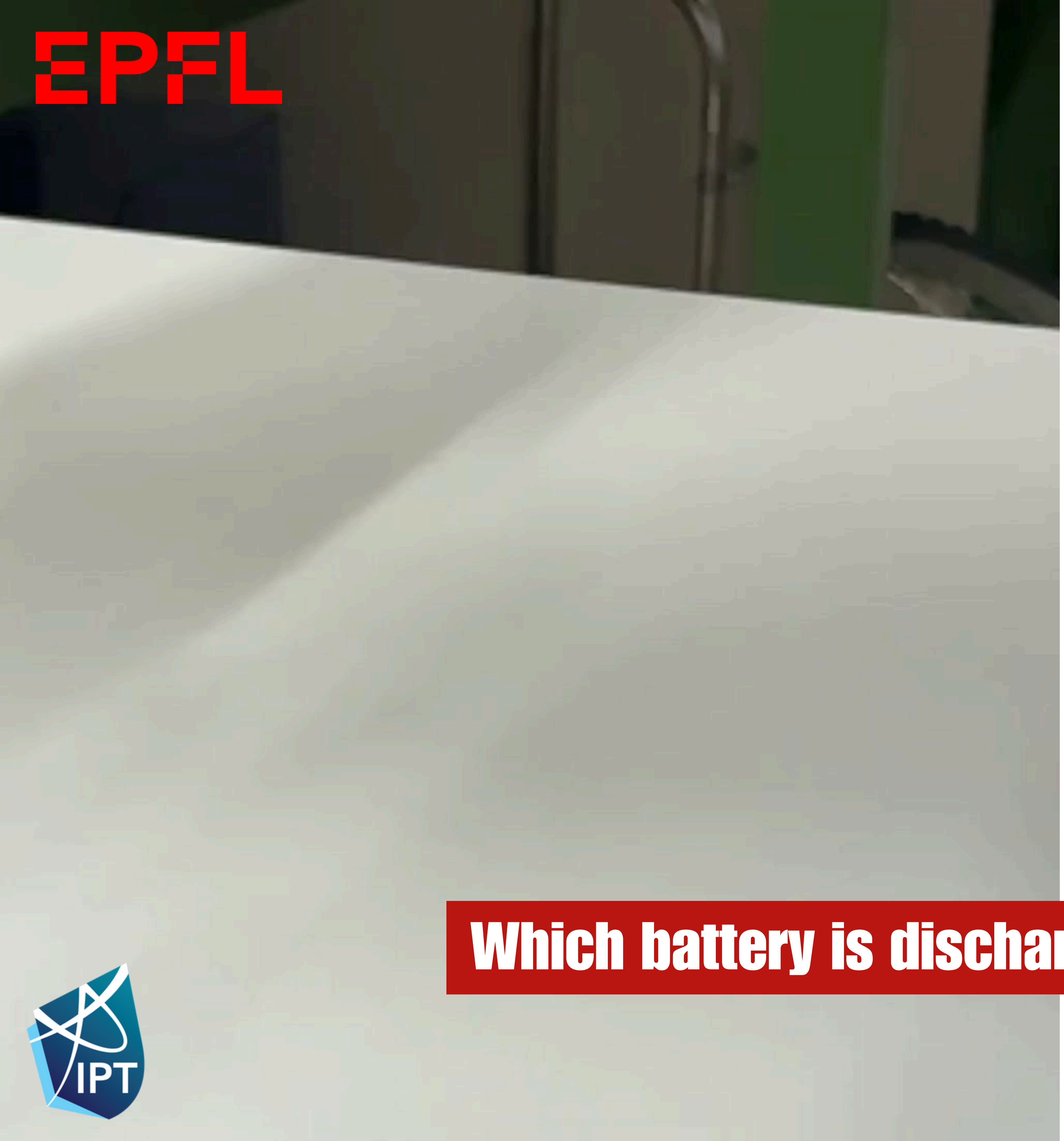
EPFL



12. Kinetic Voltmeter

Bryan Pasquier, Nassia Lopes

Which battery is discharged ?

IPT

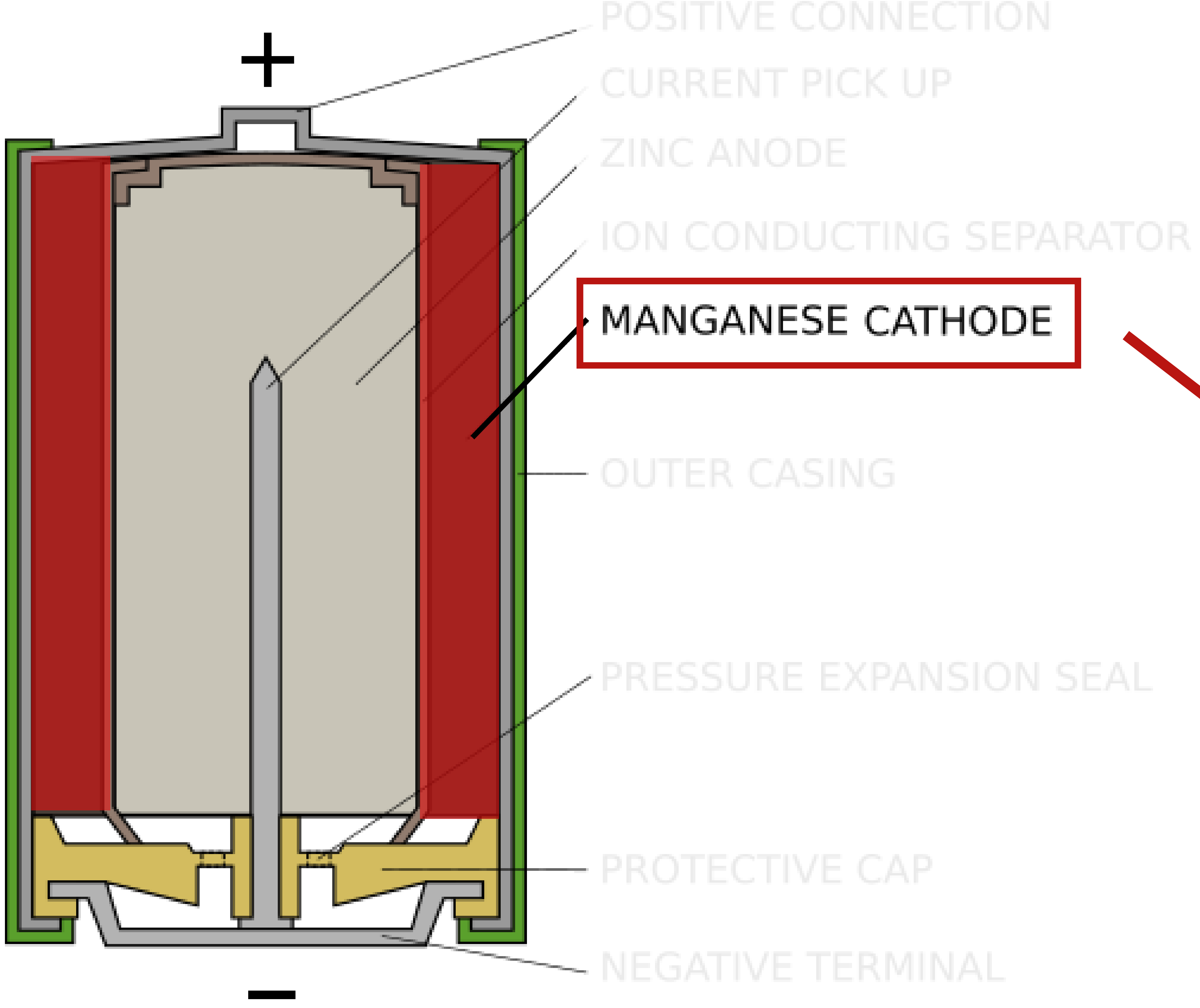
Problem statement

A DIY method of testing the charge of a battery is to drop it on a hard surface and observe whether it bounces. **Explain the phenomenon** and **find other non-invasive mechanical methods** to estimate the remaining charge. **Optimize the accuracy** of your method.

Which battery is discharged ?

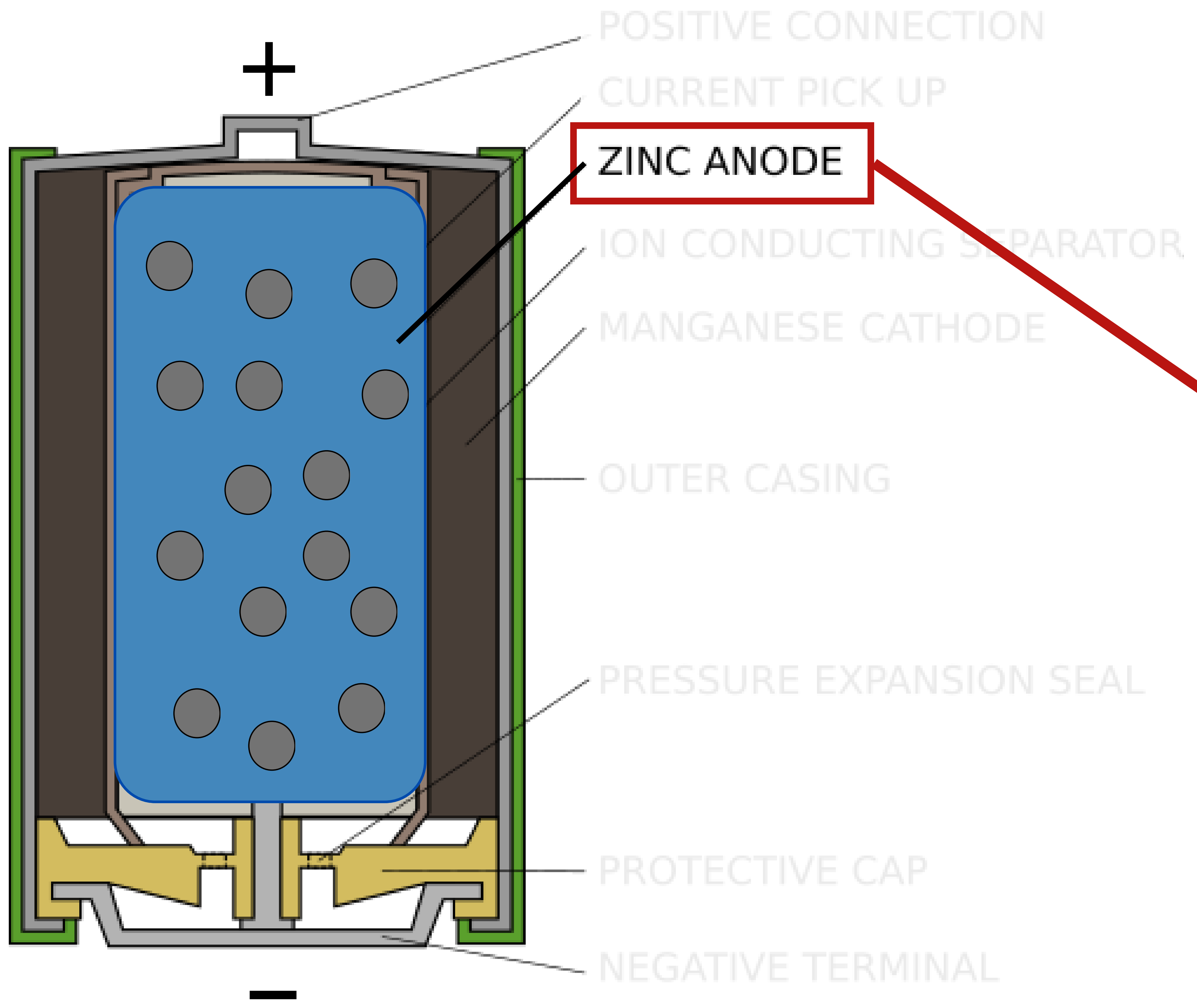
Spoiler : the right one !

What is a battery ? Zc-Mn alkaline batteries



Paste of manganese dioxide (MnO_2) and carbon

What is a battery ? Zc-Mn alkaline batteries



© Wikipedia, Alkaline Battery

Zinc powder (Zn) dispersed in a gel

Potential difference and discharging

EPFL

RedOx reaction

Anode (-) wants to **give electrons**

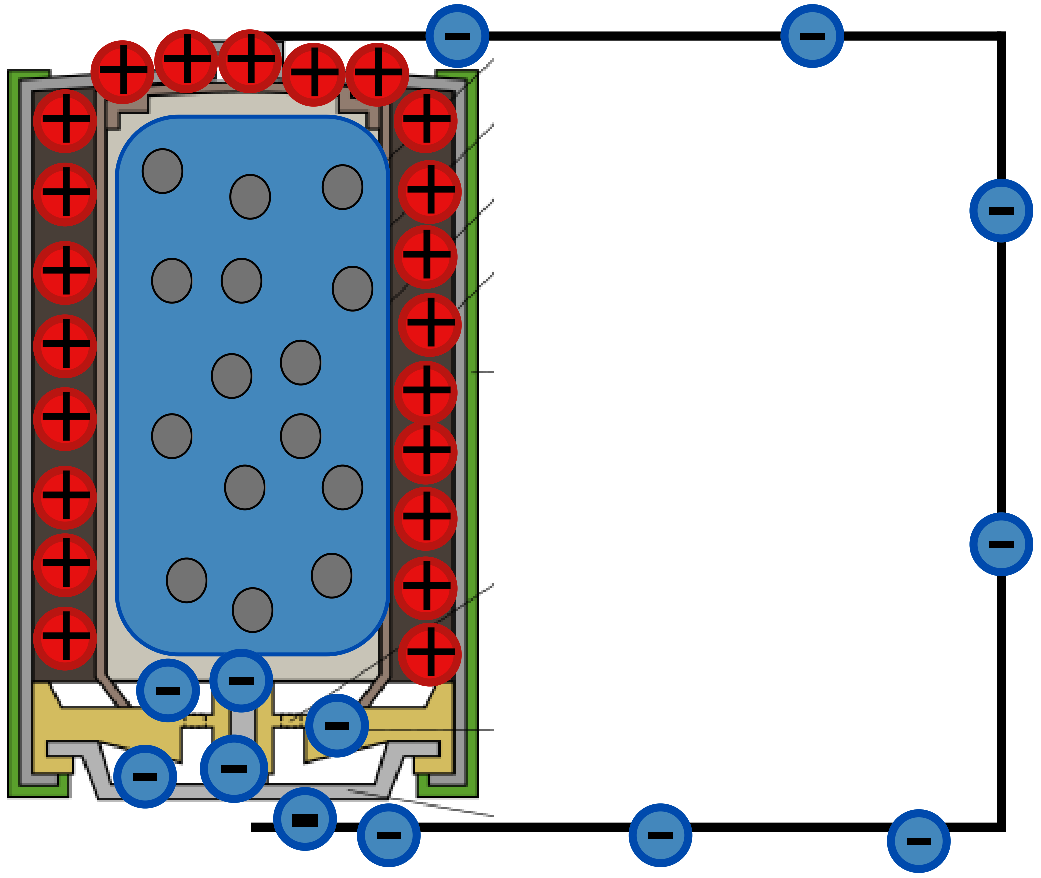
$$Zn + 4OH^- \rightarrow Zn(OH)_4^{2-} + 2e^-$$

$$Zn(OH)_4^{2-} \rightarrow ZnO + H_2O + 2OH^-$$

Cathode (+) wants to **receive electrons**

$$MnO_2 + H_2O + e^- \rightarrow MnOOH + OH^-$$

- Potential difference and current
- Chemical changes of the anode and cathode

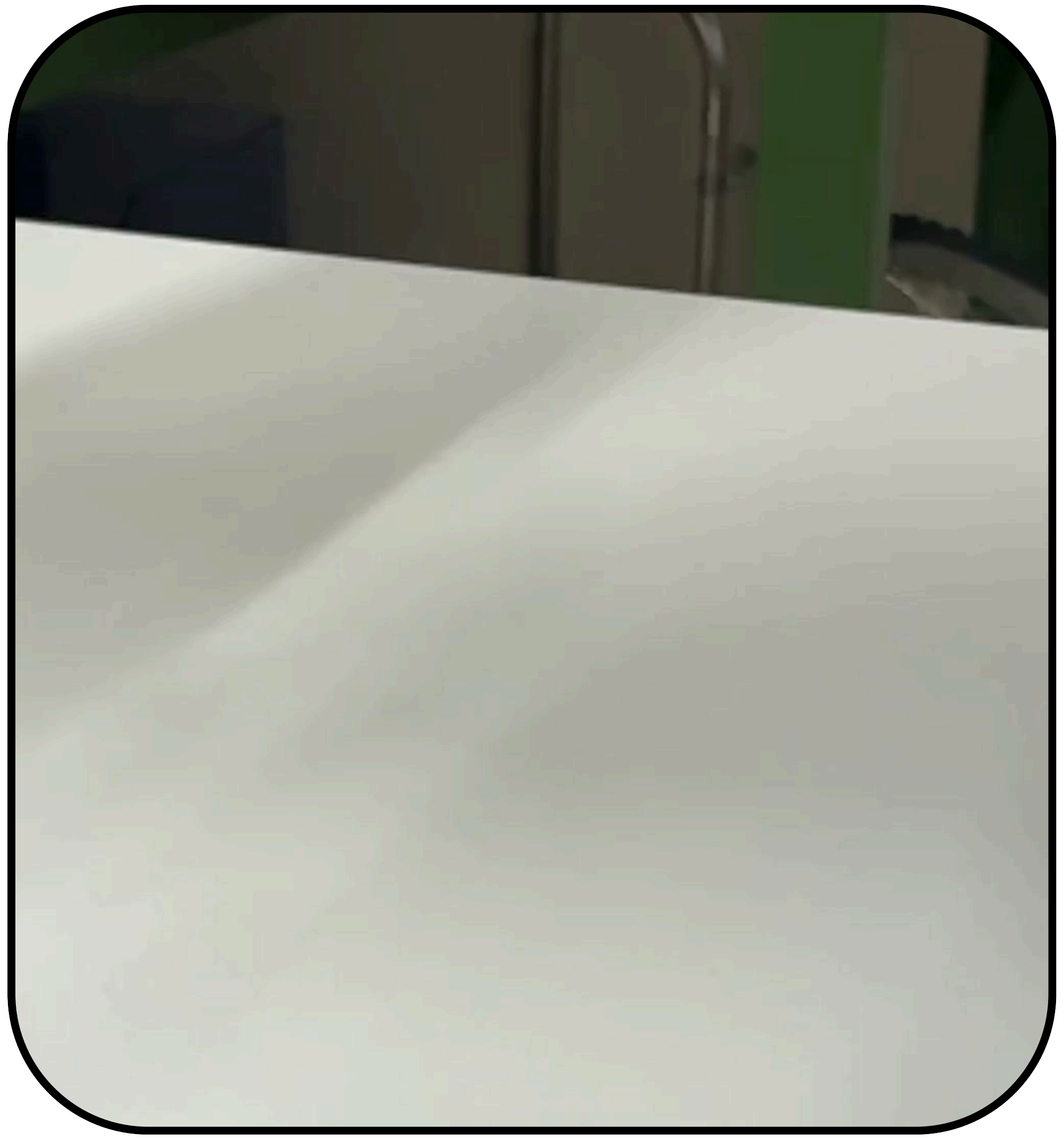


State of the art - Bouncing method

How much energy is restituted from a rebound

One significant study :

Bhadra, Shoham, et al. « ***The Relationship between Coefficient of Restitution*** (CoR) ***and State of Charge of Zinc Alkaline Primary LR6 Batteries*** ». Journal of Materials Chemistry A, vol. 3, n° 18, **April 2015**, p. 9395-400.



Increase of the CoR with dischargment

Physical explanation : multi-technique analysis
(mass measurements, anode microscopy, X-ray diffraction and mechanical characterization).

State of the art - Bouncing method

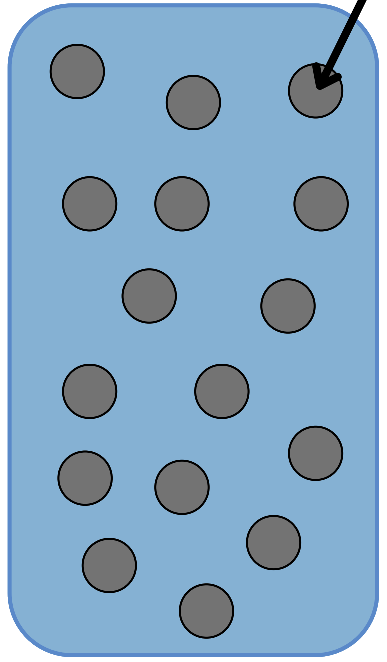
Structural change in the anode

Transition from Zn to ZnO

→ Rigid ZnO networks

Restricted mobility of the Zinc grains

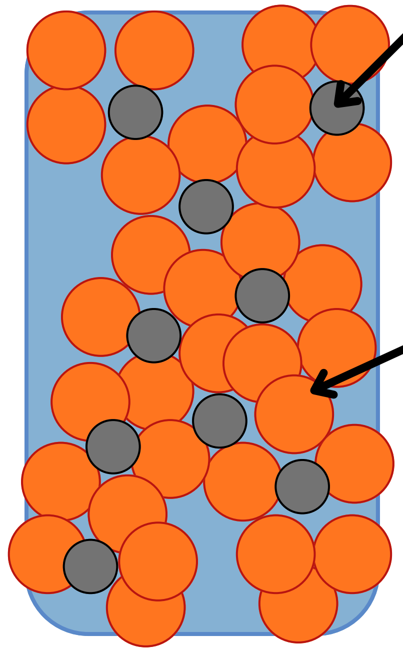
Zinc grain



© Warped, YouTube

Zinc grain

ZnO network



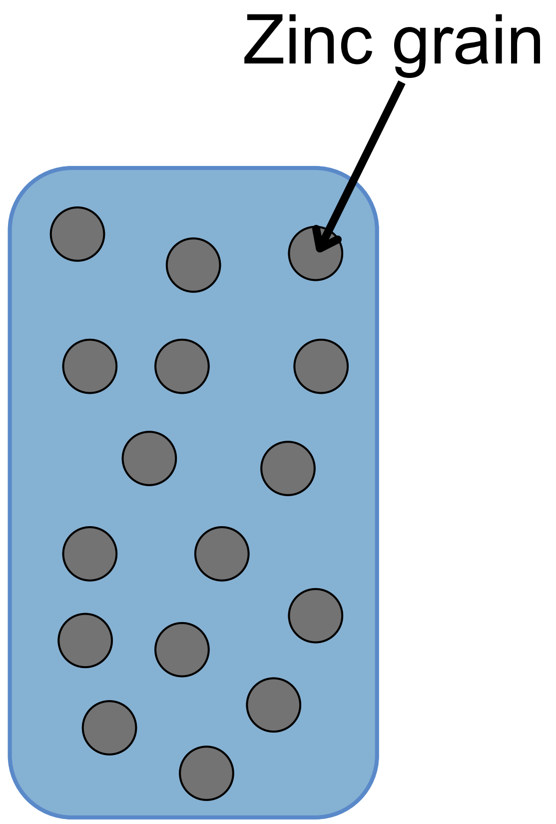
State of the art - Bouncing method

Structural change in the anode

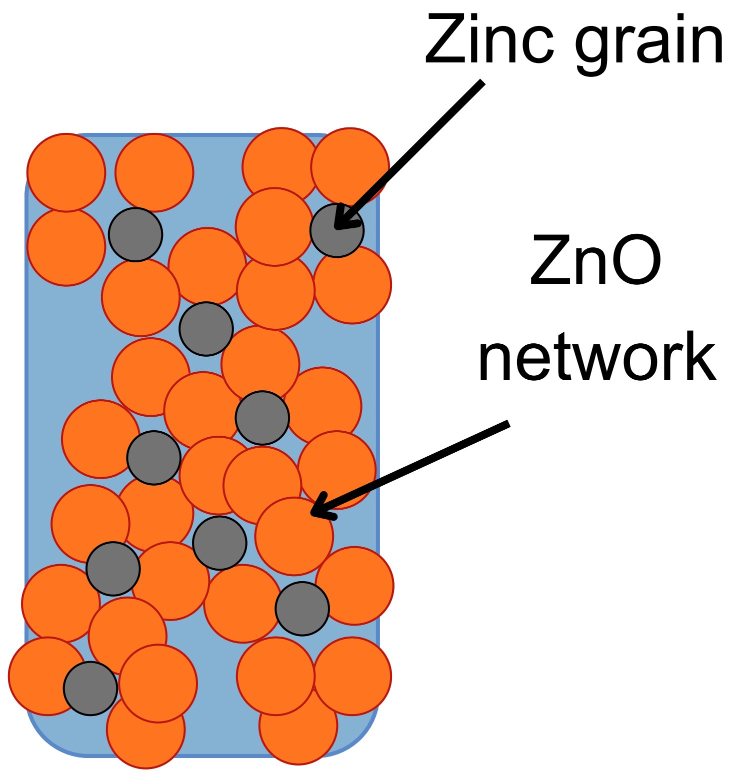
Less energy dissipation

Restricted mobility of the Zinc grains

Increase of the coefficient of restitution



© Warped, YouTube



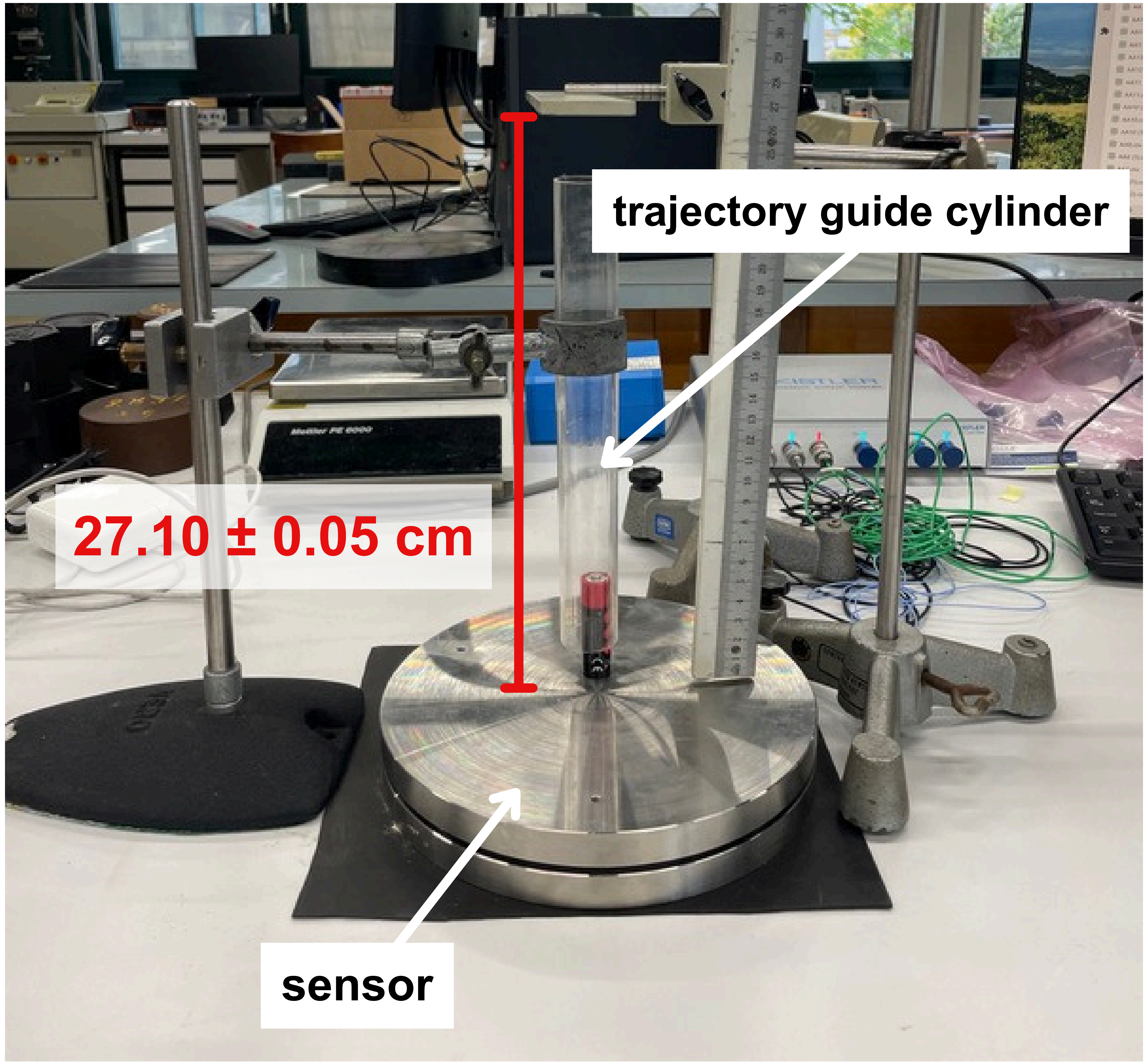
Bouncing method – Experimental setup

EPFL

OBI Alkaline LR06 AA

1.4 cm

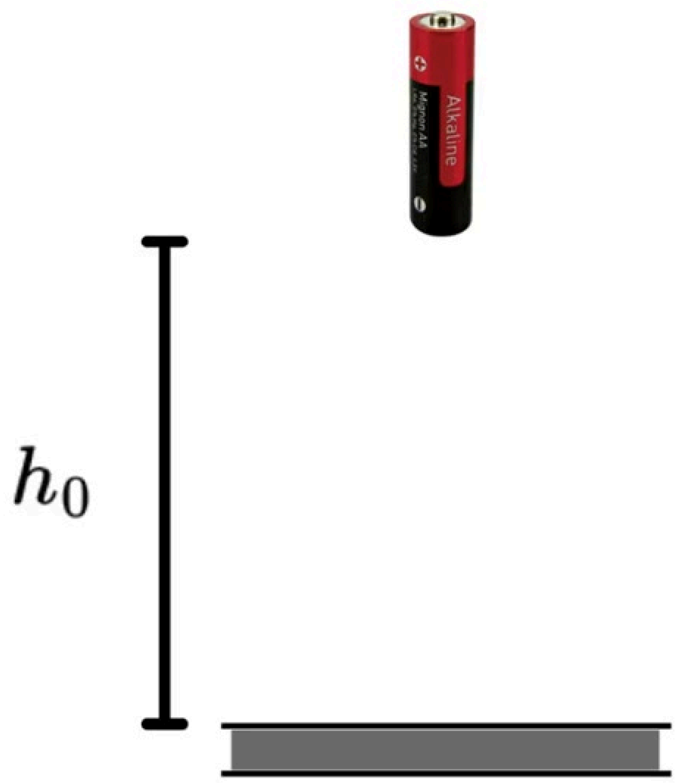
5.0 cm



Capacity [mAh]:

Discharging ⟷ Removing capacity

Bouncing method – Approach



Relevant parameters :

Time of bounce :

$$\Delta t_{\text{bounce}}$$

Bounce height (mechanical energy conservation) :

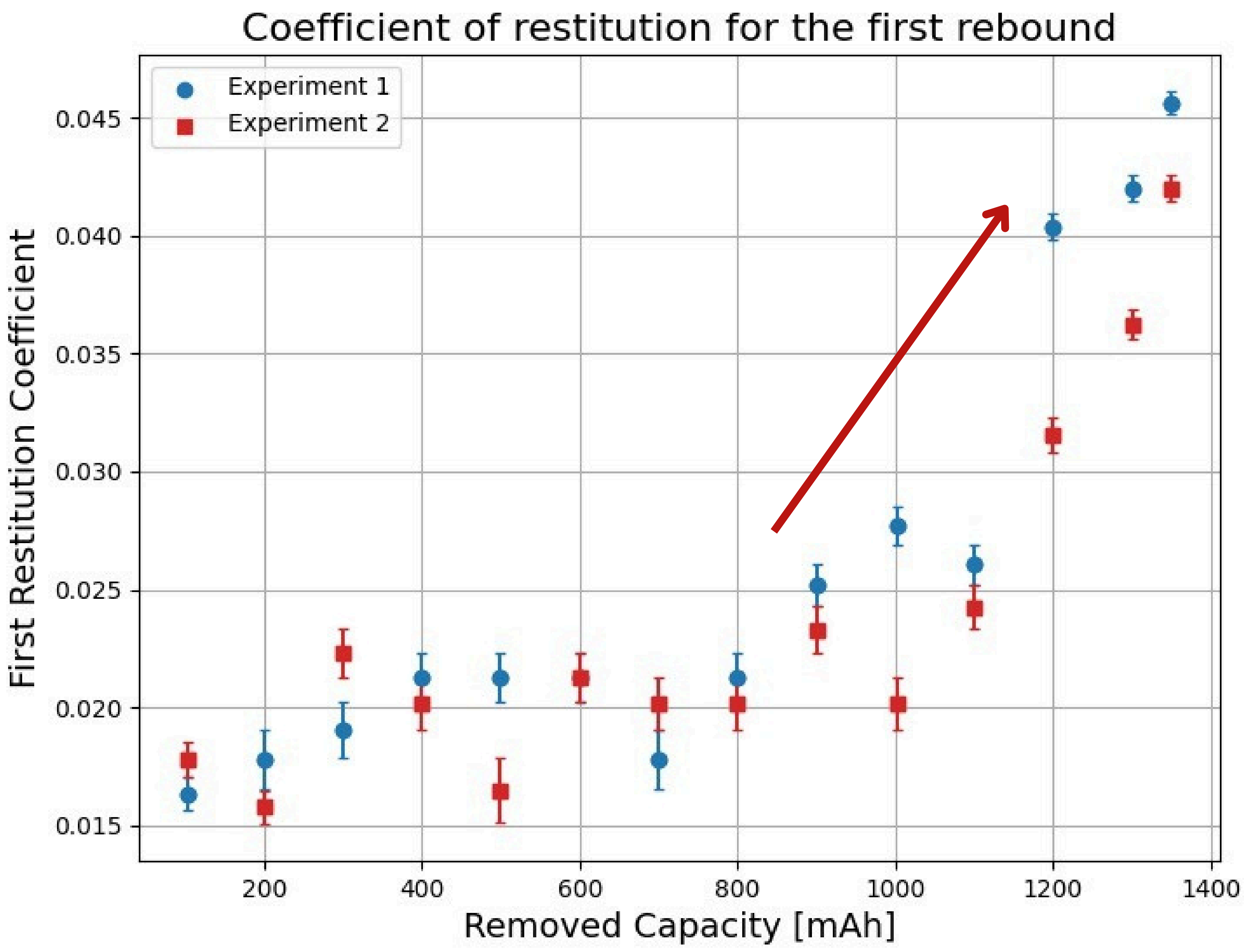
$$h_1 = \frac{1}{2} g \left(\frac{\Delta t_{\text{bounce}}}{2} \right)^2$$

Coefficient of restitution (COR), ratio of kinetic energy K :

$$\text{COR} = \frac{v_0}{v_1} = \sqrt{\frac{h_1}{h_0}} = \sqrt{\frac{K_1}{K_0}}$$

→ **characterize energy dissipation**

Bouncing method – Experimental results



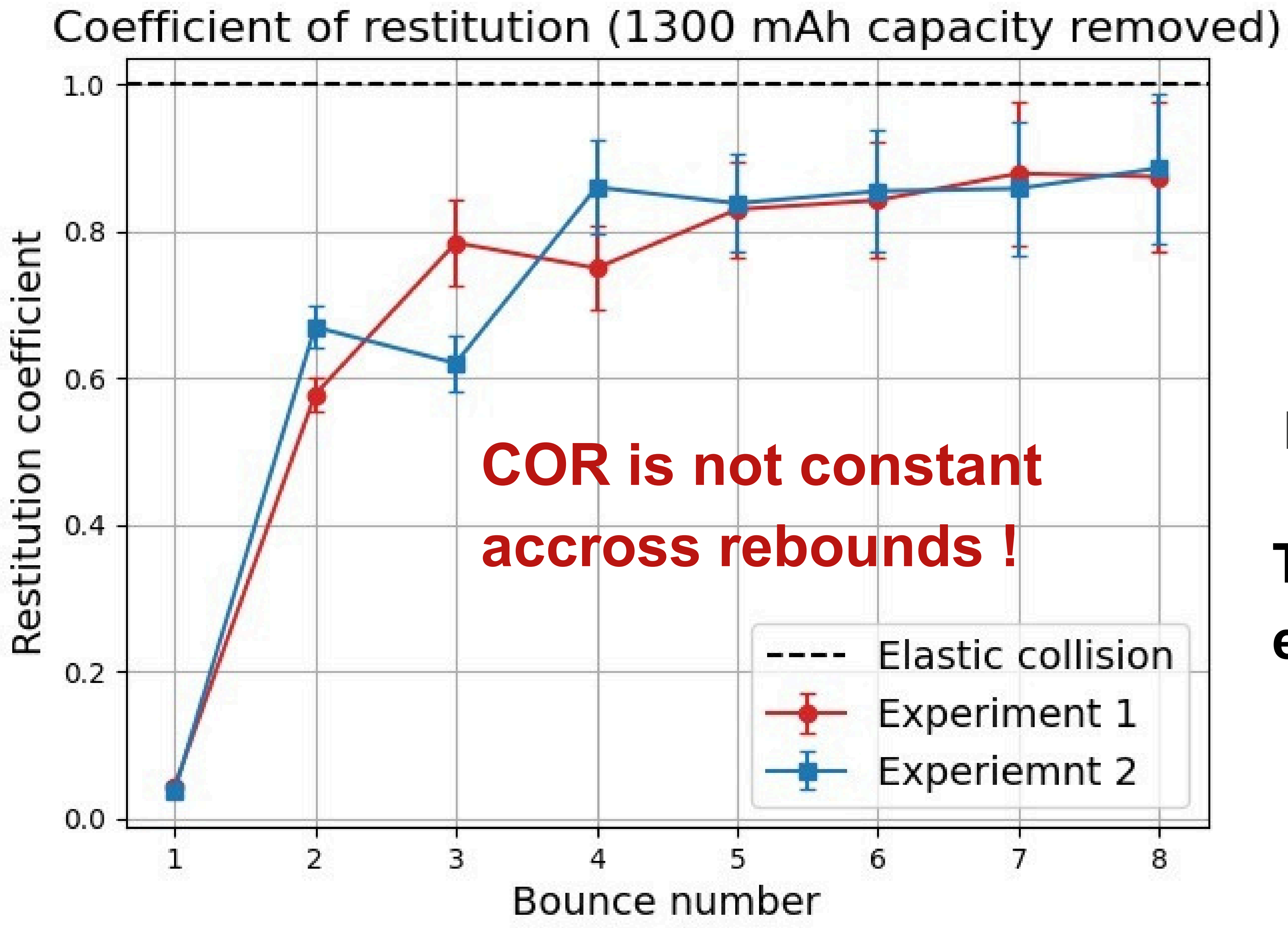
Increase of bouncing property around 900 mAh removed capacity

Limitation :

900 mAh identification threshold

Bouncing method – Experimental results

What was unexpected



COR is not constant accross rebounds !

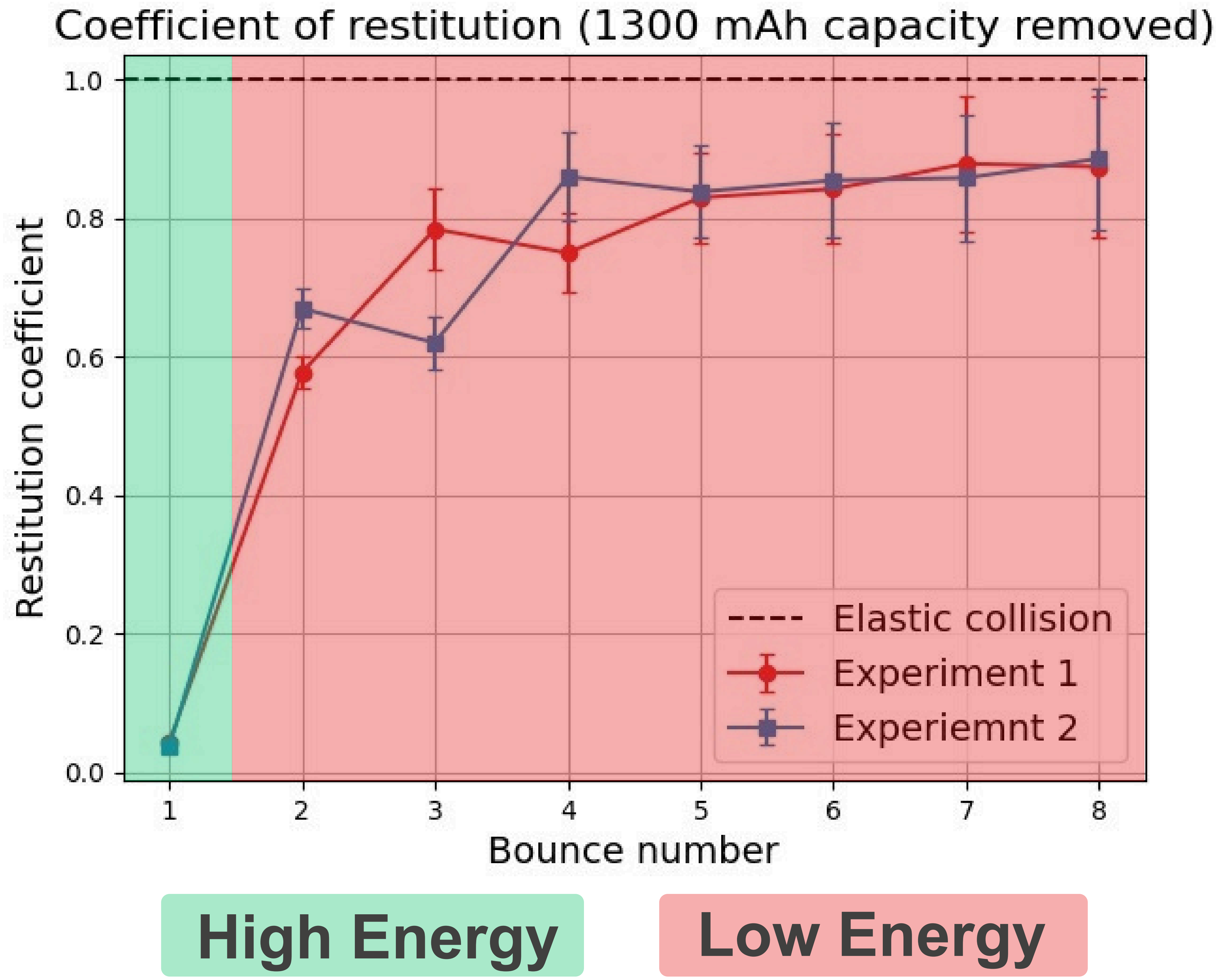
Each rebound gets **more elastic**

The smaller the rebound the more the energy is restituted

Bouncing method – Experimental results

EPFL

What was unexpected



→ At **low energies**, the **damping less pronounced**

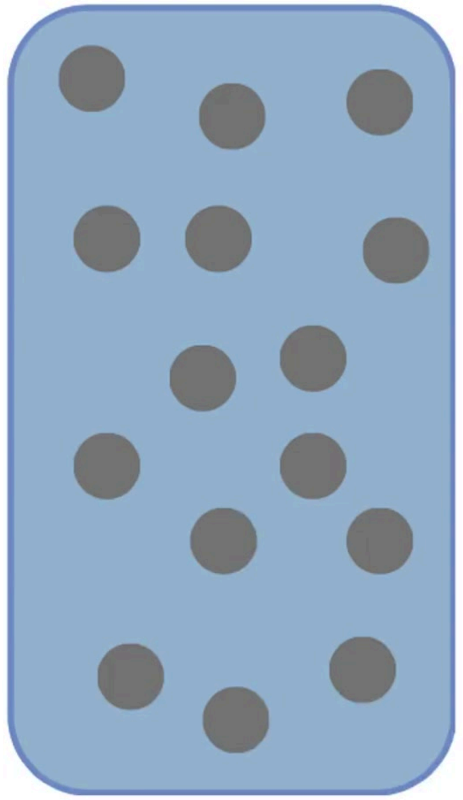
Hypothesis :

Power maybe insufficient for significant **energy dissipation through displacement of zinc grains**

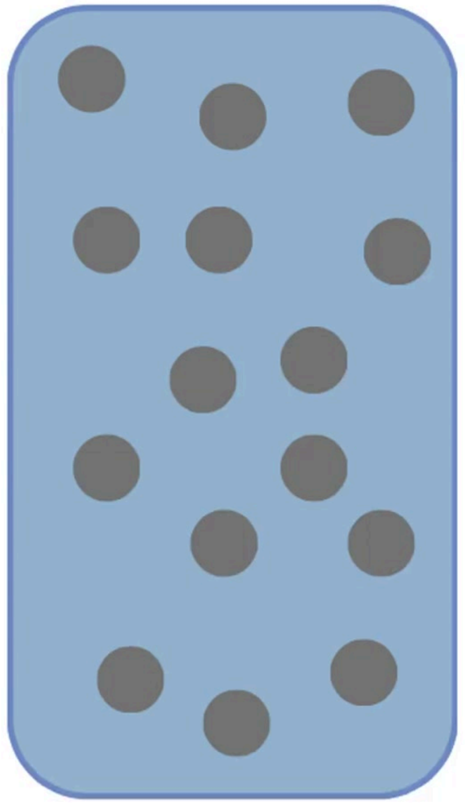
Bouncing method – Experimental results

During a rebound

Low power

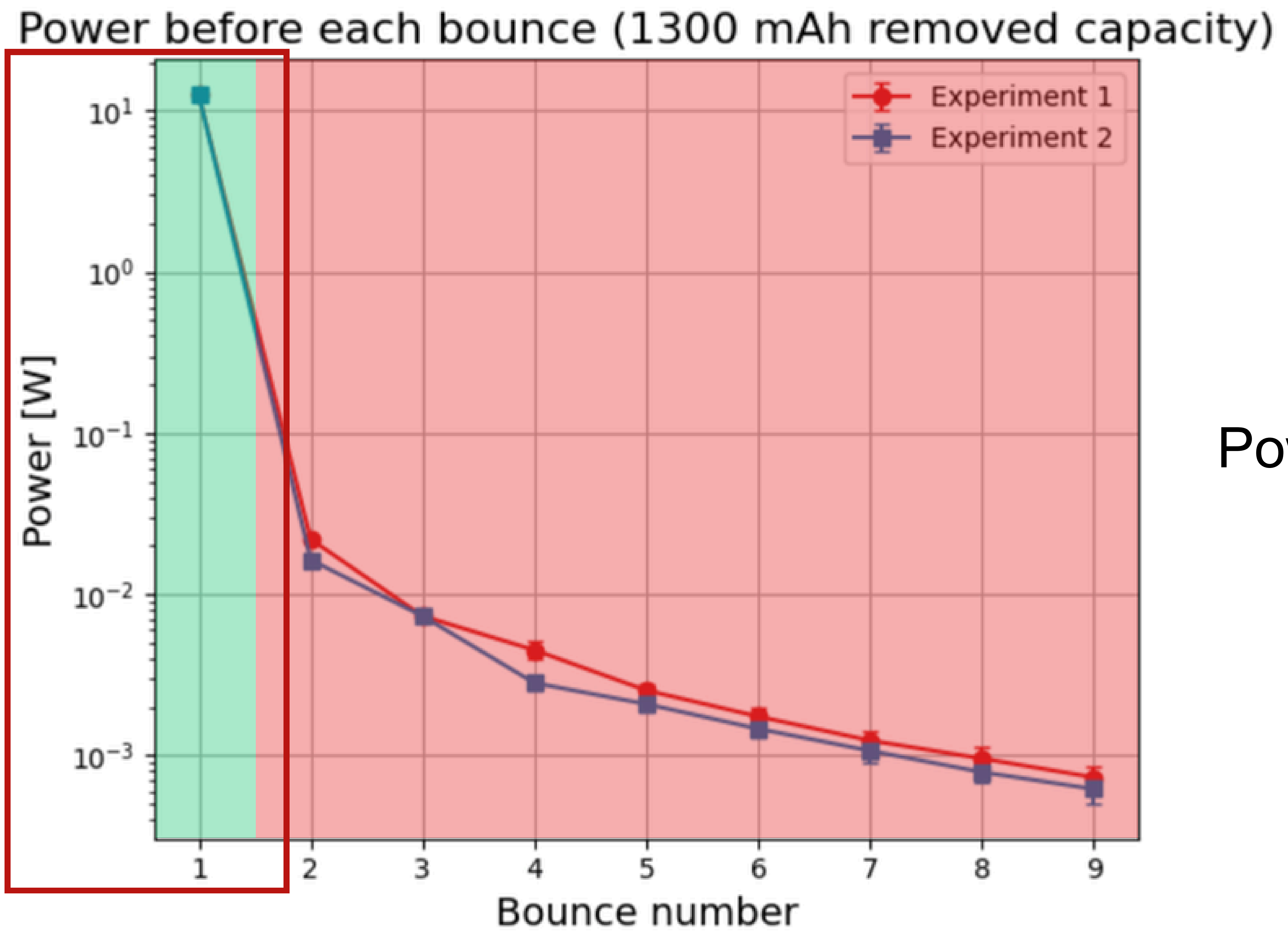


High power



Bouncing method – Power domain computation

Empirical threshold power for significant damping observation



Significant damping observed

Power : $P = \frac{mgh}{\Delta t_{impact}} = 12\text{W}$

Empirical power domains synthesis

$P \gtrsim 12\text{W}$	$P \ll 12\text{W}$
→ **High** power	→ **Low** power
→ SoC identification : • **Zinc grain damping** • **Bouncing method**	→ **Unknown** behavior

SoC = State of charge

Our own methods to determine the state of charge of a battery

Mechanical resonance method – Approach

Potential difference ⟷ Mechanical deformation

→ We can **emit and receive a mechanical wave**

Transmit a **wave through the battery :**

Mechanical resonance method – Approach

Potential difference ⟷ Mechanical deformation

→ We can **emit and receive a mechanical wave**

Receptor piezo

Emitter piezo

Transmit a **wave through the battery :**

Discharging → Internal change → Different wave behaviours

Mechanical resonance method – Which power domain ?

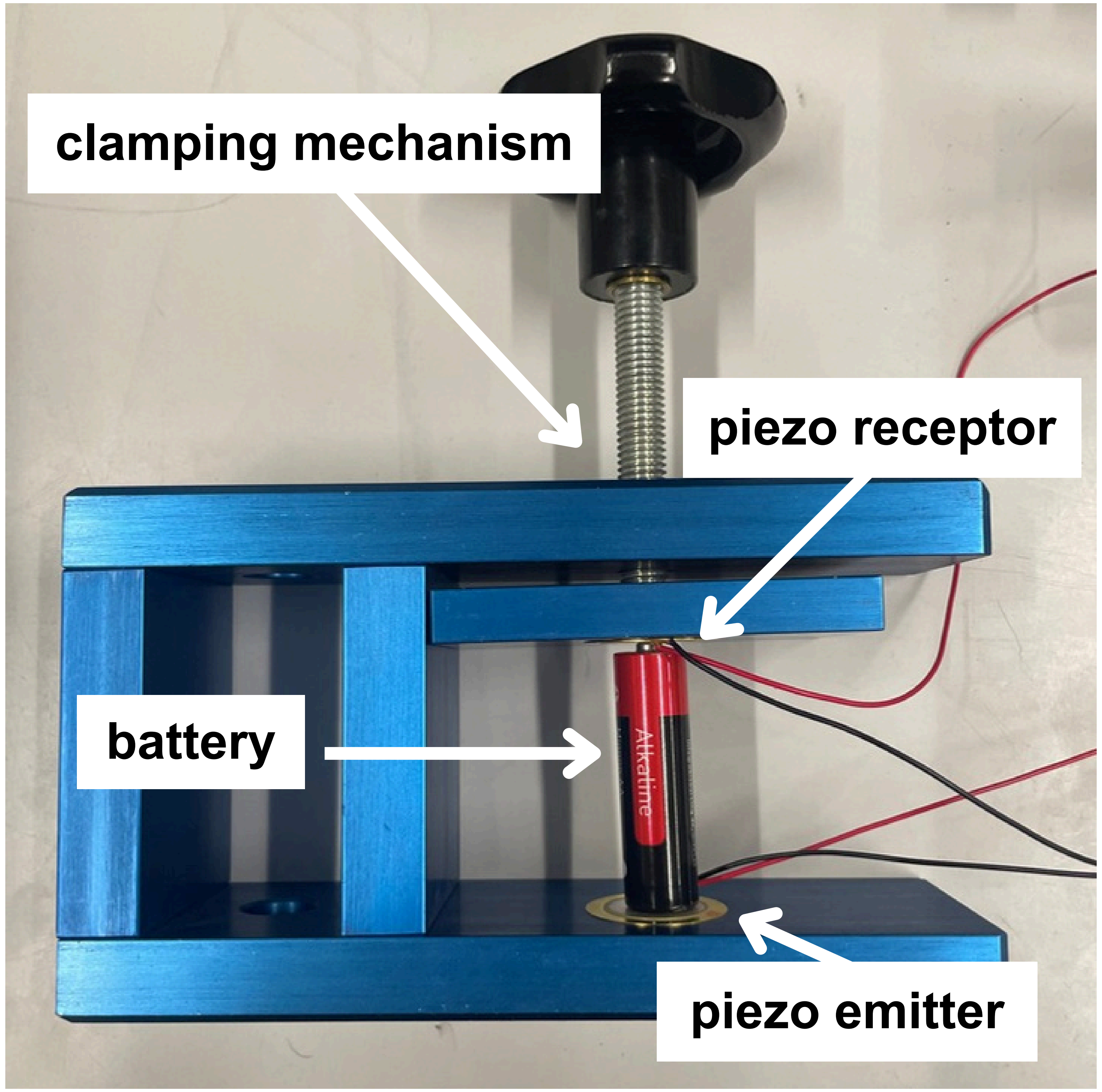
Piezo's max power

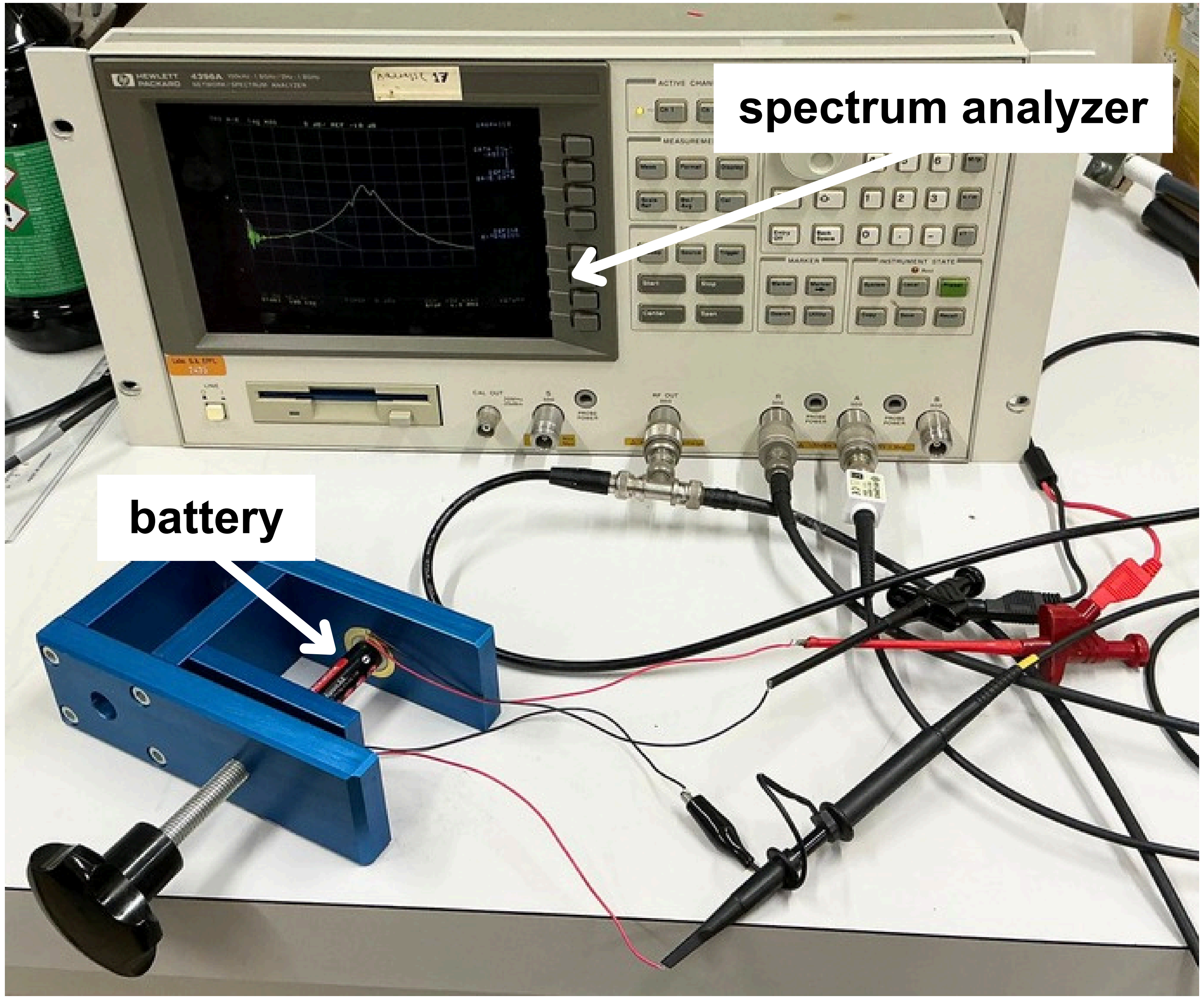
$$P \leq P_{max} = \text{force} \times \text{frequency} \times \text{deformation} = 0.05\text{W}$$

$$\boxed{0.05\text{W} \ll 12\text{W}}$$

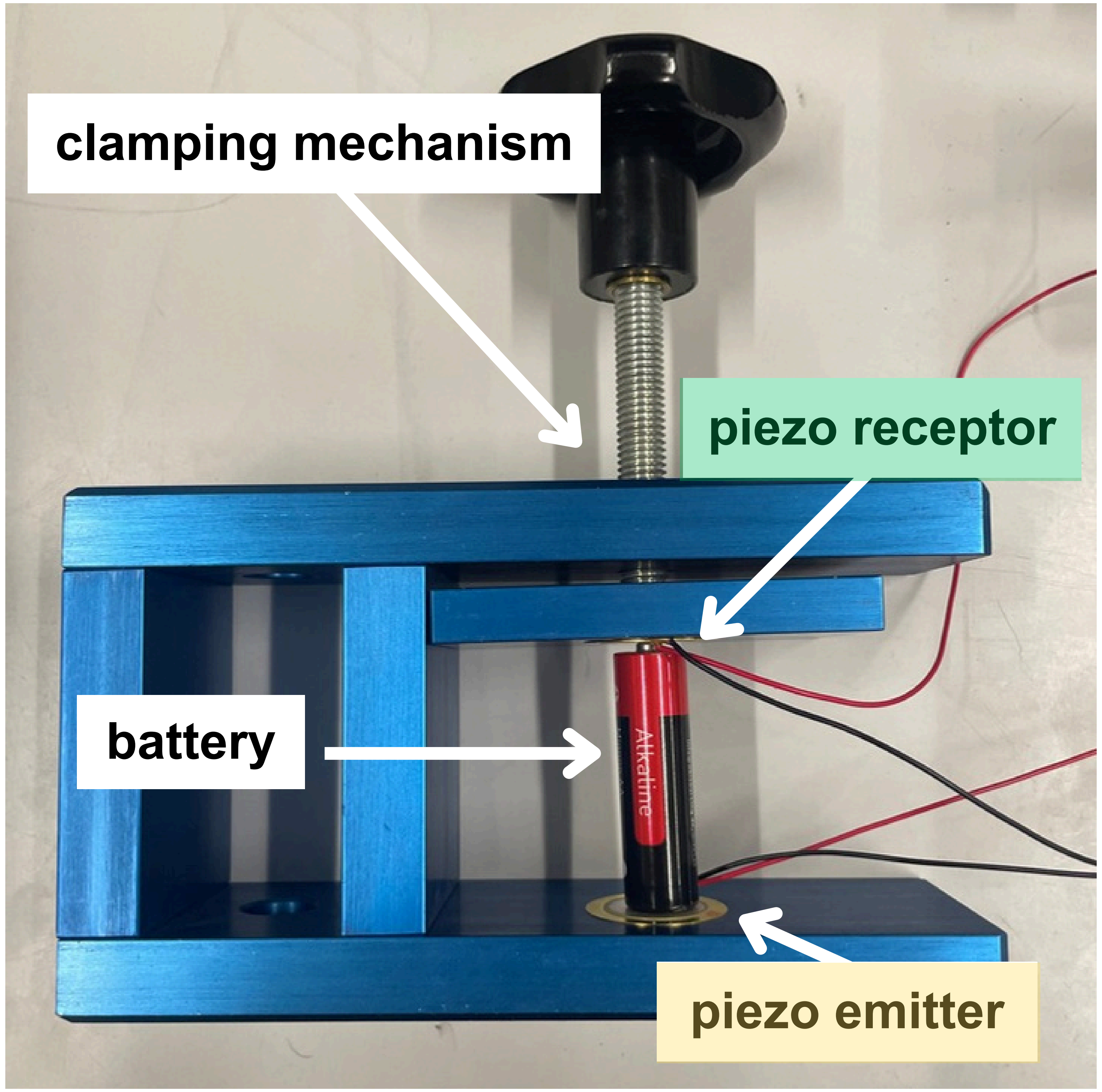
➡ **Low power**

Mechanical resonance method – Experimental setup





Mechanical resonance method – Experimental setup

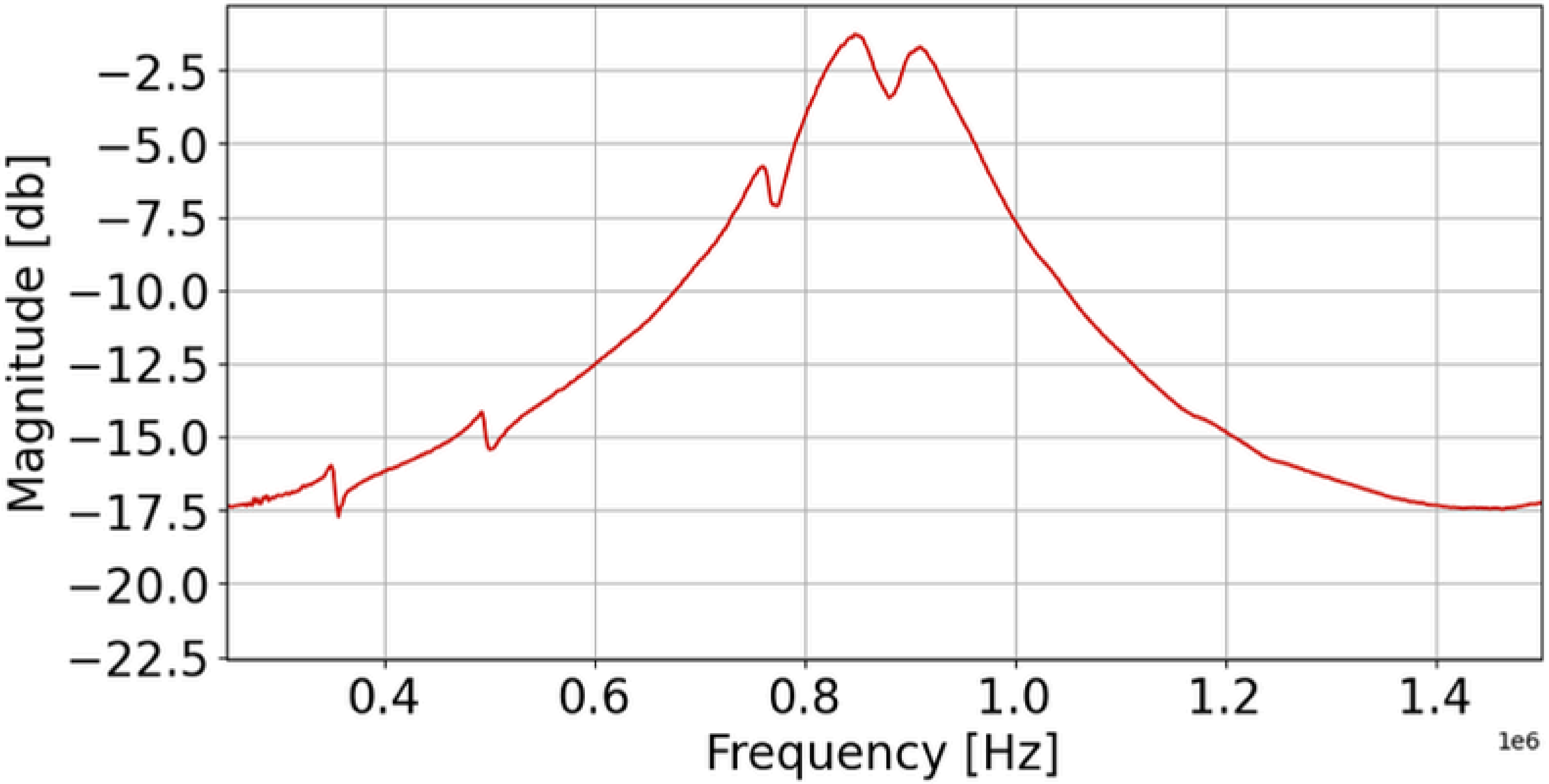


Relevant quantity :

$$\text{Gain} = \frac{\text{received amplitude}}{\text{emitted amplitude}}$$

Mechanical resonance method – Experimental results

Typical gain curve for one battery



→ Typical **damped forced oscillator** curves

Mechanical resonance method – Damped force oscillators

Damped forced oscillator equation :

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F_0 \sin(\omega t)$$

Damping (system = battery) : $\zeta = \dfrac{c}{2\sqrt{mk}}$

Q **factor :** $Q = \dfrac{1}{2\zeta}$

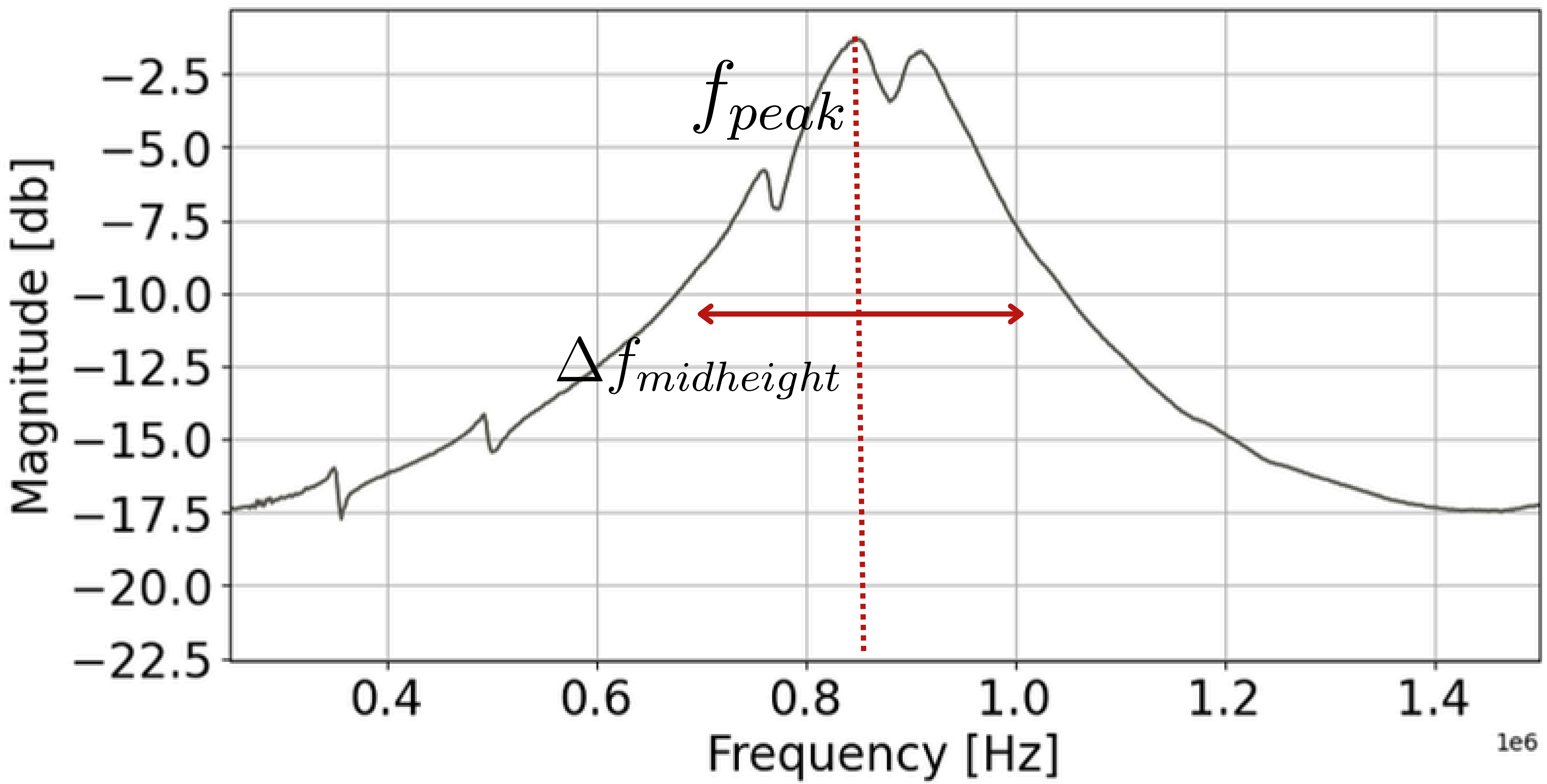
High Q $\Leftrightarrow$ Small damping

Mechanical resonance method – Experimental results

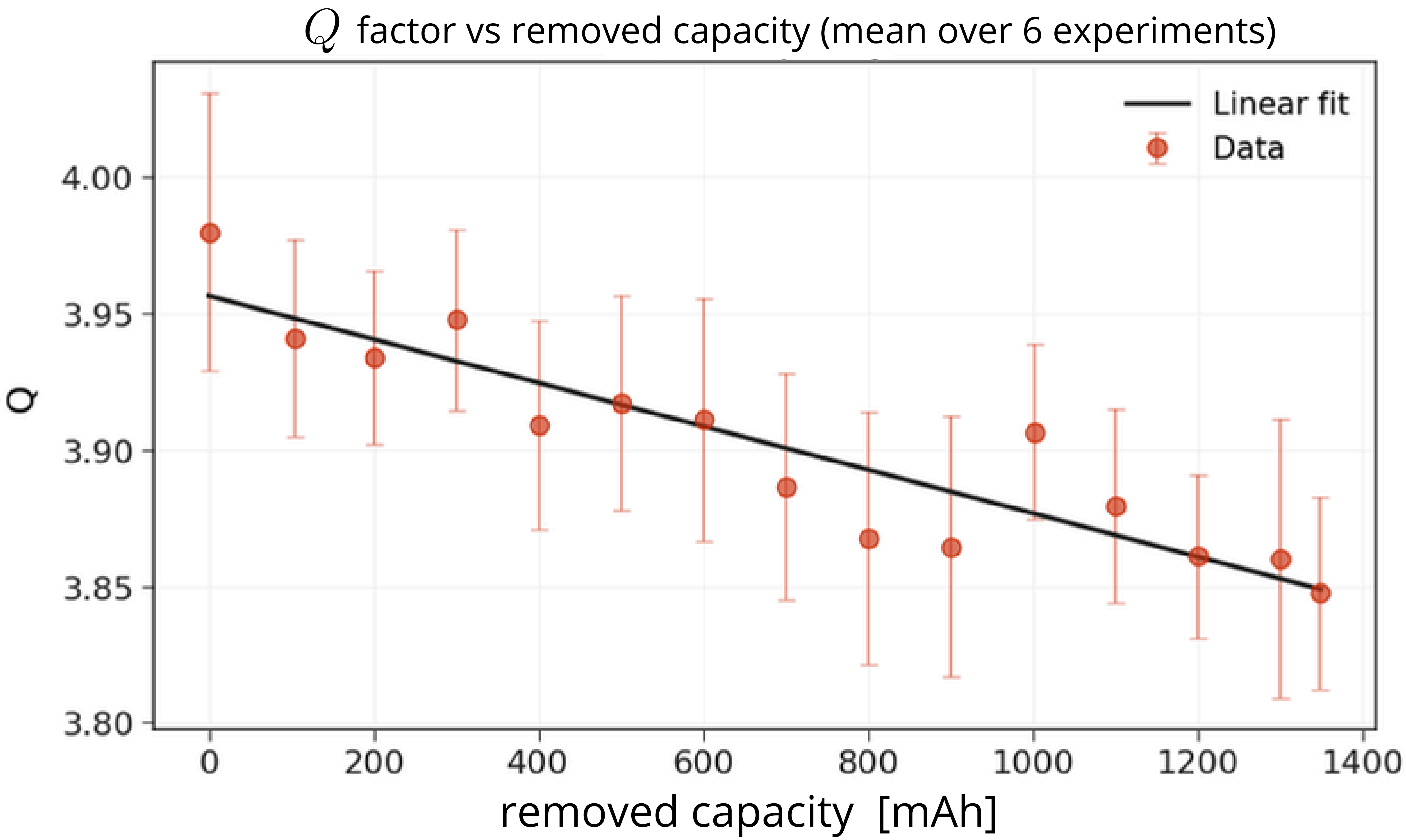
Q factor for our experimental curve

$$Q = \frac{f_{peak}}{\Delta f_{midheight}}$$

Typical gain curve for one battery



Mechanical resonance method – Experimental results



High Q ⟺ Small damping

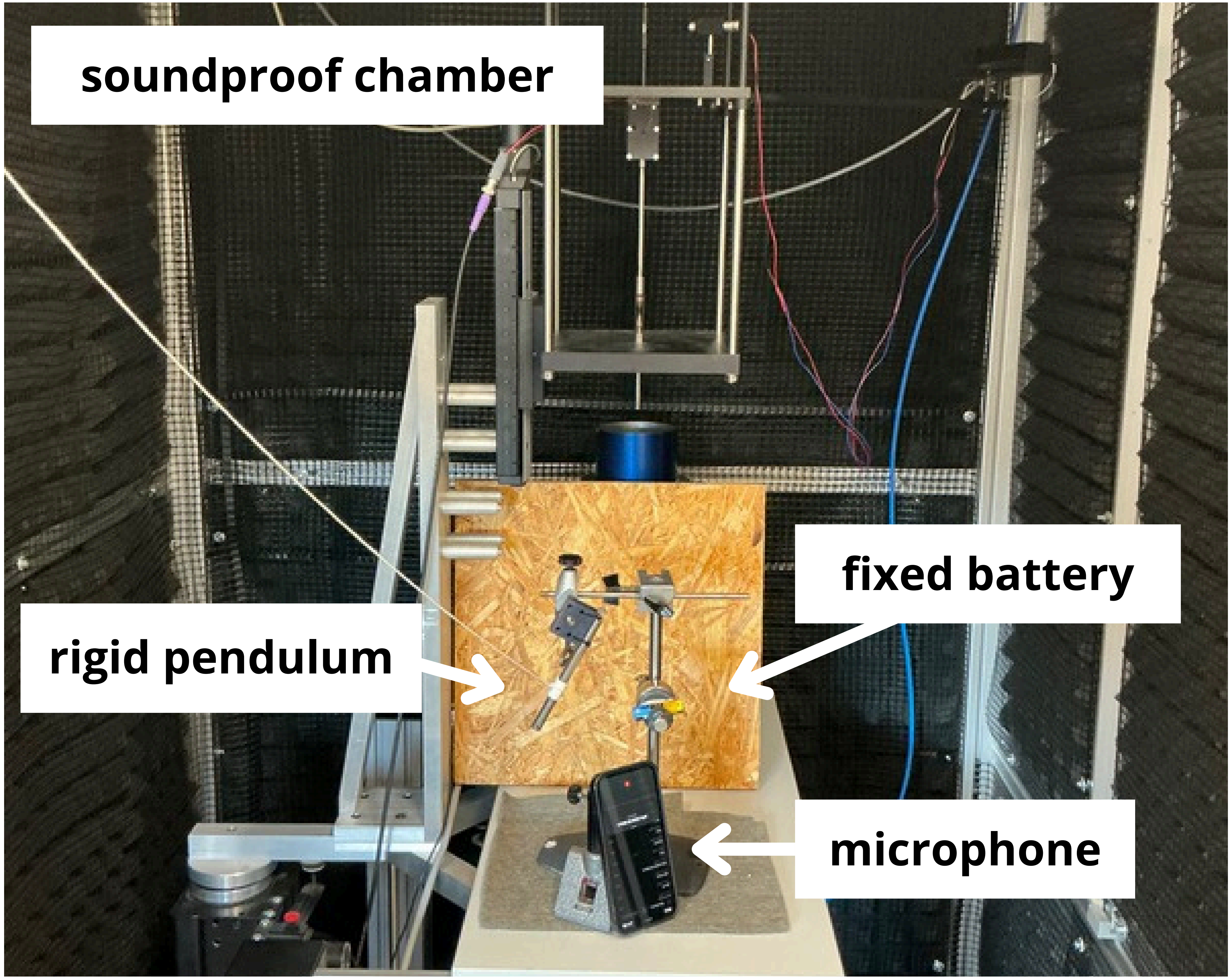
We can **guess the state of charge with a precision of 20%!**

Empirical power domains synthesis

$P \gtrsim 12\text{W}$	$P \ll 12\text{W}$
→ **High** power	→ **Low** power
→ SoC identification : • **Zinc grain damping** • **Bouncing method**	→ SoC identification : • **Other damping trend** • **Mechanical resonance method**

SoC = State of charge

Collision sound analysis method – Experimental setup



Collision sound analysis method – Power domain

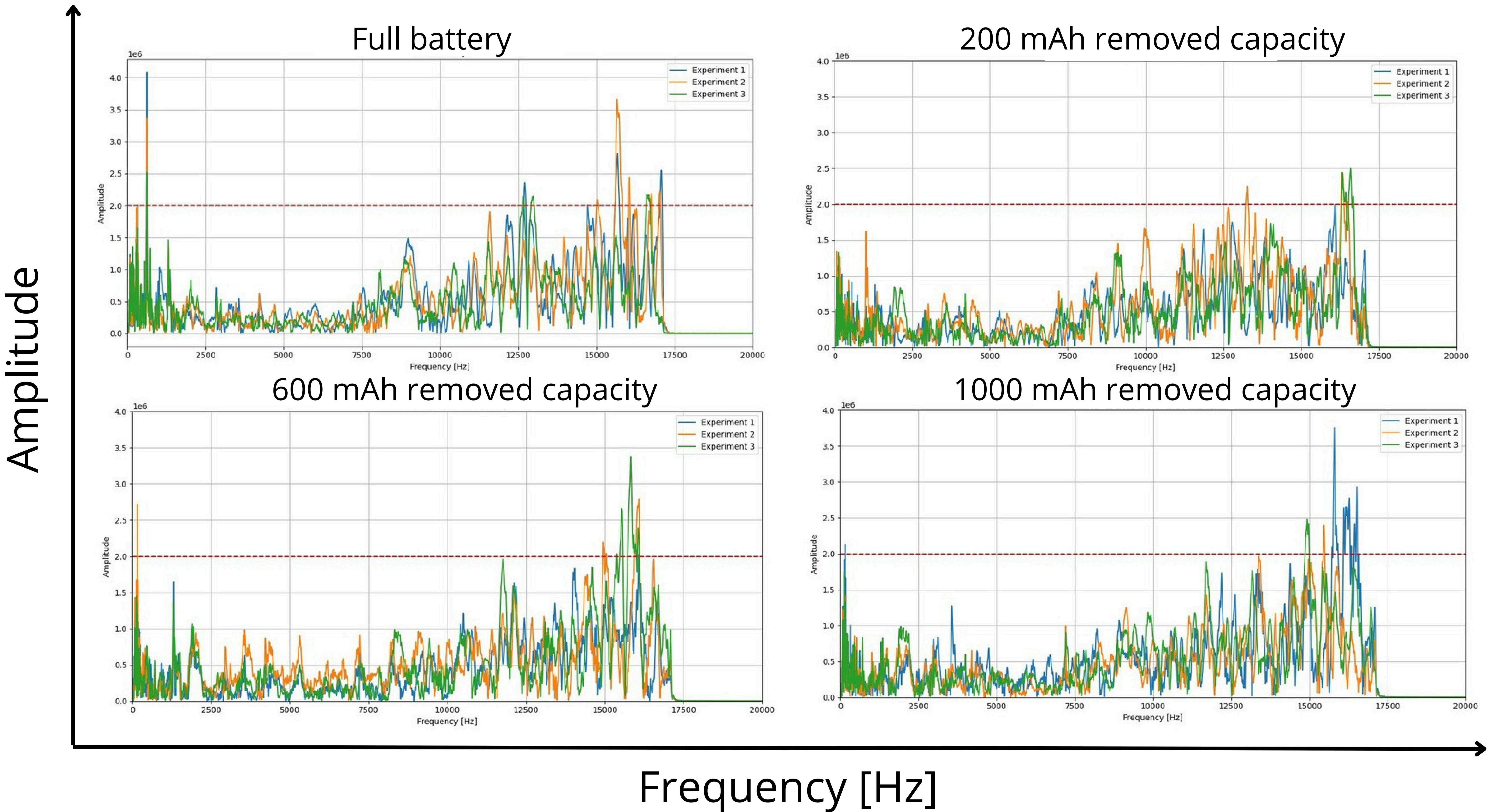
$$P = \frac{mg\frac{L}{2}\left(1 - \cos\theta\right)}{\Delta t_{impact}} \simeq 20\mathrm{W}$$

High power

We'd expect the Zinc grain damping to come into play

Collision sound analysis method – Approach

Frequency spectrum for different state of charge



Collision sound analysis method – Approach

Difficult to analyze !

- Hard to single out a parameter to look at

But...

- We can use **Machine Learning** in an attempt to find that out

Collision sound analysis method – Classification approach

EPFL

Testing with different brands

Take a lot of discharged and charged batteries

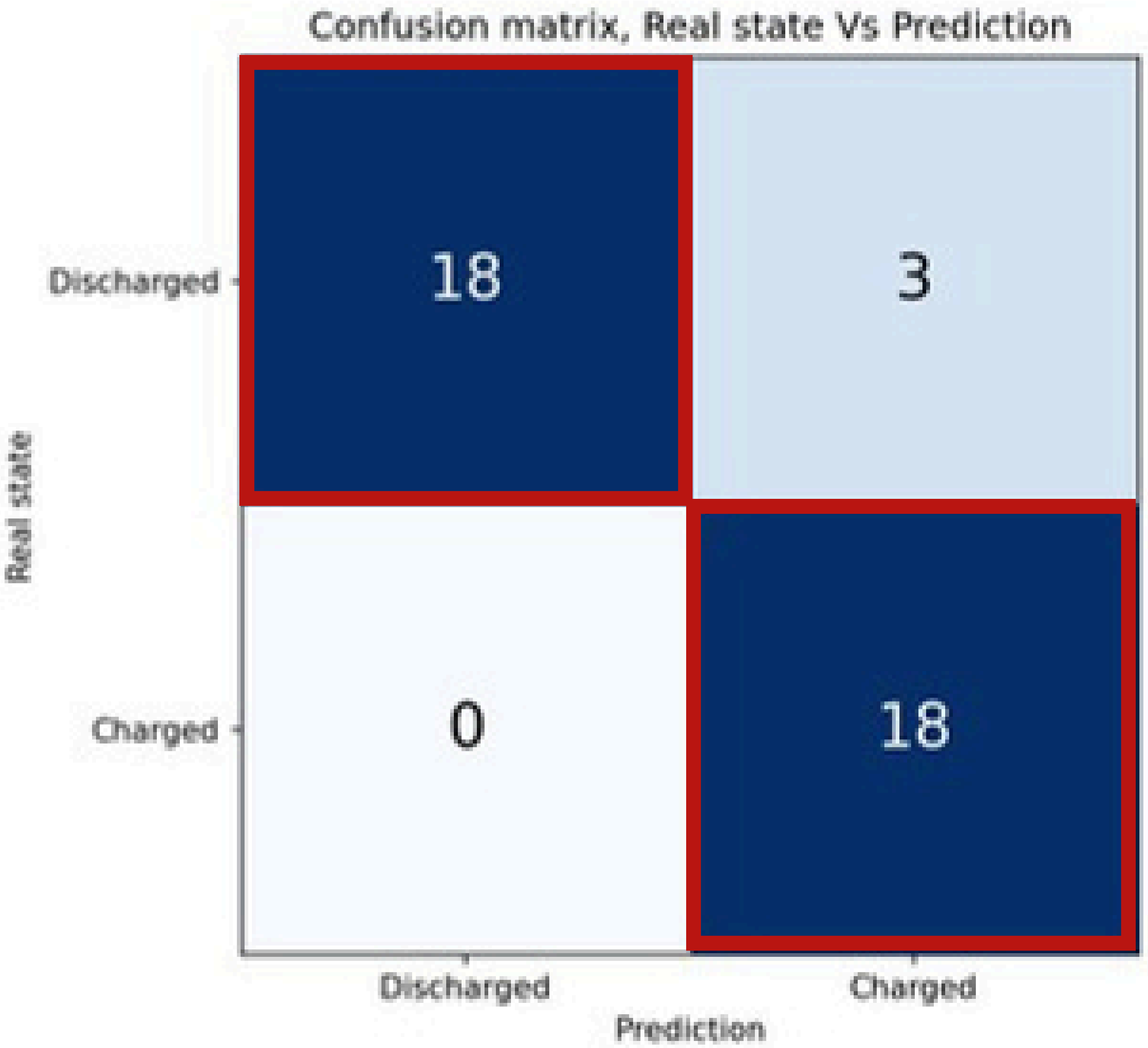
Record the sound they make

Train a model to learn what is the difference between charged and discharged

Apply that knowledge to identify different states of charge

Collision sound analysis method – Results

Model performance on a random train-test data splitting

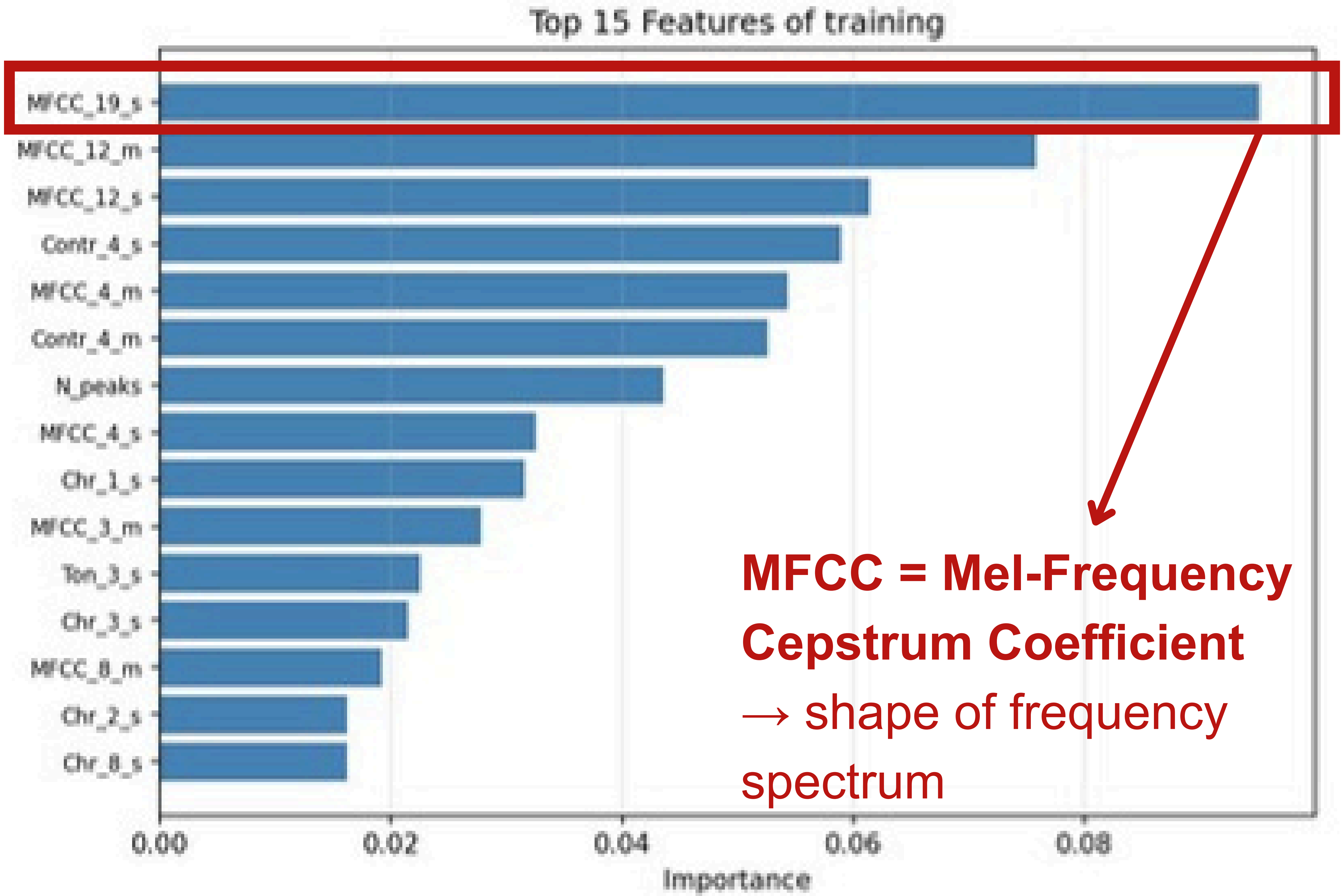


92 % of accuracy !

Correctly predicted state

Collision sound analysis method – Results

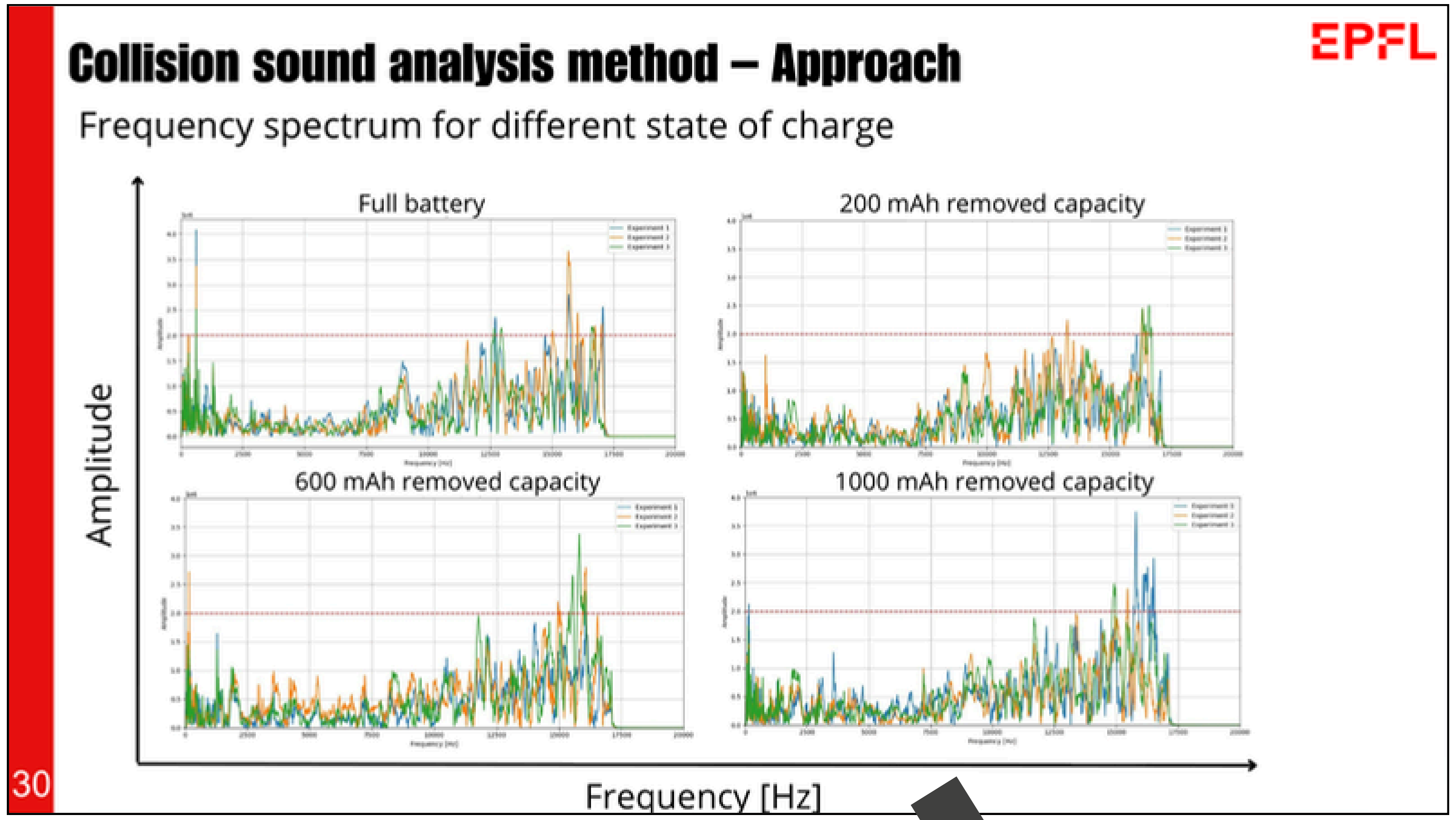
Most important sound feature for training – what differentiates the two states ?



MFCC = Mel-Frequency Cepstrum Coefficient

→ shape of frequency spectrum

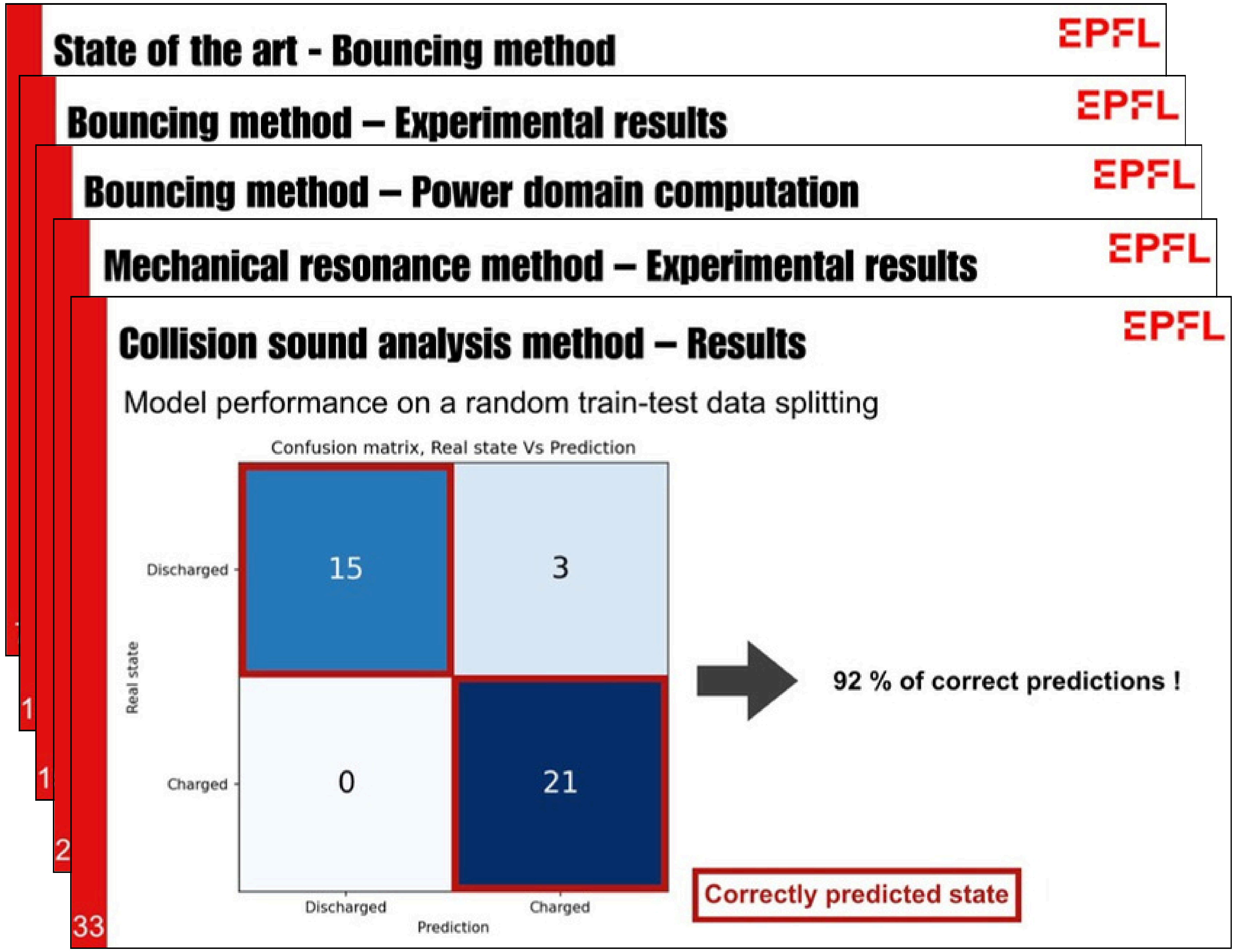
Collision sound analysis method – Analysis



Possible to now **differentiate them consistently in a way that makes sense**

MFCC (Cepstrum Analysis)

Summary



→ Understanding the **bouncing experiment**

→ The two different **power regimes**

$P \gtrsim 12\mathrm{W}$	$P \ll 12\mathrm{W}$
→ **High** power	→ **Low** power
→ SoC identification : • **Zinc grain damping trend** • **Bouncing method** • **Collision sound analysis** • **MFCC**	→ SoC identification : • **Other damping trend** • **Mechanical resonance method**

Thank you for your attention !

Appendices

Why alkaline battery ?

→ Type of batteries presented in the reference video of the IPT problem

→ Most common non rechargeable batteries, phenomenon does not occur for Ni-MH rechargeable batteries

→ Phenomenon depends on the material of the batteries and the element produced in the oxydation process

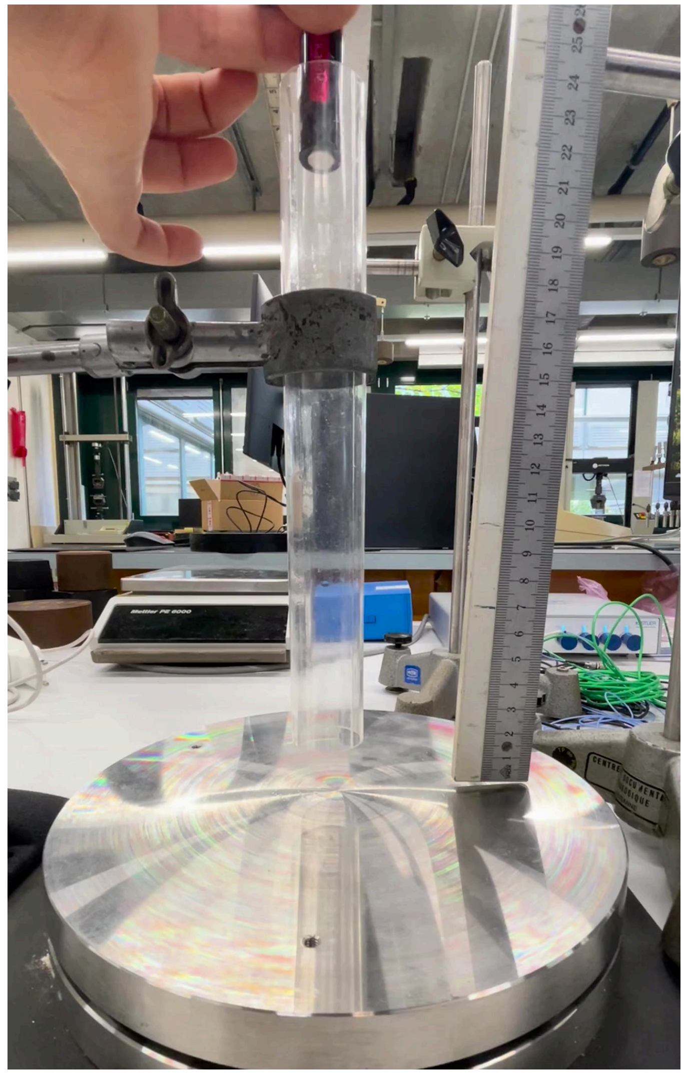
Discharge protocol

→ Different states of charge were established by discharging the batteries at a constant current of 0.5A for controlled durations, thereby extracting well-defined amounts of capacity
→ Total of 15 batteries were discharged in 100 mAh increments
→ Maximum extractable capacity was slightly below 1400 mAh, which proved sufficient to observe and characterize the bouncing phenomenon

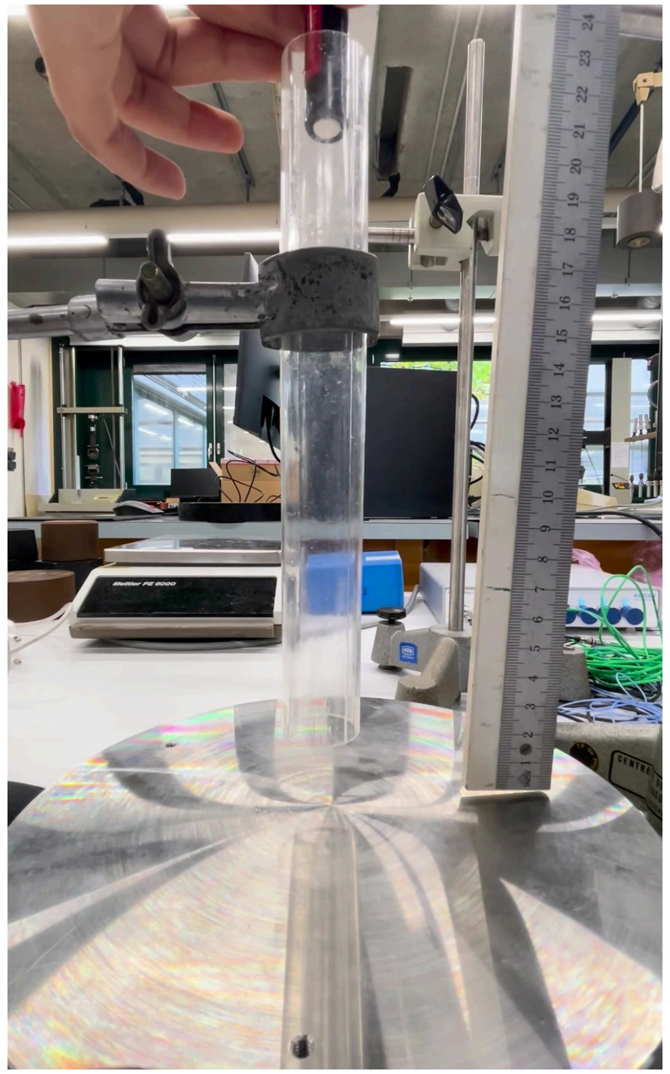
Absima charger CTC-1 Touch, used in discharger mode

Causes of the difference between two bounce experiments

Uncertainty caused by the setup



Full capacity



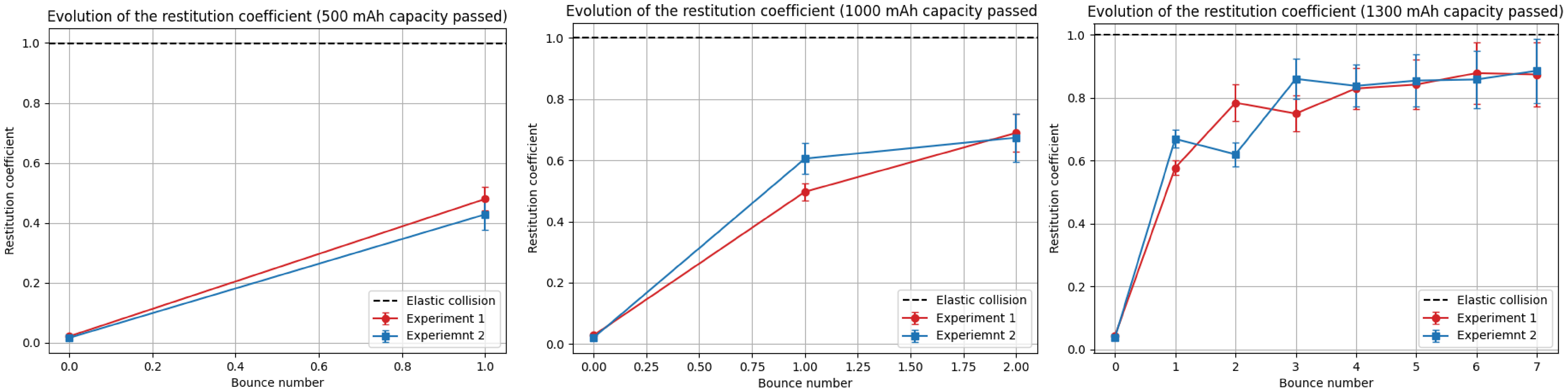
800 mAh passed capacity

1300 mAh passed capacity

→ Friction induced by the battery rotating during the fall → dissipation of energy before collision

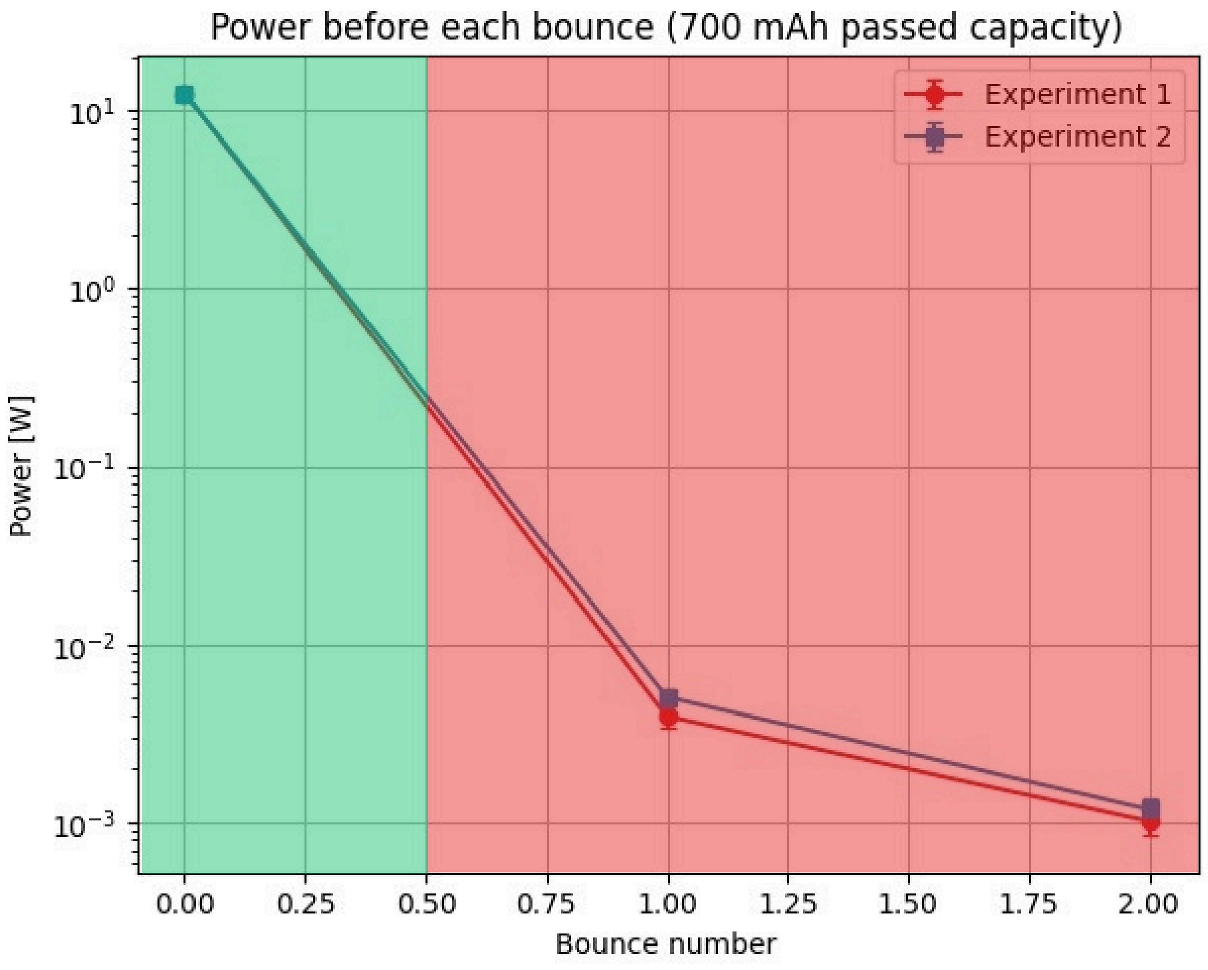
→ Difference in the angle of collision → collision surface not completely flat which induced slightly different bounce

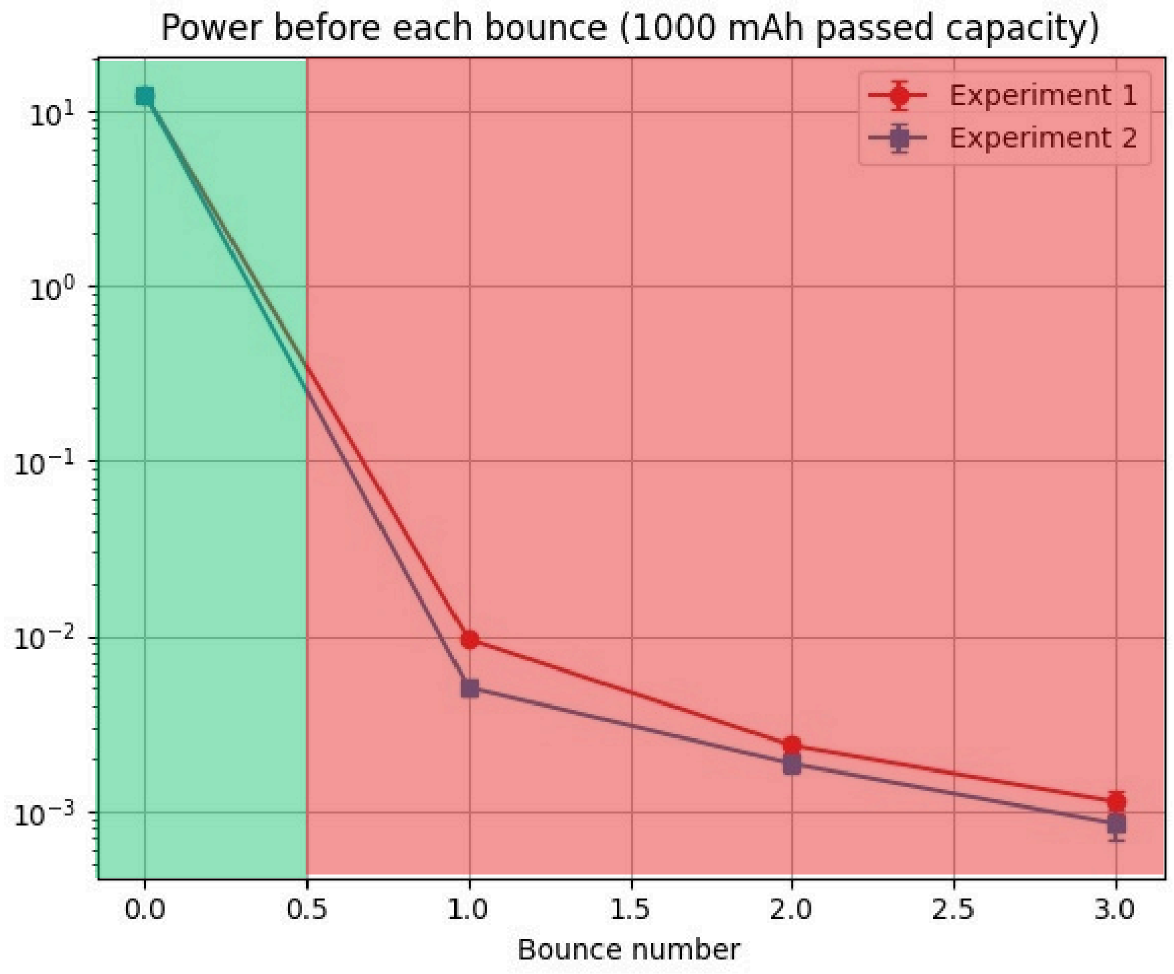
Evolution of non constant COR for different batteries

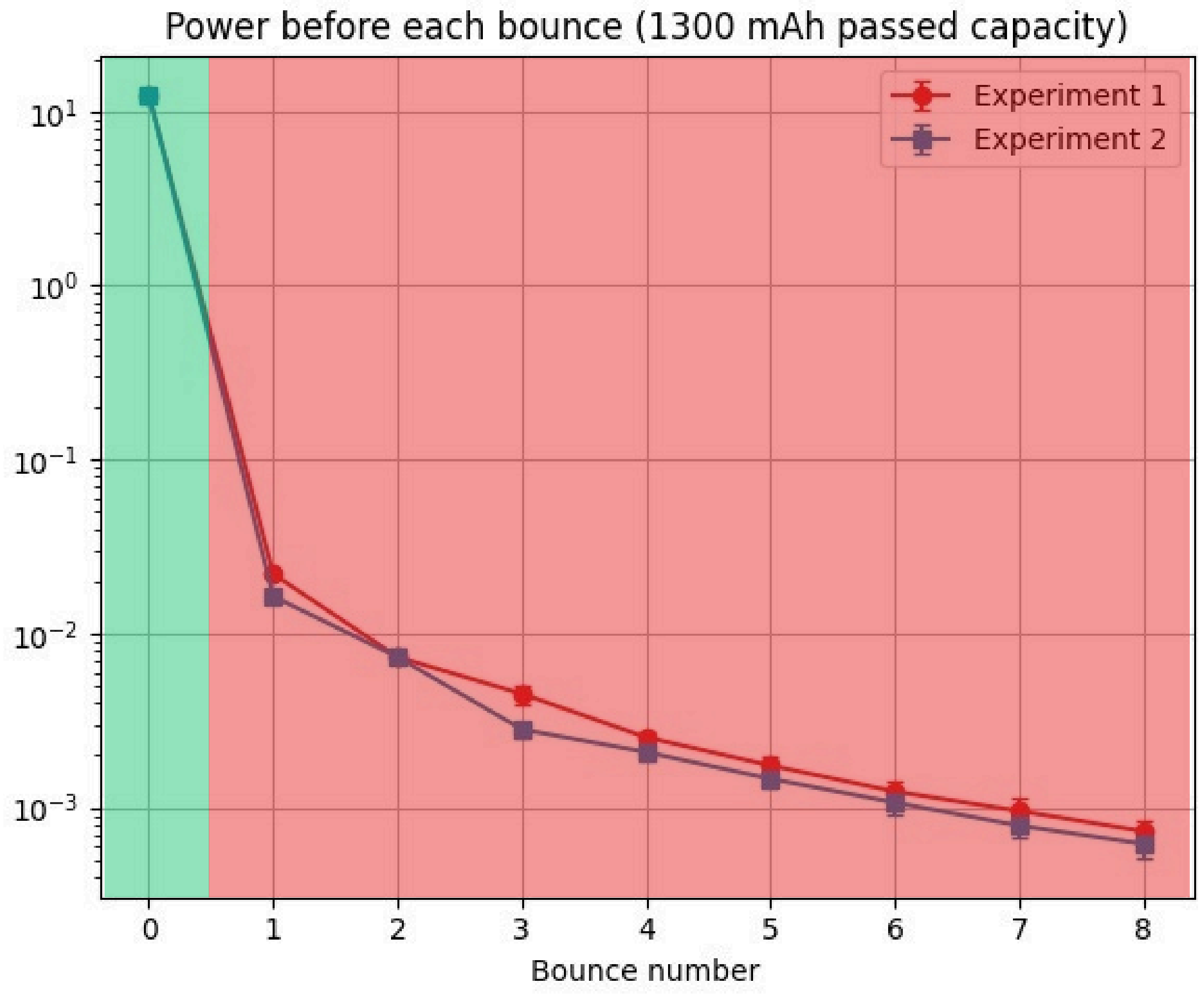


→ Increase of the coefficient of restitution measurable for batteries that underwent more than two bounces, suggesting a evolution of damping property as a function of the transmitted energy

Power domains for different batteries



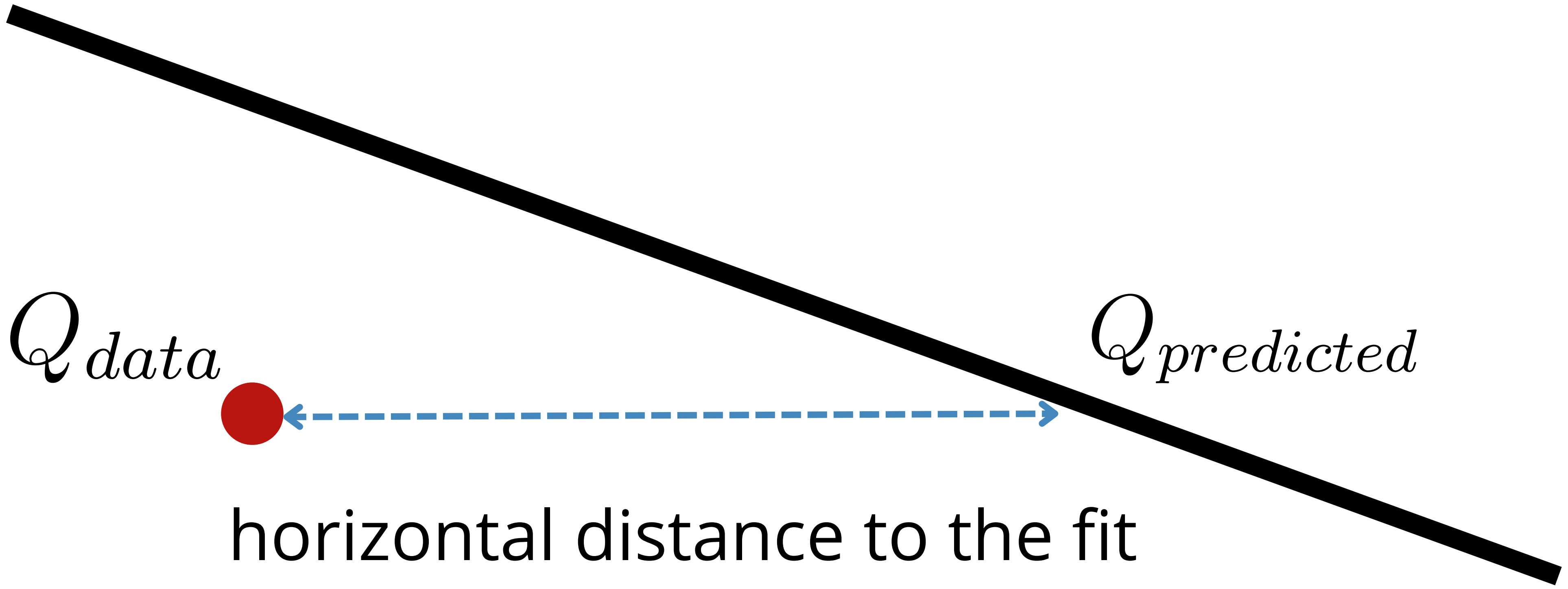




High Energy

Low Energy

Prediction precision



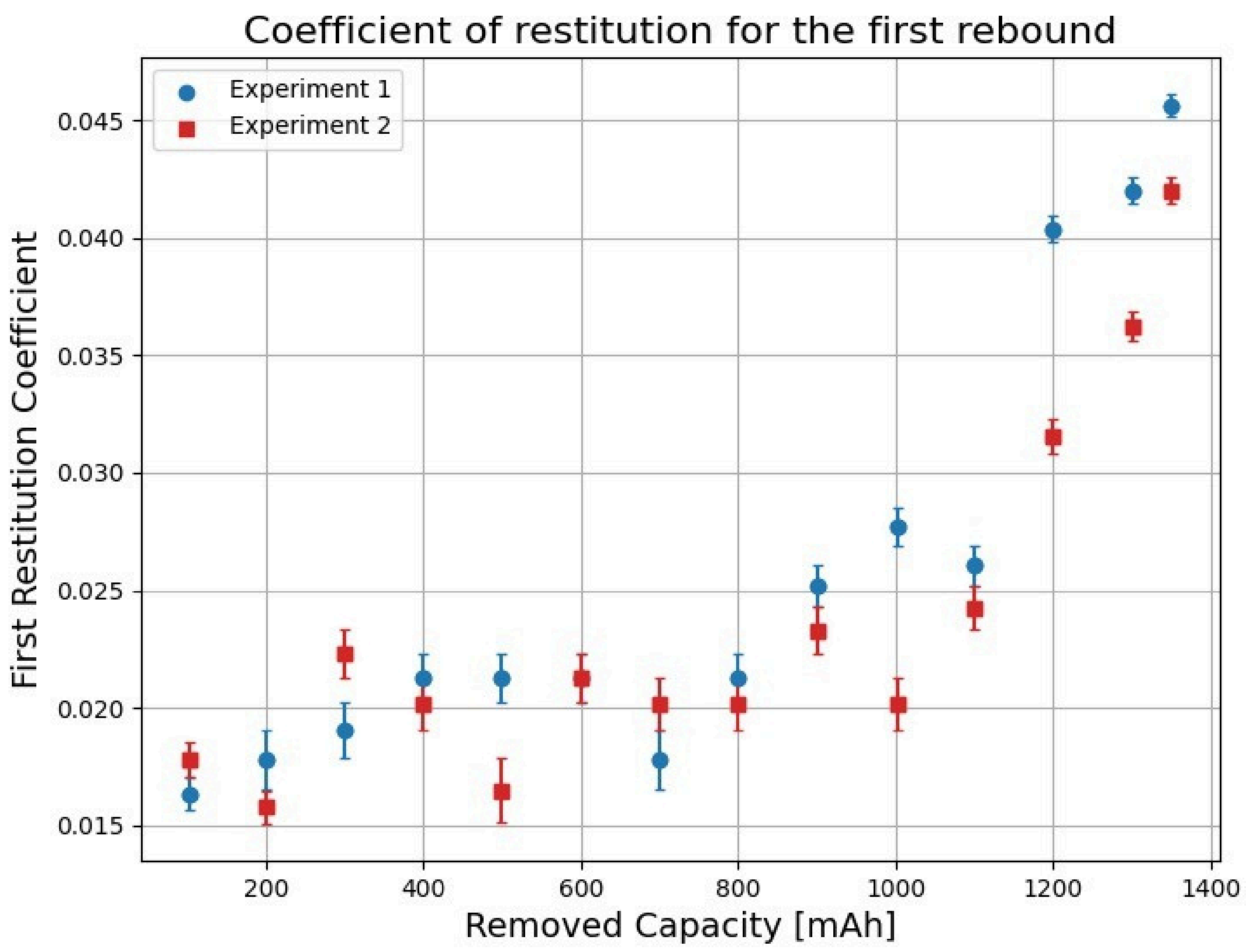
Normalized mean absolute error :

$$MAE_{normalized} = \frac{\langle |Q_{predicted} - Q_{data}| \rangle}{\overline{Q}_{data}}$$

$$= 20\%$$

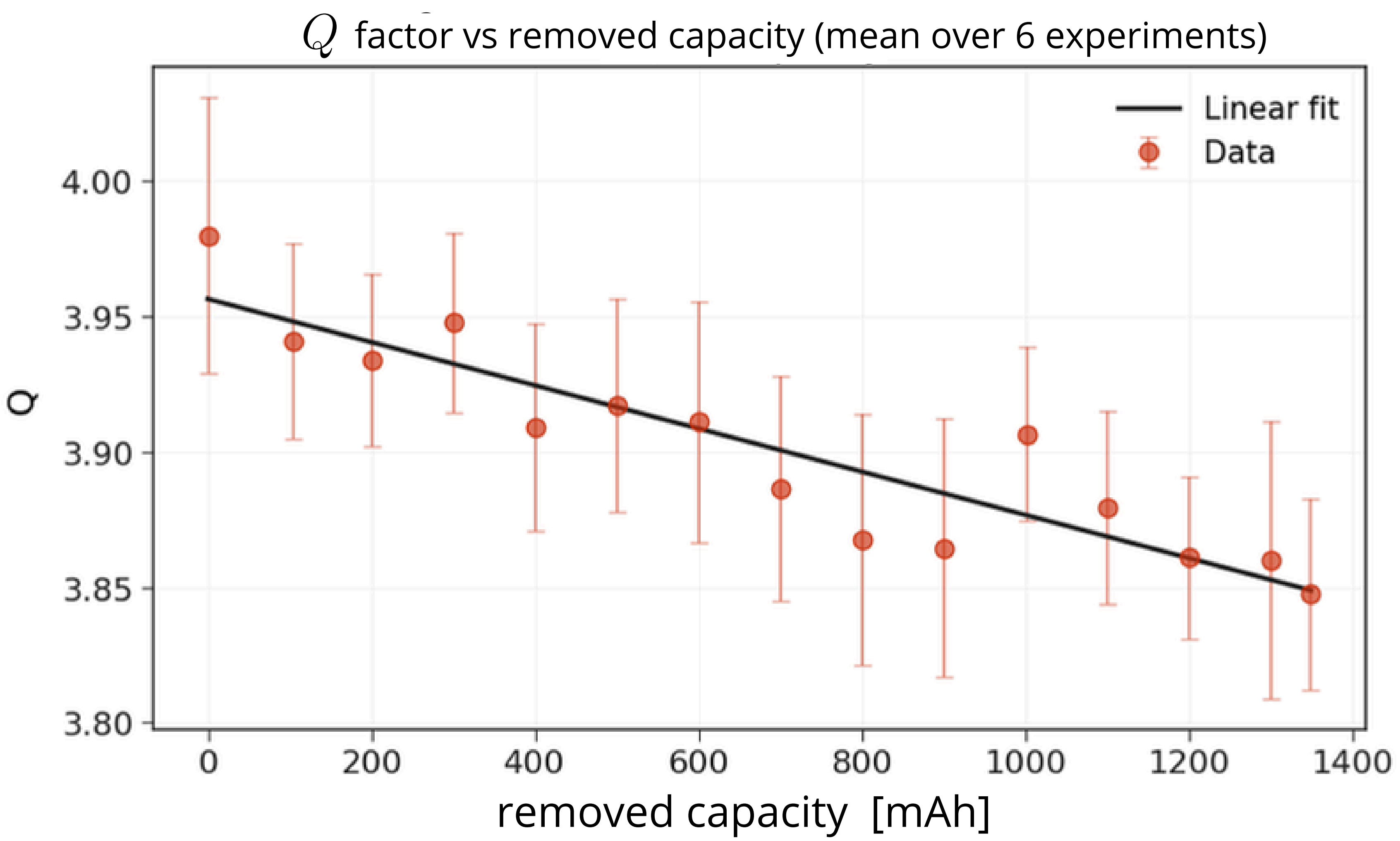
Comparison of the rebound and resonance

Rebound



- Deacreasing damping

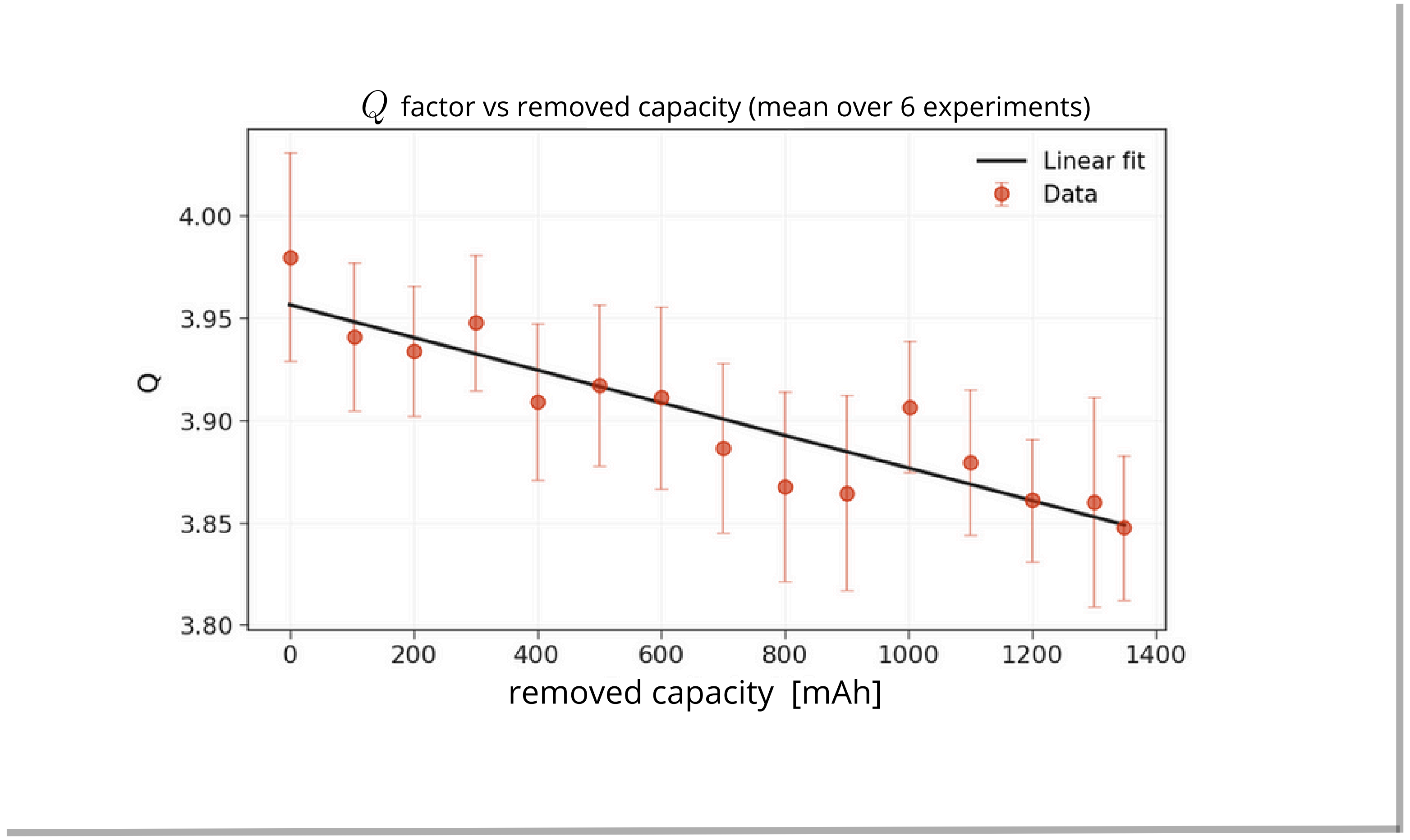
Resonance



- Increasing damping damping

2 fundamentally different phenomenon

Explanation of the linear trend



RedOx reaction

Oxidation

$$Zn + 4OH^- \rightarrow Zn(OH)_4^{2-} + 2e^-$$

$$Zn(OH)_4^{2-} \rightarrow ZnO + H_2O + 2OH^-$$

$$MnO_2 + H_2O + e^- \rightarrow MnOOH + OH^-$$

Reduction

- gradual dischargment with constant current

➡ The chemical reaction evolves at constant rate

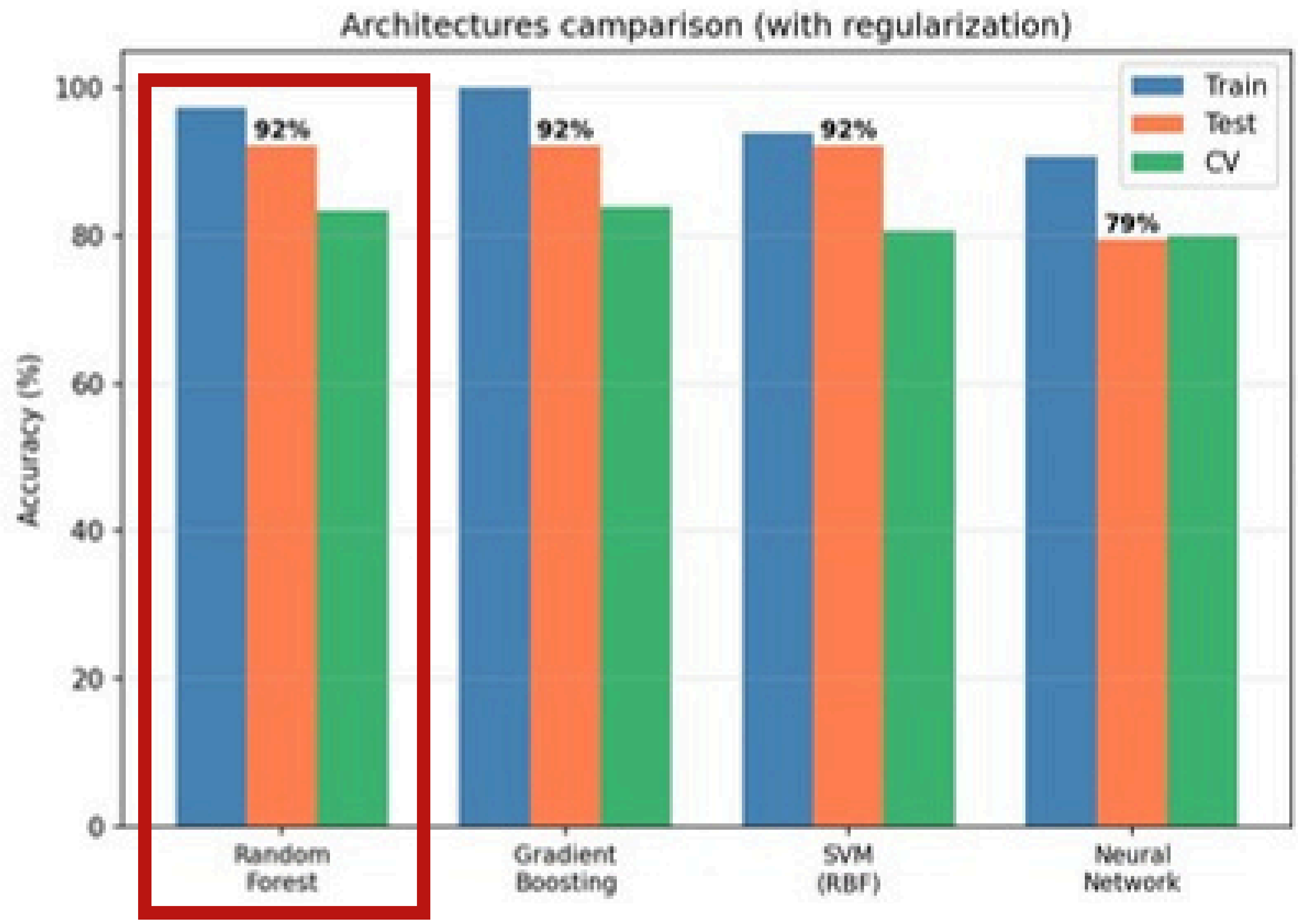
➡ Not surprising to see linear behaviours for different passed capacities

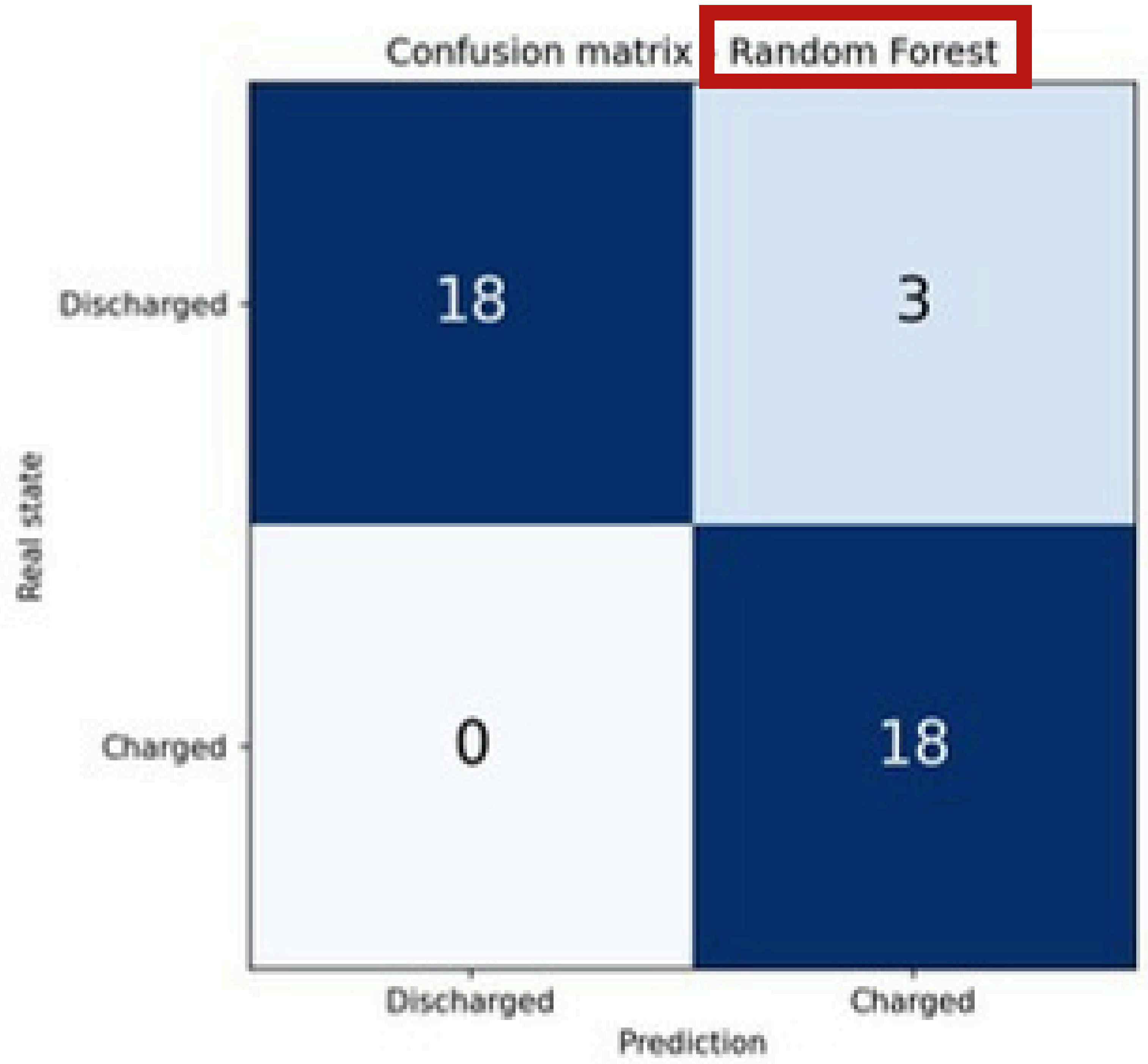
Power calculation of the sound method

potential energy of the bar being released at 90°,
taking into consideration the center of gravity

$$P = \frac{mg\frac{L}{2}\left(1 - \cos\theta\right)}{\Delta t_{impact}} \simeq \frac{0.130 \times 9.81 \times \frac{0.13}{2}}{0.004} \simeq 20\mathrm{W}$$

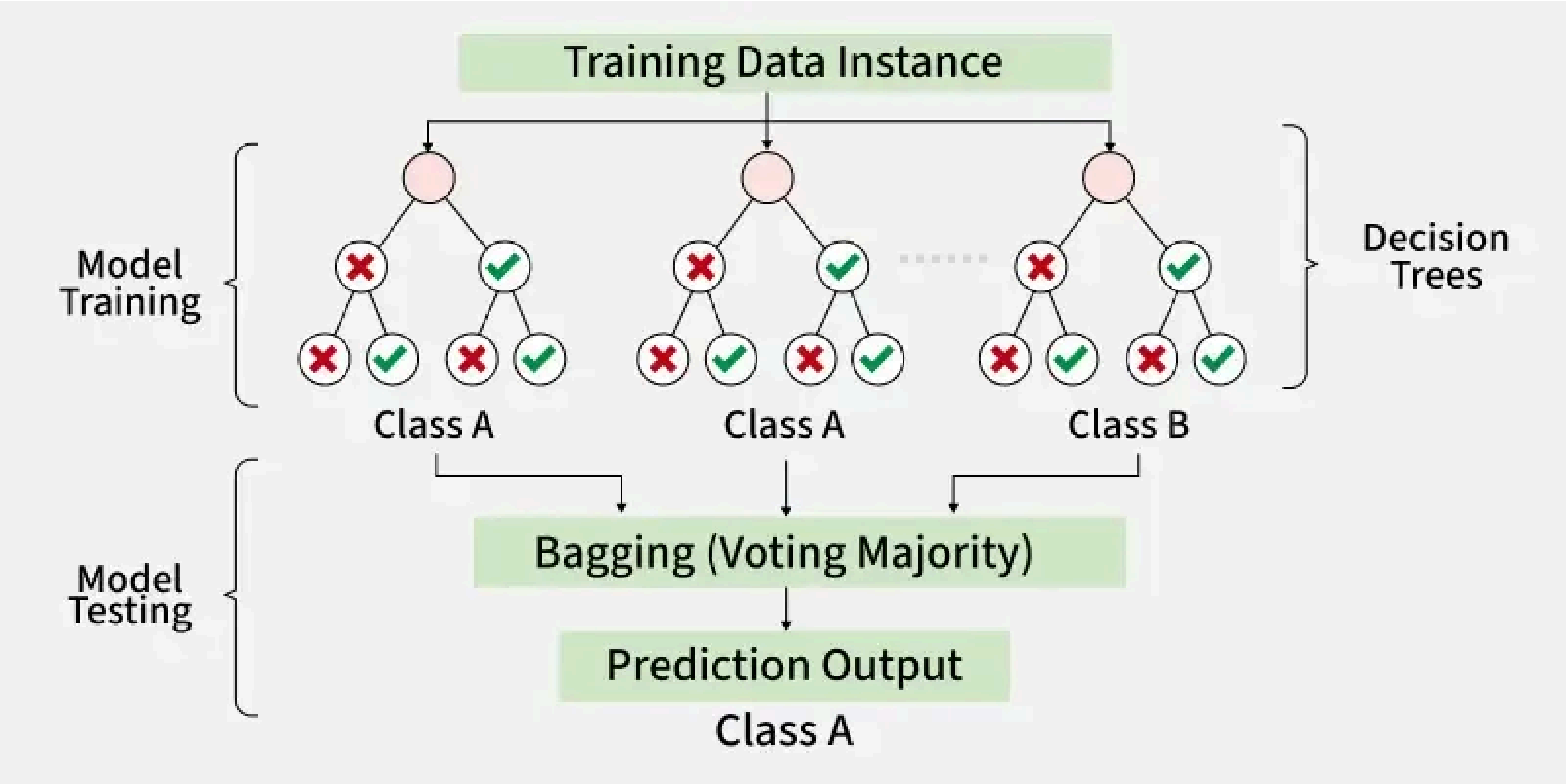
Machine Learning – Model training precision



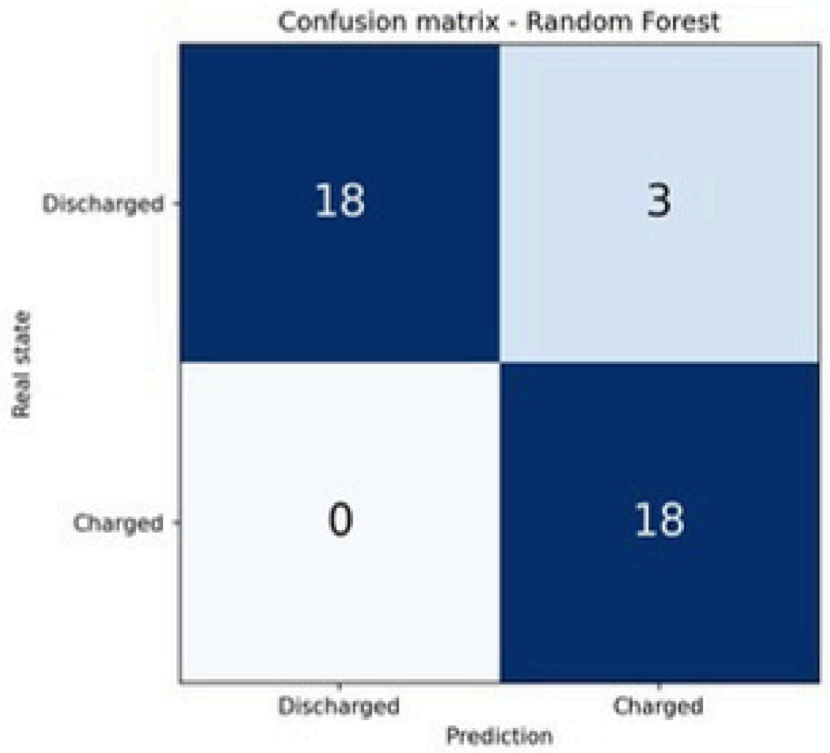


Accuracy :

Machine Learning – Random forest



Machine Learning – metrics

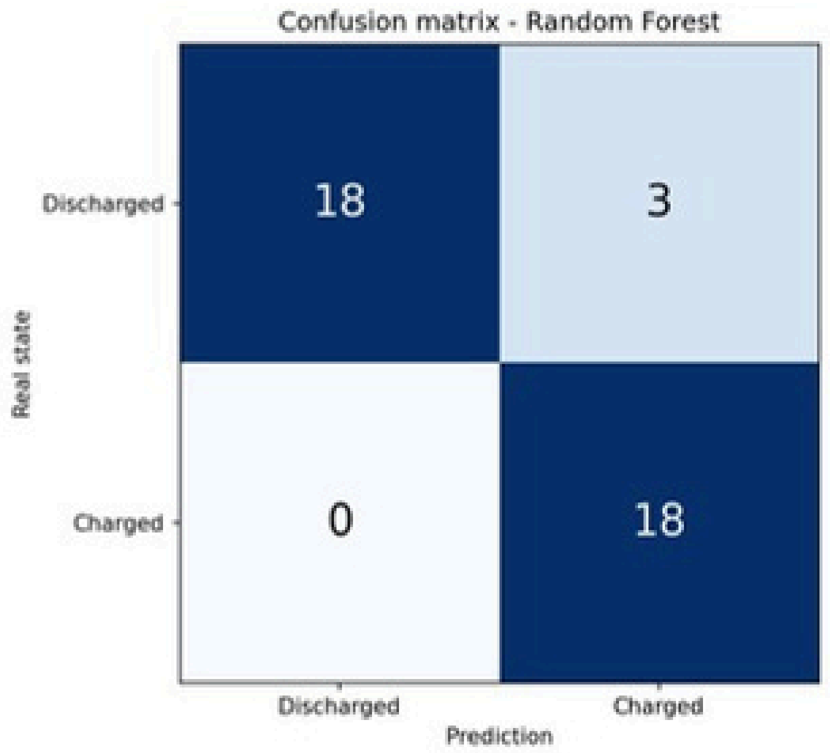


$$\text{Accuracy} = \frac{TP+TN}{TP+TN+FP+FN}$$ = 92%

$$\text{Precision} = \frac{TP}{TP+FP}$$ for discharged : 86% for charged : 100%

$$\text{Recall} = \frac{TP}{TP+FN}$$ for discharged : 100% for charged : 86%

Machine Learning – metrics

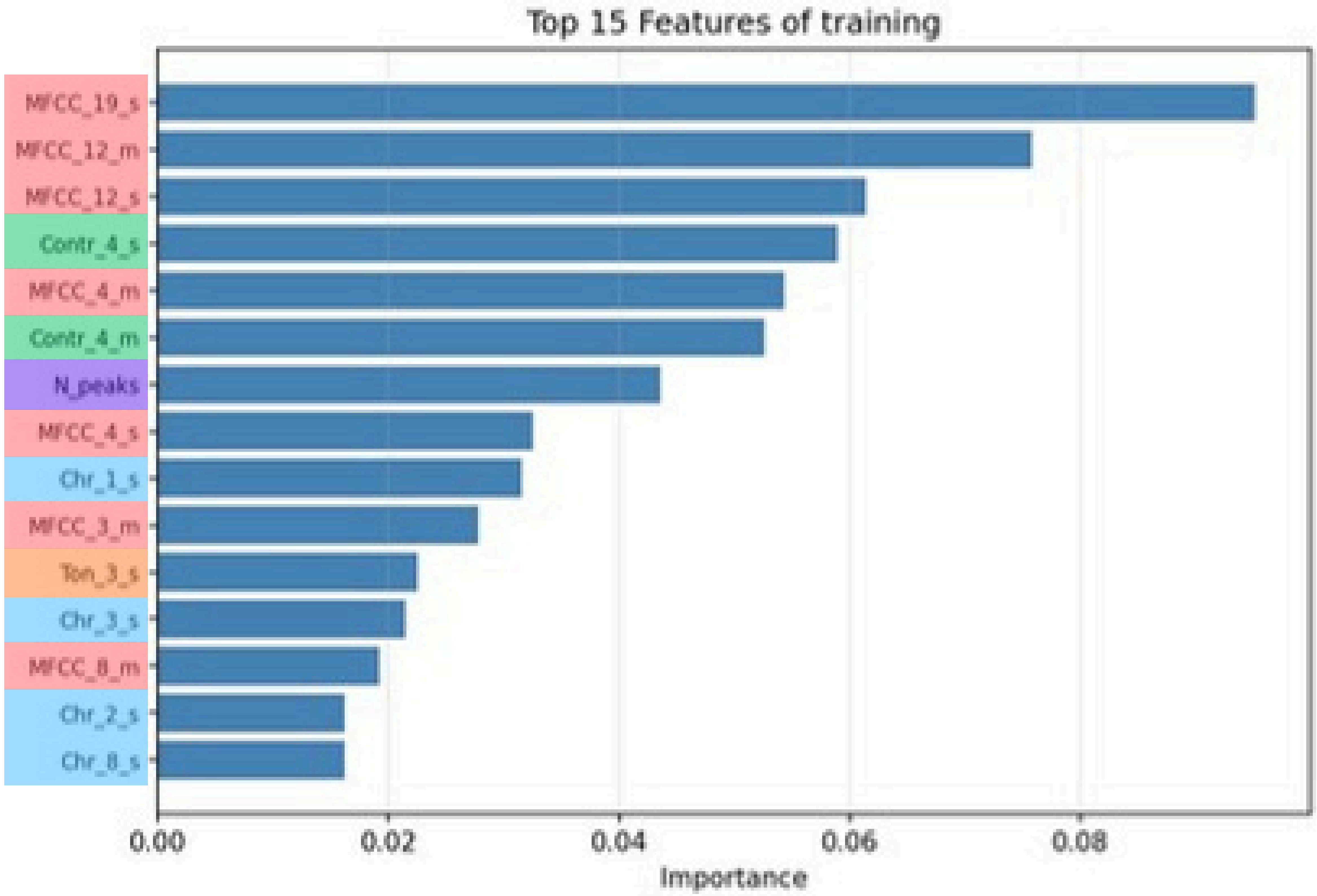


F score to maximise the precision and recall :

$$F_1 = 2 \cdot \frac{\mathrm{Precision} \cdot \mathrm{Recall}}{\mathrm{Precision} + \mathrm{Recall}} = 92\%$$

Excellent !

Machine Learning – Feature explanations



MFCC (Mel-Frequency Cepstrum Coefficient)

Contr (spectral contrast)

N_peaks (number of peaks)

Chr (chroma)

Ton (Tonnetz)

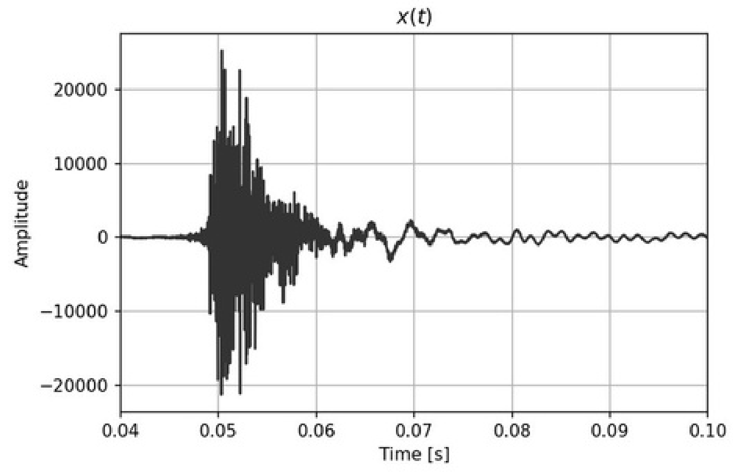
Collision sound analysis method – Analysis

MFCC, the spectrum of the spectrum

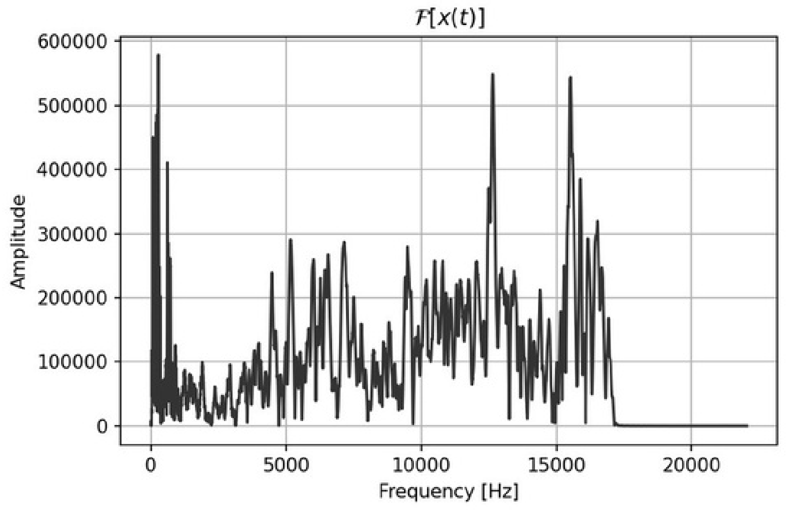
Mel-Frequency Cepstrum Coefficient

$$C_{\mathrm{MFCC}}(t) = \mathcal{F}^{-1}\left[\log\left(\mathcal{F}[x(t)]\right)\right]$$

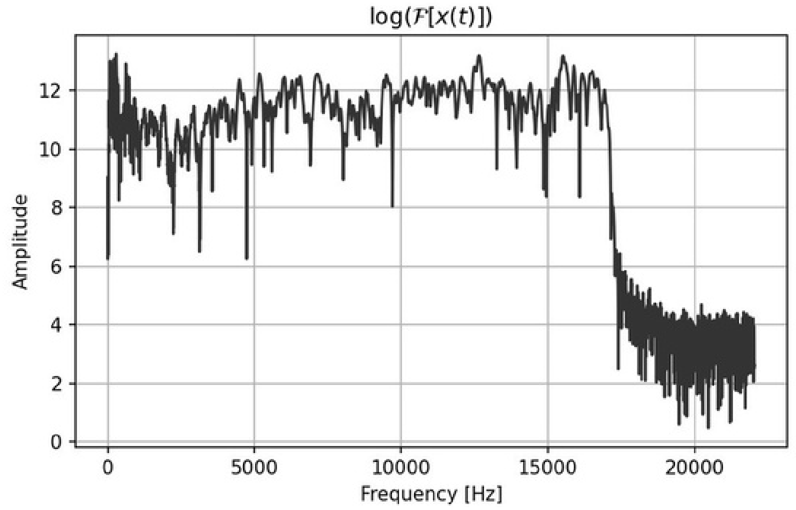
Sound signal



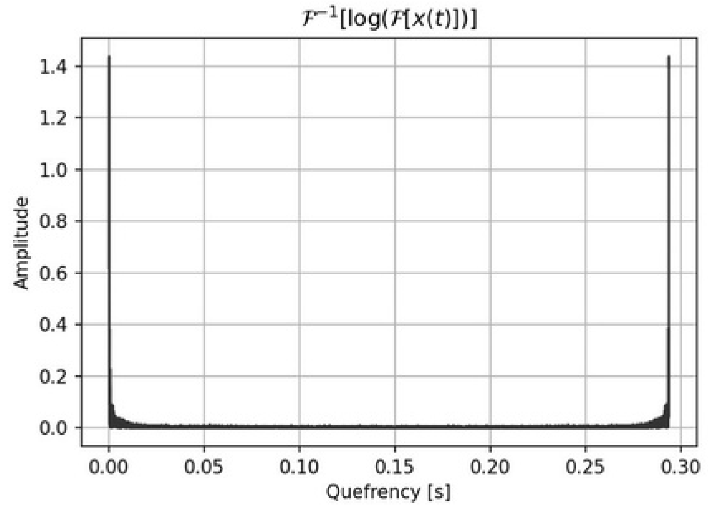
Fourier transform



Logarithm



Inverse fourier transform

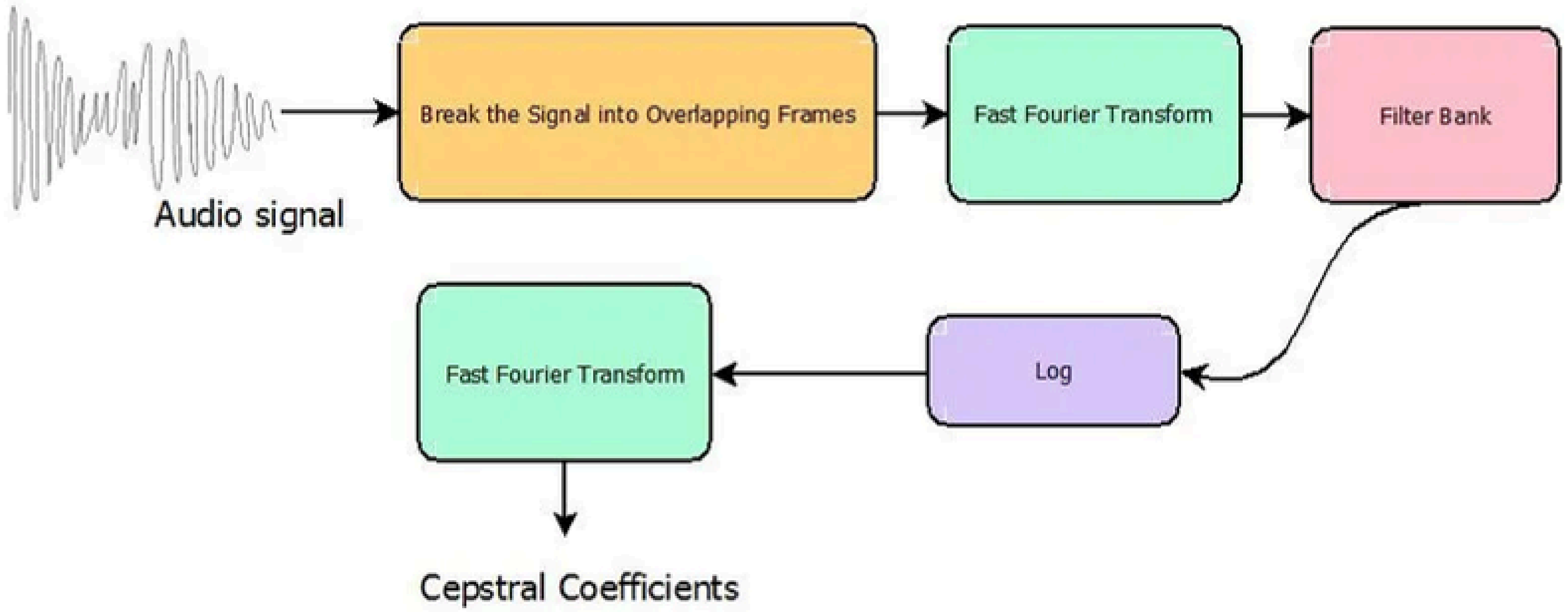


→ analysis of the **periodic properties of the frequency spectrum**

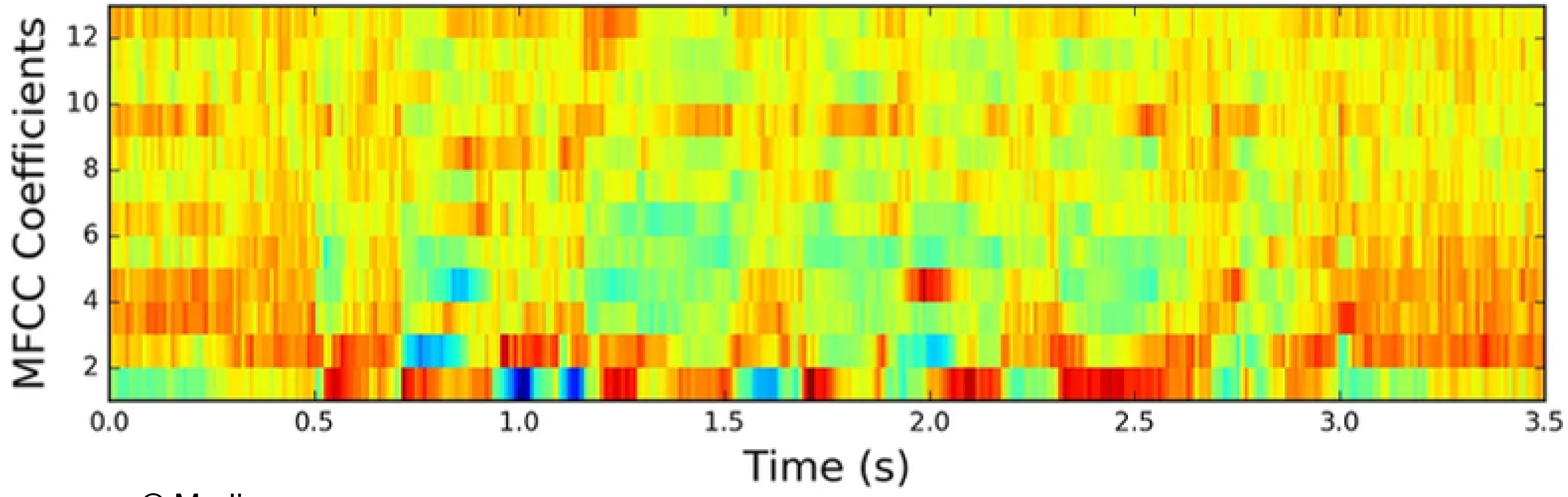
→ give **new insight** on complex signal !

Machine Learning – Feature explanations simlpified

MFCC (Mel-Frequency Cepstrum Coefficient)



Complex coefficient describinng the shape of the frequency spectrum



mean or std accross the time gives respectively MFCC_i_m or MFCC_i_s

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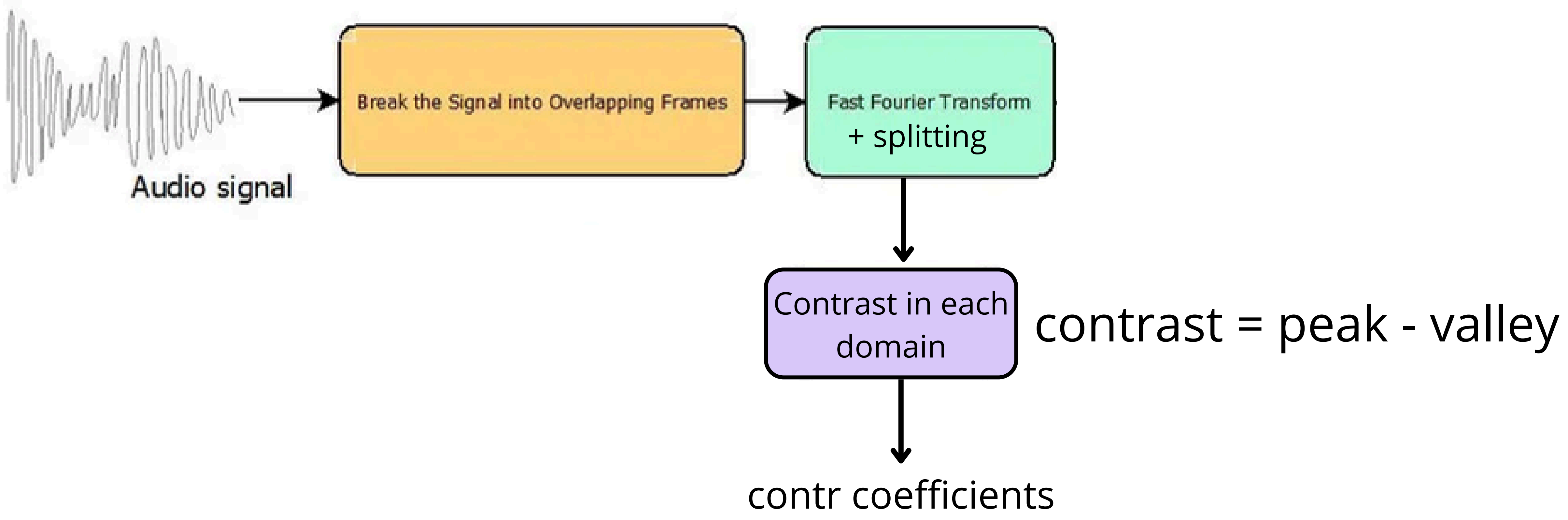
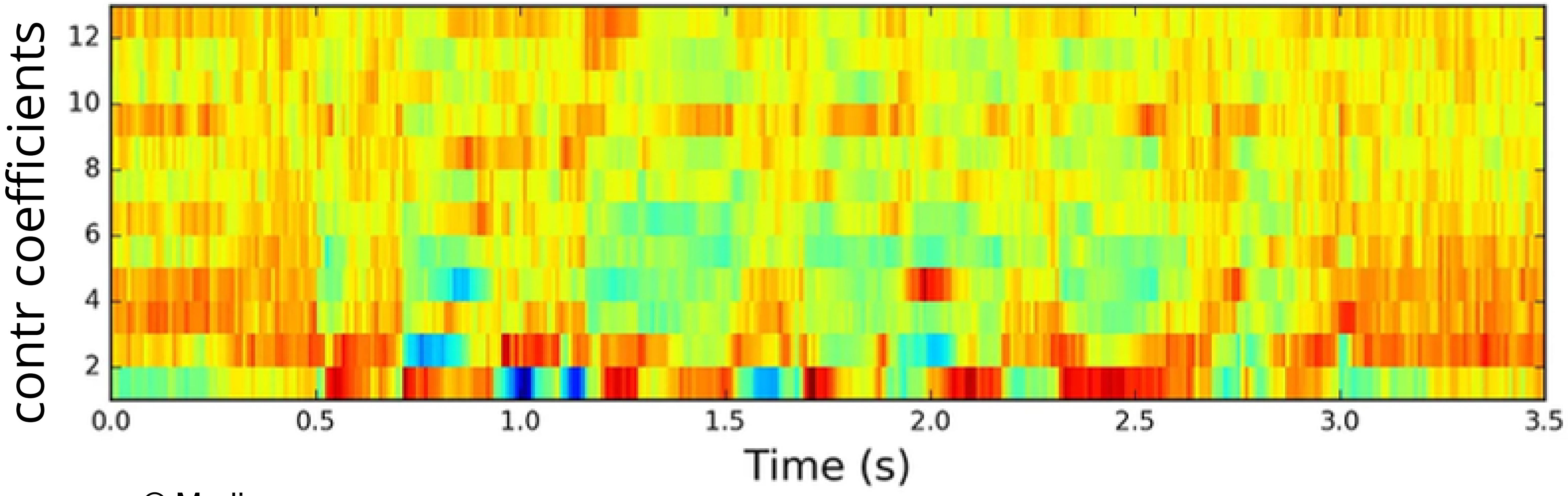
Contr (spectral contrast)





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mean or std accross the time gives respectively contr_i_m or contr_i_s

Analyzing the smoothness of the frequency spectrum
→ **Whether there is a lot of. harmonics, if it is a resonant material**

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Chr (chroma)

Ton (Tonnetz)

Also complex coefficients used in **musical analysis**

Measures of whether or not a signal has stable harmonics

Less important features here

Other method ideas – Rotating battery

DC motor

1)

- make it turn fast,
- cut the alimentation,
- and study the exponential decay of the angular momentum

No violent tenergy transfers → unlikely to observe somehting

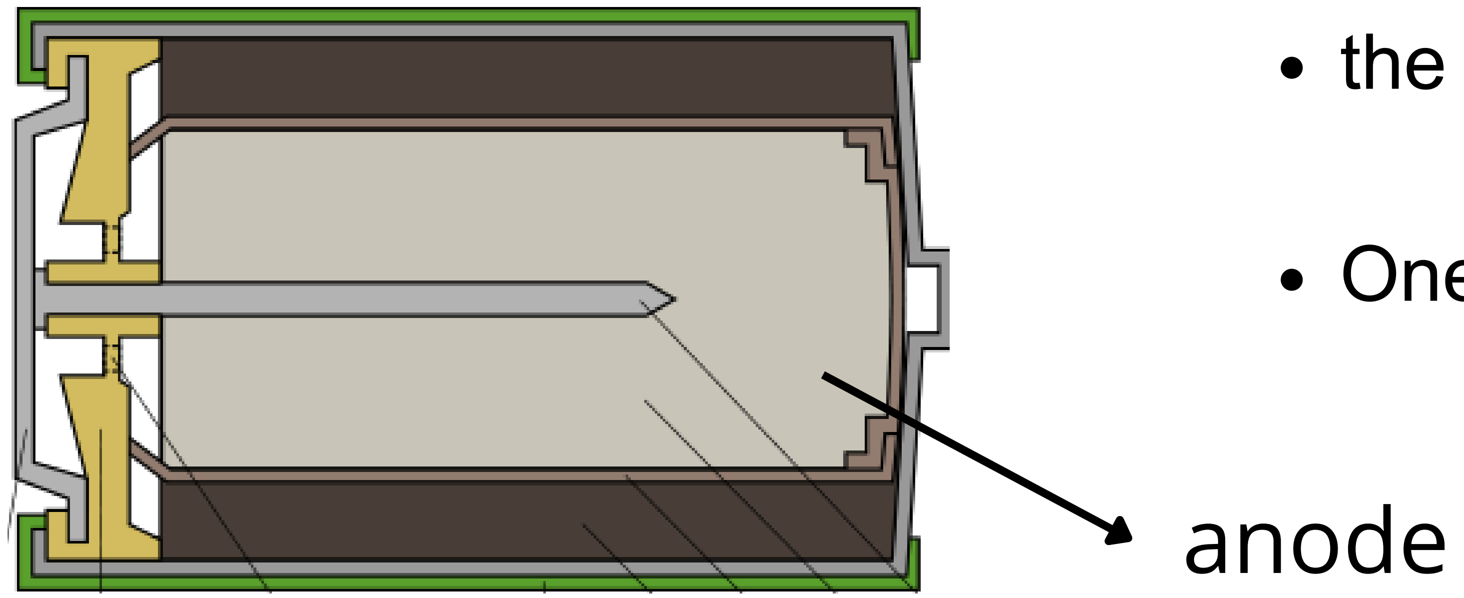
2)

- Put an AC potential for the motor
- Observe how rapidly the movement is able to follow
- More powerful transfers
- Suspiciously low power
- Peak to peak estimation :

$$P = 10^{-8}\mathrm{W}$$

Other method ideas – Time of flight

- Give an impulsion, or just a few cycles of a frequency
- determine the speed of sound by measuring the time it takes for the wave to come back
- Assuming the wave is low energy enough, we neglect the damping, and the amplitude of the returned wave is determined via the reflection coefficient : $R = \frac{Z' - Z}{Z' + Z}$
- the acoustic impedence is also given by $Z = \rho v$
- One can experimentally find the density ρ



One can model directly via the known density change of the anode