R&D: Quantum Sensing, Metrology and Materials

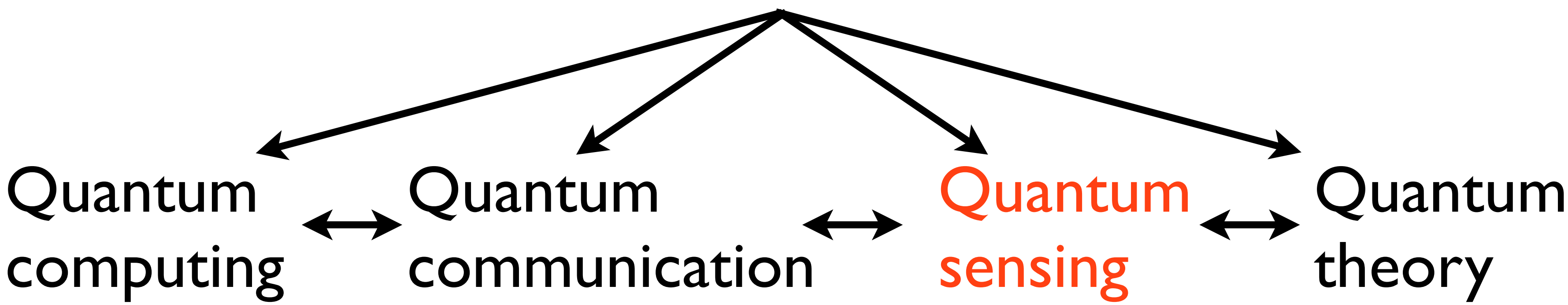
https://quantum.cern
https://quantum.cern/quantum-sensing-metrology-and-materials

QUANTUM TECHNOLOGY INITIATIVE

Focus on 2 thrusts of CERN's Quantum Technology Initiative:

- where can different activities at CERN benefit from advances in quantum technologies?
- can we find CERN technologies that benefit activities in the fields related to quantum technologies?

Four areas:



M. Doser

First year:

- identify ongoing detector R&D projects that immediately benefit / can potentially benefit; provide them with a doctoral student

Three projects

- Scintillators: explore use of nanodots / perovskites ⟶ timing
- MSGD: explore use of graphene ⟶ avalanche control
- Automated experiment control systems: explore use of AMO standard ⟶ Development of a ns-precise distributed automated experiment control system for remote automated running of low energy (antiatoms, nuclear physics) experiments

M. Doser

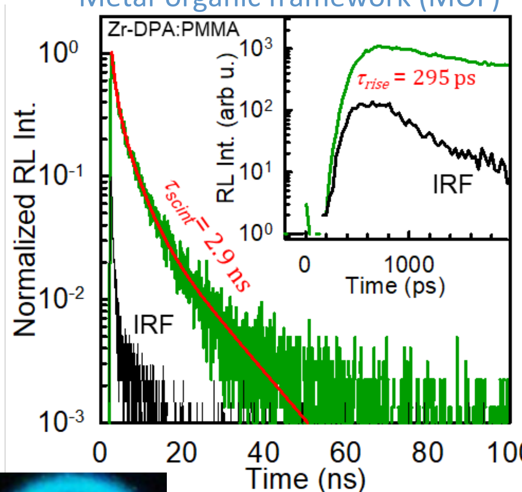
R&D on nanoscintillators in the Crystal Clear collaboration (RD-18)

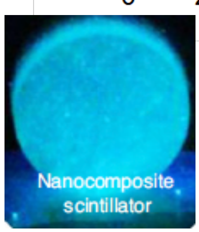
PhD student Isabel Frank /
E. Auffrey Hillemanns

- Investigation of scintillating properties of various types of nanomaterials produced by CCC members:
  - Perovskite nanocrystals: $CsPbBr_3$ with CTU Prague, Glass to Power Italy
  - 2D perovskites with UCB Lyon & CINTRA Singapore
  - Metal-organic framework with UNIMIB
  - InGaN/GaN QW with FZU
- Development/improvement of instrumentation to measure scintillating properties
- Possibility to use these new materials for future *fast timing* detectors:
  - eg: nanocomposites: nanocrystals embedded to polymer : to compete with plastic scintillators

Some examples of scintillating nanomaterials with sub-*ns* emission

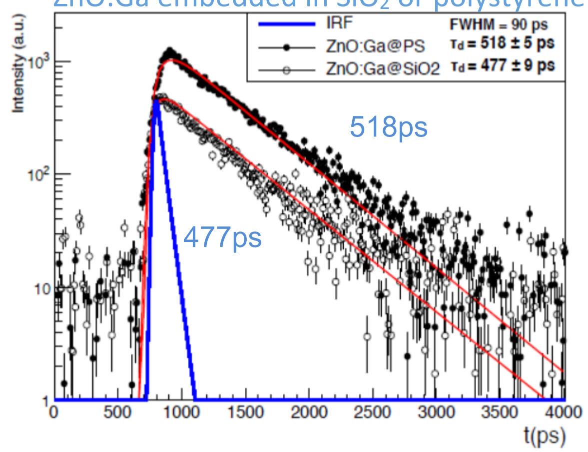
Metal-organic framework (MOF)

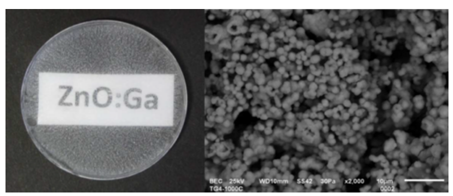




Perego, J *et al. Nat. Photonics* (2021).
https://doi.org/10.1038/s41566-021-00769-z

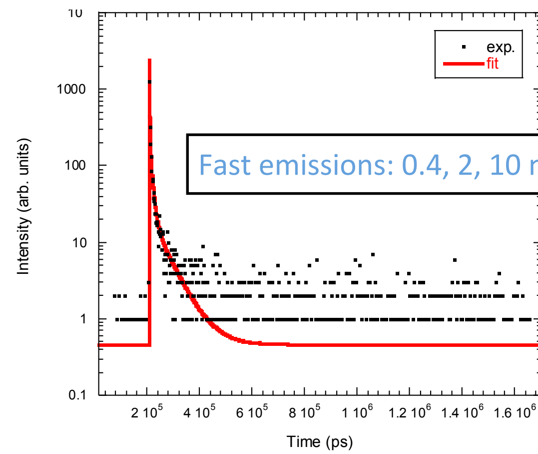
ZnO:Ga embedded in SiO_2 or polystyrene

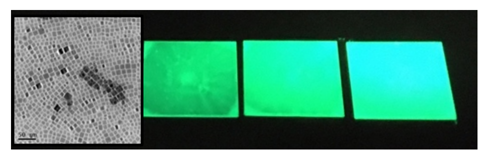




Procházková et al., Radiat Meas 90, 2016, 59-63
R. Turtos Phys. Status Solidi RRL 10, No. 11, 843–847 (2016)

$CsPbBr_3$ thin films deposited on glass substrate





Courtesy V. Čuba, K. Děcká, A. Suchá CTU, Prague

A novel Control System for HEP-related experiments

PhD student Marco Volponi / M. Doser

- ARTIQ (**A**dvanced Real-Time Infrastructure for Quantum physics)
  - System designed for quantum physics experiments (emerging standard)
  - Versatility exploitable in HEP ?
- Various applications possible thanks to ns precision and programmable I/O, e.g. in AEgIS:
  - Synchronization of two lasers with different frequencies
  - Control of antiproton trap: needs concurrent detection of trigger signals and activation of high voltage generators for trap electrodes with precise (ns) delays
  - Useable for all experiments that require active modification of device parameters in the course of implementing measurements (dynamic and situation-dependent modifications of device parameters: amplification gains, physical movement of detectors or passive devices, complex logic, ...)

fully script-based

```
@kernel
def run(self):
    self.core.reset()
    # waiting for trigger pulse
    t_gate = self.ttl0.gate_rising(200*s)
    while True:
        t_trig = self.ttl0.timestamp_mu(t_gate)
        if t_trig != -1:
            at_mu(t_trig)
            delay(4*us)
            # setting signal lines
            with parallel:
                self.ttl1.on()
                self.ttl8.on()
```

Graphene-based functional structures and nanostructures for novel gaseous detectors

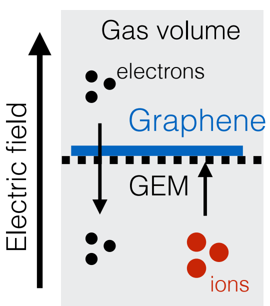
F. Brunbauer

PhD project of Giorgio Orlandini (FAU Erlangen-Nürnberg) in EP-DT-DD Gaseous Detector Development lab

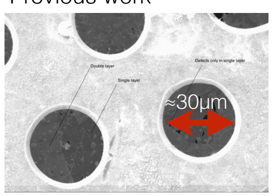
The unique properties of two-dimensional materials such as graphene as well as carbon-based nanostructures offer new perspectives for novel gaseous radiation detectors. This may include performance improvements for detectors for HEP experiments as well as new application fields combining wideband sensitivity of advanced materials with high gain factors and granularity offered by Micro Pattern Gaseous Detectors.

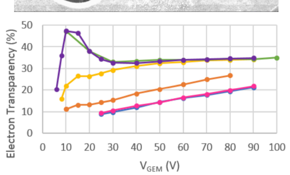
Application 1:

Suspended graphene for ion back-flow suppression and gas separation



Previous work



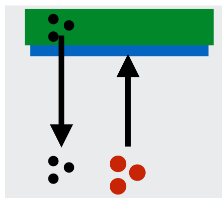


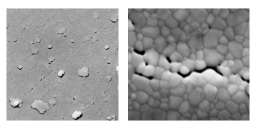
https://doi.org/10.1016/j.nima.2015.11.077

Suppressing ion back flow can significantly **improve high-rate capabilities** and **reduced electric field distortions** in Time Projection Chambers.

Application 2:

Protection of photocathodes with graphene layers

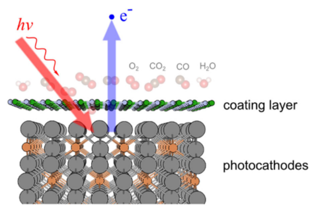




Damage of CsI

https://doi.org/10.1016/j.nima.2009.05.179

Protection and decrease of work function by coating layer

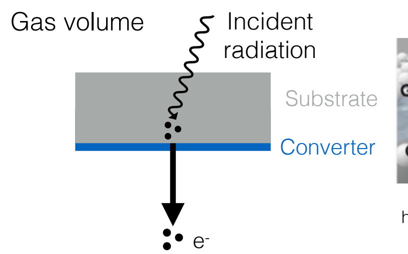


https://www.nature.com/articles/s41699-018-0062-6

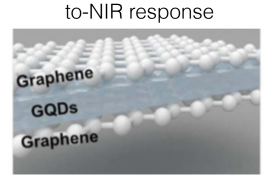
Atomically thin coating layers could **protect sensitive photocathodes** such as CsI against environmental factors and ion bombardment, which is important for preserving specifications of precise timing detector in harsh ion-back flow conditions. Additionally, **modifications of the work functions** of converter layers can be used to increase QE.

Application 3:

Graphene and nanostructures for photoconversion and as solid converters



Possible system with UV-to-NIR response



https://www.nature.com/articles/srep05603.pdf

Graphene quantum dots (GQD), carbon nanotubes and graphene have been shown to exhibit **broadband sensitivity** and could be used as versatile **conversion layers**. Utilising solid conversion layers enables high **detection efficiencies** and can be used for **precise timing** with gaseous radiation detectors.

Second year:

• identify opportunities for joint detector R&D projects that potentially benefit in the longer term / open up new directions for particle physics approaches (including at low energy)

Examples:

- Axion searches in existing experiments (BASE) ⟷ superconducting analog electronics (amplifer)
  S. Ulmer, J. Devlin / BASE experiment @ AD
- mid-IR / THz generation / detection (CAST/IAXO) ⟷ highly sensitive detection of ultra-low energy γ's
  first discussions started w/ DESY
- tuneable RF cavities ⟷ accelerator improvements
  Axion heterodyne detection, first discussions betw. Maurizio Pierini / SLAC group
- atom interferometry for DM, GW (AION) ⟷ CERN infrastructure and expertise: shafts, vacuum, manufacturing
  recent workshop @ CERN, ongoing discussions with O. Buchmuller, J. Ellis

many initiatives in the field of low energy particle physics (magnetic detectors, kinetic detectors, superconducting sensors, metamaterials (0/1/2 dimensional materials), optomechanical sensors, spin-based sensors, clocks and clock networks, atomic/molecular/ionic systems, quantum materials)

Examples cont.: (*crazy!* ideas for HEP, feasibility g^{ly} not yet evaluated):

CPAD Instrumentation Frontier Workshop 2021 https://indico.fnal.gov/event/46746/timetable

- atomic / nanostructured DM detectors in "MATHUSLA" zone
  ⟶ BE condensate, suspended nanospheres ⟶ recoil ?
  first discussions with ColdQuanta / UK
- polarizable (NV diamonds) scatterers ⟶ particle polarization?
  https://journals.aps.org/prb/abstract/10.1103/PhysRevB.87.125207
- Rydberg enhanced signals in gaseous det^s? ⟶ material reduction
- optical detection of atomic relaxation after ionization in gas?
  ⟶ redundancy, optical tracking?
  3D optical readout of a TPC using a single photon sensitive Timepix3 based camera
  A. Roberts et al., https://arxiv.org/abs/1810.09955
- detection of e.m. pulse in calorimeter showers? ⟶ ps, redundancy CPAD
  Askaryan Calorimeter Experiment, Remy Prechelt (prechelt@hawaii.edu)
- custom-built Quantum Cascade Lasers: can the first element of the cascade be tuned to obtain FIR γ's from ionization electrons?
  ⟶ few ps charged particle timing
- very low work function photocathodes via "quantum priming" ? CPAD
  or via novel low work function semiconductors? Cs_3Sb: David Winn (winn@Fairfield.edu)

Challenges & next steps

- identify opportunities for joint detector R&D projects that potentially benefit in the longer term / open up new directions for particle physics approaches (including at low energy)...

- ... while having very limited resources (possibly 1/2 doctoral student per project); not clear though that short of a *big* push, much more is warranted at this point in time, given the breadth of the possible areas which could be looked into.

- main focus: try to trigger brainstorming, discussions, and help provide contacts ⟶ still in exploratory phase

→ | "matchmaking service" ? between CERN (e.g. cryogenics group, with expertise on dilution refrigerators, TES, "remote cooling") & external groups (universities, labs, companies) with their expertise and interests

→ | implementation under consideration / being prepared

→ | ongoing: contact potentially interested groups (inside CERN, but also international labs, universities, companies)