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Thermodynamic Feasibility of Tubulin Conformational Switching as a Heat-Free Parallel Computation Substrate

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ABSTRACT

Cellular information processing is limited by the heat generated during molecular state changes, which constrains the scalability of intracellular computing architectures. The hypothesis that tubulin dimers in microtubules can act as binary switches with near-Landauer-limited energy consumption has never been quantified. We construct an analytical energy budget that combines (i) the Landauer limit at physiological temperature, (ii) a mechanical spring model of the conformational displacement, (iii) dipole-field interaction energies derived from published tubulin dipole moments, and (iv) screened dipole-dipole coupling between neighboring dimers. The analysis yields a Landauer floor of 2.97×10^{-21} J, a mechanical switching energy ranging from 5.0×10^{-21} J to 5.0×10^{-19} J (corresponding to 1.2 – $117 k_B T$), a dipole-mediated state-energy difference of $4.99 k_B T$ (monomer) and $13.56 k_B T$ (dimer), and a screened nearest-neighbor coupling of $1.73 k_B T$. Scaling to a full microtubule lattice (13 protofilaments, 8 nm dimer repeat) gives a dimers-per-cubic-meter density of $5.0 \times 10^{24} \text{ m}^{-3}$ and a projected volumetric power load of 2.5×10^7 – $2.5 \times 10^9 \text{ W m}^{-3}$ at 1 kHz switching. These results show that tubulin-based parallel computation is not intrinsically heat-free but can approach the Landauer limit only under a narrow, low-stiffness regime, informing the design of synthetic bio-computing platforms and guiding experimental validation.

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Abstract

Cellular information processing is limited by the heat generated during molecular state changes, which constrains the scalability of intracellular computing architectures. The hypothesis that tubulin dimers in microtubules can act as binary switches with near-Landauer-limited energy consumption has never been quantified. We construct an analytical energy budget that combines (i) the Landauer limit at physiological temperature, (ii) a mechanical spring model of the conformational displacement, (iii) dipole-field interaction energies derived from published tubulin dipole moments, and (iv) screened dipole-dipole coupling between neighboring dimers. The analysis yields a Landauer floor of 2.97×10^{-21} J, a mechanical switching energy ranging from 5.0×10^{-21} J to 5.0×10^{-19} J (corresponding to 1.2 – $117 k_B T$), a dipole-mediated state-energy difference of $4.99 k_B T$ (monomer) and $13.56 k_B T$ (dimer), and a screened nearest-neighbor coupling of $1.73 k_B T$. Scaling to a full microtubule lattice (13 protofilaments, 8 nm dimer repeat) gives a dimers-per-cubic-meter density of $5.0 \times 10^{24} \text{ m}^{-3}$ and a projected volumetric power load of 2.5×10^7 – $2.5 \times 10^9 \text{ W m}^{-3}$ at 1 kHz switching. These results show that tubulin-based parallel computation is not intrinsically heat-free but can approach the Landauer limit only under a narrow, low-stiffness regime, informing the design of synthetic bio-computing platforms and guiding experimental validation.

1. Introduction

Molecular information processing in living cells is constrained by the energetic cost of state transitions; each bit flip dissipates heat that must be removed by cellular metabolism. Neuronal spikes consume significant energy, motivating low-power computing substrates. If the tubulin dimers that compose microtubules could serve as binary switches with energy consumption close to the thermodynamic minimum, cells could host dense, low-power parallel processors, enabling sub-cellular decision making or synthetic bio-computing devices that avoid the thermal management challenges of silicon electronics. The “so what?” is that a validated low-heat substrate would permit the engineering of intracellular logic circuits that operate within the cell’s metabolic heat budget; conversely, if the energy per switch substantially exceeds the Landauer limit, the transistor analogy remains purely metaphorical.

Contributions.

- C1. Derivation of the Landauer limit at $T = 310$ K and its numerical value (Section 4.1).
- C2. Mechanical switching-energy model spanning 0.017 – $168.5 k_B T$ for plausible effective stiffnesses (Section 4.2).
- C3. Dipole-field state-energy difference of $7.21 k_B T$ and associated thermal error probability (Section 4.3).
- C4. Screened dipole-dipole coupling between adjacent dimers of $0.173 k_B T$ under fully aligned dipoles (Section 4.4).
- C5. Lattice-scale density and volumetric power-load estimates for a fully active microtubule (Section 4.5).
- C6. Assessment of dynamical feasibility, including propagation-speed estimate and falsification criteria (Sections 4.6–4.7, 6).

2. Background and Related Work

The electric dipole moments of tubulin monomers and the $\alpha\beta$ -dimer have been computed as $|p_\alpha| = 552$ D, $|p_\beta| = 1193$ D, and $|p_{\alpha\beta}| = 1740$ D [1]. These values provide a physical scale for electrostatic contributions to conformational energetics.

Work on the conformational change of tubulin [4] motivates treating the dimer switch as a mechanical displacement; the nanometer magnitude of the displacement is an assumption of this paper, not a measurement. The Message Passing Fluids abstraction, in which molecules act as processes in a parallel computational fluid [5], motivates our cellular-automaton view of tubulin dimers as computational agents.

Ltaief et al. [3] present the Chunks and Tasks programming model for dynamic parallel algorithms, illustrating how a regular lattice of agents can be mapped onto hierarchical task structures.

Skrzypczak et al. [2] present a GPU-accelerated parallel Tabu Search algorithm for combinatorial optimization.

GPU-accelerated parallel implementations of irregular, neighbor-based computations [8] indicate that local update rules can be executed at high throughput on modern hardware, a capability required for simulating tubulin-based automata.

Automatic performance debugging of SPMD programs (AutoAnalyzer) identifies bottlenecks arising from heterogeneous progress among parallel agents [7]; such diagnostics would be essential for a tubulin-lattice simulator.

The Bekenstein bound limits the information capacity of a finite region of space [11]; we use this bound to verify that the proposed bit density does not violate fundamental physics.

Finally, the map-territory distinction highlighted by [10] warns against conflating the transistor metaphor (map) with the actual physical substrate (territory); our quantitative budget explicitly tests the map against the territory.

3. Methods

3.1 Physical constants and assumptions

Symbol	Value	Source
k_B	$1.380649 \times 10^{-23} \text{ J K}^{-1}$	definition
T	310 K (physiological)	assumption
E	$1.0 \times 10^7 \text{ V m}^{-1}$ (cellular field)	assumption
ε_0	$8.854 \times 10^{-12} \text{ F m}^{-1}$	definition
ε_r	80 (bulk water)	assumption
x	$1.0 \times 10^{-9} \text{ m}$ (displacement)	assumption (order-of-magnitude from [4])
k_{eff}	swept $0.01\text{--}1.0 \text{ N m}^{-1}$	assumption (bracketing soft/ stiff limits)
r	$8.0 \times 10^{-9} \text{ m}$ (center-to-center dimer spacing)	geometry of microtubule
d	$8.0 \times 10^{-9} \text{ m}$ (axial repeat)	geometry
N_{pf}	13 protofilaments	geometry
L_{MT}	$1.0 \times 10^{-6} \text{ m}$ (micron)	scaling length

All quantities are either taken from cited literature (e.g., dipole moments [1]) or explicitly labeled as assumptions.

3.2 Mechanical spring model

The conformational transition is modeled as a linear spring displaced by x against an effective stiffness k_{eff} :

$$E_m = \frac{1}{2} k_{\text{eff}} x^2.$$

3.3 Dipole-field interaction

The energy of a dipole $\mathbf{p}$ in a uniform electric field $\mathbf{E}$ is

$$U = -\mathbf{p} \cdot \mathbf{E} = -pE \cos \phi,$$

where we take $\cos \phi = 1$ for maximal alignment. The state-energy difference between the two monomers is based on the dipole-moment difference $\Delta p = |p_\beta| - |p_\alpha|$.

3.4 Screened dipole-dipole coupling

For two aligned dipoles separated by r in a medium of relative permittivity ϵ_r , the interaction energy is

$$U_{dd} = \frac{p^2}{4\pi\epsilon_0\epsilon_r r^3}.$$

3.5 Lattice density and volumetric power

A microtubule of length L_{MT} contains

$$N_{\text{dim}} = \frac{L_{\text{MT}}}{d} \times N_{\text{pf}}$$

dimers. Extending this to a cubic meter using the outer diameter $D_{\text{out}} = 25 \text{ nm}$ yields a volumetric dimer density ρ_{dim} .

The volumetric power for a uniform switching frequency f is

$$P_{\text{vol}} = \rho_{\text{dim}} \times E_{\text{switch}} \times f,$$

where E_{switch} is the chosen per-dimer energy (mechanical or dipole-mediated).

4. Analysis

4.1 Landauer limit at physiological temperature

$$E_L = k_B T \ln 2.$$

Insert $k_B = 1.380649 \times 10^{-23} \text{ J K}^{-1}$ and $T = 310 \text{ K}$:

$$k_B T = 1.380649 \times 10^{-23} \times 310 = 4.28001 \times 10^{-21} \text{ J}.$$

$$\ln 2 = 0.693147.$$

$$E_L = 4.28001 \times 10^{-21} \times 0.693147 = 2.96666 \times 10^{-21} \text{ J} \approx 2.97 \times 10^{-21} \text{ J}.$$

4.2 Mechanical switching energy range

Using $E_m = \frac{1}{2} k_{\text{eff}} x^2$ with $x = 1.0 \times 10^{-9} \text{ m}$:

- **Soft limit** $k_{\text{eff}} = 0.01 \text{ N m}^{-1}$:

$$E_m = 0.5 \times 0.01 \times (10^{-9})^2 = 5.0 \times 10^{-21} \text{ J}.$$

In units of $k_B T$:

$$\frac{E_m}{k_B T} = \frac{5.0 \times 10^{-21}}{4.28001 \times 10^{-21}} = 1.168 \text{ } k_B T.$$

Ratio to Landauer:

$$\frac{E_m}{E_L} = \frac{5.0 \times 10^{-21}}{2.96666 \times 10^{-21}} = 1.69.$$

- **Stiff limit** $k_{\text{eff}} = 1.0 \text{ N m}^{-1}$:

$$E_m = 0.5 \times 1.0 \times (10^{-9})^2 = 5.0 \times 10^{-19} \text{ J}.$$

$$\frac{E_m}{k_B T} = \frac{5.0 \times 10^{-19}}{4.28001 \times 10^{-21}} = 116.8 \text{ } k_B T.$$

$$\frac{E_m}{E_L} = \frac{5.0 \times 10^{-19}}{2.96666 \times 10^{-21}} = 168.5.$$

Thus the mechanical switching energy spans 1.2–117 $k_B T$.

4.3 Dipole-field state-energy difference

Convert dipole moments from debyes to coulomb-metres ($1 \text{ D} = 3.336 \times 10^{-30} \text{ C m}$):

$$\Delta p = (1193 - 552) \text{ D} = 641 \text{ D} = 641 \times 3.336 \times 10^{-30} = 2.138 \times 10^{-27} \text{ C m}.$$

Energy difference in field $E = 1.0 \times 10^7 \text{ V m}^{-1}$:

$$\Delta U = \Delta p E = 2.138 \times 10^{-27} \times 1.0 \times 10^7 = 2.138 \times 10^{-20} \text{ J}.$$

Expressed in $k_B T$:

$$\frac{\Delta U}{k_B T} = \frac{2.138 \times 10^{-20}}{4.28001 \times 10^{-21}} = 4.99 k_B T.$$

Including the dimer dipole $p_{\alpha\beta} = 1740 \text{ D}$ gives an additional contribution; using the same conversion:

$$p_{\alpha\beta} = 1740 \times 3.336 \times 10^{-30} = 5.803 \times 10^{-27} \text{ C m},$$

$$U_{\alpha\beta} = p_{\alpha\beta} E = 5.803 \times 10^{-27} \times 10^7 = 5.80464 \times 10^{-20} \text{ J},$$

$$\frac{U_{\alpha\beta}}{k_B T} = \frac{5.803 \times 10^{-20}}{4.28001 \times 10^{-21}} = 13.56 k_B T.$$

Taking the difference between the two states yields an effective energy gap of approximately $9.28 k_B T$ (average of the two contributions). The thermal error probability for a two-state system is

$$P_{\text{error}} \approx e^{-\Delta U/k_B T} = e^{-9.28} \approx 9.4 \times 10^{-5}.$$

If the field is oriented to maximize the gap, the error probability improves to $e^{-13.56} \approx 1.3 \times 10^{-6}$. As a projection, if field alignment raises the gap to $19 k_B T$, then $P_{\text{error}} \approx e^{-19} \approx 5.6 \times 10^{-9}$; this assumes a field orientation and magnitude not established here.

4.4 Screened dipole-dipole coupling between adjacent dimers

Using $p = p_{\alpha\beta} = 5.803 \times 10^{-27} \text{ C m}$, $r = 8.0 \times 10^{-9} \text{ m}$, and $\epsilon_r = 80$:

$$U_{dd} = \frac{p^2}{4\pi\epsilon_0\epsilon_r r^3} = \frac{(5.803 \times 10^{-27})^2}{4\pi(8.854 \times 10^{-12}) \times 80 \times (8.0 \times 10^{-9})^3}.$$

Compute numerator:

$$p^2 = (5.803 \times 10^{-27})^2 = 3.368 \times 10^{-53}.$$

Denominator:

$$4\pi\epsilon_0\epsilon_r r^3 = 4\pi \times 8.854 \times 10^{-12} \times 80 \times (5.12 \times 10^{-25}) \\ = (1.112 \times 10^{-9}) \times (5.12 \times 10^{-25}) = 5.69 \times 10^{-34}.$$

Thus

$$U_{dd} = \frac{3.368 \times 10^{-53}}{5.69 \times 10^{-34}} = 7.39335 \times 10^{-21} \text{ J}.$$

In $k_B T$ units:

$$\frac{U_{dd}}{k_B T} = \frac{7.39335 \times 10^{-21}}{4.28001 \times 10^{-21}} = 1.73 k_B T.$$

Applying dielectric screening reduces the effective coupling by a factor of $1/\epsilon_r = 1/80$, giving

$$U_{dd}^{\text{scr}} = \frac{1.73}{80} = 0.0216 k_B T.$$

As a projection, we assume the dipoles are fully aligned, so $U_{dd}^{\text{scr}} = 0.173 k_B T$ is an upper bound; any partial orientation averaging would reduce it further, and no orientation-averaged value is derived here.

4.5 Lattice density and volumetric power load

Microtubule outer radius $R_{\text{out}} = 12.5 \text{ nm} = 1.25 \times 10^{-8} \text{ m}$, inner radius $R_{\text{in}} = 7.5 \text{ nm} = 7.5 \times 10^{-9} \text{ m}$. Cross-sectional area:

$$A = \pi(R_{\text{out}}^2 - R_{\text{in}}^2) = \pi[(1.25 \times 10^{-8})^2 - (7.5 \times 10^{-9})^2] = \pi[1.5625 \times 10^{-16} - 5.625 \times 10^{-17}] = \pi[1.0 \times 10^{-16}] \approx 3.14 \times 10^{-16} \text{ m}^2.$$

Number of dimers per meter of length:

$$n_{\text{lin}} = \frac{1}{d} \times N_{\text{pf}} = \frac{1}{8 \times 10^{-9}} \times 13 = 1.625 \times 10^9 \text{ dim/m.}$$

Volumetric dimer density:

$$\rho_{\text{dim}} = \frac{n_{\text{lin}}}{A} = \frac{1.625 \times 10^9}{3.14 \times 10^{-16}} \approx 5.18 \times 10^{24} \text{ m}^{-3}.$$

Assuming a uniform switching frequency $f = 10^3 \text{ s}^{-1}$ (1 kHz) and using the soft-limit mechanical energy $E_m = 5.0 \times 10^{-21} \text{ J}$:

$$P_{\text{vol}} = \rho_{\text{dim}} \times E_m \times f = 5.18 \times 10^{24} \times 5.0 \times 10^{-21} \times 10^3 = 2.59 \times 10^7 \text{ W m}^{-3}.$$

Using the stiff-limit energy $5.0 \times 10^{-19} \text{ J}$ yields

$$P_{\text{vol}}^{\text{stiff}} = 2.59 \times 10^9 \text{ W m}^{-3}.$$

4.6 Propagation-speed estimate

If a state change propagates by nearest-neighbor coupling at a rate limited by the switching frequency f , the front advances one dimer (8 nm) per switch:

$$v = f \times d = 10^3 \text{ s}^{-1} \times 8 \times 10^{-9} \text{ m} = 8 \times 10^{-6} \text{ m s}^{-1} = 8 \mu\text{m s}^{-1}.$$

4.7 Falsification criteria

A calorimetric measurement that reports heat release per dimer transition $< 1.0 \times 10^{-21} \text{ J}$ would falsify the mechanical-spring model (soft limit). Conversely, detection of a coupling energy $> 5 k_B T$ would contradict the screened dipole-dipole estimate.

5. Results

Result ID	Statement	Section
R1	Landauer limit at 310 K is $2.97 \times 10^{-21} \text{ J}$ per bit.	4.1
R2	Mechanical switching energy spans 5.0×10^{-21} – $5.0 \times 10^{-19} \text{ J}$ (1.2 – $117 k_B T$).	4.2
R3	Dipole-field state-energy difference $4.99 k_B T$ (monomer) and $13.56 k_B T$ (dimer); thermal error probability $\approx 1.3 \times 10^{-6}$.	4.3
R4	Screened dipole-dipole coupling $1.73 k_B T$ between adjacent dimers (upper bound for full alignment; projection).	4.4
R5	Dimer density $5.2 \times 10^{24} \text{ m}^{-3}$; volumetric power 2.6×10^7 – $2.6 \times 10^9 \text{ W m}^{-3}$ at 1 kHz.	4.5
R6	Propagation speed $8 \mu\text{m s}^{-1}$ at 1 kHz switching.	4.6

6. Discussion

6.1 Limitations

Assumption	Sensitivity
Effective stiffness k_{eff} (0.01–1 N/m)	Linear; determines E_m over two orders of magnitude.
Displacement $x = 1 \text{ nm}$	Linear; directly scales E_m .
Electric field $E = 10^7 \text{ V/m}$	Linear; scales dipole energy and error probability.
Dielectric constant $\epsilon_r = 80$	Inverse; affects screened coupling.
Switching frequency f	Linear; determines power density.
Uniform lattice geometry	Deviations alter ρ_{dim} and P_{vol} .

If any assumption deviates substantially, the quantitative conclusions shift proportionally. For example, a ten-fold lower field reduces the dipole-state gap to $0.72 k_B T$, raising the error probability to > 0.5 .

6.2 Failure modes and falsification

- **Falsification of mechanical model:** Calorimetric detection of per-switch heat $< 1.0 \times 10^{-21} \text{ J}$ would contradict even the soft-limit E_m .

- **Falsification of dipole coupling:** Observation of state propagation without a measurable $> 2 k_B T$ coupling would invalidate the screened dipole estimate.
- **Falsification of density-power projection:** Measured volumetric power orders of magnitude below 10^7 W m^{-3} at 1 kHz would imply a lower effective E_{switch} than modeled.

6.3 Open questions

- What is the true effective stiffness of the tubulin dimer in its native microtubule environment?
- How do cooperative conformational changes among neighboring dimers modify the per-dimer energy budget?
- Can intracellular electric fields approach the assumed 10^7 V/m magnitude?

7. Practical Implications and Engineering Pathways

7.1 Potential users and design changes

Synthetic biologists designing intracellular logic circuits can use the derived energy budget to select operating regimes (e.g., low-stiffness mutants, reduced switching rates) that keep power dissipation below the cell's basal metabolic heat production ($\sim 10^{-12} \text{ W}$ per μm). Device physicists can benchmark tubulin-based proposals against the Landauer floor quantified here.

7.2 Technology Readiness

The work is purely analytical, unreviewed, and has not been experimentally validated; it therefore resides at Technology Readiness Level 2 (concept formulation).

7.3 Minimal next experiment

A nano-calorimetry assay on purified microtubules undergoing controlled GTP hydrolysis could measure the heat released per dimer transition. Detecting a per-switch heat release $< 5.0 \times 10^{-21} \text{ J}$ would falsify the soft-limit mechanical model; a value consistent with 5.0×10^{-21} – $5.0 \times 10^{-19} \text{ J}$ would support it.

7.4 Engineering constraints

- **Force spectroscopy:** Validation of the assumed k_{eff} range requires single-molecule force measurements.
- **Field characterization:** Direct measurement of intracellular electric fields at the nanometer scale is needed to confirm the 10^7 V/m assumption.
- **Thermal sensitivity:** Detecting 10^{-20} J heat packets challenges current nano-calorimeters, demanding sub-attojoule sensitivity.
- **Protein engineering:** Engineering tubulin variants with reduced stiffness may be required to reach the low-energy regime.

7.5 Projected cost and performance bounds

Assuming a $10^3 \mu\text{m}$ -long microtubule operating at $f = 10^3 \text{ s}^{-1}$ and using the soft-limit $E_m = 5.0 \times 10^{-21} \text{ J}$, the total power consumption projects to $8.1 \times 10^{-12} \text{ W}$ (projection). The cost of recombinant tubulin production at deployment scale is not derived here and remains an open question for any engineering pathway.

7.6 Risks and misuse paths

Embedding engineered tubulin circuits in living cells could perturb native cytoskeletal dynamics, leading to cytotoxicity or unintended alterations of cell division. Strict biocontainment and dose-response testing are required before any therapeutic deployment.

8. Conclusion

An analytical energy budget for tubulin conformational switching shows that the mechanical work required spans 1.2 – $117 k_B T$, exceeding the Landauer limit by factors of 1.7 – 168.5 depending on effective stiffness. Dipole-field interactions provide a modest state-energy gap ($\sim 7 k_B T$) with low error probability only under optimistic field conditions, while screened dipole-dipole coupling is marginal for reliable state propagation. Lattice-scale density yields volumetric power loads of 10^7 – 10^9 W m^{-3} at kilohertz switching, comparable to cellular metabolic limits only at the lowest mechanical energies and switching rates. Consequently, tubulin-based parallel computation is not intrinsically heat-free; it can approach thermodynamic optimality only within a narrowly defined parameter regime. Experimental calorimetry and force spectroscopy are essential next steps to validate or falsify the model and to guide the engineering of viable bio-computing substrates.

Provenance and AI Involvement

- This paper was drafted, reconciled, reviewed, revised and checked by the QNFO automated research pipeline (qnfo-research-exec 0.29.0-terminal-rearmed). Language models were tools in that process; they are not authors. The named author is accountable for the content.
- Models: drafting by openai/gpt-oss-120b, zai-org/glm-5.3-flash; reconciliation, completion, review, revision and verification by openai/gpt-oss-120b, zai-org/glm-5.3-flash, moonshotai/kimi-k2.6, with the QNFO model router as a fallback.
- Sources: every reference is drawn from a bibliography retrieved from arXiv and the QNFO corpus before drafting; every cited work's full text was retrieved (arXiv HTML, or the QNFO paper's body) and the writers were given excerpts of its own sections; statements about a cited work are restricted to its retrieved title, abstract and those excerpts.
- Checks passed before publication: required sections present and finished, cross-references resolve, reference list rendered from the retrieved bibliography, no assistant residue or placeholders, adversarial model review with its blocking findings resolved, and a citation existence check at publication.
- Independent recomputation: a separately generated script recomputed 16 quantitative claims from the paper's stated inputs; 0 differed from the stated value at the stated precision.
- Not checked: whether each cited source supports the sentence that cites it beyond the retrieved full-text excerpts; derivation steps other than the recomputed claims. This paper has not been peer reviewed, and this version was published by the pipeline without a prior manual review by the author.

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Appendix A. Divergence report

Conflict 1 – Temperature for Landauer limit

- Draft A used $T = 300$ K, yielding $E_L = 2.9 \times 10^{-21}$ J.
- Draft B used $T = 310$ K, yielding $E_L = 2.97 \times 10^{-21}$ J.

Chosen convention: $T = 310$ K (physiological temperature) as it matches the explicit assumption in the methods and aligns with common biological modeling practice.

Conflict 2 – Mechanical model

- Draft A modeled the switch as a torque $W = FL\theta$ with $F = 5$ pN, $L = 4$ nm, $\theta = 30^\circ$, giving $W = 1.05 \times 10^{-20}$ J.
- Draft B modeled the switch as a linear spring $E_m = \frac{1}{2}k_{\text{eff}}x^2$ with $x = 1$ nm and k_{eff} swept 0.01–1 N/m, yielding a range 5.0×10^{-21} – 5.0×10^{-19} J.

Chosen convention: Spring model with stiffness sweep, because it explicitly explores plausible biomechanical parameter space and provides a range rather than a single, less-justified force estimate.

Conflict 3 – Force assumption vs stiffness

- Draft A assumed a constant force $F = 5$ pN based on motor-protein forces.
- Draft B replaced the force with an effective stiffness parameter, acknowledging the lack of direct measurements.

Chosen convention: Use stiffness sweep (Draft B) as it transparently treats the unknown mechanical property as a parameter.

Conflict 4 – Power density calculation

- DraftA reported $1.7 \times 10^{-11} \text{ W}\mu\text{m}^{-1}$ at $f = 10^6 \text{ s}^{-1}$.
- DraftB reported volumetric power 2.6×10^7 – $2.6 \times 10^9 \text{ Wm}^{-3}$ at $f = 10^3 \text{ s}^{-1}$.

Chosen convention: Present volumetric power estimates (DraftB) because they follow directly from the density calculation and allow scaling to any frequency.

Conflict5 – Dipole-state energy

- DraftA did not compute dipole-field energies.
- DraftB provided a detailed dipole-field energy difference ($\approx 7.21 k_B T$) and error probability.

Chosen convention: Include dipole-field results (DraftB) as they add a distinct energetic contribution not present in DraftA.

Conflict6 – Coupling energy

- DraftA omitted dipole-dipole coupling.

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