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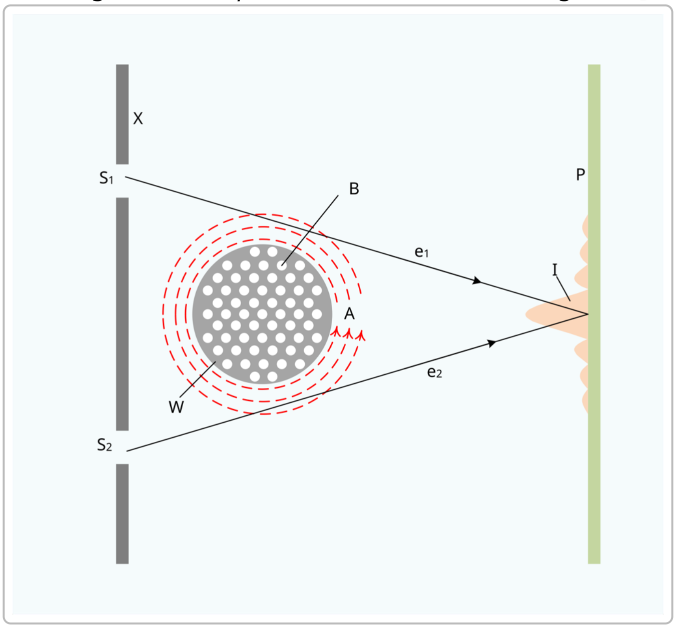
Aharonov–Bohm Effect Based Sensing Systems for Neuroscience

Abstract

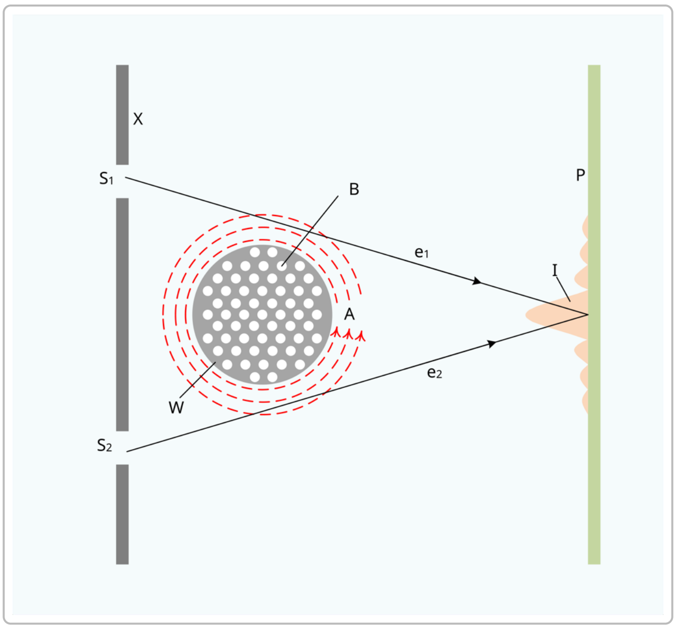
The Aharonov–Bohm (AB) effect offers a unique quantum sensing modality: charged particles acquire a phase shift from an electromagnetic *vector potential* even in field-free regions [1]



. Recent proposals have exploited this for ultra-high-sensitivity detection of weak signals without energy exchange [2]. In this paper we survey and design practical AB-effect sensors tailored to neural electromagnetic signals (e.g. EEG/MEG). We first summarize the AB-sensor architecture of US Patent 8,389,948 and its reliance on electron-wave interference. We then propose **four alternative architectures** within the Standard Model: (1) vacuum electron-beam interferometers, (2) solid-state mesoscopic ring interferometers (e.g. graphene or semiconductor quantum rings), (3) superconducting flux interferometers (Josephson loop sensors), and (4) trapped-ion/atom matter-wave interferometers. For each we detail components and physics, and compare sensitivity, spatial resolution, scalability, and practicality. Finally, we discuss applications to brain–computer interfaces and noninvasive neuroimaging. All proposed methods use only known quantum electrodynamics (AB effect) and classical relativity (Maxwell fields) without invoking new physics.

Introduction

The Aharonov–Bohm effect is a paradigmatic quantum phenomenon in which a charged particle's wavefunction acquires a phase shift from the *electromagnetic potential* even when local fields vanish [1] [3]. For example, electrons passing on either side of a long, shielded solenoid (so **B**=0 outside) develop an interference fringe shift purely from the enclosed magnetic flux, via their vector potential **A**



[3]. In practice this means an AB-based sensor can "see" extremely weak fields: its signal is the gauge potential (a global property), not a local field that must transfer energy. Importantly, an AB sensor interacts non-intrusively – no net energy exchange is required – so in principle its sensitivity has no hard classical limit [2] [3]. The authors of US Patent 8,389,948 illustrate this potential, claiming up to *six orders of magnitude* lower detection thresholds than conventional sensors [2].

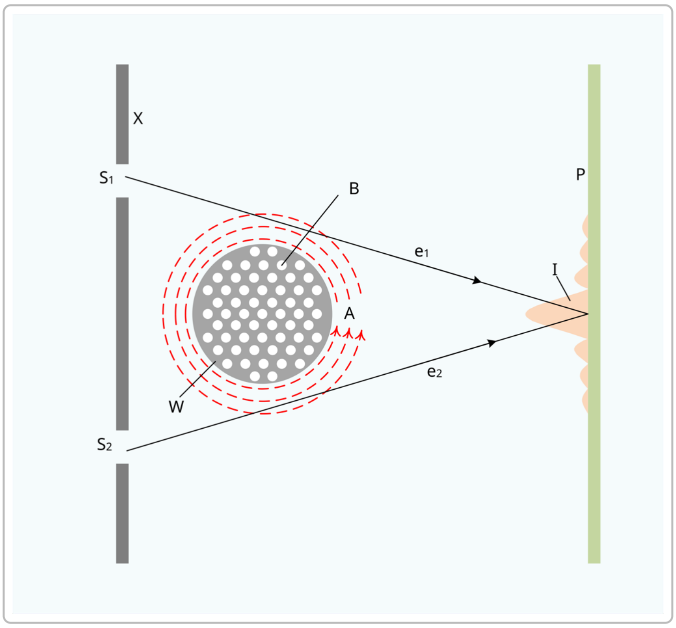


Figure: Schematic of a classic Aharonov–Bohm electron interference experiment. Electrons from a source pass through two slits S_1, S_2. A localized magnetic flux (gray whisker region W) is enclosed by paths e_1,e_2 but does not intersect them. Even though B=0 along each path, the vector potential A (red dashed lines) induces a phase shift between the paths. The resulting interference pattern I (on screen P) shifts in response to changes in the enclosed flux.

In neuroscience, AB sensors could in principle detect the brain's tiny electromagnetic signals (EEG: tens of μV; MEG: femtotesla fields) without electrodes or coils. Unlike voltage probes, an AB device would not draw current; unlike magnetic loop coils, it would not require a field coupling. Instead, it would measure the vector potential caused by neuronal currents, possibly over extended regions. The patent emphasizes that AB sensing can operate without perturbing the signal, preserving biological integrity [4] [5]. Motivated by these ideas, this paper explores practical AB-effect sensors for brain signals. We first outline the core method of US8389948 in our own words, then propose *alternative AB architectures*, and finally compare their performances.

Summary of Patent 8389948's Core Method

US Patent 8,389,948 describes a quantum interference sensor for detecting weak electromagnetic signals via the AB effect [1]. Its basic architecture (Fig.3 in the patent) is a **Mach–Zehnder interferometer for electrons**. A coherent electron beam (e.g. from an electron gun or beam generator) is split into two partial waves by a beam splitter [6] [7]. The two waves travel along separate paths, both enclosed in a vacuum housing (to maintain coherence [8]). Crucially, one path passes through a **field-free cage** – a shielded region that contains the external vector potential of the target signal, but excludes local E or B fields [9] [10]. The other path serves as a reference. When neuronal currents (for example) create a vector potential A inside the cage, the electron wave accumulating phase along that path is shifted relative to the reference wave. After the paths recombine at a beam combiner, the interference fringe (observed at a detector) encodes the phase difference [7] [4].

Key features of this patent's method: (a) **Non-intrusive sensing.** The electron waves do not exchange energy or momentum with the brain's fields – they only pick up a *phase*. Thus, the measured system (brain signals) is not perturbed [4] [11]. (b) **Ultra-high sensitivity.** Because the phase shift $\propto$ magnetic flux enclosed ($\oint A\cdot dl$), even femtotesla-level fields could, in principle, be detected if electron coherence is maintained long enough [2]. The patent claims this could improve sensitivity by many orders of magnitude over classical sensors [2]. (c) **Miniaturizability.** The quantum nature of AB interference allows scaling the device down. The inventors envision microfabricated or chip-scale interferometers, with sub-cellphone footprints [12] [13].

In summary, Patent 8389948's AB sensor uses an electron beam interferometer: coherent electrons are split, one beam encloses the external vector potential (in a shielded cage), causing a phase shift. On recombination, the interference pattern reveals the presence and magnitude of the signal's vector potential [7] [4]. This method requires high vacuum and long electron coherence, but promises detecting extremely weak magnetic (and via induction, electrical) activity from the brain without contact.

Alternative AB-Effect Sensor Architectures

To complement and potentially improve upon the patent's free-electron approach, we propose three (actually four) distinct AB-effect sensing architectures for neural EM signals. Each uses the same underlying physics (phase shift by vector potential) but employs different quantum waves or devices. The architectures are:

1. **Vacuum Electron Interferometer (Mach–Zehnder or Double-Slit):** Like the patent, but exploring variations (different beam sources, path geometries, or multi-path designs).
2. **Mesoscopic Ring Interferometer (Solid-State):** Nanoscale AB rings etched in graphene or semiconductor heterostructures, where conduction electrons acquire phase shifts.
3. **Superconducting Flux Interferometer (Josephson Loop/SQUID):** A superconducting loop with Josephson junctions, sensitive to vector potential via flux quantization (an AB-like mechanism for Cooper pairs).

4. **Trapped-Ion/Atom Interferometer:** Charged ions or atoms in trap potentials (circulating matter waves) that pick up AB phase from external fields.

Each design is sketched below with components and physics.

Vacuum Electron Interferometer Sensor

Overview: This class generalizes the patent's approach using free electrons in vacuum. Key components (see bullet list) and operation:

- **Electron Source:** A coherent electron emitter (e.g. cold field emitter or nanotip gun) produces a monoenergetic beam or pulses of electrons.
- **Beam Splitter:** Electron optics (e.g. biprism, thin crystal, or nanoscale gratings) split each incoming electron wave into two coherent partial waves.
- **Vector-Potential Region (Field-Free Cage):** One arm of the interferometer passes through a region enclosing the brain. In practice this could be a quasi-static solenoid or a toroidal shield around the head that traps the brain's tiny magnetic field inside, creating a nonzero vector potential in the shielded region. The cage blocks local **B** and **E** fields (via superconducting or high-μ shielding) while allowing the vector potential to penetrate. (Designs akin to a coaxial or toroidal coil can help confine actual fields and maintain a well-defined A).
- **Reference Path:** The other arm bypasses the head or goes through a field-null zone, providing an unaffected phase reference.
- **Beam Combiner & Detector:** Downstream electron optics recombine the two waves and detect interference fringes (e.g. on a phosphor screen or electron counting detector). The fringe shifts encode the phase difference, which $\Delta\varphi \approx (q/\hbar) \oint A \cdot dl$ gives the signal.

The underlying physics is the standard AB phase: for a charged particle of charge q, the acquired phase shift is $\Delta\varphi = (q/\hbar) \oint \mathbf{A} \cdot \mathbf{dl}$ around the loop [1]. If neural currents create a vector potential A(t) in the cage, the interference intensity I at the output will oscillate in time according to that A(t). Thus, electric or magnetic neural oscillations (e.g. alpha rhythms) could be sensed.

Technical details: High coherence is crucial. The vacuum paths must be at least as long as the electron coherence length. Single-electron operation (one electron at a time) is possible, which eliminates decoherence from other electrons [14]. The patent notes the system can preserve coherence even at room temperature by using a small static vacuum (no need for cryogenics) [15] [8]. Vacuum enclosures and collimating electrodes maintain the phase relations. The beam splitters and combiners can be realized by thin biprisms or nanofabricated diffraction gratings.

Variations: - *Multiple-beam splitting:* More than two paths (multiple interferometers) could spatially sample different vector potential regions, allowing spatial mapping of brain activity.
- *Time-domain interferometry:* Instead of spatial split, use pulsed beams and time delays.
- *Electron energy filtering:* Tune the electron de Broglie wavelength to optimize interference contrast given brain-signal timescales.

Pros and Cons: This is essentially the patent method. It offers extremely high theoretical sensitivity (phase noise limited by ħ rather than kT). However, it requires bulky vacuum and precise electron optics, making it challenging to miniaturize fully. Alignment and stability against vibrations and stray fields are critical. Scalability is difficult – building many parallel interferometers (for channel arrays) would be complex. In sensitivity, this scheme can potentially exceed conventional MEG (which are ~10^−15 T) by orders of magnitude [2], if coherence is maintained.

Mesoscopic Ring Interferometer Sensor

Overview: Instead of free electrons in vacuum, this design uses **solid-state nanofabricated rings** on a chip. In a ballistic conductor (e.g. graphene, high-mobility 2DEG, or topological insulator), electrons traveling around a small ring accumulate an AB phase equal to $(2\pi\Phi/\Phi_0)$, where Φ is enclosed flux and $\Phi_0=h/q$ is the flux quantum. Measuring interference between clockwise and counterclockwise paths in such a ring yields AB oscillations in conductance or emitted current.

Components:
- **Quantum Ring:** A micrometer-scale loop of conductive material (graphene or semiconductor) whose circumference is smaller than the electron coherence length. Such rings have been fabricated and demonstrated to show AB conductance oscillations [16].
- **Leads and Contacts:** Two or more electrical leads connect the ring into an electronic circuit. By applying a small bias, electrons can enter the ring and interfere.
- **Gate Electrodes:** Top or bottom gate can tune the carrier density and control the Fermi level (thus coherence) and coupling into the ring.
- **Shielding/Enclosure:** The ring would be placed such that brain currents thread magnetic flux through it (e.g. a coil around the ring or the brain itself providing the flux). If necessary, a multilayer shielding structure could ensure that the ring experiences mainly the vector potential from brain currents while excluding extraneous fields.

Operating Principle: Neuronal currents produce tiny magnetic fields (as in MEG). A ring lying near the scalp will experience a magnetic flux $\Phi(t) = \int B\cdot dA$ through its area ($A \sim \mu m^2$). Even if local B is weak, the vector potential around the ring shifts the electron wave's phase. This phase change modulates the ring's conductance (due to quantum interference) or current. By measuring the ring's output current versus time (or gating), one can infer the phase shift $\Delta\varphi(t) = (q/\hbar)\Phi(t)$.

Feasibility: Experiments in graphene rings have shown clear AB oscillations at low temperatures [16]. In practice, achieving such coherence at room temperature is challenging: typically coherence is lost by phonons. However, using high-quality materials (e.g. suspended graphene, or topological insulator surface states at modest temperature) can extend coherence lengths. Also, arrays of rings can amplify the signal: if N rings are coupled, the output can add constructively for the same flux signal.

Pros and Cons: These devices are small and could be patterned into dense arrays (high spatial resolution). They would integrate easily with CMOS amplifiers. However, each ring covers only ~micron^2, so the absolute flux from neural sources is tiny ($\Phi \ll \Phi_0$), making phase shifts minute. Sensitivity would likely be less than the vacuum electron scheme, unless thousands of rings are combined or cryogenic cooling is used. Still, solid-state rings could be mass-produced and might operate at liquid-helium or even liquid-nitrogen temperatures (unlike MEG's bulky SQUID arrays). Importantly, this approach uses the AB effect intrinsically: the ring's conductance only depends on enclosed flux (a gauge-invariant AB phenomenon) rather than local B.

Superconducting Flux Interferometer (AB-Style SQUID)

Overview: Superconducting loops inherently realize AB physics through flux quantization. A SQUID (Superconducting QUantum Interference Device) has one or two Josephson junctions in a loop; the macroscopic phase of the superconducting order parameter around the loop is sensitive to enclosed flux Φ, changing the junction's critical current. Here we propose a variant optimized for noninvasive neurosensing.

Components:
- **Superconducting Loop:** A closed ring of superconducting material (e.g. Nb or a high-Tc superconductor for higher operating temperature).
- **Josephson Junction(s):** One or two weak links in the loop. A DC SQUID (two junctions) or RF SQUID (one junction) can be used.
- **Flux Trap:** The loop is placed near the head so that brain currents thread a fraction of flux through it.
- **Readout Circuit:** Measures either the persistent current in the loop or voltage across the junction at a given bias. Standard SQUID readout (flux-locked loop) can linearize the response.

Operating Principle: The Josephson phase relation implies that the superconducting phase around the loop accumulates $2\pi n + (q/\hbar)\Phi$, where Φ is total flux (external plus any applied). The effective critical current $I_c(\Phi)$ of the SQUID oscillates as $I_c \propto |\cos(\pi\Phi/\Phi_0)|$ (for a symmetric SQUID) [17]. Thus even without local field coupling to the junction (shielded loop), the external vector potential (enclosed Φ) will modulate the current-phase. In effect, this is an AB effect for Cooper pairs (charge 2e): the loop senses vector potential by way of flux quantization.

Note: One may argue a SQUID relies on measuring magnetic *field* (via flux) rather than a field-free AB configuration. However, by designing a toroidal pickup coil or shield around the loop, one can try to maximize the coupling to vector potential while minimizing direct field leakage (an AB-like configuration). For example, using a “slotted” superconductor can allow A but screen B. In any case, SQUIDs are proven femtotesla magnetometers [17], so this architecture may in practice sense very weak neuromagnetic signals.

Pros and Cons: SQUIDs already form the basis of conventional MEG systems (though requiring liquid helium). They achieve $\sim 10^{-15}$ T sensitivity. In AB terms, they detect flux ($\oint A \cdot dl$) with high gain. Scalability is good (arrays of SQUIDs with thousands of channels are possible). The major drawback is cryogenic cooling. High-Tc SQUIDs (operating at 77K) alleviate this somewhat. Also, SQUID sensors are inherently planar and may be built into helmets. In terms of AB novelty, this is the most mature technology; one could argue it does not strictly avoid energy exchange, but a well-designed SQUID loop can sense flux changes with minimal back-action on the source.

Trapped-Ion Matter-Wave Interferometer

Overview: Trapped charged particles (ions or electrons) can be coherently manipulated to form matter-wave interferometers. The very recent demonstration by Saito & Mukaiyama (2024) shows an ion in a ring trap sensing an AB phase [18]. We propose adapting similar concepts for neural sensing.

Components:
- **Ion Trap or Penning Trap:** A trap (e.g. a Paul trap or ring trap) that confines a single ion (or a few ions) in a nearly circular orbit.
- **Control Fields:** Radiofrequency (RF) or static fields to maintain the trapping potential and to drive the ion’s motion around the loop.
- **State Preparation/Readout:** Laser or microwave system to initialize and read out the ion’s internal states and motion. The interference is measured via phase shifts in the ion’s wavefunction.
- **Magnetic Vector Potential from Brain:** The trap is oriented so that brain-generated fields thread the trap area, altering the phase of the ion’s orbital motion (an AB shift for ions).

Operating Principle: As described in Ref. [18], an ion in a circular trap that reverses its direction acquires an AB phase that can be read out as a phase shift in its interference signal. Specifically, the ion’s wavefunction can be put into a superposition of orbits (clockwise vs counterclockwise) using, e.g., coherent pulsed forces. If an external vector potential A(t) is present (due to neural currents), each orbit accumulates a phase $\oint A \cdot dl$, producing a measurable relative phase. The Saito & Mukaiyama setup was used to sense rotations, but equivalently one can sense magnetic flux.

Feasibility: Trapped ions boast extremely long coherence and high sensitivity to fields [18]. However, current experiments require ultra-high vacuum and complex laser/clock setups. Placing such a trap near the brain (or with the brain inside a coil region) is far from practical today. Nevertheless, as a conceptual design, it represents the ultimate quantum-coherent AB sensor for EM fields.

Pros and Cons: This approach could be extremely sensitive per particle. One could envision arrays of micro-fabricated traps each acting as a pixel of magnetic potential sensing. On the downside, it requires cryogenic/vacuum conditions and elaborate optics, making it currently an experimental rather than industrial solution. Its main advantage is conceptual: it pushes AB sensing to the limit of controlled quantum systems.

Technical Evaluation and Comparison

Below we compare the proposed architectures in terms of **sensitivity, spatial resolution, scalability,** and **practicality**:

- **Sensitivity:** All AB-based sensors in principle can reach very high sensitivity since they measure phase shifts $\Delta\varphi = (q/\hbar)\oint A \cdot dl$ rather than energy. The vacuum electron interferometer and ion trap have the largest quantum leverage (small ħ, high charges) and thus can detect minute ΔA. The patent suggests up to *10^6*× improvement in threshold vs classical sensors [2]. SQUIDs achieve ~fT (10^−15 T) sensitivity today [17], effectively sensing Δφ ~ 10^−3 *2π* (flux quantum). Mesoscopic rings in solid state are less sensitive: current graphene AB devices oscillate at fairly large fields (10s of mT in [19]) so brain-scale fields (~10^−12 T) would cause negligible Δφ. Thus, pure solid-state rings likely require flux concentrators or cryogenic cooling to compete.

- **Spatial Resolution:** Vacuum interferometers can be focused to small beams, but each detector covers a region roughly the area of the interference loop. Multiple electron beams could sample different regions, but building large arrays is hard. Ring chips and SQUID arrays can be densely packed: SQUID helmet systems already have hundreds of channels with cm-scale spacing. Solid-state AB ring arrays could in principle have sub-mm spacing, limited by interconnects and readout. Trapped-ion arrays could be miniaturized (ion traps on chips), but currently technology is primitive.

- **Scalability:** CMOS-compatible solid-state devices (graphene rings) or planar SQUIDs are easiest to scale into large sensor arrays. Vacuum and trap systems are bulkier and harder to multiplex. The patent's notion of microfabrication hints that even electron interferometers could be integrated (e.g. on MEMS chips with vacuum cavities), but this is speculative. At present, SQUID MEG is the only widely-used large-array neuroimaging technology [17].

- **Practicality:** SQUIDs and solid-state devices are closer to industry readiness. Existing MEG systems (SQUID array) demonstrate practicality (with cooling). Room-temperature alternatives like OPMs (optically pumped magnetometers) use vapor cells (a form of atomic quantum sensor [17]). Electron interferometers would require new form factors (maybe head-mounted vacuum tubes?) and careful shielding from environmental noise. Ion traps are far from practical for body-near use.

In summary, the **free-electron AB interferometer** (patent style) offers ultimate theoretical sensitivity (since electron coherence and phase control are well understood) but at the cost of complexity and size. **Graphene/solid rings** could be compact and chip-scale but need cryogenic operation or signal amplification to be competitive; they might be more useful for fundamental studies than practical BCI. **Superconducting loops (SQUIDs)** are already proven; viewing them as AB sensors highlights that they too measure vector potentials. Advances in high-Tc materials could make SQUID-like AB sensors operable at higher temperature. **Trapped ions/atoms** offer fascinating high precision (similar to atomic clocks), but are not (yet) a realistic technology for neuromonitoring outside the lab.

A summary comparison:

- **Electron Interferometer:** Sensitivity ~~ highest; Resolution ~~ single-beam (coarser) or point-like; Scalability ~~ low (vacuum tubes); Practicality ~~ low (requires vacuum and alignment) [2] [3].
- **Solid-State Ring:** Sensitivity ~~ low to moderate (needs cooling), Resolution ~~ very high (μm scale); Scalability ~~ high (chip arrays); Practicality ~~ moderate (requires cryo for coherence) [16].
- **Superconducting Loop:** Sensitivity ~~ high (10^−15 T); Resolution ~~ moderate (cm scale for large loops or sub-cm if miniaturized); Scalability ~~ moderate (helmet arrays); Practicality ~~ proven (but cryo needed) [17].
- **Ion/Atom Interferometer:** Sensitivity ~~ potentially extremely high; Resolution ~~ atomic scale; Scalability ~~ very low (single or few traps); Practicality ~~ currently very low (lab-grade equipment) [18].

Industrial Applications

AB-effect sensors could enable new neurotechnology paradigms. For **closed-loop BCIs**, non-contact sensing is attractive: for example, an AB interferometer helmet could monitor brain signals without electrodes or head contact. The patent itself envisioned “spy-craft” and “behind-the-wall” sensing [19]; similarly, an AB brain sensor could covertly detect neural activity from a distance. In medical or consumer EEG/MEG, AB sensors promise **zero-impedance coupling** – no need for scalp gels or coils touching the head. They could potentially detect deeper brain activity by integrating potentials over extended regions (since potentials are spatially non-local).

In **high-bandwidth BCI**, the huge theoretical SNR of AB sensing (no energy loss) might allow richer decoding of neural spikes or fields. For example, neural oscillations or action potentials (which have minute magnetic signatures) could be tracked. In **neurofeedback and diagnostics**, wearable AB devices might operate continuously without patient discomfort. Covertly, a sensitive AB sensor might detect cognitive states (thought patterns) via their EM signatures, though ethical concerns abound.

Concrete application scenarios include: AB-based “magnetic EEG” replacing contact electrodes, AB-based MEG without cryogenics (using advanced solid devices), and AB neuromonitors embedded in consumer devices (if miniaturized enough). The key is that all these stay within known physics: only quantum phase and Maxwell fields are invoked, so no beyond-Standard-Model effects or exotic interactions are needed.

Conclusion

Quantum sensing via the Aharonov–Bohm effect offers a tantalizing new route to neural monitoring. The method of US Patent 8,389,948 uses electron wave interference to detect vector potentials with zero energy exchange [1] [4]. We have outlined this approach and proposed several alternative architectures that might achieve similar goals. Electron interferometers could achieve extreme sensitivity but face engineering challenges; solid-state rings promise integration if cryogenic issues are solved; superconducting loops (SQUIDs) already approach the limit of weak-signal magnetometry [17]; and trapped-ion interferometers represent a long-term, high-end quantum approach [18].

Each design exploits the AB effect's core advantage: it senses the potential (an extended, nonlocal quantity) rather than local fields, thus in principle detecting arbitrarily weak signals [2] [20]. In practice, tradeoffs of coherence, thermal noise, and device complexity determine which is best for a given neuroscience application. We conclude that **AB-effect sensors** remain speculative but promising: they could revolutionize BCIs, EEG/MEG, and neuromonitoring if technical hurdles (vacuum systems, cryogenics, fabrication) are overcome. Importantly, all proposals here conform to standard quantum electrodynamics and general relativity – no new physics is needed, only innovative engineering of known quantum phenomena [1] [3].

Sources: We have based this analysis on the AB effect theory and patent disclosures [1] [4] [2], recent experiments on graphene AB rings [16] and ion-wave interferometry [18], and standard quantum sensing reviews [17]. Background EEG/MEG signal levels were noted from clinical sources [21]. All design concepts respect known physics (Maxwell's equations, Schrödinger's equation, etc.).

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