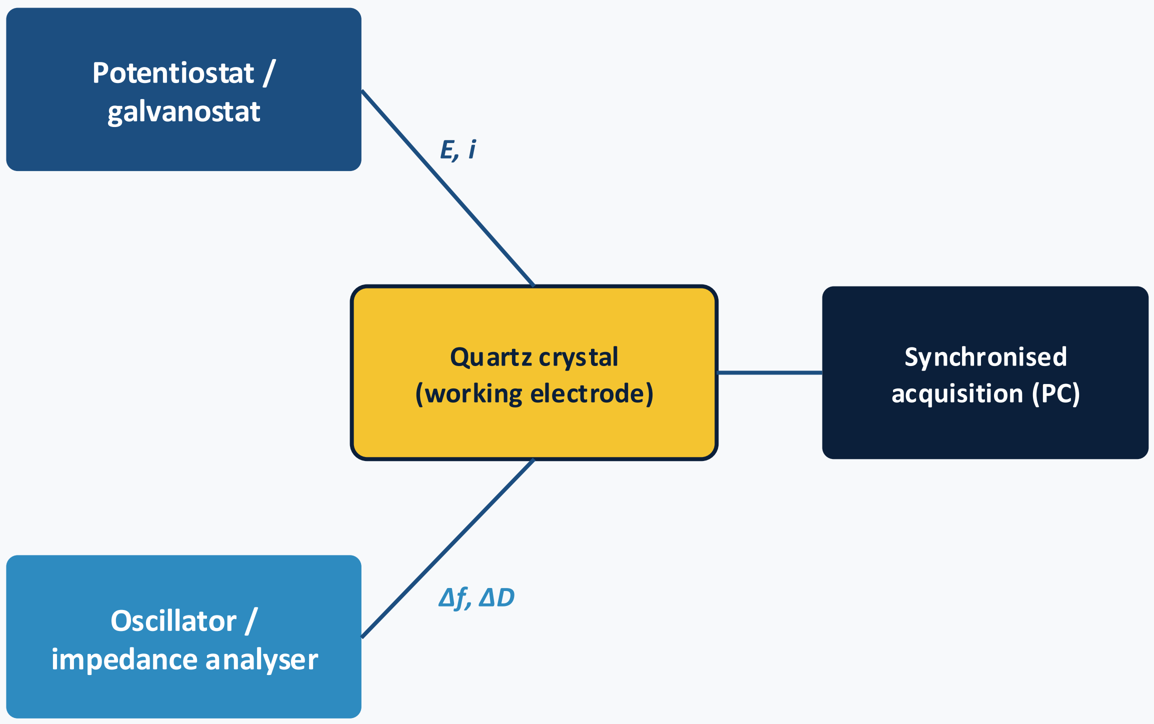
25 min

Key idea of this section

Above all, an EQCM cell is a three-electrode cell. What changes is that the working electrode is a quartz disk vibrating at 5–10 MHz — so anything that couples mechanically to the crystal (sealing, flow, roughness, cleanliness) becomes an experimental variable.

Anatomy of an EQCM setup

Two synchronised acquisition chains share the same crystal



Key points

Double role.

The quartz disk is both the working electrode and the mass sensor.

Two channels.

Electrochemistry reads E and i; oscillator reads Δf and ΔD.

Common time base.

Without synchronisation you cannot correlate features.

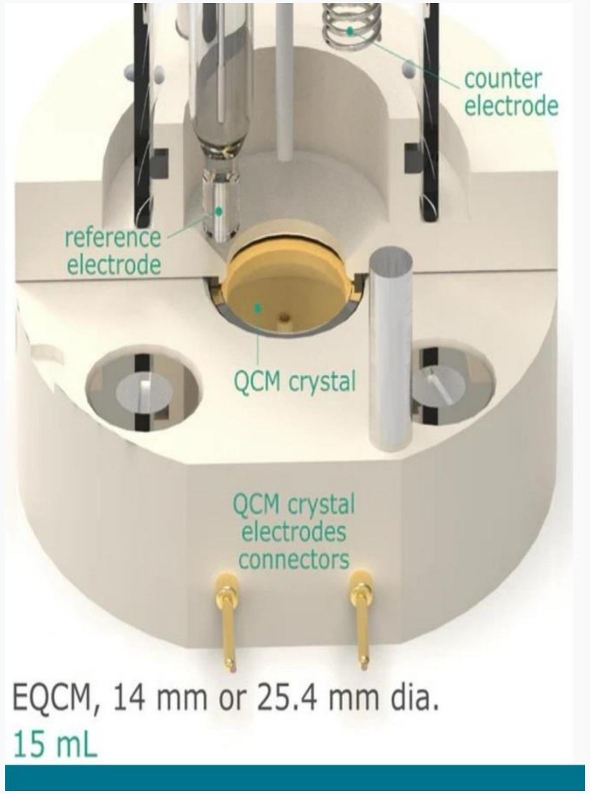
Floating grounds.

Electrochemical and piezoelectric grounds must not form a loop.

2.1 THE EQCM CELL · REAL HARDWARE

What the cell actually looks like

A commercial EQCM cell: crystal, counter and reference electrodes share one small volume



Cutaway of a 15 mL EQCM cell, 14 / 25.4 mm crystal.

What the labels mean

Counter electrode

A wire or coil positioned symmetrically around the working electrode to keep current distribution uniform.

Reference electrode

Placed close to the crystal without blocking flow or shading the active area.

QCM crystal

The gold disk at the bottom of the well — simultaneously the working electrode and the mass sensor.

Crystal electrode connectors

Feed the oscillator / impedance analyser signal to the back face of the crystal.

Choosing the crystal coating

The metallic film on top of the quartz is your working electrode

Au

Gold

Default choice. SAMs, biosensors, metal electrodeposition, conducting-polymer growth.

Pt

Platinum

Stable in strong acids (H_2SO_4, $HClO_4$). Preferred for H-adsorption and oxide studies.

GC

Glassy carbon

Wide potential window. Useful when Au or Pt would interfere chemically with the analyte.

ox

Oxides (SiO_2, Al_2O_3, TiO_2)

Polyelectrolyte deposition depends strongly on substrate. Pick by surface charge.

Note — the piezoelectrically active area is smaller than the geometric area: only the region where the two gold electrodes overlap actually vibrates.

Flow vs. static cell, and the cleaning rule of thumb

Pick the geometry that fits the question; never skip the cleaning protocol

Flow cell

Good for: layer-by-layer, electrolyte exchange, adsorption kinetics.

Watch out: temperature mismatch with reservoir, bubbles, pressure pulses.

Sealing: Viton O-rings + PTFE channels. Never silicone with organic solvents.

Static cell

Good for: long voltammetric runs, equilibrium and relaxation studies.

Watch out: harder to swap solutions; analyte depletion in small volumes.

Counter electrode: Pt plate often acts as the cell ceiling — volume ≈ 100 µL above sensor.

Cleaning protocol for Au crystals (Easley et al., J. Polym. Sci. 2022)

1. **UV / Ozone** — 10 min →
2. **Alkaline H_2O_2** — 5:1:1 H_2O : NH_4OH : H_2O_2 →
3. **Ultrapure water** — Rinse →
4. **Dry with N_2** — Gentle flow →
5. **UV / Ozone** — 10 min

SECTION

Instrumentation

2.2

25 min

Key idea of this section

Two families of instruments coexist: oscillator-based (Δf only) and impedance / ring-down (Δf + ΔD at multiple harmonics). The architecture you pick decides which questions you can ask.

2.2 INSTRUMENTATION · EVOLUTION

Three generations of EQCM instruments

From the home-built oscillator to multi-harmonic QCM-D

1980s–1990s
Generation 1
Home-built oscillator

What it measures
Fundamental harmonic only.
No dissipation measurement.

✓ **Strengths**
Cheap, fast, ideal for rigid film deposition in air.

⚠ **Limitations**
Loses lock when the film damps strongly.

1990s–2000s
Generation 2
Integrated commercial

What it measures
Δf and motional resistance R_1
on the fundamental harmonic.

✓ **Strengths**
Coupled to potentiostat, validated electronics.

⚠ **Limitations**
Single-harmonic — no depth information.

2000s onward
Generation 3
QCM-D / impedance

What it measures
Δf and ΔD at 1, 3, 5, 7, 9, 11, 13
harmonics simultaneously.

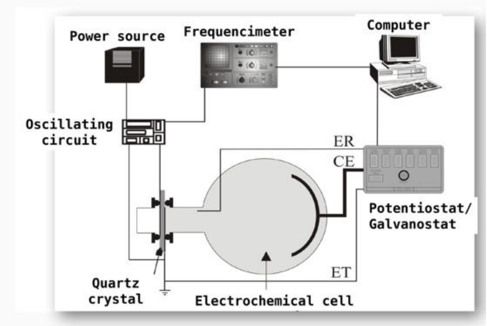
✓ **Strengths**
Works on soft, hydrated films. Depth-resolved.

⚠ **Limitations**
More expensive; slower; needs more analysis.

2.2 INSTRUMENTATION · REAL HARDWARE

What each generation looks like in the lab

From a home-built oscillator to a modern multi-harmonic QCM-D system



Generation 1

Home-built oscillator + electrochemical cell

Generation 2

Stanford Research System — integrated commercial unit

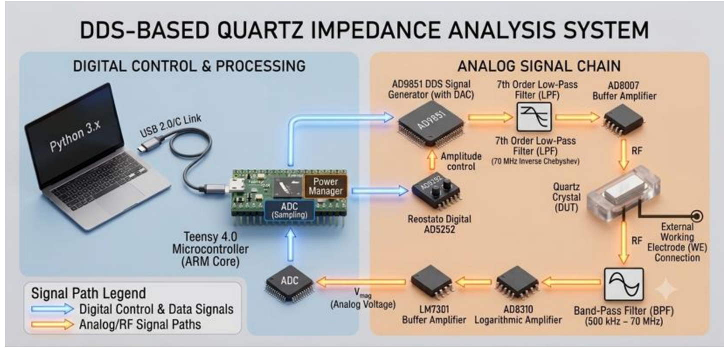
Generation 3

Q-Sense E4 — multi-harmonic QCM-D with electrochemistry module

Photos: R. M. Torresi course materials; instruments shown are illustrative of each generation, not an endorsement.

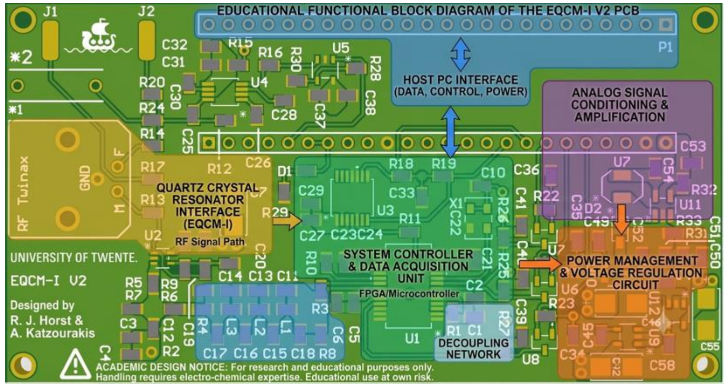
Open-source EQCM-I: democratising the technique

A €200 impedance-based EQCM-I (Horst et al., 2022) reproduces the essentials of instruments costing 10× more



Block diagram

A microcontroller drives a DDS sine sweep through the crystal; a log amp reads the damped response — the same principle as Module 2.2, built for €200.



Printed circuit board

Floating grounds let the EQCM-I run simultaneously with an external potentiostat, exactly like the commercial designs in 2.1.

€176

bill of materials, vs. €1,500–10,000 for commercial EQCM-D/I systems

Cost & validation

Validated on Cu electrodeposition (Cf = 30 ng cm^{-2} Hz^{-1}) and on PANI growth, tracking the dissipation rise as the film softened.

Source: Horst, Katzourakis, Mei & de Beer — HardwareX 12 (2022) e00374. Open-source design (CC BY-SA 4.0); full schematics, firmware and Python DAQ script on OSF.

Oscillator vs. impedance / ring-down

The single most important distinction in this module

Oscillator mode

Active circuit keeps the crystal in resonance continuously

Measures: *Δf only* (sometimes also R_1).

+ Simple, fast (>100 Hz), inexpensive.
+ Robust for metal electrodeposition in air or aqueous media.

– Loses lock with heavily damped (viscous, soft) films.
– No direct viscoelastic information.

Impedance / ring-down mode

Excite a pulse, switch off, listen to the free decay

Measures: *Δf and ΔD* at multiple odd harmonics, near-parallel.

+ Works on heavily damped systems (polymers, biofilms).
+ Multiple harmonics → mechanical tomography of the film.

– More expensive instrument and analysis.
– Lower effective sampling rate; not ideal for fast transients.

QCM-D vs. QCM-I: two ways to reach the same D

Both recover R_1 and L_1 of the BVD circuit — from different measurement strategies

QCM-I · impedance spectroscopy

Step the frequency across the resonance peak

Measures: $D = BW / f_0$ (half-power bandwidth of the peak).

+ Recovers the full BVD circuit (R_1, L_1, C_1, C_0) every sweep.
+ Pairs naturally with the fast impedance-scanning EQCM of this course.

– Must settle at each frequency step — slower acquisition than a decay.
– Accuracy hurt by shunt capacitance C_0 unless compensated in software.

QCM-D · ring-down (“pinging”)

Excite briefly, switch off, fit the free decay

Measures: $D = R_1 / (2\pi f L_1)$ read straight off one decaying sinusoid.

+ One decay gives f and D together — fastest time resolution.
+ Short-circuit mode is largely immune to shunt-capacitance error.

– Historically the pricier instrument class (e.g. QSense QCM-D).
– Needs a fast, clean switch-off — harder to engineer than a sweep.

Why impedance beats oscillators under heavy damping

Blood-viscosity sensing with a single QCM crystal (Liao et al., Sensors 2022)

Reading this comparison

- Oscillating-circuit method: cheap and fast, but only ±5.2% accurate, 5.5% SD — the same “loses lock when damped” weakness flagged for oscillators in 2.2.

- Impedance-analysis method: ±1.8% accurate, 0.9% SD, and needs 7× less sample (2.5 µL vs. 17.5 µL).

- Both fit the same BVD circuit; only the added resistance R_2 is needed to convert the electrical signal into viscosity.

- Lesson for EQCM: whenever the film or liquid load damps the crystal heavily, the extra complexity of impedance / ring-down readout pays for itself.

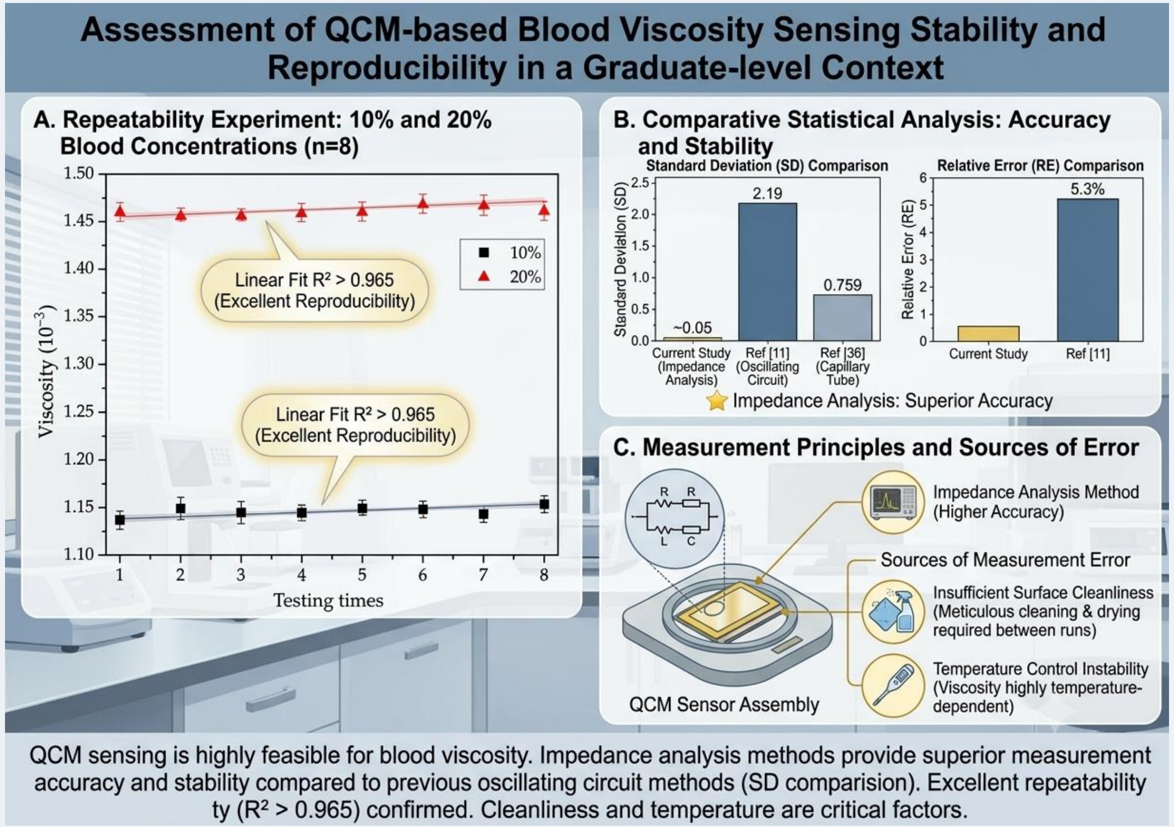
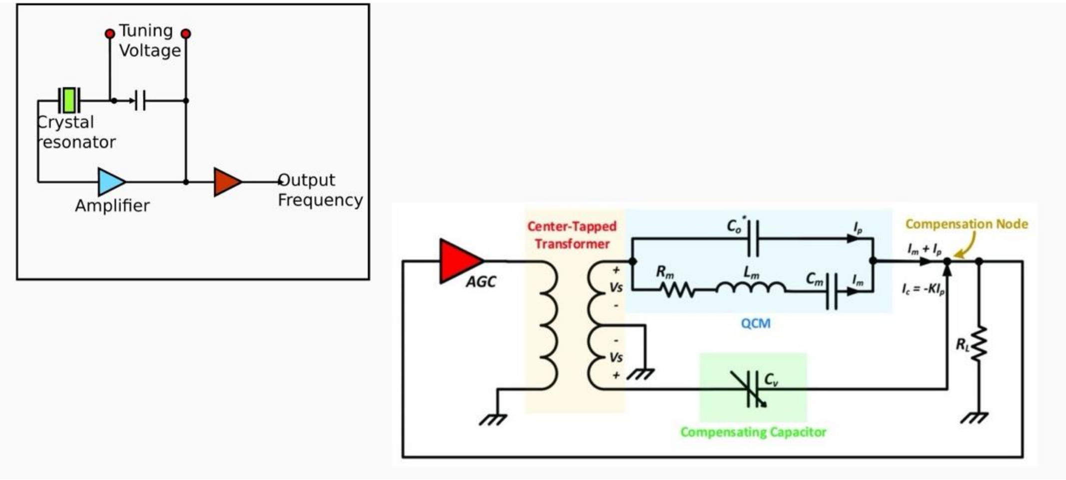


Fig. 4, Liao et al., Sensors 2022 — repeatability (N = 8) of blood viscosity measured by the impedance-analysis QCM method, 10% and 20% concentration

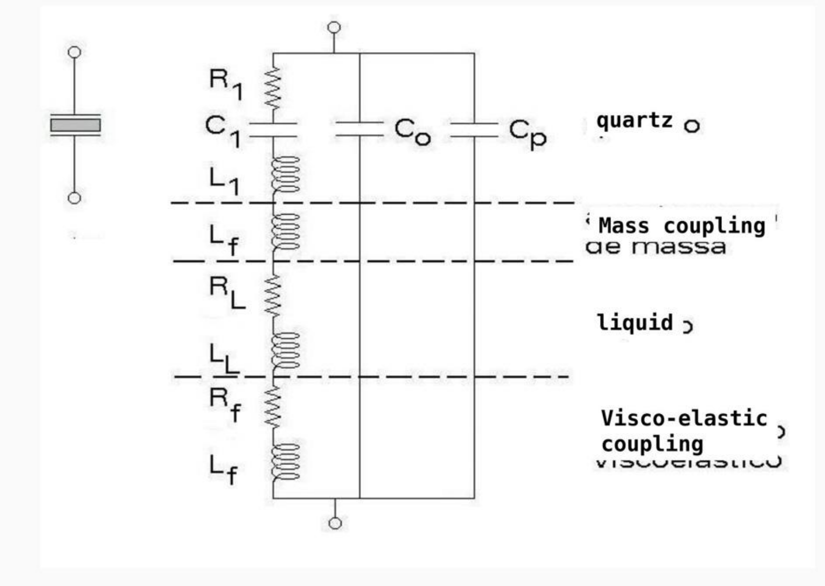
Liao, Ye, Chen, Zhang, Xu & Tan — Sensors 2022, 22, 3804.

What is inside the two architectures

The oscillator drives the crystal directly; impedance mode is read through the BVD equivalent circuit



Crystal oscillator drive circuit

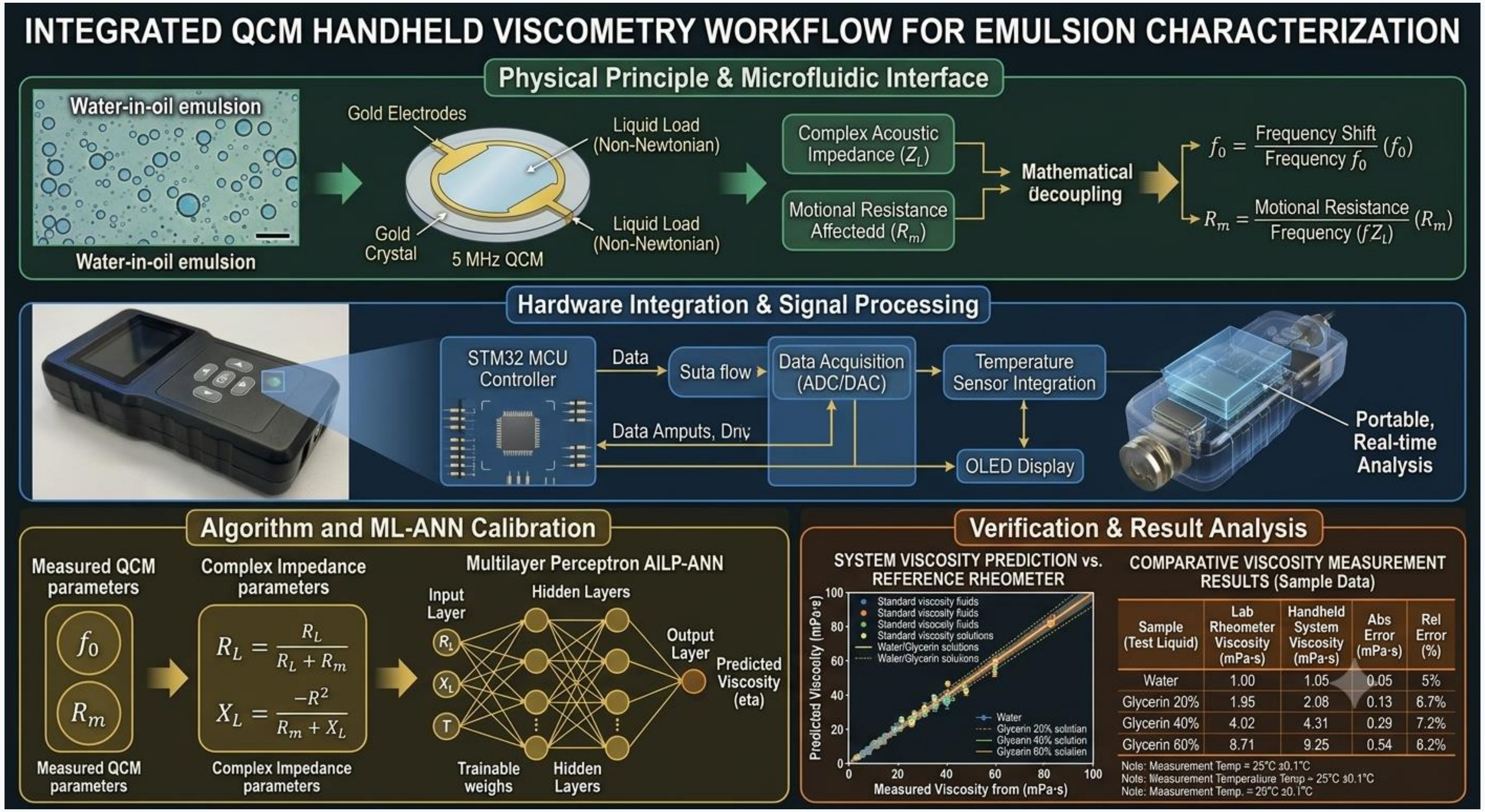


Butterworth–Van Dyke (BVD) equivalent circuit

Same crystal, two readouts. The BVD model splits the response into a static branch (C_0) and a motional branch (R_1, L_1, C_1) whose element values shift with mass, liquid loading and viscoelastic coupling.

Software-defined impedance analysis

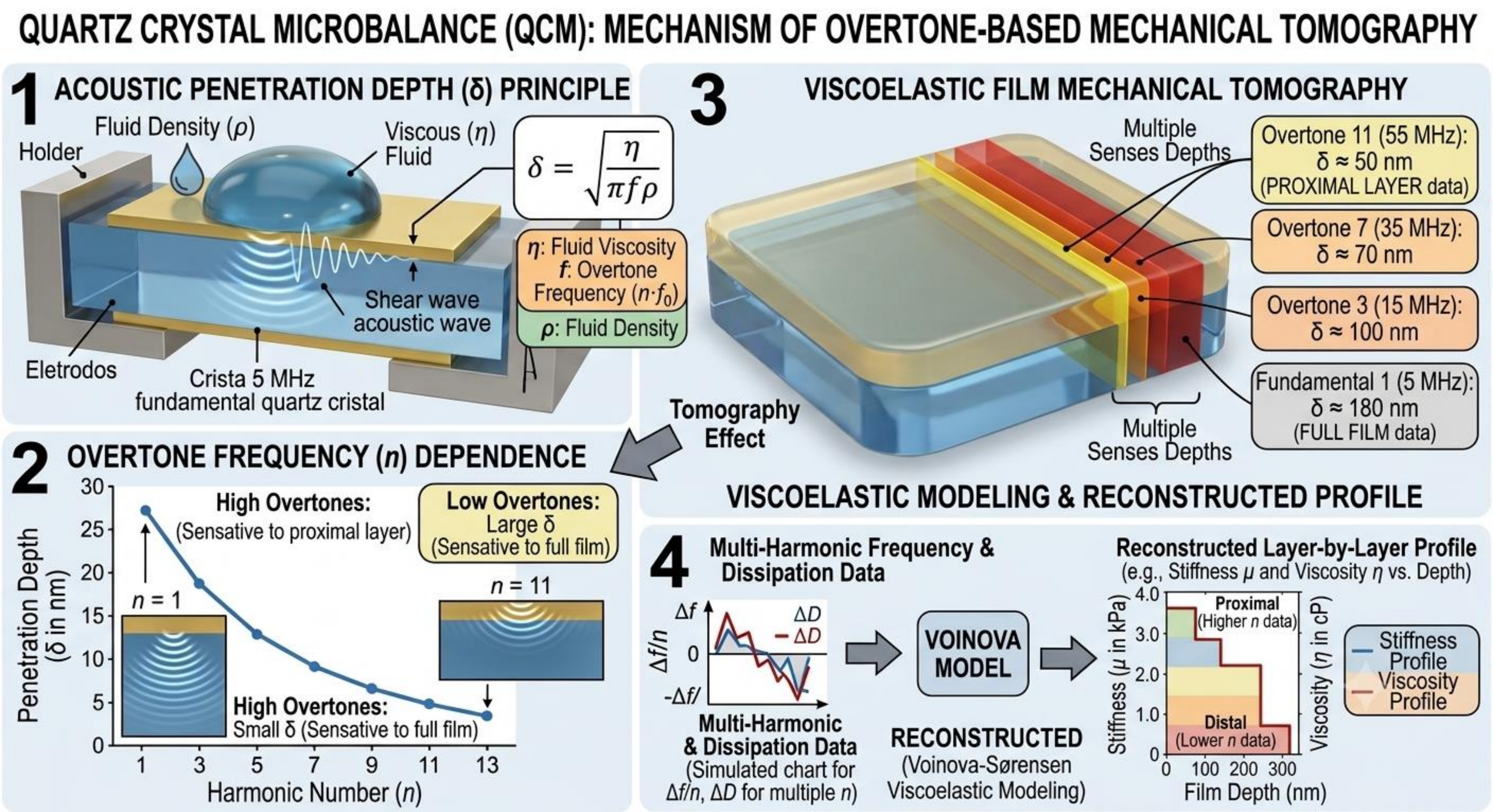
A $200 virtual instrument (Analog Discovery 2 + Python) extracts the full BVD circuit from one frequency sweep



Instead of analog nulling circuits, C_0 is measured live at one low frequency and subtracted algebraically (Burda, Eq. 12) — the same real-time-fitting spirit as the rapid impedance-scanning EQCM discussed next.

Each harmonic probes a different depth

Multi-harmonic data is a mechanical tomography of the film



Reading the harmonics

Always plot Δf_n **/ n.**
If the curves overlap, the film is rigid (Sauerbrey applies).

Exclude n = 1
from viscoelastic fits — edge effects dominate.

Use ≥ 3 harmonics
to fit the Voigt model with reasonable confidence.

Penetration depth
$\delta = (\eta / \pi n f_0 \rho)^{1/2}$ — Easley, eq. 1.

Rapid impedance scanning: fit fast, not just accurately

A Padé rational-function fit turns a full sweep into R_1, L_1, C_1 within tens of milliseconds

Full-spectrum scan time

200 ms

full resonance spectrum

for a 20 kHz band at 0.2 Hz resolution

Scanning only the series resonance frequency narrows this further, to a few ms per point (Wudy et al., Electrochim. Acta 2008).

Why a linear fit beats non-linear here

1. **One point per second, the old way**
   Classical network analysers fit the BVD circuit with slow Levenberg–Marquardt iterations that need good starting guesses.
2. **Padé approximant**
   The raw response is fitted to a rational function that is linear in its coefficients — a single least-squares matrix solve.
3. **44 ms vs. 107 ms**
   Linearising 53,000 points takes 44 ms; an optional non-linear refinement (2 iterations) takes 107 ms and changes χ^2 by <0.01%.
4. **500,000 points per second**
   The electronic sweep rate is fast enough that resolution — not hardware — becomes the limiting choice.

SECTION

Calibration and validation

2.3

25 min

Key idea of this section

The theoretical sensitivity K is only a starting point. With your crystal, your cell and your electrolyte you must measure C_p experimentally before trusting any mass number. Faraday's law is your gold standard.

Why the theoretical K is not enough

Real C_p can differ by 5–10% between nominally identical crystals

Theoretical (Sauerbrey)

K

≈ 56.6 ng cm^{-2} Hz^{-1}

for a 5 MHz AT-cut crystal

Useful as an order-of-magnitude check — but never as a final calibration in liquid.

What actually changes C_p in real life

1. **Electrode geometry**
   The piezoelectrically active area is smaller than the geometric area; only the overlap region vibrates.

2. **Gaussian amplitude distribution**
   Mass deposited at the centre weighs more than mass at the edges (radial sensitivity profile).

3. **Surface roughness**
   Liquid trapped in microcavities adds "parasitic" mass that scales with roughness.

4. **Hydrostatic pressure & temperature**
   Both shift the resonance condition; AT-cut is only T-stable around 25 °C.

Calibrating against Faraday's law

Silver or copper bulk deposition is the standard reference experiment

1 Prepare

$AgNO_3$ ≈ 5 mmol L^{-1} + 0.1 mol L^{-1} supporting electrolyte.

2 Deposit

Step to overpotential (−0.2 V vs. Ag/AgCl). Diffusion-controlled regime.

3 Integrate i

Get total charge Q from ∫ i dt during deposition.

4 Compute Δm

Faraday: $\Delta m = Q \cdot M / (n \cdot F) = Q \times 1.118$ mg C^{-1} for Ag.

5 Get C_p

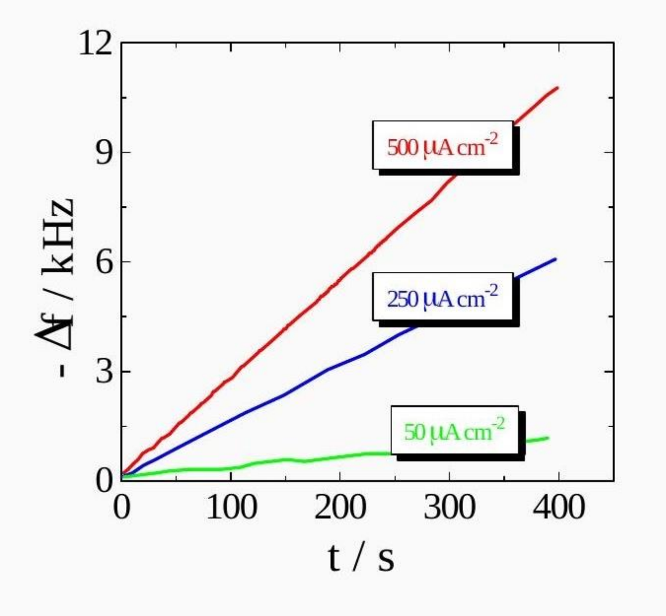
$C_p = \Delta f / \Delta m$. Repeat at two or three charge levels.

Worked example · Bismuth

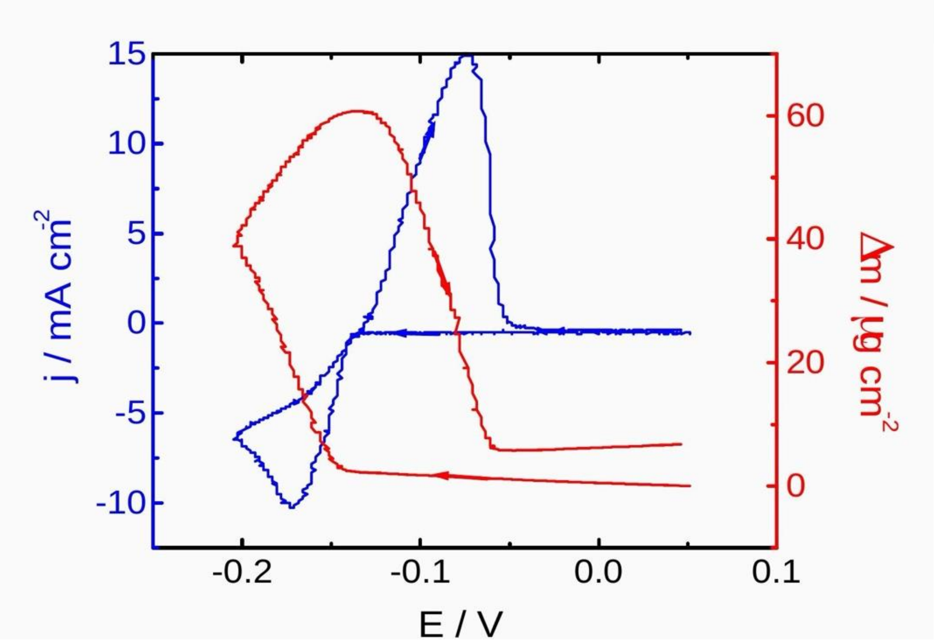
For $Bi^{3+} \rightarrow Bi$: n = 3, M = 208.98 g mol^{-1}. Theoretical $\Delta m / \Delta Q = 208.98 / (3 \times 96\,485) = 0.722$ mg C^{-1} → **720 µg C^{-1}**. Compare with the experimental slope of Δm vs. ΔQ during voltammetry of a Bi film. Agreement within 5–10% → Faradaic efficiency ≈ 100% and the calibration is valid.

Faraday calibration, from real experiments

Silver and bismuth depositions both confirm the Δf–Δm relationship



Ag deposition: −Δf vs. t at three current densities



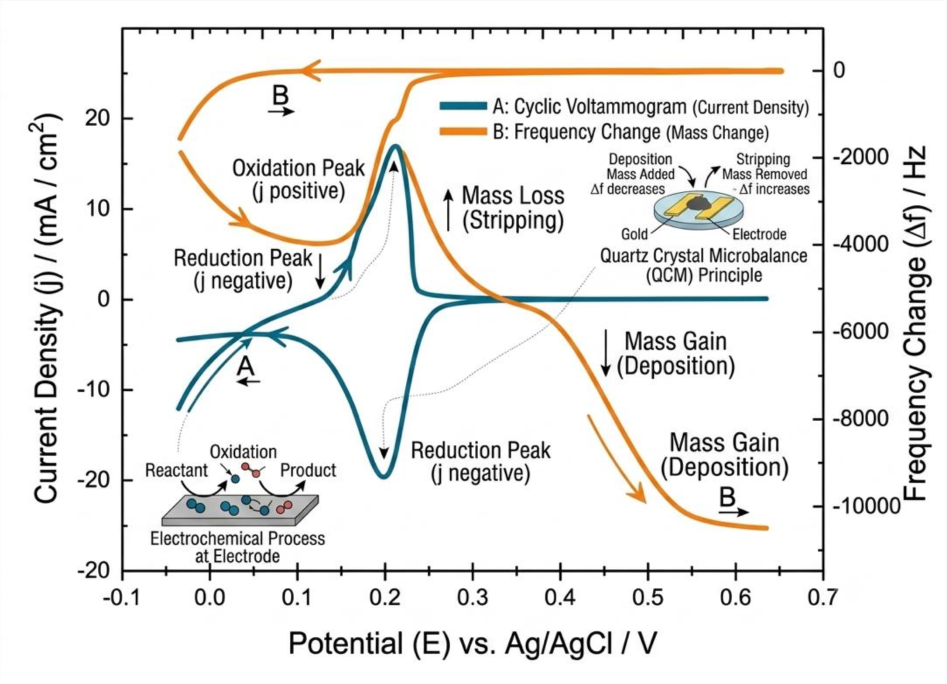
Bismuth: CV (blue) and Δm (red) vs. E

Measured Bi Δm/Δq: 752–975 µg C^{-1} across electrolytes, vs. 720 µg C^{-1} theoretical — within the 5–10% window used to validate Cf.

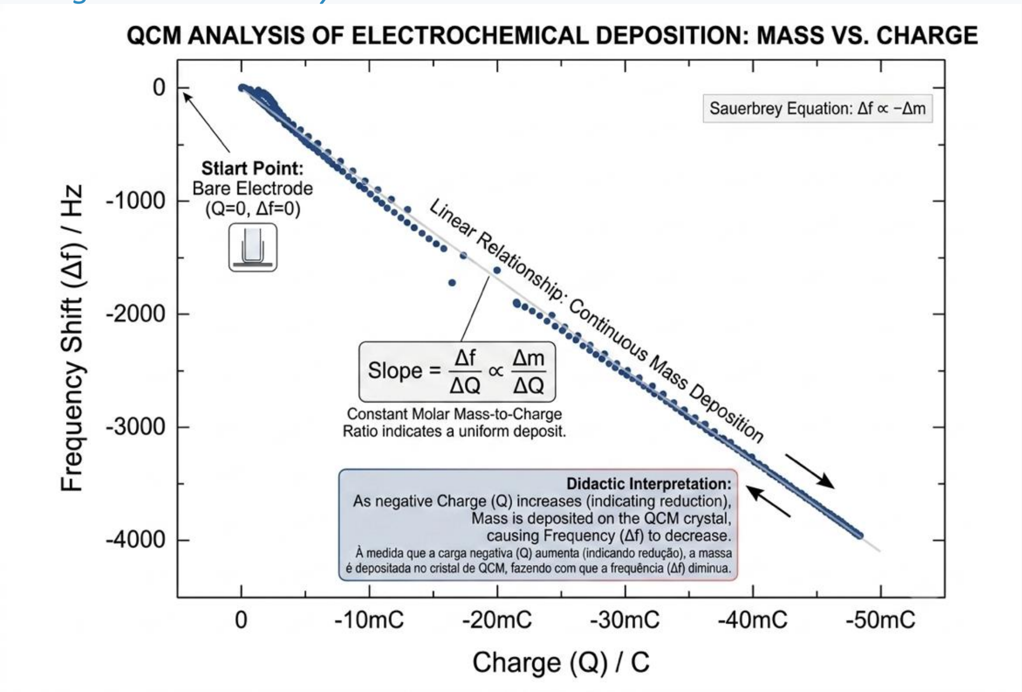
2.3 CALIBRATION · CROSS-CHECK

Cross-check: impedance-scanning EQCM confirms Sauerbrey

A fast impedance-scanning EQCM (Wudy et al., 2008) calibrated on Cu deposition agrees with theory to 0.35%



Cu deposition/dissolution: CV and Δf vs. E



Calibration slope: Δν vs. charge Q

Measured C_p = 246 Hz/µg Cu (slope 81.1 kHz/C, cathodic/anodic within 0.35%), vs. 228 Hz/µg from the theoretical Sauerbrey C_p — a cross-check on an entirely different instrument architecture from the Faraday calibration above.

Common artifacts — and how to spot them

If you cannot rule out an artifact, you cannot trust the mass

Liquid contact

Δf ≈ 1.5–2.0 kHz drop just by immersing in water.

Remedy. Always run a baseline in the working electrolyte.

Temperature drift

Cross 25 °C → Δf drifts 1–2 Hz min^{-1}.

Remedy. Equilibrate the cell for 15–20 min; spec: < 0.5 Hz h^{-1} (air).

Mounting stress

Tight screws bend the crystal; Δf without mass change.

Remedy. Tighten only to fingertight; check Q after mounting.

Bubbles

Sudden Q drop, noisy signal on all harmonics.

Remedy. Degas the solution; equilibrate flow to cell T.

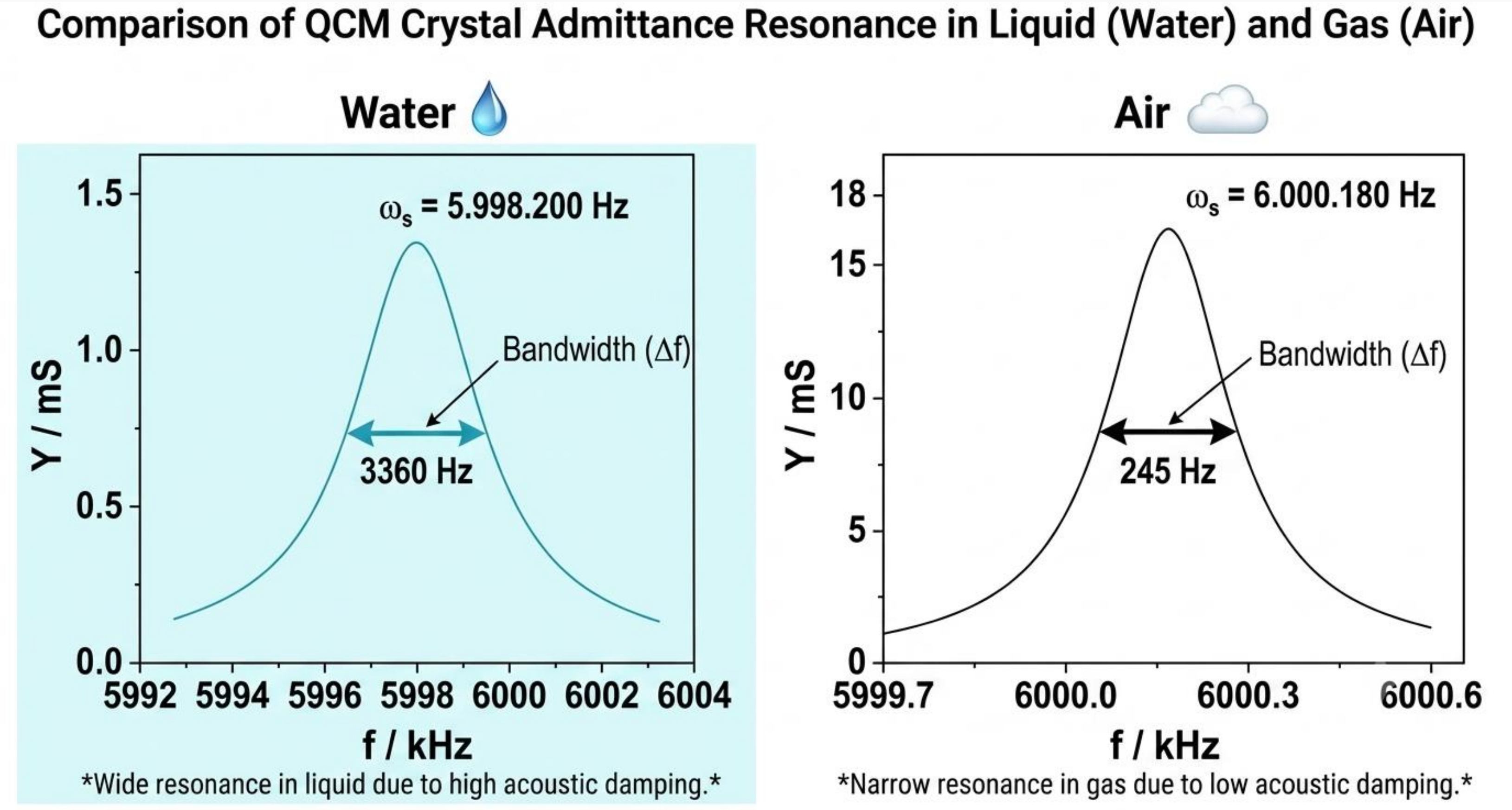
Pre-experiment sanity checks

1. Clean crystal in air for 15–20 min: drift should be < 0.5 Hz h^{-1} (Q-Sense spec).
2. Same crystal in working electrolyte: drift < 1.5 Hz h^{-1}.
3. Blank cycle without analyte: Δf response should be flat.
4. Reproducibility: three nominally identical crystals must give C_p within 5–10%.

2.3 CALIBRATION · REAL ARTIFACT DATA

The liquid-contact artifact, quantified

Immersing the same crystal in water shifts and broadens the resonance dramatically



Linewidth grows from 245 Hz in air to 3360 Hz in water (~14×) — the same crystal, only the medium changed. This is exactly the kind of shift the “liquid contact” artifact check is designed to catch.

SECTION

Data analysis and live demonstration

2.4

30 min

Key idea of this section

Reading an EQCM experiment means correlating three curves: i vs. E, Δf vs. time, and ΔD vs. time. The M/z analysis (Δm / ΔQ) translates frequency into chemical identity — cation, anion or solvent.

Anatomy of an EQCM dataset

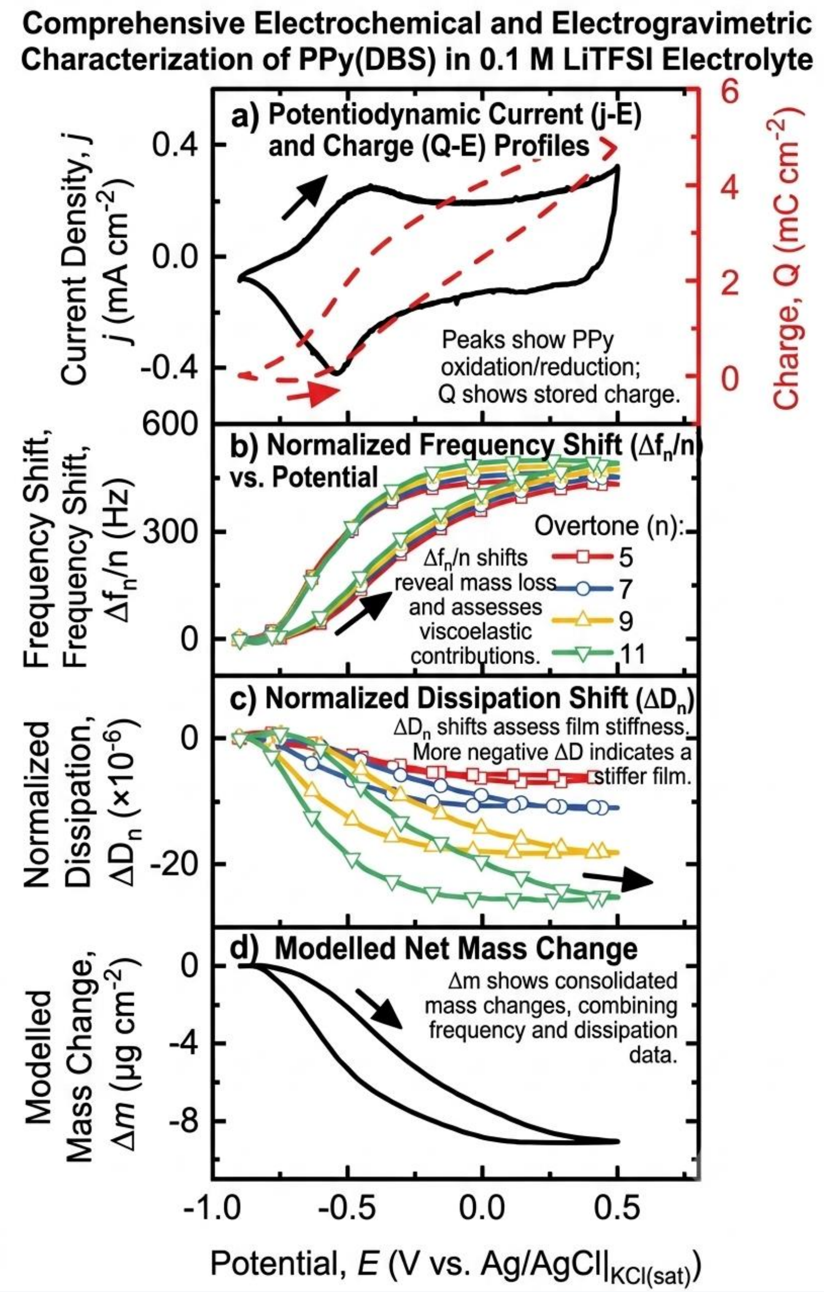
How to read it

Step 1.
Align the three panels along the shared axis (potential or time).

Step 2.
On every i peak ask: does Δf move? In which direction?

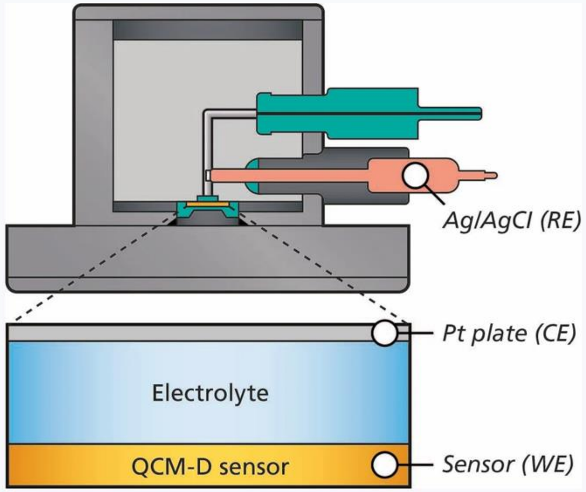
Step 3.
Check ΔD. If it rises with Δf, the film is softening — do not use Sauerbrey.

Reminder.
Δf negative = mass gain. Positive = mass loss.

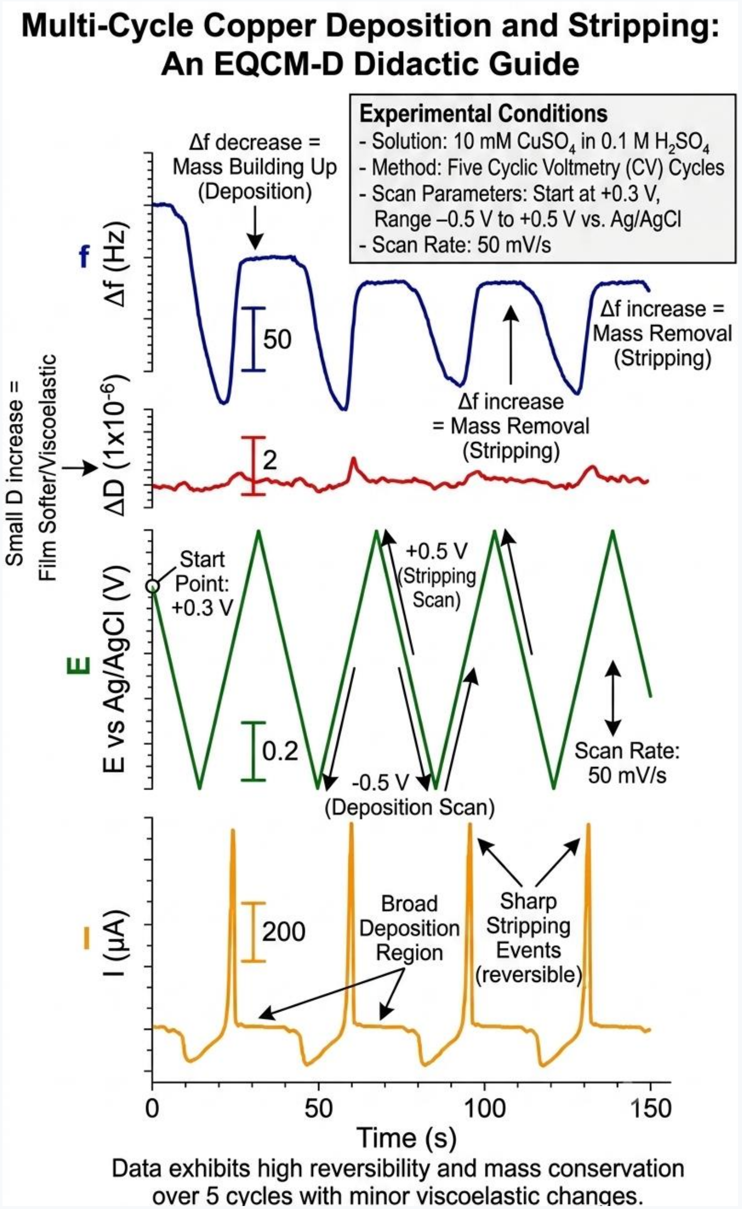


A real EQCM-D trace: copper deposition and stripping

Five CV cycles of Cu on Au, monitored simultaneously in f and D (Biolin Scientific, QSense EQCM-D)



The 3-electrode EQCM-D module



The sensor crystal itself is the working electrode. Across the cycles, f drops as Cu plates on and rises again as it strips — a fully reversible process — while D rises with the mass, flagging a softer, more viscoelastic deposit than the idealized rigid-film case.

M/z analysis: identifying the transported species

The slope of Δm vs. ΔQ reveals which ion (or solvent) is moving

From Faraday's law

$$\Delta m / \Delta Q = M_{app} / (n \cdot F)$$

Plot Δm vs. ΔQ during half a redox cycle. The slope gives the apparent molar mass per electron transferred.

Comparing the slope to candidate ions

- $M_{app} \approx M(cation)$ → Pure cation transport.
- $M_{app} \approx M(anion)$ → Pure anion transport.
- $M_{app} >$ any ion → Solvent is co-transported.
- $M_{app} <$ expected ion → Mixed transport (cation + anion in opposite directions).

When solvent is co-transported (Easley, eq. 7)

$$(\Delta m \cdot n \cdot F) / \Delta Q - M(ion) = n_{solv} \times M(solvent)$$

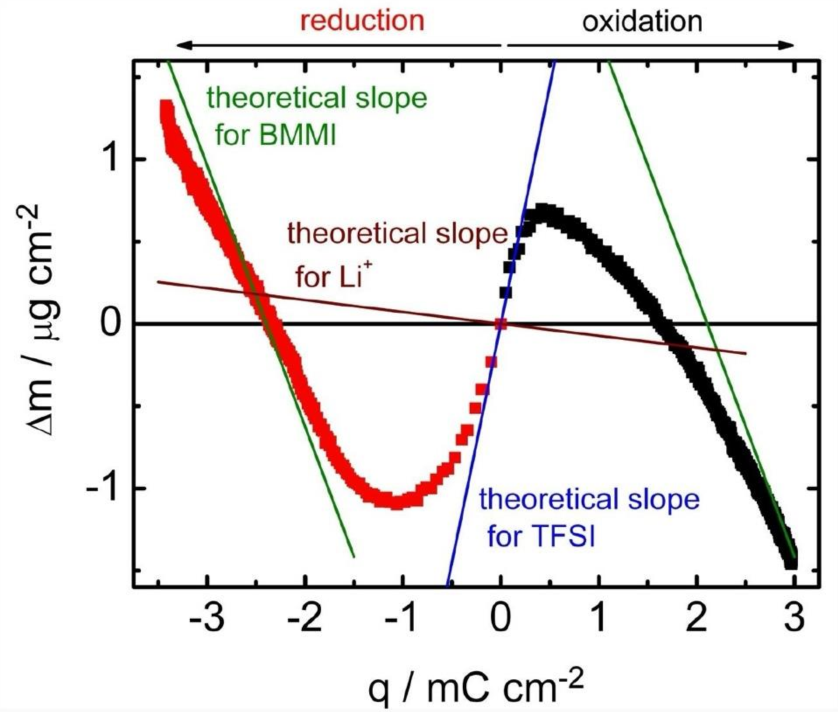
The excess mass beyond the expected ion gives the number of solvent molecules dragged along.

Matching a real slope to a candidate ion

Δm vs. ΔQ during MnO_2 redox cycling in an ionic liquid electrolyte

Reading this plot

- During reduction, the data track closest to the theoretical slope for the $BMMI^+$ cation — the ionic liquid cation is inserted.
- During oxidation, the slope bends toward $TFSI^-$ — anion expulsion dominates instead.
- The Li^+ line sits far from the data across the whole cycle: lithium is not the main carrier here.
- This is the M/z logic from the previous slide, applied to a real redox couple instead of an idealised case.



Benedetti, Bazito, Ponzio & Torresi — Langmuir 2008, 24, 3602–3610.

When Sauerbrey fails: viscoelastic models

Use the dissipation as the trigger to switch models

Quick criterion

If $|\Delta D_n / (\Delta f_n / n)| < 4 \times 10^{-7}\ Hz^{-1}$ → Sauerbrey is valid *(Reviakine et al., Anal. Chem. 2011).*

Sauerbrey

Rigid, thin, uniform film. $\Delta D \approx 0$.

Use for. Glassy polymers in air, metal coatings.

Voigt / Kelvin–Voigt

Spring + dashpot in parallel. Default for QSoft/QTools.

Use for. Polymer films in liquid, swollen films.

Extended Voigt

G′ and G″ frequency-dependent (power law).

Use for. Polyelectrolyte multilayers, polymers near Tg.

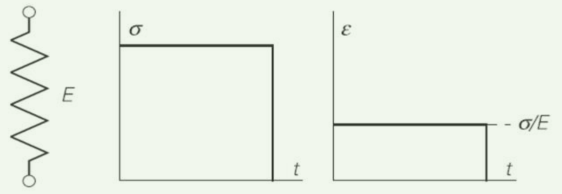
Hydrodynamic

Accounts for entrained liquid in pores.

Use for. Porous battery / supercapacitor electrodes.

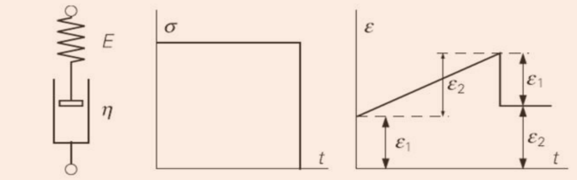
From ideal spring to real film

Every viscoelastic model in this module is built from two elements: the spring and the dashpot



Spring (elastic)

Sauerbrey limit: instant, fully recoverable strain.



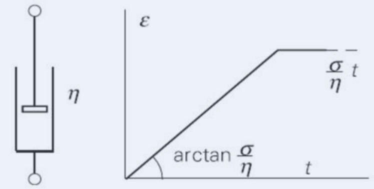
Response of a Maxwell element.

Maxwell (series)

Instant elastic jump, then viscous flow — stress relaxation.

$d\varepsilon/dt = \dot{\varepsilon}$;

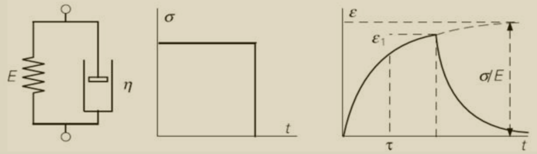
$\sigma = \eta \cdot \dot{\varepsilon}$



Dashpot (viscous)

Strain grows linearly with time — no elastic recovery.

$\sigma_1 = E \cdot \varepsilon(t)$ $\sigma_2 = \eta \cdot \frac{d\varepsilon(t)}{dt}$ $\sigma_1 + \sigma_2 = \sigma$



Kelvin–Voigt (parallel)

Delayed, recoverable strain — the basis of the Voigt model.

The Extended Voigt and Hydrodynamic models used in this course combine these elements with frequency-dependent or pore-scale terms.

SECTION

Hands-on exercise

2.5

15 min

Key idea of this section

Each small group receives a real EQCM trace. The task: identify deposition, stripping and ion-exchange regions; classify Sauerbrey or viscoelastic; and propose a transport model.

2.5 HANDS-ON · GROUP EXERCISE

Group exercise: read a real EQCM trace

15 minutes · groups of 3–4 · one trace per group

Criteria ruler

$|\Delta D / (\Delta f / n)| < 4\times10^{-7}\ Hz^{-1}$
→ Sauerbrey is valid.

Harmonics collapse onto $\Delta f_n / n$
→ the film is rigid.

Δf decreases during reaction
→ mass gain (deposition / insertion).

Δf increases during reaction
→ mass loss (stripping / dissolution).

Guiding questions

1. At what potential does the reaction start? How much mass is gained per cycle?
2. Does ΔD rise or stay flat? What does it say about film rigidity?
3. Do the harmonics overlap when plotted as $\Delta f_n / n$?
4. What M_app do you estimate from the Δm vs. ΔQ slope?
5. Which ion (or combination) explains your M_app?

MODULE 2 · TAKEAWAY

What you should leave with

1. Set up a working EQCM cell with the right geometry, the right counter / reference placement, and a clean crystal.
2. Pick the instrument that matches the question: oscillator for rigid films; impedance / QCM-D for soft, hydrated systems.
3. Calibrate against Faraday's law before trusting any mass number. The theoretical K is only a sanity check.
4. Recognise when Sauerbrey fails (ΔD rises, harmonics diverge) and switch to a viscoelastic model.
5. Read a CV + Δf + ΔD dataset by aligning the three panels and extracting M_app from Δm vs. ΔQ.

Read next

Easley et al.
J. Polym. Sci. 2022, 60, 1090

Buttry & Ward
Chem. Rev. 1992, 92, 1355

Reviakine et al.
Anal. Chem. 2011, 83, 8838

Johannsmann & Reviakine
Nat. Rev. Methods Primers 2024

Next — Module 3 · Applications of EQCM

Electrodeposition · Corrosion · Batteries · Supercapacitors · Bioelectrochemistry

Module 2 — References

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2.Horst, R.J.; Katzourakis, A.; Mei, B.T.; de Beer, S. Design and validation of a low-cost open-source impedance-based quartz crystal microbalance for electrochemical research. HardwareX, v. 12, e00374, 2022. https://doi.org/10.1016/j.ohx.2022.e00374.

3.Biolin Scientific. EQCM and EQCM-D | Measurements. Disponível em: https://www.biolinscientific.com/measurements/eqcm-d. Acesso em: 1 jul. 2026.

4.Jayasvasti, S.; Isarakorn, D.; Nundrakwang, S. Electromechanical Impedance Techniques. Department of Instrumentation and Control Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand, IEEE, 2016. (978-1-5090-3940-1/16)

5.Pettersson, F. QCM-D vs QCM-I – what is the difference? Biolin Scientific Surface Science Blog, 31 maio 2022. Disponível em: https://www.biolinscientific.com/blog/qcm-d-vs-qcm-i-what-is-the-difference. Acesso em: 1 jul. 2026.

6.Biolin Scientific. The working principles of QCM and QCM-D technology. Overview. Disponível em: https://www.biolinscientific.com. Acesso em: 1 jul. 2026.

7.Burda, I. Quartz Crystal Microbalance with Impedance Analysis Based on Virtual Instruments: Experimental Study. Sensors, v. 22, n. 4, p. 1506, 2022. https://doi.org/10.3390/s22041506

8.Liao, S.; Ye, P.; Chen, C.; Zhang, J.; Xu, L.; Tan, F. Comparing of Frequency Shift and Impedance Analysis Method Based on QCM Sensor for Measuring the Blood Viscosity. Sensors, v. 22, n. 10, p. 3804, 2022. https://doi.org/10.3390/s22103804