

Neuromorphic Silicon Neuron Controller for Adaptive Deep Brain Stimulation in Parkinson's Disease

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Presentation outline

Roadmap for today's talk: from the problem motivation to the hardware-software co-designed aDBS results.

Outline

- 01 Background: what is DBS and what is DBS for PD?
- 02 Motivation and research gap
- 03 SiLIF-DBS concept and transistor-level controller
- 04 Matched surrogate and closed-loop model
- 05 Results: beta suppression and energy efficiency
- 06 Team, acknowledgments, and conclusion

Background: Deep Brain Stimulation (DBS) and DBS for Parkinson's disease (PD)

A brief clinical context for why adaptive and energy-efficient stimulation matters.

What is DBS?

- Deep brain stimulation, or DBS, is an implantable neuromodulation therapy that delivers electrical pulses to specific deep brain targets.
- A pulse generator sends stimulation through implanted leads to modulate abnormal neural activity and improve symptoms.
- Because stimulation is delivered chronically, controller design must consider efficacy, safety, latency, and power consumption.

What is DBS for PD?

- For Parkinson's disease, DBS is used to reduce motor symptoms such as tremor, rigidity, bradykinesia, and motor fluctuations when medication is insufficient.
- Common targets include the subthalamic nucleus, or STN, and the globus pallidus internus, or GPi.
- Adaptive DBS aims to adjust stimulation according to disease-related biomarkers, such as pathological beta-band STN activity, instead of stimulating continuously.

Why this matters: better controllers should respond to pathological activity, not stimulate at a fixed level all the time.

Motivation: adaptive DBS needs hardware-efficient stimulation

Clinical benefit depends on symptom suppression under strict implant power constraints.

>1%

age 60+

Parkinson's disease is linked to pathological beta-band activity in the STN.

13-30 Hz

beta

Beta-band oscillations are a widely used feedback biomarker.

**always on
DBS**

Continuous open-loop DBS stimulates even when the pathological state changes.

**battery
limited**

Implants require low latency, low area, and low power.

Why not rely only on software controllers?

- Fuzzy, reinforcement-learning, and neural-network controllers can add computational overhead [4, 9, 17, 19].
- Implantable DBS controllers must balance therapeutic suppression with energy and thermal limits [11, 21, 26].
- Neuromorphic silicon neurons offer physical integration, leakage, thresholding, reset, and refractoriness [14, 18].

References correspond to the ICONS paper reference numbering.

Research gap and main contributions

We connect a transistor-level neuromorphic primitive to system-level aDBS validation.

Gap in existing aDBS work

- Most controllers are algorithm- and simulation-driven.
- Hardware constraints are often treated after the controller is designed.
- A refractory-enabled silicon neuron controller with a matched computational twin is missing.

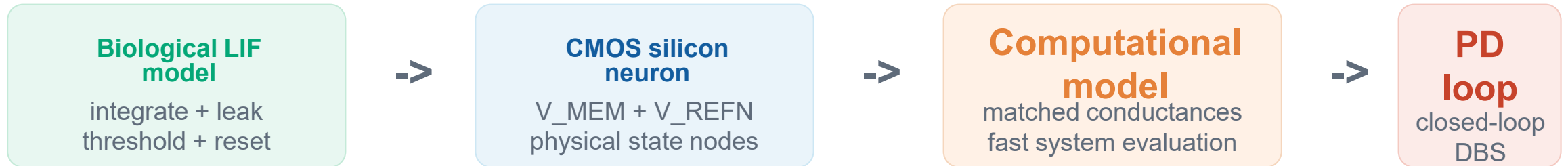
This work contributes

- Transistor-level SiLIF-DBS controller with membrane, leak, threshold, reset, and refractory blocks.
- Matched computational surrogate preserving the same two-state dynamics.
- Closed-loop PD model driven by beta-filtered STN-LFP and Beta_ARV.
- Controller-level benchmarking against open-loop and conventional adaptive DBS baselines.

Core claim: a physical refractory mechanism can become the controller state for energy-aware adaptive DBS.

SiLIF-DBS concept: one controller across three views

Biology-inspired dynamics, CMOS circuit realization, and a fast computational surrogate.



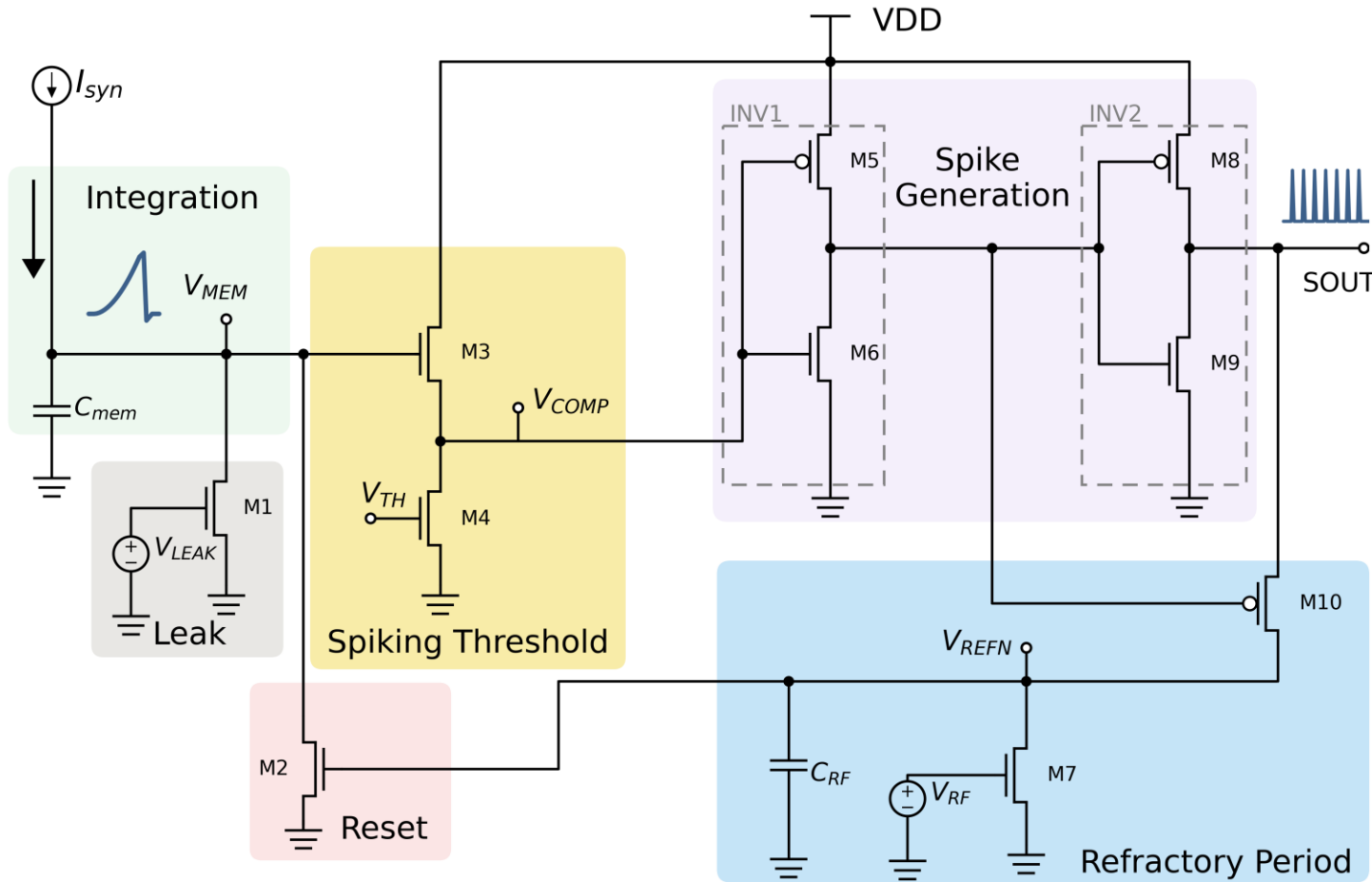
Design principle

The same refractory process that shapes silicon neuron spike timing also shapes the controller response and energy-suppression tradeoff.

not a software-only controller

Transistor-level refractory-enabled SiLIF-DBS controller

Two physical state nodes carry membrane and refractory dynamics.



Functional blocks

- Synaptic-current integration on V_{MEM}
- Leak path through M1 biased by V_{LEAK}
- Threshold detection through M3-M4
- Spike generation with cascaded inverters
- Reset and refractory dynamics through M2, M7, and M10

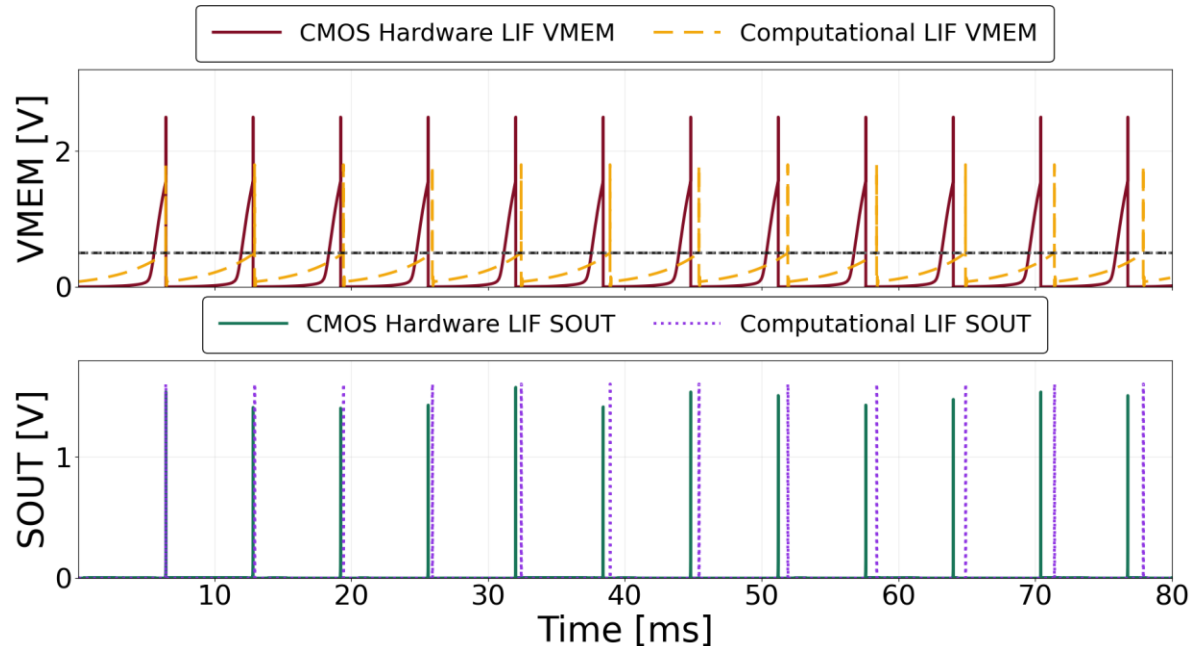
V_{RF}

SkyWater 130 nm
CMOS implementation

Main programming knob controlling
refractory discharge and firing rate

Matched computational surrogate for system-level validation

The reduced model preserves the circuit state variables and conductance laws.



State equations retained

$$C_{\text{mem}} \frac{dV_{\text{MEM}}}{dt} = I_{\text{syn}}(t) - [g_{\text{leak}} + g_{\text{rst}}(V_{\text{REFN}})] V_{\text{MEM}}$$

$$C_{\text{RF}} \frac{dV_{\text{REFN}}}{dt} = -g_{\text{m7}}(V_{\text{RF}}) V_{\text{REFN}}$$

Spike event: $V_{\text{MEM}} \geq V_{\text{TH}} \rightarrow \text{reset} + \text{refractory kick}$

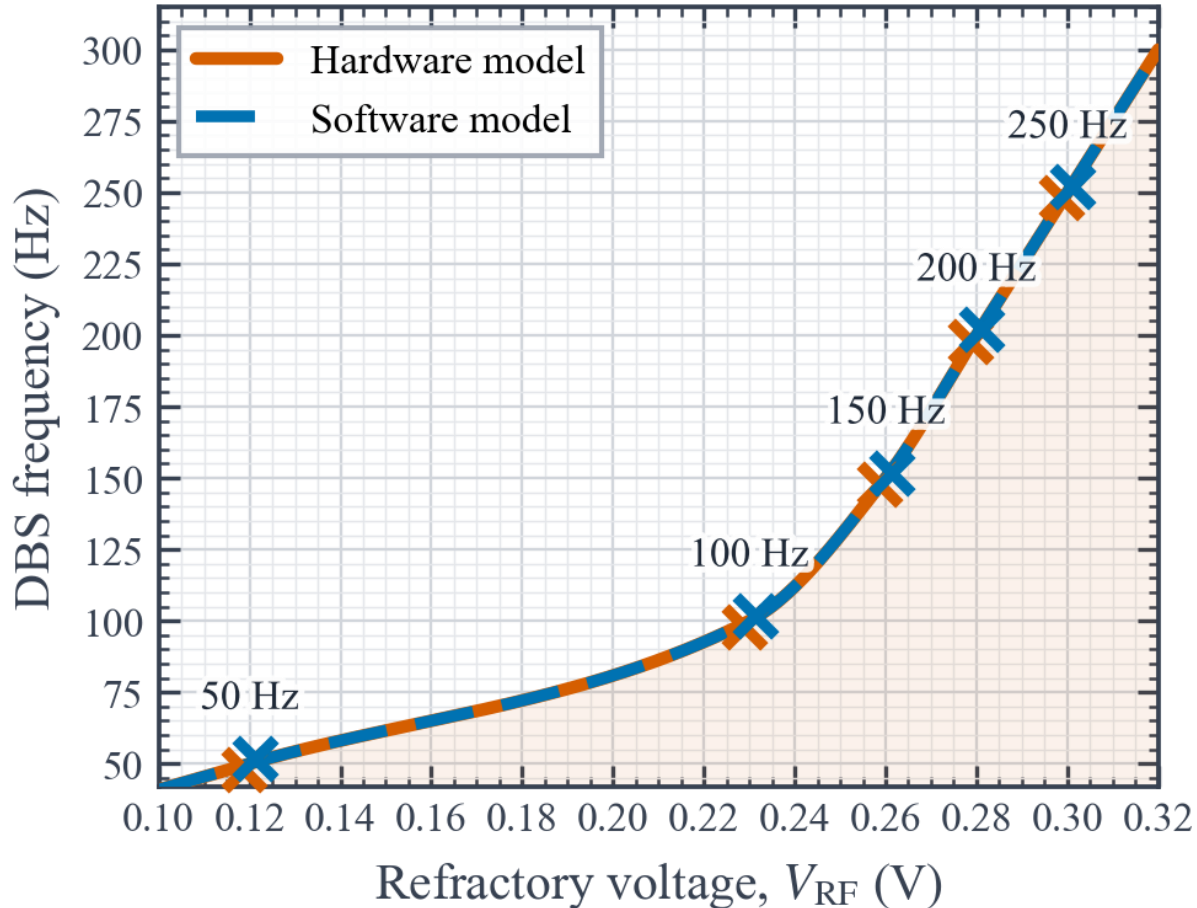
Why this matters

Direct circuit simulation is too slow for closed-loop PD model exploration. The surrogate enables fast simulation while remaining circuit-interpretable.

Result shown: HW-SW waveform-level agreement at 150 Hz

Controller programmability through refractory bias V_{RF}

A single circuit-level knob tunes the DBS event frequency from 50 Hz to 250 Hz.



50 -> 250 Hz calibrated operating range

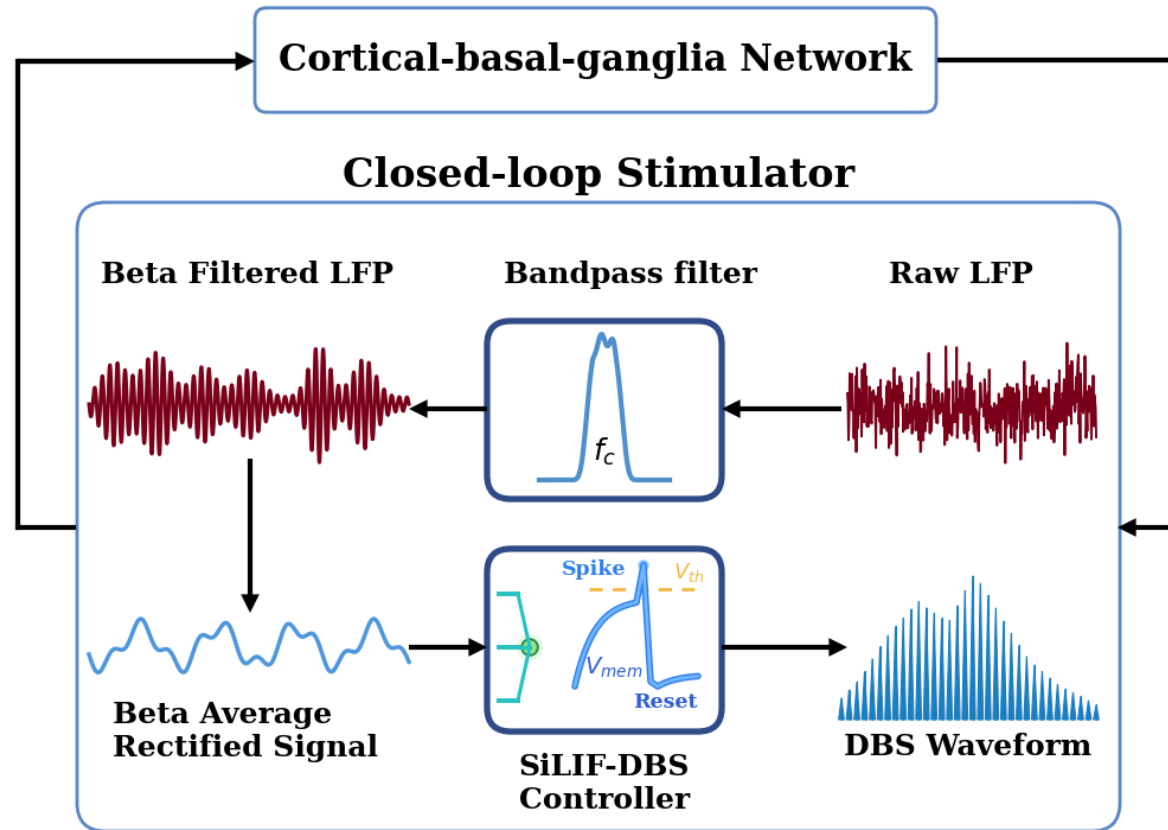
Interpretation

- Higher V_{RF} increases refractory discharge strength.
- Faster refractory recovery allows higher firing rate.
- Frequency tuning maps the silicon neuron output to DBS control behavior.

Message: tunability is intrinsic to the circuit, not added as a separate high-complexity controller.

Embedding SiLIF-DBS into a Parkinsonian closed-loop model

Beta-band STN-LFP drives a silicon-neuron-based amplitude command.



Closed-loop signal path

Raw STN-LFP

Beta bandpass filter (13-30 Hz)

Rectification + Beta_ARV

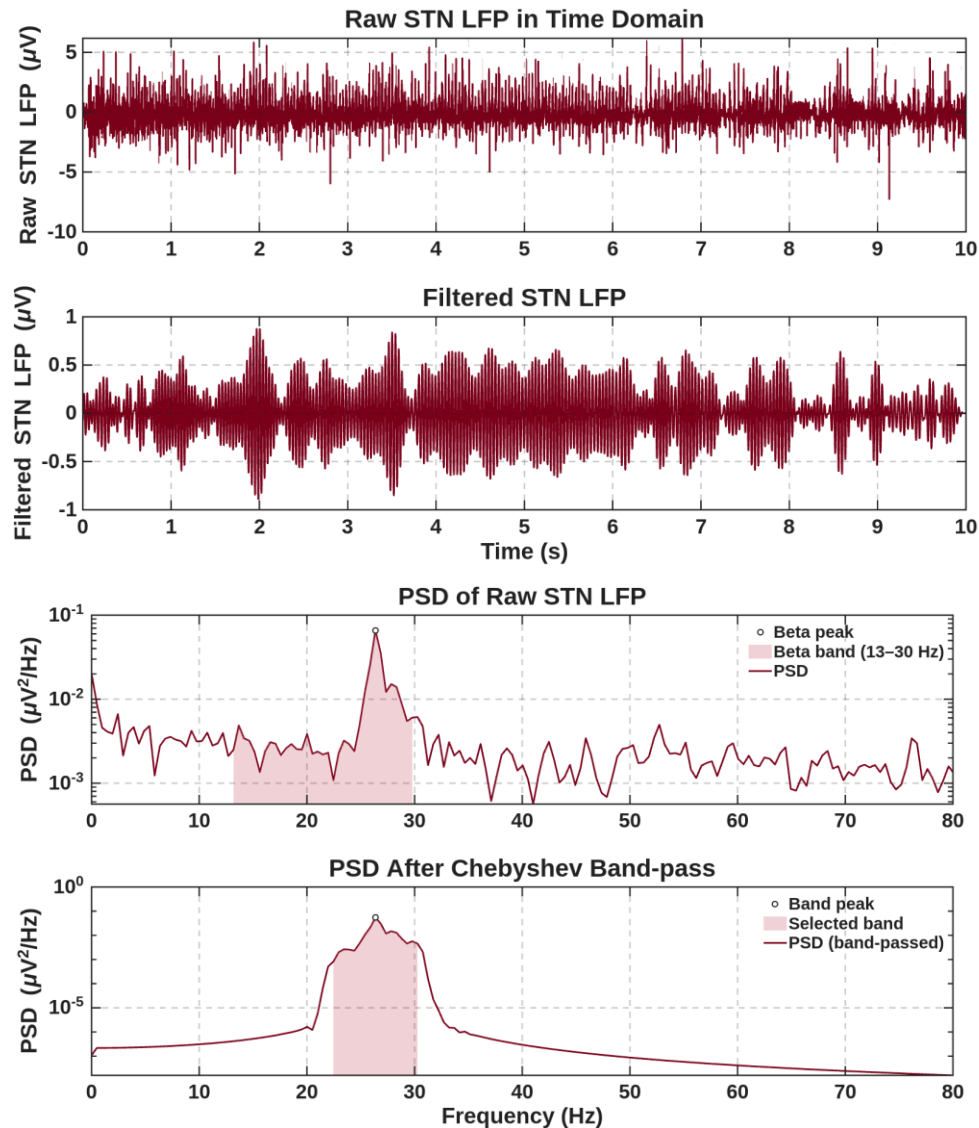
SiLIF-DBS spike-rate estimate

Amplitude-modulated DBS waveform

controller update period $T_s = 20$ ms

Biomarker extraction: why beta-filtered STN-LFP and Beta_ARV?

Filtering isolates the control-relevant pathological oscillatory component.



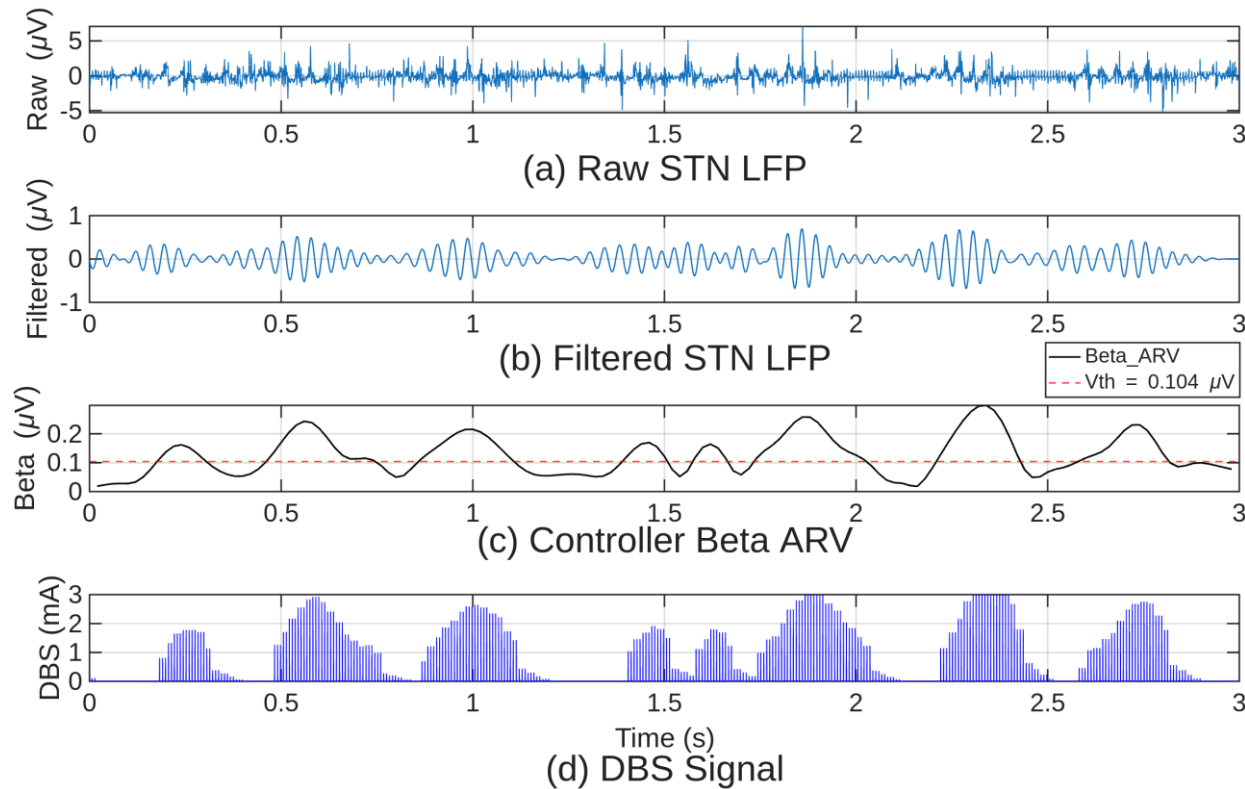
Observation from the feedback signal

- Raw STN-LFP is broadband and noisy for direct thresholding.
- Beta-band filtering reveals oscillatory packets tied to pathological activity.
- PSD confirms dominant energy in the selected 13-30 Hz band.
- Beta_ARV provides a smooth control feature for stimulation decisions.

control biomarker = Beta_ARV

Adaptive stimulation generated from Beta_ARV dynamics

SiLIF-DBS produces temporally sparse DBS bursts rather than continuous stimulation.



Controller behavior

- Beta_ARV crosses the threshold during pathological beta events.
- The silicon-neuron spike-rate estimate maps biomarker strength to DBS amplitude.
- Short moving-window smoothing avoids abrupt on-off switching.

0-3 mA

Amplitude command
bounds

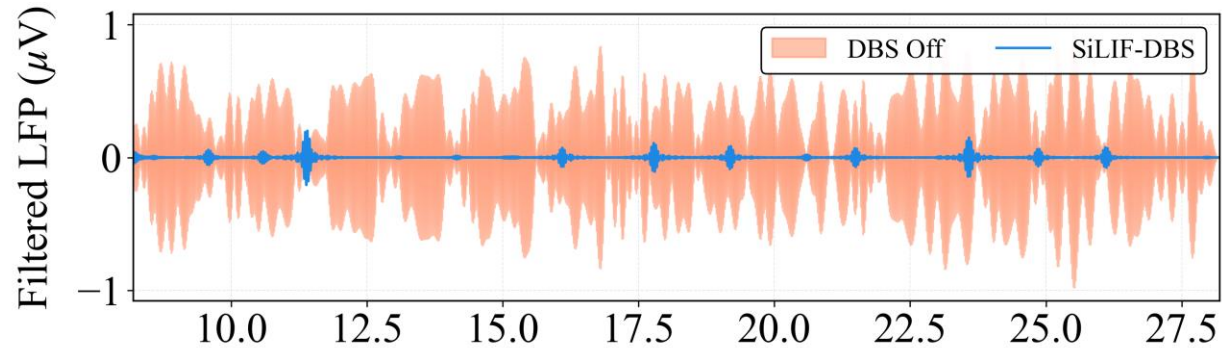
250 Hz

r_max

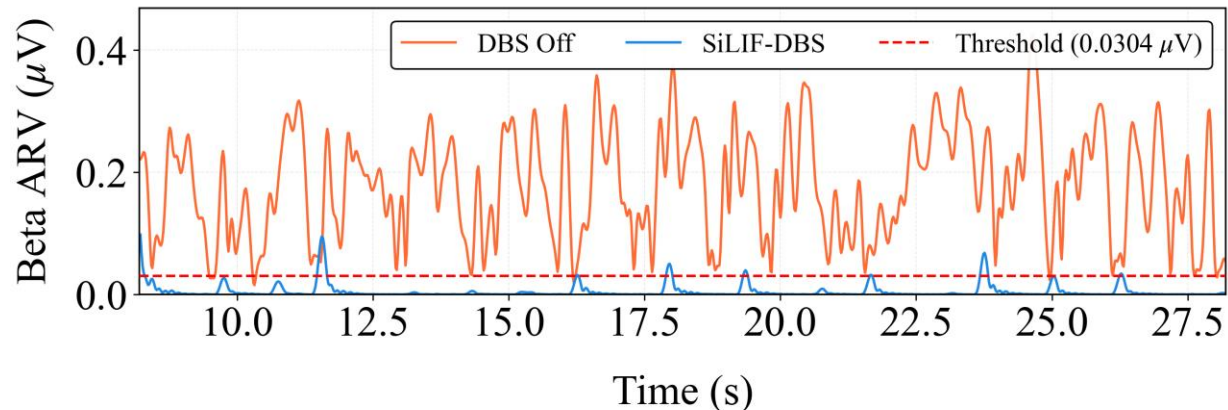
Spike-rate calibration

Closed-loop result: suppression of pathological beta activity

SiLIF-DBS reduces beta-band oscillations and keeps Beta_ARV near the threshold.



(a) Filtered LFP (beta band, 13-30 Hz)



(b) Beta ARV

Main result

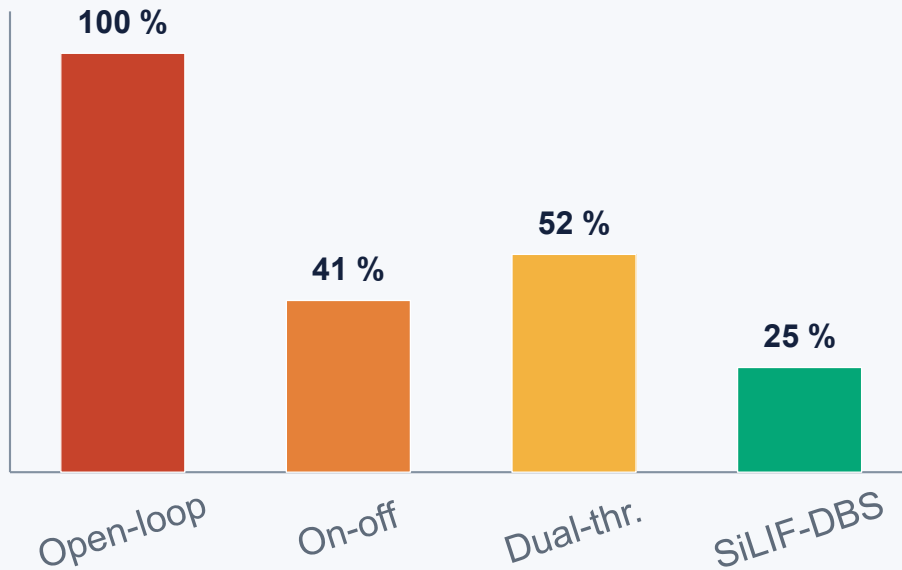
- DBS-off condition shows strong beta-band LFP oscillations.
- With SiLIF-DBS, filtered beta activity is strongly attenuated.
- Beta_ARV remains near or below the threshold most of the time.

Interpretation: the controller targets pathological episodes rather than delivering fixed high-amplitude stimulation continuously.

Energy-efficiency benchmarking against controller baselines

SiLIF-DBS reduces power to 25% of open-loop while retaining strong suppression efficiency.

Power consumption



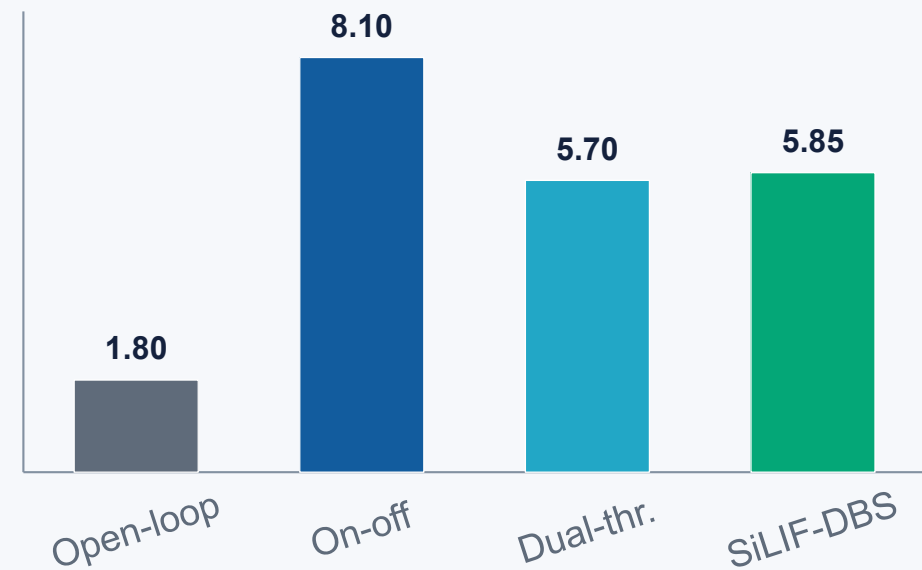
25%

SiLIF-DBS power

5.85 %/uW

SiLIF-DBS efficiency

Suppression efficiency



On-off 8.10

Highest efficiency baseline

100%

Open-loop baseline

How SiLIF-DBS differs from software-first aDBS controllers

The proposed method jointly emphasizes circuit realizability and closed-loop validation.

Existing controller families

On-off / PI / PID [7,10,24]	Algorithms + simulation	amplitude, frequency
Fuzzy logic [4]	Algorithms + simulation	on/off decision
Reinforcement learning [9,19]	Algorithms + simulation	amplitude
Machine learning [13,17,22]	Algorithms + simulation	amplitude
SiLIF-DBS (Ours)	Analog CMOS circuit	frequency + amplitude

References correspond to the ICONS paper reference numbering.

SiLIF-DBS positioning

- Controller dynamics are physically realizable in CMOS.
- Hardware and software models are matched before system-level validation.
- Refractory bias directly links circuit tuning with DBS control behavior.
- Beta suppression is evaluated with energy-aware metrics.

takeaway: hardware-software co-design

Conclusion: refractory-enabled silicon neurons are promising for implantable aDBS

SiLIF-DBS provides circuit interpretability, tunability, and energy-aware beta suppression.

Designed

A CMOS refractory-enabled silicon LIF controller with membrane, leak, threshold, reset, and refractory subcircuits.

Validated

A matched computational surrogate showed close waveform-level agreement and was embedded into the Parkinsonian closed-loop model.

Demonstrated

Adaptive beta suppression using only 25% of open-loop power with 5.85 %/uW suppression efficiency.

Future direction: advance toward post-layout/hardware validation and patient-specific biomarker-driven tuning.

Our Team and Collaborators

SiLIF-DBS is a collaborative effort between Michigan Technological University and University College Dublin.

Project authors

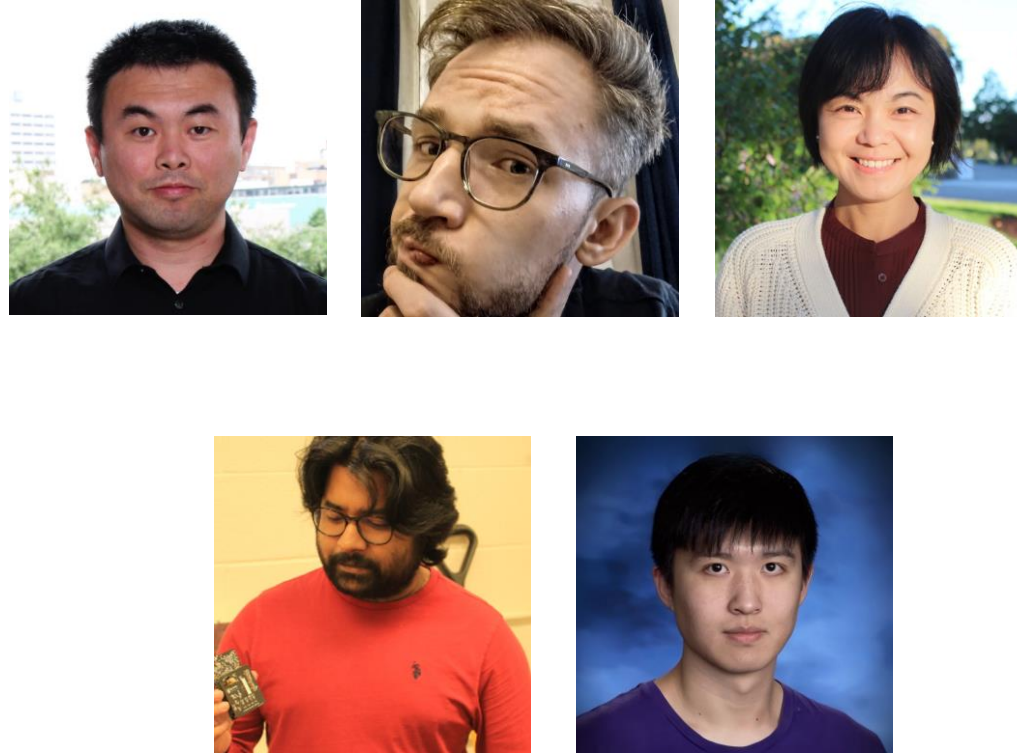
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Research team

Collaborative group members and lab collaborators are shown on the right.



**Michigan
Technological
University**



Interdisciplinary team in neuromorphic engineering, biology, and closed-loop brain stimulation

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Thank you

Questions?