Time-of-flight technologies

Roger Forty  (CERN)

Introduction
1. Scintillator
2. Gaseous
3. Silicon
4. Cherenkov
General considerations
Time-of-flight principle is conceptually simple: measure difference in arrival time of particle at two planes $t = t_1 - t_0$ then velocity: $\beta = L / ct$

Combine with a measurement of its momentum: $p = \beta \gamma mc$

Mass of particle can then be calculated:

$$m^2 = \frac{p^2}{c^2} \left( \frac{c^2 t^2}{L^2} - 1 \right)$$

At high energies particles are relativistic: velocity saturates $\rightarrow c$, time difference drops fast

Focused on long-lived charged-particle identification (e, $\mu$, $\pi$, K, p) in particular charged hadron separation at low momentum

The time for a kaon to travel 10 m is 33.37 ns at 10 GeV, while for a pion it would be 33.34 ns: the difference is only 35 ps

The separation in standard deviations: $N_\sigma \approx \frac{|m_1^2 - m_2^2|}{2 \sigma_t c} L$
Motivation (1)

- European Strategy for Particle Physics: the next future collider should be an $e^+e^-$ Higgs factory → expect this to be a focus for the R&D Roadmap

- Dedicated particle identification detectors have been absent from the designs of experiments, until recently — main focus has been on Particle Flow calorimetry and lepton ID, rather than hadron ID

- However, they do all feature excellent $dE/dx$ from tracker (or even more performant cluster counting $dN/dx$)

  Drawback for particle ID is region where $dE/dx$ curves cross at around 1-2 GeV for $p$-$K$-$\pi$ separation

- Combination of a modest TOF detector can cover this hole, provides PID up to a few GeV, complemented with $dE/dx$ at higher momenta

- Here assumed 100 ps/hit, over 10 layers of calorimeter
Complications

- Energy loss + multiple scattering between the IP and TOF detector → track length and momentum measurement biased → minimize material before TOF detector
- Combining signals within a layer, and between layers, of the TOF detector requires care (see example illustrated)
- Dedicated TOF detector placed after tracker but before calorimeter → its own material budget should be limited
- Increasing the path length improves TOF (linearly), but the area to be covered by the detector increases as the square → detectors typically need to cover large areas, cost-effectively
- Radiation tolerance is an issue for application at hadron colliders
- Start time \((t_0)\) needed, from dedicated detector or elsewhere
- Electronics: balance between time resolution, spatial resolution, data rate and power consumption
- System issues: synchronization over a large area challenging
Motivation (2)

- Highest priority of ESPP is of course the full exploitation of the LHC Upgrades of ATLAS & CMS for HL-LHC: R&D now ≈ complete
  However, future upgrades still planned: for LHCb & ALICE at least
- Excellent hadron ID is essential for flavour physics, and there is an broad future programme planned—likely to increase in priority if recent evidence of Lepton Flavour non-Universality persists
- RICH detectors are the technology of choice at high momentum
  But limited coverage <10 GeV with gas radiators (unless pressurized)
  Silica aerogel as radiator might cover the low-momentum end, but (due to its low density) gives few photons, difficult reconstruction in the busy environment of the LHC → abandoned by LHCb
- Pushing TOF to 10 ps per track over 10 m path would cover region up to 10 GeV for K-π separation → target for LHCb future upgrade
- One can dream of pushing further towards the picosecond level → cover the full range of particle ID required, with a single system (but bear in mind, 1 ps = 300 µm at the speed of light)
Fast timing

• Fast timing has *many* other applications beyond TOF particle ID
• A fast timing revolution is underway, as detectors that traditionally have been spatially segmented now add time as an extra dimension: typical target is 30–50 ps resolution/MIP

• This has been driven by *pile-up* suppression in hadron colliders—in particular the unprecedented challenges of the HL-LHC: signal events will have up to 200 min-bias collisions superposed Can be separated by binning in *time* as well as *space*

• **4D tracking** \((x,y,z,t)\), and **5D calorimetry** \((x,y,z,t,E)\):
  Contribution to tracking pattern recognition, shower analysis—imagine going from a static image of showers, to a movie where neutral hadrons arrive later than the photons, etc.

• Timing can also extend physics reach, e.g. for long-lived particle (LLP) reconstruction—a booming field of dark sector searches

• This extends well beyond the TOF application (e.g. see ≈ all of the other task forces) → should drive synergy in the R&D roadmap
Resolution

- Contributions to timing resolution:
  \[ \sigma_{\text{total}}^2 = \sigma_{\text{det}}^2 + \sigma_{\text{elec}}^2 + \sigma_{\text{clock}}^2 \]

  - Example of LHC end-cap timing layers: the detector contribution \( \sigma_{\text{det}} \) comes from Landau fluctuations in the silicon sensors.
  - The electronics contribution \( \sigma_{\text{elec}} \) has following components:
    \[
    \sigma_{\text{elec}}^2 = \left( \frac{t_{\text{rise}}}{S/N} \right)^2 + \left( \frac{V_{\text{thr}}}{S/t_{\text{rise}}} \right)_{\text{RMS}}^2 + \left( \frac{TDC_{\text{bin}}}{\sqrt{12}} \right)^2
    \]
    Jitter Time walk TDC binning
  - Need fast signal and excellent \( S/N \)
    LGAD gain: increase signal \( S \), but keep noise \( N \) under control
    Contribution from the TDC bin width, must also correct for integral non-linearity (INL, from uneven bin sizes)
  - The clock contribution (needed to synchronize detector) \( \sigma_{\text{clock}} \)

- Other contributions: transit-time spread (TTS) in photodetectors, pixel size, emission point of photon in radiator, start-time \( t_0 \), chromatic effects, cross-talk, etc. → Careful calibration is essential

\[ \sim 40 \text{ ps} = 25 \oplus 25 \oplus 15 \text{ ps} \]

[Target resolution for timing layer, ATLAS-TDR-031]
Many of the technologies used cross over with other disciplines, from tracking to calorimetry, and use the sensors discussed elsewhere in this (and the other) task forces.

1. **Scintillators**: classic solution, now developed for timing layers (TF5+6, SiPM)
2. **Gaseous detectors**: multigap RPCs, new ideas to push timing resolution with MPGDs (TF1)
3. **Silicon detectors**: recent development of LGADs for end-cap timing layers (TF3, LGAD)
4. **Cherenkov-based detectors**: pushing for ultimate resolution (MCP)

Cannot cover exhaustively, instead selected a few examples to illustrate detector systems (existing / in preparation / future development) for each technology + will have to pass quickly over detectors that have been covered elsewhere

Tried to include detectors mentioned in the questionnaire responses, apologies for any omissions + bias toward experiments discussed at CERN—this symposium is opportunity to gather missing input

Disclaimer: references given to where information collected, rather than original sources —thanks to all who have provided material
1. Scintillators

- Fixed-target experiments have geometry well adapted to TOF. Take as example **NA61** (SHINE), flight distance 13 m.
- Most recently added scintillator hodoscope: Forward-ToF 2.5 cm-thick bars of plastic scintillator (Bicron BC-408) rise time 0.9 ns, decay time 2.1 ns, attenuation length 210 cm.
- Read out at both ends with fishtail PMMA light-guides to 2” photomultipliers (Fast-Hamamatsu R1828).
- TOF resolution ~110 ps.

**S. Afanasiev et al., CERN-EP/99-001**

**dE/dx + TOF combined** (5-6 GeV, NA49 Pb-Pb)

**Roger Forty N Abgrall et al 2014 JINST 9 P06005**

**N Abgrall et al 2014 JINST 9 P06005**

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**TOF technologies**
T2K Near Detector upgrade

- The near detector of T2K (long-baseline ν experiment) is being upgraded
T2K Near Detector upgrade

• The near detector of T2K (long-baseline $\nu$ experiment) is being upgraded
• TOF system required to give unambiguous determination of the flight direction of charged particles, to ensure tracks come from $\nu$ interaction

• 1 cm-thick cast plastic scintillator bars (EJ-200) read out by array of large area SiPM (6 × 6 mm$^2$ Hamamatsu S13360-6050PE MPPC)

• SiPM: compact, robust, insensitive to B field, operate at low voltage, low power consumption, photodetection efficiency up to 40%; *Drawbacks:* high dark count rate (DCR), radiation sensitivity → cooling

Similar solution explored for PANDA TOF, with smaller scintillator tiles/rods

Overlapping scintillator bars

SiPM array (MUSIC readout)

~ 130 ps resolution

T. Lux, SPSC 13/4/21

C. Betancourt et al, JINST12 (2017) P11023
CMS Timing Layer

MIP Timing Detector (MTD)

Barrel (BTL) instrumented with scintillator bars Endcaps (ETL) with silicon detectors (LGAD)

Technology selected according to requirements:

Both detectors cost $\sim 10$ MCHF, but...

BTL covers $3x$ area of ETL with $25x$ fewer channels

However, it would not handle $10x$ higher radiation
CMS Barrel Timing Layer

- Faster scintillators: LYSO:Ce (Lutetium Yttrium Orthosilicate crystals doped with Cerium): excellent radiation tolerance, high light yield (∼ 40,000 photons/MeV), fast scintillation rise-time (< 100 ps), relatively short decay-time (∼ 40 ns)

- Well-established in PET scanners: excellent cross-fertilization! TOF also very relevant there: provides resolution along line-of-flight

- 166k LYSO crystals readout with SiPMs at each end, attached to the inner wall of Tracker Support Tube (r = 1.15 m, length = ±2.6 m) → has to be installed before tracker

- Thermoelectric coolers to improve SiPM radiation tolerance: run at -45°C

- Time resolution: 35 ps at start and 60 ps by the end of HL-LHC

Time-of-flight particle ID as a “bonus”: 2σ K-π separation up to p ~ 2 GeV
Quantum fast-scintillator R&D [see TF5]

- Colloidal Quantum Dots irradiated with a UV light: different sized nanoscale dots emit different colours of light due to quantum confinement
- Semiconductor scintillator based on InAs Quantum Dots functioning as luminescence centres embedded in a GaAs matrix can have uniquely fast scintillation properties with low self-absorption
Quantum fast-scintillator R&D [see TF5]

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• Related R&D pursued by RD18 (Crystal Clear) [see E. Auffray, TF5]
  CdSe nano-platelets deposited on LYSO substrate → faster response

• Challenge to produce large-scale samples: **3D printing** of scintillator being investigated, to produce arbitrary shapes

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Cadmium selenide nano-platelets

R. Turtos et al., JINST 11 (2016) P10015

YAG (voxel size ~ 50 x 50 x 10-50 μm)

G. Dosovitky, Kurchatov Institute
2. Gaseous detectors [see TF1]

- **Multi-gap RPC** well-established technique, excellent timing, easily segmented, work in strong magnetic field, relatively easy to build e.g. ALICE TOF
- Stacks of 1 mm glass plates, total of 10 gas gaps of 250 μm
  - High resistivity plates required (> $10^{10} \, \Omega \text{cm}$) to limit discharge area
- Gas used is $\text{C}_2\text{F}_4\text{H}_2 + \text{SF}_6 + \text{C}_4\text{H}_{10}$
- Timing resolution 56 ps achieved

3.7 m from IP
150 m$^2$ total area!
1638 modules

F. Carnesecchi, arXiv:1806.03825
Gaseous-detector R&D

- **MRPC** are in widespread use for TOF systems: upgrade of NA61, proposals SHiP and Water Cherenkov Test Experiment @CERN HADES@GSI, EMPHATIC@Fermilab, E50@J-PARC, BGOegg@Spring-8, CBM, STAR...

- Developments towards:
  - faster timing (e.g. increasing number of gaps)
  - Higher rate capability: managing gas flow, glass resistivity

- Fast timing micro-pattern gas detectors also being developed e.g. FTM based on the µ-RWELL structure [see P. Verwilligen, TF1]

- ~300 ps resolution seen for simulation [Y. Maghrbi et al, NIMA 954 (2020) 161666]

- Alternative approach: couple Cherenkov radiator to MPGD

Roger Forty  
TOF technologies  
C. Williams, AiDAinnova 14/4/21  
M. Hartz, SPSC 13/4/21  
PICOSEC development

- Hybrid detector: Cherenkov signal (CsI PC) amplified via MPGD
  Developed with RD51 [see next talk, F. Tessarotto]

- Micromegas: 80% Ne + 10% C₂H₆ + 10% CF₄ (COMPASS gas)
  Signal has two distinct components: fast electron peak (≈ 0.5 ns)
  slow ion tail (≈ 100 ns)

- Now working on detector stability, photocathode robustness (DLC, nano-diamond), large-area coverage: 10x10 pad module planned
  Considered for muon system of ENUBET (R&D for tagged ν beam)

24 ps for muons
(≈ 10 p.e./muon)

J. Bortfeldt et al, NIM A 903 (2018) 317
3. Silicon detectors  [see TF3]

- Low-gain avalanche diodes (LGAD) are currently the silicon detectors of choice for fast timing, adopted by ATLAS/CMS. Initial idea was for “APD with low gain” to compensate for charge loss after irradiation  [P. Fernandez, PhD thesis 2014]

  Multiplication layer adds modest gain x10–20: improves signal slope while keeping noise under control

- Early adopter: HADES prototype beam telescope
  150 µm strips, provides start time $t_0$ for TOF system

  Corresponds to 47 ps/hit

  S. Grinstein, IAS-HEP 2021

Insensitive area around gain layer
Junction Termination Extension (JTE): 50-100 µm
limits ability to achieve fine pitch

ATLAS/CMS use 1.3 x 1.3 mm$^2$ pads
Need to scale up from ~cm$^2$ to ~10m$^2$ area

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ATLAS Timing Layer

- High Granularity Timing Detector (HGTD) for the end-caps (similar design for CMS ETL, some common development)
- Active area: $12 \text{ cm} < r < 64 \text{ cm}$, 2 disks per side, each supporting double $50 \mu\text{m}$ sensor layers: $15 \times 30$ pads of $1.3 \times 1.3 \text{ mm}^2$
- Bump-bonded to readout ASICs, flex tail to outer-radius electronics
  Cooling plate operates at $-30^\circ \text{C}$: evaporative CO$_2$, 20 kW/endcap
- Maximum fluence: $2.5 \times 10^{15} \text{ MeV n}_{eq}/\text{cm}^2$, 2 MGy by end of HL-LHC
  Inner ring will be replaced every 1000 fb$^{-1}$ due to radiation damage
  Layout optimised for uniform performance vs radius

Cross-section of disk

Effect of irradiation

3.6 M channels, 6.4 m$^2$, 30-40% $X_0$
Fast silicon R&D

• Very active area, in the framework of RD50 and elsewhere: LGAD stability after heavy irradiation remains a concern → increase radiation tolerance further + achieve finer granularity + push timing

For single (thin) layers, timing resolution < 20 ps has been achieved
Would be difficult to achieve for a large system? [discussion at TF3]

• **AC-LGAD**: gain layer charge coupled capacitively to surface through thin (~ 500 nm) oxide layer, segmentation provided simply by surface electrodes
Excellent spatial resolution can be achieved via charge-sharing

Also Deep Junction (DJ-LGAD), Trench isolated (TI-LGAD), Inverse (iLGAD)...

• Other approaches to fast timing in silicon may also compete: 3D, Timepix...
Solid-state Electron Multiplier (**SSEM**): amplification layer obtained via a GEM-like metal structure embedded within the silicon bulk

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**LGAD timing**

Y. Zhao et al, NIM 924 (2019) 387

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**3D silicon**

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Silicon prospects

- **ALICE3**: new detector based around CMOS MAPS (Monolithic Active Pixel Sensors) under study for the HL-LHC era
  
  TOF resolution < 20 ps needed at system level, requires advances both on sensors and microelectronics  [L. Musa, input symposium 19/2/21]

- **Belle II** detector upgrades planned in ~2026: pile-up suppression not an issue for e⁺e⁻ colliders, but use of timing layer under consideration to cover gaps between radiator bars of TOP detector

- **EIC**: now an approved project, detector technologies not yet fixed

- **FCC-hh**: pileup 1000, timing requirement to mitigate even more severe: resolution < 10 ps required “or very clever new ideas needed…”  
  [M. Aleksa, input symposium 19/2/21]

  + radiation dose 10x higher—but there is time for R&D, technical design would only start in O(15 years)

- **Muon collider** experiments: fast timing at 10 ps level needed to reject beam-induced background  [N. Pastrone, input symposium 19/2/21]
4. Cherenkov-based detectors

- Cherenkov radiation is prompt, ideal for ultimate timing: detect photons rather than charge.
- Adding timing to RICH detectors: only available for particles which are above threshold → main use is for background suppression there, at least for gaseous radiators. Room for clever ideas with aerogel? but few photons → use solid quartz (synthetic fused silica).

**ATLAS Forward TOF:** L-shaped bars

- **ToF:** Cerenkov 4 Trains × 4 Bars
- **σ_x ≈ 30 ps/Bar**
- **SiT:** 3D Pixels
  - 50μm(x) × 250μm(y)
  - σ_x ≈ 7 μm/track

**Another example:** EMPHATIC $t_0$ counter

- **Resolution of 6A**
  - Entrain: 25253
  - Mean: -9.286
  - σ: 0.02764
  - $z$ / r (μm): 87.33 / 18
  - Constant: 0.000001
  - Mean: 0.0215 ± 0.0000 ± 0.00018

**T. Sykora, INSTR2020**

- **Excellent performance ~ 20 ps**, but for a small system—how can this be achieved over large areas?
LAPPD development

• One approach is to develop large-area picosecond-level photodetectors and use to time Cherenkov light produced in their entrance window

• LAPPD™ development: use cheaper MCP-PMT components to limit cost e.g. borosilicate float glass + ALD treatment, strip-line readout
  Now commercialized by Incom Inc.

• Adopted by ANNIE (Accelerator Neutrino Neutron Interaction Experiment): water-Cherenkov neutrino experiment at Fermilab with 30 tons of Gadolinium-loaded water, to help in their muon reconstruction

• Also explored as a timing layer at shower-max in the LHCb calorimeter upgrade: 18.6 ps timing resolution achieved for 5.8 GeV e⁻ test beam

• Second generation under development with capacitive-coupled anode to allow pad readout more suitable for high-rate environments
  Lifetime and B-field sensitivity? [see talk of K. Inami]

• Issue: although cheaper than traditional MCPs, they are not that cheap
  Tiling a large area is currently still prohibitive, $O(1 \text{ MCHF/m}^2)$
DIRC evolution

• To avoid tiling the full area, propagate the photons to photodetectors located at the edge using total-internal reflection in highly-polished quartz radiator [see previous talk, J. Schwiening]

• Issue to be handled: chromatic dispersion of the material—trade-off between photon bandwidth to increase yield, vs resolution

From $E_\gamma = 2–4 \text{ eV}$, refractive index changes $\Delta n = 7\%$

Over 1m propagation $\rightarrow$ time difference $= 300 \text{ ps}$

• FDIRC: demonstrated use of photon timing to improve the $\Theta_C$ resolution, adapting BaBar DIRC

• TOP: time-of-propagation detector of Belle II timing vs position enhances $K$-$\pi$ separation

• Disc DIRC (PANDA): move from bars to planar geometry

• These elements all brought together for TORCH concept
TORCH concept

- **TORCH** (Timing Of internally Reflected CHerenkov light) uses polished 1-cm thick quartz plate as radiator (~10% $X_0$) Measure precisely arrival time and position of individual photons, and combine to measure track arrival time

- Requires ~1 mrad precision on angle of photon, so that path length in radiator can be reconstructed: focused with a cylindrical lens onto fine-granularity pixellised detector

- **Key innovation:** measured Cherenkov angle used to correct dispersion: $n = 1/\beta \cos \Theta_C \rightarrow$ effectively determine wavelength for each photon i.e. Cherenkov angle is used to correct timing (cf DIRC, where timing is used to correct the Cherenkov angle)

- Resolution on photon arrival time has contributions from pixel size and photodetector (intrinsic + electronics)—target to keep each ~50 ps, giving overall resolution 70 ps per photon

On average 30 photons detect per track through radiator → per-track resolution of 10-15 ps — if independent some uncertainties (e.g. from track) common between p.e.
TORCH in LHCb

- Proposed for upgrade of LHCb in ~2027 for HL-LHC (Upgrade 2) \( \rightarrow \) needs to handle luminosity \( \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
- Location after tracker, before RICH2 which will be upgraded at same time [see talk of C. D'Ambrosio] \( \rightarrow \) flight path 10 m, area 30 m

- **Practicalities**: subdivide into identical modules, reflection off sides to reach photodetectors at top/bottom edge
- Performance (full simulation): clean K-\(\pi\) separation up to 10 GeV as required
TORCH development

- TORCH concept has been tested using ≈ full-size prototype
- Instrumented with two 512-channel MCP-PMT photodetectors
  Campaign of measurements with low-momentum $\pi/p$ beam from SPS
  → Target of 70 ps timing resolution per detected photon achieved
- **Next step:** confirm that combination gives expected $VN_{pe}$ behaviour
  → prototype will be fully instrumented with MCP-PMTs for further tests

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![TORCH prototype](image)

**Project along time axis**

![Time vs position (for one MCP column)](image)

*Time vs position (for one MCP column)*

$\sigma_t = 70$ ps/pe

*M. Kreps, ICHEP2020*
Cherenkov-based TOF prospects

- **Forward TOF** of ATLAS is being upgraded for the next run
- **TORCH** features in Framework-TDR for LHCb upgrade  \(\to\) LHCC, 9/2021
- Interest for \(e^+e^-\) Higgs factory designs—the circular ones at least perhaps due to their phenomenal \(Z \to b\bar{b}\) statistics

Conceptual layout for use of TORCH in an **FCC-ee** experiment:
Flight distance < LHCb \(\to\) TOF lower, but TOP increases (they add)

- Also for future fixed-target/beam-dump experiment proposals:
e.g. **TauFV**: search for LFV \(\tau \to \mu\mu\mu\) in beam dump at the SPS

- **Related concept**: **DTOF** at Super Tau Charm facility  [B. Qi et al, arXiv:2104.05297]
similar to FTOF detector proposed for SuperB  [N. Arnaud et al, NIMA 718 (2013) 557]
General considerations

- End with discussion of some more general aspects relevant to different technologies, where R&D is in progress/needed

Focus on issues relevant to this task force, illustrated with examples from work on TORCH that I know best

Radiator/detector material [see talks of I. Idachi, J. Schwiening]

- Quartz: needs high clarity, radiation tolerance, surface quality, polishing to sub-nm surface roughness—currently a cost driver

- Larger area plates: would allow module size to be adapted to track occupancy in LHCb

- RPC gas systems: [see TF1] target leak free + gases with reduced environmental impact:

  B. Mandelli, TF1
Sensors

- For silicon see TF3, for scintillator see TF5+6; fast photodetectors: MCP-PMT and SiPM [see talks of K. Inami, S. Korpar, Y. Musienko]

- For MCP: push towards finer granularity, lifetime, rate capability, etc. Connectivity: e.g. using anisotropic conductive foil (ACF)
  Fast + longer lifetime MCPs relevant for future high-intensity kaon experiments

- For SiPM: naturally fine granularity, but developments to improve active-area, radiation tolerance, noise, adjust spectral sensitivity

- Increasing quantum efficiency increases photon yield (+ occupancy)
  Cherenkov spectrum ~ flat with photon energy → extending toward UV can increase yield, but requires control of full optical system

TORCH MCP-PMT (developed with Photek)

60 mm
Front

Back

Bare back

64 x 64 anode pads

Roger Forty

TOF technologies

K. Matsuoka, RICH2016

M. van Dijk, CERN-THESIS-2016-039
Readout electronics [see TF7]

- **NINO + HPTDC** chipset developed in 2004 (0.25 μm CMOS) for ALICE TOF, and now widely used—also for single p.e. although intended for the larger charge of MRPC signals
  - TDC: 32 channels for 100 ps bins, or 8 ch for 25 ps bins

- **FastIC + PicoTDC** successors recently developed (65 nm) [R. Ballabriga, J. Christiansen et al, Users meeting] —many potential clients
  - FastIC addresses NINO limitations (non-linearity of energy measurement, power consumption) suitable to operate with SiPM, PMT, MCP, i.e. a wide range of detector capacitances
  - PicoTDC has increased channels (64 ch), finer binning (12/3ps)

- **ASICs for LHC timing layers** (130 nm): HGTD front-end **ALTIROC**
  - MTD-BTL uses **TOFHIR** ASIC developed from TOFPET
  - MTD-ETL uses **ETROC**; baseline for distributing the clock is to use DAQ links (**lpGBT**, 65 nm)

CMS developing a backup distribution system: pure clock link
- Requires development of a rad-hard fan-out ASIC and board and deployment of ~ 2000 additional fibres
Start time

- To determine the time-of-flight a start time ($t_0$) is required.
- This may be achieved using timing information from the accelerator, but if bunches are long (~ 20 cm at the LHC) → have to correct for vertex position.
- Can use a dedicated detector, e.g. the T0 detector of ALICE and those shown earlier from HADES and EMPHATIC or e.g. a vertex detector (if equipped for fast timing).
- Alternatively use other tracks in the event, from the primary vertex—as also done by ALICE, due to limited T0 acceptance.
- Most PV tracks are pions, so for TORCH the reconstruction logic can be reversed, and the start time determined from average of tracks from primary vertex assuming they are $\pi$.
  Outliers from other particle types removed, iteratively → Should be able to achieve few-picosecond resolution on $t_0$ from the detector itself, using the other tracks in the event.
Conclusions

• Development of TOF technologies is currently booming with general interest in **fast timing**
  Provides a very compact particle ID detector, e.g. suitable for collider experiments

• Well-established technologies: **scintillator** hodoscopes and **MRPCs** with resolution $O(100 \text{ ps})$
  good for covering low momenta up to a few GeV, e.g. complementing $dE/dx$ from trackers

• Fast-timing detectors developed for the LHC upgrades: fast scintillators and **LGAD silicon**
  aim for 30-50 ps resolution for pile-up suppression, will also provide TOF particle ID as a bonus

• To achieve momentum coverage up to 10 GeV for K-π separation (to complement RICH coverage)
  requires pushing beyond current state-of-the-art, towards 10 ps resolution
  – Cherenkov radiators very suitable: **PICOSEC, LAPPD** and other approaches under development
  – **TORCH** achieves this by combining many photons per track, with modest individual resolution
  – Scintillators this fast (e.g. quantum R&D) would be breakthrough for **TOF-PET**: mm-resolution

• Long-term goal to reach **picosecond-level** timing, could satisfy the **full** particle ID needs
  – Requires vigorous R&D on radiators, sensors, electronics
  – System aspects will become increasingly more important

→ Fast timing should feature strongly in the R&D Roadmap + reserve some space for new ideas!