Static Speaker

Alberto Rolandi
&
Mathieu Suter

Build an audio speaker without any moving part. Discuss the Maximum bandwidth, Signal-to-noise ratio and Power efficiency achieved with your design. Is it possible to modify your device to use it as a Microphone?

- Maximum bandwidth
- Signal-to-noise ratio
- Power efficiency
- Microphone

What is sound?

Pressure wave: $$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$$

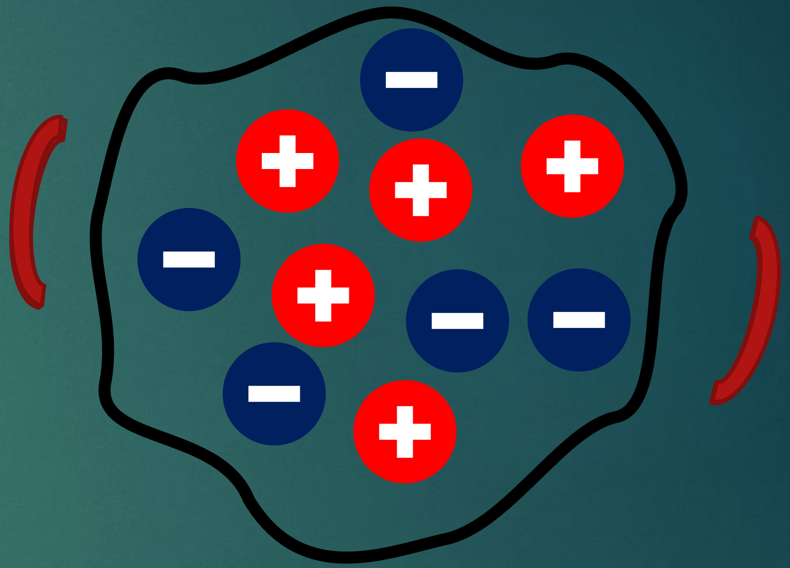
Plasma speaker

What is a plasma?

- Ionized gas
- Neutrality
- Dominated by collective effects
- Very good conductor

Plasma speaker

Modulation of the volume of a plasma with temperature to produce a pressure wave



$$pV = Nk_BT$$

$\Rightarrow$ Change T and V to modify p

Sound production

- Mass conservation

$$\frac{\partial \delta}{\partial t} + \rho_0 div\, \vec{u} = Q$$

- Momentum conservation

$$\rho_0 \frac{\partial \vec{u}}{\partial t} + \overrightarrow{grad}\ p = \vec{F}$$

- Energy conservation

$$\rho_0 T_0 \partial s / \partial t = H$$

- State equation

$$\delta = \left(\frac{\partial \rho}{\partial P}\right)_S + \left(\frac{\partial \rho}{\partial S}\right)_P = (1/c^2)p - (\rho_0/c_P)s$$

Q : mass transfer rate (volumic)

$\vec{F}$: momentum transfer rate (volumic)

H: energy transfer rate (volumic)

[1]

Sound production

Equation for pressure of neutrals

Momentum transfer

$$\Rightarrow \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \nabla^2 p = \frac{(\gamma-1)}{c^2}\frac{\partial H}{\partial t} - div\vec{F}$$

Wave propagation

Joule heating

Sound production

Hypothesis:
Collisions between electrons and neutrals

$$H \propto T_e^{3/2} N_e N_n \langle\sigma\rangle$$

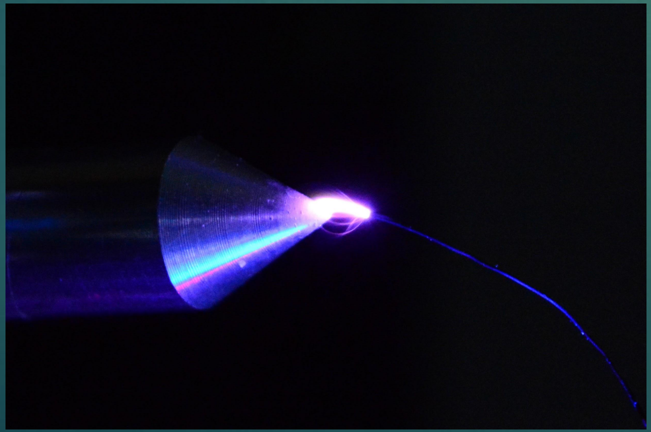
$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \nabla^2 p = \frac{\gamma - 1}{c^2}\frac{\partial}{\partial t}\left(C \cdot N_e N_n T_e^{3/2}\right)$$

Sound from current

Possible setups

Joule heating speaker

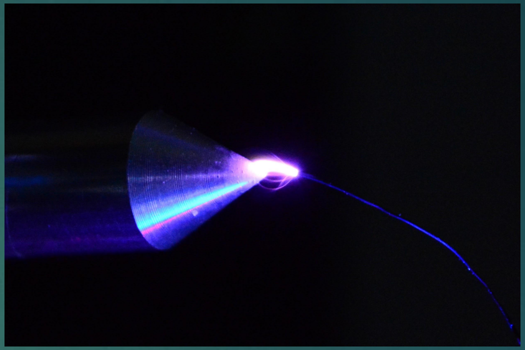
RF discharge



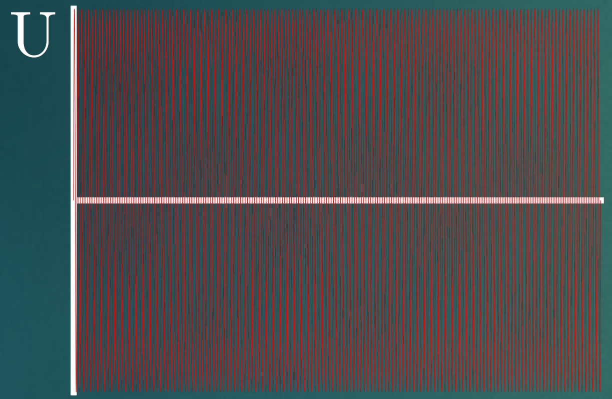
Arc discharge

RF Discharge

1. Produce a plasma with a high voltage

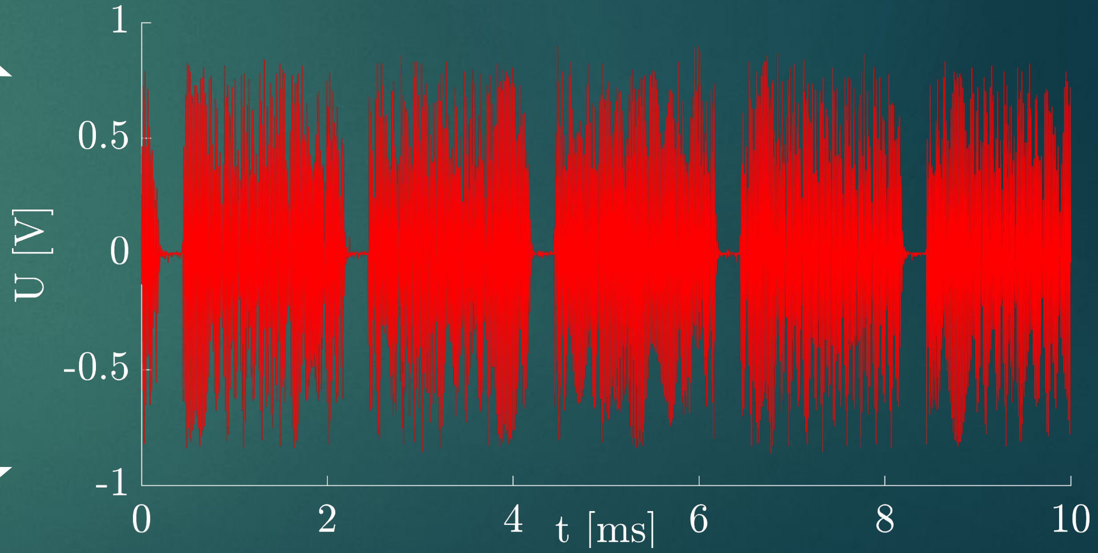


2.

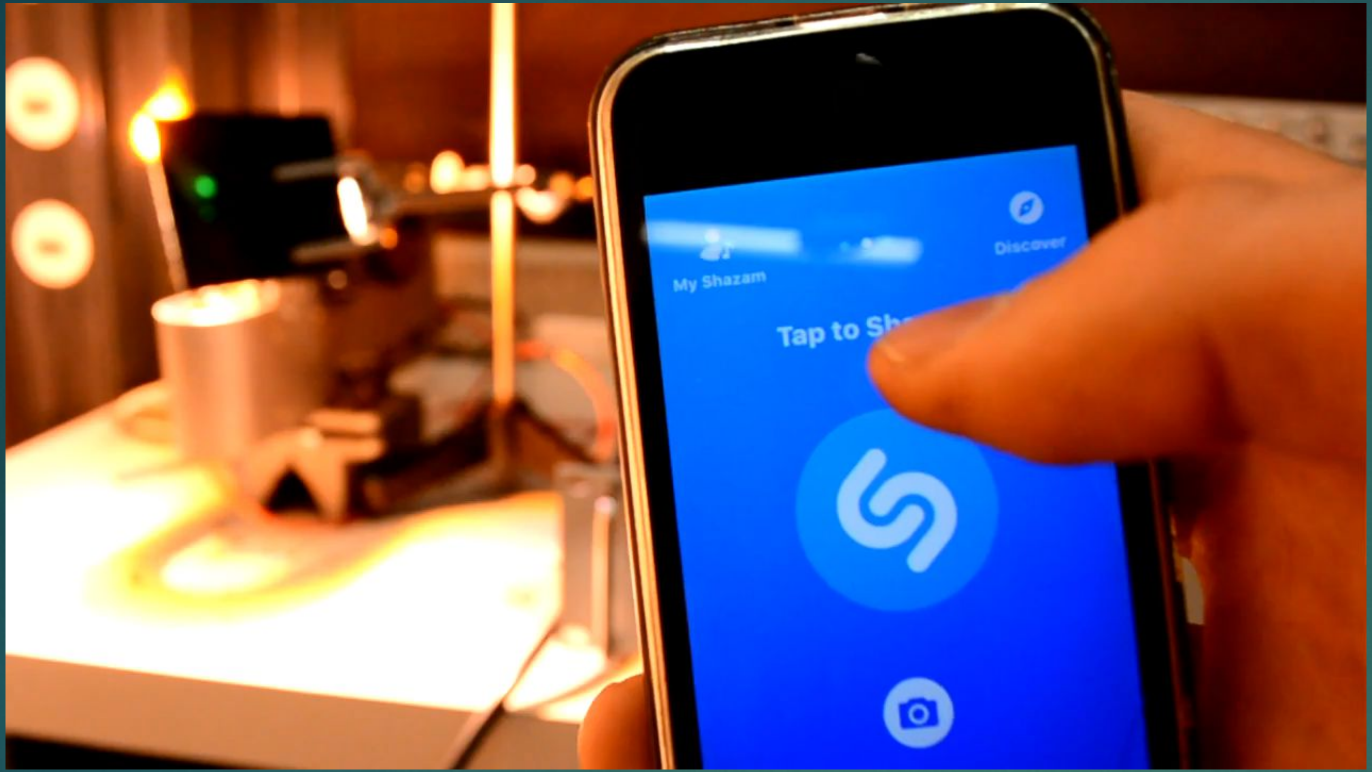


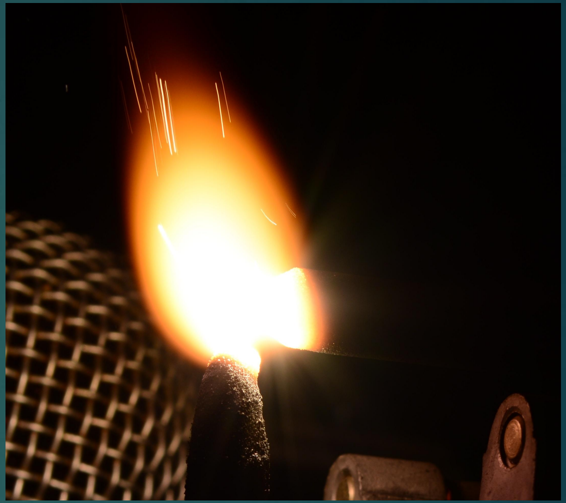
3 MHz

500 Hz



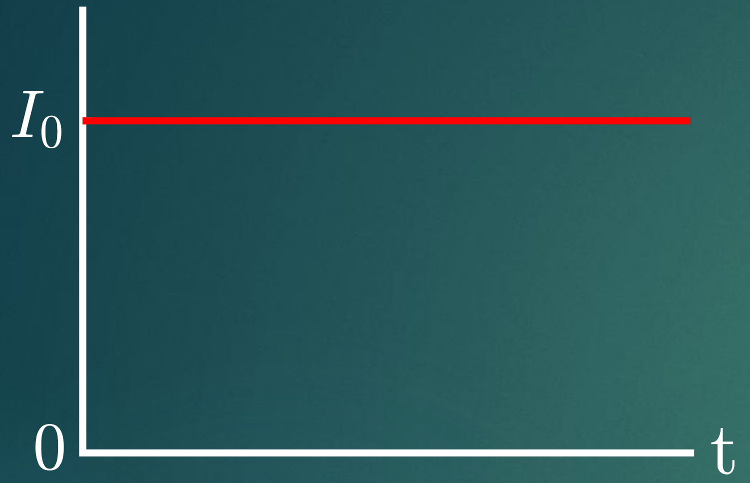
Arc discharge

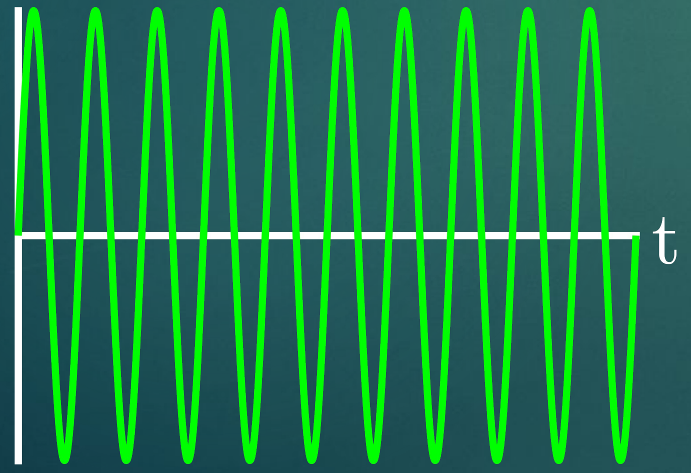


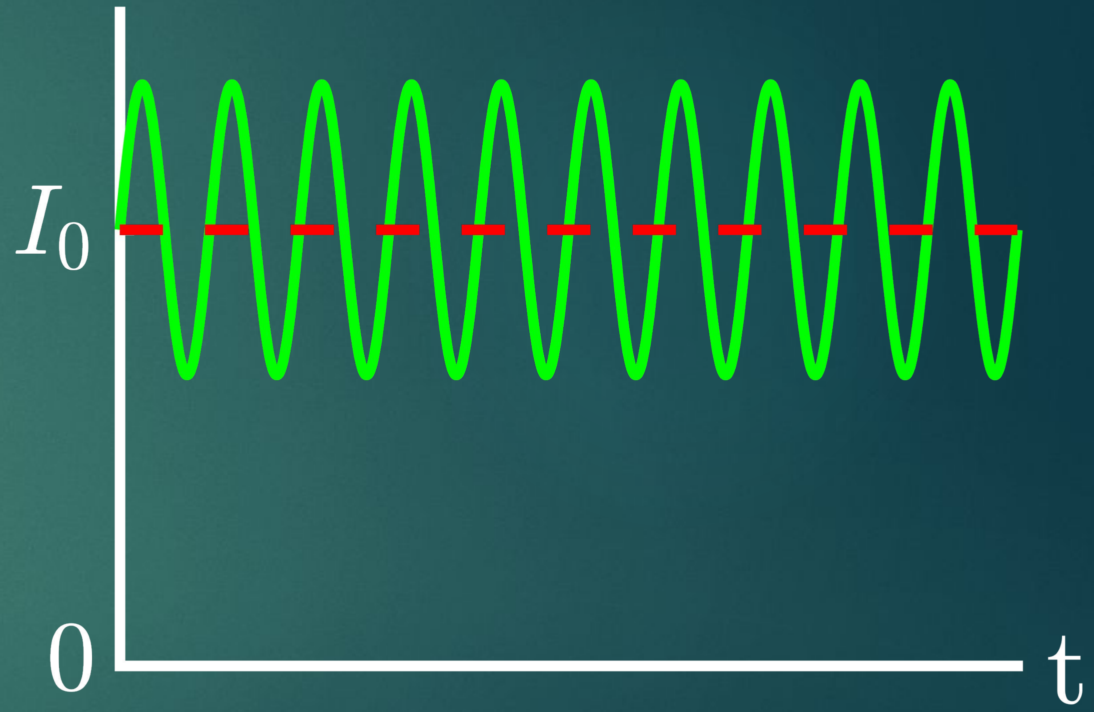


Freq Gen — Power Supply — Arc Speaker

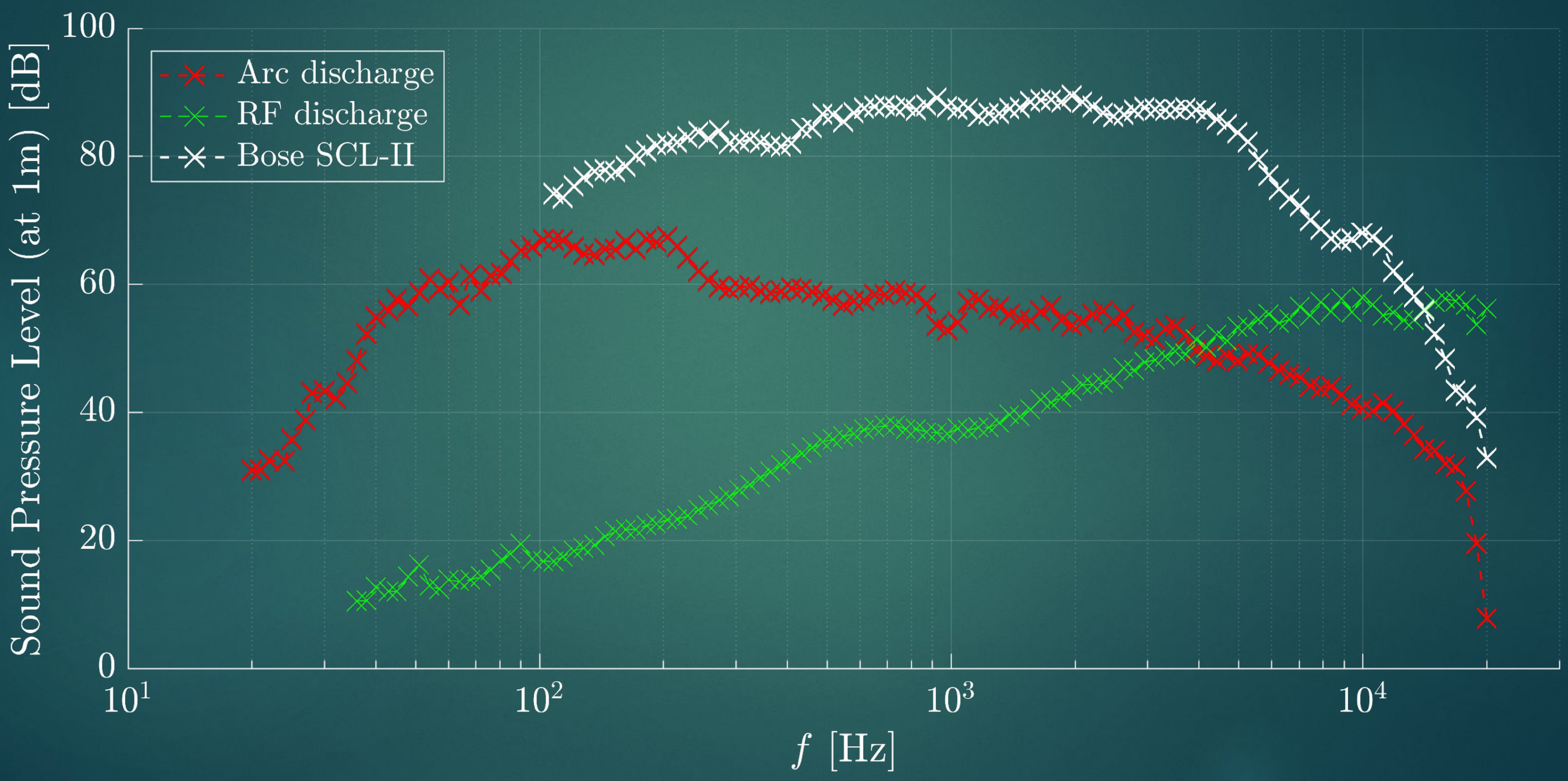
Arc discharge





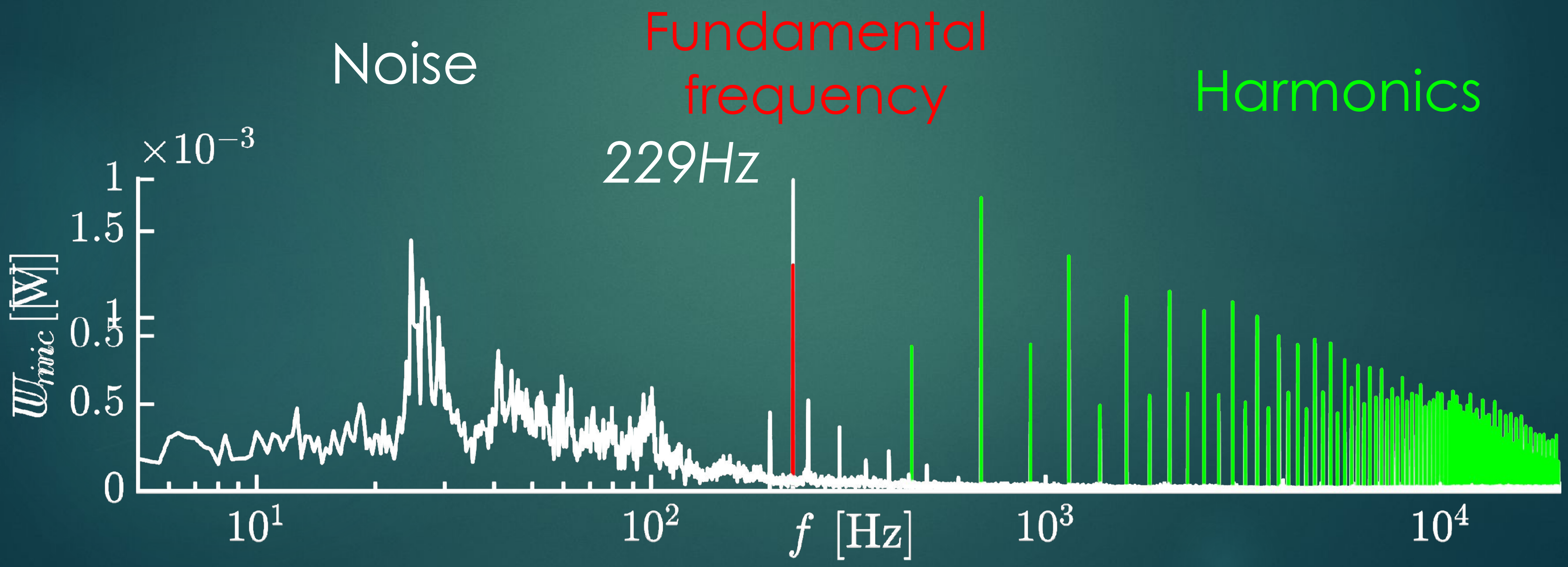


Frequency Response

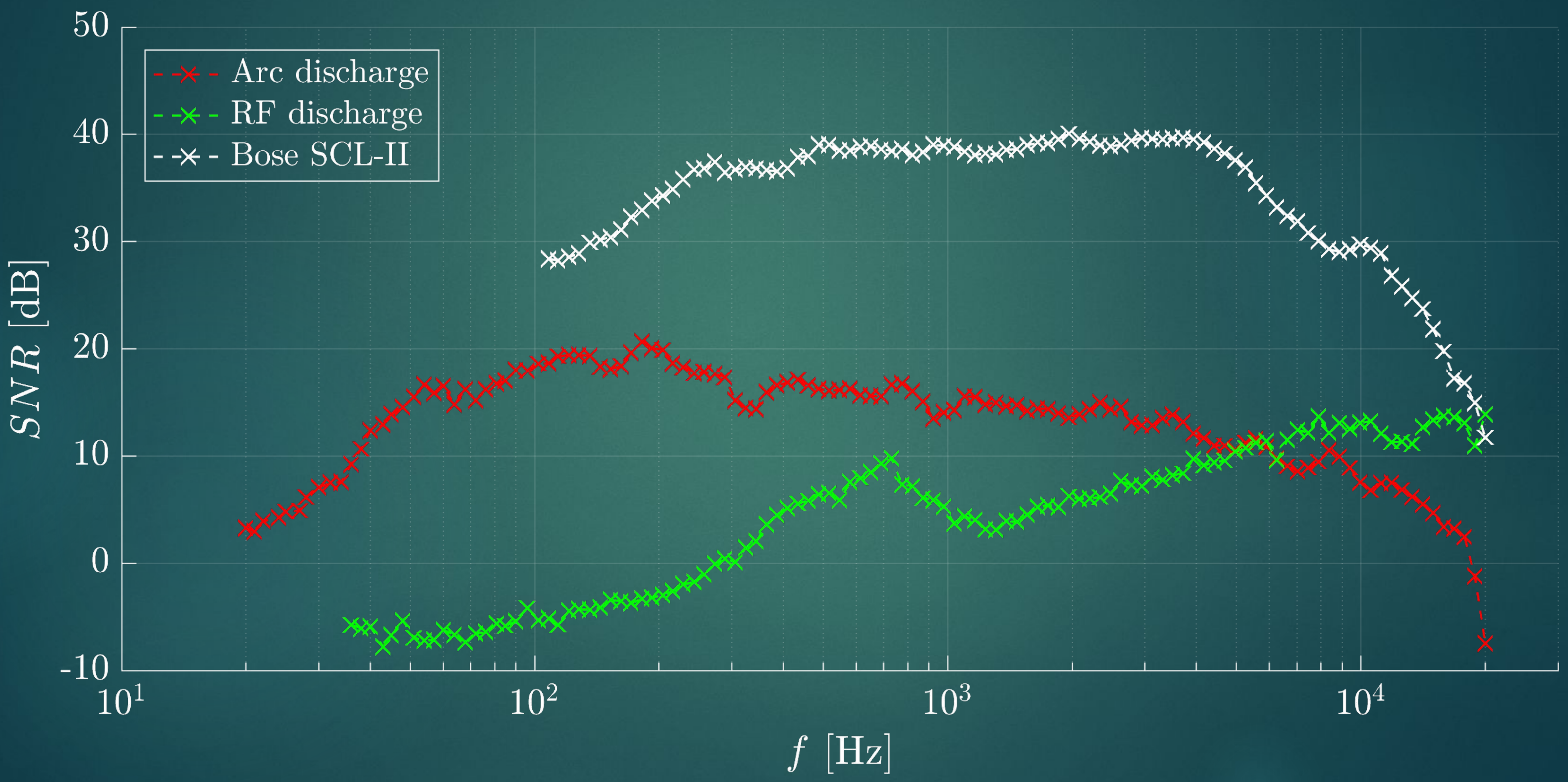


Signal-to-noise ratio

$$SNR = \frac{P_{signal}}{P_{noise}}$$

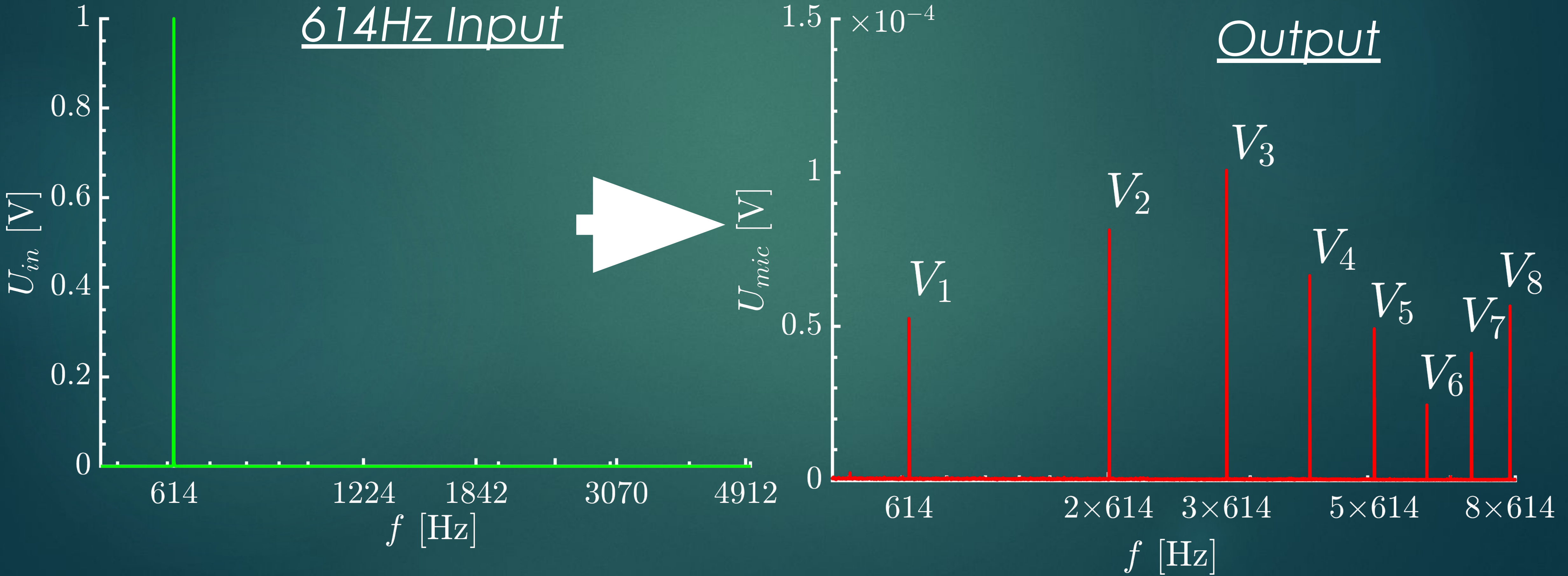


Signal-to-noise ratio

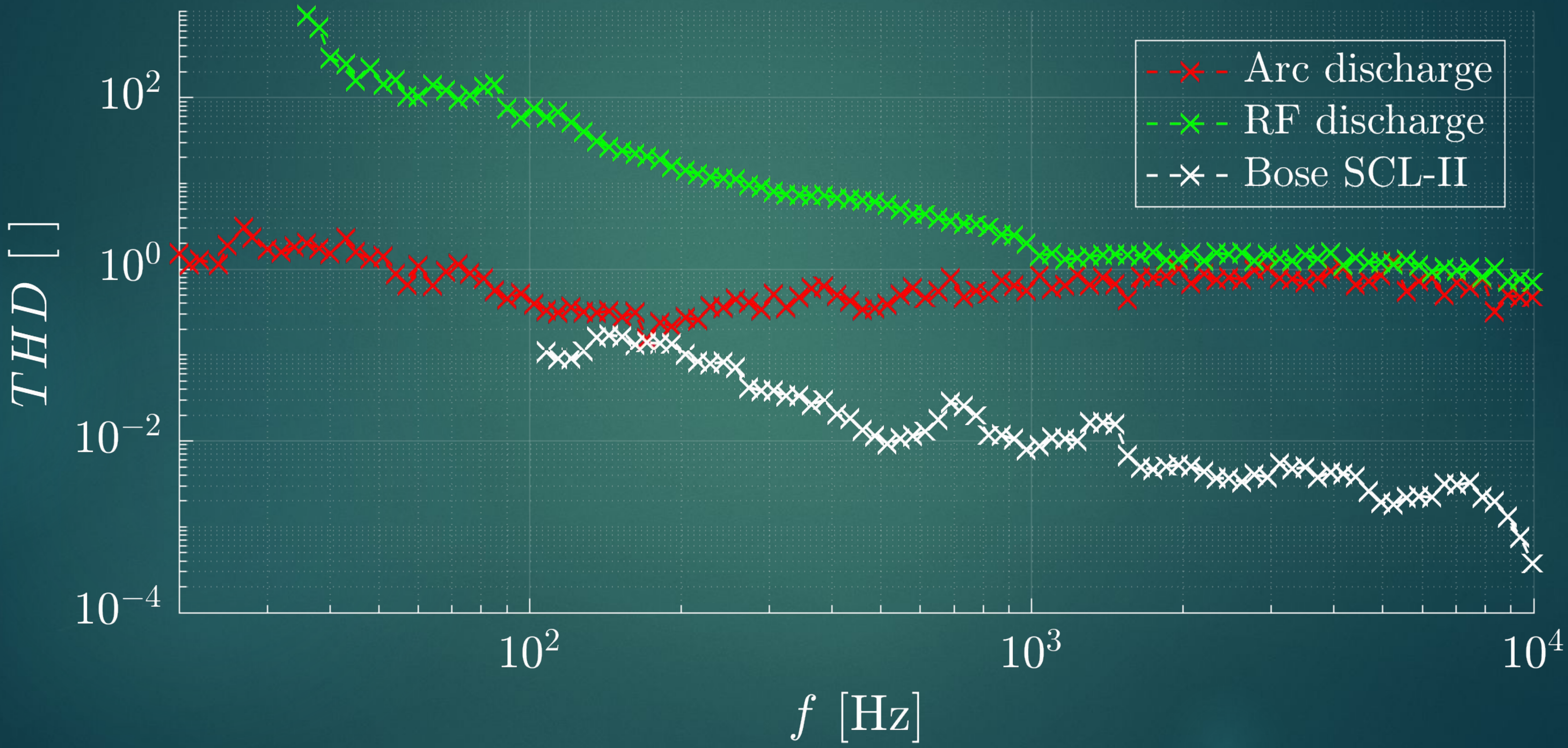


Total harmonic distortion

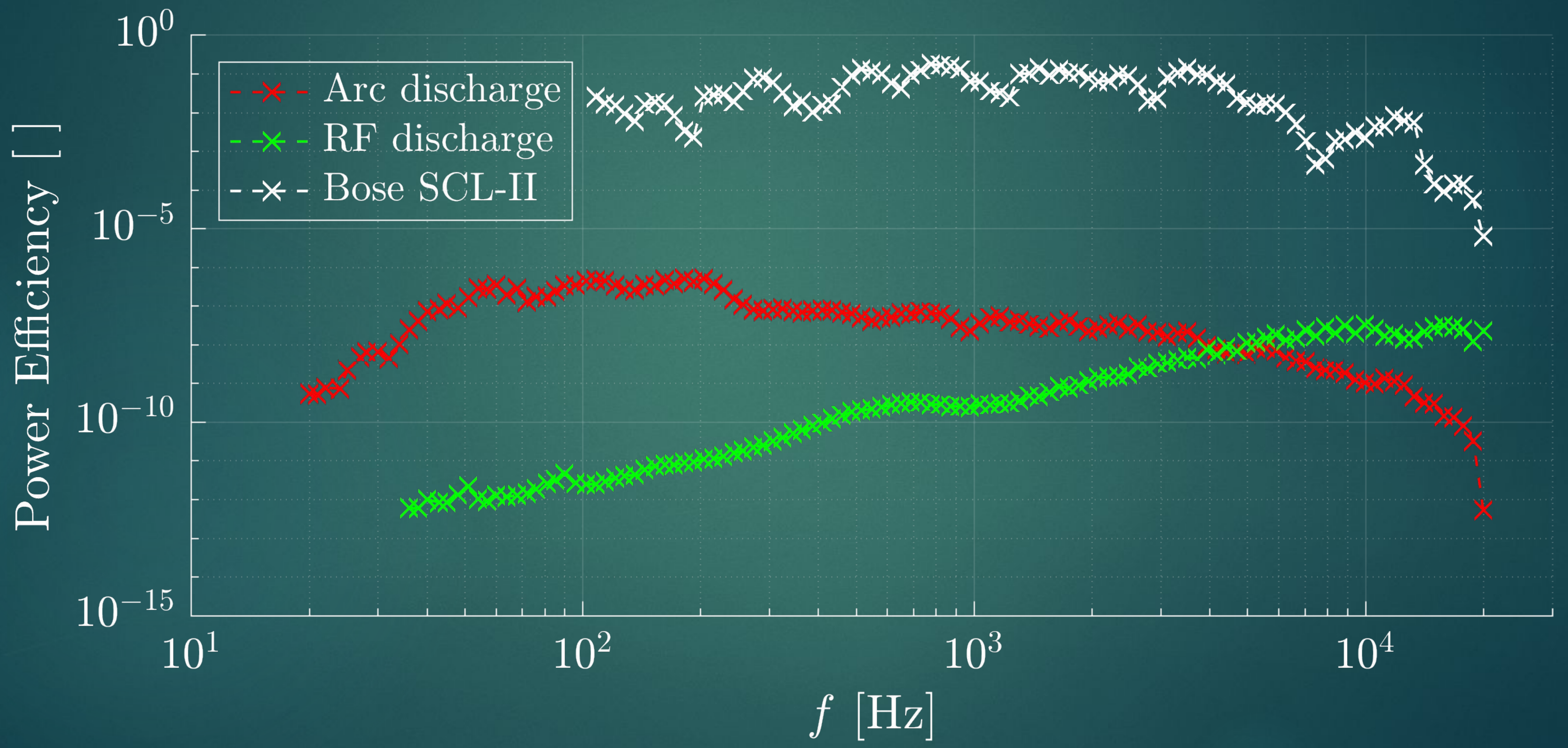
$$THD_F = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots}}{V1}$$



Total harmonic distortion

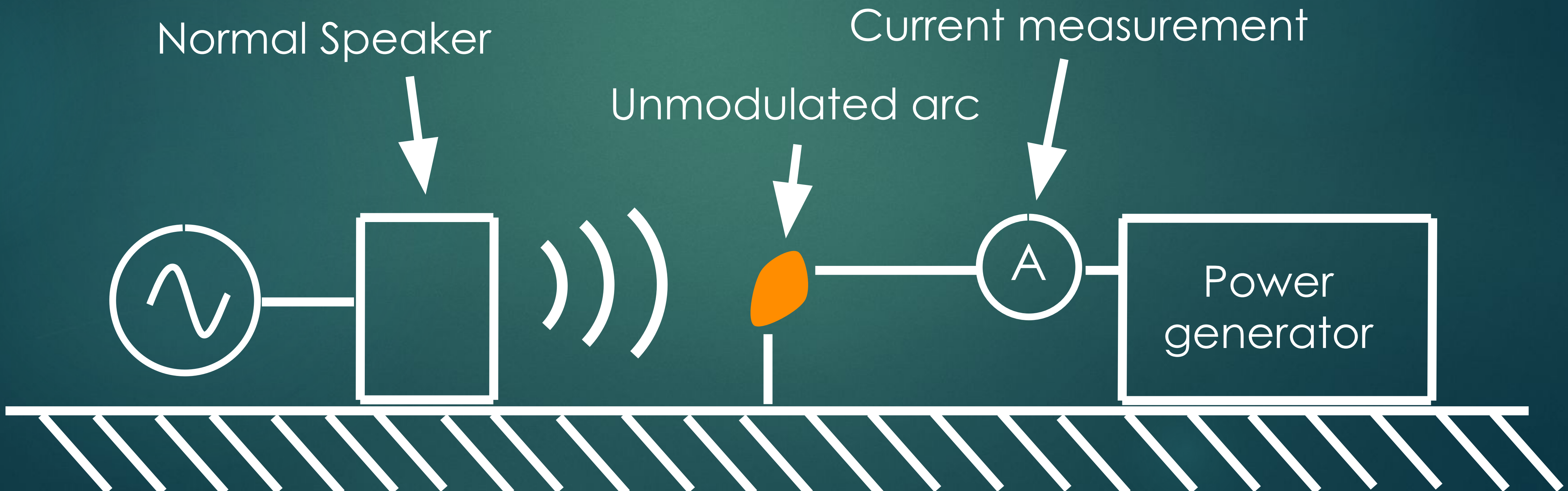


Power efficiency

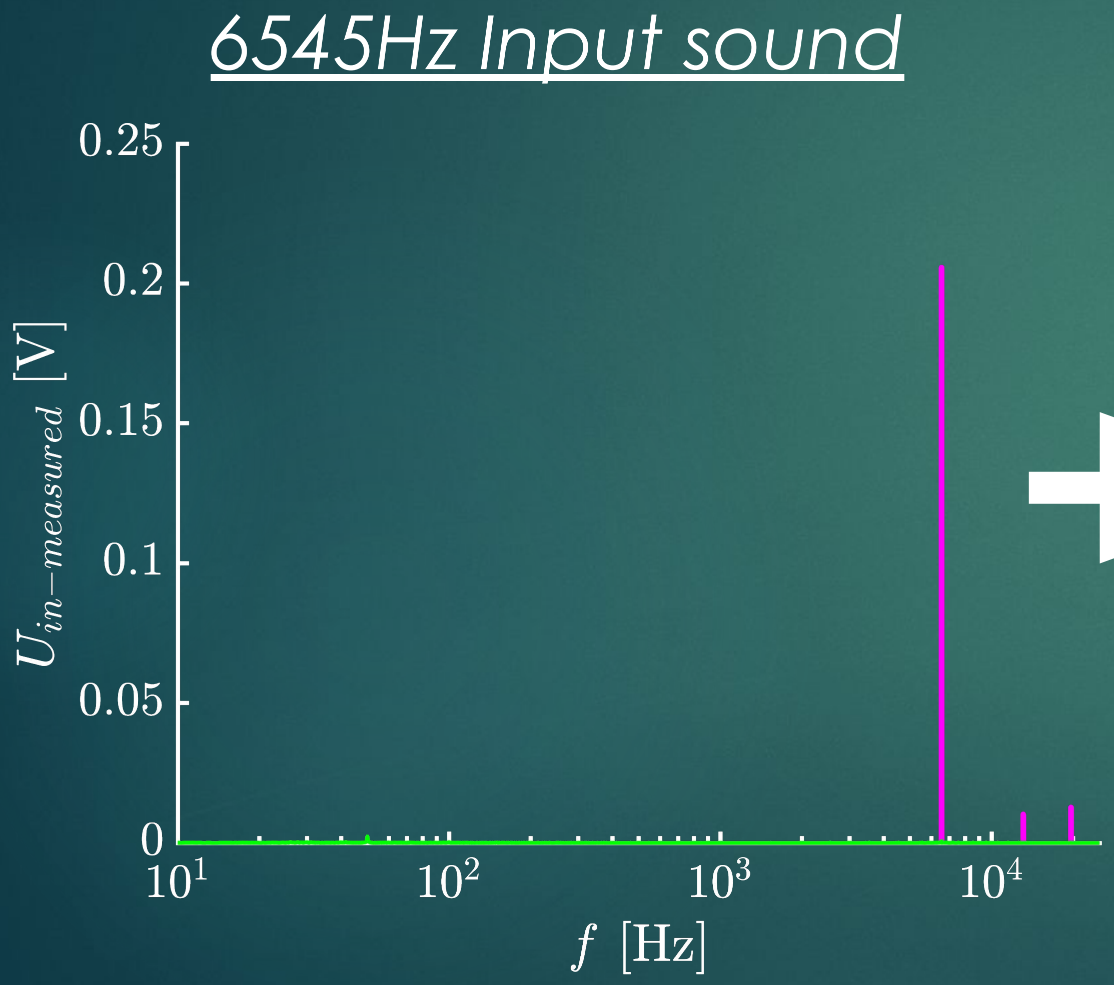


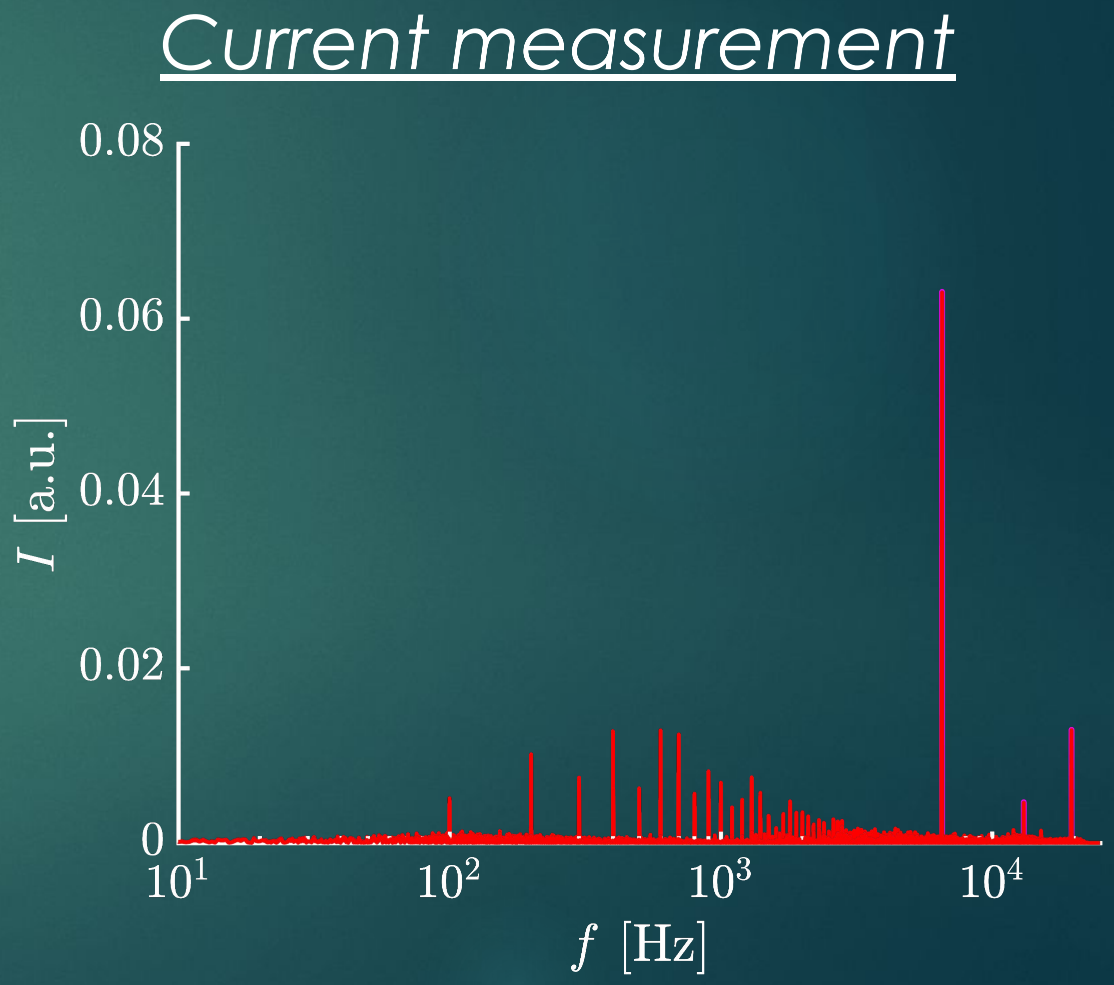
Microphone?

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\gamma - 1}{c^2}\frac{\partial H}{\partial t} + \nabla \cdot \mathbf{F}$$

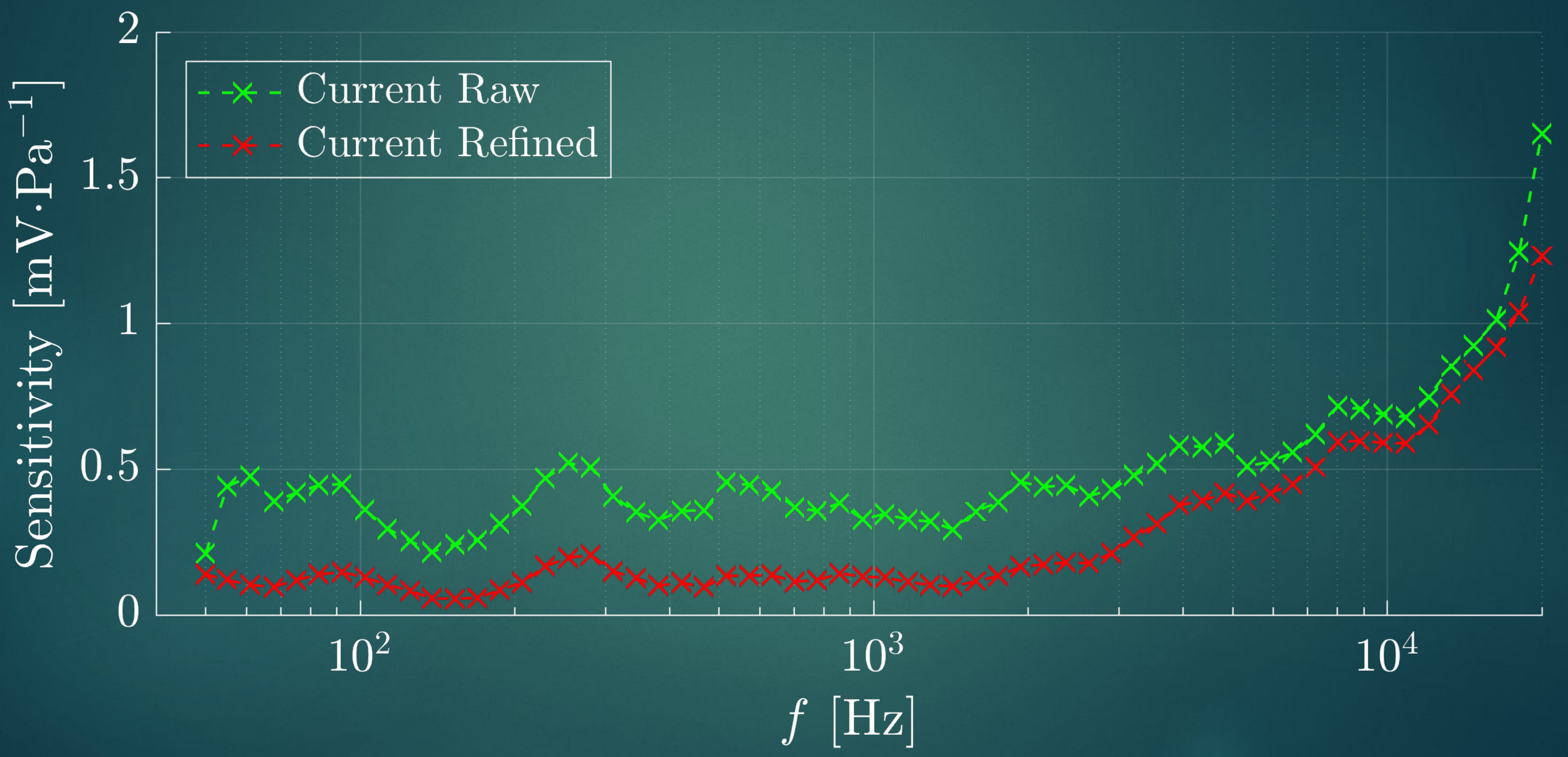


Microphone?


6545Hz Input sound
0.25
0.2
0.15
0.1
0.05
0
$U_{in-measured}$ [V]
10^1
10^2
10^3
10^4
f [Hz]


Current measurement
0.08
0.06
0.04
0.02
0
I [a.u.]
10^1
10^2
10^3
10^4
f [Hz]

Microphone Sensitivity



Conclusion

- Explained sound production using plasma
- Built a working plasma speaker
  - Compared it with another model and a normal speaker
- Studied the properties of the Speaker
  - Frequency response, SNR, THD, Power efficiency.
- Turned it into a microphone

Limitations

- Safety issues
  - Flame
  - Ozone production
- Unpractical solution
  - High current (20A)
  - Low power efficiency
- Melting carbon rods shape

Further improvements

- 3-way speaker (tweeter, mid-range & woofer)
- Add substance to increase ions density
- Study optimal gap and position of the rods

Thank you for your attention!

Special thanks to Gérard Gremaud, Pedro Molina, Arthur Parmentier, Quentin Dubey, Daniele Mari, Nicolas Turin, Iva Tkalcec Vâju and Evgenii Glushkov

Sound pressure level

$$SPL_p = 20 \log \frac{p}{p_0} \; [dB]$$

$$p_0 = 2 \cdot 10^{-5} Pa$$

$0 \; dB$
Hearing threshold

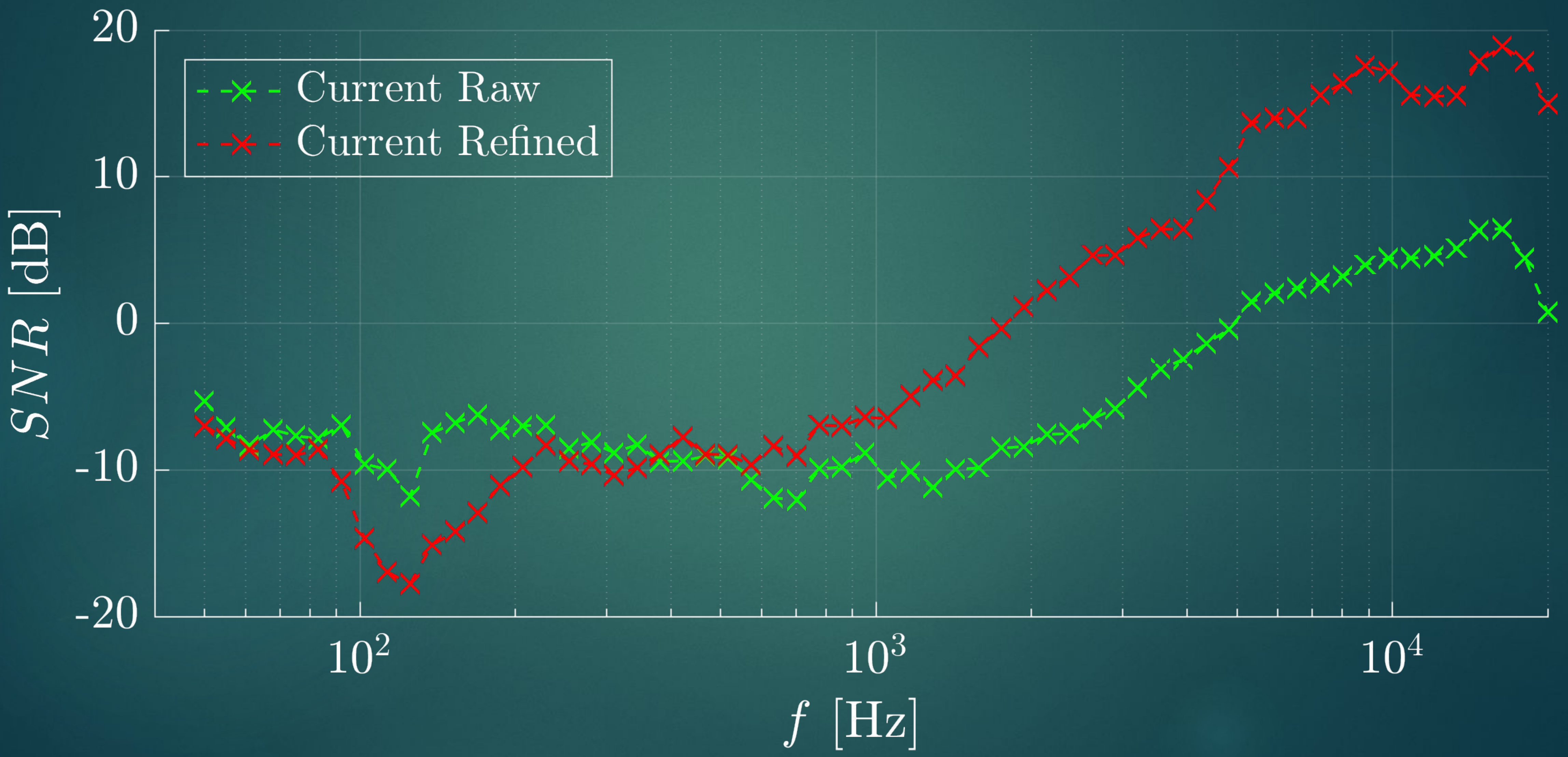
$65 - 70$ dB
Human voice

$140 - 180$ dB
Fighter jet launch

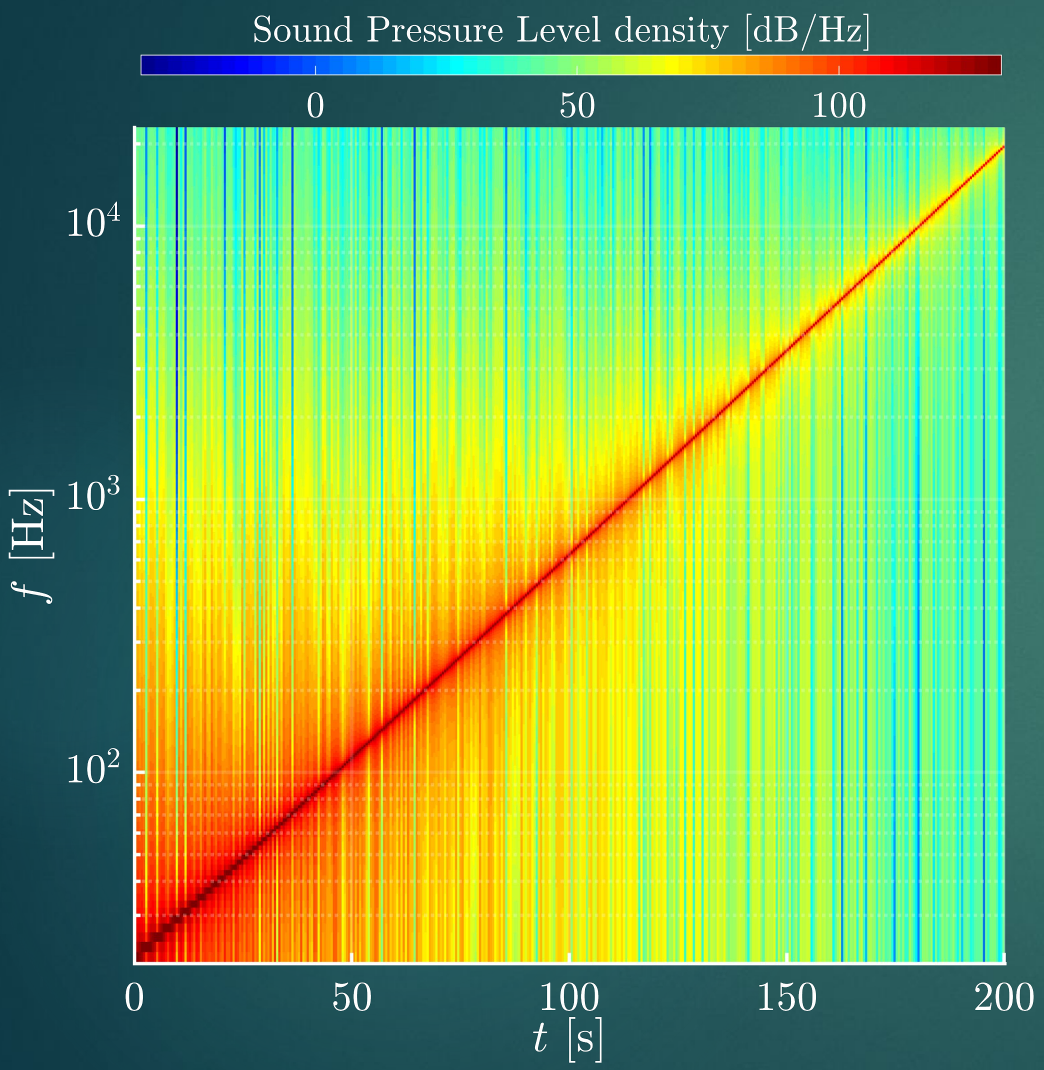
Whisper
$15 - 25$ dB

Orchestral Climax
$100 - 110$ dB

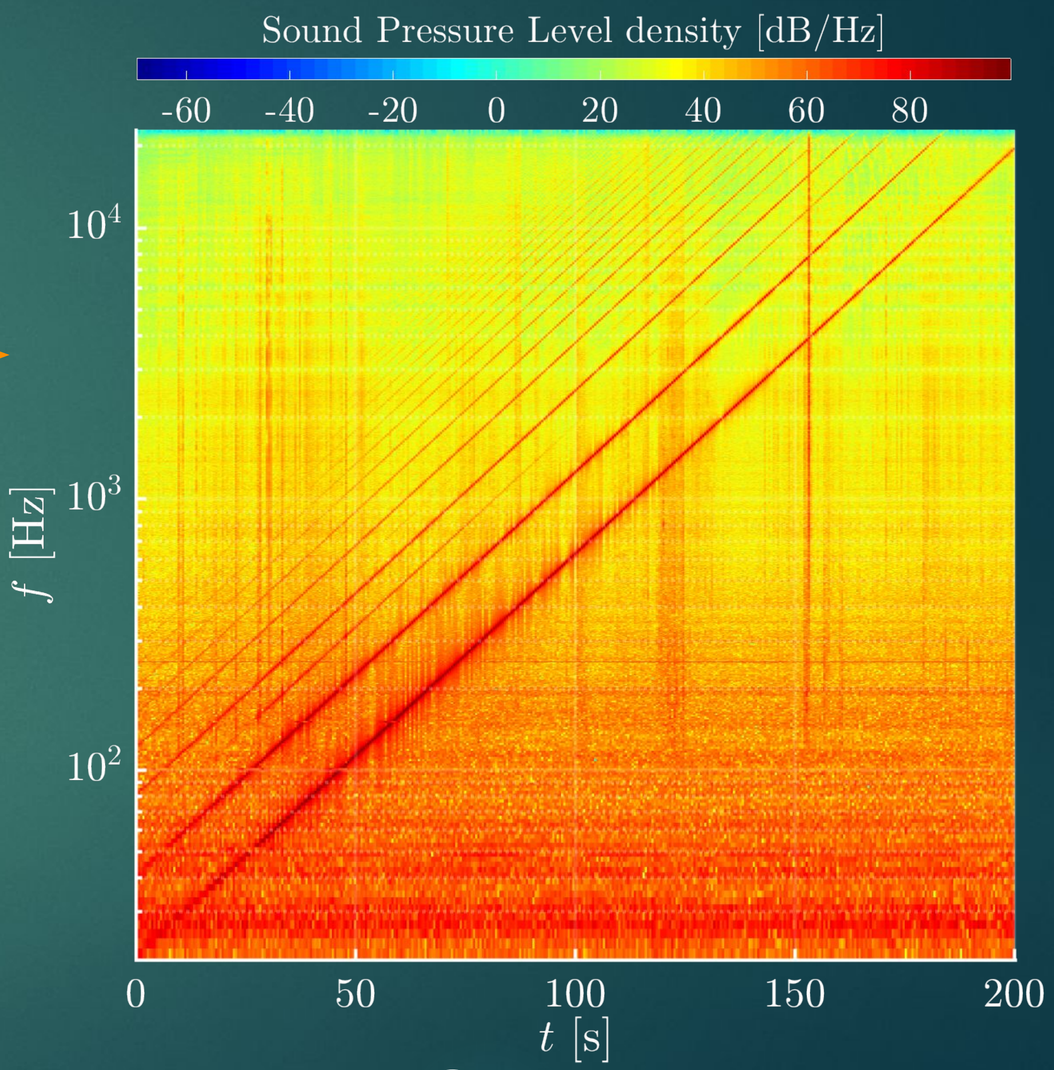
Microphone SNR



Spectrogram

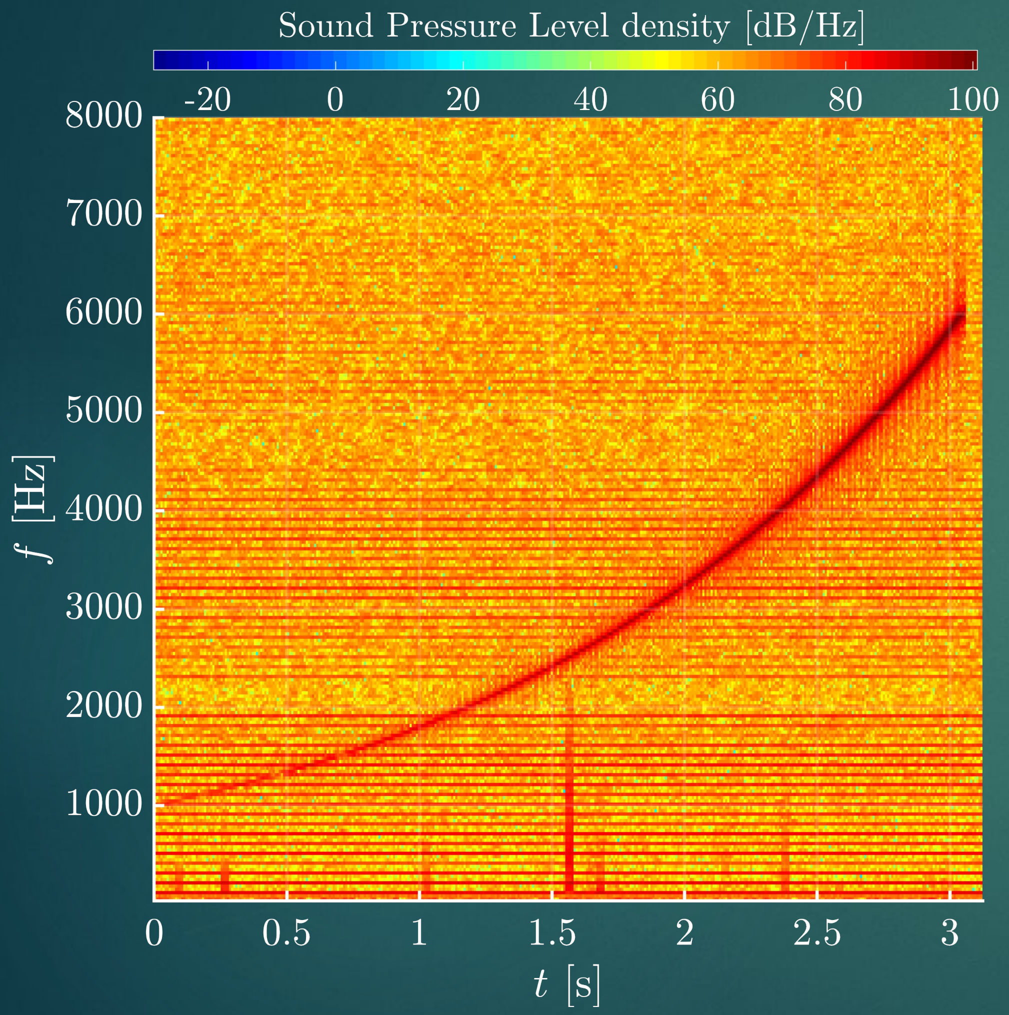


Input

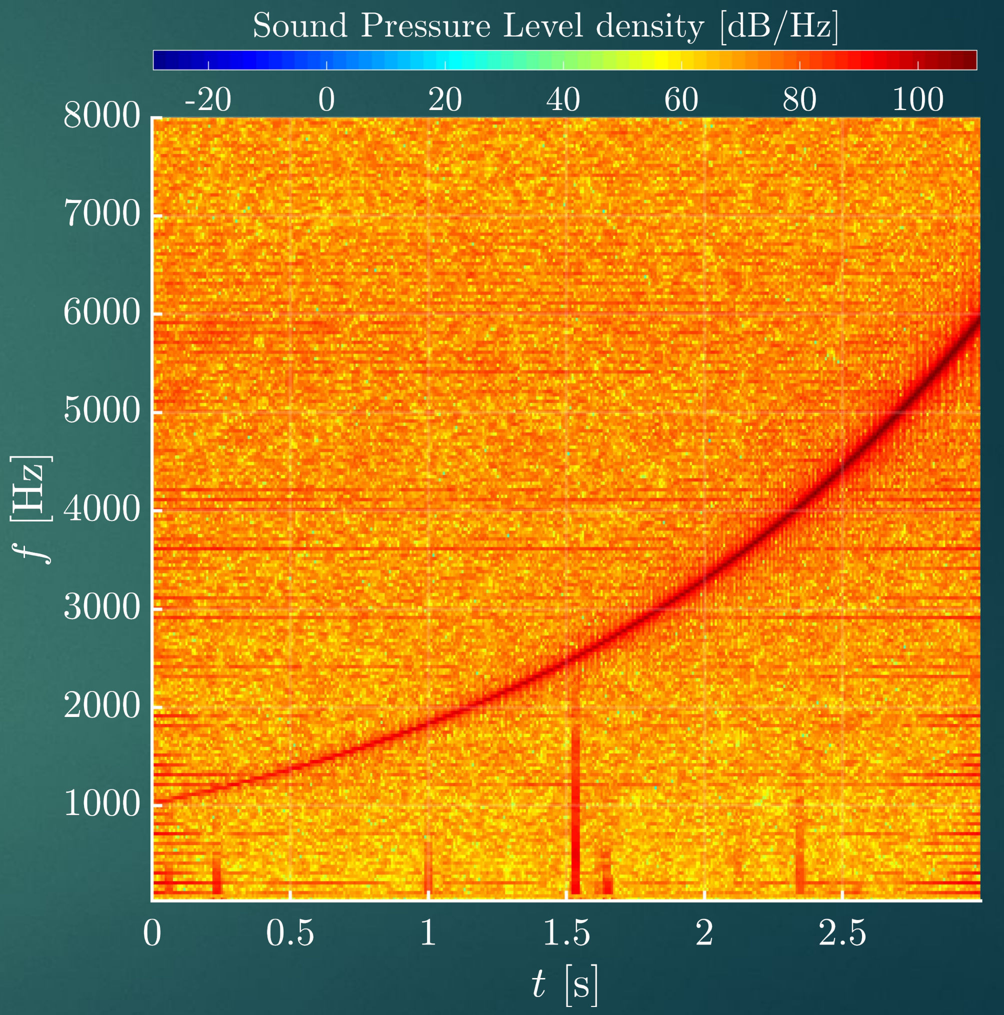


Output

Microphone spectrogram



Before processing



After processing

Sound production

$$A = C\left(\frac{d(IV)}{dt}\right) \qquad [1]$$

A - amplitude of the sound wave
I - current across the electrodes
V - voltage between the electrodes
C - constant coefficient

Square/ triangular wave harmonics

Square: $$x(t) = \frac{4}{\pi} \sum_{k=1}^{\infty} \frac{\sin\left(2\pi(2k-1)ft\right)}{2k-1}$$

$$x_{\text{triangle}}(t) = \frac{8}{\pi^2} \sum_{k=0}^{\infty} (-1)^k \frac{\sin\left((2k+1)\omega t\right)}{(2k+1)^2}$$

Hissing noise

- Crater shape formation on carbon rods [2]
- Oxygen reaching the crater and combining with local carbon
- Results in drop of current leading to noise

References

Modeling of a dc glow plasma loudspeaker

Michael S. Mazzola, and G.Marshall Molen

F Bastien 1987 *J. Phys. D: Appl. Phys.* **20** 1547

[1] Ingard U 1966 *Phys. Rev.* **145** 41-46

[2] Ayrton, "The hissing of he electric arc", Journal of the Institution of Electrical Engineers (Volume: 28, Issue: 140, June 1899)

Saha law

y : ionisation rate

$$\frac{y^2}{1-y} = \frac{1}{n}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} exp\left(-\frac{\chi}{k_B T}\right)$$

$$a=\frac{1}{n}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2}\exp\left(-\frac{\chi}{k_B T}\right)>0$$

$$y=\frac{-a+\sqrt{a^2+4a}}{2}$$

UV from arc discharge