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Aharonov–Bohm Effect Based Brain–Computer Interface for Defense Applications

Abstract

We propose a novel brain–computer interface (BCI) architecture leveraging the quantum Aharonov–Bohm (AB) effect to achieve non-contact neural sensing and stimulation. Theoretical foundations of the AB effect in the Standard Model are reviewed, emphasizing how electromagnetic **vector potentials** ($\mathbf{A}$-fields) can induce phase shifts in charged particles without local fields, enabling *phase-based quantum sensing*. We explain how an AB-based sensor can detect cortical electromagnetic activity remotely by measuring phase shifts induced by the brain's vector potential, with no direct energy exchange [1] [2]. The AB sensor design by Chase *et al.* (Lockheed Martin) is analyzed in depth: an electron interferometer with a field-free enclosure that registers minuscule phase modulations due to ambient potentials [3]. We detail the sensor's architecture, signal path, detection principle, and fundamental sensitivity limits, noting that a potential of order 1 nV can produce a π/2 phase shift in microseconds [4] – six orders of magnitude more sensitivity than classical electromagnetic sensors [5]. A complete hardware blueprint for an AB-BCI system is presented, integrating quantum sensor tiles (e.g. Rydberg atom electrometers, nitrogen-vacancy diamond magnetometers, optically pumped magnetometers) for multi-modal field detection, AB-driven $\mathbf{A}$-field shaping arrays for *stealth neuromodulation*, control electronics, and safety interlocks. We develop a signal processing model comprising quantum interference demodulation, source current inversion, adaptive filtering, phase-coherence analysis, and closed-loop stimulation scheduling. Defense and national security implications are discussed, including **stealth neural monitoring** (covert mind-reading at distance), battlefield cognitive augmentation for warfighters, operator–vehicle neural coupling, and cybersecurity of neuro-quantum channels. Dual-use opportunities in medicine and human performance are outlined alongside a technology maturation roadmap. **Results** from theoretical modeling and prior art are presented to validate the feasibility: the AB sensor's phase response scales with source potential and inversely with distance [6], offering high SNR detection of neural signals without disturbing them [7] [8]. We conclude that an AB-effect BCI could fundamentally surpass traditional EEG/MEG in sensitivity and stealth, though significant engineering challenges remain in coherence maintenance, integration, and ethical deployment.

Introduction

Non-invasive brain–computer interfaces have tremendous potential for defense applications, enabling warfighters to communicate and control systems directly with neural signals. However, today's non-invasive BCIs (e.g. EEG, MEG, transcranial stimulators) suffer from limited signal resolution, range, and stealth. Conventional sensors rely on detecting local electric or magnetic fields, which attenuate rapidly with distance and often require contact or bulky cryogenics. In this paper, we explore a radically different BCI design based on the **Aharonov–Bohm (AB) effect**, a quantum phenomenon where electromagnetic *potentials* affect a particle's phase even in regions with zero field. The AB effect, first predicted by Ehrenberg and Siday and later analyzed by Aharonov and Bohm, revealed that the electromagnetic four-potential $(\phi, \mathbf{A})$ has physical significance in quantum mechanics beyond the classical fields **E** and **B** [9] [10]. In a classic AB experiment, an electron passing around a shielded magnetic flux acquires a measurable phase shift $\Delta\varphi$ proportional to the enclosed flux (magnetic field **B** times area), even though **B** is zero along the electron's path [11] [12]. This phase difference is given by the AB phase formula $\displaystyle \Delta \varphi = \frac{q\,\Phi_B}{\hbar}$ for an electron of charge q encircling magnetic flux Φ_B [13]. The AB effect was famously confirmed by electron interference experiments (e.g. Tonomura *et al.* 1986), establishing that potentials—and not just fields—can influence quantum systems in a gauge-invariant way [9] [14].

Significance: The AB effect's validation was a milestone for gauge theory in the Standard Model, proving that potentials are "physical" and that the principle of locality must be re-examined at quantum scales [15] [16]. Chen-Ning Yang noted it as the only direct experimental proof of the gauge principle in electromagnetism [9]. Fundamentally, AB showed that classical field-based descriptions (Maxwell's **E** and **B**) are incomplete – a charged particle's phase can be altered by the presence of a vector potential **A** even when **E**=**B**=0 locally [17] [18]. In practical terms, this means one can, in principle, sense electromagnetic activity *without* exchanging energy or momentum with the source, by detecting geometric phase shifts. This intriguing non-local property is the basis for a new class of "interaction-free" quantum sensors [19] [8].

In the defense context, an AB-based BCI could enable **remote neural monitoring and stimulation** that is fundamentally stealthy. By measuring the vector potential emanating from active neurons (which produce magnetic fields and thus **A**-fields), one could reconstruct brain activity without electrodes on the scalp – indeed, without any contact at all [1]. Likewise, by generating tailored vector potential distributions in a target's vicinity (with negligible classical fields), it might be possible to modulate neural circuits covertly, since classical detectors would register little to no energy emission. Such capabilities foreshadow applications like **mind-reading at a distance**, silent communication, and induced neural modulation for cognitive enhancement or disruption – scenarios of high interest for intelligence, special operations, and cybersecurity.

This paper details the theory behind an AB-effect BCI design and presents a conceptual system architecture for defense applications. In **Methods**, we first review the theoretical background of the AB effect as it relates to quantum phase-based sensing (Section 2). We then explain how the AB effect can be harnessed to detect or influence cortical states via the electromagnetic potential, without physical contact (Section 3). Section 4 dissects the patented AB sensor by Arman and Chase [20] [21], describing its interferometric architecture, signal path, detection mechanism, and sensitivity limits. In Section 5, we propose a hardware blueprint integrating the AB sensor with supporting quantum sensor *tiles* (Rydberg atom electrometers, diamond NV-center magnetometers, optically pumped magnetometers) and with **A-field emitter arrays** for feedback stimulation. A signal processing model is developed in Section 6, covering demodulation of the quantum interference signal, source localization in the brain, adaptive filtering, phase coherence analysis, and closed-loop stimulation scheduling. In the **Results** section, we present analytical expressions and simulations of the AB sensor's performance, demonstrating its unprecedented sensitivity (detecting nanovolt-scale neural signals at standoff distances) and discussing practical resolution limits due to quantum decoherence and noise. Finally, in **Discussion**, we examine the relevance of this AB-BCI approach to defense and national security: enabling **stealth neuromodulation**, **battlefield cognitive augmentation**, direct brain-to-vehicle control links, and safeguarding the neuro-informational domain. We outline dual-use implications in healthcare and human performance, and propose a technology development roadmap, noting current achievements and steps needed to transition this nascent quantum BCI concept from laboratory theory to field-deployable reality.

Theoretical Background: Aharonov–Bohm Effect and Phase-Based Sensing

2.1 Potentials in the Standard Model and the AB Effect

In classical electromagnetics, fields are the primary physical quantities – electric fields **E** produce forces on charges, and magnetic fields **B** deflect moving charges. Potentials (the scalar potential ϕ and vector potential **A**) were introduced as convenient mathematical tools since **E** and **B** can be expressed as derivatives ($\mathbf{E}=-\nabla \phi - \partial \mathbf{A}/\partial t$, $\mathbf{B}=\nabla\times \mathbf{A}$). Classical physics regarded potentials as non-physical, arbitrary up to a gauge transformation, because only **E** and **B** were thought to have observable effects [22] [16]. The advent of quantum mechanics overturned this notion. The **Aharonov–Bohm effect** demonstrated that the potential **A** itself can alter a quantum particle's phase, with observable consequences, even in regions where **E** = **B** = 0. In a seminal thought experiment, electrons are sent through a two-slit interferometer with a long solenoid (carrying magnetic flux) positioned so that electrons pass *outside* the solenoid (encircling it) (Figure 1). Classically, if the magnetic field is perfectly confined inside the solenoid, electrons outside should not be affected. Quantum mechanically, however, the electron wavefunctions in the two paths acquire a phase difference proportional to the enclosed flux Φ_B even though **B** is zero along each path. This phase shift shifts the interference pattern on the screen [11] [12]. The magnitude of the shift is $\Delta\varphi = \frac{e\,\Phi_B}{\hbar}$ for electron charge e [13], showing explicitly that the vector potential (which exists outside the solenoid due to the enclosed flux) has a physical effect. The **direction** of the vector potential circulation (given by the right-hand rule around the magnetic flux) determines the sign of the phase shift [23]. This is illustrated in **Figure 1**, where the arrow indicates the circulating $\mathbf{A}$-field outside the solenoid (or "whisker") that causes fringe shifts when the enclosed flux (and hence the line-integral of **A** around the loop) is changed [24].

Figure 1: Aharonov–Bohm effect demonstrated by a double-slit electron interference experiment. A long solenoid (center, grey) carries a magnetic flux B *confined inside it (pointing ⊗ out of page). Electron waves travel through two slits (paths left and right) to an observation screen, enclosing the solenoid. Even though the magnetic field is zero along both paths, the vector potential A (blue circular arrow) permeates the space around the solenoid. The phase difference between the two electron paths is proportional to the magnetic flux enclosed, causing a shift in the interference fringes on the screen when the flux is varied [11] [12]. This confirms that the electromagnetic potential A, not just the local fields, can influence quantum phase.*

The AB effect has profound implications. It proved that **electromagnetic potentials are physical** in quantum theory [16]. In gauge field language, it exemplifies how a gauge field can have observable effects: the AB phase is a gauge-invariant loop integral of **A** (related to the holonomy of the gauge connection) even though the local gauge field (**B**) is zero in the region of the particle. This insight generalizes to other gauge theories in the Standard Model – for instance, it underpins our understanding that fundamental interactions (electroweak, QCD) can have physically significant potentials and phases even in the absence of forces. Indeed, Yang and others pointed out that the AB effect is a direct demonstration of the gauge principle and the need for potentials in formulating physical laws [9] [15]. The AB effect also highlights the concept of **topological phase**: the phase depends on the global property of winding around the flux, not on local forces, linking to topology in quantum mechanics (e.g. quantized flux in superconducting loops is essentially an AB-like effect requiring the wavefunction phase around a loop to be $2\pi n$ [25]).

From a sensing perspective, the AB effect suggests a way to detect electromagnetic influences *without absorbing energy or momentum*. Traditional electromagnetic sensors (antennas, magnetometers, EEG electrodes) all interact via forces – an electromagnetic wave induces a voltage or current, transferring energy. In contrast, an ideal AB sensor could register a signal's presence through phase shifts alone, with **no energy exchange** from the signal source [26] [27]. The interaction is purely geometric/quantum: the signal's potential modifies the phase landscape through which the sensor's probe particles travel [27]. As a result, many limitations of classical sensors can be overcome. **Sensitivity:** Without needing to siphon energy from the source, the detection threshold can be extremely low – the only fundamental limit is set by quantum phase uncertainty (ultimately the Heisenberg uncertainty principle) rather than thermal noise or signal power [28]. In theory, "there may be no lower limit to the signal strength" detectable by an AB sensor [19] [28]. **Non-disturbance:** Because virtually no energy is removed from or imparted to the signal source, the measurement does not perturb the phenomenon being measured [29] [26]. This is critical for faithfully observing delicate systems (like the brain's fields) without interference. **Extended spatial information:** Fields like **E** and **B** are local (defined at a point), whereas potentials aggregate information over regions (e.g. **A** arises from currents in a distributed way). Thus an AB-type measurement can integrate information over an extended region in one go. It has been noted that potentials carry **phase information** about the entire configuration, whereas classical measurements lose this phase in squaring amplitudes [30] [31]. In summary, an AB sensor is a **phase-modulating quantum sensor** that exploits the primacy of potentials to achieve extreme sensitivity and non-invasiveness [5] [17].

2.2 Phase-Based Quantum Sensing for Neural Signals

The brain's electromagnetic activity is an attractive target for AB-based sensing because neural currents produce extremely weak fields – often at the edge of detectability by classical means – yet still produce potentials that could, in principle, be sensed via phase shifts. Neurons communicate via ionic currents (action potentials and synaptic currents) that generate electric and magnetic fields in surrounding tissue and beyond. Techniques like electroencephalography (EEG) and magnetoencephalography (MEG) can detect aggregates of these signals, but EEG requires direct electrode contact and conductive coupling (and is susceptible to skull attenuation), while MEG uses superconductor quantum interference devices (SQUIDs) that are bulky and need cryogenic cooling to detect femtotesla-level fields from the brain. Even advanced optically-pumped magnetometers and diamond NV-center magnetometers are approaching the needed sensitivity [32] [33], but still, all classical approaches are fundamentally measuring field strengths that drop with distance (typically as \$1/r^2\$ or \$1/r^3\$ for dipole sources). By contrast, an AB sensor would be sensitive to the *vector potential* produced by neural currents. Crucially, the fall-off of **A** from a localized current source can be slower; for example, modeling a neural current as an oscillating electric dipole, the vector potential in the radiation zone contributes to electromagnetic waves, but even in near-field/quasi-static regimes, a curl-free **A** can extend into regions where **B** or **E** might be attenuated. The Chase **et al.** patent analysis for a dipole source found that to first order, the induced phase shift \$\Delta\varphi\$ in an AB sensor is *proportional to the source's potential amplitude and inversely proportional to the distance* \$d\$ [6]. In other words, \$\Delta\varphi \sim \frac{P}{d}\$ for a small dipole producing potential amplitude \$P\$ at the source, suggesting a long-range interaction (for comparison, a dipole's magnetic field decays faster, \$\sim1/d^3\$ in quasi-static regime, so measuring via **A** may extend the range of detection). This implies that an AB-based detector might pick up brain signals at distances where classical field magnitudes are vanishingly small.

How would an AB sensor measure neural activity? Consider a region of active cortex emitting time-varying electric currents (synchronously firing neuron populations). These currents generate time-varying magnetic flux that in turn create a vector potential field extending into space. If we place a quantum interference sensor (our AB device) at some standoff (even outside the body), the presence of the brain's **A**-field within the sensor's interference loop will induce a phase shift in the sensor's probe particles proportional to the line-integral of **A**. This phase shift encodes information about the neural currents. Importantly, this can occur even if the sensor is *not intercepting any flux or field lines directly* – it suffices that the vector potential from the brain pervades the sensor's enclosed area (which it will, since

A is not shielded by skull in the way **E** is, and extends outside any magnetically confined region). The AB sensor essentially performs a **phase demodulation** of the brain's electromagnetic potentials.

The Lockheed Martin patent text makes bold claims about this capability: *"AB sensor 100 [the AB device] is so sensitive that it can detect waves emanating from a human's nerve system... a person's mind may be read without the person realizing it. Based on the direction and strength of a signal, the distribution of currents (e.g., thoughts) in the brain can be mapped out."* [1] . In theory, a single AB sensor could act like a highly sensitive MEG pickup, detecting aggregate neural oscillations (e.g. alpha waves ~10 Hz, or event-related potentials) from a distance. In fact, the patent suggests it could pick up "intelligence signals from electronically hardened, well-protected assets hundreds of miles away" [7] – a dramatic illustration of the no-exchange sensitivity. While hundreds of miles for neural signals is likely hyperbole, it underscores that the **energy-free sensing** approach circumvents the usual $1/r^2$ power loss limitations: since the AB sensor does not rely on receiving radiated power, extremely weak or distant signals might still imprint a detectable phase change [5] [7] .

To use an AB sensor for *brain mapping*, one would ideally have multiple sensors or a movable sensor to triangulate the origin of signals. The mapping mentioned ("distribution of currents... can be mapped out" [34]) implies solving an **inverse problem**: reconstructing neural current sources from measured phase shifts. In Section 6 we discuss how an array of quantum sensors could perform source localization (similar to solving EEG/MEG inverse problems but using phase data). The patent provides a mathematical approach, with an expression relating the phase $\Phi(x,y,t)$ at the sensor to an integral over current density J in the source region [35] . Although that detailed equation is beyond our scope, conceptually the sensor measures an integrated effect of all currents, and with multiple measurements one can invert this to estimate current distribution (the "thoughts"). This would effectively yield a functional brain image remotely.

Equally compelling is the reciprocal possibility: **modulating cortical state via a vector potential**. The AB effect is time-reversal symmetric – if a changing vector potential can affect a particle's phase, then in principle changing a particle's phase (or introducing a quantum state difference) could induce an electromagnetic response. While we won't rely on exotic time-reversed quantum signaling, we consider using specially arranged coils or metamaterials to project an **A-field into the cortex** without delivering a strong field. Typically, to stimulate neurons non-invasively, methods like transcranial magnetic stimulation (TMS) induce electric fields via time-varying magnetic fields (Faraday induction). These necessarily involve significant energy deposition and are not stealthy (they generate detectable magnetic pulses). Imagine instead using a configuration akin to a shielded solenoid (like in the AB experiment) placed around or near the head: inside the coils, a magnetic flux is oscillating, but outside the coils, one can arrange near-complete field cancellation, leaving a vector potential in the exterior region. Neurons in that region would classically feel no force (no **B**, and if coils are designed to avoid inducing **E**, no electric field), yet the electrons and ions in neurons could acquire quantum phase shifts as they traverse loops around or through these potentials. Normally, such phase shifts won't directly trigger neurons (since neural processes are largely classical at the macro scale). However, if one could synchronize an A-field oscillation with ongoing neural oscillatory activity, one *might* subtly bias interference among ion channel currents or alter synaptic transmission probabilities via quantum phase interference at the molecular scale. This idea ventures into speculative territory, but it is conceptually grounded in the Aharonov–Bohm and Aharonov–Casher effects (the latter is a related phenomenon where an electric dipole moving in an electric potential acquires a phase). In any case, an **A-field stimulator** could be designed to inject energy *minimally* while still affecting phase, providing a form of **stealth neuromodulation** (since external sensors would hardly detect a field, yet the brain might be influenced). Section 5 describes hardware for generating controlled A-fields. It's worth noting that if neural signals themselves are quantum coherent or sensitive to phase (this is not established – the brain is noisy and mostly classical at neuronal scales), then AB-phase interventions could have a direct effect. If not, one might need to use the AB sensor's readings to *time conventional stimuli* in a minimally invasive way (e.g., deliver tiny focused EM pulses only at the precise phase of an oscillation to nudge it – a hybrid classical-quantum approach).

In summary, the AB effect opens a gateway to **phase-based sensing and actuation**: reading neural state by detecting phase shifts in a probe, and potentially writing neural state by imparting phase shifts to neural currents. This can, in principle, be done without direct physical contact or significant energy transfer, making it uniquely suited to covert or portable BCIs. The next sections will describe how an actual device can realize these principles and what its performance might be.

Methods: Aharonov–Bohm Sensor Design and System Architecture

3.1 Aharonov–Bohm Sensor Architecture (Chase *et al.* Design)

To practically harness the AB effect for sensing, one needs a **coherent probe** that can accumulate phase from ambient vector potentials. The AB sensor design patented by Moe J. Arman and Charles Chase (U.S. Patent 8,389,948 B2, 2013) provides a concrete implementation [36] [37]. **Figure 2** depicts the core architecture of their AB sensor. It is essentially a miniature electron interferometer operating in vacuum. The main components (as labeled in the patent) are:

- **Beam generator (electron source) 102:** a source that emits a coherent electron beam (ideally one electron at a time, to maintain coherence). This could be a field-emission electron gun or cold cathode producing a monochromatic electron wave [38] [39].
- **Beam splitter 106:** a nanoscale beam splitter (for electrons, this could be a thin crystal film or nanofabricated grating) that splits the incoming electron wavefunction into two partial waves (first and second wave) which travel along two separate paths [40] [41]. The two waves are coherent (entangled phases). After the splitter, the system essentially has an electron in a quantum superposition of Path 1 and Path 2.
- **Field-free cage 112 (on Path 1):** a critical feature, this is a region (such as a small conductive or superconductive enclosure or a magnetic shielding tube) along the first path where external *fields* are excluded, but *potentials* can penetrate [42] [43]. For example, it might be a grounded Faraday cage that blocks electric fields and is non-magnetic (or a hollow waveguide) so that any magnetic field is zero inside, yet the vector potential from external sources can exist inside (because a static magnetic vector potential is not stopped by a simple conductor if there's an external flux linking the enclosure). In practice, one could use a toroidal coil around this region to create a known reference phase, and external signals (like the brain's A-field) also superpose here. The **phase of the electron wave on Path 1** is shifted by an amount $\Delta\varphi$ proportional to the vector potential of the signal present inside this cage [44] [43]. Path 2, by contrast, is arranged to avoid the region of significant vector potential, serving as a reference (its phase remains unshifted except for baseline reference phase).
- **Second path 110 (reference arm):** The second electron wave travels via Path 2, which does not go through the field-free cage (or sometimes the design may even send both paths through the cage in opposite directions – a variation mentioned in claims – but let's assume one path is exposed to the potential while the other is not, for clarity) [45] [46]. This reference arm experiences no phase shift from the external signal (because either it is shielded or goes through a region with no vector potential).
- **Beam combiner 114:** After traversing their paths, the two electron waves are recombined at a beam combiner (which could be another nanoscale beam splitter or mirror arrangement) [47]. Here, the two partial waves interfere with each other, forming a single combined electron beam

(or an interference pattern of electrons) whose properties (intensity distribution, electron arrival rate, etc.) depend on the phase difference between the two paths [48] [49]. Essentially, the relative phase $\Delta\varphi$ (acquired due to the signal's vector potential) is converted into an **amplitude modulation** of the recombined beam.

- **Detector 120:** Finally, a detector measures the interference outcome – for instance, a microchannel plate or electron-counting screen that records the intensity of the combined beam [21]. Because interference can turn phase shifts into measurable intensity changes, the detector output will vary in response to the external signal's potential. The patent notes that the detector "receives the second electron beam and detects the signal based on the modulation of the beam" [49] [50]. In practice, one might measure the current at a specific point or fringe contrast that is extremely sensitive to small phase shifts.

Operation: In absence of any external signal in the cage, the two paths have some reference phase difference (one can bias it to e.g. zero or $\pi/2$ via a known magnetic flux to operate at the most sensitive point on the interference fringe). When a signal (say, a time-varying vector potential from brain activity) is present, Path 1's phase is $\varphi_1 = \varphi_\text{ref} + \delta\varphi(t)$ while Path 2's phase is just $\varphi_2 = \varphi_\text{ref}$. The phase difference $\Delta\varphi(t)=\varphi_1-\varphi_2=\delta\varphi(t)$ caused by the signal will translate into oscillations in the detected intensity $I \propto I_0 \cos^2[\Delta\varphi(t)/2 + \phi_0]$ (if using a standard two-beam interference formula), or equivalently a modulation of the electron beam intensity at the detector [49]. By demodulating this intensity modulation, the original signal (e.g. neural oscillation waveform) can be recovered.

Because the AB sensor uses *electron matter-waves* rather than photons, maintaining coherence is challenging but achievable in a small package. The inventors addressed key issues:

- **Vacuum housing 122 and coherence length:** Electrons easily lose phase if they collide with air molecules or if their path lengths differ too much. The sensor is enclosed in a vacuum chamber to eliminate air collisions [51] [52]. Moreover, the entire geometry is made small (on the order of millimeters or less) so that the electron coherence length exceeds the path length difference. The patent specifies designing the vacuum housing such that the coherence length of each wave is at least 1 mm or 1 cm, ensuring the two electron waves remain phase-coherent when recombined [53] [54]. Indeed, it notes the device can be very small (vacuum volume <0.1 cm^3) and still work at room temperature (no cryogenics needed) [55] [56]. This miniaturization is made possible by the quantum nature of the effect – the sensor can be integrated on a microchip scale [57] [58].
- **One electron at a time regime:** To preserve coherence, they even consider operating in a regime where only one electron is in the interferometer at any given time (to avoid electron-electron interactions). The beam splitter is described as splitting the first beam "one electron at a time" [59] [60], implying a sequence of single-electron interference events. Each electron's detection gives a probabilistic outcome, but averaging many electrons yields an interference pattern.
- **No energy exchange with signal:** By design, the electrons do not absorb energy from the external signal in the cage – they simply pass through a region of non-zero vector potential. There is *no classical interaction* (no forces) if the field is truly zero in that region [61] [62]. Thus the measurement ideally does not dampen the signal source.
- **Sensitivity and noise:** The AB sensor's phase shift is proportional to the enclosed vector potential. Patent calculations show that even a tiny potential of 1 nanovolt can induce a large phase shift given enough interaction time or path length. For example, it is claimed that a 1 nV potential acting over 1 ms yields about $\pi/2$ radians phase shift [63] [4], and similarly 1 nV over 1 μs yields nearly $\pi/2$ [4] (the difference suggests perhaps different assumptions about path length or electron velocity). These numbers imply extraordinary sensitivity: a nanovolt is

10^{-9} of a volt – such an electric potential difference is far below thermal noise at room temperature, yet as a vector potential it can significantly alter quantum phase. The **effect-to-cause ratio** can be enormous; one statement notes it can be 10^6 times larger than typical EM sensors, meaning the phase effect is amplified relative to the signal [64] [5]. This corresponds to extremely high signal-to-noise (SNR) capability. Indeed, the device is described as "nearly a million times more sensitive than conventional sensors" [65]. In practical terms, the main limitations will come from maintaining coherence and mitigating decoherence noise (e.g. mechanical vibrations, fluctuations in the electron source, stray fields that sneak into the cage). By isolating the beams in vacuum and shielding external disturbances, the inventors assert these challenges can be overcome [66] [67].

Figure 2: Simplified diagram of an Aharonov–Bohm (AB) sensor for electromagnetic signals (based on Chase et al. *patent). A coherent electron beam from source 102 is split by beam splitter 106 into two waves: one travels Path 1 through a field-free cage 112, the other travels Path 2 as a reference [40] [41]. An external signal (e.g. neural currents) creates a vector potential A (green dashed lines) that penetrates the cage without any magnetic or electric field inside. The electron wave on Path 1 accumulates a phase shift $\Delta\varphi$ in response to A [44]. The two waves recombine at beam combiner 114 and produce an interference pattern at detector 120, which is modulated by the phase difference [48]. Because no energy is taken from the signal (no forces on the electrons), the AB sensor can detect extremely weak signals without perturbing them [5] [29]. In this illustration (adapted from patent Fig. 6), a dipole source 34 (analogous to an active neuron) emits a vector potential wave (green arrows) that causes a measurable phase shift at sensor 32 [68] [69].*

The AB sensor effectively converts the elusive potential-induced phase into a measurable intensity modulation. One can think of it as an **atomic scale interferometric receiver**. The output of the detector is an encoded version of the original signal (for example, if the brain is emitting a 10 Hz rhythmic potential, the detector might see a 10 Hz oscillation in electron count rate). Because it's a coherent detector, we can also measure the phase of the incoming neural oscillation relative to a reference, which is important for techniques like phase synchronization and feedback.

For completeness, we note that the patent also describes configurations for direction-finding (Fig. 8 in the patent) where multiple cages or multiple devices are oriented differently to sense the direction from which the signal's **A**-field is coming [69]. By comparing phases at different orientations, one can infer direction cosines of the incoming potential wave – similar to how a radio direction finder works, but here using phase of potentials. This could be useful if trying to localize a neural signal source from a distance using a few sensors. Another variant (Fig. 7 in patent) is a more specific implementation of the device internals, but the essence is the same as described.

Resolution and limitations: The ultimate resolution of the AB sensor is determined by how small a phase shift can be distinguished above noise. In principle, quantum phase can be measured extremely precisely (with techniques like phase locking or multiple passes). If needed, one could amplify the phase shift by employing multiple loops or multiple electrons and averaging. The practical limit will include decoherence – if the electron interacts with stray fields, the interference contrast drops. As per the patent, ensuring a coherence length of >1 mm and vacuum isolation were key; achieving that implies using electron energies and path lengths such that phase randomization is minimal over the device length. If the device is ~1 mm, and electrons travel at ~10^6 m/s (very roughly for a few eV electrons), they spend ~1e-9 s (a nanosecond) in the apparatus. The sensor can thus have an *instantaneous* bandwidth potentially up to GHz (since an electron picks up phase in a nanosecond traversal). However, measuring at high bandwidth would require detecting enough electrons in short time windows. The patent suggests even electromagnetic signals in the RF and VHF range could be detected, and specifically notes applications in high-frequency direction finding [70]. The ability to detect AC signals means the AB sensor can function like a wideband receiver. In fact, unlike an LC circuit that is resonant, the AB sensor directly measures phase shifts and could be broadband (limited by how fast one can source electrons and read the detector).

One can adjust the sensor operating point: for maximum sensitivity to small signals, you'd bias the interferometer at mid-fringe (e.g. $\Delta\varphi = \pi/2$ in absence of signal, so that a slight phase change from $\pi/2$ will cause a linear change in intensity). This can be done by threading a constant magnetic flux through the cage or by slightly unbalancing the path lengths.

In summary, the AB sensor design provides a feasible blueprint for a **quantum potential sensor** that could serve as the "front-end" of our BCI. It is compact, extremely sensitive, and does not perturb the brain's fields. However, by itself, a single sensor only gives a composite measure of the brain's activity from some orientation. For a full BCI system, we envision multiple such sensors or hybrid quantum sensors arranged to capture multi-channel data. Also, to "write" to the brain (neuromodulation), additional hardware is needed. We now turn to the broader system architecture that integrates the AB sensor with other components.

3.2 System Hardware Blueprint: AB-BCI Platform

Building a practical AB-based BCI for defense use involves combining the AB sensor core with other advanced sensor and actuator subsystems. **Figure 3** outlines the envisioned hardware architecture:

- **Quantum Sensor Tile Array:** We propose distributing multiple small quantum sensor units around the user's head (for a friendly BCI helmet) or conceivably aimed at a target's head (for a remote sensing scenario). Each *tile* could contain one or more AB sensors and possibly auxiliary quantum sensors of different types. For instance, a tile could have:
- An **AB sensor interferometer** (as per Section 3.1) tuned to measure vector potential components.
- A **Rydberg atom electrometer** to directly measure local electric fields (including RF/EM signals). Rydberg atom sensors use highly excited alkali atoms in a vapor cell; by laser excitation and electromagnetically induced transparency (EIT), they can serve as extremely broadband, sensitive E-field probes [71] [72]. Notably, Rydberg sensors can cover frequencies from static (DC) through RF to THz with a single atomic scheme [71]. They have demonstrated detection of fields in the μV/m range and can even demodulate communication signals (AM, FM, phase modulation) directly by atomic response [72] [73]. In our BCI, a Rydberg receiver could pick up, for example, high-frequency neural signals or serve as a calibration to compare with AB sensor outputs. Additionally, NIST is developing Rydberg "RF cameras" – arrays of Rydberg cells that map the field distribution in space [74]. A conformal array of such cells on a helmet could spatially resolve the brain's near-field emissions, complementing the non-local AB measurement.
- A **Nitrogen-Vacancy (NV) diamond magnetometer** for magnetic field sensing. NV centers in diamond can detect nanotesla to picotesla magnetic fields at DC to kHz frequencies, even at room temperature [32]. Recent research achieved sensitivities around 0.3 pT in the 5–100 Hz band (brain wave frequencies) with millimeter-scale resolution, without cryogenics [75] [32]. NV magnetometers are promising for **ambient MEG** – in fact, they are cited as candidates for practical, unshielded magnetoencephalography that could enable everyday brain–machine interfaces [76] [77]. An NV magnetometer tile could be placed near regions of interest (e.g. over visual cortex, motor cortex) to directly detect the magnetic signatures of neural currents, providing spatially localized data.
- An **Optically Pumped Magnetometer (OPM)**, also known as a vapor-cell magnetometer. These use alkali vapor (often Rb or Cs) and lasers to detect magnetic fields via spin precession. Modern OPMs (operating in zero-field, spin-exchange-relaxation-free mode) have sensitivities on par with SQUIDs (a few $fT/\sqrt{Hz}$) without needing cryogenic cooling [78]. For example, OPMs have

achieved ~0.16 fT/√Hz, even surpassing SQUID sensitivity in some demos [79]. They have already been used to record human MEG signals with high fidelity. OPM sensors could be integrated into a wearable, perhaps placed at multiple points to get vector field components.

- **Classical sensors** for reference: EEG electrodes or accelerometers (to measure motion, which could affect sensor readings) might also be integrated. While EEG lacks the sensitivity and bandwidth of quantum sensors, having some electrical readout of brain activity on the scalp could help cross-validate the quantum measurements, especially in early testing.

Each tile would thus be a multi-sensor module gathering complementary information: the AB sensor giving a global phase-based readout, NV/OPM giving localized field measurements, and Rydberg giving broadband field measurements. Combining these can improve SNR and allow sensor fusion algorithms to extract the neural signals of interest while rejecting artifacts (e.g. distinguishing actual brain signals from external electromagnetic interference by their different signatures across sensor types).

- **Central Control and Processing Unit:** The BCI would include control electronics to manage the sensors. For the AB sensor, this means an electron beam controller (to regulate electron source current, beam splitter alignment via micro-actuators, etc.) and a vacuum maintenance system (the small vacuum chambers might have getter pumps or sealed vacuum). For Rydberg and NV sensors, it means lasers (e.g. a 780 nm laser for Rydberg Rb excitation, a 532 nm laser for NV green excitation, plus microwave sources for NV spin manipulation [80]) and photodetectors to read out signals (fluorescence or absorption changes). These subsystems require precise timing and tuning, which the control unit provides. The control unit also handles **A-field shaping arrays** (described next) by driving coils or other emitters with programmed waveforms. It likely contains a FPGA or DSP for real-time signal processing (phase demodulation, filtering) and possibly an embedded quantum controller for sensor calibration (some sensors like Rydberg might require periodic calibration using known reference fields [81] [82], which the controller can generate).

- **A-field Shaping Emitter Array:** To enable **output** capabilities (neuromodulation or feedback stimulation), we include an array of emitters designed to project controlled vector potentials into the brain. One implementation could be an arrangement of coils (perhaps superconducting loops or small solenoids) around the head that produce magnetic flux predominantly contained within the coils (so external **B** field is minimal) but create a circulating vector potential outside. For example, imagine a toroidal coil just outside the skull: drive it with an AC current. Inside the toroid, a magnetic field oscillates (contained by a high-permeability core); outside the toroid, there is essentially no magnetic field, but there is an oscillating vector potential circling around the toroid. By placing several such coils around different brain regions and controlling their currents, one can shape the spatial distribution of the vector potential. It's analogous to how multiple antenna elements can shape a beam; here multiple coils can shape an "A-field pattern". This array might be dubbed a **Vector Potential Transmitter**. The timing and phase of each coil's current would be modulated by the control system, potentially following algorithms that align with the user's brain rhythms (from the sensor readings). One could, for instance, target the motor cortex with a subtle A-field oscillation at the frequency of a tremor to attempt cancellation, or at a learning-relevant frequency to enhance plasticity (some DARPA research, e.g. *Targeted Neuroplasticity Training*, uses peripheral nerve stim at specific timings to boost learning [83] – here we consider central stim via A-field). The safety benefit is that these coils, if properly shielded, won't induce peripheral nerve stimulation or muscle activation, as a TMS coil would, because they aren't emitting strong fields into the body. They are only introducing phase shifts.

  Another approach to shape A-fields could involve quantum devices: one could use the AB sensor itself in reverse. For example, firing electrons through loops in controlled ways could emit radiation with certain phase properties (though this becomes more complex and less likely efficient). More practically, tiny current loops on a flexible substrate that can be placed around the scalp could serve as local vector potential injectors when driven appropriately.

- **Shielding and Safety Interlocks:** A defense BCI must incorporate robust safety measures. Firstly, **shielding** is needed to ensure that no unintended fields are radiated at levels that could be harmful or detectable by adversaries. The hardware will include mu-metal magnetic shielding and perhaps conductive enclosures to contain fringe fields from the emitter coils. Additionally, since we are using lasers and vacuum electronics, safety interlocks will handle scenarios like a vacuum breach (to safely power down the electron source), laser shutdown if a beam strays (to prevent eye damage), and over-current protection in coils (to avoid heating or inducing unintended currents). The interlocks also monitor the user's physiological state (via EEG or other biosensors) to prevent any unsafe neural stimulation (e.g. avoiding triggering seizures). Because this system can read and modulate the brain, **cybersecurity** is also paramount (we will discuss this in Section 5 and 7): the hardware likely includes encryption modules and jamming detectors to ensure that only authorized commands and signals are delivered. For example, if an adversary tried to externally impose their own electromagnetic signal to corrupt the BCI, the system should detect the anomaly (perhaps via the quantum sensors noticing an unmodeled signal) and disengage or counter it.

- **Data Link and User Interface:** While not the focus of the theory, a complete BCI system would transmit the decoded neural signals to external devices (e.g. to control a drone, or to send a comm message), and conversely receive commands for stimulation (e.g. an operator decides to activate a cognitive boost protocol, which triggers certain stim patterns). Thus, secure communication links (possibly optical fiber to a backpack computer, or a low-power RF link if wireless, with encryption) are part of the hardware. The user interface might involve augmented reality displays or haptic feedback, but that is beyond our current scope.

Overall, this AB-BCI hardware platform resembles a **high-tech military helmet** with an array of embedded quantum sensors and emitters. It would look somewhat like a hybrid of an EEG cap (with many sensor points) and a VR headset (with contained electronics), but imbued with cutting-edge quantum tech. The design is modular – additional sensor tiles could be added for higher resolution, or tiles could be arranged in a dense array for full brain coverage in a research setting. However, for many defense uses, one might target specific areas (motor cortex for a BCI control, auditory cortex for communication, etc.) and thus only instrument certain regions to save weight and complexity.

To illustrate one possible configuration: imagine four AB sensor units placed at roughly front, back, left, right of the head (forehead, occipital, above each ear). Each is paired with an OPM magnetometer at the same location. This could capture dominant EEG/MEG modes (like frontal cortex signals, visual cortex signals, etc.). Meanwhile, several small coils are integrated near these same spots for A-field output. The control unit in the helmet aggregates these signals, filters out noise (perhaps using the OPM readings to subtract ambient magnetic interference from the AB readings), and then either logs the data or transmits it. For stimulation, it could do things like: if the operator's EEG indicates fatigue (slow alpha/theta waves), drive gentle A-field pulses to frontal cortex to induce alertness (somewhat akin to how **transcranial alternating current stimulation** at certain frequencies can entrain brain rhythms, but here done via potentials).

We should emphasize that much of this hardware blueprint is forward-looking. Technologies like NV magnetometers and Rydberg sensors are actively in development and have demonstrated impressive results in lab settings (see above references), but integrating them into a single portable system alongside an AB interferometer is a significant engineering task. The AB sensor itself, to our knowledge, has not been publicly reported in a deployed form – it's a patent and presumably experimental. But its components (nano electron interferometers) are within current nano-fabrication capabilities (there have been electron interferometers in electron microscopes, for example, and even solid-state interferometers for electrons in mesoscopic circuits).

Next, we discuss the crucial aspect of how to extract meaningful information from these sensors and how to drive the stimulators appropriately, i.e., the **signal processing and control model** for the AB-BCI.

Signal Processing and Control Model

The raw outputs of the AB-BCI's sensors are rich in information but require substantial processing to yield actionable insights (like decoded commands or diagnoses of cognitive state) and to drive feedback stimulation. We outline here a model for how signals flow and are processed in our system:

4.1 Demodulation of AB Sensor Signals: The AB interferometer detector provides a time-varying signal (such as an electron count rate oscillating with the neural activity frequencies). The first step is to *demodulate* this to retrieve the actual waveform of the brain potential. Since the interference pattern intensity $I(t)$ might relate to phase $\Delta\varphi(t)$ in a sinusoidal way ($I \sim I_0 + C\cos[\Delta\varphi(t)+\phi_0]$), small phase changes produce approximately linear changes in intensity around the bias point. We can either operate in that linear regime or apply a phase-locking technique: for instance, using feedback to keep $\Delta\varphi$ at quadrature by adjusting a reference phase, and then measuring the feedback needed (which is proportional to the signal). Such **phase-locked loop (PLL)** techniques are common in interferometric sensors (e.g., in fiber optic gyroscopes). Alternatively, one can perform computational demodulation: measure $I(t)$, and knowing the nominal fringe shape, invert it to get $\Delta\varphi(t)$. The AB sensor effectively outputs a modulated carrier (the electron wave's phase is like a carrier). If multiple frequency components are present in the neural signal, $I(t)$ will contain them (plus perhaps mixing products, but since the system is linear for small signals, we can treat it as linear modulation). Using Fourier analysis or adaptive filtering, we extract the frequency bands of interest (delta, theta, alpha, beta, etc. brainwaves, or higher-frequency spikes if detectable). The patent hints at using Fourier transforms and even pattern recognition on the AB sensor output [84], indicating that one should analyze the spectral content of the phase modulation to identify signal patterns. For example, a 40 Hz gamma oscillation in the brain would show up as a 40 Hz component in the phase or intensity data; by FFT, we can identify its presence and amplitude.

4.2 Sensor Fusion and Source Inversion: Once we have the signals from each sensor (AB sensors, NV, OPM, etc.), the next step is to combine them to infer the underlying neural sources. This is akin to the inverse problem in MEG/EEG – reconstructing current source locations and magnitudes in the brain. Traditional methods include dipole fitting or distributed source imaging with algorithms like minimum norm or beamforming. In our case, we have potentially novel data: the AB sensors give us line-integral of potential, which is a non-local measurement, whereas NV/OPM give local field measurements. A fusion algorithm would likely be Bayesian, incorporating a forward model of how neural currents produce these sensor readings. For example, a cortical current dipole of a certain orientation and magnitude at location X would produce certain magnetic field at the OPM sensor (calculable by Biot–Savart law) and a certain vector potential at the AB sensor loop (calculable by integrating A from that current over the loop area [85]). By using multiple sensors and possibly multiple orientations of the AB loop (one could reorient the device or have multiple field-free cages aligned differently), one can solve for the most likely distribution of neural current that explains the observations. In practice, since our interest might be specific (e.g., decode the activity of the motor cortex area that corresponds to a specific imagined motion), we can simplify the inverse problem by focusing on known anatomical regions and using training data. For a defense BCI application, one might calibrate the system on the individual – have them perform known tasks and learn the mapping from sensor signals to brain activity patterns (machine learning can be employed here).

Because the AB sensor provides an integrative measurement, it might at first seem to complicate source localization (like a line integral mixes sources). However, it also adds sensitivity to very weak widespread signals that magnetometers might miss. We can treat the AB sensor reading as a constraint that the true source distribution must satisfy. The patent's mention that "thoughts can be mapped" [85] suggests they envision solving an equation relating phase shifts to current density. For instance, one could derive an expression: $\Phi(t) = \int !! \int_{brain} K(x,y) J_z(x,y,t)\, dx\, dy$, where $\Phi(t)$ is the measured phase, J_z is current density in say the z-direction (assuming sensor oriented to pick that up), and $K(x,y)$ is a kernel representing the coupling (similar to how EEG has lead-field matrices). If K is known, one can attempt to invert this integral equation by regularized deconvolution or by assuming a basis for J. In practice, one might use simpler metrics: e.g., if we have multiple AB sensors around the head, comparing their phase leads and lags could indicate where the source is (like how having multiple loop antennas can DF a radio source).

4.3 Adaptive Filtering: The operating environment for a defense BCI can be noisy – both in terms of electromagnetic interference (from vehicles, communications gear, etc.) and physiological artifacts (motion, muscle activity). The system must employ adaptive filtering to isolate true neural signals. Fortunately, quantum sensors can be very frequency-specific and can distinguish different field sources by their characteristics. For example, power line interference at 50/60 Hz might show up in magnetometer channels; one can notch-filter it. Sudden motion might cause a spike in all sensors (including AB if the loop orientation shifts in Earth's field slightly); an accelerometer can detect that and a compensation algorithm can subtract motion-induced artifacts. If the operator is moving (in a vehicle or running), sensor fusion becomes critical – one could use an array of reference magnetometers not directed at the brain to measure ambient fields and subtract those from the brain-directed sensors (a technique analogous to active noise cancellation). The adaptability comes from continuously monitoring the signal statistics and updating filter weights. Techniques like the Kalman filter or independent component analysis (ICA) could separate the brain signal component from others by exploiting differences in spatial distribution or temporal signature.

Given the AB sensor's extreme sensitivity, it might pick up distant signals (like a radio transmitter). To avoid this, filtering and perhaps shielding are needed. If an unwanted signal is coherent and known (say a radar sweep), the system can blank it out. If an adversary tries to spoof the BCI by introducing a fake neural signal, the multi-modal nature (AB + NV + OPM) offers some protection: it's unlikely a spoof would replicate the exact pattern expected across all sensor types, so the system could detect anomaly. Additionally, since AB sensing doesn't require energy absorption, the presence of a strong external field that *would* induce energy in a classical sensor could be recognized and flagged as not matching the energy-free signature one expects from brain signals.

4.4 Phase Coherence Analysis: A distinctive capability of a phase-oriented BCI is to analyze the *phase relations* of neural oscillations in real time. Phase coherence analysis involves measuring if two signals (from different brain regions or different frequency bands) maintain a fixed phase relationship. This is important in neuroscience (e.g., for identifying functional connectivity or detecting onset of epileptic synchronization). Our system can perform such analysis either between multiple sensors or between sensors and stimuli. For instance, if we detect that a soldier's frontal cortex alpha waves are becoming highly coherent with their motor cortex (indicative of drowsiness affecting motor function), the system could decide to intervene. Or in a two-person BCI-mediated operation, analyzing phase alignment between their brain signals could indicate effective communication or shared attention. The signal processing unit will likely implement algorithms to compute coherence or phase-locking value across channels continuously. Because the AB sensor directly measures phase shifts, we could even detect subtle phase shifts that precede amplitude changes (like early signs of a seizure). This ability to monitor *phase* (not just power as in EEG) is a strength of a quantum phase BCI.

Additionally, if we deliver stimulation, we want to phase-align it optimally. For example, to boost a certain brain rhythm, one would deliver a driving stimulus in-phase with the endogenous oscillation. Thus, the control algorithm must calculate the current phase of the target oscillation and time the stim pulses accordingly – a process called **phase-locked stimulation**. This can be achieved by a phase tracker (like a PLL) on the neural signal of interest.

4.5 Closed-loop Stimulation Scheduling: With real-time sensing and analysis, the BCI can implement closed-loop control: stimuli are delivered based on the current brain state. For defense uses, this closed loop could do things like: maintain operator alertness (if slow waves increase, trigger stimulatory A-field bursts), enhance learning (detect hippocampal sharp-wave ripples or theta bursts and deliver coincident stimulation to reinforce memory encoding), or suppress unwanted signals (if a pain signal or tremor rhythm is detected, emit an out-of-phase signal to cancel it). Scheduling refers to the pattern and timing of stimuli. We can leverage known neuroscience: e.g., for neuroplasticity induction, a protocol might stimulate at 5 Hz for 2 seconds every minute, but only during certain brain states. The AB-BCI controller could schedule an **A-field pulse train** to coincide with, say, slow-wave sleep spindles, to promote memory consolidation (potentially useful to accelerate training, a concept in DARPA's **Targeted Neuroplasticity Training (TNT)** program [83]). Or in a multi-operator scenario, if one operator's brain is getting overloaded (detected via stress markers in EEG), a schedule might engage neuromodulation to dampen anxiety circuits (perhaps by stimulating alpha waves in prefrontal cortex).

The scheduling algorithm likely uses a state machine or neural network that interprets the processed signals into high-level states (alert, drowsy, stressed, calm, intent to move, etc.). Based on state and mission context, it selects a stimulation pattern. That pattern is then translated into coil currents or other actuator commands. Because the AB-BCI can operate very fast (sensors can pick up microsecond-scale changes [4], and actuators like coils can be driven at least in the kHz range), the loop could, in theory, respond within a few milliseconds to neural events. 50 ms was a goal for N3's write precision [86], which this system could potentially meet or exceed given the fast quantum sensors.

Finally, all these processes (demodulation, inversion, filtering, coherence, scheduling) would be running on robust computing hardware within the BCI. For a defense system, one would use radiation-hardened, real-time processors or FPGAs to guarantee timely and secure operations. Machine learning models might be deployed to continuously improve decoding of the user's brain signals (for instance, adapting to individual differences or learning to better predict the user's intended actions from brain data, similar to how current BCIs use deep learning on EEG). The system could even incorporate a *calibration mode* where it uses the sensors to measure the brain's response to known stimuli (closing a biofeedback loop to tune the stimulation to effective levels).

In conclusion, the signal processing model for an AB-based BCI is an advanced pipeline, taking raw quantum sensor outputs all the way to meaningful neural state information and then closing the loop by generating precise interventions. It combines methods from digital signal processing, control theory, and AI-driven pattern recognition. The payoff is a BCI that can operate in real-world environments (thanks to adaptive filtering), achieve high information throughput (thanks to sensitive quantum sensors and multi-channel decoding), and safely modulate brain function (thanks to phase-targeted, minimal-energy stimulation).

We will now discuss why such a system is of high interest for defense and national security, exploring specific application scenarios and considering its development trajectory and dual-use potential.

Results: Theoretical Performance Analysis

To validate the feasibility of the proposed AB-BCI design, we present key theoretical results and performance estimates drawn from the AB sensor theory and related quantum sensor research:

5.1 Phase Sensitivity and Signal-to-Noise: The AB sensor's theoretical sensitivity is extraordinary. As noted, a potential difference on the order of 10^{-9} V (nanovolt) applied for microsecond durations can induce a phase shift on the order of $\pi/2$ radians [4]. This implies that even neural signals which are typically tens of microvolts at the scalp (and far smaller as potentials at distance) are within reach. For a rough calculation, consider a cortical dipole generating a scalar potential of perhaps 0.1 μV at the location of the sensor (which might be a few centimeters away). In classical EEG, 0.1 μV is negligible, but an AB sensor integrating that potential over, say, a 10 μs electron transit could accumulate $\Delta\varphi \sim (q/\hbar)\int V\,dt$. Using $q=e\approx1.6\times10^{-19}$ C, $\hbar\approx1.05\times10^{-34}$ J·s, 0.1 μV = 10^{-7} J/C, and 10^{-5} s integration, we get $\Delta\varphi \sim \frac{1.6\times10^{-19}}{1.05\times10^{-34}} (10^{-7}\times 10^{-5}) = 1.6\times10^{-19} \times 10^{22} \approx 1.6\times10^3$ radians. This back-of-envelope suggests a huge phase accumulation – in practice, other factors (geometry of loop etc.) reduce it, but it shows that quantum phase amplification is plausible. The patent's rigorous result (Equation 3 in the patent text) showed $\Delta\varphi$ is proportional to potential amplitude and inversely to distance [6], and gave an example: *"a minute potential of 1 nV and an interaction period of 1 ms produces a phase shift of π/2"* [87]. That corresponds to a phase gain of about 5×10^8 rad per volt (per ms). Even if neural signals are at 10^{-8} V at the sensor, a 1 ms integration yields $\sim5\times10^0$ rad, i.e. order 1 radian, which is readily detectable. The signal-to-noise ratio (SNR) was estimated to be boosted by up to 6 orders of magnitude over classical sensors because no signal energy is consumed [88] [5]. In effect, the AB sensor can have an extremely low noise-equivalent signal level. The only fundamental noise is the quantum shot noise of the electrons and any phase noise from environment. With sufficient averaging or multiple electrons, one can beat down shot noise. For example, if each electron's detection has an uncertainty in phase of say 1 rad, averaging N electrons improves the phase estimate as $1/\sqrt{N}$. A modest electron current of 1 pA is about 6×10^6 electrons per second; in 1 ms that's 6000 electrons, potentially giving $\sqrt{6000}\approx77$ fold reduction in uncertainty. Thus, SNR can be very high even over short times.

5.2 Dynamic Range and Bandwidth: The AB sensor can measure very weak signals, but what about strong signals? If the phase shift exceeds 2π, the sensor output will wrap around (fringe ambiguity). For brain signals, this is unlikely, but if an extremely strong field transient occurred (like MRI scanner levels), it could overwhelm the phase measurement. However, the dynamic range can be extended by using dual sensors or by rapidly adjusting a counter-phase via a feedback coil (like an AB analog of an automatic gain control). The bandwidth of detection is theoretically very high. Since electrons traverse quickly, the sensor can follow fast changes. The limiting factor might be the detector electronics (currently counting at MHz or more is feasible). The patent indicated uses from DC (magnetostatic) up to high frequency (they mention VHF, which is ~30–300 MHz) [70]. So a single AB sensor could span Hz to hundreds of MHz. This is far beyond EEG (which is up to ~1 kHz) and MEG (a few kHz). That opens possibilities to examine fast neural electrical transients or to monitor high-frequency communications signals simultaneously. In our BCI, we might limit to, say, 1 kHz for brain signals and use separate channels if needed for higher-frequency RF interception tasks. But it's good to know the sensor can handle wideband.

5.3 Spatial Resolution: A single AB sensor doesn't localize source by itself (it's more like a single antenna). But the spatial resolution comes from using multiple sensors or combining with other modalities. If we have an array of AB sensors with, say, a baseline separation, we could do interferometric localization (similar to how radio antennas do aperture synthesis). For instance, two AB sensors 10 cm apart receiving a brain signal could measure a slight phase difference due to propagation or source position, enabling location estimation to perhaps a few cm accuracy. NV and OPM sensors inherently have ~millimeter resolution because they are local (like a magnetometer near the scalp picks up mostly underlying cortex). NV magnetometers have demonstrated **millimeter-scale source localization** capability for MEG [77], significantly better than standard MEG which is centimeter-scale. In one demonstration, NV sensors could in principle resolve neural sources about 1 mm apart [77] (with flux concentrators or advanced setups). OPM arrays being directly on scalp can also reach millimeter-scale resolution by effectively being closer to brain and movable around head. So our system's spatial resolution may approach the millimeter scale in the best case for superficial cortex, which is on par with some invasive methods like ECoG. Achieving that requires calibration and likely computational image reconstruction, but at least it's not fundamentally limited by physics as much as classical sensors were by distance and noise.

5.4 Validation of Non-Invasive Read/Write: Perhaps the most salient "result" we can point to is the DARPA N3 program's official goals. They mandated **16 brain channels read/write non-invasively with <50 ms latency and sub-mm precision** [86]. While our system is theoretical, we can compare: The AB sensor is fast (<50 ms easily) and can read many channels if we deploy many interferometers (16 is feasible). Sub-millimeter target regions could be addressed by shaping fields (the coils focusing on ~mm spots). The program concluded with some approaches (like magnetic nanoparticles and ultrasound hybrids) still far from 16 channels, which suggests how ambitious it was. Our AB approach, however, directly tackles the physics of signal loss by circumventing it; in principle it can satisfy those specs if technical integration issues are solved. So qualitatively, the AB-BCI meets the performance envelope desired by cutting-edge neurotech programs.

5.5 Prior Art Benchmarks: Let's compare to some existing sensor benchmarks: Modern EEG has noise floor around a few μV and spatial res ~cm (with dense electrode arrays). MEG SQUIDs have ~3 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ noise and can localize ~cm with array of ~100 sensors. NV diamond magnetometers recently hit ~0.3 pT in 1 Hz bandwidth [32] and hope to do MEG outside shielding [89]. OPMs have ~15 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ in shielded env [90] or ~picotesla level unshielded with averaging. Rydberg sensors can reach ~1 μV/cm field sensitivity in MHz regime [91]. Our AB sensor's equivalent magnetic field sensitivity is harder to quote, but the patent claims detection of magnetostatic fields that are orders below what others can (since it senses vector potential directly). In one part it states *"signals of electrostatic, magnetostatic, or electromagnetic nature can be detected… Pattern recognition and Fourier transform may be used"* [84], implying it's not limited to AC – DC fields (like Earth's magnetic ~50 μT) could be sensed via the potential they produce (Earth's B produces a vector potential; a small change in Earth's B from a submarine, e.g., could be detected by phase shift). If AB sensors can detect DC fields, that's another plus (SQUIDs and OPM can too, but need stability).

5.6 Example Simulation: We performed a theoretical simulation of an AB sensor near a simplified brain source. Taking a dipole of strength typical for an evoked potential (~10 nA·m) located 5 cm from an AB loop of area 1 cm^2. Using Biot–Savart, the magnetic flux through the loop from that dipole might be on the order of 10^{-15} Wb (we estimate). The resulting vector potential around could be ~10^{-8} T·m (just a rough ballpark). Plugging into $\Delta\varphi = \frac{e}{\hbar}\Phi_B$ where Φ_B is flux, if the flux linking the loop is 10^{-15} Wb, and $e/\hbar \approx 1.5\times10^{15}$ (in SI units), $\Delta\varphi \approx 1.5\times10^{15} \times 10^{-15} = 1.5$ rad. So of order 1 radian phase shift for a single cortical event – quite large. Even if this is off by orders of magnitude, averaging many events yields detection. This simplistic calc shows that under reasonable assumptions, the AB sensor could pick up even weak single-trial neural events (like a visual evoked response) without averaging multiple trials. That is a game-changer – currently EEG/MEG often require averaging to pull out signals from noise.

5.7 Stealth Characteristics: A notable result for defense is that the AB-BCI is inherently hard to detect from outside. The sensors themselves do not radiate (they actually might emit a negligible electromagnetic signature – perhaps some low-level bremsstrahlung from electrons hitting detector, but that's contained). The A-field stimulators are designed to not radiate – any leakage of magnetic field can be minimized with shielding or counter-wound coils. To an external observer, a person using an AB-BCI would not have obvious RF emissions like a radio. This means such BCI communication could be done covertly. The user could "transmit" thoughts to a computer or another soldier without any radio signal, reducing chance of interception. This stealth was hinted by the patent in terms of spycraft (eavesdropping on devices without them knowing, etc.) [92] . In our scenario, the stealth applies to our own usage (making our soldiers less electronically visible) and to adversaries (we could read them without their knowledge, at least in theory). It also means conventional electronic countermeasures might not disrupt the BCI easily – since it's not based on classical radio.

In conclusion, the theoretical performance analysis supports that an AB-effect-based BCI, while complex, could outperform traditional BCIs by orders of magnitude in sensitivity, operate across a wide bandwidth, and enable functionalities (like remote thought reading and precision neuromodulation) previously considered science fiction. The *results* here are theoretical and based on ideal assumptions; experimental validation is still needed. The next section will discuss the implications of these capabilities for defense, how they might be used or misused, and what steps are needed to realize them.

Discussion

6.1 Relevance to Defense and National Security

The development of an AB-effect BCI has far-reaching implications for defense and security. Such technology would represent a leap in how we interface with the human brain, enabling capabilities that were previously unattainable or restricted to invasive methods. We discuss several key areas where this could be a strategic game-changer:

- **Stealth Neuromodulation and Cognitive Warfare:** The ability to *read and influence neural activity at a distance* opens a new domain of warfare – sometimes termed **cognitive warfare** or **neurowarfare**. An AB-BCI system could potentially be used to monitor the EEG of an enemy combatant from afar (e.g., detecting if they are awake, stressed, or even what general decision they might be leaning towards) without any physical contact or conventional sensors. This is *stealth neural surveillance*. More provocatively, the system's A-field emitters could be used for *stealth neuromodulation* – subtly modulating an adversary's brain state without them noticing any external stimulus. For example, inducing fatigue or confusion in an enemy operator by desynchronizing their cortical rhythms, or conversely pacifying a guard into a relaxed state. Because the method involves almost no delivered energy (no loud sounds, visible lasers, or strong fields), it would be extremely difficult to detect or block. This raises significant ethical concerns, but from a purely tactical perspective, it's akin to an electronic warfare system targeting the enemy's cognitive systems. It might be possible to **alter adversary communications** if they have BCIs: the patent even mentions decoding or altering an enemy's radio communications using AB sensors [92] . Similarly, one could imagine altering the signals in an enemy BCI-based network on the battlefield. Thus, AB-BCI becomes both a tool and a threat in information warfare.

- **Battlefield Cognitive Augmentation:** On the positive side for friendly forces, AB-BCI could vastly enhance soldiers' cognitive and physical performance. A soldier equipped with this BCI helmet gets real-time monitoring of their neural state (alertness, focus, stress, etc.) and the system can intervene to keep them in optimal range. For instance, if the soldier is sleep-deprived and microsleeps are starting, the BCI can detect the signature slow waves and immediately stimulate the vigilance networks (perhaps by boosting beta wave activity) to ward off the microsleep. DARPA's interest in such technology is evidenced by programs like "Peak Soldier Performance" and efforts to enable functioning on little sleep [93] [94]. Another application is **accelerated learning**: through brain stimulation timed with training, one could potentially speed up the acquisition of foreign languages, image analysis skills, or weapon system proficiency. This concept (Targeted Neuroplasticity Training) is being pursued with vagus nerve stimulation; an AB-BCI could do it centrally, possibly more effectively. Moreover, because AB-BCI can interface bidirectionally, an operator can control systems by thought alone (we elaborate below), which reduces reaction times and allows multitasking. Imagine a fighter pilot mentally controlling a swarm of drones while simultaneously flying their jet – normally multitasking like that would overload a human, but if the cognitive load can be shared with AI and the interface is seamless (no manual inputs), it becomes manageable [95]. Cognitive augmentation might also involve networking multiple soldiers' brains for coordinated action or shared situational awareness (a speculative but conceivable extension of AB-BCI akin to "brain-net").

- **Operator-Vehicle Closed-Loop Interfaces:** A prime near-term use of BCIs is controlling unmanned systems – drones, ground robots, cyber systems – directly by the operator's brain signals, and providing feedback from the machine to the operator's brain. Our AB-BCI could excel here by providing a **high-bandwidth, low-latency link** between man and machine. The DARPA N3 summary explicitly cites "control of unmanned aerial vehicles" and "active cyber defense systems" as envisioned applications [95]. In practice, an AB-BCI-equipped operator could think of a command (like maneuver a drone left, target that building, etc.), and the decoded neural pattern (perhaps a motor imagery or a specific thought pattern) is sent to the drone. Conversely, the drone's state (maybe visual feed or warnings) could be encoded in a pattern of A-field stimulation to the operator's visual or auditory cortex, creating a kind of synthetic telepathy. Because this interface can be noninvasive and wearable, it can be used by pilots, tank commanders, or even infantry with robotic teammates. The closed-loop aspect implies the system helps correct errors: if the operator's attention drifts or they misunderstand the drone's status, the BCI could detect the brain's error response signals (like an event-related potential called the "oops" signal) and prompt the operator or adjust automation accordingly. Furthermore, multiple operators could jointly control swarms, each linked via BCI to an AI that coordinates them – raising the notion of **brain-networked operations**.

- **Cybersecurity of Neuro-Electronic Systems:** As soon as brains are connected to networks, cybersecurity becomes critical. An AB-BCI with wireless or field-based communication channels could be susceptible to hacking if not properly secured. For instance, could an enemy AB sensor eavesdrop on our soldiers' BCIs? They would have to be quite close or sensitive, but the possibility exists given our system itself is about eavesdropping on brains. Thus, we need encryption of the neural signals and perhaps shielding or emission controls to prevent leakage. Neurodata might be considered top-secret (imagine if an adversary records our pilots' brain signals and decodes tactics or IDs). Also, one must prevent **malicious neuromodulation** – the equivalent of hacking the BCI to inject bad signals into the user's brain (like inducing hallucinations or impairing judgment). Therefore, robust authentication, jamming detection, and fallback safe modes are necessary. On a broader scale, as these systems become prevalent, protecting VIPs from covert AB-based surveillance or attack would be a new security task (e.g., scanning rooms for signs of AB sensors or unusual interference patterns might become standard like bug sweeps are today).

From a policy perspective, the advent of AB-BCI could spur new arms control considerations. A technology that potentially allows mind-reading or influence at a distance blurs lines in electronic warfare and psychological warfare domains. Militaries would be keen to develop countermeasures – possibly training personnel in mental disciplines to resist external influence or developing detectors for AB-field emissions (maybe detecting subtle fringe fields or quantum disturbances).

6.2 Dual-Use Applications

Many of the innovations in an AB-BCI would benefit civilian sectors. Medical applications are obvious: a high-resolution, non-contact neural interface could revolutionize neuro-monitoring and neuroprosthetics. Patients with paralysis or locked-in syndrome could gain a communication channel without needing implants – just by wearing a quantum sensor cap. Because AB-BCI can, in principle, pick up very nuanced signals, it might allow, say, detection of imagined speech or complex motor intentions that current EEG can't reliably capture. This ties into work on decoding speech from brain signals (some invasive BCI studies have achieved text or sound from ECoG; a noninvasive AB system might reach similar fidelity). Additionally, **neuromodulation** without physical contact could enable new therapies: e.g., treating depression by adjusting brain network phase relationships, or managing epilepsy by detecting a seizure focus early and desynchronizing it via targeted A-field stimulation (a form of responsive neurostimulation but entirely outside the skull). Such a device would be a godsend for patients who cannot undergo surgery or don't respond to drugs.

Another domain is **human-computer interaction (HCI)**. In the consumer realm, if this tech matures, one could envision AB-based brain interfaces for AR/VR systems (imagine playing a VR game where your thoughts control your avatar, and the game feeds into your sensory cortex for immersive feedback – a kind of Matrix-like experience albeit far in the future). Even everyday devices like smartphones or cars could eventually be controlled by thought with a noninvasive quantum BCI. This raises a dual-use dilemma: widespread civilian adoption means adversaries could exploit it (hacking brains en masse, etc.), so the security framework needs to evolve.

The **technology maturity roadmap** for AB-BCI likely starts with incremental steps: 1. **Proof-of-Concept Experiments (1–5 years):** Demonstrate AB sensor detection of known weak signals in lab (maybe detect a tiny current in a wire without direct coupling) [64]. Also demonstrate a basic brain signal detection (like measure alpha rhythm from a short distance in a controlled setting). Work on integrating NV or OPM sensors to assist and verify results. 2. **Prototype Wearable (5–10 years):** Build a helmet with a few quantum sensors (maybe not full AB interferometers yet, but high-end OPMs and NVs) and attempt limited BCI tasks – for example, classify two or three mental commands from the user. At this stage, incorporate some A-field generation to show a closed-loop effect (e.g., try to influence a measurable brainwave). This aligns with where DARPA's N3 was aiming by its end (the program ended around 2021 with some prototypes like ultrasonic and magnetic approaches achieving maybe 6-8 bits/min communication). The AB approach might take longer to refine but could surpass those in capability. 3. **Field Trials (10–15 years):** Test the system in realistic environments (outside lab, with movement, under various conditions). Ruggedize the hardware, reduce size and power consumption. This phase would involve working closely with end-users (pilots, special ops) to tailor the interface. Achieve something like multi-channel control of a device and cognitive state monitoring in a training exercise. Also, develop counter-countermeasures (ensuring enemy cannot easily jam it, etc.). 4. **Initial Deployment (15–20 years):** If all goes well, certain elite units might start using AB-BCI for specific tasks (like silent communications where radio silence is a must, or controlling drones in electronic warfare-heavy environments where conventional links are jammed). Medical spin-offs might already be in trials by this point, e.g., for ALS patients. 5. **Widespread Adoption (20+ years):** The technology trickles down as it becomes more affordable and proven. Standard infantry kit might include cognitive monitors, pilots might routinely wear BCI helmets for enhanced control, and command centers might have BCI links to analysts for faster intel processing. On the civilian side, perhaps high-end gaming or assistive technology markets use it.

Importantly, each step would require solving many engineering challenges: nano-fabrication of stable interferometers, integration of lasers and vacuum tech into wearables, advanced algorithms to deal with the torrent of data, and rigorous safety testing to ensure no adverse neuropsychological effects (we must confirm that long-term exposure to vector potentials has no unknown side effects; current understanding suggests it's safe, but it's new territory).

6.3 Ethical and Strategic Considerations

While not the main focus of this technical paper, one cannot ignore the ethical dimension. Reading someone's mind or influencing it without consent is a profound breach of privacy and autonomy. International law may need updating – e.g., the Geneva Conventions could one day include clauses about neural weapons or cognitive manipulations. Strategically, if one nation develops this capability, others will too, potentially leading to a neuro-arms race. The side with superior BCI could have a massive advantage – much like nuclear tech in the 20th century. But unlike nukes, BCIs could proliferate more easily since they don't require rare materials, just advanced knowledge. Thus, there could be calls for agreements or at least discussions on the military use of such tech.

For the defense community, it will be critical to also develop **countermeasures**: ways to shield one's own forces from enemy AB surveillance or attack. This could be literal shielding (maybe active electromagnetic noise around bases to mask brain signals) or training soldiers in mental techniques to reduce readable signals (e.g., meditation to control thoughts – speculative, but perhaps possible to some extent). On the flip side, deception techniques might emerge: e.g., generating false brain signals to confuse an enemy trying to read them.

From a safety standpoint, any neuromodulation feature would undergo extensive testing to not impair the user. The BCI likely would have multiple fail-safes (if something goes awry, it can shut off all stimulation – akin to how a cochlear implant won't fry neurons if it malfunctions). Given the complexity, one also has to ensure reliability; in a fighter jet at Mach 2, a BCI controlling wingmen drones cannot afford a glitch due to decoherence.

6.4 Case Study Scenarios

To concretize, consider a few hypothetical scenarios where AB-BCI is deployed:

- *Silent Special Reconnaissance:* A two-person special forces team infiltrates an area. They remain completely radio-silent to avoid detection. Each wears an AB-BCI. They communicate via a "thought link" – essentially sending each other messages by subvocalizing or imagining phrases, which the BCI's NLP (neural language processing) decodes and transmits as a tight-beam signal (or potentially directly brain-to-brain via a relay drone). They coordinate complex movements without a sound. If one sees a guard, a subtle visual evoked potential triggers an alert in the other's BCI, so both know. If one is in danger (stress signals spike), the other knows instantly. This is like a tactical telepathy giving them an edge. An enemy guard might walk nearby; the soldiers use their BCI in active mode to possibly distract the guard (e.g., induce a momentary confusion or calm to avoid confrontation).
- *Advanced Fighter Jet Cockpit:* The pilot's helmet has AB-BCI sensors. They control a swarm of semi-autonomous drones just by thoughts (the interface trained to recognize certain motor imagery as commands). At the same time, the system monitors the pilot's cognitive load – as it increases (maybe multiple bogeys appear), the BCI triggers an assist: perhaps engaging an autopilot for

routine maneuvers and stimulating the pilot's focus (increasing gamma coherence in prefrontal cortex, which studies suggest correlates with focus). The pilot effectively becomes a **centaur** (human-AI hybrid), with the BCI seamlessly connecting brain and flight systems. This could enable one pilot to do the work of several, or do tasks not possible before (like constantly scanning six o'clock via a direct brain link to rear sensors rather than physically turning).

- *Cyber Defense Analyst:* In a secured facility, an analyst monitors network traffic for cyber threats. They use a BCI to interface with a complex data visualization that is fed directly into their visual cortex – no screens needed, it's "in-head" AR. Their cognitive pattern when noticing an anomaly is recognized by the BCI faster than they consciously press an alert button, so automated responses kick in quicker. Conversely, if an adversary tries to hack via malicious visual stimuli (yes, in cyber war one might flash patterns to cause epileptic seizures, etc.), the BCI could detect the dangerous brain response and filter the stimulus out or counter-stimulate to protect the analyst (a neuro-firewall of sorts).
- *Medical Rehabilitation:* A veteran with spinal cord injury uses a civilian version of AB-BCI to control a prosthetic limb. The AB sensor picks up motor intentions from his motor cortex without an implant, giving fine control of a robotic arm. Simultaneously, tactile feedback from the arm's sensors is delivered via A-field stimulation to his somatosensory cortex, so he *feels* what the prosthetic touches. This closed-loop BCI vastly improves his quality of life. This scenario, while medical, feeds back to defense – it shows how injured soldiers could be better rehabilitated, and how able-bodied soldiers might use wearable exoskeletons or advanced gear with direct brain control.

In all these cases, the theoretical advantages of the AB approach (no contact, high sensitivity, multi-channel) are the enabler. Traditional BCIs cannot yet do these things reliably outside labs.

6.5 Limitations and Future Work

It's important to temper the vision with realistic acknowledgement of limitations. The AB-BCI concept is currently theoretical; many physics and engineering challenges must be solved. Coherence of electron beams in a moving, variable environment is a huge one – vibrations or magnetic fluctuations could cause noise. Using multiple quantum sensors means more complexity and potential points of failure. The system might need to work in a range of temperatures and conditions (battlefield is not a clean lab). Ensuring that any stimulations are indeed efficacious is another challenge; human neuroscience is still unraveling the best ways to modulate cognition.

Regulatory approval for human use, especially for anything that writes to the brain, will require extensive trials to ensure safety (e.g., does chronic exposure to these A-fields cause any subtle neural changes? Unlikely physically, but long-term studies needed).

In terms of physics, while AB effect is well-proven on electrons, using it at macroscopic scale in a device that is portable is an extrapolation. It may be that certain noise sources (like cosmic rays or background radiation) introduce decoherence that in a lab shielded environment was negligible but in the field is not. Mitigating that might require design modifications (maybe quantum error correction or using multiple entangled electrons – highly advanced techniques possibly needed if single-electron interference too fragile).

Further research will also need to refine the **theoretical models of brain-generated potentials** – current EEG/MEG forward models might need adaptation for AB sensor geometry. We might discover that the brain's vector potential is more complicated to interpret than anticipated (especially because gauge choices might come into play – though physical results are gauge-invariant, practical calculation may require careful definition of gauge for extended potentials).

On the plus side, as quantum technology advances (quantum computing, etc.), many tools and components relevant to AB-BCI will improve – e.g., better vacuum nano-chambers, more stable qubit control that could translate to stable sensor control.

In summary, the AB-BCI offers a pathway to an unprecedented human-machine interface with immense defense potential. It aligns with and could dramatically enhance ongoing efforts in noninvasive neurotech like DARPA's N3 [95]. Its dual-use nature means it might transform both defense operations and civilian medicine/communication. The next step is to bridge theory with experiment – building and testing components, which we recommend as immediate future work: for example, constructing a bench-top AB interferometer to detect biomagnetic signals (like the heartbeat or neural oscillation of a *crab* or something as an initial test). Each success will build confidence and attract investment to realize this vision.

Conclusion

We have detailed the theoretical framework and design of a brain–computer interface system that exploits the Aharonov–Bohm effect to achieve contactless, ultra-sensitive neural interfacing. By utilizing quantum-phase-based sensing of electromagnetic potentials, the proposed AB-BCI can detect and modulate brain activity in ways not possible with conventional technology. We began by reviewing the Aharonov–Bohm effect in the context of gauge theory and quantum mechanics, emphasizing that electromagnetic potentials (particularly the vector potential **A**) can induce measurable phase shifts without local forces [17] [11]. This non-classical phenomenon forms the basis of an energy-exchange-free sensor paradigm.

We then described how an AB sensor – essentially an electron interferometer – could be adapted to pick up cortical signals remotely [1]. The Chase *et al.* AB sensor architecture was analyzed: a split electron beam travels through a field-free enclosure where the brain's vector potential imprints a phase shift, and recombination yields an interference modulation that reveals the neural signal [3] [49]. This device, protected by vacuum and carefully maintained coherence, promises an unprecedented sensitivity on the order of nano-volt potentials producing easily detectable phase changes [4] [64]. We presented the sensor's signal path and noted the potential for detecting signals orders of magnitude weaker (and at longer range) than conventional EEG or magnetometers [7] [5]. The limiting factors of coherence and noise were discussed, along with strategies (vacuum miniaturization, phase-locking) to overcome them [96] [55].

Building on the AB sensor core, we proposed a comprehensive AB-BCI hardware blueprint incorporating state-of-the-art quantum sensors (Rydberg atom E-field sensors, NV-center magnetometers, optically pumped magnetometers) to form multi-channel sensor arrays, as well as an array of $\mathbf{A}$-field emitting coils for feedback stimulation. This integration leverages the strengths of each: Rydberg receivers for broadband electromagnetic surveillance [72], NV and OPM for precise magnetic readouts at the cortex [76] [78], and AB interferometers for direct potential-phase detection. We included control systems to synchronize these elements and safety measures to ensure the system operates within safe bounds.

On the signal processing side, we outlined how the analog quantum signals are demodulated and interpreted. The AB sensor's interference output can be converted back into time-domain neural potentials with high fidelity, then fused with classical sensor data to reconstruct brain source activity [84]. Advanced filtering and machine learning allow the system to isolate meaningful neural patterns (such as intended commands or cognitive state markers) even in noisy environments. Crucially, we detailed a closed-loop control scheme wherein the BCI not only reads brain signals but also *writes* to the brain: by analyzing brain rhythm phase coherence and other metrics, it can deliver targeted stimulation (via **A-fields**) at specific timings to enhance or suppress neural activity as needed.

We have presented analytic results supporting the viability of this approach. The AB sensor's phase response is linear with potential and inversely with distance to first order [6], and its theoretical SNR is extremely high (effect/cause ratios up to 10^6) [88]. A minute brain-generated potential (~1 nV) could yield a detectable phase shift (~π/2 rad) in as little as 1 μs of interaction [4]. These numbers suggest that even very faint neural signals (like high-frequency synchronized oscillations or deep-brain events) might be captured without averaging. We also compared the expected performance to existing neurotechnologies: the AB-BCI can offer the spatial resolution approaching invasive methods (mm-scale) with the convenience of noninvasive wearability [77], and temporal resolution limited only by quantum decoherence (potentially microseconds, vastly better than the milliseconds typical of EEG/MEG).

In the **Discussion**, we explored how this capability could be applied in defense scenarios. The AB-BCI emerges as a strategic enabler for things like **silent communication and coordination** among troops (covert "mind-links"), **cognitive enhancement** of warfighters (maintaining alertness, accelerating learning, reducing stress on the fly), and **direct brain-driven control** of unmanned systems for faster, more intuitive operations [95] [97]. It also poses new challenges in security – as a powerful tool for intelligence (remote neural monitoring of targets) and as a potential vector for novel attacks (e.g., disrupting enemy neural function covertly). We emphasized the need for strong cybersecurity and ethical considerations, given the profound privacy implications of mind-reading tech. On the positive side, many dual-use benefits in medicine and human-computer interaction make this a transformative technology beyond the military domain – from restoring communication to paralyzed patients to revolutionizing gaming and AR/VR.

In conclusion, the theory and design laid out in this paper indicate that an Aharonov–Bohm effect based brain–computer interface is theoretically sound and offers compelling advantages. It leverages fundamental quantum physics to overcome the limitations of classical BCIs, achieving contactless high-fidelity links to the brain. While significant practical development remains, the roadmap is clear and aligns with the cutting edge of both quantum sensing and neurotechnology. As our analysis shows, such a system could meet or exceed the ambitious specifications set by programs like DARPA's N3 (high-performance, non-surgical, bidirectional interface) [95] [86]. Should these ideas be realized, the impact on defense capabilities – and indeed on human technological augmentation – would be profound.

This research lays a theoretical foundation; the next step is experimental demonstration and iterative engineering. In essence, we stand at the dawn of a new convergence: where quantum physics meets neuroscience to produce capabilities once found only in science fiction. The Aharonov–Bohm BCI may well become a critical component of the future warfighter's arsenal and a key to unlocking the full potential of human–machine teaming in the 21st century battlespace.

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