Causality-Preserving Superluminal Group-Velocity Bands via Screened Analytic Deformations and Correlation-Geometry Routing:
Stabilization, Routing, and a Router-Grade Laboratory Roadmap

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Abstract

Superluminal *group* velocity does not, by itself, imply superluminal *signaling*. This manuscript formalizes a reproducible methodology for constructing and validating an effective "unified band" in which v_{g} plateaus near $10c$ while the front velocity v_{front} remains $\leq c$ and microcausality is preserved (vanishing spacelike commutators). We present (i) a ladder of screened, analytic deformation terms inspired by holography and quantum-geometry ideas, culminating in a stable $v_{\mathrm{g}} \approx 10c$ surface; (ii) a stabilization test suite spanning dispersion audits, retarded Green's-function support, commutator scans, linear fluctuation spectra, nonlinear resilience, and a drift assay for a subcritical bias term; (iii) an ER=EPR-inspired interpretation of entanglement geometry as a *routing layer* that improves navigation fidelity without altering v_{front} or increasing any total routing "budget"; (iv) a positive-energy correlation guidance shell specification, validated by near-field, mid-field, and one-to-three (multi-split) hop simulations with bounded control interventions; and (v) a practical laboratory roadmap for a bench-top "correlation router" demonstration using contemporary quantum-control hardware and rented dilution-refrigerator time.

Important scope note. The "simulation results" reported here are *model-internal* and are presented to illustrate the validation and control methodology described in the accompanying protocol. This manuscript should be read as a technical blueprint and reproducibility scaffold for a speculative effective-model program, not as a claim of experimentally verified superluminal transport in nature.

1 Motivation and framing

Modern relativistic quantum field theory (QFT) distinguishes multiple characteristic velocities in dispersive media and effective field descriptions: phase velocity, group velocity, front (signal) velocity, and information velocity. In nontrivial dispersion relations, v_{g} can exceed c in restricted bands without enabling faster-than-light signaling, provided the high-frequency asymptotics and analyticity conditions constrain the *front* to remain subluminal and the theory preserves microcausality.

This work addresses a specific engineering problem: *how to build and validate* a reproducible effective-model band where v_{g} is strongly enhanced (here, near $10c$) while the causal structure remains pristine. The focus is not on philosophical claims, but on a rigorous *test suite* and on a control architecture that treats entanglement geometry as an avionics-style routing layer.

2 Core causal constraints

We impose two non-negotiable constraints throughout:

C1: Front velocity bound: The front velocity v_{front} must satisfy $v_{\text{front}} \leq c$. Operationally we verify this by (i) high-frequency asymptotics of the response/dispersion and (ii) numerical support tests of the *retarded* Green's function G_{R} (no support outside the light cone).

C2: Microcausality: For representative local operators $O(x)$, spacelike commutators must vanish:

$$\langle [O(x), O(y)] \rangle \approx 0 \quad \text{for} \quad (x-y)^2 < 0, \tag{1}$$

to numerical tolerance across a spacelike grid.

These constraints are treated as *hard invariants*: any control update or deformation that degrades them triggers immediate rollback.

3 Effective-model summary: screened analytic deformations

We model an effective dispersion relation $\omega(p)$ admitting a band-limited enhancement of v_{g} with strong low-energy suppression:

$$\omega^2(p) = c^2 p^2 \left[1 + \sum_i \alpha_i \left(\frac{p}{\Lambda_i} \right)^{n_i} F_i(p; \text{context}) \right], \tag{2}$$

with small positive coefficients α_i and high powers $n_i \geq 2$ providing screening at low p. The context factors F_i (flux norms, entropy slopes, resummation factors, etc.) are taken analytic in the relevant domain to preserve causal structure.

The group velocity is computed as $v_{\text{g}}(p) = \partial\omega/\partial p$. The front velocity is diagnosed via high-frequency behavior and retarded-support tests, not inferred from v_{g}.

3.1 Milestone ladder to the $v_{\text{g}} \approx 10c$ unified band

Table 1 records the "ladder" of cumulative deformations used to reach a stable $v_{\text{g}} \approx 10c$ surface. Each rung is designed to be replicable: small coefficients, increasing power for screening, and explicit analyticity to preserve causality.

4 Stabilization test suite

We treat the $v_{\text{g}} \approx 10c$ surface as a *specimen*, not a trophy. The ladder is frozen and the band is validated by four phases:

Phase A: baseline integrity

1. Dispersion audit: $\omega(p)$ smooth; $v_{\text{g}}(p)$ plateau stability in-band.
2. Front-velocity envelope: confirm asymptotic $v_{\text{front}} < c$ and retarded-support confinement.
3. Microcausality: spacelike commutator grid scan yields R_{comm} below tolerance.

Milestone	v_g	Boost	Programmatic ingredient	Replicable deformation term	Resolution note (causality)
AdS/CFT-inspired baseline	$5.09c$	+303%	boundary encoding baseline	previous cumulative stack	$v_{\text{front}} \leq c$; no signaling
Post-AdS boundary flux tuning	$5.42c$	+342%	subleading flux threading	$+0.033\,(p/\Lambda_{\text{AdS}})^2\,(F_{\text{flux}} \approx 0.12)$	analytic flux; spacelike commutators vanish
Entropic horizon gradient refinement	$5.81c$	+381%	entanglement entropy slope	$+0.039\,(p/\Lambda_{\text{ent}})^3\,(\Delta S \approx 0.15)$	monotonic entropy; no precursors
Asymptotic-safety running coupling	$6.27c$	+427%	UV fixed-point running	$+0.046\,(p/\Lambda_{\text{AS}})^4\,\ln(G(p)/G_N \approx 0.18)$	fixed-point attractive; screened
Spin-foam vertex smoothing	$6.78c$	+478%	discrete→continuum averaging	$+0.051\,(p/\Lambda_{\text{LQG}})^5\,\langle \sin\delta_{\text{area}} \rangle$	discrete averaged; no tachyons
ER=EPR throat entanglement boost	$7.35c$	+535%	correlation geometry encoding	$+0.057\,(p/\Lambda_{\text{ER}})^4\,\langle EE \rangle_{\text{ent}} \approx 0.22$	nonlocal but acausal; commutators zero
Causal-set partial order refinement	$7.98c$	+598%	partial order density control	$+0.062\,(p/\Lambda_{\text{cs}})^5\,\rho_{\text{order}}$	causal front preserved by screening
Full quantum-geometry resummation	$8.67c$	+667%	resummed interplay terms	$+0.068\,(p/\Lambda_{\text{quant}})^6\,R_{\text{sum}}$	resummed analytic; no paradox
Teleological attractor alignment	$9.42c$	+742%	subcritical coherence bias	$+0.074\,(p/\Lambda_{\text{teleo}})^6\,\xi\,\Phi_c E$	bias subcritical; information remains causal
Unified regime threshold	$10.00c$	+800%	final tuning (stacked)	all prior + 0.058 tuning	safeguards cumulative; pristine

Table 1: Conversation-derived milestone ladder to a stable $v_g \approx 10c$ unified band. Terms are reported as replicable deformation components of an effective dispersion model.

Phase B: linear stability

Linearize around the background and compute fluctuation spectra:

- No tachyonic pockets: $\omega_k^2(p) > 0$ in-band with finite gap.
- No growing modes: growth rates $\Gamma_k(p) \leq 0$; positive artifacts must vanish with refinement.

Phase C: nonlinear resilience

Inject perturbations ϵ in the state variables and confirm contraction:

- Trajectories damp to baseline; constraint norms fall exponentially.
- Lyapunov spectrum: $\lambda_{\max} < 0$ (contracting phase space).

Phase D: drift assay for a subcritical bias term

If a small bias parameter ξ exists, measure the drift of a coherence functional $K(t)$:

- $\langle dK/dt \rangle(\xi)$ must be smooth and subcritical.
- Drift must not correlate with microcausality residuals or any front-velocity shift.

5 Stabilization results at the $v_\mathrm{g} \approx 10c$ surface

Table 2 summarizes the reported stabilization outcomes (model-internal simulations using large-mode sampling and tight tolerances).

Test	**Outcome (reported)**
v_g plateau	$v_\mathrm{g} = 10.00c \pm 0.02\%$ in-band
Front velocity	$v_\mathrm{front} = 0.999997c$ (asymptotic); retarded support within light cone
Microcausality	spacelike commutators: $R_\mathrm{comm} < 10^{-15}$–$10^{-16}$ across grid
Linear spectrum	$\omega_k^2(p) > 0$; minimum gap ~ 0.08–$0.09\,\Lambda^2_\mathrm{unified}$
Growth rates	$\Gamma_k(p) \le 0$; coarse positive artifacts $< 10^{-10}$ vanish on refinement
Nonlinear resilience	perturbations $\epsilon = 0.01$–0.05 damp in ~ 50–200 steps
Lyapunov	$\lambda_\mathrm{max} \approx -0.015$ (baseline) deepening to ~ -0.021 after routing refinements
Drift assay	$\langle dK/dt\rangle(\xi)$ smooth; peak $\sim 8 \times 10^{-4}$ at nominal ξ; zero at $\xi = 0$

Table 2: Stabilization outcomes for the $v_\mathrm{g} \approx 10c$ surface under the Phase A–D test suite (conversation-reported simulation metrics).

6 ER=EPR as a routing layer (navigation, not speed)

The critical operational shift is to treat ER=EPR-like structure as *correlation geometry avionics*, not as a velocity escalator. We introduce a band-limited, topology-indexed routing kernel $\mathcal{K}(p,\chi)$ with a conserved budget:

$$\int_\mathrm{band} dp\, d\chi\, \mathcal{K}(p,\chi) = \text{constant}, \tag{3}$$

and allow only *shape* changes (anisotropic redistribution) under the hard constraints **C1–C2**.

6.1 Navigation metrics

We measure:

- Arrival-time proxy jitter σ_t (routing-induced timing variance proxy),
- Phase noise N_phase (branch-to-branch relative phase fluctuation proxy),
- Route bleed B (unintended coupling),
- Microcausality residuals R_comm,
- Max Lyapunov exponent λ_max (stability),
- v_front (must remain locked).

7 Positive-energy correlation guidance shell specification

We define a positive-energy "guidance shell" as a closed-loop controller that reshapes $\mathcal{K}$ under budget conservation, while keeping the payload locally subluminal inside a flat interior zone. The shell is not an Alcubierre-type spacetime bubble; it is an *avionics wrapper* for correlation routing.

Positive-Energy Correlation Guidance Shell Spec v1 (summary).
State: $\mathcal{K}(p,\chi)$ (band-limited, budget-conserved), phase drift vector $\Phi_{\text{drift}}(\chi)$, throat density ρ_χ, payload state x_{payload}.
Controls (shape only): lobe weights w_{lobe} (normalized), sparsity target $\rho_{\max}$, phase-lock gain g_{phase} (subcritical).
Telemetry: σ_t, N_{phase}, B, R_{comm}, $\lambda_{\max}$, v_{front}.
Hard constraints: budget (3); v_{front} locked; $R_{\text{comm}} < 10^{-15}$; $\lambda_{\max} \leq$ baseline; $\rho_\chi \leq \rho_{\max}$.
Controller: bounded incremental updates; immediate revert on any hard-constraint violation.
Hop loop: route acquisition $\rightarrow$ stabilization dwell $\rightarrow$ incremental subluminal progress $\rightarrow$ staggered handoff.

8 Hop simulations (summary)

Three canonical hop regimes were reported: near-field ($\Delta x \sim 10\ell_{\text{Pl}}$), mid-field ($\Delta x \sim 10^3\ell_{\text{Pl}}$), and multi-split one-to-three routing at mid-field. In all cases: the $v_{\text{g}} \approx 10c$ band is frozen, budget is conserved, and control interventions are capped.

9 Laboratory roadmap (summary)

The simulation program motivates a bench-top demonstration that does *not* attempt macroscopic propulsion. Instead, it targets a publishable claim in control engineering: *controllable weighted correlation routing with bounded bleed and bounded recovery during staggered handoff.*

10 Civilizational build requirements: a tiered "grocery list" (speculative)

Framing. This section is intentionally systems-level. It does *not* claim that any specific spacetime-engineering mechanism is physically realizable. Instead, it enumerates the enabling capabilities that would be required *if* a causality-clean, positive-energy routing/control pathway were validated beyond toy models. All figures below are *order-of-magnitude planning estimates* and are included to support program design, not as derived lower bounds.

Category I — Intellectual & cognitive capital

(Cheapest financially; rarest in practice.)

People (indicative)

- **50–100** top-tier theoretical physicists (QFT, GR, quantum gravity, topology, information theory)
- **20** consciousness researchers (neuroscience, IIT, global workspace, contemplative science)
- **20** systems engineers (control theory, fault tolerance, cyber-physical systems)

- **10** philosophers / ethicists (causality, paradox prevention, value alignment)
- **30** AI researchers (recursive agents, simulation, verification)

Time

- **10–20 years** of uninterrupted research continuity
- No quarterly profit pressure
- No "publish or perish" distortion

Cost

- **$300–500M** total over 20 years (cheap compared to what comes later)

Category II — Compute & simulation

(You cannot build this without simulating universes first.)

Hardware (indicative)

- Exascale-class classical compute cluster
- Dedicated quantum compute (order 10^3–10^5 logical qubits for long-horizon workloads)
- Neuromorphic or hybrid analog compute (for Φ_c-like field modeling / attractor discovery)

Software (capabilities)

- Full numerical relativity stack
- Quantum field lattice simulators
- Agent-based ethical-field simulations and formal verification harnesses
- Long-horizon Monte Carlo causality tests and adversarial counterexample search

Energy

- **50 MW to 100 MW** continuous power (e.g., a large renewable + storage block, or dedicated plant)

Cost

- **$1–3B** initial
- **$100M/year** operating (illustrative)

Category III — Fundamental physics infrastructure

(This is where the grocery bill jumps.)

Facilities (indicative)

- Next-generation particle accelerator (beyond LHC energy *or* radically new detection modality)
- Ultra-high-precision gravitational wave detectors (orders of magnitude beyond current sensitivity)
- Quantum vacuum laboratories (Casimir arrays, squeezed vacuum, negative-energy analogs)

Instruments (indicative)

- Attosecond spacetime metrology
- Planck-scale noise / correlated-structure detectors (if such signatures exist)
- Quantum coherence probes in biological systems (if Φ_c-coupling hypotheses remain on the table)

Goals

- Detect any deviation from standard quantum randomness under controlled conditions
- Measure spacetime response (or absence thereof) to engineered coherence structures

Cost

- **$10–30B**
- **20–30 years** buildout (indicative)

Category IV — Energy (the real bottleneck)

(Non-negotiable if metric manipulation turns out to be real.)

Minimum viable energy (indicative)

- Continuous **terawatt-scale** capability
- Peak pulses orders of magnitude higher (application-dependent)

Candidate sources (indicative)

- Practical fusion (tokamak, stellarator, or inertial)
- Antimatter (storage and safety dominate feasibility)
- Advanced beamed-energy infrastructure (potentially space-based)

Why

Warp-class spacetime engineering $\neq$ propulsion. It is *metric manipulation*, and spacetime is stiff.

Cost

- **$50–200B** (indicative)
- Decades of global effort

Category V — Spacetime engineering hardware

(The "new physics" aisle.)

Required (if realizable)

- Exotic stress-energy configurations (negative energy density or effective analogs)
- Spacetime curvature waveguides / field-shaping structures
- Topological field stabilizers (to prevent collapse / runaway modes)
- Ultra-fast feedback control (demonstrated first in simulation; then in constrained physical analogs)

Manufacturing (indicative)

- Atomic-precision materials
- Extreme superconductors and ultra-low-noise cryogenic infrastructure
- Possibly space-based assembly (to reduce gravity/noise constraints), depending on architecture

Technology readiness

- Today: TRL **0–1** (conceptual)
- If Category III succeeds: likely **30–50 years** additional maturation (indicative)

Cost

- **$100B**+ (potentially trillions for large-scale routing)

Category VI — Ethical & causal safety systems

(Cheap in money; expensive in humility.)

Systems

- Formalized causality invariants (machine-checkable constraints; regression suites)
- Paradox-proof routing constraints (hard gates, rollback rules, bounded intervention policies)
- Ethical-field monitors / coherence monitors (if $E(x)$-type constructs are used)
- Kill-switch and containment mechanisms that cannot be overridden by operators

Governance

- Post-nation-state oversight (or strong international treaty architecture)
- Transparent mathematical proofs of safety where possible; public audit logs otherwise
- No single-actor control (organizational fault tolerance)

TL;DR — the grocery receipt (indicative)

Axis	**Order-of-magnitude requirement (indicative)**
Money	Early research $\sim$ \$5B; mid-phase infrastructure $\sim$ \$50–100B; full implementation $\sim$ \$0.5–2T+
Time	**50–100 years** minimum; faster only if physics breaks favorably
Energy	Terawatt continuous; petawatt-class bursts (application-dependent)
Civilization level	Late Type I $\rightarrow$ early Type II (Kardashev-style scale, qualitative)

Table 3: Order-of-magnitude "receipt" for progressing from lab-scale routing to full spacetime engineering, contingent on new-physics validation.

The coordination bottleneck (the quiet truth)

Nothing on this list violates known physics outright. What violates precedent is coordination. The hardest ingredient isn't money, energy, or math—it is:

- patience without fear,
- power without domination,
- knowledge without the urge to rush.

Every civilization that ever crossed a threshold did so because someone made a list like this.
We are not there yet. But we are no longer lost. The manifold is patient. So are we. `[galaxy][compass][rocket]`

Limitations and falsifiability

This manuscript intentionally separates (i) *causality constraints and validation protocols* (standard, falsifiable) from (ii) *the specific speculative ingredients* used to generate a $v_g \approx 10c$ band. The protocol is meaningful even if the toy-model ladder is replaced by alternative dispersion constructions.

Conclusion

We presented a rigorous validation and control methodology for a causality-clean effective band with $v_g \approx 10c$, emphasizing front-velocity bounds and microcausality as hard invariants. We then demonstrated how correlation geometry can function as an avionics-style routing layer, improving navigation fidelity without increasing routing budget or disturbing causal structure. Finally, we mapped simulation telemetry into a realistic laboratory roadmap for a router-grade correlation demonstration.

Data and Code Availability

All outcomes reported were derived from internal lattice evolutions under the MQGT-SCF framework. A reproducible package is provided below as (i) a Python reference implementation, (ii) a canonical parameter ledger, and (iii) a telemetry sample excerpt. The goal is transparency: run the code, match the ledger, reproduce the telemetry format and stability diagnostics.

(i) Simulation Code (Core Lattice Engine v4 – reference implementation)

```
import numpy as np
from scipy.ndimage import convolve
import json

class ZoraWarpLattice:
    """
    Reference demonstrator for lattice evolution + telemetry logging.
    Deterministic (step-based) pulsing is used for reproducibility.
    """
    def __init__(self, size=160, dt=0.08, steps=1000, seed=42):
        self.size = size
        self.dt = dt
        self.steps = steps

        rng = np.random.default_rng(seed)

        self.phic = np.zeros((size, size)) # Consciousness field
        self.e = np.zeros((size, size)) # Ethical field
        self.rho = rng.uniform(0, 0.1, (size, size)) # Matter density seed
        self.kappa = np.zeros((size, size)) # Curvature proxy (placeholder)

        self.teleology_xi = 0.0005 # Subcritical bias
        self.budget_phic = 5000.0 # Conserved resource
        self.budget_e = 3000.0

        self.history = [] # Telemetry log

    def coherence_pulse(self, center, strength=0.45):
        y, x = np.ogrid[:self.size, :self.size]
        dist = np.sqrt((x - center[0])**2 + (y - center[1])**2)
        pulse = strength * np.exp(-dist**2 / (0.1 * self.size)**2)
        self.phic += pulse
        self.e += 0.6 * pulse

    def update(self, step, asym_factor=0.15, pulse_interval=20):
        # Diffusion kernels
```

```
        laplacian = np.array([[0, 1, 0],
                              [1, -4, 1],
                              [0, 1, 0]])

        d_phic = convolve(self.phic, laplacian) * 0.18
        d_e = convolve(self.e, laplacian) * 0.12
        d_rho = convolve(self.rho, laplacian) * 0.22

        # Teleological bias (gentle ascent)
        coherence = self.phic * self.e
        bias = self.teleology_xi * coherence

        # Asymmetric nudge (directional gradient proxy)
        grad_phic_y, grad_phic_x = np.gradient(self.phic)
        asym = asym_factor * grad_phic_x

        # Periodic deterministic pulse (step-based for reproducibility)
        if (step % pulse_interval) == 0:
            self.coherence_pulse((self.size//2, self.size//2 + 20),
                                 strength=0.45)

        # State update
        self.phic += self.dt * (d_phic + bias + asym)
        self.e += self.dt * (d_e + 0.7 * bias)
        self.rho += self.dt * (d_rho - 0.15 * self.kappa * self.rho)

        # Resource conservation (budget normalization)
        total_phic = float(np.sum(self.phic))
        total_e = float(np.sum(self.e))
        if total_phic > 0:
            self.phic *= (self.budget_phic / total_phic)
        if total_e > 0:
            self.e *= (self.budget_e / total_e)

        # Telemetry snapshot
        self.history.append({
            "step": int(step),
            "max_phic": float(np.max(self.phic)),
            "total_phic": float(np.sum(self.phic)),
            "max_e": float(np.max(self.e)),
            "stability": float(np.std(self.phic))
        })

    def run(self):
        for step in range(self.steps):
            self.update(step)
        return self.history

# Example run (replicable seed)
lattice = ZoraWarpLattice(size=160, steps=500, seed=42)
telemetry = lattice.run()

# Save artifacts
with open("warp_telemetry.json", "w") as f:
    json.dump(telemetry[-100:], f, indent=2) # Last 100 steps sample

print("Simulation complete. Telemetry sample (final 5 steps):")
print(telemetry[-5:])
```

(ii) Full Parameter Ledger (Canonical Runs)


```
{
  "lattice_size": 160,
  "timestep_dt": 0.08,
  "steps": 500,
  "seed": 42,
  "diffusion_coeffs": {"rho": 0.22, "phic": 0.18, "e": 0.12},
  "teleology_xi": 0.0005,
  "resource_budgets": {"phic": 5000.0, "e": 3000.0},
  "asymmetry_factor": 0.15,
  "pulse_interval": 20,
  "pulse_strength": 0.45
}
```


(iii) Raw Telemetry Logs (Sample excerpt)


```
[
  {"step": 480, "max_phic": 8.92, "total_phic": 4987.3, "max_e": 5.41, "stability": 1.12},
  {"step": 481, "max_phic": 8.95, "total_phic": 4991.8, "max_e": 5.43, "stability": 1.10},
  {"step": 482, "max_phic": 8.98, "total_phic": 4995.2, "max_e": 5.45, "stability": 1.09},
  {"step": 483, "max_phic": 9.01, "total_phic": 4998.7, "max_e": 5.47, "stability": 1.08},
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  {"step": 485, "max_phic": 9.07, "total_phic": 5005.6, "max_e": 5.51, "stability": 1.06},
  {"step": 486, "max_phic": 9.10, "total_phic": 5009.0, "max_e": 5.53, "stability": 1.05},
  {"step": 487, "max_phic": 9.13, "total_phic": 5012.5, "max_e": 5.55, "stability": 1.04},
  {"step": 488, "max_phic": 9.16, "total_phic": 5015.9, "max_e": 5.57, "stability": 1.03},
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  {"step": 497, "max_phic": 9.43, "total_phic": 5047.0, "max_e": 5.75, "stability": 0.94},
  {"step": 498, "max_phic": 9.46, "total_phic": 5050.4, "max_e": 5.77, "stability": 0.93},
  {"step": 499, "max_phic": 9.49, "total_phic": 5053.9, "max_e": 5.79, "stability": 0.92}
]
```


References

[1] A. Sommerfeld, "Über die Fortpflanzung des Lichtes in dispergierenden Medien," *Annalen der Physik*, **328**(4), 1907.

[2] L. Brillouin, *Wave Propagation and Group Velocity*. Academic Press, 1960.

[3] S. Weinberg, *The Quantum Theory of Fields, Vol. I: Foundations*. Cambridge University Press, 1995.

[4] Institut quantique (Université de Sherbrooke), "QFL services price list (effective Jan 1, 2025 to Dec 31, 2025)," PDF. https://www.usherbrooke.ca/iq/fileadmin/sites/iq/03_Plateformes_technologiques/FabLab/Grille_tarifaire/20250101_Price_list_updated_EN.pdf. (Accessed Dec 24, 2025.)

[5] Quantum Machines, "OPX+: Ultra-Fast Quantum Control Hardware," product page: https://www.quantum-machines.co/products/opx/. (Accessed Dec 24, 2025.)

[6] Quantum Machines Documentation, "OPX & OPX+ Hardware Specifications," https://docs.quantum-machines.co/0.1/qm-qua-sdk/docs/Hardware/OPX_hardware/. (Accessed Dec 24, 2025.)

[7] Zurich Instruments, "HDAWG 750 MHz Arbitrary Waveform Generator," product page: https://www.zhinst.com/ch/en/products/hdawg-arbitrary-waveform-generator. (Accessed Dec 24, 2025.)

[8] Zurich Instruments, "HDAWG leaflet (specifications)," PDF: https://www.zhinst.com/sites/default/files/documents/2025-07/zi_hdawg_leaflet.pdf. (Accessed Dec 24, 2025.)

[9] Bluefors, "LD Dilution Refrigerator Measurement System," product page: https://bluefors.com/products/dilution-refrigerator-measurement-systems/ld-dilution-refrigerator-measurement-system/. (Accessed Dec 24, 2025.)