Electrodes and Inline Reactors:
How Sono-Electrochemistry Improves Efficiency

Ultrasonically generated cavitation for mass-transfer enhancement, electrode activation and scalable electrochemical processing

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TAKE-HOME MESSAGE

Sono-cavitation changes conditions directly at the electrode-electrolyte interface. Acoustic streaming, cavitation and surface vibration can reduce mass-transfer limitations, detach gas bubbles, disrupt deposits and continuously renew the electrolyte adjacent to the electrode.

At fixed voltage, electrolyte and geometry, the change in electrical current is a direct and convenient experimental response to sonication.

1 Why sonicate an electrochemical interface?

Electrochemical reactions can be limited by transport and surface coverage — not only by intrinsic electrode kinetics.

ELECTROLYTE → DIFFUSION / BOUNDARY LAYER (reactant depletion, product accumulation) → ELECTRODE (electron transfer)

Without forced convection, concentration gradients, gas films and deposits can reduce the electrochemically accessible interface.

2 What power ultrasound changes

Five mechanical effects at the electrode

Sonication Cavitation

- **Boundary-layer thinning** — Faster electrolyte renewal
- **Bubble removal & degassing** — Microbubbles coalesce and detach
- **Enhanced mass transport** — Reactants in / products out
- **Electrode cleaning** — Deposits and fouling are disrupted
- **Surface-area recovery** — Gas-covered area becomes accessible

→ **measurable change in electrical current at constant voltage**

3 Selected literature evidence

1 Hydrogen evolution
Pt/H_2SO_4: ultrasound increased HER current density; high-speed imaging linked the dominant effect to hydrogen-bubble removal.
[2] Pollet et al., 2020

2 Electrochemical oxidation
Sono-electrochemical 2,4-D treatment showed lower cell voltages under the tested ultrasonic conditions.
[3] Souza et al., 2015

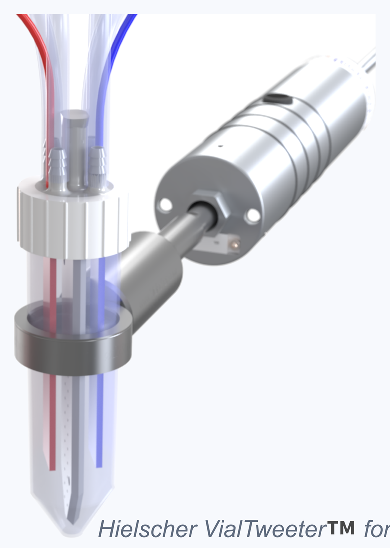
3 Electrodeposition
Ultrasonic agitation improved Cu-Sn-TiO_2 coating morphology and surface distribution of TiO_2.
[4] Kharitonov et al., 2021

4 H_2O_2 generation
Ultrasound-enhanced mass transport increased current efficiency for electrochemical H_2O_2 formation.
[5] González-García et al., 2007

Literature effects are system-dependent; sonication is not a universal enhancement factor [6,7].

4 Rapid preliminary screening

50mL Falcon™-tube electro-sonication cell



Two interchangeable electrodes
electrodes positioned directly in the cavitation field

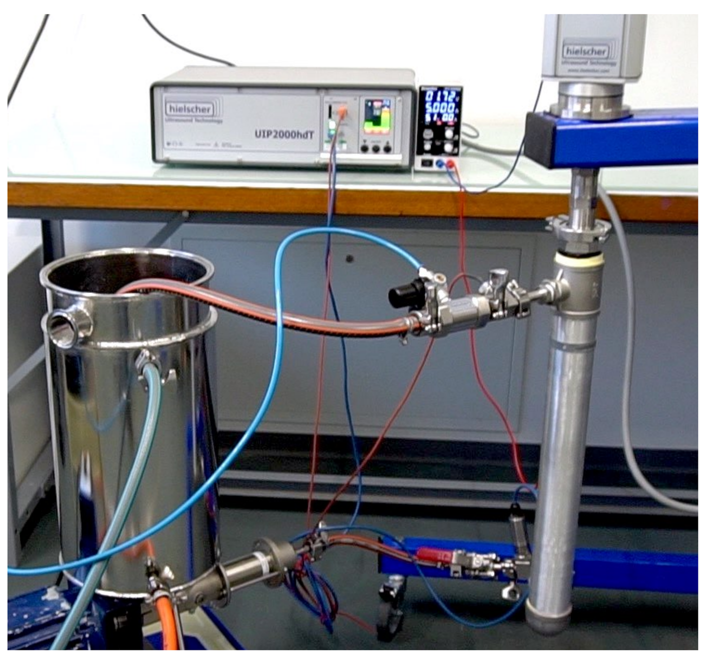
optional liquid / gas ports for recirculation, sampling or gas removal

Purpose: fast comparison of electrode material, polarity, electrolyte and silent/sonicated current response before transfer to an inline ultrasonic-electrode reactor.

Hielscher VialTweeter™ for 50mL Falcon™-Tubes

13 Industrial radial-surface probes: scale by area

Industrial scale-up favors large vibrating electrode surfaces rather than simply increasing vessel size.



Industrial focus: large-area radial surface probes in concentric inline reactors; scale-up with multiple UIP2000hdT systems and larger sonotrodes.

5 From separate horn to ultrasonic electrode

Conventional sono-electrochemistry

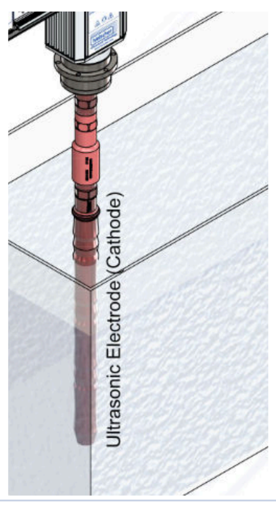
ULTRASONIC HORN → LIQUID acoustic field → ELECTRODE

Separate ultrasonic source and electrode

Horn position, distance and orientation become additional experimental variables.

6 Ultrasonic sonotrode = electrode

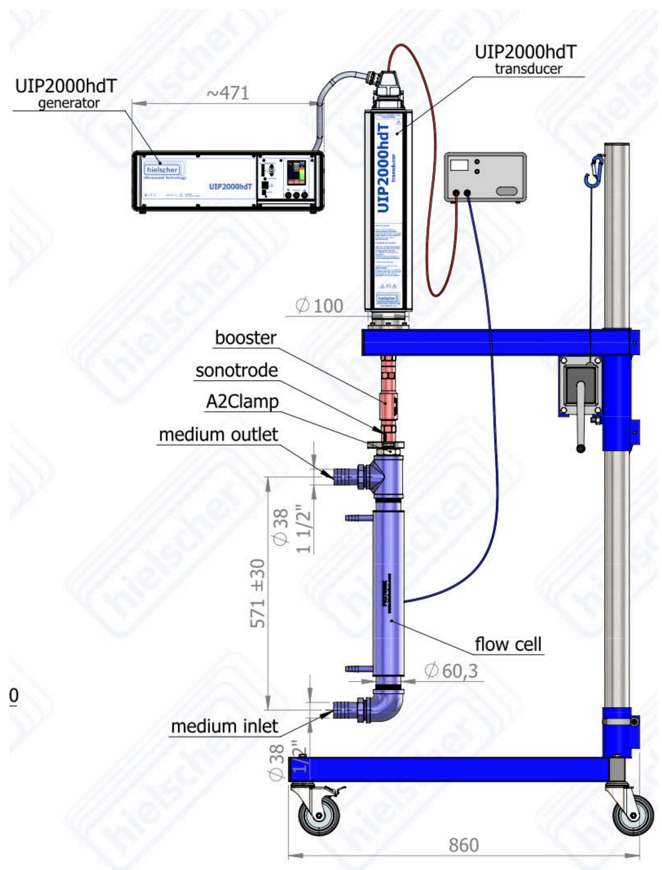
Hielscher electro-sonication electrically isolates the vibrating sonotrode so the sonotrode itself can operate as an anode or cathode.



- Cavitation and streaming originate at the active electrochemical surface.
- No separate horn-to-electrode positioning is required.
- Standard sonotrode geometries can be upgraded electrically.
- Titanium standard; Al, steel, stainless steel, Ni-Cr-Mo and Nb are possible.
- Patent application: WO2022175124A1 (electro-upgrade / vibrating conductor in current circuit).

7 Concentric inline electrode reactor

Central ultrasonic electrode + conductive cylindrical reactor wall = compact radially symmetric electrochemical flow cell



Why the concentric geometry matters

- A uniform radial gap reduces geometry-induced variation in ohmic path length and can improve current-density uniformity; shorter / lower-resistance paths otherwise carry more current.
- The insulating seal can allow the reactor wall itself to act as the second electrode.
- Pressure-tight inline operation supports controlled flow, gas handling, viscous electrolytes and slurries.
- Large-area radial probes extend both ultrasonic emitting area and electrochemical surface area for scale-up.

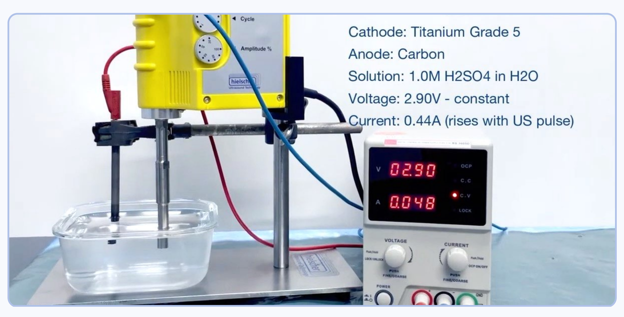
8 From screening to industrial inline processing

Scale-up table

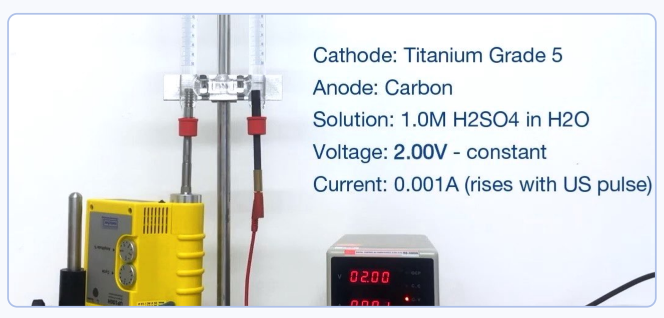
Stage	Configuration	Purpose	Scale-up focus
Preliminary screening	50mL Falcon™ cell	Fast comparison of electrodes, electrolyte, polarity and sonication on/off	Simple, low-volume experiments
Process development	UIP1000hdT, 20kHz + ultrasonic electrode	Establish industrial-type operating window	Amplitude, power, gap, pressure, flow
Production-relevant inline	UIP2000hdT, 20kHz + radial surface electrode + concentric flow cell	Continuous electro-sonication with controlled radial gap	Surface area, throughput, pressure, thermal control
Industrial scale-out	Multiple UIP2000hdT inline modules in parallel	Increase total active area and flow capacity	Replicate optimized treatment modules

Scale-up principle: preserve the relevant local operating conditions - especially amplitude / surface intensity, electrode geometry and gap, pressure, flow and temperature - rather than merely increasing vessel volume.

14 Equipment / setup options



Batch Setup, 100W

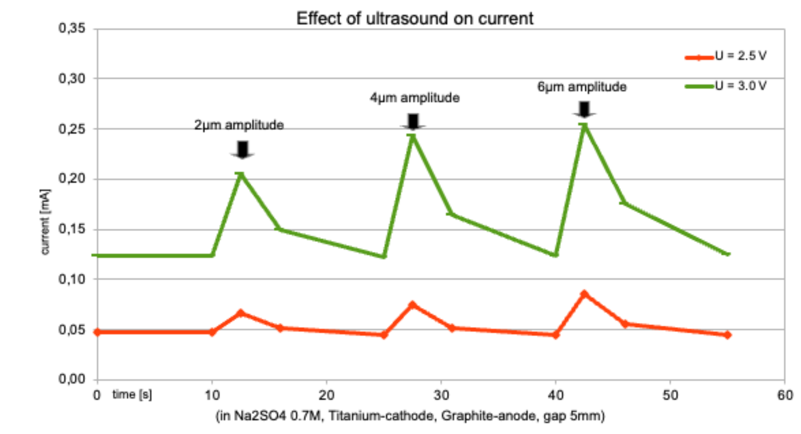


H-Cell Setup, 100W

9 Primary experimental response

What we measure

Voltage	Current	Amplitude	Ultrasonic power
U [V]	I [mA]	A [µm]	P [W]



ΔI is a process-response metric, not by itself Faradaic efficiency; temperature, conductivity, gas fraction and electrode condition should be controlled.

10 Key design and research parameters

Parameter	Why it matters
Ultrasonic amplitude	Primary adjustable ultrasonic parameter. Start with low-medium amplitudes (~1-20µm) for near-electrode mechanical effects and controllable cavitation.
Ultrasonic power	Record net ultrasonic power together with amplitude and electrode geometry.
Surface / volume power density	Relates acoustic input to emitting area or treated volume and supports scale comparison.
Electrode gap distribution	Controls electrolyte resistance and current distribution; shortest / lower-resistance paths carry more current.
Electrode surface area	Sets local current density and is a principal scale-up variable.
Electrode materials	Affect kinetics, corrosion, passivation and whether an electrode is inert or sacrificial.
Polarity / arrangement	Ultrasonic sonotrode may be anode or cathode; reaction products and deposits depend on polarity.
Flow rate / residence time	Controls replenishment, product removal and ultrasonic exposure in inline operation.
Pressure	Changes cavitation threshold [8], collapse intensity and gas solubility; pressurized flow cells also support forced-flow processing of viscous electrolytes and slurries.
Temperature	Changes conductivity, viscosity, kinetics, gas solubility and cavitation. Both ohmic and ultrasonic heating matter.
Gas release	Sonication mobilizes dissolved gas into microbubbles and promotes bubble coalescence / detachment; pressure also shifts gas release. Optional: Add membrane to separate gas bubbles.

11 Pressure, thermal management & gas handling

Pressure
Moderate pressure can intensify cavitation once cavitation occurs, while increasing static pressure also raises the cavitation threshold. At sufficiently high pressure for a given acoustic amplitude, inertial cavitation can therefore be strongly reduced or suppressed; wave propagation and mechanical vibration remain.

Thermal management
Electrical resistance and ultrasonic power both heat the electrolyte. Use jacketed flow cells or chill / heat the electrolyte inline before or after the reactor to keep comparisons at controlled temperature.

Gas handling
Sonication helps draw dissolved gas into microbubbles, promotes micro-bubble coalescence and detaches bubbles from surfaces, producing larger bubbles that are easier to separate. Pressure simultaneously changes gas solubility and release.

Bader et al., JASA 2012 for static-pressure effects on inertial cavitation.

12 Advantages of a scaleable fixed frequency platform

Industrial Hielscher electro-sonication uses the standard resonant sonicator platform. In the industrial setups considered here, frequency is fixed at 20 kHz rather than treated as a process variable.

The practical optimization focus is therefore:
amplitude → power density → pressure → electrode geometry & gap → flow → temperature

Sono-Electro-Chemistry is driven by acoustic streaming and cavitation. Therefore, amplitude and pressure are the most important parameters affecting the process.

01 INTERFACE
Sono-cavitation can improve mass transport, remove bubbles, disrupt boundary layers and clean electrode surfaces.

02 INTEGRATION
Using the sonotrode itself as an electrode puts the ultrasonic source directly at the electrochemical interface and enables concentric inline cells.

03 SCALE
Screen in 50mL, develop on UIP1000hdT, transfer to UIP2000hdT inline modules and scale out by replicating optimized reactors.

SCAN FOR ELECTRO-SONICATION

hielscher.com/electro-sonication-ultrasonic-electrodes.htm

PATENT APPLICATIONS

US20240083782A1, DE112022000134A5: Device for producing a closed current circuit with a flowable medium and a vibrating metal conductor
US20230294133A1: Device for transmitting mechanical vibrations to flowable media; used here as the basis for large-area radial-surface resonator geometries

SELECTED REFERENCES

[1] Foroughi et al., Catalysts 2021, 11, 284. [2] Pollet et al., Ultrason Sonochem 2020, 69, 105238. [3] Souza et al., Sep Purif Technol 2015. [4] Kharitonov et al., Ultrason Sonochem 2021, 75, 105593. [5] González-García et al., Ultrason Sonochem 2007, 14, 113-116. [6] Dietrich et al., Ultrason Sonochem 2017. [7] Kim et al., Ultrason Sonochem 2015, 24, 172-177. [8] Bader et al., J Acoust Soc Am 2012, 132, 728-737. [9] https://www.hielscher.com/SEC