Optimal Electrode Design of Cochlear Implants using Multiobjective Optimization

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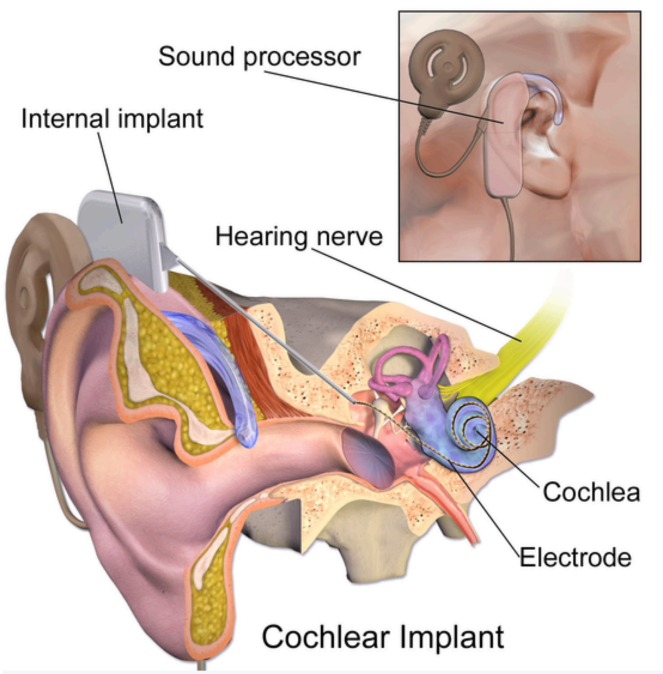
What is a cochlear implant?

- Cochlear implant is a transductor that transform acoustics signals in electrical signals that stimulate the auditory nerve.

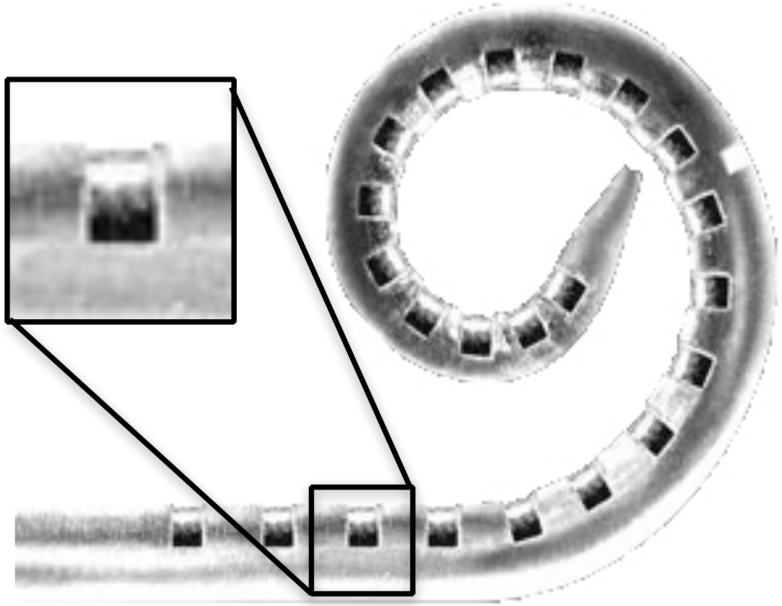
- It provides a sense of sound to a person with severe to profound sensorineural hearing loss in both ears

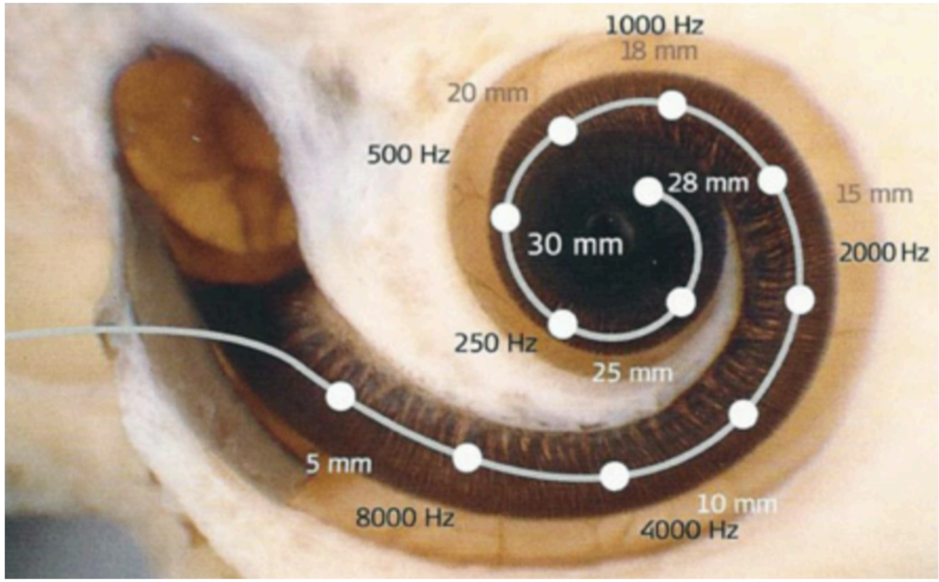


Cochlear implant

What is a cochlear implant?

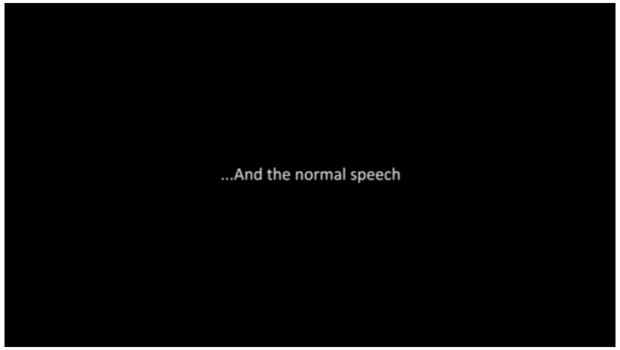
- Electrode array implanted in the cochlea
- Each electrode stimulates a part of the cochlea associated to a range of frequencies (tonotopy)





How do you hear with a cochlear implant?

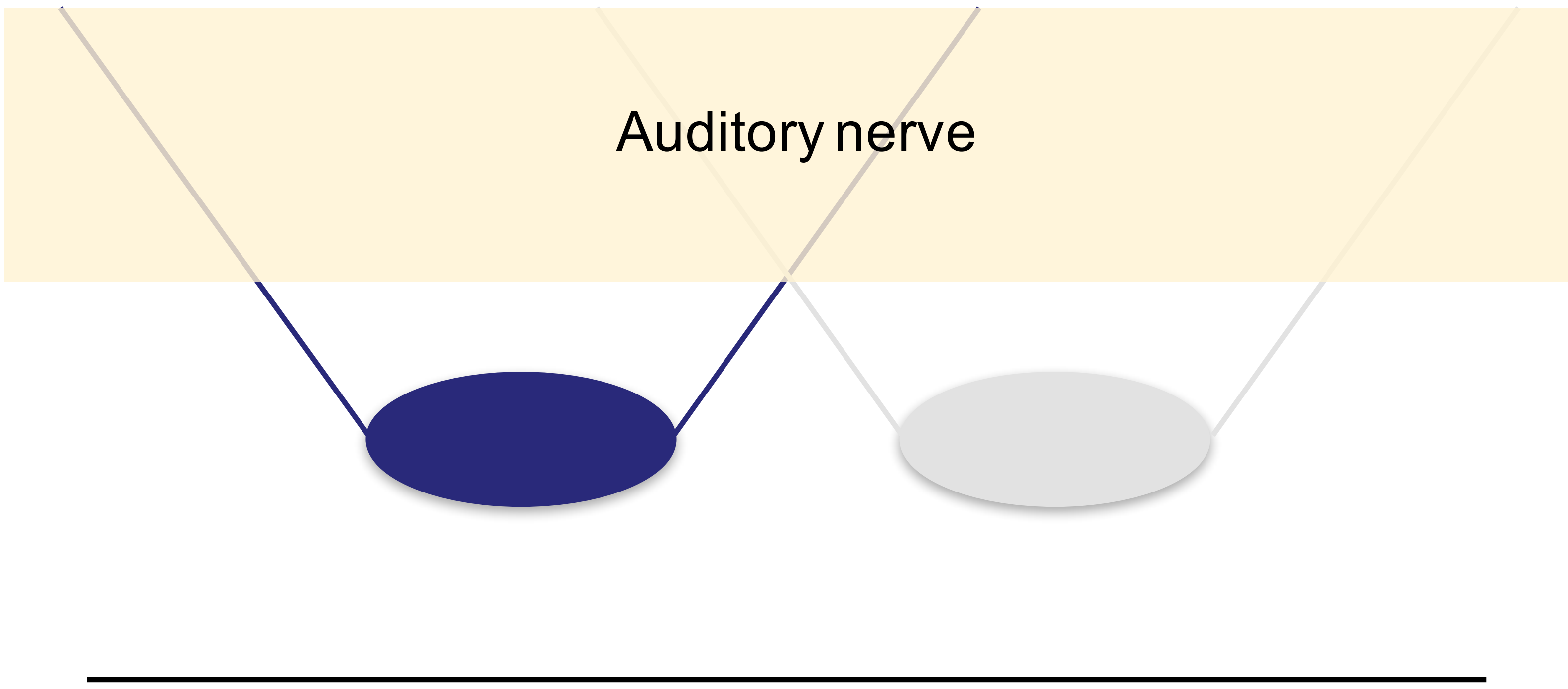
- Simulation of how deaf people hear with a cochlear implant



- Nowadays cochlear implants arrays have around 20 electrodes

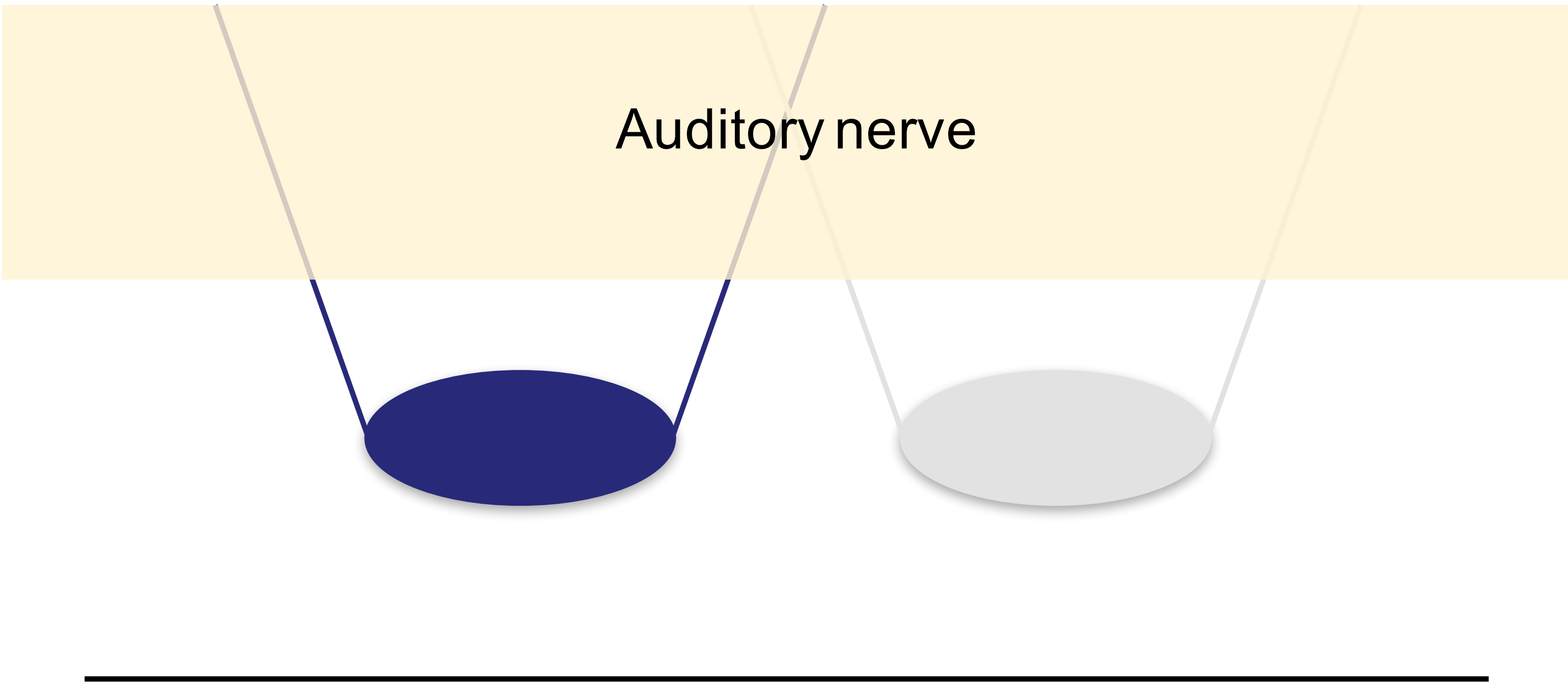
Can we increment the number of electrodes?

- Yes, but we must diminish the interaction between neighbor electrodes



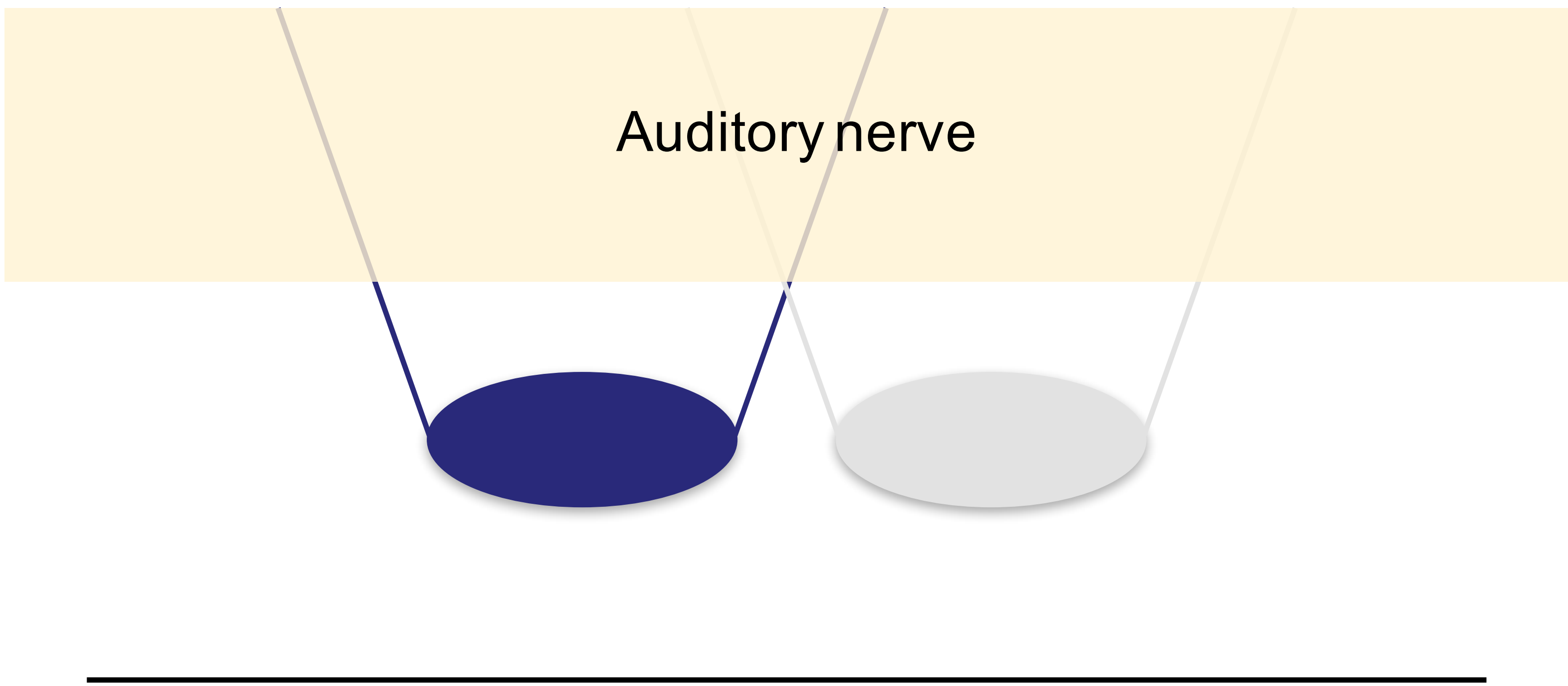
Can we increment the number of electrodes?

- That is, we have to increment the focalization



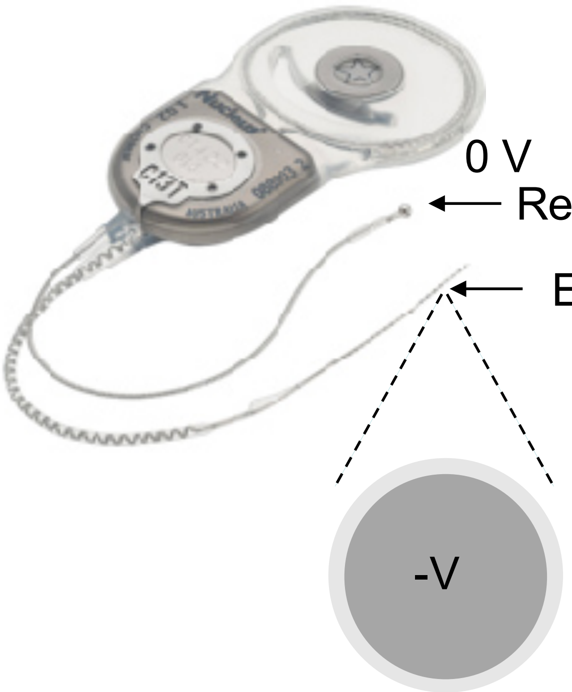
Can we increment the number of electrodes?

- More focalization ➡ more "independent" electrodes ➡ better additive quality



Can we increment the focalization of the standard electrode?

Standard cochlear implant

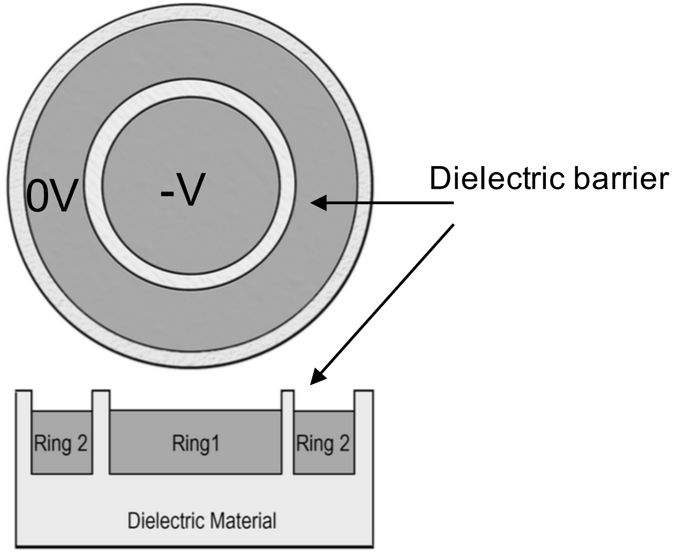


0 V
Reference electrode

Electrode array

Standard electrode: ≈ disc at -V volts

Our proposed ring electrode



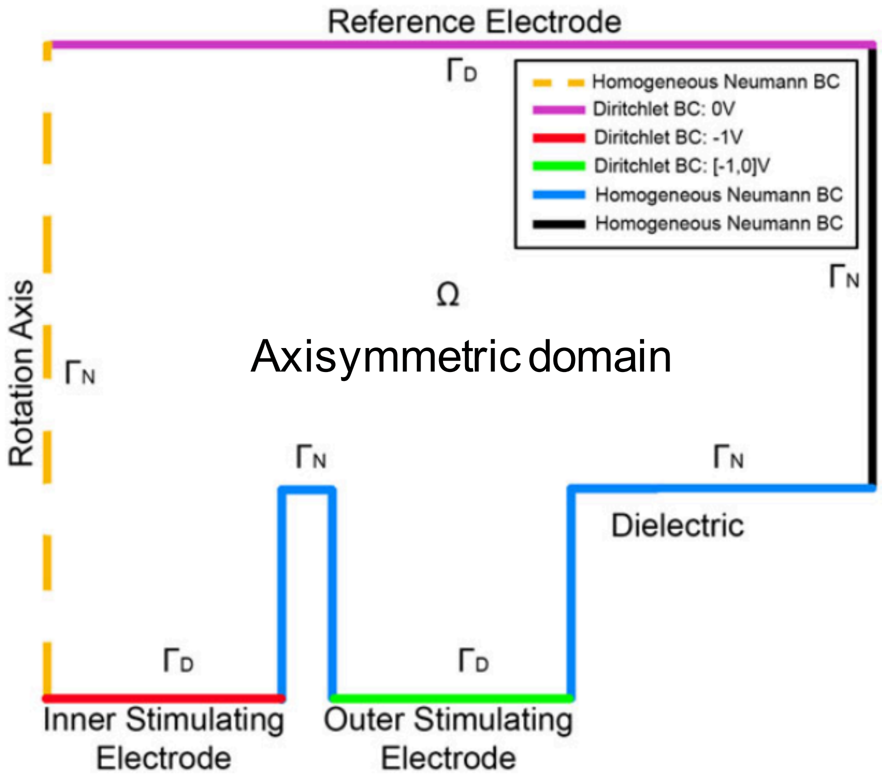
2 RINGS with DIFFERENT POTENTIAL
+ REFERENCE electrode

Can we design the shape of the metal electrodes and the size of the dielectric barrier in order to maximize the focalization and minimize the consume?

How to define the concept of focalization and how to measure it?

Computational model

Schematic domain

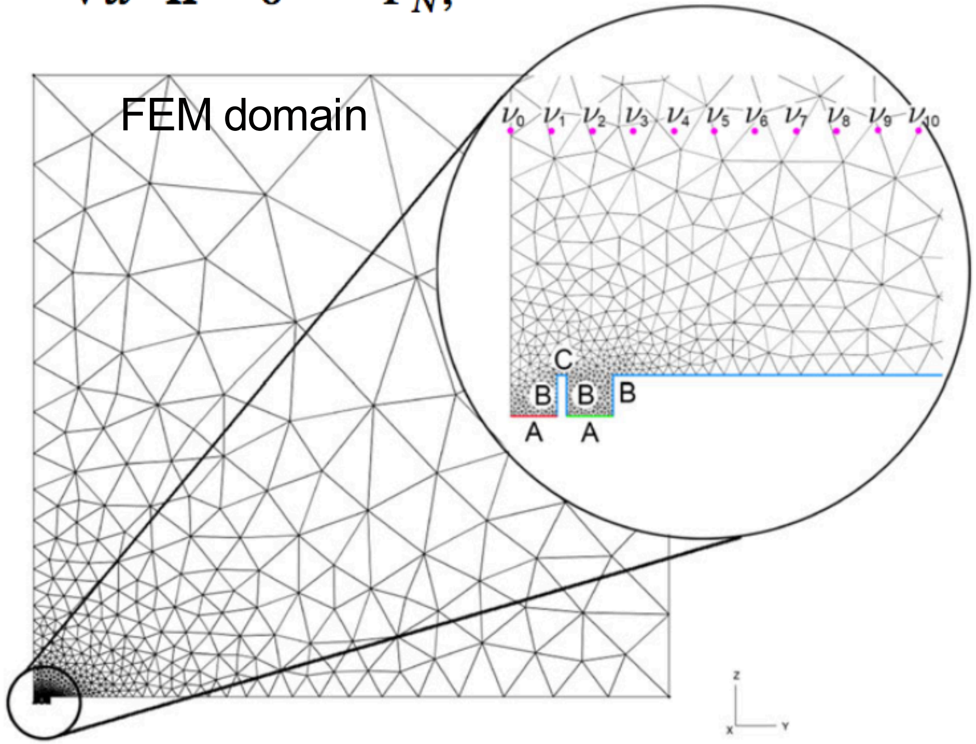


Electrostatic FEM problem

$$\Delta u = 0 \qquad in \;\; \Omega,$$

$$u = g \qquad on \;\; \Gamma_D,$$

$$\nabla u \cdot \mathbf{n} = 0 \qquad \Gamma_N,$$

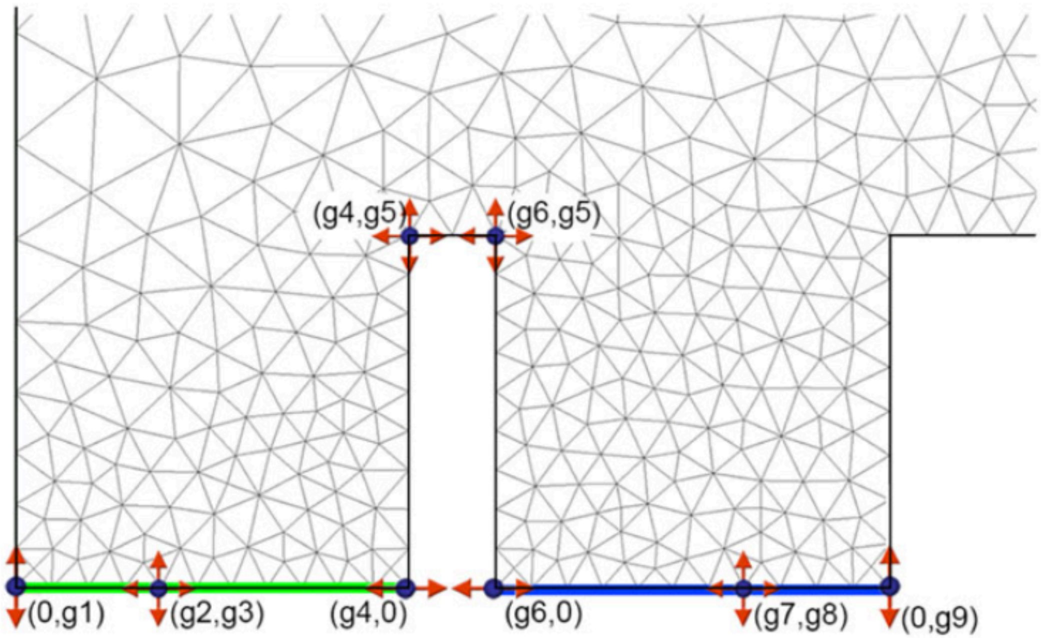


- Objective: Find optimal electrode designs that maximize focalization and minimize consume

- Using multiobjective evolutionary algorithms

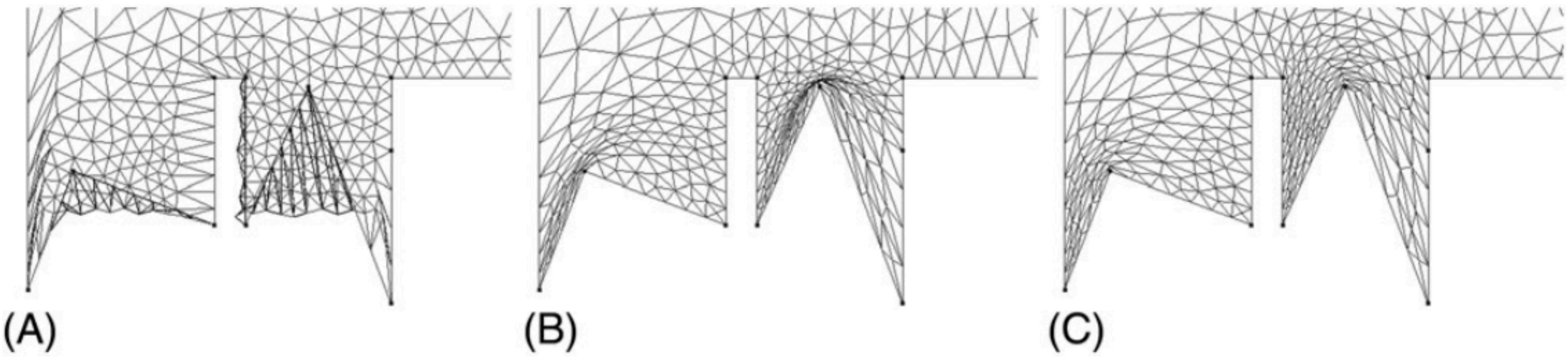
Genes used in the evolutionary algorithm

- The genes of the evolutionary algorithm used to optimize the shape of the electrode and the size of the dielectric barrier
- The change in the position of the free vertices produces a deformation of the mesh



Remesh or adapt the mesh?

- We have opted for mesh adaption because mesh adaption keeps constant the number of elements and therefore (aprox.) the discretization error

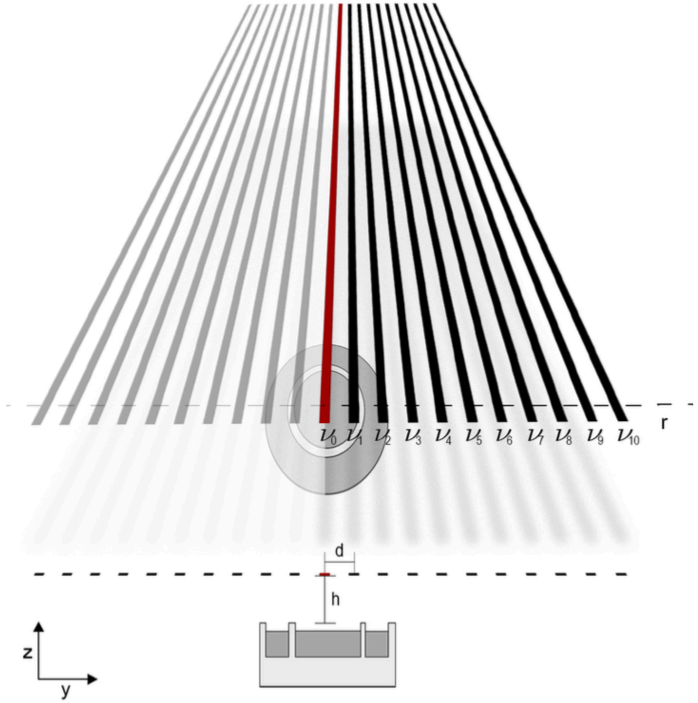


Mesh boundary deformation — Initial vertex repositioning — Mesh after untangling and smoothing

Focalization measurement

- Focalization is measured in terms of the response of simulated neurons using NEURON software

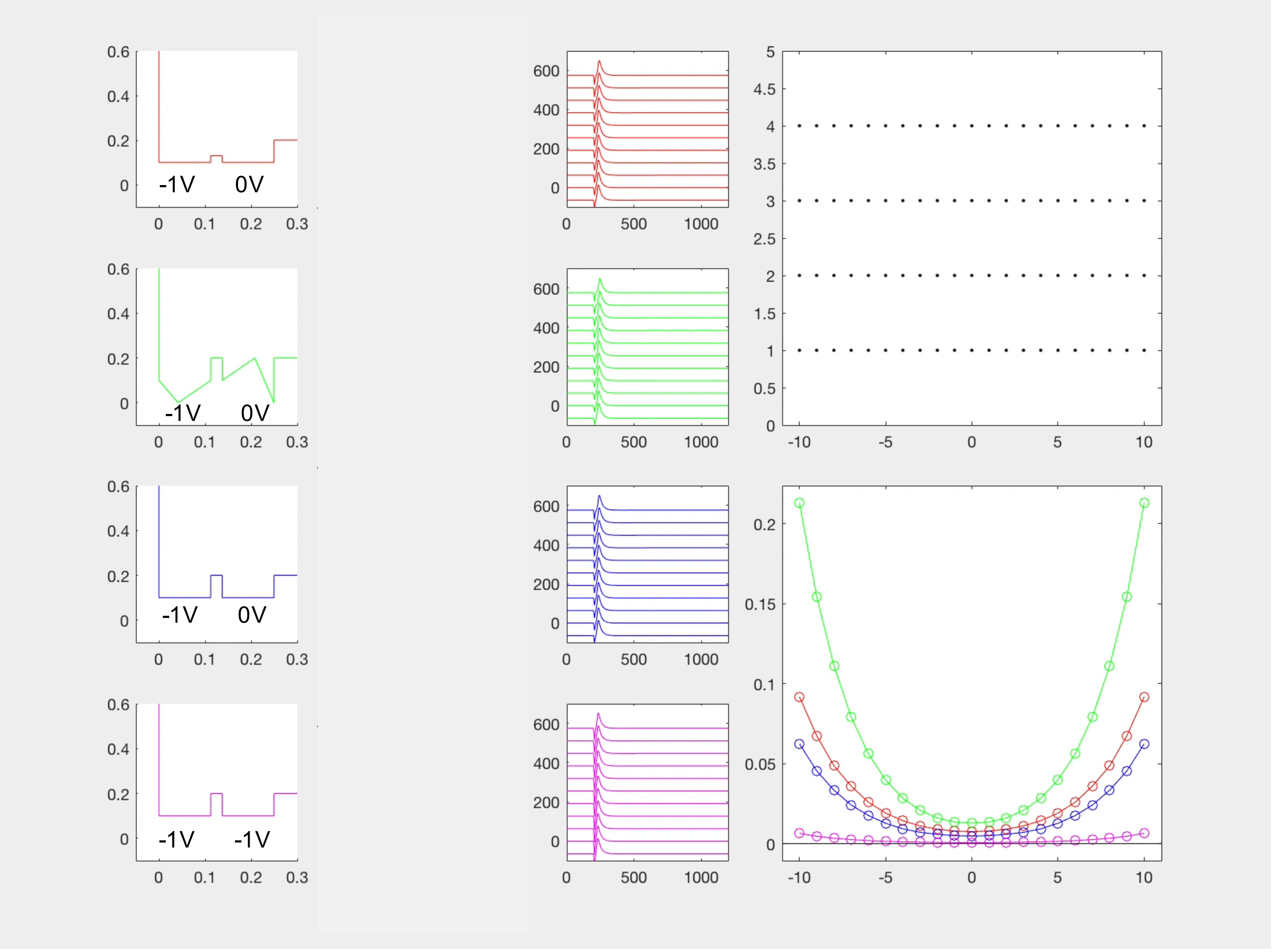
- NEURON is based on Hodgking-Hudxley model, defined by a set of nonlinear ODE



- High focalization: Closer neurons are much more easily excitable than distant neuros

- Low focalization: Closer and distant neurons are excited almost simultaneously

Focalization: neuron excitation



How the electrode design influences in focalization and consume?

Three examples: standard disc, flat ring and ring dielectric barrier electrodes

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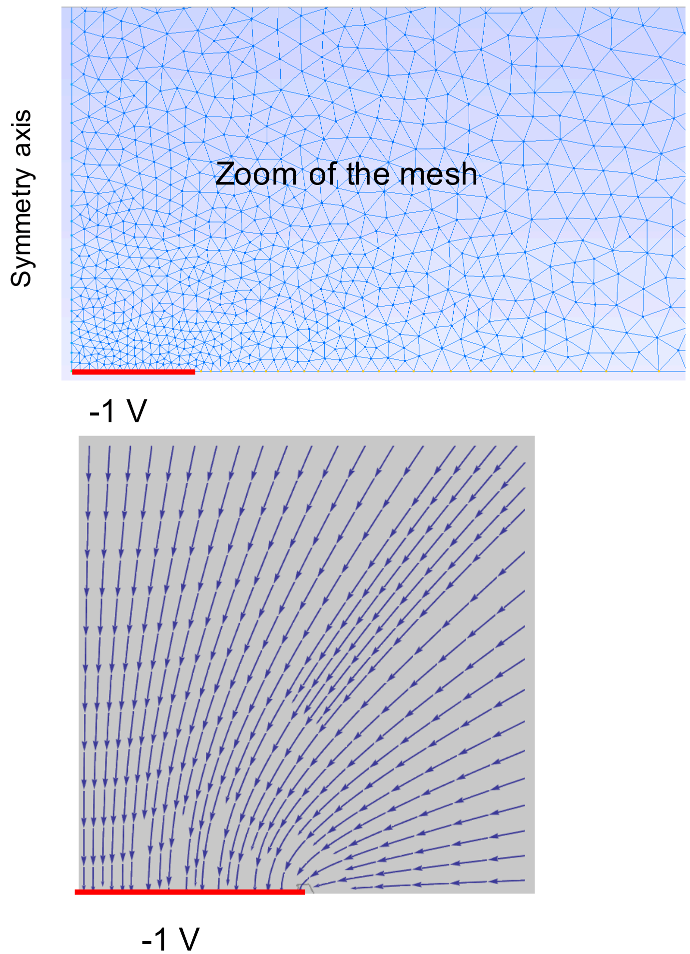
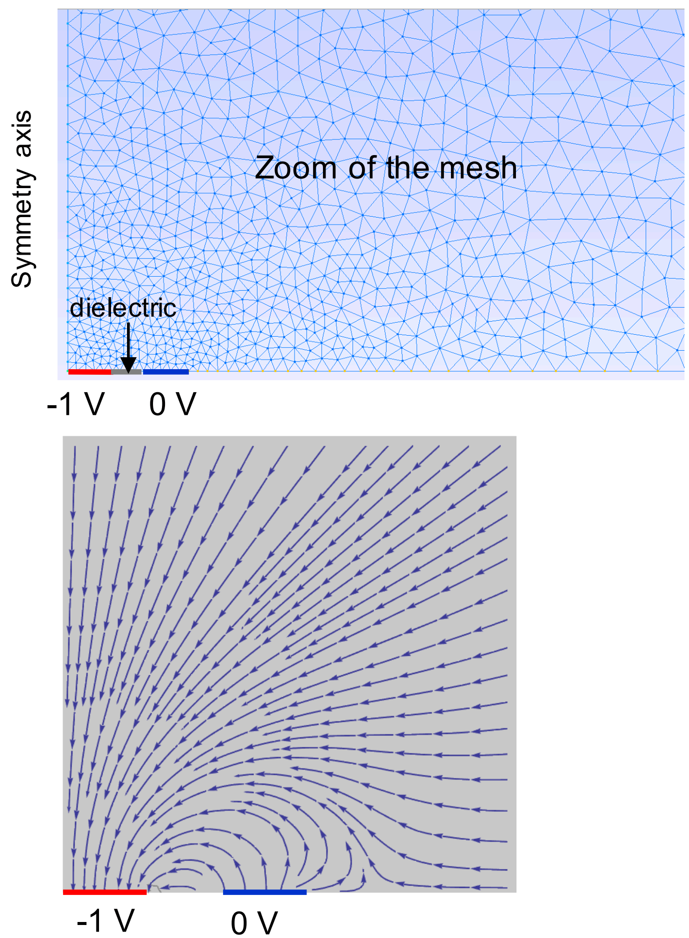
Disc electrode



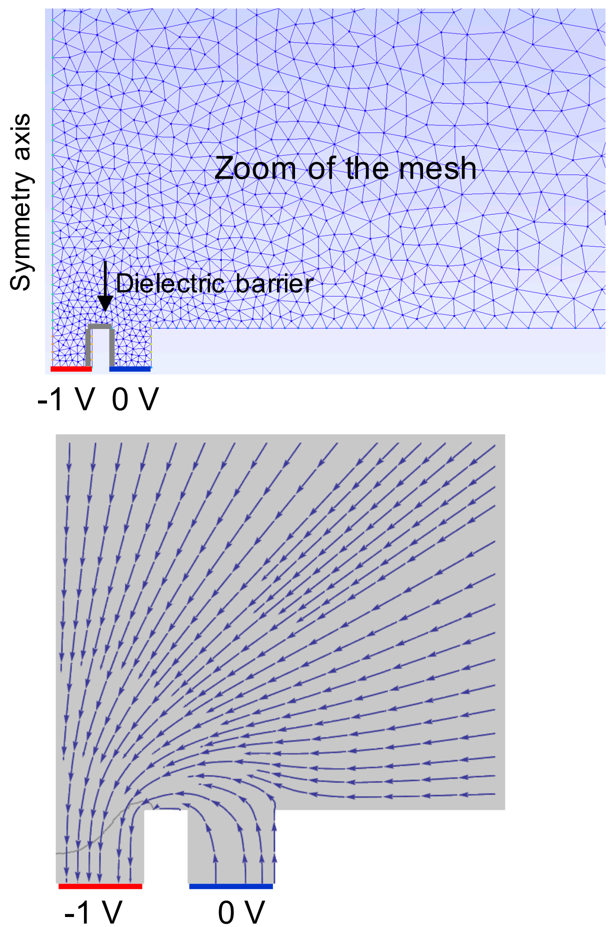
Low consume but poor focalization

Flat ring electrode



High focalization but high consume

Ring electrode with dielectric barrier



High focalization and acceptable consume

Automatic designs with multiobjective evolutionary algorithms

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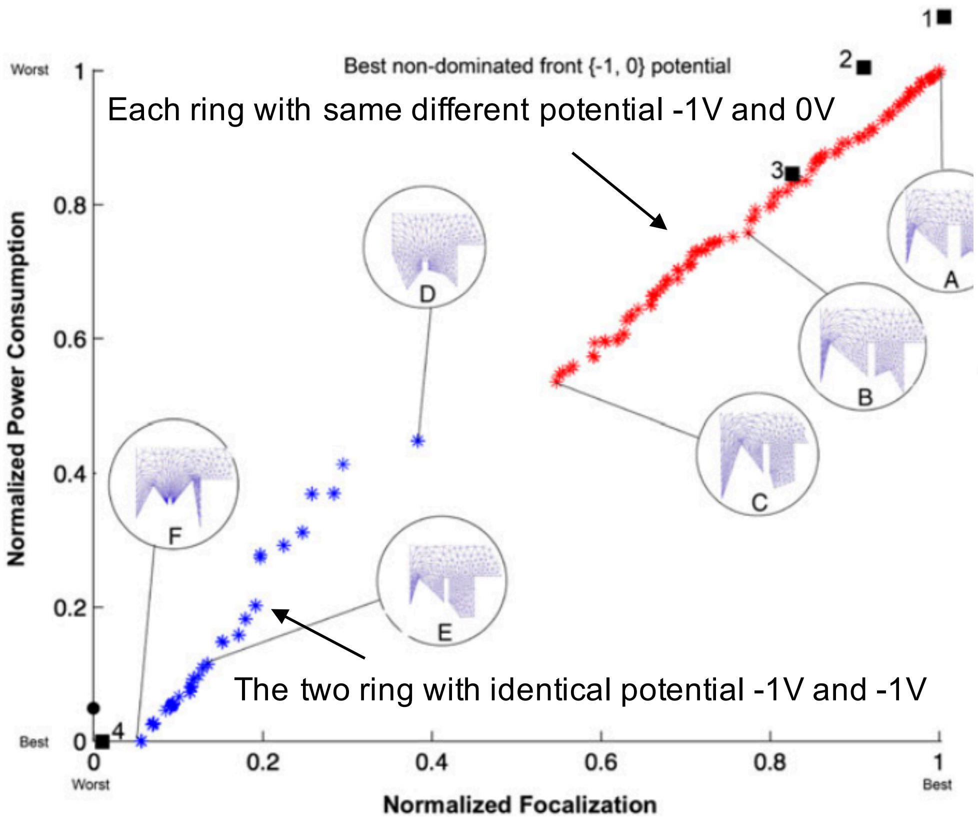
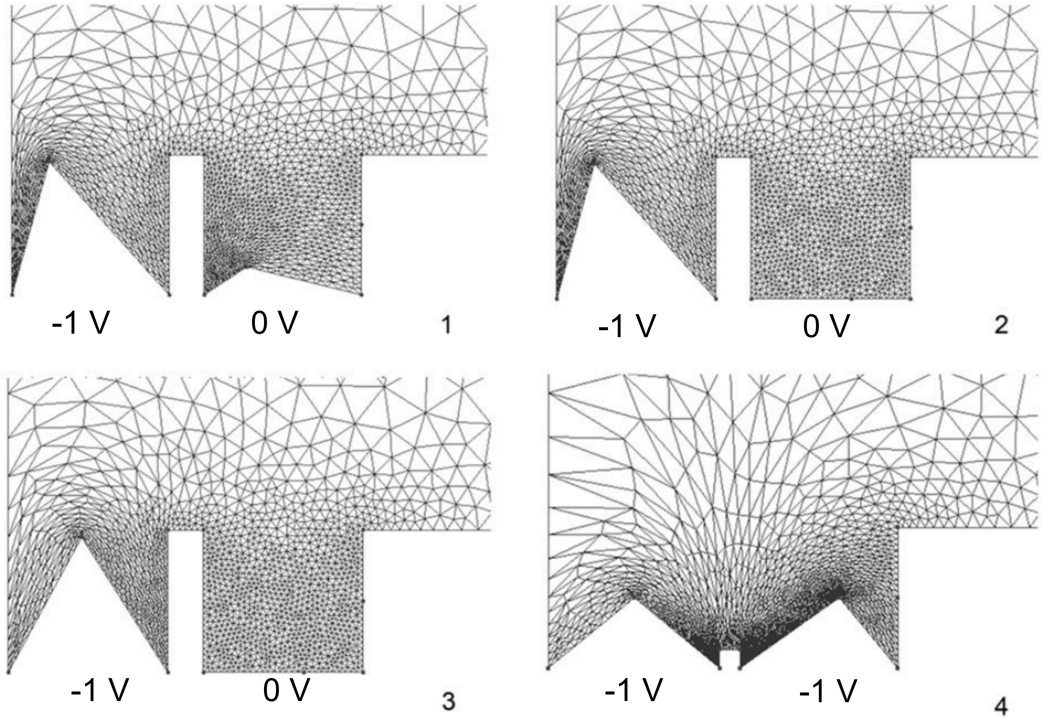
4 simplified designs





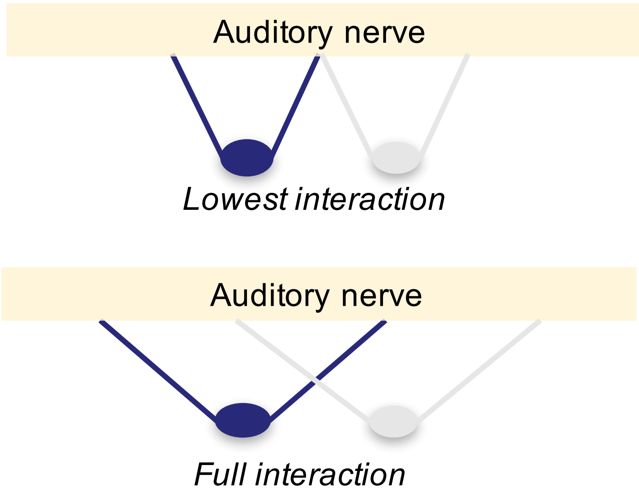
Designs restricted to potential -1V and 0V

Design 1: high focalization and high consume

Design 4: low focalization and low consume
(due to both rings are at the same potential)

Practical results

- Number of electrodes extra with respect to the standard array of 22 mm length and 22 electrodes



Nondominated design	Lowest interaction	Full interaction
Best focalization	46	28
Lowest power consumption	1	1
Same power as standard	3	3

Consume increment	Number of extra electrodes
Slightly smaller	1
Same consume	3
5 times more	46

Conclusion and future research

CONCLUSIONS

- We have design a “ring” electrode able to increment the focalization.
- We have used multiobjective evolutionary algorithm to improve the design attending to the focalization and consume.

FUTURE RESEARCH

- Perform more accurate simulations of the proposed electrodes in an anatomically realistic model
- Compare the results of different multiobjective evolutionary algorithms

Thank you very much

A. Ramos-de-Miguel, J.M. Escobar, D. Greiner, A. Ramos-Macias.
A multiobjective optimization procedure for the electrode design of cochlear implants. *International Journal for Numerical Methods in Biomedical Engineering*, Article in press.

Potentials along the neurons

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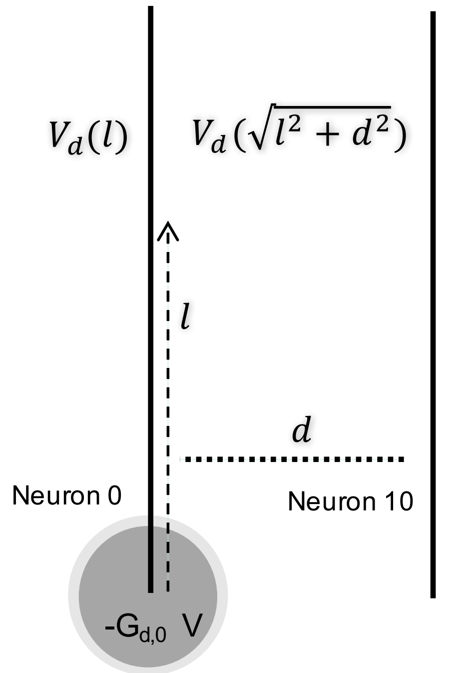
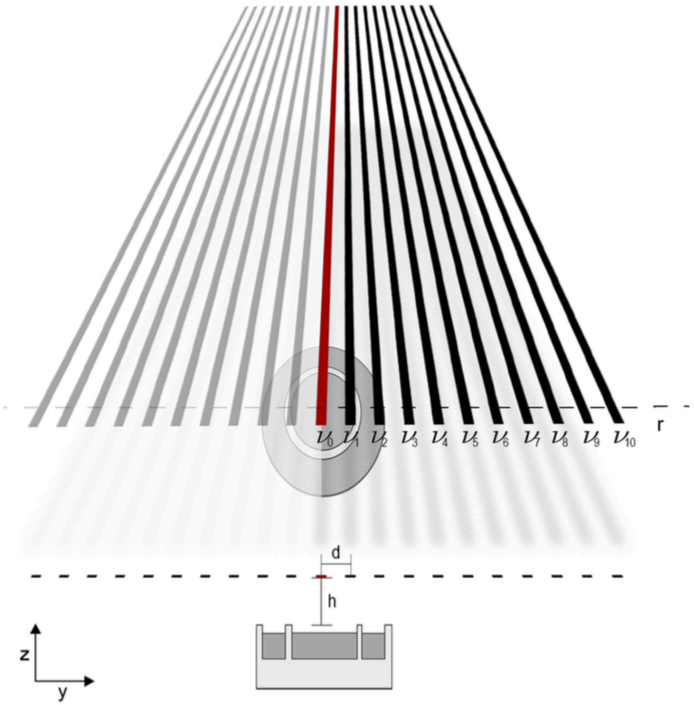


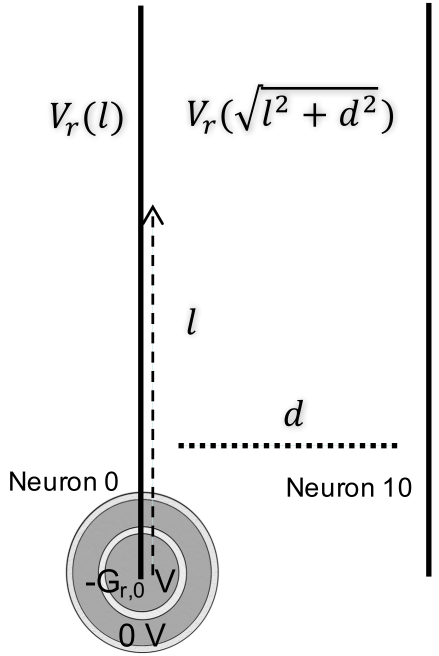
Standard disc electrode

Reference electrode 0 V



h= height of the neuron above the electrode. Typically around 0.6 mm

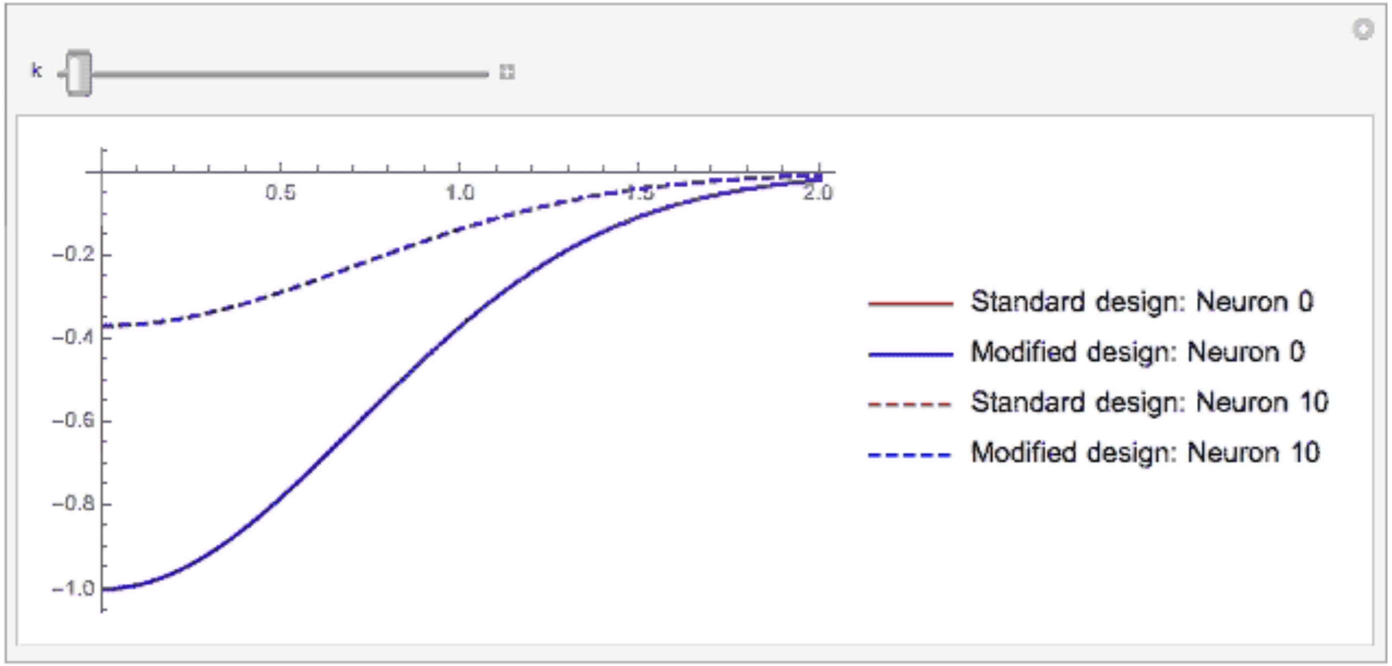
$G_{d,0}$ and $G_{r,0}$ are the threshold voltage of the disc and ring electrodes to excite the neuron 0 (red)



Proposed ring electrode

Reference electrode 0 V

Typical behavior of the potential curves for different designs



Narrower curve along the Neuron 0 implies less potential difference between extremes of Neuron 10

⬇

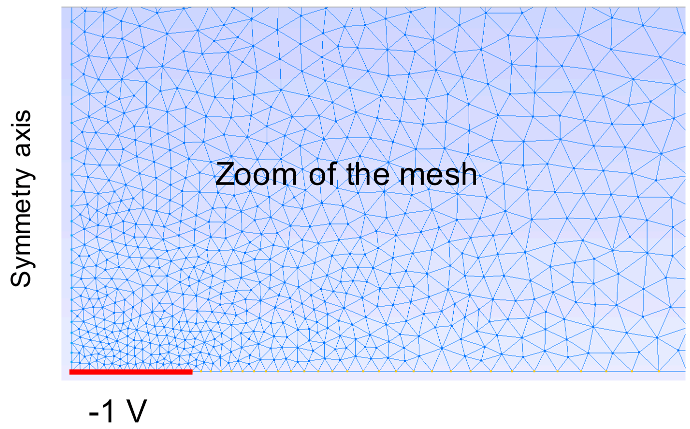
Greater difficulty to excite the neuron 10

⬇

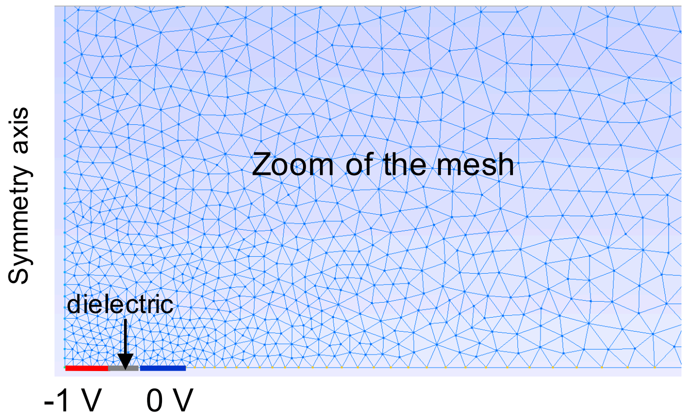
Greater focallization

Different designs: standard disc, flat ring and ring dielectric barrier electrodes

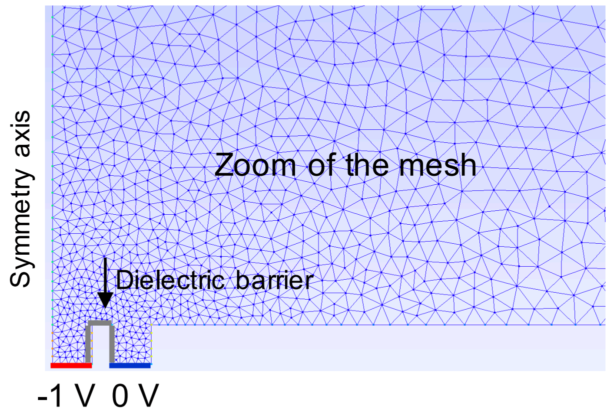
Disc electrode



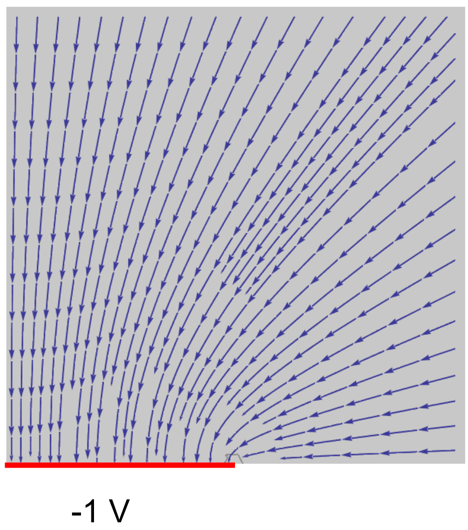
Flat ring electrode



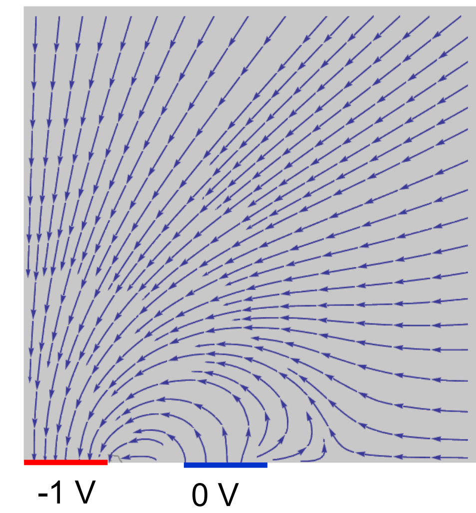
Ring electrode with dielectric barrier



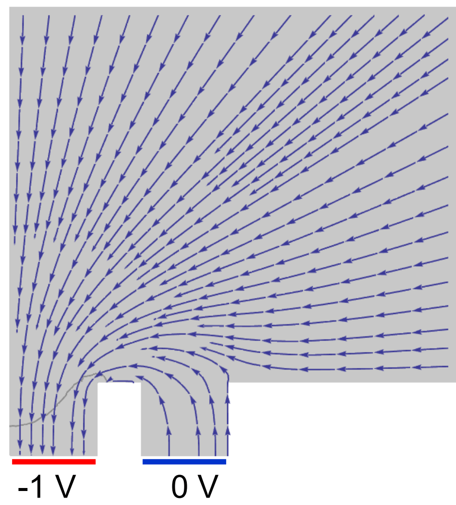
Current lines



Current lines

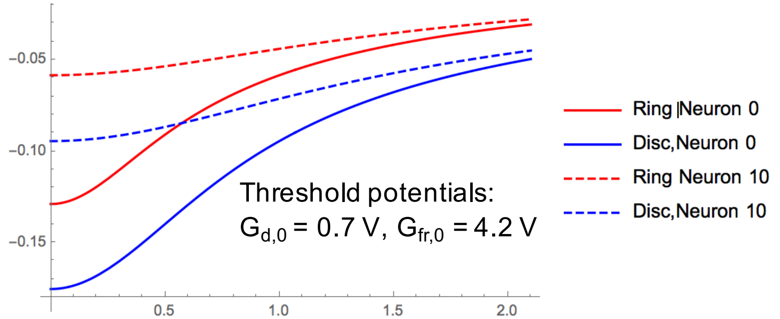


Current lines

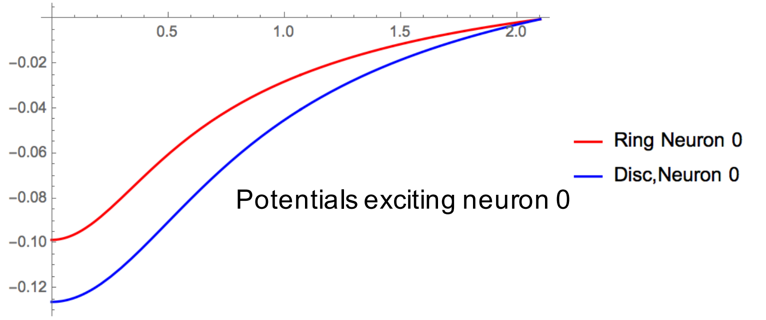


Potential along the neurons for the disc and flat ring electrodes

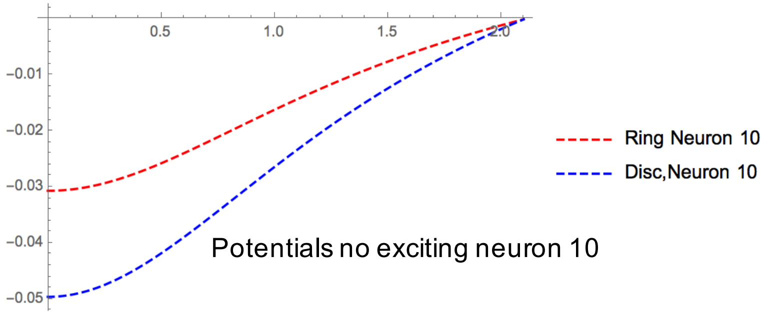
Height above the electrode, h=0.6 mm.



Potentials along neuron 0 and 10 for both designs



Potentials along neuron 0 translated to be compared



Potentials along neuron 10 translated to be compared

Consume:

h=0.6 mm.
P_{fr} = 20.9 P_d

h=0.4 mm.
P_{fr} = 7.8 P_d

P_r power consumed by flat ring electrode

P_d power consumed by dic electrode

Flatter curve

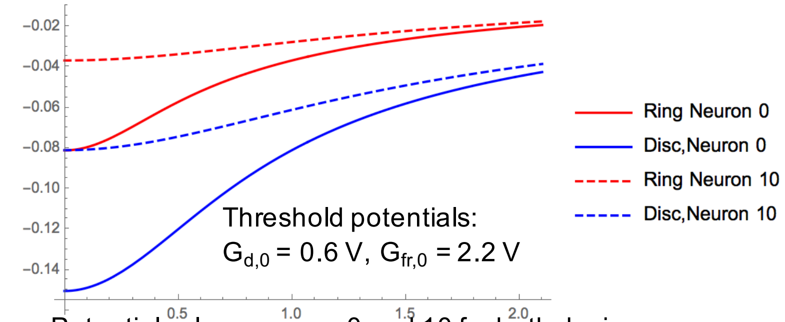
↓

Greater voltage to excite the neuron

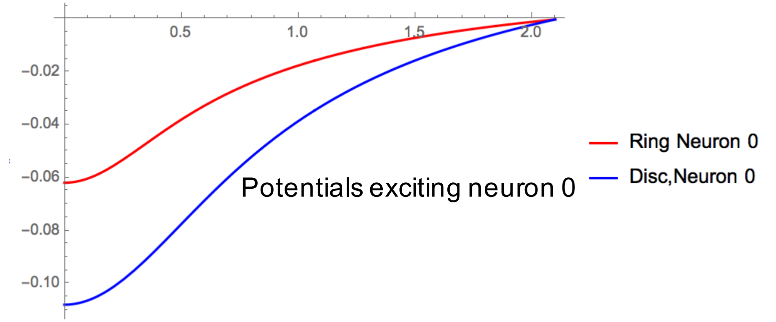
↓

Greater focallization

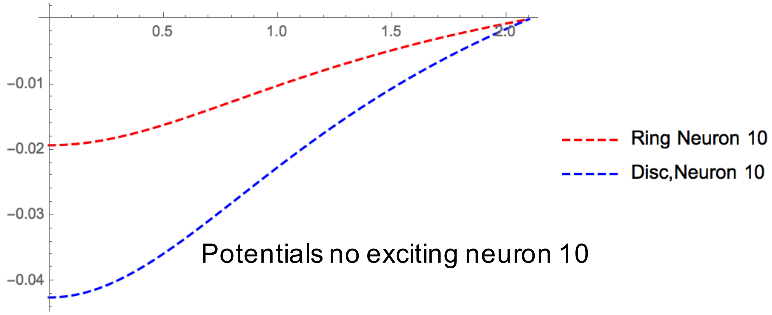
Height above the electrode, h=0.4 mm.



Potentials along neuron 0 and 10 for both designs



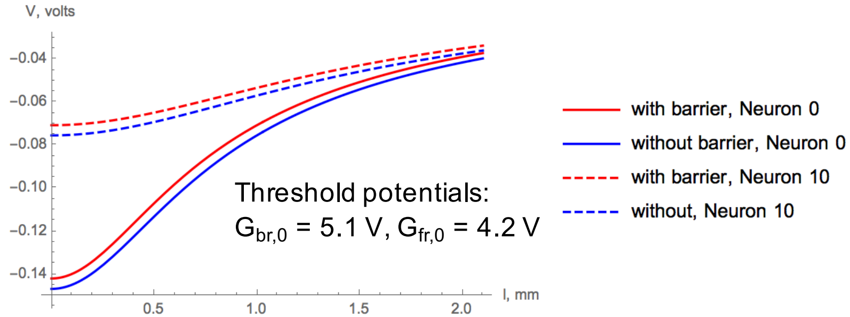
Potentials along neuron 0 translated to be compared



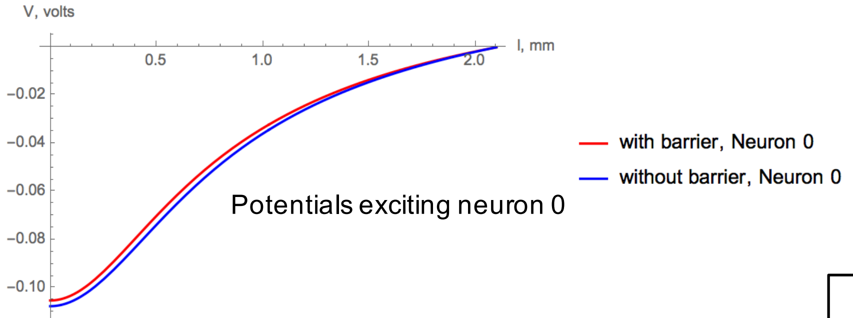
Potentials along neuron 10 translated to be compared

Potential along the neurons for electrode with and without barrier

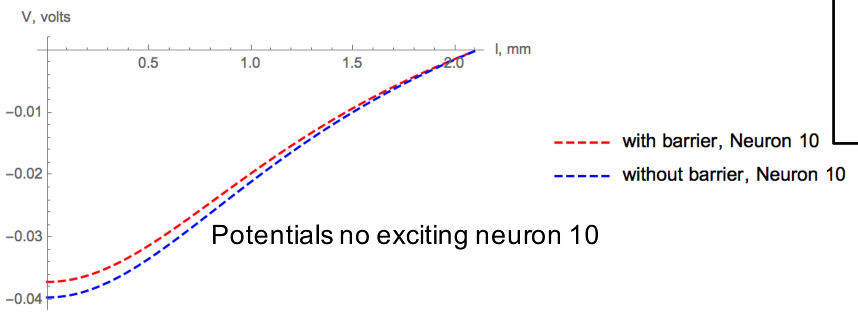
Height above the electrode, h=0.6 mm.



Potentials along neuron 0 and 10 for both designs



Potentials along neuron 0 translated to be compared



Potentials along neuron 10 translated to be compared

Consume:

h=0.6 mm.
$\mathbf{P_{br} = 0.47\ P_{fr} = 9.8\ P_d}$

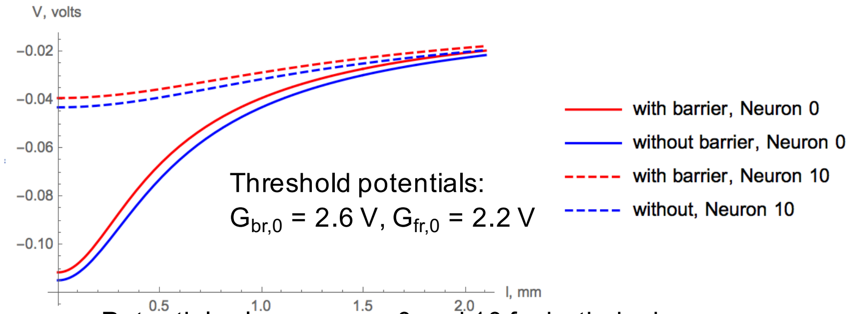
h=0.4 mm.
$\mathbf{P_{br} = 0.44\ P_{fr} = 3.4\ P_d}$

P_{br} power consumed by electrode with barrier

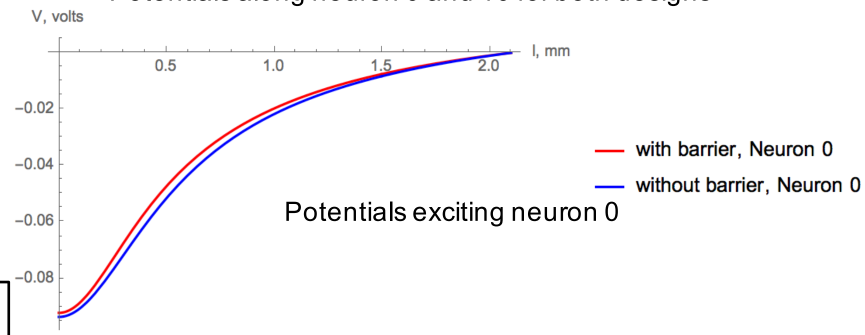
P_{fr} power consumed by electrode without barrier (flat ring)

Both designs have **similar focallization** but the **consume** of the electrode **with barrier** is **1/2 without barrier** (flat ring electrode)

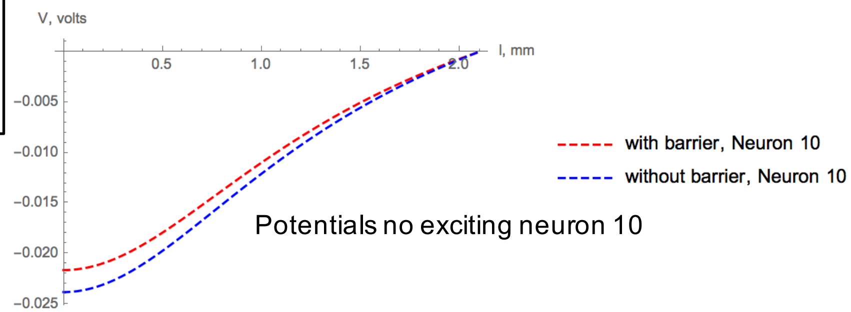
Height above the electrode, h=0.4 mm.



Potentials along neuron 0 and 10 for both designs



Potentials along neuron 0 translated to be compared



Potentials along neuron 10 translated to be compared

Characteristics of the proposed electrodes

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Ring electrode has better focallization and more power consume than standard disc electrode

Dielectric Barrier reduce the power consume of the ring electrode

Reference electrode reduce the power consume