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Original Paper

Applicability and safety review of Raman LiDAR standoff gas detection for hydrogen-fueled and hydrogen-carrier ships

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Abstract: The maritime sector is adopting hydrogen as a low-carbon fuel and cargo; however, its wide flammability range, very low ignition energy, and nearly invisible flames make leak detection more demanding than for liquefied natural gas (LNG). This study presents a regulation-based applicability and safety review of how a Raman LiDAR standoff gas-detection technique could complement onboard detection on hydrogen-fueled and hydrogen-carrier ships, using the established LNG fuel gas supply system (FGSS) hazardous-area and detection framework as the basis. International and domestic regulations, including the IMO IGC and IGF Codes, the interim recommendations for liquefied hydrogen carriage, the interim guidelines for hydrogen-fueled ships, classification-society rules, and the IEC 60079-29/-28 series, were reviewed, and hydrogen and methane properties were compared to derive detection requirements. The fixed-detection spaces of IGF 15.8.1 were mapped to candidate, supplementary Raman LiDAR arrangements, and a column-density-to-threshold conversion framework and a standards-conformity gap analysis were proposed. The analysis is conceptual rather than experimentally validated; CFD dispersion, line-of-sight and detection-time analyses, and standoff experiments are identified as essential future work. We conclude that Raman LiDAR should complement, not replace, mandated point detectors, with hydrogen-rescaled thresholds and a layered safety architecture.

Keywords: Hydrogen ship, Raman LiDAR, Standoff gas detection, Hazardous area, Fuel gas supply system

1. Introduction

International efforts to decarbonize shipping have accelerated the adoption of low- and zero-carbon fuels, among which hydrogen is regarded as a key long-term energy vector, used either as a marine fuel or carried as liquefied cargo **[1]**. However, hydrogen has a more demanding safety profile than liquefied natural gas (LNG). Its flammability range in air is far wider (approximately 4–75 vol%), its minimum ignition energy is approximately one-fifteenth that of methane, and its flame is almost invisible; therefore, leaks can ignite from weak sources and burn undetected **[2][3]**.

The onboard safety architecture for gas-fueled ships is built around hazardous-area classification and fixed gas detection, as codified in the IGF Code and elaborated in the design practice for LNG fuel gas supply systems (FGSS) **[4][5]**. This framework assumes that fixed-point detectors are installed inside enclosed spaces. For hydrogen, whose interim guidelines currently confine fuel systems mainly to the open deck and whose releases are buoyant and rapidly dispersing, point detectors alone leave spatial and path-related blind spots; indeed, computational studies of shipboard hydrogen leakage and dispersion show that detector siting must account for compartment geometry, ventilation, and even ship motion **[6]**.

Raman LiDAR is a standoff, open-path optical technique that identifies a gas species, its concentration, and its range remotely from the inelastic (Raman) scattering of a probe beam. This study reviews its application to hydrogen ships. The objectives are to (i) compare hydrogen and LNG properties relevant to detection, (ii) review the applicable regulations, (iii) assess the conceptual suitability of Raman LiDAR for hydrogen, (iv) map candidate sensor locations and criteria to the regulatory-required detection spaces, and (v) provide a safety review and a standards-

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conformity gap analysis. The intent is not to replace mandated detection, but to define a complementary standoff layer.

This study is positioned as a regulation-based applicability review rather than a validated design study. Its contributions are (i) consolidating the applicable regulatory framework and deriving hydrogen-specific detection requirements from fuel properties, (ii) mapping the fixed-detection spaces of IGF 15.8.1 to candidate, supplementary Raman LiDAR arrangements, (iii) proposing a column-density-to-threshold conversion framework for an open-path alarm, and (iv) identifying standards-conformity gaps. Quantitative computational fluid dynamics (CFD) dispersion modeling, line-of-sight (LOS) and detection-time analysis, systematic risk assessment, and experimental standoff validation are beyond the present scope and are identified as essential future work (Section 6.4).

2. Hydrogen versus LNG for Detection

The safety-design skeletons of hydrogen and LNG ships largely coincide: both fuels are buoyant once warmed to ambient temperature (hydrogen at all temperatures, and methane above approximately −110 °C) and accumulate at high points and openings, both require cryogenic storage with cold-hazard and double-barrier considerations, and both rely on forced ventilation, fixed gas detection, and emergency shutdown (ESD) interlocks. The hazardous-area logic (Zone 0/1/2) and the IGF 15.8 detection framework therefore apply structurally to hydrogen. Nevertheless, several property differences, summarized in **Table 1**, drive stronger requirements for sensitivity, response, and spatial coverage.

Notably, released liquefied hydrogen forms a cold plume that travels downwind and may flash back to the vent from distant ignition sources before it is diluted below 4 vol%, a hazard explicitly identified in the interim recommendations **[2][7]**. This is a spatial, path-related hazard that local point detectors cannot readily capture, thereby motivating remote, area-based sensing. Moreover, hydrogen's wide flammability envelope motivates fire-prevention measures such as nitrogen inerting, for which the limit-oxygen-concentration criteria of hydrogen-methane blends under leakage-representative strain conditions have recently been quantified for nitrogen-inerted marine compartments **[8]**.

Table 1: Safety- and detection-relevant properties of hydrogen and methane (LNG).

Property	Hydrogen	Methane/LNG	Implication
Flammability (vol%)	4–75	5–15	Wide-range monitoring
Detonation (vol%)	~18–59	~6.3–14	Early standoff alarm
Min. ignition energy	~0.017 mJ	~0.28 mJ	Strict ignition control
20% / 40% LEL	0.8 / 1.6 vol%	1.0 / 2.0 vol%	Rescale thresholds
Buoyancy / diffusion	Very high	High	Fast plumes; area view
Flame visibility	Nearly invisible	Visible	UV/IR flame detection
Liquid temp. (1 atm)	−253 °C	−162 °C	Cold plume; O_2 enrichment

3. Regulatory Framework

3.1 IMO Instruments

The regulatory basis depends on ship type. Liquefied hydrogen carriers follow the IGC Code, supplemented by the interim recommendations for the carriage of liquefied hydrogen in bulk, first adopted as Resolution MSC.420(97) (2016) and subsequently revised as Resolution MSC.565(108), adopted at MSC 108 on 24 May 2024. At MSC 111, these recommendations were consolidated and superseded by Resolution MSC.597(111), adopted on 18 May 2026, which revoked MSC.565(108) and introduced a new Part D for membrane-type cargo containment systems with insulation spaces maintained under vacuum **[2][7][9][10]**. These require flammable (F) vapor detection and closed (C) gauging for hydrogen; hydrogen-suitable flame detectors with voting logic to prevent false ESD; and fixed and portable hydrogen detection in cargo holds and pump rooms, and at vent masts.

Hydrogen-fueled ships follow the IGF Code, together with the Interim Guidelines for the Safety of Ships Using Hydrogen as Fuel, finalized at CCC 11 (2025) and approved at MSC 111 (2026) **[3][4]**. These goal-based guidelines currently prioritize compressed and liquefied hydrogen on the open deck, deferring enclosed-space arrangements. Consequently, hydrogen fuel systems are concentrated on the open deck, which directly shapes the sensor-placement strategy presented in Section 5.

3.2 Class and domestic standards

Classification societies specify these instruments in their own rules for gas-fueled and low-flashpoint-fuel ships and for

liquefied hydrogen carriers **[11][12][13]**. In Korea, the Korean Register (KR) has developed liquefied-hydrogen-carrier requirements and marine fuel-cell guidance, whereas the Ministry of Oceans and Fisheries (MOF) has issued an interim standard for shipboard hydrogen fuel-cell installations **[13][14]**. Where the IGF Code is silent regarding a space, such as enclosed or semi-enclosed bunkering stations, class rules may still explicitly require detection; therefore, both must be applied together.

3.3 Detection Performance Standards

Shipboard detection performance is governed by IGF 15.8 and the IEC 60079-29 series. The general requirements and test methods for gas-detection equipment—previously distributed across IEC 60079-29-1 (point detectors) and IEC 60079-29-4 (open-path, line-of-sight detectors)—have been consolidated in IEC 60079-29-0:2025, which is now the current general standard and explicitly covers open-path systems; the earlier parts therefore inform, rather than constitute, the latest framework **[15][16][17][18]**. A key distinction is that IGF thresholds are defined for point detectors measuring the local concentration (vol%), whereas an open-path device, including Raman LiDAR, measures the path-integrated (column) concentration in LEL·m units. In addition, because the proposed arrangement directs a 532 nm laser beam into hazardous areas, the optical-radiation ignition requirements of IEC 60079-28:2025 (equipment and transmission systems using optical radiation) apply, and the applicable inherently-safe-optical-radiation limits and any exemptions must be examined **[19]**. These standards define the performance-verification frame for Raman LiDAR and are revisited in Section 6.

4. Raman LiDAR for hydrogen

4.1 Principle and Suitability

In Raman LiDAR, a probe beam undergoes inelastic scattering from gas molecules, shifting in wavelength by molecule-specific vibrational or rotational energy, while the returned spectrum and time-of-flight yield species, concentration, and range simultaneously and remotely. Recent Raman-LiDAR hydrogen-detection studies have progressed from laboratory experiments toward field applications; **Table 2** summarizes the performance indicators, including the limit of detection (LOD), of representative studies **[20][21]**.

Table 2: Raman LiDAR-based hydrogen-detection research.

Study	Method	Laser	LOD	Eff. range / env.
Shiina (2018)	DPSS Compact Raman LiDAR	532 nm	1 vol%	50 m; indoor/outdoor
Shiina (2018)	LED Mini Raman LiDAR	532 nm	1 vol%	20 m; indoor/outdoor
Melison *et al.* (2025)	Non-dispersive Raman	532 nm	125 ppm	Short range; indoor

The ppm-level sensitivity was, however, obtained by Melison et al. with a short-range laboratory Raman system using a pressurized gas cell, not with a standoff Raman LiDAR; the mini-Raman LiDARs of Shiina demonstrated a 1 vol% detection limit at ranges of 20–50 m. This 125 ppm value therefore indicates intrinsic spectroscopic capability and an apparent margin relative to the 20% LEL hydrogen alarm threshold (0.8 vol% = 8,000 ppm), but it cannot be directly generalized to long-range shipboard detection; the effective standoff range, signal-to-noise ratio, and response time remain to be demonstrated for outdoor and marine conditions.

Hydrogen is especially favorable: its vibrational Raman Q-branch shift (approximately 4155 cm^{-1}) is clearly separated from those of nitrogen (2331 cm^{-1}), oxygen (1556 cm^{-1}), water vapor (approximately 3652 cm^{-1}), and methane (2917 cm^{-1}); therefore, spectral interference is effectively absent, and its strong pure-rotational lines allow multi-line confirmation. Thus, hydrogen is in principle a favorable target for species-specific, low-cross-sensitivity standoff detection, which offsets the cross-sensitivity and response lag of conventional catalytic or electrochemical point sensors for colorless, odorless gases.

4.2 Complementarity with Point Detectors

A point detector reports only the concentration at its own location. When the leak point and the detector are offset, or when buoyant plumes move quickly through open or semi-enclosed spaces, dead zones arise, and hydrogen aggravates this.

The rationale for considering Raman LiDAR among the available detection principles follows from these limitations, as summarized in **Table 3**. Catalytic and electrochemical point sensors require direct contact and exhibit cross-sensitivity and finite recovery times; thermal-conductivity sensors are insensitive at low

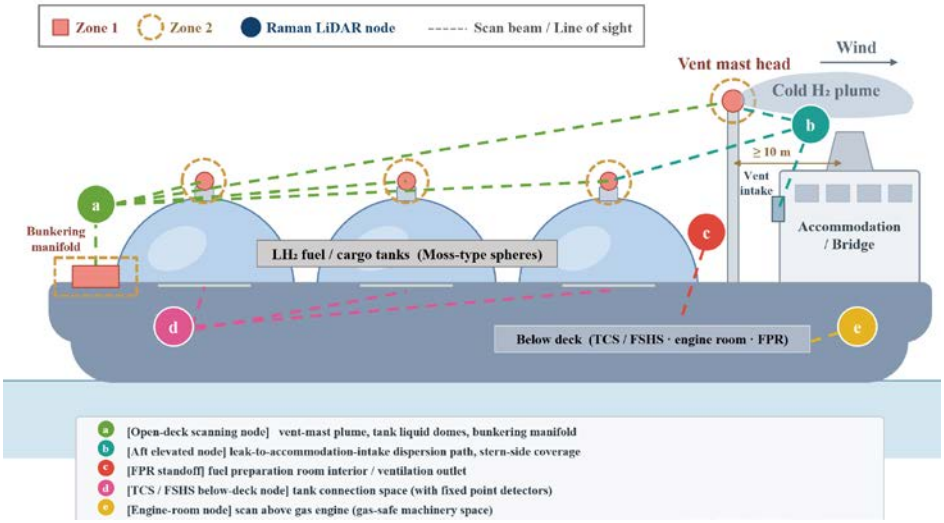

Figure 1: Conceptual arrangement of Raman LiDAR standoff detection nodes (a–e) on a liquefied-hydrogen ship (authors' schematic)

Table 3: Comparison of hydrogen gas-detection technologies

Technology	Type	Range	Response	Remote	Remarks
Electrochemical	Contact	0–4 vol%	20–100 s	No	Recovery time
Catalytic	Contact	0–4 vol%	<30 s	No	Direct contact
Thermal conductivity	Contact	1–100 vol%	–	No	Low-conc. blind
TDLAS (optical)	Non-contact	ppm level	<1 s	Yes	No H_2 IR absorption
Raman LiDAR (optical)	Non-contact	125 ppm–100 vol%	10–600 s	Yes	Area / plume tracking

concentrations; and tunable diode laser absorption spectroscopy (TDLAS), the principal optical open-path method for hydrocarbons, is ineffective for hydrogen because hydrogen is a homonuclear diatomic molecule with no permanent dipole and hence negligible infrared absorption **[21][22]**. Raman scattering is therefore one of the few optical approaches capable of remote, species-specific hydrogen detection. **Table 3** summarizes these technologies and their suitability for shipboard hydrogen service. A single Raman LiDAR head can scan a wide volume and locate hydrogen remotely, covering open decks, large spaces, and inaccessible positions (vent-mast head, tank domes, bunkering manifolds, pipe racks) that are impractical to cover with point detectors. The recommended posture is layered: retain all mandated point detectors, and add Raman LiDAR for (a) open-deck remote release and plume monitoring, (b) dispersion-path surveillance toward ignition sources and accommodation intakes, and (c) scanning of high or large, hard-to-access spaces.

5. Sensor Placement and Criteria

This section maps Raman LiDAR to the required-detection spaces, using the hazardous-area and detection provisions of the IGF Code as the basis **[4]**. **Figure 1** shows the authors' conceptual arrangement based on an open-deck (X-DF/ME-GI) FGSS layout.

5.1 Mapping to IGF 15.8.1 Spaces

IGF 15.8.1 lists ten spaces requiring fixed gas detection. **Table 4** maps each to a candidate supplementary Raman LiDAR role. Small enclosed spaces and ducts are best served primarily by point detectors, whereas large spaces, open areas, and plume paths favor a complementary Raman LiDAR scan. All Raman LiDAR roles in **Table 4** are supplementary to the mandated point-detection required by the IGF Code; the LiDAR scan augments, but does not replace, the fixed point detectors in each space.

5.2 Open-Deck Priority Elements

5.2.1 Vent Mast Head

The vent-mast head height is at least B/3 or 6 m, with Zone 1 around the head and Zone 2 for a further 1.5 m. Hydrogen is released here as a cold plume that travels downwind and may flash

back before dilution below 4 vol%. Because the vent head is elevated, permanently open, and hard to access, it is poorly suited to point detectors. A Raman LiDAR at a safe deck position (node a in **Figure 1**) could, in principle, provide a remote indication of release onset and relative plume concentration along the line of sight; quantitative confirmation of the dilution distance to 4 vol% would require dispersion modeling and field calibration.

5.2.2 PRV and Separation Distances

The IGF Code requires at least 10 m between the pressure-relief valve (PRV; vent) discharge and air intakes, openings, accommodation, control spaces, and machinery exhaust. In principle, a standoff scan along the vent axis could provide an operational indication of whether the dispersing plume remains within the design separation envelope; quantitative verification would require CFD dispersion analysis and field calibration and is identified as future work.

5.2.3 Bunkering Station and Tank Domes

For an open-deck bunkering station, Zone 1 extends 3 m around manifolds, valves, and spillage coamings and up to 2.4 m above the deck; scanning the manifold volume could help detect coupling and flange leaks at connection. Enclosed or semi-enclosed stations are entirely Zone 1 and, per class rules, require point gas and low-temperature detection. Where a non-type-C tank is exposed on deck, Zone 1 extends 2.4 m from the surface and 3 m from the outlet; open-deck nodes can sequentially scan multiple tank domes to provide sequential spatial coverage (subject to scan-rate and line-of-sight constraints).

5.3 Hazardous-Zone Installation Principles

The optical-head location is governed by the explosion-protection class. Placing the head in a non-hazardous area or outside the Zone 2 boundary and aiming the beam into the hazardous zone is advantageous for certification and maintenance. Because the illuminated target is Zone 1, the optical-ignition risk of the source (wavelength, average power, beam divergence) must be assessed against IEC 60079-28:2025 **[19]**. Consistent with IGF 15.8.4, scan targets and lines of sight should pass through ventilation outlets and the expected accumulation (upper) regions.

6. Safety Review and Gap Analysis

6.1 Thresholds and Column Density

IGF 15.8.6 requires an audible and visual alarm at 20% LEL and a safety-system action at 40% LEL on two detectors. With a hydrogen LEL of 4 vol%, these correspond to 0.8 and 1.6 vol% (and 1.2 / 2.4 vol% for the 30% / 60% duct case); thresholds must be set for hydrogen. The core conformity issue is that the regulatory thresholds assume a local vol% from a point detector, whereas Raman LiDAR measures the path-integrated column density. Formally, a line-of-sight device measures the column density $N = \int c(x)\,dx$ over the path length L, whereas the IGF threshold is a local volume fraction c_{th} (e.g., 0.8 vol% at 20% LEL). Under the simplifying assumption of a uniform concentration over an illuminated plume segment of length ℓ, the reading maps to an equivalent local value $c_{eq} = N / \ell$, so that an equivalent-threshold alarm is raised when

$$N \geq c_{th} \cdot \ell \tag{1}$$

Because ℓ and the true profile c(x) are generally unknown, this conversion requires an assumed or independently estimated plume-segment length ℓ and site-specific calibration; it is therefore proposed here as a framework rather than a validated setting, and its experimental calibration is identified as future work (Section 6.4). A layered safety function is therefore recommended: Raman LiDAR provides wide-area early warning (alarm on exceedance of a column-density equivalent to 20% LEL), while the mandated 40% LEL two-detector automatic ESD and tank-valve closure are confirmed by certified point detectors using voting logic (for example, 2oo3).

6.2 Response, Redundancy, Spurious Shutdown

IGF 15.8.9 requires continuous detection without delay, and IGF 15.2.5 requires preventing spurious shutdown caused by a faulty detector or a wire break. Raman LiDAR achieves continuous detection through real-time range-resolved scanning, but a single head failure can create a wide gap. Therefore, overlapping fields of view from multiple nodes, optical-head self-diagnostics with fault output (per the functional-safety intent of the IEC 60079-29 series), and ESD determined by point-detector voting are needed so that a LiDAR misdetection does not directly trigger a false ESD, consistent with the flame-detector voting requirement for liquefied hydrogen carriers. Reliability-centered analyses of monitoring devices for liquefied-hydrogen ship systems

Table 5: Standards-conformity gaps and resolution directions

Gap	Resolution direction
Measurand mismatch	Column-density alarm + point-detector ESD; conversion/calibration protocol (Eq. 1)
Performance standard	Apply IEC 60079-29-0:2025 (general requirements/test methods, incl. open-path) with scattering-specific supplementary tests
Threshold rescaling	Document hydrogen settings (0.8 / 1.6 vol%)
Ex / optical safety	Zone-rated or non-hazardous head placement; optical-radiation ignition assessment per IEC 60079-28:2025
Reliability	FAT/sea trials, self-diagnostics, overlapping nodes
Validation	CFD dispersion, LOS/detection-time analysis, and systematic risk assessment (Section 6.4)
Domestic certification	Demonstration linked to KR and MOF interim standards

similarly emphasize failure-mode identification and diagnostic coverage as prerequisites for reliable detection **[23]**.

6.3 Gap Analysis

Table 5 summarizes the principal standards-conformity gaps identified in this review, together with the corresponding resolution directions.

6.4 Limitations and Future Work

This study is a regulation-based applicability review; **Figure 1** and **Tables 4**-**5** are conceptual proposals derived from the regulatory framework and reported device characteristics, not experimentally validated designs. Three limitations follow directly. First, the standoff detection performance (effective range, detection time, and limit of detection at 20–50 m) has not been demonstrated and is supported only by short-range laboratory data. Second, the column-density-to-threshold conversion (**Equation 1**) depends on an assumed plume-segment length and concentration profile and requires site-specific calibration. Third, the sensor placements and separation-distance recommendations have not been verified against quantitative leakage behavior. Accordingly, the following are identified as essential future work: (i) CFD modeling of representative hydrogen leakage and dispersion scenarios, building on validated shipboard dispersion models such as [6], to establish realistic plume geometries; (ii) line-of-sight and detection-time analysis for each candidate node against those scenarios; (iii) a systematic risk assessment (e.g., HAZID/HAZOP) linking detection coverage to ESD effectiveness; and (iv) standoff Raman LiDAR experiments with field and sea-trial calibration under marine conditions. These steps are required before the proposed arrangement can be adopted as a verified design.

7. Conclusion

This study presented a regulation-based applicability and safety review of Raman LiDAR standoff gas detection for hydrogen-fueled and hydrogen-carrier ships. The LNG FGSS hazardous-area and detection framework transfers structurally to hydrogen, and hydrogen's wide flammability, very low ignition energy, invisible flame, and open-deck-oriented arrangement make remote, area-based sensing attractive as a complement to mandated point detectors. Hydrogen's well-separated Raman shift makes it, in principle, a favorable target for species-specific standoff detection. On this basis, the study (i) mapped the IGF 15.8.1 detection spaces to candidate, supplementary Raman LiDAR roles, prioritizing the vent-mast plume and the leak-to-intake dispersion path; (ii) proposed hydrogen-rescaled thresholds and a layered architecture pairing column-density early warning with point-detector voting for automatic ESD; and (iii) identified standards-conformity gaps against IEC 60079-29-0:2025 and IEC 60079-28:2025. The contribution is therefore a conceptual applicability assessment and a research roadmap, not a validated design: the reported sensitivities are laboratory-scale, the alarm-conversion framework requires calibration, and CFD dispersion, line-of-sight/detection-time analysis, systematic risk assessment, and standoff experiments remain essential future work. As the IMO hydrogen instruments remain at the interim stage, the applicable class rules and the latest code revisions (including Resolution MSC.597(111)) should be confirmed at the design stage.

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Park; Resources, H. J. Kim; Data Curation H. S. Kim; Writing-Original Draft Preparation, B. J. Park; Writing-Review & Editing, B. J. Park; Visualization, D. C. Min; Supervision, D. C. Min; Project Administration, B. J. Park; Funding Acquisition, B. J. Park.

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