

Millimeter-Scale Lagrangian Sensor Spheres for Local State Monitoring in SMART Reactors: Towards Energy-Autonomous Operation

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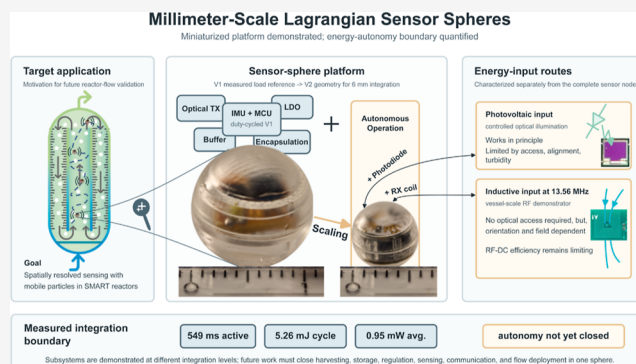
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ABSTRACT: Flow-following sensor particles are a promising route to obtaining spatially resolved measurements in (bio)-chemical reactors. However, their practical deployment is limited by miniaturization, power supply, and packaging. This work presents a millimeter-scale Lagrangian sensor-node platform that integrates an inertial measurement unit (IMU) and a low-power microcontroller unit (MCU) on a high-density interconnect (HDI) printed circuit board (PCB), illustrating the evolution from a first demonstrator (V1) toward a reduced-footprint design (V2) intended for spherical encapsulation. The main contribution is a quantitative system-level feasibility boundary that links miniaturized sensor-node design, duty-cycled energy demand, candidate energy-input routes, and spherical packaging constraints at the targeted millimeter scale. We analyze the baseline power demand of the current duty-cycled implementation, including a cycle-based charge and energy budget, and relate this demand to two experimentally investigated energy-input routes: photovoltaic harvesting under controlled optical illumination and resonant inductive power transfer at 13.56 MHz. The harvesting experiments are performed on dedicated evaluation platforms and are used to quantify candidate energy-input routes. A closed energy-autonomous sensor-in-flow demonstration is not yet claimed. The results show that the platform concept, compact HDI integration, low-power duty cycling, optical data transmission, and a glass-based encapsulation route are technically feasible at the targeted size. At the same time, neither harvesting route yet closes the gap to robust energy-autonomous operation under realistic reactor conditions. Photovoltaic powering appears strongly constrained by alignment, optical access, and geometric coupling. Inductive transfer is more promising but remains highly sensitive to orientation, field distribution, and RF-to-DC conversion efficiency. The presented measurements therefore define both the current feasibility range and the remaining engineering requirements for future energy-autonomous sensor spheres.



INTRODUCTION

Modern (bio)chemical reactors require spatially resolved process information in real-time to improve efficiency, reduce energy consumption, and avoid waste.¹ Fixed probes provide robust measurements but do not capture spatial gradients and mixing dynamics across the reactor volume.² Imaging approaches offer high spatial resolution but often do not generalize to large-scale, opaque, or chemically harsh systems.^{3–5} Flow-following (Lagrangian) sensors moving with the process fluid can address these limitations by sampling process conditions along trajectories through the reactor, enabling distributed measurements without line-of-sight imaging constraints.^{6–8} Bisgaard et al.⁹ provide a

comprehensive review, including a detailed timeline, of the development of Lagrangian sensors. A well-documented challenge, however, is that Lagrangian sensors are typically too large to truly follow the flow in the reactor.¹⁰ How closely a sensor or particle follows the fluid depends on the

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Table 1. Published Mobile Sensor Spheres/Instrumented Particles (Selected)^a

platform (first author, year)	size	operation (what is measured/used for)	link/storage	energy (reported)
sens-o-spheres (Lauterbach, 2019) ¹⁴	7.9 mm	mobile microsensor sphere; temperature demonstrated as minimal payload	433 MHz RF bursts to base station; inductive infrastructure used in the system concept	inductively rechargeable microbattery; strict duty cycling reported
instrumented particle (Cabrera & Cobelli, 2021) ¹⁸	36 mm	measures 3D translational acceleration and angular velocity; logs to removable SD card	onboard data logging (SD), no wireless link required	Li-ion polymer battery; up to 8 h autonomous operation
LSP class (Buntkiel, 2022) ¹⁹	40 mm	IMU + pressure sensor for orientation-resolved motion metrics	onboard logging/postprocessing (as stated in accessible summaries)	runtime not available from the open excerpt
autonomous sensor capsule (Todtenberg, 2015) ¹⁵	44 mm	capsule prototype for bioreactors; link reliability characterized in nutrient solution	433 MHz RF link; packet error rate and path loss reported in liquid tests	battery powered; current/energy not reported in the excerpt

^aOnly systems with documented hardware are included.

importance of inertial effects, which is expressed by the Stokes number, a nondimensional number that expresses the ratio of the response time of the particle to the characteristic time scale of the carrier liquid.¹¹ Depending on the size of the sensor and the viscosity of the fluid, Lagrangian devices have Stokes numbers ranging from 10^{-2} up to 10. Only for Stokes numbers of $O(0.1)$ and smaller can particles be genuinely considered to be flow-following, with errors of 1% or less.¹² Consequently, miniaturization is not only an integration challenge but directly linked to measurement fidelity: decreasing the size of Lagrangian sensors and optimizing their mass distribution reduces the Stokes number and makes their trajectories more representative of the conditions experienced by cells and reactants.^{8,13}

Prior work indicates that the decisive bottleneck is system-level co-optimization: aggressive miniaturization must preserve sensing and computation capabilities of the sensor and enable a viable power and data transfer strategy within a constrained packaging envelope. This becomes evident when comparing published devices: millimeter-sized spheres achieve long-duration operation only through strict duty cycling and simplified on-node power management. Larger capsules can accommodate richer payloads but still face significant link degradation in liquid media.^{9,14,15} Table 1 provides a summary of published systems and highlights the trade-offs between size, sensing payload, link approach, and energy strategy.

The specific contribution of this work is not the isolated use of an IMU, duty cycling, wireless energy transfer, or encapsulation, since each of these concepts is established in related sensor-node and Lagrangian-particle research. Instead, the contribution lies in their system-level codesign under the severe geometric, energy, and packaging constraints of subcentimeter reactor-deployable sensor spheres. Specifically, this work (i) demonstrates a miniaturized IMU/MCU sensor-node architecture and its evolution from V1, the first functional HDI-based demonstrator, toward V2, a reduced-footprint platform redesign intended for improved spherical integration, (ii) provides a measured cycle-level charge and energy budget that defines the load-side requirement for energy-autonomous operation, (iii) evaluates photovoltaic and 13.56 MHz inductive energy-input routes under size-compatible boundary conditions, and (iv) relates these results to spherical encapsulation and density constraints. The resulting contribution is therefore a quantitative integration and feasibility boundary for future energy-autonomous Lagrangian sensor spheres, rather than a claim that all individual subsystem principles are new. The study should accordingly be understood as a platform-integration and energy-feasibility study

rather than as a completed reactor-deployment validation. Under severe size constraints, far-field RF energy harvesting is fundamentally power-limited and increasingly dominated by antenna inefficiency and environmental detuning.¹⁶ Near-field inductive transfer at 13.56 MHz (NFC-like) is a well-established route to deliver energy to compact receiver coils and tags.¹⁷ In addition, we experimentally assess photovoltaic harvesting using wire-bonded photodiodes under controlled illumination as a complementary energy input that is straightforward to quantify via I – V and P – V characterization.

SYSTEM REQUIREMENTS AND PLATFORM CONCEPT

Flow-Following Criterion via Stokes Number

A common measure of how closely a particle follows the carrier flow is the Stokes number eq 1

$$St = \frac{\tau_p}{\tau_f} \quad (1)$$

i.e., the ratio of the particle momentum response time τ_p to a characteristic time scale of the flow τ_f , e.g., eddy turnover time, impeller time scale, or circulation time.¹² For small particle Reynolds numbers (Stokes drag regime), the particle response time eq 2 can be approximated as

$$\tau_p \approx \frac{\rho_p d_p^2}{18\mu} \quad (2)$$

with particle density ρ_p , particle diameter d_p , and dynamic viscosity μ .¹² This expression is strictly valid only in the Stokes regime; for larger particles and higher relative velocities, the drag deviates from Stokes drag. It can nevertheless be interpreted as a conservative (worst-case) indicator of inertia-driven slip. Hofmann et al.¹¹ analyze the Stokes numbers of Lagrangian devices for typical time- and length-scales in a chemical reactor at different impeller speeds. They find that to “cover at least the flow-following behavior in the reactor bulk region, approximate sensor sizes of 0.9 mm or 0.7 mm would be necessary”. Although this level of miniaturization remains out of reach for the foreseeable future and the LS design proposed in this paper will still experience inertial effects, Hofmann et al. also show that the difference in motion will be less substantial than for larger particles, making smaller Lagrangian sensors follow the flow more closely.

A mobile sensor node must remain mechanically protected while supporting intermittent sensing and data egress, and it must be density-matched to the carrier liquid or designed with

controlled buoyancy so that it neither rises nor sinks but remains suspended and advected with the flow. In this manuscript, we focus on the electronics and energy subsystems as the limiting factors for long-duration, scalable deployment. We distinguish between (a) sensing and computation, (b) power delivery/storage, and (c) data egress. Data egress is intentionally treated as a secondary aspect: we do not require a complete receiver chain to establish platform readiness and energy feasibility. This choice of scope avoids overclaiming communication performance that is not yet robust under reactor constraints.

Minimal Sensor Node for Position Detection

Under severe volume constraints, the platform must prioritize functions that maximize process information per unit energy and per unit volume. An IMU coupled to a low-power microcontroller is a particularly efficient core, because it provides accelerations and angular rates that can be mapped to mixing- and transport-relevant features while enabling strict duty cycling and event-driven operation. Orientation information is essential to interpret accelerations in a reactor-fixed frame. Orientation-resolved Lagrangian measurements have been demonstrated by combining inertial sensing with a magnetic reference in postprocessing and filtering frameworks.¹⁹ We therefore select a 9-axis IMU (accelerometer/gyroscope/magnetometer) as the minimal sensing set, where the magnetometer can serve as a reference for heading/orientation stabilization and can also act as a detector for external magnetic beacons, which is relevant for localization.^{19,20}

Wireless data egress in conductive, high-permittivity liquids is not a free subsystem. Prior work reports substantial link degradation for 433 MHz capsule telemetry in liquid media, consistent with attenuation, antenna detuning, and uncontrolled orientation.¹⁵ While millimeter-scale systems, such as Sens-o-Spheres, demonstrate that 433 MHz transmission can be realized via aggressive duty cycling, they also highlight that space and energy constraints force system-level simplifications and tight integration of power management and communication.¹⁴ Motivated by these constraints, we introduce optical emission (LED) as a minimal on-node transmitter element. It can reduce on-node RF frontend complexity and allows the receiver (photodetector/TIA/optics) to be placed outside the vessel when optical access is available. In this manuscript, optical communication is treated as a design direction. Receiver validation and range characterization are explicitly out of scope.

System Power Minimization Approaches for Harvesting Feasibility

Energy harvesting at the millimeter scale is fundamentally area- and volume-limited. For inductive links, shrinking the receiver coil reduces coupling and increases sensitivity to detuning and losses, especially near metallic structures. Near-field 13.56 MHz harvesting is established in principle, but performance strongly depends on coil geometry, matching and environment.^{17,20} For photovoltaic harvesting, shrinking photodiode area reduces the available electrical power at a given irradiance. Thus, realistic operation requires either controlled illumination or extremely low average load power enabled by strict duty cycling. Dual-source concepts, combining photovoltaic and inductive inputs, underline that realistic energy autonomy typically relies on minimizing average power consumption rather than maximizing harvester size. Consequently, this work

treats power reduction by a verified deep-sleep envelope as a first-class design objective and evaluates harvesting primarily as feasibility under realistic geometric constraints, rather than claiming battery-less operation.

Protective Encapsulation against Harsh Environments

Mobile sensor nodes for (bio-) chemical reactors must withstand chemically aggressive substances, shear and long exposure times, while maintaining electrical insulation and stable functionality. Spherical encapsulation is attractive because it minimizes sharp edges and reduces the probability of mechanical snagging and preferential orientation in the flow. However, the encapsulation material and process impose strong constraints on size, assembly, and interface accessibility.

In this work, we pursue a glass-based encapsulation route, using fused silica components fabricated via selective laser-induced etching (SLE), as a chemically robust and hermetic candidate for reactor deployment. We treat encapsulation as a packaging boundary condition and demonstrate prototype-level glass encapsulation feasibility and mechanical integration concepts. Detailed buoyancy matching to achieve neutral buoyancy and long-term chemical aging tests are beyond scope and will be addressed in future work.

Neutral buoyancy is a distinct design objective that couples material selection, internal void fraction, and mass distribution. While buoyancy matching is expected to improve flow-following behavior and reduce wall interactions, its realization requires additional design degrees of freedom (e.g., controlled internal cavities or density-tuning fillers) and process validation. At the current maturity stage, we therefore focus on electronics and energy feasibility. Buoyancy matching will be considered and integrated once the reduced-footprint electronics (V2) and harvesting interfaces are validated.

First-Order Harvesting Scaling and Effective Efficiency

To make the geometric limits explicit without introducing a new figure of merit, we use standard first-order receive-side relations from the inductive-link and photovoltaic literature.^{17,21–24}

For inductive links, Faraday's law relates the induced open-circuit electromotive force $\mathcal{E}$ of a reception coil to the time-variation of linked magnetic flux $\mathcal{E} = -Nd\Phi_B/dt$ with $\Phi_B = \iint \mathbf{B} \cdot d\mathbf{A}$. For approximately uniform sinusoidal flux density $B(t) = B_0 \sin(\omega t)$ across the loop area A , this yields the scaling eq 3

$$V_{\text{oc,rms}} \approx \frac{N\omega AB_0}{\sqrt{2}} \quad (3)$$

which highlights the direct dependence on available coil area.²¹ For a narrowband receive chain, the coil and its resonant matching network can be represented to first order by a Thevenin-equivalent source with open-circuit voltage V_{oc} and an effective series loss resistance R_{th} (including coil AC loss, capacitor ESR, and environment-dependent damping). The maximum RF power transferable to a matched load is then eq 4

$$P_{\text{RF,avail}} \approx \frac{V_{\text{oc,rms}}^2}{4R_{\text{th}}} \quad (4)$$

and the delivered DC power at the rectifier output can be written using the standard RF-to-DC conversion efficiency definition eq 5

$$P_{\text{DC,out}} = \eta_{\text{eff,ind}} P_{\text{RF,avail}} \quad (5)$$

where $\eta_{\text{eff,ind}}$ summarizes matching, rectification, and, if present, regulation losses. Delivered DC power is strongly dependent on coupling, load, and operating point and is used as a bookkeeping parameter, not a new device-independent FOM.^{17,22}

For photovoltaic harvesting, the electrical power at the maximum power point scales approximately like eq 6

$$P_{\text{MPP}}(d) \approx \eta_{\text{eff,pv}} E(d) A \quad (6)$$

with irradiance $E(d)$ and illuminated area A , i.e., the usual power-conversion-efficiency relation evaluated at the maximum power point.^{23,24} In contrast to inductive links, $E(d)$ can be measured directly with an optical power meter, which allows for the quantitative determination of $\eta_{\text{eff,pv}} = P_{\text{MPP}}/(EA)$ from experiments.

Scope Summary

Based on these constraints, we distinguish between (a) sensing and computation, (b) power delivery/storage, and (c) data egress. The present manuscript focuses on platform integration, packaging constraints, and energy-feasibility assessment. Data egress is intentionally treated as secondary: we do not require a complete receiver chain to establish the readiness of the sensor-node platform and to quantify the energy gap toward future autonomous operation. The subsystems considered in this work and their present role in the manuscript are summarized in Table 2.

Table 2. Targeted Functions and the Status in This Manuscript

subsystem	target	status in this work
sensing/compute	IMU + MCU	demonstrated on V1; reduced-footprint V2 design and assembly shown
encapsulation	chemical protection	glass and silicone encapsulation (prototype level)
power delivery	toward battery-free or assisted operation	load-side energy budget measured; photovoltaic and inductive energy-input routes evaluated separately
communication	wireless egress	only discussed but not evaluated

ESTIMATOR-LEVEL TRAJECTORY ASSESSMENT

Accurate trajectory reconstruction of flow-following devices is essential for turning time series of sensor readings into spatially resolved, interpretable information about the reactor state. While our platform provides inertial measurements, IMU-only dead-reckoning drifts over time due to bias, noise, and gravity-compensation errors.^{19,20} Here, we explore whether magnetometer information from an external magnetic landmark could support drift correction in an IMU-based trajectory estimator, following an approach widely used in magnetic-field-based positioning systems.²⁵ The magnetic beacon used in the estimator is represented by an idealized dipole field and should therefore be interpreted as a best-case external landmark rather than as a fully engineered coil implementation.

Localization Algorithm

To give a first proof-of-concept for localization by accelerometers and magnetometer, the IMU is rigidly mounted on a robot arm whose end-effector follows a prescribed vertical circular trajectory of diameter 0.6 m. Real acceleration measurements are used for demonstration purposes, while the magnetic field is synthetically generated by a dipole field model due to the

difficulty of providing a controlled magnetic landmark with a precisely characterized field. Figure 1 shows the robotic arm

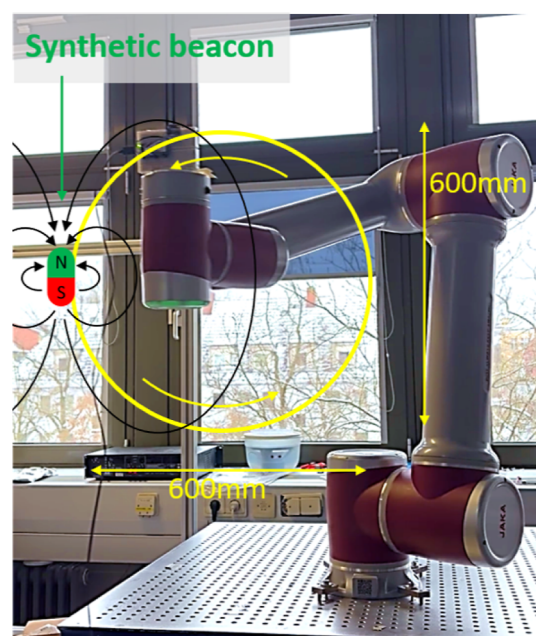


Figure 1. Setup for the tracking process: an IMU on the robotic arm follows a vertical 0.6 m-diameter circular path (yellow), starting at the right and moving counterclockwise (arrow). The magnetic beacon used in the estimator is synthetic and is defined mathematically relative to the center of this reference circle.

and the vertical circular path that its end-effector follows. The robot trajectory provides a controlled reference path along which the IMU data are recorded and then processed offline by the estimator. In simulations we implement a synthetic beacon that generates a dipole field

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \frac{3(\mathbf{m} \cdot \mathbf{r})\mathbf{r} - \mathbf{m}r^2}{r^5} \quad (7)$$

to which we add Gaussian noise with an amplitude of 5% of the local field magnitude, emulating the noise level of the on-board magnetometer. Here, μ_0 is the vacuum permeability, $\mathbf{r}$ the position vector measured from the source, $r = \|\mathbf{r}\|$ its magnitude, and $\mathbf{m}$ the magnetic dipole moment of the equivalent source, oriented normal to the current-enclosing area. Our synthetic beacon is positioned at $\mathbf{r}_0 = [0.11, -0.3, 0]^T$ m relative to the center of the reference circle, i.e. offset by 0.3 m in-plane from the center and by 0.11 m out of the plane of the circle, with the magnetic moment $\mathbf{m}$ oriented along the z -axis.

Tracking Algorithm

We use an Unscented Kalman filter to estimate two-dimensional state vector eq 8

$$\mathbf{x}_k = [p_{y,k}, v_{y,k}, a_{y,k}, p_{z,k}, v_{z,k}, a_{z,k}]^T \quad (8)$$

where p_y and p_z denote a particle's position, v_y and v_z velocity, and a_y and a_z acceleration along the two observed spatial axes. The IMU provides specific force and angular-rate measurements to which we add synthetic measurements of the magnetic field eq 7 to counteract drift. The angular rate measurements are neglected in the estimator since the robot arm only performs nonrotational y - z -plane motion and the

IMU is fixed at the robot end-effector. Note that the dipole field eq 7 is a nonlinear function of the device position. Therefore, the overall mapping from sensor state to measurements is nonlinear, which requires us to rely on an unscented Kalman filter instead of a standard linear Kalman filter.

For the dynamic model, we assume constant acceleration between sensor readings. Because of the IMU's sampling rate of 100 Hz, time increments are only $\Delta t = 0.01$ s. Device acceleration over this short time can be well approximated as piecewise constant. Since the IMU supplies the acceleration directly, this has the advantage that no computationally expensive ODE solve is required in the filter.

We use the unscented Kalman filter as implemented in the PYKALMAN Python library²⁶ to merge the sensor readings with the dynamic model. The prediction eqs (eq 9) are

$$\mathbf{f}(\mathbf{x}) = \mathbf{F}\mathbf{x} + \boldsymbol{\eta}, \quad \boldsymbol{\eta} \sim \mathcal{N}(\mathbf{0}, \mathbf{Q}) \quad (9)$$

where $\boldsymbol{\eta}$ is the process noise, $\mathbf{Q}$ is the process noise covariance matrix and $\mathbf{F}$ is the state transition matrix eq 10

$$\mathbf{F} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{A} \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} 1 & \Delta t & \frac{1}{2}\Delta t^2 \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix} \quad (10)$$

where $\mathbf{A}$ represents the constant-acceleration model in one dimension while the full matrix $\mathbf{F}$ describes the motion along the two independent spatial axes. The process noise covariance matrix eq 11 is set to

$$\mathbf{Q} = \text{diag}(\sigma_p^2, \sigma_v^2, \sigma_a^2, \sigma_p^2, \sigma_v^2, \sigma_a^2) \quad (11)$$

with standard deviations $\sigma_p = 1 \times 10^{-3}$ m (position), $\sigma_v = 1 \times 10^{-2}$ m s⁻¹ (velocity) and $\sigma_a = 0.05$ m s⁻² (acceleration), so that the largest process uncertainty is assigned to the acceleration states that absorb the unmodelled dynamics.

The measurement model eq 12 reads

$$\mathbf{z}_k = \mathbf{g}(\mathbf{x}_k) + \mathbf{w}_k, \quad \mathbf{w}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{R}) \quad (12)$$

where the nonlinear function $\mathbf{g}$ maps the state to the two accelerometer components and the two beacon magnetic-field components, $\mathbf{g}(\mathbf{x}) = [a_y, a_z, B_y, B_z]^T$, with B_y, B_z being the dipole field components at the device position calculated using eq 7. Furthermore, $\mathbf{w}_k$ is the measurement noise and $\mathbf{R}$ is the measurement covariance matrix eq 13

$$\mathbf{R} = \text{diag}(\sigma_{a_y}^2, \sigma_{a_z}^2, \sigma_{B_y}^2, \sigma_{B_z}^2) \quad (13)$$

where $\sigma_{a_y} = \sigma_{a_z} = 0.02$ ms⁻² are the accelerometer standard deviations and $\sigma_{B_y} = \sigma_{B_z} = 1 \times 10^{-6}$ T are the standard deviations of the magnetic-field measurements along the y and z axes, respectively. The estimator is initialized with the state mean $\mathbf{x}_0 = [0.3 \text{ m}, 0, 0, 0, 0]^T$, corresponding to the known starting point on the reference circle (radius 0.3 m) with zero initial velocity and acceleration and with the diagonal initial covariance $\mathbf{P}_0 = 0.2\mathbf{I}_6$. A substantial portion of the accelerometer noise originates from the stepper motors of the robotic test platform, which inject noticeable disturbances into the inertial signal. Nevertheless, as shown in Figure 2, using the synthetic beacon, the unscented Kalman filter reconstructs the circular reference path with a mean position error in the centimeter range. After an initial transient, likely due to the spin-up of the robot motion, the estimated

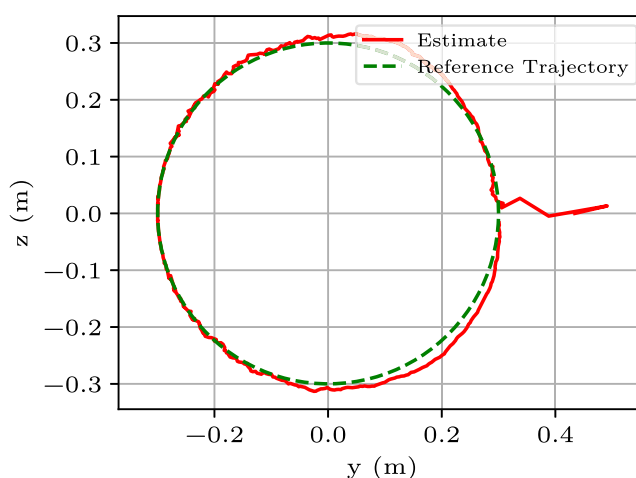


Figure 2. Estimated trajectory (red) in comparison with the reference trajectory (green dashed).

trajectory follows the 0.6 m-diameter reference circle, with a mean position error of 11.5 mm over the full revolution.

The results provide a first estimator-level indication that external magnetic landmarks could help constrain IMU drift. Tracking Lagrangian devices in a chemical reactor will, however, introduce additional complications that are beyond the scope of the present paper. In recent work, we demonstrated that fusing acceleration data with readings of a magnetic field produced by external beacons enables reconstruction of the trajectories of synthetic Lagrangian devices in the flow field of a lab-scale stirred tank reactor with reasonable accuracy.²⁷ That study also discusses further obstacles, e.g. the need for knowledge of the reactor flow field from experiments or computational modeling using tools such as CFD or rCFD, as well as challenges from magnetic reactor vessels.

HARDWARE ARCHITECTURE AND BASELINE POWER

The V1 platform integrates an IMU (ICM-20948) and an MCU (MAX32660) on a high-density interconnect PCB with microvia-in-pad routing. The previously reported PCB dimensions are 7.5 mm × 7.4 mm × 2.6 mm.²⁸ V1 served as an integration testbed for firmware development, timing verification, and a first proof-of-feasibility study of optical data transmission.

Figure 3 summarizes the V1 architecture. The IMU provides FIFO-buffered inertial data and a watermark interrupt to wake the MCU from deep sleep. This event-driven architecture avoids the need for a continuously running high-accuracy timing source at the system level. A buffered power domain supports short high-current events, such as LED transmission bursts, without requiring a continuously high supply current. The TLV733P low-dropout regulator (LDO) provides a stable 1.8 V rail for the IMU, MCU, and I²C bus, while helping to decouple LED current peaks from the supply.

In the previously published V1 demonstrator, the firmware was operated without duty cycling; under this continuous operating mode, including transmission activity, the platform showed an RMS current consumption on the order of 12.6 mA.²⁸ Such current levels are incompatible with long-duration operation from miniature energy-storage elements and exceed what is realistic for batteryless harvesting in typical reactor

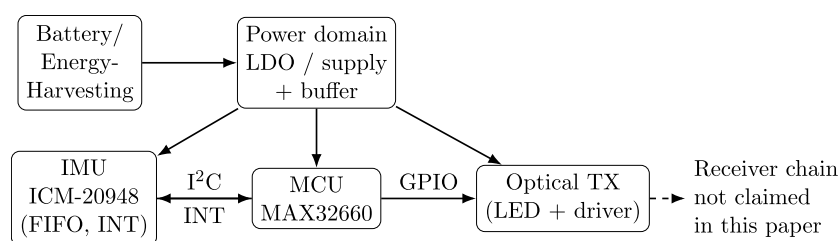


Figure 3. V1 hardware block diagram (conceptual). The IMU FIFO and watermark interrupt enable event-driven wake-ups of the MCU for duty-cycled operation.

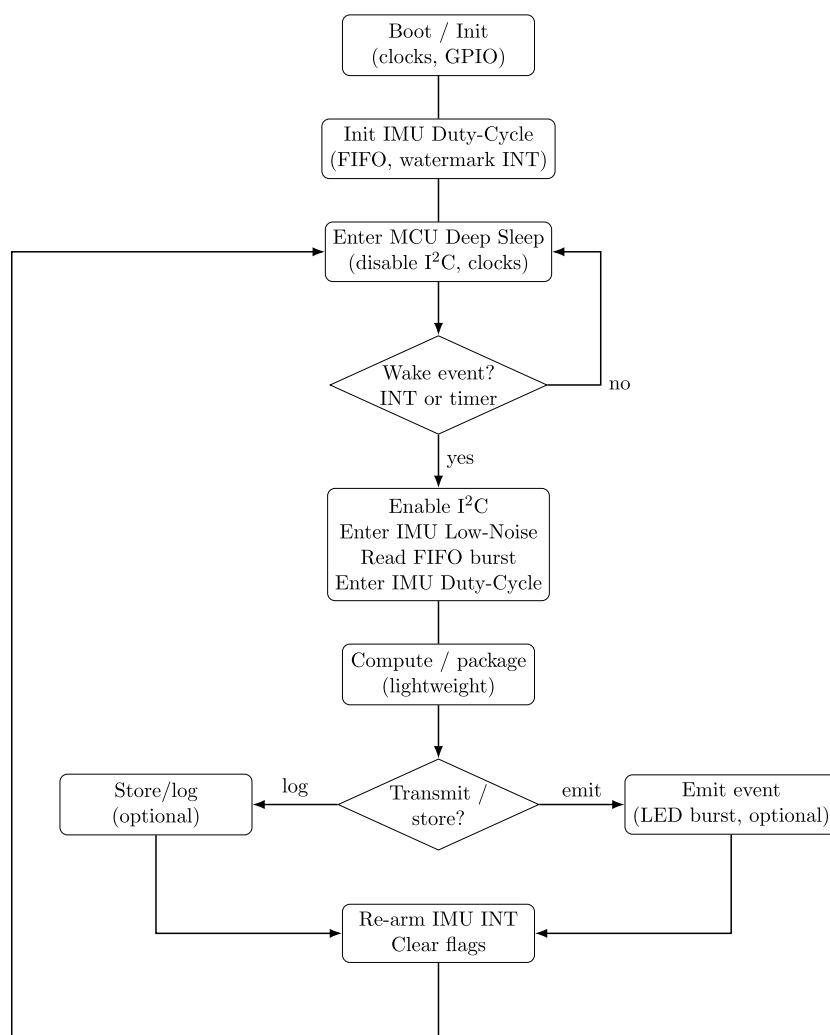


Figure 4. Low-power firmware flow (conceptual). The IMU runs in a reduced-power mode and wakes the MCU via FIFO watermark interrupt; the MCU performs short burst activity and returns to deep sleep.

environments. Even with a miniature primary cell, for example a silver-oxide coin cell in the sub-10 mm class, sustained multimilliamperes operation would rapidly deplete the available capacity and is often further limited by peak current capability and internal resistance.¹⁴ Therefore, V1 is operated in a duty-cycled regime in which the IMU provides low-power motion monitoring and wakes the MCU only when sufficient data have accumulated in the FIFO or when a timer-based maintenance task is required.

Low-Power Firmware Concept

The low-power strategy follows an event-driven pattern: the MCU remains in deep sleep with most peripherals disabled,

while the IMU operates in a reduced-power measurement mode and accumulates samples in its FIFO. Once a programmable FIFO watermark is reached, the IMU asserts an interrupt to wake the MCU. The MCU then performs a short acquisition and bookkeeping phase, optionally triggers a transmission or indicator event, and returns to deep sleep.

Figure 4 shows the firmware flow used as the basis for power minimization. In this operating mode, the electrical load is dominated by short active phases, while the quiescent intervals are determined by the deep-sleep current and low-power sensing mode of the IMU. As a result, the average energy demand depends primarily on the wake-up interval, the

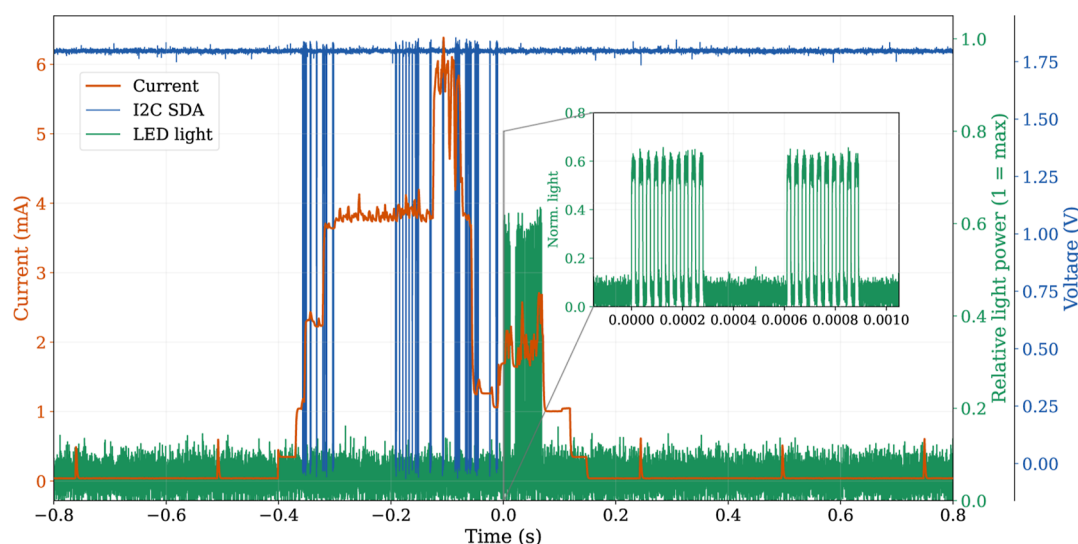


Figure 5. Aligned current-consumption trace, digital communication activity, and optical transmission signal for the V1 platform.

number of FIFO samples processed per burst and whether a transmission event is triggered. In the current implementation, one active measurement-and-transmission event lasts approximately 549 ms. Executing such events back-to-back would correspond to an upper-bound sample rate of about 1.82 Hz. Inserting sleep intervals for energy saving lowers the effective sample rate, see the discussion of cycle-energy analysis below. As shown in Figure 5, the optical link used in the demonstrator employs a carrier near 34 kHz and an active bit interval of the order of 300 μ s. If each interval is interpreted as one transmitted bit, this corresponds to a raw bit rate of around 3.3 kbit s⁻¹ before accounting for framing overhead and implementation-specific gaps between bursts.

In order to minimize firmware and decoding overhead, the transmission deliberately follows a very simple custom framing scheme rather than a more elaborate line code such as Manchester coding. Four training bits are transmitted to support receiver clock synchronization, followed by an ID field, the payload bits, and a checksum. The payload currently contains time information as well as accelerometer, gyroscope, magnetometer, and temperature data. This allows the receiver to synchronize to the sensor sphere and to perform a basic plausibility check on packet completeness. More advanced coding schemes, for example Hamming coding, could improve robustness and permit bit-error correction, but only at the expense of additional transmitted bits and therefore higher transmission energy.

Scope-Limited Communication Options and Practical Constraints

This manuscript does not present a complete wireless receiver chain. Nevertheless, communication choices strongly impact the power budget and infrastructure requirements in liquid-filled, metal-walled reactors. Table 3 summarizes three realistic options for millimeter-scale mobile nodes and is intended as a qualitative design-level comparison rather than a benchmark study. It highlights why this work prioritizes energy subsystem validation before end-to-end communication benchmarking.

For optical links in scattering or turbid liquid environments, line-of-sight conditions, alignment, and particle-induced fading are central practical constraints.²⁹ For sub-1 GHz active radios, typical TX/RX currents can be taken directly from transceiver

datasheets like CC1101-class devices and should be translated into energy per message using $E = VIt$.^{30,31} For the fundamental limitation of mm-scale far-field RF energy harvesting and the general RF EH landscape, see established reviews.³² For 13.56 MHz coil behavior near metal and tuning sensitivity, see NFC antenna design/matching guidance and published studies on metal proximity effects.^{33,34}

V2 Reduced-Footprint Design Concept

V2 targets a reduced footprint to increase encapsulation margin and to allocate perimeter area for distributed photodiodes for photovoltaic harvesting or for receiver coils for near-field inductive coupling. Key architectural changes relative to V1 are (i) redistribution of power conditioning components, including the LDO and capacitors, to reduce local congestion and enable a smaller core footprint; (ii) minimization of the LED driver circuitry and addition of a secondary LED option for flexible optical experiments; and (iii) a two-PCB architecture with the outer faces reserved for photodiodes or coils. A glass interposer is used to ensure robust alignment and interconnection between the two boards, enabling higher routing density while keeping the external surfaces available for energy interfaces. In V2, the IMU and MCU are placed on separate PCBs that are aligned and interconnected through the interposer. This arrangement frees the outer surfaces for energy-harvesting structures while maintaining electrical interconnection between the sensing and processing subsystems via I²C. The power-conditioning network was redistributed to reduce routing congestion and to support a smaller central footprint. In addition, the optical transmitter circuitry was simplified by selecting highly compact components, including the TCR5RG18ALF LDO, the PMX100UNEZ transistor, the LAUB0712FP1 LED, and a compact current-limiting resistor. Figure 6 shows micrographs of the assembled inner faces and the interposer. The stacked configuration keeps the LED near the center while distributing test pads, passive components, and buffer capacitors around the perimeter. With PCB thicknesses of approximately 400 μ m each, the assembled stack reaches a total height of about 2.7 mm, which enables integration into a sphere with a diameter of about 6 mm, as illustrated in Figure 7.

Table 3. Qualitative Comparison of Practical Data-Egress Options for Millimeter-Scale Mobile Sensor Nodes in Reactor-Like Environments^a

option	what it provides	power/energy implications	reactor constraints (liquid + metal)	integration burden
optical TX (LED) + external photoreceiver	node emits light bursts to an external photoreceiver	TX can be energy-decoupled and triggered only when buffer energy is available	needs optical access and is sensitive to turbidity, bubbles, and geometry. Metal walls are less problematic than blocked line of sight	low on-node complexity; external optics and receiver characterization required
sub-1 GHz RF (e.g., 433 MHz) active TX/RX	bidirectional communication without line of sight	RX/TX currents are typically in the 10 mA–100 mA range and can dominate the energy budget	mm-scale antennas perform poorly in liquids; metal vessels attenuate and detune the link. Far-field RF powering is impractical	high RF and firmware complexity
13.56 MHz near-field (NFC-like)	can combine powering and data when coupling is present	near-field coupling can provide useable power, but operation depends on field presence and coil tuning	metal and conductive media degrade coupling and shift resonance; mitigation often needs ferrite and careful tuning	requires coil, matching, rectifier, and modulation/demodulation infrastructure

^aValues are Indicative.

Encapsulation Route

To move from a planar electronics demonstrator toward a deployable sensor sphere, the electronics must be integrated into a chemically robust encapsulation. In the present approach, fused silica is structured by selective laser-induced etching (SLE), a two-step subtractive 3D microfabrication process for transparent materials.^{35,36}

In a first step, the fused silica is locally modified using LightFab's 3D printer (LightFab GmbH, Aachen, Germany) and a highly focused femtosecond laser. The localized multiphoton absorption produces nanograting-like modified regions within the written voxel while leaving the surrounding glass largely unaffected.³⁶ In the current process, the laser operates at a wavelength of 1030 nm, a repetition rate of 750 kHz, a pulse duration of 0.5 ps, a writing speed of 200 mm s⁻¹, and a pulse energy of 300 nJ.

In a second step, the written structure is etched in 8 mol L⁻¹ KOH at 82 °C in an ultrasonic bath. Under these conditions, the modified regions can be removed with a selectivity reported to reach up to about 1400 relative to the unmodified material, enabling precise subtractive structures with micrometer-scale resolution.³⁵ For the present sensor concept, this route is attractive because it enables the production of accurate glass components without the shrinkage and residual stress commonly associated with many additive manufacturing approaches. In the hardware stack shown in Figure 6c, the glass interposer already serves as a mechanically precise alignment and interconnection element between the two PCBs. The same fabrication route therefore provides the geometric basis for the spherical encapsulation concept shown in Figure 7, where the reduced-footprint V2 layout is designed to fit into a fused-silica sphere of about 6 mm diameter.

Initial mass measurements of encapsulated demonstrators also show that buoyancy-neutral operation will require deliberate density tuning. A fused-silica sphere with a diameter of 11 mm, containing PCB and battery, weighed about 1.1 g, which corresponds to an effective average density of approximately 1.58 g cm⁻³ if the overall geometry is spherical. A lithographically molded PDMS alternative with the same outer diameter reached about 0.891 g, corresponding to about 1.28 g cm⁻³. This approach, however, does not currently provide comparable structuring precision. For the reduced fused-silica concept at 6 mm diameter, the measured mass was about 0.167 g, corresponding to an effective average density of about 1.48 g cm⁻³. Since these values remain above the density of water-like media, additional internal void volume or other density-compensation features must be integrated if near neutral buoyancy is desired. The advantage of the SLE-based fused-silica route is that such voids and compensating cavities can still be fabricated with high geometric precision, allowing buoyancy adjustment to be treated as part of the encapsulation design rather than as an uncontrolled postprocessing step.

POWER CONSUMPTION AND ENERGY HARVESTING

A credible autonomy discussion requires an explicit energy budget tied to the actual operating cycle of the node. In the previously published V1 demonstrator, firmware operation without duty cycling, including transmission activity, resulted in an RMS current of approximately 12.6 mA.²⁸ Such current levels are incompatible with long-term operation from miniature storage elements and exceed what is realistic for

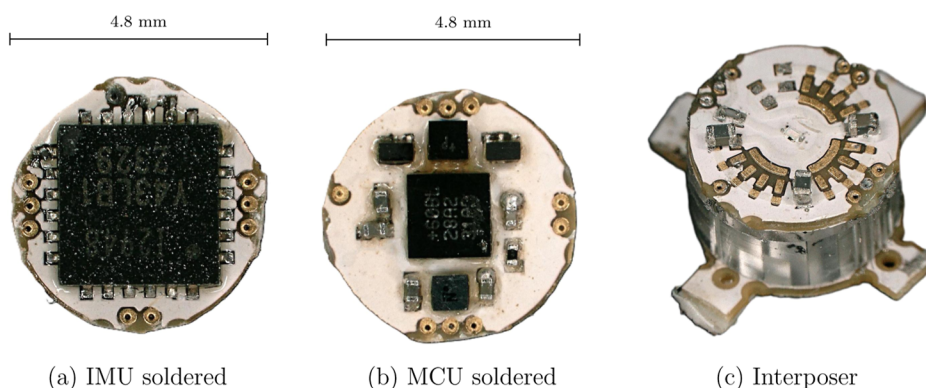


Figure 6. Assembly details of the reduced-footprint platform: (a) soldered IMU, (b) soldered MCU, (c) interposer component.

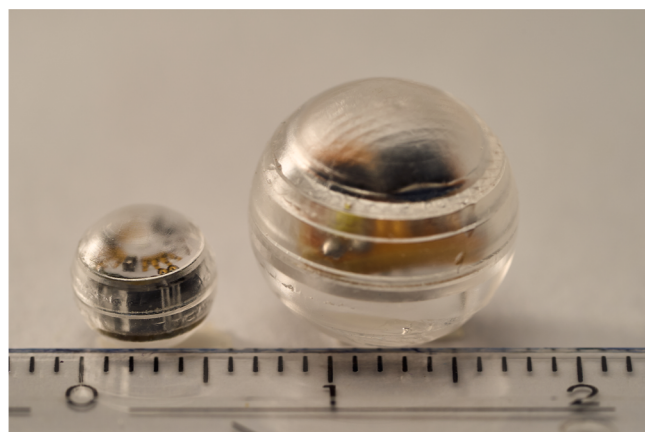


Figure 7. Comparison of the two platform generations. On the left, the V2 platform with a diameter of 6 mm is shown; on the right, the V1 platform with a diameter of 11 mm is shown. The reduced V2 footprint provides additional perimeter area for photodiodes or coils.

batteryless harvesting under the geometric constraints of millimeter-scale reactor probes. Therefore, the relevant question is not the continuous-operation current, but the charge and energy required by one duty-cycled measurement-and-transmission event.

In the present manuscript, the node is described by a generic cycle model consisting of a deep-sleep interval and a short active interval for sensing, processing, and optional transmission. The average cycle energy eq 14 can be written as

$$E_{\text{cycle}} = V_{\text{sys}}(I_{\text{act,avg}}t_{\text{act}} + I_{\text{sleep}}t_{\text{sleep}}) \quad (14)$$

where $I_{\text{act,avg}}$ is the average current during the active phase, t_{act} its duration, and I_{sleep} the quasi-static sleep current over the remaining interval t_{sleep} . For completeness, we additionally report the RMS current during the active phase eq 15

$$I_{\text{act,rms}} = \sqrt{\frac{1}{t_{\text{act}}} \int_0^{t_{\text{act}}} i^2(t) dt} \quad (15)$$

as a descriptor of the pulsed load profile. However, for the harvesting and buffer-dimensioning discussion below, the dominant quantities are average current and charge balance rather than the RMS value.

The charge drawn during one active event eq 16 is

$$Q_{\text{act}} = \int_0^{t_{\text{act}}} i(t) dt \approx I_{\text{act,avg}}t_{\text{act}} \quad (16)$$

and the total charge required for one complete cycle eq 17 is

$$Q_{\text{cycle}} = Q_{\text{act}} + I_{\text{sleep}}t_{\text{sleep}} \quad (17)$$

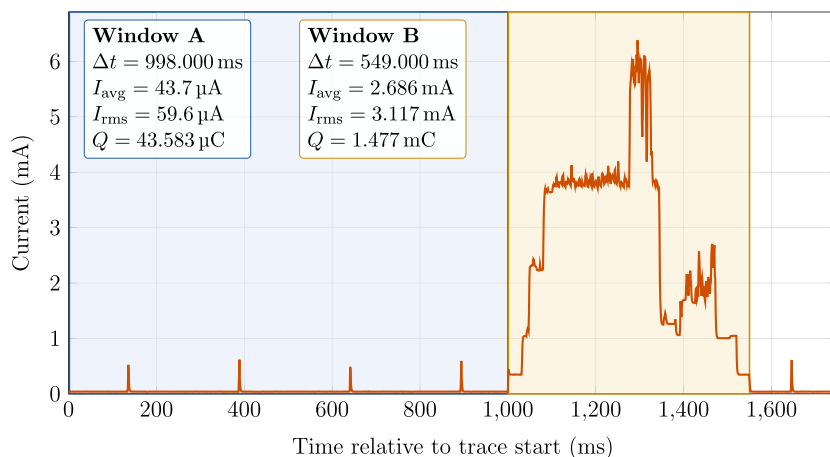


Figure 8. PPK2-based separation of the V1 current profile into a low-current pause interval and an active measurement/transmission interval. Window A provides the sleep-current estimate that is extrapolated to the 5s pause used in the cycle model, while Window B provides the active-event charge used in Table 4.

If a storage capacitor must provide this charge while allowing a maximum voltage droop of $\Delta V = 0.2$ V, the minimum required capacitance eq 18 follows from

$$C_{\text{req}} \geq \frac{Q_{\text{cycle}}}{\Delta V} \quad (18)$$

If only the active burst is to be buffered from the capacitor while the sleep interval is replenished by the harvester, the relevant lower bound eq 19 reduces to

$$C_{\text{req,act}} \geq \frac{Q_{\text{act}}}{\Delta V} \quad (19)$$

Using the presently measured values, extracted from Figure 8 and summarized in Table 4, $I_{\text{sleep}} = 43.7 \mu\text{A}$, $I_{\text{act,avg}} = 2.686$

Table 4. Measured Current and Charge Quantities Used for the V1 Cycle-Energy Model, Assuming One Measurement/Transmission Event after a 5s Pause

metric	symbol	value
deep-sleep current	I_{sleep}	43.7 μA
active-phase average current	$I_{\text{act,avg}}$	2.686 mA
active-phase RMS current	$I_{\text{act,rms}}$	3.117 mA
active duration	t_{act}	549 ms
sleep duration	t_{sleep}	5 s
charge per active event	Q_{act}	1.477 mC
charge per cycle	Q_{cycle}	1.696 mC
cycle-averaged current	$I_{\text{cycle,avg}}$	305.5 μA
cycle-averaged power at 3.1 V	$P_{\text{cycle,avg}}$	0.95 mW
required capacitance for active burst, $\Delta V = 0.2$ V	$C_{\text{req,act}}$	7.39 mF
required capacitance for full cycle, $\Delta V = 0.2$ V	C_{req}	8.48 mF

mA, $t_{\text{act}} = 549$ ms, and a representative sleep interval of $t_{\text{sleep}} = 5$ s, the charge drawn by the active measurement/transmission event eq 20 is

$$Q_{\text{act}} = 1.477 \text{ mC} \quad (20)$$

while the charge consumed during the preceding sleep interval eq 21 is

$$Q_{\text{sleep}} = I_{\text{sleep}} t_{\text{sleep}} = 218.5 \mu\text{C} \quad (21)$$

This yields a total charge demand eq 22 of

$$Q_{\text{cycle}} = Q_{\text{act}} + Q_{\text{sleep}} = 1.696 \text{ mC} \quad (22)$$

for a complete V1 cycle consisting of a 5s pause followed by one measurement/transmission event. The corresponding cycle duration eq 23 is

$$T_{\text{cycle}} = t_{\text{sleep}} + t_{\text{act}} = 5.549 \text{ s} \quad (23)$$

which leads to a cycle-averaged current eq 24 of

$$I_{\text{cycle,avg}} = \frac{Q_{\text{cycle}}}{T_{\text{cycle}}} \approx 305.5 \mu\text{A} \quad (24)$$

For a V1 supply based on two SR512SW silver-oxide button cells in series, a nominal system voltage of approximately 3.1 V can be assumed at a pack capacity of 5.5 mA h.³⁷ Under this assumption, the average cycle power eq 25 becomes

$$P_{\text{cycle,avg}} = V_{\text{sys}} I_{\text{cycle,avg}} \approx 0.95 \text{ mW} \quad (25)$$

and the energy per cycle eq 26 is

$$E_{\text{cycle}} = V_{\text{sys}} Q_{\text{cycle}} \approx 5.26 \text{ mJ} \quad (26)$$

If the battery pack were the only energy source, the resulting idealized runtime eq 27 would be approximately

$$t_{\text{bat}} = \frac{5.5 \text{ mAh}}{0.3055 \text{ mA}} \approx 18 \text{ h} \quad (27)$$

neglecting voltage conversion losses, pulse-load derating, and end-of-life constraints.

These numbers also define the target for the harvesters. To sustain repeated operation, the average harvested power must exceed roughly 0.95 mW over the full cycle. If recharge is intended primarily during the 5s pause, the required average recharge current rises to about 339 μA , corresponding to approximately 1.05 mW at 3.1 V. With an allowed storage-voltage droop of only 0.2 V, buffering the active burst alone eq 28 requires

$$C_{\text{req,act}} \geq \frac{Q_{\text{act}}}{\Delta V} \approx 7.39 \text{ mF} \quad (28)$$

whereas buffering the complete cycle charge eq 29 would require

$$C_{\text{req}} \geq \frac{Q_{\text{cycle}}}{\Delta V} \approx 8.48 \text{ mF} \quad (29)$$

Both values exceed the presently integrated storage of 18.8 μF per side by roughly 3 orders of magnitude. Consequently, the existing capacitor network is suitable only as a local smoothing and short-term buffering element, but not as a stand-alone energy reservoir for the full V1 measurement/transmission burst. These quantities define the energy target that any harvesting strategy must meet.

Photovoltaic Energy Harvesting

Photovoltaic harvesting is attractive for miniaturized sensor nodes because it converts incident light into electrical power without moving parts, galvanic contacts, or mechanically stressed interfaces. In low-power sensor systems, light harvesting is especially appealing when optical access already exists, when maintenance access is difficult, or when battery replacement is undesirable. Prior work on photovoltaic wireless sensor nodes under low illumination and feasibility studies for indoor-light harvesting both identify sensing and telemetry as natural target applications, while emphasizing that viability depends strongly on illumination level, duty cycle, and power-management overhead.^{23,38} Recent reviews on indoor and low-light photovoltaics further show that device selection and achievable efficiency under weak or spectrally narrow illumination differ fundamentally from conventional outdoor solar operation.²⁴

For SMART-reactor instrumentation, however, photovoltaic harvesting is not universally suitable. Its usefulness depends strongly on whether sufficient illumination can reliably reach the sensor node through the vessel wall and process medium. Optical attenuation by turbid liquids, bubbles, deposits, biofouling, geometric shadowing, and uncertain node orientation all reduce the harvestable power. Consequently, photovoltaic harvesting is most attractive in reactor concepts with deliberate optical access, transparent sections, short optical paths, or dedicated illumination infrastructure. It is less attractive in opaque vessels or highly scattering media, where the optical power required at the transmitter side may become system-dominant. In such cases, photovoltaic harvesting

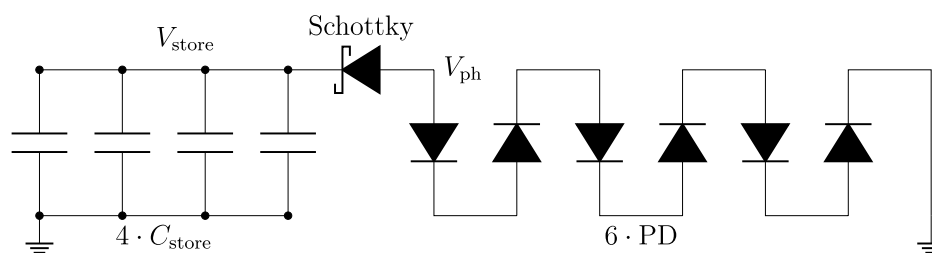
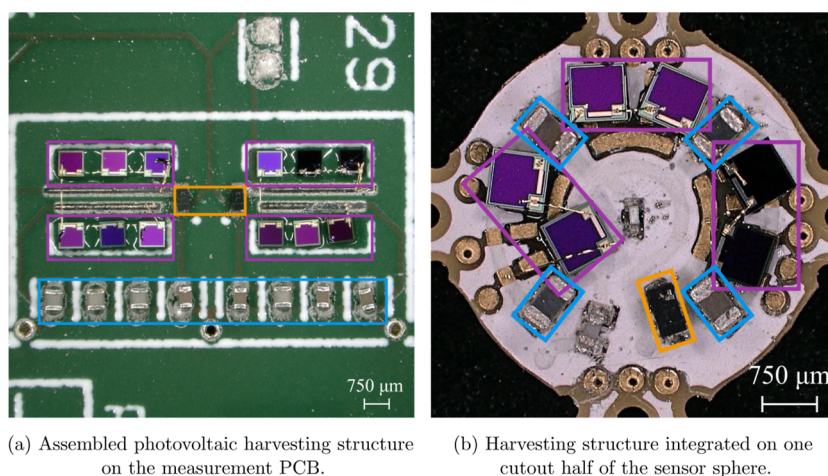


Figure 9. Simplified circuit representation of one photovoltaic harvesting branch. Six series-connected photodiodes provide the harvesting voltage, a Schottky diode blocks reverse discharge, and four capacitors in parallel provide local energy buffering.



(a) Assembled photovoltaic harvesting structure on the measurement PCB.

(b) Harvesting structure integrated on one cutout half of the sensor sphere.

Figure 10. Photovoltaic harvesting hardware used in this work. The side-by-side views illustrate both the measurement-platform implementation and the geometric integration on the sensor sphere. Purple highlights the photodiodes, orange the Schottky diodes, and blue the storage capacitances.

should be interpreted less as ambient scavenging and more as optically provisioned power delivery.

This distinction is important at the system level. The receiver-side implementation can remain compact, but the complexity may shift toward the external light source, alignment, and coverage of the vessel volume. In this sense, the present setup is closer to a deliberately engineered optical power link than to unconstrained ambient scavenging, which is consistent with the feasibility boundaries discussed in the indoor-light harvesting literature.^{24,38} For this reason, photovoltaic harvesting is discussed here primarily as a feasible complementary energy input for low-duty-cycle operation, not as a universally deployable route to energy autonomy.

System Topology. To evaluate this approach experimentally, a photodiode-based harvesting frontend was integrated on the sensor PCB. The implemented topology uses a total of 12 photodiodes, with six devices mounted on each side of the sensor platform. The selected photodiodes are LA PD28AP2 devices, which combine a sensitivity maximum at 570 nm with a compact outline of $720 \mu\text{m} \times 720 \mu\text{m} \times 280 \mu\text{m}$.³⁹ On each side, the six photodiodes are connected in series to obtain a sufficiently high output voltage for charging the local storage node, targeting an output in the range of approximately 3 V under illumination.

A blocking diode is placed in each branch to suppress reverse discharge of the storage capacitors through the photodiode string when illumination decreases or is absent. In the realized implementation, this function is provided by an NSR01L30MXT5G Schottky diode in an X3DFN2 package with an approximately $0.62 \text{ mm} \times 0.32 \text{ mm}$ footprint, i.e. in

the same miniaturized size class as 0603-metric passives.⁴⁰ Local energy buffering is provided by four GRM033R60J475ME05D capacitors of $4.7 \mu\text{F}$ per side, each in a 0201 (0603 metric) footprint.⁴¹ This distributed capacitor arrangement was selected mainly to fit the available PCB area while preserving local buffering close to the harvesting branches. The resulting topology is therefore a layout-constrained but electrically functional compromise between active area, obtainable voltage, and local storage capability.

Figure 9 shows a simplified circuit representation of one photovoltaic harvesting branch. The full sensor platform contains two such branches, one on each side of the particle.

Figure 10 summarizes the realized harvesting hardware, showing both the assembled characterization PCB and the harvesting structure integrated on one-half of the sensor sphere.

Harvesting Performance. The photovoltaic harvesting performance was characterized by load sweeps under different illumination powers and transmitter–receiver distances. For each operating point, the load voltage was measured and converted into received electrical power according to eq 30

$$P_{\text{load}} = \frac{V_{\text{load}}^2}{R_{\text{load}}} \quad (30)$$

From these measurements, the maximum received electrical power and the corresponding effective operating region of the photodiode array were extracted. One data set therefore resolves the load-dependent power transfer at a fixed distance of 5.0 cm for different LED drive conditions, while the second

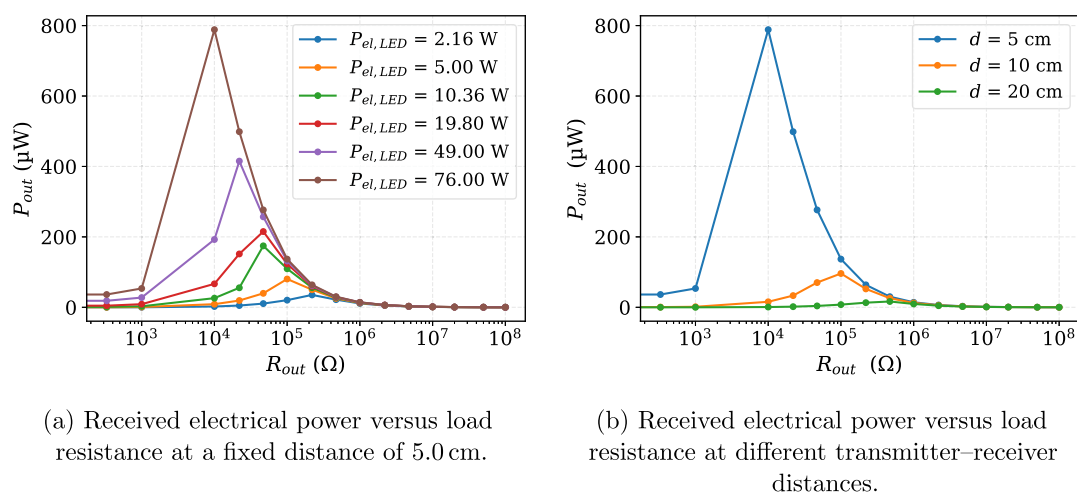


Figure 11. Photovoltaic harvesting measurements showing both the electrical load dependence and the geometric distance dependence of the received power.

resolves how the received power changes with separation distance at a fixed LED drive condition.

Rather than claiming a full optical-to-electrical conversion efficiency of the complete system, the present measurements characterize the electrical power that can be made available to the node under defined optical conditions. This distinction is important because the overall system performance depends not only on the photodiodes themselves, but also on optical coupling, source geometry, node orientation, and the charging behavior of the downstream storage network. Similar system-level dependencies on illumination level, storage design, and duty-cycled load management are also emphasized in prior photovoltaic sensor-node studies under low-light operation.^{23,38}

Figure 11 summarizes both aspects of the photovoltaic characterization. Panel (a) shows the received electrical power as a function of load resistance at a fixed transmitter–receiver distance of 5.0 cm. As expected, the optimum load is not fixed but shifts with illumination level and therefore with the operating point of the photodiode array. Panel (b) complements this view by showing how the achievable received power decreases with increasing transmitter–receiver distance at a fixed LED electrical drive condition. Together, these two measurements define both the preferred electrical operating region of the harvesting frontend and the geometric limits of the optical link.

This distance dependence is critical for feasibility in reactor applications. The employed high-power LED (Luminus CBT-90 G) is specified at a typical forward voltage of 3.1 V and a test current of 13.5 A, corresponding to an electrical input power of approximately 42 W, while the same datasheet reports a typical radiometric flux of only 5.5 W under those conditions.⁴² Even before propagation losses are considered, this implies that only a limited fraction of the electrical input is converted into useable optical output. At higher electrical loading, thermal management becomes even more critical, and sustained operation is expected to become less favorable. The LED datasheet also shows a broad angular intensity distribution rather than a tightly collimated beam; we therefore infer that only a fraction of the emitted optical power can be intercepted by the small harvesting area without additional optical concentration.⁴²

Taken together, the measurements suggest that this photovoltaic approach is most credible as a short-range, deliberately aligned power link. Practical deployment would likely require optical focusing or otherwise improved beam shaping, short distances, and controlled relative positioning between source and sensor. In realistic reactor installations, additional losses should be expected from refraction and reflection at each optical interface, including the LED-side window, the reactor wall, the liquid phase, and the encapsulation of the sensor sphere. Turbid liquids, bubbles, deposits, and changing sphere orientation would further reduce the effective coupling. This conclusion is in line with the broader literature, which consistently frames indoor and low-light photovoltaic harvesting as application-specific and strongly dependent on optical boundary conditions rather than as a universally available energy source.^{24,38} The photovoltaic route therefore appears best suited as a feasibility demonstration and as a possible niche solution for optically accessible reactors, rather than as a generally robust path to energy autonomy across arbitrary SMART-reactor conditions.

For the photovoltaic route, the present distance-dependent measurements indicate that the dominant limitation is geometric optical coupling rather than the photovoltaic conversion principle itself. With the current unfocused illumination geometry, only a small fraction of the emitted optical power can be intercepted by the millimeter-scale receiver area. Additional orientation- or liquid-environment tests using the same optical setup would therefore not yet constitute a meaningful closed autonomy validation, because the experiment would remain dominated by uncontrolled beam spread, reflection and refraction losses at optical interfaces, liquid attenuation, and sphere orientation. A more realistic next optical step is to improve the optical power path first, for example by beam shaping, optical concentration, Fresnel or lens-based focusing, or active illumination control that follows the expected sensor-sphere region. The photovoltaic route should therefore be understood as a possible niche solution for optically accessible reactors, but only after the optical coupling and illumination-control problem has been addressed.

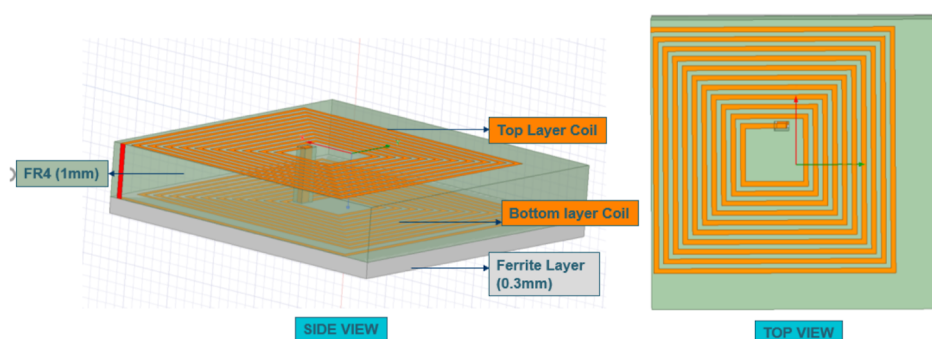


Figure 12. Design of the miniaturized PCB receiver coil for inductive energy harvesting at 13.56 MHz.

Inductive Energy Harvesting at 13.56 MHz

In addition to optical harvesting, inductive energy transfer at 13.56 MHz was investigated as a second candidate for powering miniaturized Lagrangian sensor nodes. In contrast to photovoltaic approaches, inductive coupling does not require optical access and is therefore attractive for opaque vessels, visually inaccessible environments, or applications in which illumination of the complete reactor volume would be impractical. Furthermore, low-frequency near-field coupling is substantially better aligned with the geometric constraints of millimeter-scale receivers than far-field RF harvesting, where the available antenna area becomes the dominant limitation. We therefore investigate resonant inductive transfer at 13.56 MHz as a practically relevant alternative for compact sensor spheres.

A key advantage of inductive transfer is that energy can be delivered contactlessly through nonmetallic vessel walls and liquid media, while the receiver can remain compact and structurally simple. At the same time, this approach is strongly dependent on coil geometry, resonance tuning, position, and orientation. The achievable received power is therefore not only a function of transmitter power, but also of the local magnetic field distribution inside the reactor volume and of the instantaneous alignment between transmitter and receiver coils. Experiments showed that measurable RF power can be coupled into a receiver coil in the 5 mm size class, but also revealed strong sensitivity to orientation and spatial location within the test volume.

The influence of the surrounding medium must be interpreted carefully. Since inductive transfer at 13.56 MHz is dominated by magnetic near fields, water does not automatically improve power transfer in a fundamental sense. However, the liquid environment can alter parasitic capacitances, detune resonant circuits, and modify the effective operating point of the coupled system. In the experiments, higher RF levels were observed in the water-filled setup than in the dry setup. These data indicate that the medium and packaging can significantly affect the resonant operating condition, but they do not yet isolate water as the sole cause of improved coupling. By contrast, increasing salinity consistently reduced the measured received RF power, which is plausible because higher conductivity leads to stronger induced losses in the surrounding medium.

Despite these advantages, several boundary conditions can severely complicate inductive powering in realistic reactor systems. Metallic vessels or nearby conductive structures can distort the magnetic field, introduce eddy-current losses, and reduce coupling efficiency. Likewise, strongly conductive

process media, large transfer distances, uncontrolled receiver orientation, and broad spatial distributions of mobile particles all reduce the amount of power that can be delivered reliably. Inductive transfer should therefore be understood as a promising, but geometry- and environment-dependent powering approach whose practical usefulness must be evaluated together with the reactor architecture.

System Topology. To evaluate the feasibility of inductive harvesting within the targeted size class, a PCB-based receiver coil was designed for operation at 13.56 MHz. The receiver geometry was constrained to approximately 5 mm and implemented as a multiturn planar spiral on a rigid PCB substrate. The design objective was to maximize inductance and unloaded quality factor while keeping the self-resonant frequency sufficiently above the intended operating frequency. In the associated characterization, the fabricated receiver exhibited an inductance of approximately $2.06 \mu\text{H}$, an unloaded quality factor of about 33, and a self-resonant frequency near 39 MHz, confirming that resonant operation at 13.56 MHz is feasible within this footprint.

A parallel tuning capacitor was added to resonate the coil at 13.56 MHz. For measurement purposes, the receiver was temporarily matched to a 50Ω source in order to verify the resonance condition and characterize the resonant tank behavior. This matching step was used for validation only; during actual wireless transfer, the receiver is excited magnetically by the transmitter coil and is therefore not operated as a conventional 50Ω RF port. The corresponding receiver layout and fabricated prototype are shown in Figures 12 and 13, respectively.

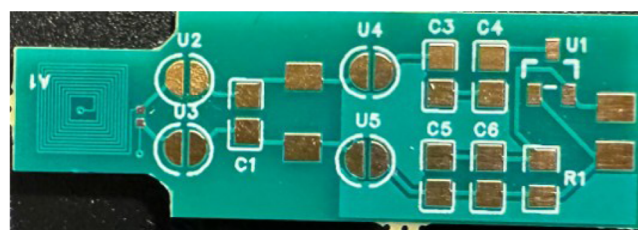


Figure 13. Fabricated receiver PCB with integrated coil, tuning network, and rectifier section.

The AC voltage induced in the receiver coil was converted into DC by a compact Dickson-type rectifier using Schottky diodes. This topology was selected because it can provide useful DC voltages with low component count, which is advantageous for miniature sensor nodes. In the demonstrator, a two-stage Dickson-inspired implementation with low-

capacitance RF components was used together with a local storage capacitor and resistive output loading for characterization. The rectifier and resonant receiver thus form a simple but representative frontend for evaluating whether inductively received RF power can be translated into useable electrical energy for a sensor node. The circuit schematic of the resonant receiver and rectifier is shown in Figure 14.

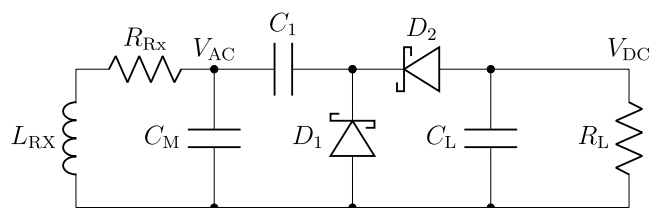


Figure 14. Simplified receiver-side equivalent topology comprising the resonant RX coil, parallel tuning capacitor, Dickson-type rectifier, storage capacitor, and resistive load.

On the transmitter side, a larger resonant excitation coil was wrapped around an acrylic cylindrical container used as a simplified reactor mock-up. This allowed first measurements of position dependence, orientation sensitivity, and medium influence under geometrical conditions more relevant than a point-to-point bench setup. The transmitter was driven from a signal generator through a power amplifier, and the transmit coil was tuned to 13.56 MHz. A photograph of the demonstrator is shown in Figure 15.

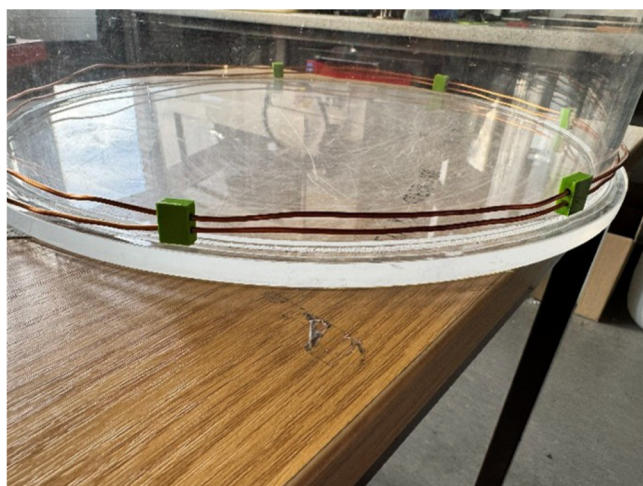


Figure 15. Inductive harvesting demonstrator with resonant transmitter coil wrapped around an acrylic cylindrical test vessel.

Harvesting Performance. The associated experiments provide an initial proof-of-principle characterization of inductive harvesting for reactor-scale deployment constraints. First, measurements without rectification showed that the received RF power depends strongly on the receiver position and orientation inside the cylindrical test volume. In the tested setup, a tilt angle of approximately 45° yielded the highest received RF power at many grid positions, while 90° generally produced the lowest values. This confirms that the transfer is not spatially uniform and that orientation statistics of freely moving particles are likely to be a major systems-level design constraint. The corresponding results are shown in Figure 16.

Second, the measured received RF power increased with increasing transmitter power while preserving the same qualitative spatial pattern. This indicates that the field structure inside the vessel remains largely unchanged, whereas the absolute received power scales with the applied excitation. Such measurements are useful for estimating the recharge time of a storage capacitor once the cycle-level charge demand of the sensor node is known. The corresponding data are shown in Figure 17.

Third, once the rectifier was connected, the harvested DC output showed a pronounced dependence on the electrical load. In the tested operating point without water, the highest measured DC output power was obtained at a load resistance of approximately 10 kΩ, where a value of about 114.5 μW was reported. This result identifies the best operating point within the tested load range, but it should not be interpreted as a fully optimized global maximum, since only a limited number of discrete load resistances were evaluated. Likewise, the reported RF-to-DC conversion efficiency of approximately 14% should be interpreted as an estimated value for this specific operating condition, not as a universal system efficiency. The measured DC output characteristics are shown in Figure 18.

For the inductive route, the present data also allow an order-of-magnitude assessment of the RF transfer loss in addition to the measured position, orientation, load, and medium dependence. The transmitter coil was tuned to 13.56 MHz and approximately matched to the 50 Ω amplifier output before the measurements. Since the RF power actually delivered to the transmitter coil inside the vessel was not independently calibrated with respect to reflected power, matching drift, and medium-induced detuning, we do not report a device-independent coupling efficiency. Instead, the received RF and DC powers are interpreted as apparent system-level transfer ratios relative to the nominal transmitter setting. At a nominal transmitter setting of 5 W, received RF powers in the mW range correspond to apparent TX-to-RX transfer ratios on the order of 10^{−4} to 10^{−3}, depending on receiver position, orientation, and medium. The representative maximum DC output power of 114.5 μW corresponds to an apparent TX-to-DC transfer ratio of approximately 2.3 × 10^{−5}, or 0.0023%, relative to the same nominal transmitter setting. These values should be interpreted as order-of-magnitude system indicators rather than calibrated link efficiencies. They nevertheless show that measurable inductive coupling into the receiver is achieved, while RF-to-DC conversion, load matching, storage, and regulation remain the limiting steps before a closed power budget with the sensor-node load can be demonstrated.

Finally, measurements with water and saline media indicated that the surrounding liquid substantially affects the received RF level. In the water-filled setup, higher RF amplitudes were observed than in the dry case, but this effect cannot yet be attributed to the liquid medium alone because packaging, retuning, and parasitic changes of the resonant receiver were not independently controlled. By contrast, increasing salinity consistently reduced the measured received RF power, which is qualitatively consistent with stronger conductive losses in the surrounding medium. Since these experiments quantified RF power before rectification only, they should be interpreted as medium-dependent coupling observations rather than as complete end-to-end harvested DC performance. These results are shown in Figures 19 and 20.

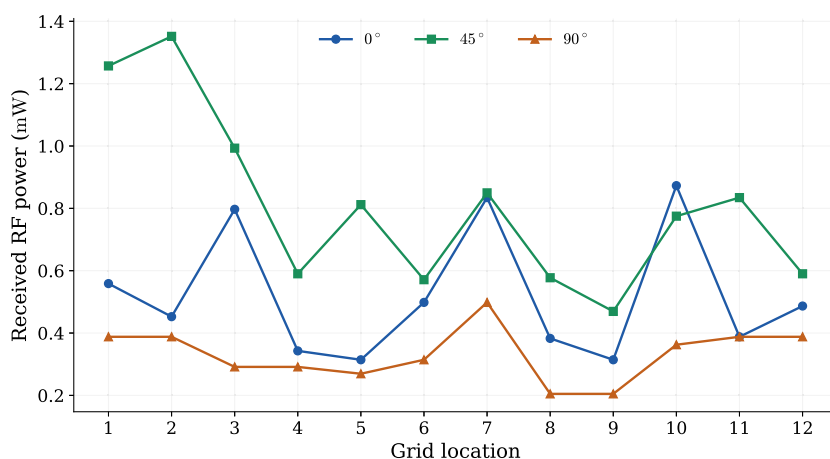


Figure 16. Measured received RF power as a function of grid position for different receiver tilt angles in the dry setup.

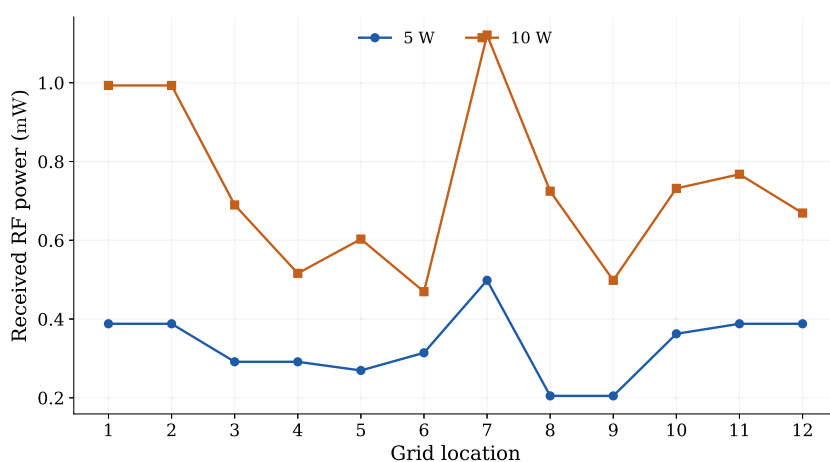


Figure 17. Measured received RF power at different transmitter power levels and grid positions.

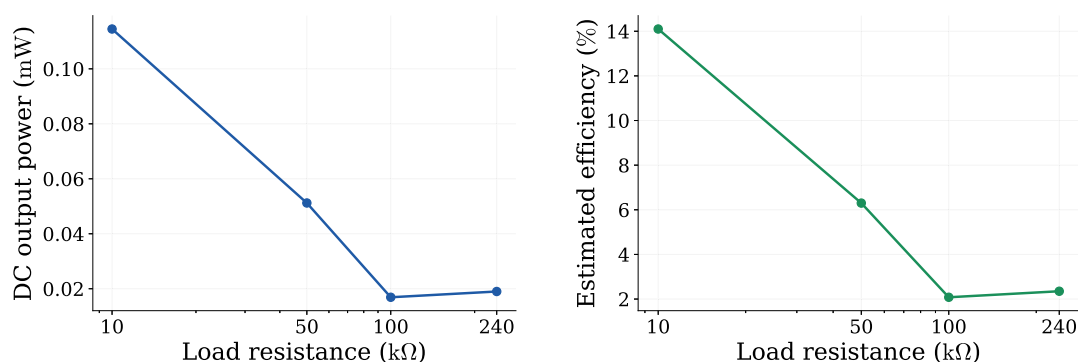


Figure 18. Measured DC output power and estimated RF-to-DC conversion efficiency versus load resistance for one representative operating point in the dry setup.

Overall, these results support the conclusion that inductive transfer at 13.56 MHz is a credible candidate for supplying intermittent power to miniaturized reactor nodes. Compared with the photovoltaic route, the inductive route is experimentally more mature in the present work because position, orientation, load dependence, and liquid-medium effects were explicitly characterized in a vessel-scale demonstrator. At the same time, the apparent transfer ratios and the cycle-energy model show that the present implementation does not yet close the full sensor-node power budget. The remaining gap is therefore no longer primarily the demon-

stration of coupling itself, but the improvement of rectifier efficiency, load matching, storage capacity, regulation, field uniformity, and spatial robustness of the transmitter architecture.

CONCLUSIONS AND OUTLOOK

This work set out to examine whether a millimeter-scale Lagrangian sensor sphere can be pushed from a functional demonstrator toward a platform that is at least plausibly compatible with future energy-autonomous operation in SMART-reactor environments. The main positive outcome is

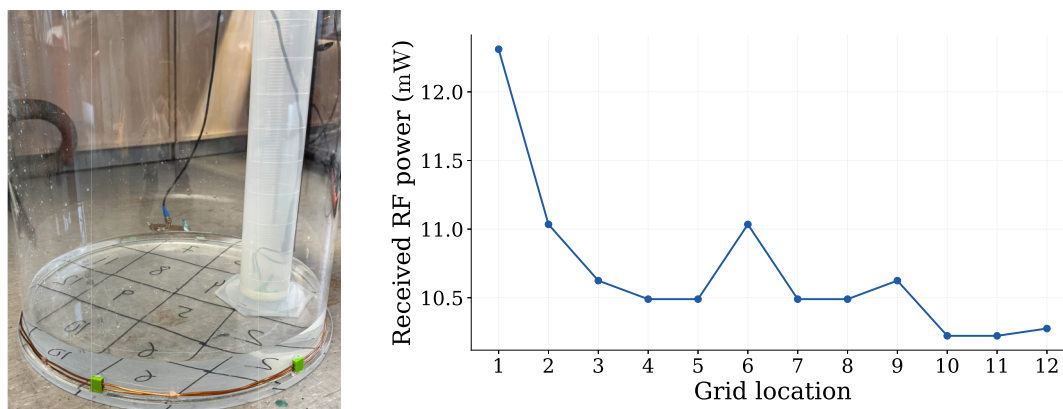


Figure 19. Measured received RF power in the water-filled setup at different grid positions.

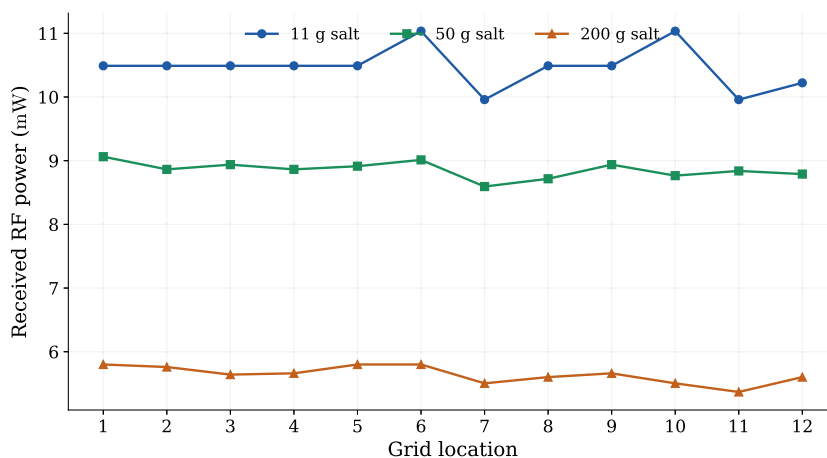


Figure 20. Measured received RF power for different added salt masses, illustrating the degradation of inductive coupling with increasing salinity.

Table 5. Integration Status of the Subsystems Addressed in This Work and Remaining Steps toward Reactor-Flow Validation

subsystem	status demonstrated in this work	remaining step toward reactor deployment
sensor-node electronics	V1 integrates IMU, MCU, power conditioning, and optical emission and was operated in a duty-cycled regime	further reduction of active-event charge and integration with a closed harvesting, storage, and regulation chain
reduced-footprint platform	V2 demonstrates the geometric scaling path toward a smaller spherical platform with outer surfaces reserved for energy interfaces	electrical validation of the full V2 stack and integration of harvesting structures on the final geometry
encapsulation	glass- and silicone-based spherical demonstrators were fabricated and evaluated geometrically and by mass	density compensation, neutral-buoyancy tuning, and long-term chemical/mechanical validation in process media
energy budget	the V1 duty-cycled current, charge, and energy demand were measured and used to define the load-side target for harvesting	verification of the final integrated power path under realistic duty cycles, including storage, regulation, and pulse-load behavior
photovoltaic energy input	a size-compatible photodiode frontend was characterized on dedicated evaluation hardware under controlled illumination	integration with the sensor-node power chain and validation under realistic optical access, distance, turbidity, and orientation constraints
inductive energy input	a 13.56 MHz receiver coil and rectifier were characterized on dedicated RF evaluation hardware, including position, orientation, load, and medium dependence	improved RF-to-DC efficiency, resonance control, field uniformity, and closed DC operation with the sensor-node load
localization and fluid-flow deployment	robotic-arm motion was used only as controlled excitation for preliminary estimator assessment	controlled stirred-tank or reactor-like flow experiments after closed integration of power, sensing, communication, and packaging

that the core system architecture is now technically credible at the targeted size scale. The V1 platform demonstrates that IMU, MCU, power conditioning, and an optical transmitter can be integrated on an HDI PCB and operated in a duty-cycled manner. The V2 concept shows a realistic geometric scaling path toward a smaller footprint that better supports spherical encapsulation and frees perimeter area for photodiodes or inductive structures. In addition, the present work establishes a fused-silica encapsulation route based on selective laser-induced etching, providing a packaging concept that is

chemically robust and geometrically compatible with the miniaturized electronics.

At the same time, the results also make clear that closed energy-autonomous operation has not yet been demonstrated. In the present work, the sensor-node electronics and the candidate energy-input routes are evaluated at different integration levels. The duty-cycled V1 platform provides the load-side reference: one active sensing, processing, and optical-emission event still requires a relatively large charge compared with what can presently be supplied by the separately evaluated harvesting frontends. Even in the duty-cycled regime, the

active event remains expensive because sensing, processing, and transmission are concentrated into a relatively long time window. The resulting active-event duration of about 549 ms corresponds to an upper-bound event rate of about 1.82 Hz if events were executed back-to-back. This may already be sufficient for selected slow process indicators, but it is restrictive for trajectory reconstruction and for resolving fast hydrodynamic fluctuations. Thus, energy consumption, temporal resolution, and the still-open integration of harvesting, storage, regulation, and sensor-node operation remain tightly coupled system-level bottlenecks.

The integration status summarized in Table 5 is important for interpreting the harvesting results: the photovoltaic and inductive experiments should be understood as feasibility indicators for candidate energy-input routes, not as proof of imminent battery-free operation of the complete sensor sphere. The photovoltaic route works in principle and is experimentally straightforward to quantify, but in its current form it resembles a deliberately aligned optical power link more than a robust ambient source. Its usefulness is strongly constrained by optical access, beam spread, alignment, reactor geometry, and additional losses caused by windows, liquid phases, turbidity, and sphere orientation. Inductive transfer at 13.56 MHz appears more promising for practical reactor deployment because it does not rely on optical access and is geometrically better matched to compact receiver structures. However, the present measurements also show pronounced sensitivity to receiver orientation, spatial position, load condition, and conductive surroundings. The demonstrated RF-to-DC stage is therefore not yet efficient or robust enough to claim reliable energy-autonomous operation across realistic reactor conditions.

The most important remaining requirements for energy-autonomous sensor spheres are therefore clear. First, the active energy per measurement event must be reduced further, especially by shortening active phases, minimizing transmission overhead, and tightening the deep-sleep envelope. Second, the harvested energy must be converted, stored, and regulated more effectively. For the optical route, this points toward optical concentration, beam shaping, or active focusing to increase the fraction of emitted light intercepted by the small receiver area. For the inductive route, the priority is a substantially more efficient AC-to-DC frontend at 13.56 MHz, together with better resonance control, improved coil design, and transmitter geometries that produce a more spatially uniform field. Third, the power-management chain must be treated as a complete system, from harvester to buffer to regulated supply rail, rather than as isolated subsystem demonstrations. Finally, communication and localization must be codesigned with the power budget: low-complexity communication remains attractive, but the low effective sampling rate of the present node makes trajectory estimation difficult unless additional landmarks, priors, or intermittent high-information updates are introduced.

Taken together, the work does not yet demonstrate an energy-autonomous Lagrangian sensor sphere in a reactor-flow environment. It does, however, replace an implicit autonomy assumption with a measured integration boundary: the load-side demand of a miniaturized sensor node is quantified and directly compared with size-compatible optical and inductive energy-input routes. This establishes the central bottleneck at the present maturity stage. The limiting question is no longer whether the individual elements can be miniaturized or

whether energy can be coupled into dedicated receivers, but whether active-event charge, harvesting efficiency, storage capacity, regulation losses, and spatial robustness can be closed in one integrated spherical system. In this sense, the contribution is a quantitative feasibility boundary and design target for future energy-autonomous Lagrangian sensor spheres.

■ ASSOCIATED CONTENT

Data Availability Statement

The data set Data for “Millimeter-Scale Lagrangian Sensor Spheres for Local State Monitoring in SMART Reactors: Toward Energy-Autonomous Operation” is available via TUHH Open Research (TORE): [10.15480/882.16934](https://doi.org/10.15480/882.16934). Hardware design files, sensor firmware, analysis scripts, and data underlying the figures and tables are provided there.

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Notes

The authors declare no competing financial interest.

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