Letter of Intent — CERN EP R&D Programme

6D Calorimetry: Towards the Ultimate Hadronic Calorimeter

Combining 5D Optical Dual-Readout Calorimetry (FLASH) with Gadolinium Neutron Capture for Complete Hadronic Shower Reconstruction

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Abstract. We propose **6D Calorimetry**, a new paradigm for hadronic calorimetry that extends the 5D dual-readout concept by adding a dedicated neutron capture channel to achieve, for the first time, complete event-by-event reconstruction of hadronic shower energy — including the invisible energy component carried by neutrons and nuclear binding losses. The concept unifies two complementary advances: (i) the FLASH strategy (SLAC / Texas Tech), which introduces single-photon time-stamping via 3D-integrated SPAD-ASIC detectors to reconstruct shower topology at the $\mathcal{O}(10\text{–}50\,\text{ps})$ level; and (ii) a novel Gadolinium-loaded scintillating fibre channel (the *N-channel*), which captures thermalized neutrons at the $\mathcal{O}(1\text{–}10\,\mu\text{s})$ timescale and converts the otherwise invisible hadronic energy into a measurable signal. Together, these channels span more than **ten orders of magnitude in time** and provide three independent observables — scintillation (S), Cherenkov (C), and neutron capture (N) — enabling a system of equations that fully constrains the electromagnetic, hadronic, and invisible energy fractions on a shower-by-shower basis. A Graph Neural Network (GNN) operating on the resulting 6D shower representation (x, y, z, t_{prompt}, E_{ch}, t_n) is expected to achieve hadronic energy resolution approaching $\sigma/E \sim 3\text{–}6\%/\sqrt{E}$ with a constant term below 0.5%, representing a factor of 3–4 improvement over existing dual-readout calorimeters. We propose a phased R&D programme culminating in a beam test at the CERN SPS.

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1. Introduction and Physics Motivation

The next generation of collider experiments — at the Future Circular Collider (FCC-ee/hh), the Compact Linear Collider (CLIC), and the proposed muon collider — places unprecedented demands on hadronic calorimeter performance. Precision measurements of hadronic final states, di-jet invariant masses, $W/Z/H$ hadronic decays, and missing transverse energy all require energy resolution at the level of $\sigma/E \sim 3\text{–}5\%/\sqrt{E}$, well beyond the capabilities of conventional technologies.

Dual-readout calorimetry [1], pioneered by the DREAM/RD52 collaboration and central to the IDEA detector concept for FCC-ee [3], addresses the dominant source of resolution degradation: event-by-event fluctuations in the electromagnetic shower fraction f_{em}. By simultaneously measuring scintillation light S (sensitive to all ionising deposits) and Cherenkov light C (predominantly from the electromagnetic component), dual-readout provides an event-by-event correction for f_{em} fluctuations, achieving $\sigma/E \sim 20\text{–}25\%/\sqrt{E}$ in practice [2]. This represents the current state of the art.

However, dual-readout calorimetry leaves a fundamental limitation unaddressed: the **invisible energy** component. In a typical hadronic shower, 10–40% of the total energy is carried by neutrons and deposited as nuclear binding energy breakup — invisible to both the S and C channels. These invisible-energy fluctuations set a floor on achievable resolution that dual-readout alone cannot overcome, and dominate the *constant term* b in $\sigma/E = a/\sqrt{E} \oplus b$, which governs performance above $\sim$300 GeV where the physics goals are most demanding.

Two complementary developments now make it possible to address this limitation directly. The **flash strategy** (Fast-timing, Low-noise, Advanced Single-photon, High-granularity), developed by SLAC in collaboration with Texas Tech University [6], introduces single-photon time-stamping at $\mathcal{O}(10\text{–}50\,\text{ps})$ precision via 3D-integrated SPAD-ASIC detectors. This transforms the dual-readout calorimeter into a 5D imaging device capable of resolving individual shower sub-structures and enabling particle-flow calorimetry within a single detector volume. Independently, the **neutron capture technique**, proven in neutrino physics via Gadolinium-loaded scintillator (Super-Kamiokande-Gd [7], JUNO), offers the means to detect thermalized shower neutrons via the $^{157}\text{Gd}(n,\gamma)$ reaction: an $\sim$8 MeV gamma cascade with a characteristic delay of 1–10 μs, cleanly separated in time from the prompt shower signal.

This Letter of Intent proposes **6D Calorimetry**: the integration of both advances into the HG-DREAM dual-readout fibre calorimeter platform [4], yielding a detector that reconstructs hadronic showers as complete, time-ordered, multi-channel events spanning more than ten orders of magnitude in time. For the first time, all three energy components — electromagnetic, hadronic, and invisible — are simultaneously constrained on an event-by-event basis.

2. The 6D Calorimetry Concept

2.1 From Dual-Readout to Triple-Readout

Conventional dual-readout provides two observables (S, C) per shower, yielding two equations in three unknowns (f_{em}, f_{had}, f_{inv}). The system is underdetermined: f_{inv} must be taken as a fixed average, contributing a residual constant term to the resolution that no amount of additional statistics or absorber optimisation can eliminate. Adding the neutron capture observable N provides the third independent equation, closing the system:

$$\begin{array}{lll} S & = e \cdot f_{\text{em}} + h \cdot f_{\text{had}} & \text{(scintillation: all ionising deposits)} \\ C & \approx e \cdot f_{\text{em}} & \text{(Cherenkov: EM component above threshold)} \\ N & \propto f_{\text{inv}} & \text{(neutron capture: invisible energy)} \end{array}$$

where e and h are the detector responses to electromagnetic and hadronic energy deposits, respectively. With all three observables, the true shower energy is reconstructed as:

$$\boxed{E_{\text{reco}} = \frac{S}{h} + \left(\frac{e}{h} - 1\right)\frac{C}{e} + k_n \cdot N} \tag{1}$$

where k_n is a calibration constant relating the measured neutron signal to the true invisible energy, determined from GEANT4-HP simulation and validated with beam data. The dual-readout correction term $(e/h - 1) \cdot C/e$ handles f_{em} fluctuations as in conventional dual-readout. The new $k_n \cdot N$ term corrects for f_{inv} fluctuations *event-by-event* — a capability never previously demonstrated in a collider-geometry dual-readout calorimeter.

2.2 The Time Domain: Ten Orders of Magnitude

The unifying principle of 6D Calorimetry is the exploitation of the *full time structure* of hadronic showers. Different physical processes deposit energy on vastly different timescales, and each timescale carries independent information about shower composition. Table 1 summarises the five relevant decades.

Table 1: Time structure of hadronic showers exploited in 6D Calorimetry.

Timescale	Physical process	Channel	Information content
< 1 ps	Cherenkov emission	C (quartz)	f_{em} per sub-shower
1–100 ps	Scintillation rise / shower front	S (FLASH SPAD)	Shower topology, longitudinal segmentation, vertex finding
1–10 ns	Scintillation decay, n elastic scattering	S (FLASH SPAD)	Hadronic sub-cluster ID, pile-up rejection
100 ns–1 μs	Neutron thermalisation in Gd-PVT	N (Gd fibre)	Neutron flux, early invisible energy
1–50 μs	^{157}Gd(n,γ) thermal capture	N (Gd fibre)	f_{inv} event-by-event

The "6D" label reflects the six dimensions of information per calorimeter tower per event: three spatial coordinates (x, y, z), prompt photon arrival time t_p from the FLASH

SPAD at $\mathcal{O}(10\,\text{ps})$, energy per channel (S, C, N), and delayed neutron capture time t_n at $\mathcal{O}(1\,\mu\text{s})$. The GNN operates on this full representation, learning correlations that no analytic correction formula can capture.

2.3 The flash Component: 5D Prompt Shower Reconstruction

The FLASH strategy addresses a fundamental bottleneck in existing dual-readout calorimeters: the inability to perform true longitudinal segmentation or particle flow within the calorimeter volume. Current HG-DREAM prototypes rely on analogue SiPMs with waveform digitisation, which do not scale to the channel densities and timing precision required for 5D calorimetry — a bottleneck identified in the FLASH proposal [6] as a fundamental limit of the analogue readout paradigm.

FLASH solves this through a **3D-integrated spad-asic device**: a high-efficiency Single-Photon Avalanche Diode sensing layer bonded to a custom fast-timing ASIC. Individual photons are time-stamped at the sensor front-end with $\mathcal{O}(10\text{–}50\,\text{ps})$ precision, eliminating waveform digitisation entirely. Analogue signals are replaced by sparse, time-tagged photon hit lists, reducing data volume and power consumption while reaching $\mathcal{O}(10\,\mu\text{m})$ spatial granularity.

Within 6D Calorimetry, FLASH provides the **prompt time window (0–50 ns)** in which it:

- Reconstructs the shower wavefront, providing effective longitudinal segmentation without mechanical layers;
- Identifies hadronic interaction vertices from secondary particle multiplicities, which correlate with invisible energy [5];
- Separates overlapping energy deposits in space and time, enabling particle flow within a single calorimeter volume;
- Provides the shower centroid used to spatially anchor the neutron capture search in the delayed time window.

2.4 The Neutron Capture Component: Closing the Invisible Energy Gap

The neutron capture channel exploits the extraordinary thermal neutron capture cross-section of ^{157}Gd ($\sigma_c = 254{,}000$ barn — four to five orders of magnitude larger than hydrogen or iron). The reaction ^{157}Gd(n, γ) produces a cascade of 3–4 gamma rays totalling $\sim$8 MeV, deposited in surrounding scintillator with a characteristic capture delay of 1–10 μs after the primary hadronic interaction. This delayed signal is cleanly separated in time from the prompt shower and is readable on the same SPAD/SiPM infrastructure with an extended readout gate.

Key nuclear data: ^{157}Gd has a natural abundance of 15.7% in natural Gd; isotopically enriched ^{157}Gd wire is commercially available and pushes the effective capture cross-section to the full 254 000 barn. The Gd(n, γ) cascade Q-value of $\sim$8 MeV is large enough to detect efficiently above SiPM dark noise via multi-hit coincidence. Capture time τ in 0.1% Gd-doped PVT is $\sim$3–5 μs (verified in Super-Kamiokande-Gd [7]).

The implementation introduces a **third fibre type** — Gd-doped PVT scintillating fibres (the *N-channel*) — interleaved within the existing HG-DREAM copper absorber matrix alongside the S (scintillating polystyrene) and C (clear quartz, Cherenkov) fibres. The inner tower rod pattern is modified to a **1S : 1C : 1N ratio**, preserving the full dual-readout capability while adding the neutron channel. The Gd-PVT fibre design incorporates:

- **PVT core doped with 0.1% Gd** as Gd_2O_3 nanoparticles: mean capture time $\sim$3–5 μs, retaining >75% of undoped light yield;
- **Wavelength-shifting inner layer** (Y-11 dye, $\sim$10 μm): shifts emission from 425 nm (blue, where Gd absorbs) to $\sim$490 nm (green, where Gd is transparent), recovering photon yield;
- **Standard PMMA cladding** for total internal reflection, fully compatible with existing HG-DREAM fibre routing and SiPM/SPAD readout.

Readout time windows. The readout ASIC/FPGA operates in two sequential time windows per beam crossing:

Window	Duration	Action
Prompt	0–50 ns	S, C, N at 250 MHz; full FLASH topology
Transition	50–500 ns	S and C stored; N switches to active gate
Neutron	500 ns–50 μs	N only at 10 MHz; $\geq$3 SiPM coincidence within 5 ns required for valid Gd-capture candidate

The multi-pixel coincidence requirement ($\geq$3 pixels within 5 ns) suppresses SiPM dark noise by $> 10^5$ relative to single-pixel dark counts, as established in neutrino detector practice. Neutron capture candidates are associated with parent showers using the FLASH-reconstructed shower centroid as the spatial anchor, with a search cone of $\sim$20 cm radius covering >95% of thermalized neutron displacements.

3. Expected Performance

Table 2 summarises projected hadronic energy resolution for each calorimeter generation. Estimates are based on GEANT4-HP simulations using the `FTFP_BERT_HP` physics list (mandatory for accurate thermal neutron tracking with the G4NDL neutron data library), analytic propagation of the triple-readout correction of Eq. 1, and extrapolation from existing DREAM and HG-DREAM beam test results.

The reduction in the constant term from $\sim$1% to <0.5% is the headline result of the 6D approach. At energies above $\sim$300 GeV — where hadronic decays of W, Z, H, and top quarks are reconstructed at FCC-hh and muon collider energies — the constant term dominates the resolution. Halving it has a larger physics impact than any achievable improvement in the stochastic term alone. The stochastic improvement (from $\sim$13% to $\sim$3–6%/$\sqrt{E}$) reflects both the FLASH contribution to shower topology reconstruction

Table 2: Projected hadronic energy resolution for successive calorimeter generations. The 6D result is a simulation-based projection; beam validation is the primary goal of this programme.

Calorimeter concept	**Stochastic**	**Constant**	**Key limitation addressed**
Conventional (Fe/scint)	50–60%/$\sqrt{E}$	∼3%	Baseline
Dual-readout (DREAM)	20–25%/$\sqrt{E}$	∼1–2%	f_{em} fluctuations
HG-DREAM + GNN	∼13%/$\sqrt{E}$	∼1%	f_{em} + shower topology
5D FLASH + GNN	8–10%/$\sqrt{E}$	∼0.8%	f_{em} + full prompt topology
6D (FLASH + N + gnn)	**3–6%/$\sqrt{E}$**	**<0.5%**	f_{em} + f_{inv} + **full shower**

and the neutron channel's reduction of shower-to-shower energy variance through the event-by-event f_{inv} correction.

4. Proposed R&D Programme

4.1 Phase I — Component R&D (Years 1–2)

flash spad-asic development (SLAC). Design, fabrication, and bench validation of the 3D-integrated SPAD-ASIC device. Target specifications: $\mathcal{O}(10\,\mu\mathrm{m})$ pitch, $\mathcal{O}(10$–$50\,\mathrm{ps})$ single-photon timing, trigger-less readout with time-tagged hit output. Integration compatibility test with existing HG-DREAM SiPM channels.

Gd-PVT fibre development (Texas Tech / fibre vendor). Systematic characterisation of Gd_2O_3 nanoparticle doping in PVT fibres as a function of Gd concentration (0.05–1.0% by mass). Measurements of: light yield vs. Gd%, emission spectrum, neutron capture time distribution $\tau([\mathrm{Gd}])$, and capture efficiency. Companion GEANT4-HP simulation of neutron capture in the fibre geometry using the full G4NDL nuclear data library.

DAQ architecture design. Design of the dual time-window readout ASIC/FPGA system. Prompt window (0–50 ns) at 250 MHz sampling; neutron window (500 ns–50 μs) at 10 MHz with coincidence trigger. Characterisation of dark-noise suppression via multi-pixel coincidence as a function of coincidence multiplicity and time window.

4.2 Phase II — Prototype Integration (Years 2–3)

Modification of 2–3 towers of the existing HG-DREAM prototype at Texas Tech to the 1S : 1C : 1N fibre ratio, with FLASH SPAD-ASIC readout on the inner tower face and full three-channel DAQ operational. Laboratory characterisation using an **Am-Be neutron source**: neutron capture efficiency vs. Gd concentration, capture time distribution, and spatial containment of delayed signals. This measurement directly validates the GEANT4-HP simulation and establishes k_n.

4.3 Phase III — Beam Test at the CERN SPS (Years 3–4)

Exposure of the 6D prototype to π^-, π^+, K^-, and proton beams at the **CERN H8/H4 SPS beamlines** at momenta of 20, 40, 60, 80, 100, 150, and 200 GeV/c, with electron beams for EM calibration. Target statistics: $\sim 10^6$ hadronic events per beam setting.

Key measurements:

- Hadronic energy resolution σ/E vs. $1/\sqrt{E}$ for S-only, $(S+C)$ dual-readout, and $(S+C+N)$ triple-readout reconstruction;
- Event-by-event correlation of the N-signal with GEANT4-HP truth-level invisible energy; calibration of k_n;
- Neutron capture efficiency and spatial containment radius as a function of Gd concentration and tower geometry;
- FLASH timing performance: longitudinal shower profile from single-photon timestamps, vertex multiplicity distribution;
- GNN training and evaluation on beam data vs. simulation; demonstration of 6D resolution improvement;
- Pile-up robustness: simultaneous beam interactions to validate spatial shower–neutron association using the FLASH centroid.

5. Relation to Existing Programmes and Novelty

The 6D Calorimetry concept builds directly on the HG-DREAM hardware platform and the GNN reconstruction philosophy developed at Texas Tech [4, 5], and on the FLASH detector technology under development at SLAC [6]. It is designed to be fully compatible with the IDEA detector concept for FCC-ee [3] and its hadronic calorimeter resolution requirements.

The closest precedents in the literature are:

- The **NECH programme** [8] (Louisiana Tech, ~2007–2012): Gd_2O_3-doped scintillator tiles for neutron detection in a conventional sampling calorimeter, abandoned before beam test stage;
- The **Snowmass 2022 Tile Multiple-Readout proposal** [9]: a conceptual framework for neutron-sensitive readout using ^{6}Li and ^{10}B in a tile geometry, without optical fibre dual-readout context.

To our knowledge, no existing proposal combines:

1. Gd-based neutron capture as a dedicated third readout channel in an *optical fibre* calorimeter;
2. Single-photon time-stamping at $\mathcal{O}(10\,\text{ps})$ via SPAD-ASIC technology;

3. GNN reconstruction operating on the combined 6D shower representation;
4. Event-by-event invisible energy correction in a collider-geometry dual-readout calorimeter.

6D Calorimetry therefore represents a genuinely novel and coherent programme, with a clear path from existing hardware (HG-DREAM) and proven detector technology (FLASH SPAD-ASIC) to a full beam test demonstration.

6. Timeline and Milestones

Table 3: Summary timeline and key milestones.

Period	Phase	Milestone
Y1 Q1–Q2	I	First SPAD-ASIC tape-out; Gd-PVT fibre samples produced
Y1 Q3–Q4	I	SPAD-ASIC bench validation; Gd fibre light yield and τ characterised
Y2 Q1–Q2	I–II	Dual time-window DAQ validated; GEANT4-HP prototype simulation complete
Y2 Q3–Q4	II	HG-DREAM tower modification (1S:1C:1N); Am-Be source characterisation
Y3 Q1–Q2	II	FLASH SPAD-ASIC integrated into HG-DREAM; full 6D readout operational
Y3 Q3–Q4	III	First SPS beam test (π/p/e, 20–200 GeV); dual time-window DAQ commissioned
Y4	III	Full-statistics beam test; GNN training; 6D resolution demonstrated; publication

7. Collaboration and Resources

The programme is led by a collaboration between **SLAC National Accelerator Laboratory** (FLASH SPAD-ASIC development and 5D calorimetry expertise) and **Texas Tech University** (HG-DREAM platform, GNN reconstruction, and hadronic calorimetry beam test experience). The beam test programme would be conducted at the CERN SPS H8 or H4 beamlines within the CERN EP R&D framework.

We invite expressions of interest from groups with expertise in:

- Gd-doped scintillating fibre production and optical characterisation;
- 3D semiconductor detector integration and fast-timing ASIC design;
- Trigger-less readout architectures for high-density photon detectors;

- GEANT4-HP neutron transport simulation and nuclear data validation;
- Graph Neural Network development for calorimeter shower reconstruction.

8. Conclusion

6D Calorimetry offers a physically complete solution to hadronic energy resolution by attacking all three sources of shower-to-shower energy variance simultaneously:

f_{em} fluctuations $\longrightarrow$ Dual-readout (S and C channels)
Shower topology ambiguity $\longrightarrow$ FLASH single-photon timing at $\mathcal{O}(10\,\text{ps})$
f_{inv} fluctuations $\longrightarrow$ Gd neutron capture (N channel)

The concept is built on existing hardware — the HG-DREAM dual-readout fibre calorimeter — and two well-defined R&D thrusts: the FLASH SPAD-ASIC device and Gd-loaded fibre integration. It requires no new fundamental physics and no exotic materials. The target performance of $\sigma/E \sim 3$–$6\%/\sqrt{E}$ with a constant term below 0.5% would represent a transformative advance in hadronic calorimeter capability, directly enabling the precision jet and hadronic final-state measurements required at FCC-ee, FCC-hh, and future lepton colliders.

We believe this LOI presents a compelling case for a dedicated R&D programme within the CERN EP framework and look forward to discussing the proposal with the community.

Acknowledgements

[To be completed.]

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