Challenges and prospects for upgrades of the CMS electromagnetic calorimeter front-end readout electronics for HL-LHC

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On behalf of the CMS Collaboration

NDIP2014, Tours, 30Jun-4Jul 2014

Outlook

- Legacy ECAL on-detector electronics
- Motivation for upgrade
- Possible design of the Phase2 on-detector electronics
- Challenges and plans

CMS detector. Electromagnetic CALorimeter (ECAL)

- The largest homogeneous crystal calorimeter ever built
- Designed to provide high electromagnetic calorimeter performance in the hadron collider environment:
  - High interaction rate
  - Hadron background
  - Pileup
- To meet this goal, the following solutions were implemented:
  - Lead tungstate scintillating crystals as a sensitive medium
  - High granularity:
    - Barrel: 61200 crystals arranged in 36 SuperMudules for pseudo-rapidity range $|\eta| < 1.48$
    - Two endcaps: each 7324 crystals arranged in four Dees for $|\eta| = 1.48 – 3.00$
  - High quality digitizer:
    - 40MeV – 1.5TeV dynamic range (14 bit)
    - 12 bit precision

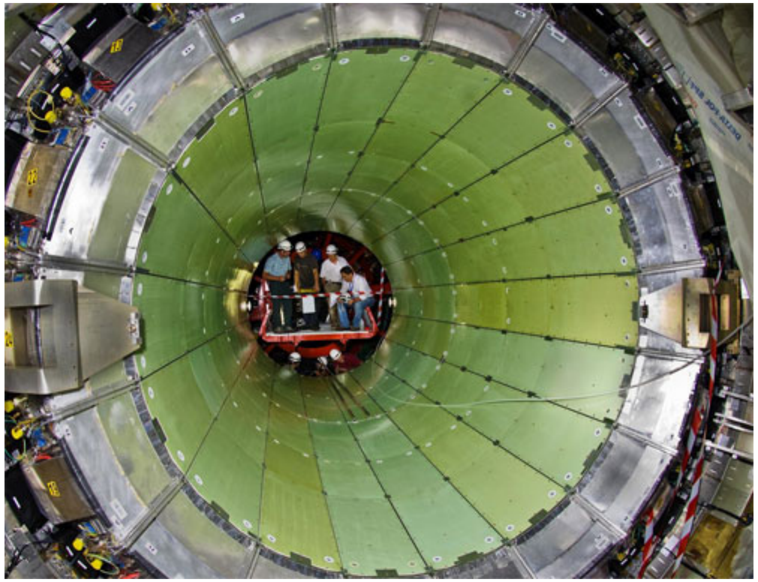
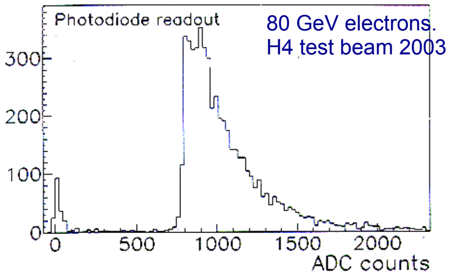
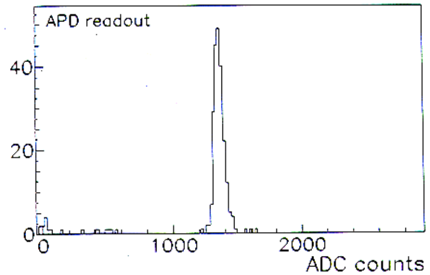
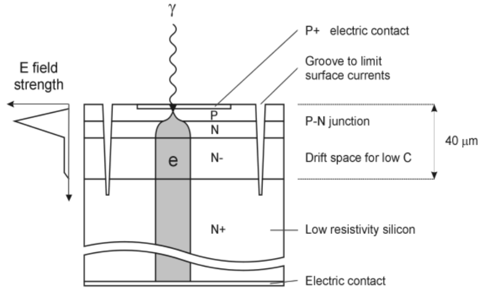


Photo detectors. ECAL Barrel: APD



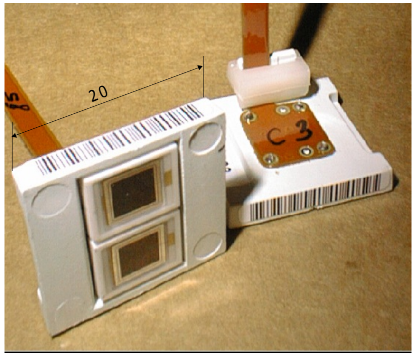


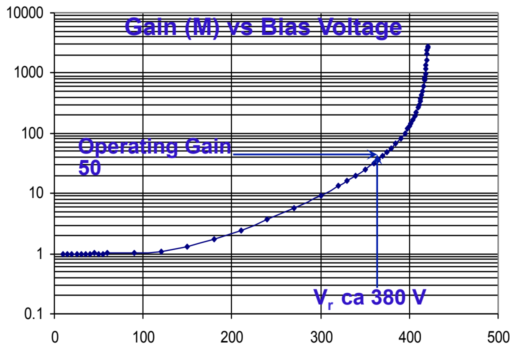
- Due to the nuclear counting effect, device with the internal gain was required
- After 8 years R&D of Hamamatsu Photonics in close collaboration with CMS ECAL groups, a new large area Avalanche Photo diode was developed

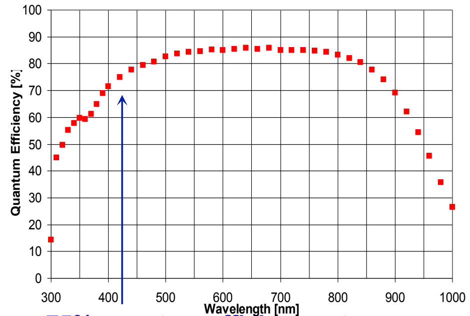


HAMAMATSU Photonics S8148 APD parameters:

Active area	5 x 5 mm
Charge collection within 20 nsec	99 ± 1%
Capacitance	80 pF (fully depleted)
Serial resistance	< 5 Ω
Dark Current (Id) before irradiation	< 50 nA (~ 5 nA typical)
Voltage sensitivity (1/M*dM/dV)	3.15 % / V
Temperature sensitivity (1/T*dM/dT) -	2.2 % / °C
Excess noise factor	2.1
Breakdown - operating voltage (Vb - Vr)	45 ± 5 V







75% quantum efficiency at PbWO peak emission 430 nm

Excellent device

~150 000 devices purchased by CMS

All fit to specification

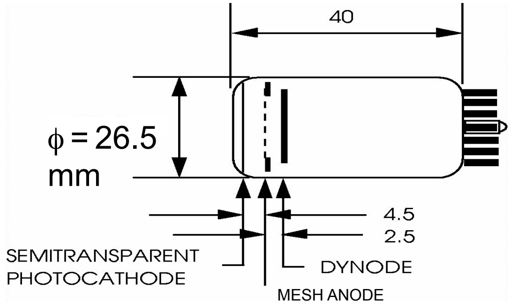
No problems associated to APD failure after 5 years of operation

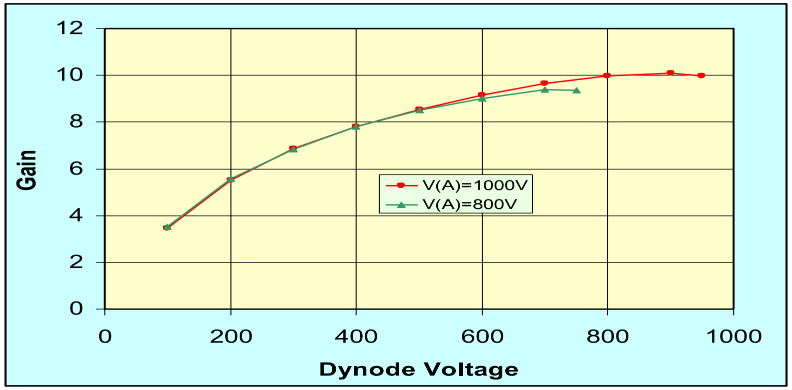
Photo detectors. ECAL EndCap: VPT

Due to the high radiation in the forward region, vacuum photo triode is used in the End Cap section of CMS ECAL

Endcaps: Vacuum phototriodes (VPT)

Produced by RIE, St Petersburg, Russia
More radiation resistant than Si diodes
(with UV glass window)
- Active area ~ 280 mm^2
- Gain ~10 (B=4T) Q.E.~ 20% (420 nm)
- Fast devices (simple planar structure)

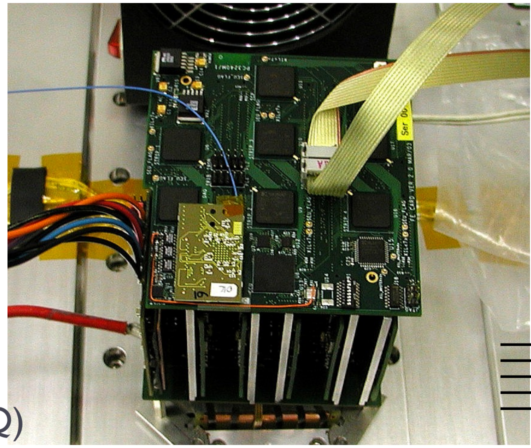


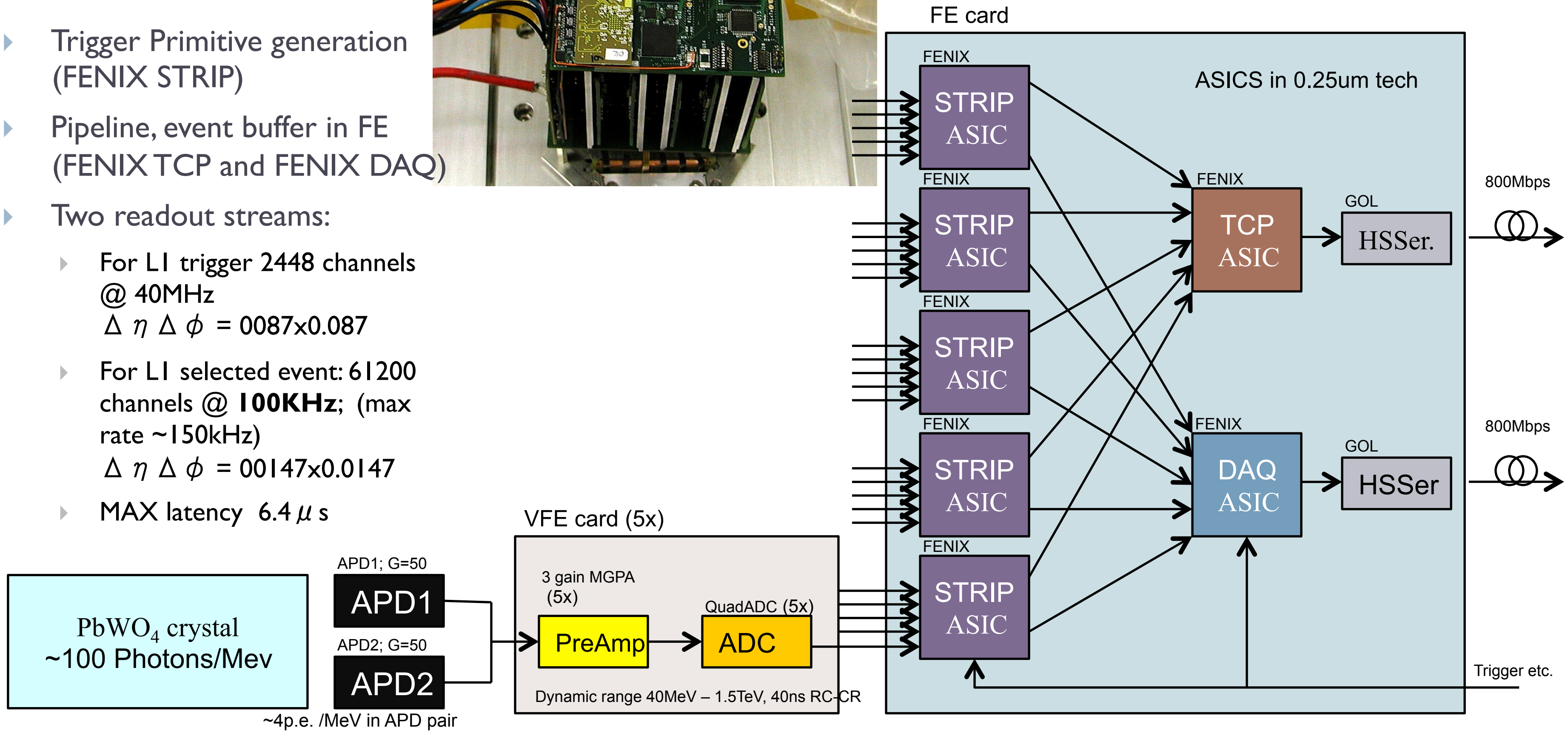


Very good performance. No known problems with VPT so far.

Legacy ECAL Barrel FE electronics system

- Modularity
  - 25 channels = 1 trigger tower
- Features
  - Trigger Primitive generation (FENIX STRIP)
  - Pipeline, event buffer in FE (FENIX TCP and FENIX DAQ)
  - Two readout streams:
    - For L1 trigger 2448 channels @ 40MHz $\Delta\eta\Delta\phi$ = 0087x0.087
    - For L1 selected event: 61200 channels @ **100KHz**; (max rate ~150kHz) $\Delta\eta\Delta\phi$ = 00147x0.0147
    - MAX latency 6.4 μ s



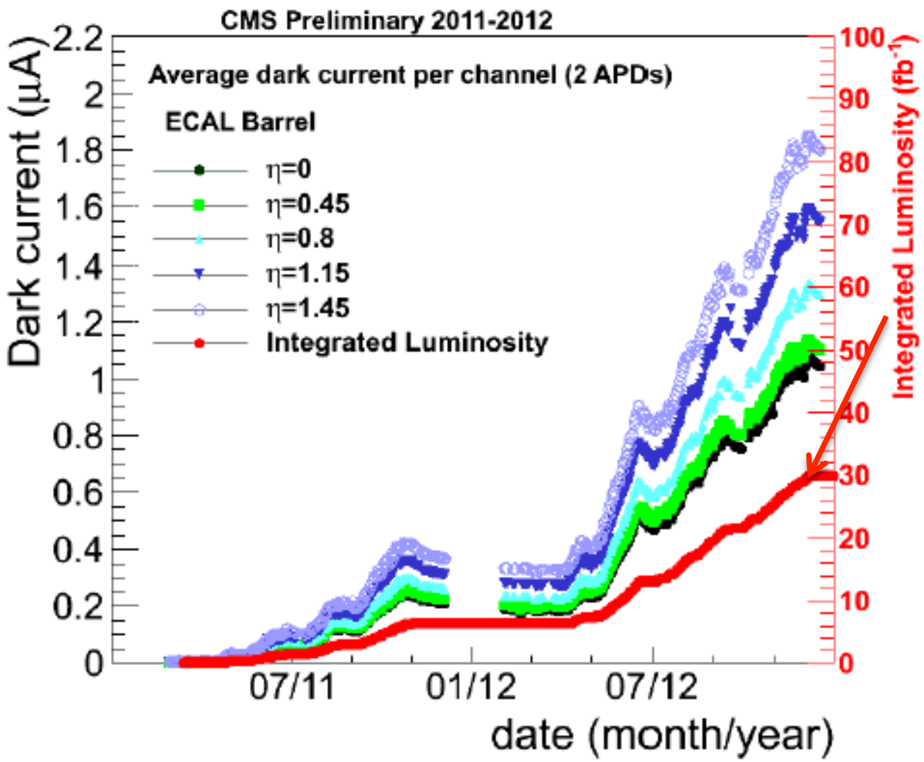


ECAL in hadron collider environment

- Known problems, taken into account by design:
  - Degradation of the signal due to the crystals transmission radiation damage
  - Increase of the APD dark current due to the neutron irradiation
- Foreseen:
  - Wide dynamic ADC range, possibility to tune APD gain
  - High precision light monitoring system
  - On-line calibration with physical events
  - Low-noise design of preamplifiers
  - Big margin in the HV supply current
  - Possible operation at lower temperature
- New problem, discovered after the start of operation
  - Anomalous signals from energy deposition directly in the bulk of the APD
    - Mimic the physical signals, have relatively high rate, much be rejected at trigger level
  - Trigger-level suppression: use of the hardware diagnostics bits to tag the suspicious events
  - Offline: special algorithms to tag and suppress anomalous signals

APD dark current

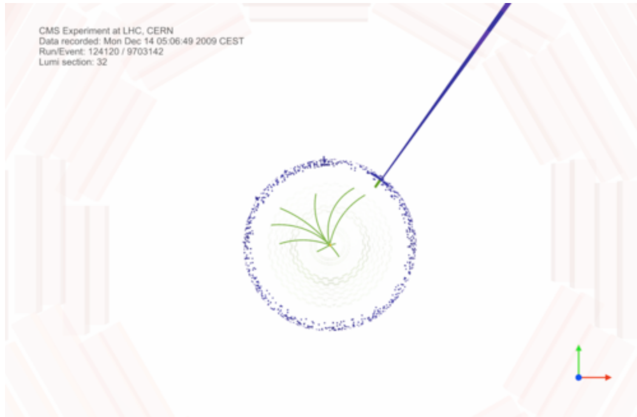
- Noise due to dark current in bulk from irradiation damage (proportional to square root of integrated luminosity)
- Noise contribution due to dark current increase from ~10 MeV at the start of operation to ~100MeV at the end of LHC operation and can reach 400MeV for HL_LHC → become a dominant factor in ECAL energy resolution
- Option to cool the ECAL from 18C to 8C, should reduce dark current by factor 2 (noise by factor √2)
- Shortening the signal shaping time will also mitigate noise (shorter integration time means less noise)



For mode details: poster of **Francesca Addesa** "Performance prospects for the CMS electromagnetic calorimeter barrel APDs for LHC runs 2 and 3: radiation hardness and longevity". Poster session Rouge.

Anomalous signals (“spikes”)

- Energy deposited directly in the bulk of APD produce a signal
  - Equivalent to multi-GeV photon shower
  - Faster than e.m. shower signal
  - Isolated channel
  - Rate proportional to instantaneous luminosity

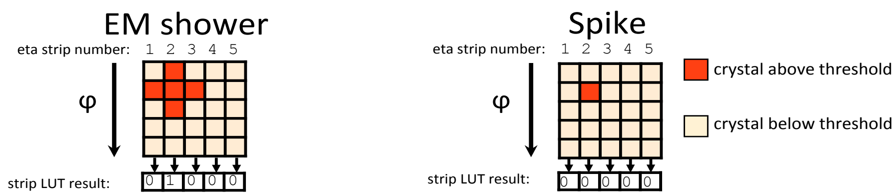


Trigger-level spikes suppression: sFGVB algorithm

Spike-like energy deposits are prevented from triggering CMS by exploiting additional functionality of the ECAL front-end electronics - the Strip Fine-grained Veto Bit (sFGVB).

This bit flags spike-like energy deposits by comparing the E_T recorded for each channel (in a 5x5 crystal region) to a configurable threshold.

An EM shower should have more than 1 crystal above threshold. A spike will typically contain only one high energy crystal. A look-up table is used to flag strips of 5 channels that contain >1 hit above threshold



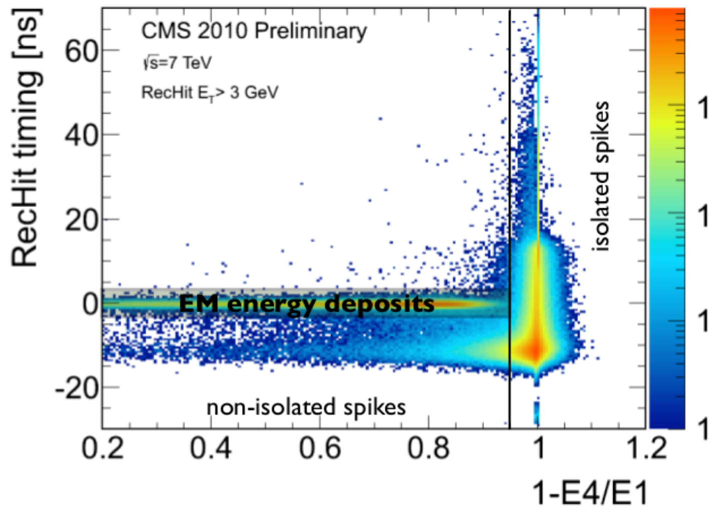
The sFGVB bit is defined as the OR of the 5 strip LUT results

sFGVB result: **1** (shower-like) sFGVB result: **0** (spike-like)

A tower is prevented from triggering CMS if the sFGVB is spike-like and the tower transverse energy is greater than a configurable threshold

1 The sFGVB has been measured to reject >95% of spikes with transverse energy greater than 8 GeV, with a small (<1%) effect on the efficiency for triggering real electrons with p_T>20 GeV

D.Petit. Upgrade week DESY, June 2013



Legacy ECAL FE electronics system, Summary

- Current ECAL FE electronics fits to the CMS design goals
- Very good performance
- Design features (including hidden ones) allow mitigation of the hostile environment – related problems

From LHC to HL_LHC

- Integrated luminosity
  - LHC: 300fb^{-1}by 2023 → HL-LHC: 3000fb^{-1} by 2035
- Instantaneous luminosity
  - LHC: 1×10^{34} cm^{-2}s^{-1} → HL-LHC: 5×10^{34} cm^{-2}s^{-1}

- Pileup
  - LHC: 30 → HL-LHC: 140
- Crystal transmission radiation damage (loss of signal)
  - HL-LHC: x5 LHC e.m. damage (saturates, ~ to the instantaneous luminosity)
  - HL-LHC : x10 hadron damage (~ to integrated luminosity)
- APD dark current
  - HL-LHC: x10 LHC (~ to integrated luminosity)

ECAL Barrel **detector**: $PbWO_4$ crystals and APDs will continue to work well in HL-LHC conditions. No replacement required.

HL-LHC: ECAL on-detector electronics requirements

- Requirements
  - Trigger rate up to 1 MHz
    - Legacy max ~150 kHz
  - Trigger latency up to ~20 us
    - Legacy max ~6 us
  - Full installation during LHC Long Shutdown 3 (2023-2025)
  - Maintained or improved reliability and availability
  - Improve the EB spike mitigation
- High on the wish list
  - ADC encoding: optimisation for new conditions, noise level, pile-up, spike rejection
  - Decrease the Low Voltage Current delivered to the Front End system in order to decrease the physical volume required for services
  - Robust failure mitigation scheme

Legacy ECAL on-detector electronics is incompatible with HL-LHC **trigger** system due to:

- Trigger rate
- Extended latency driven by tracker trigger

→ **Replacement required**

New on-detector electronics design

Legacy system:

- Digitizer at LHC clock, 40MHz
- Trigger Tower (5x5 crystals) – based readout
- Trigger primitives generated by FENIX chips on FE board are sent to L1trigger at 40MHz
- Readout at 100KHz MAX due to the limited optical data link speed, 0.8Gbps
  - L1 trigger for readout
  - On-board buffer → limited latency

Upgraded system:

- Digitizer at LHC clock, 40MHz
  - Possibility to increase digitization rate to mitigate pileup and noise problems
- Read ALL data from each crystal
  - 16bit x 25 crystals x 40MHz → 16Gbps per Trigger Tower
  - NO on-line trigger
  - NO latency limit
- Maximum use of the industrial products
- Common R&D for LHC experiments
  - Rad. Hard serializer: GBT Project

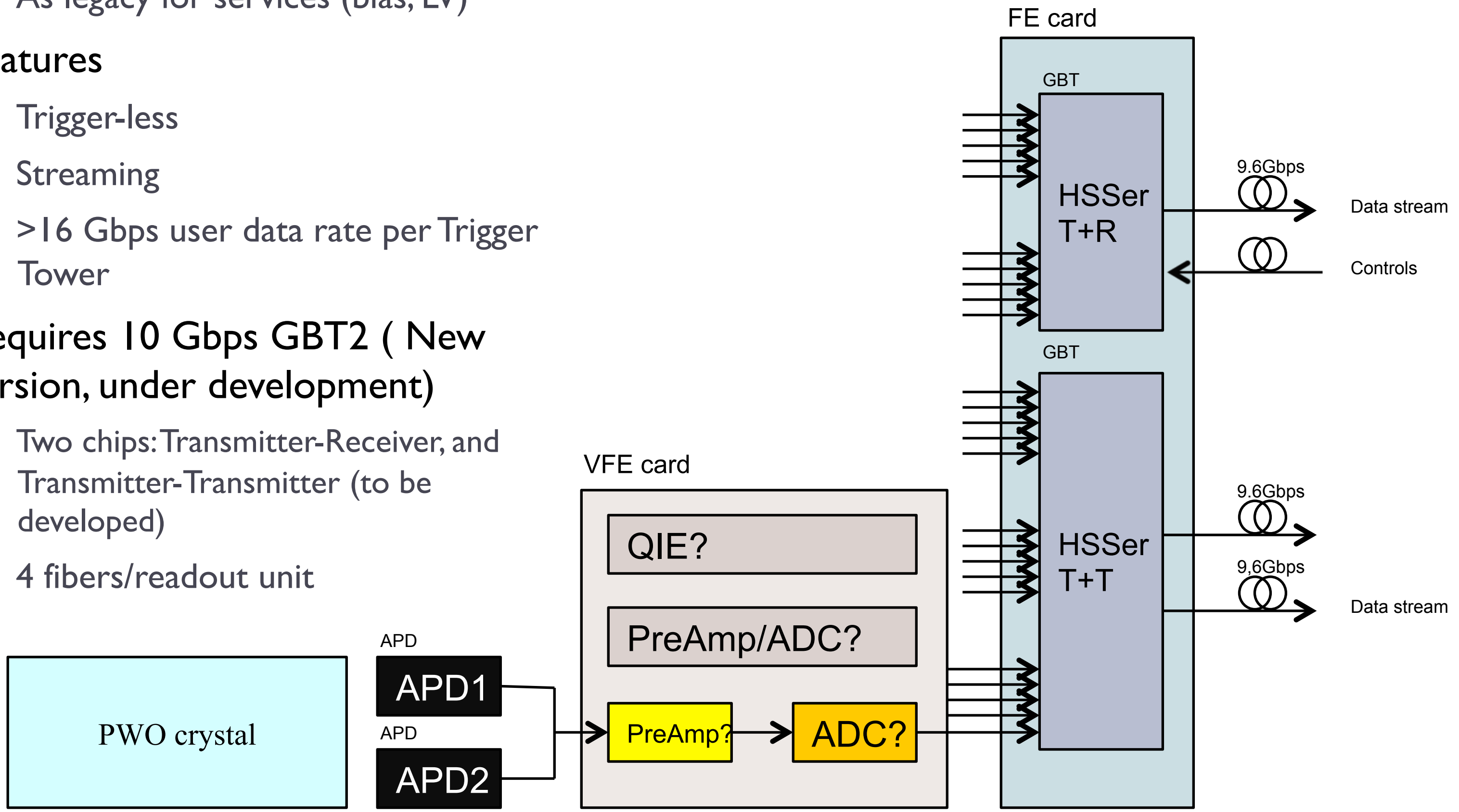
    P. Moreira et.Al **The GBT-SerDes ASIC prototype,** TOPICAL WORKSHOP ON ELECTRONICS FOR PARTICLE PHYSICS 2010, AACHEN, GERMANY
  - Rad. Hard optical transmitter/receiver: Versatile Link project

    J.Troska et.Al. **Versatile transceiver and transmitter production status,** TOPICAL WORKSHOP ON ELECTRONICS FOR PARTICLE PHYSICS 2013, PERUGIA, ITALY
  - Rad. Hard low voltage regulator

    S.Michelis et.Al. , **Custom DC-DC converters for distributing power in SLHC trackers,** Topical Workshop on Electronics for Particle Physics, 2008, Naxos, Greece

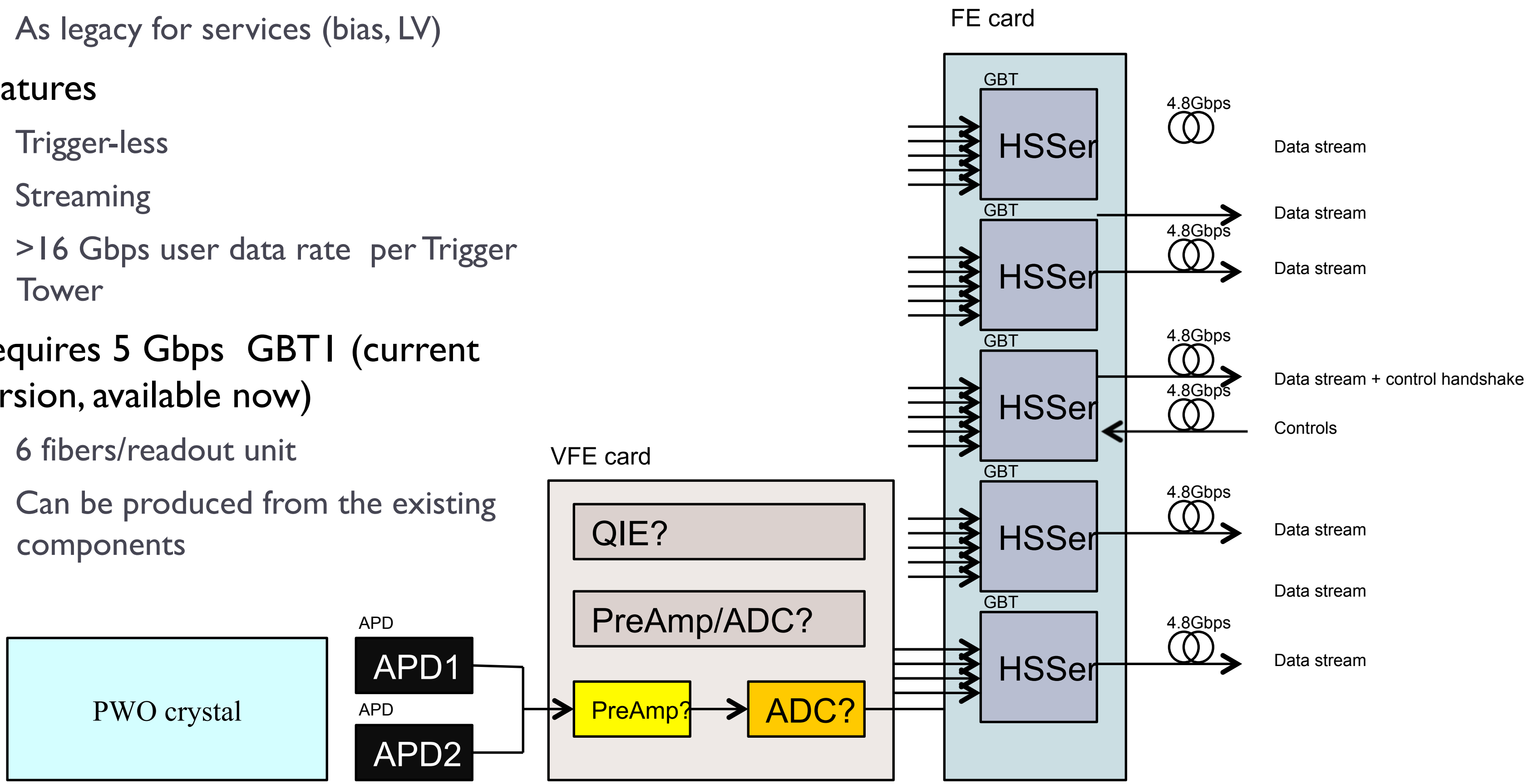
HL-LHC, ECAL barrel FE electronics
Design idea

- Modularity
  - 1 channel for readout and trigger. Trigger Tower mechanical modularity.
  - As legacy for services (bias, LV)
- Features
  - Trigger-less
  - Streaming
  - >16 Gbps user data rate per Trigger Tower
- Requires 10 Gbps GBT2 (New version, under development)
  - Two chips: Transmitter-Receiver, and Transmitter-Transmitter (to be developed)
  - 4 fibers/readout unit



HL-LHC, ECAL barrel FE electronics
Design idea, backup option

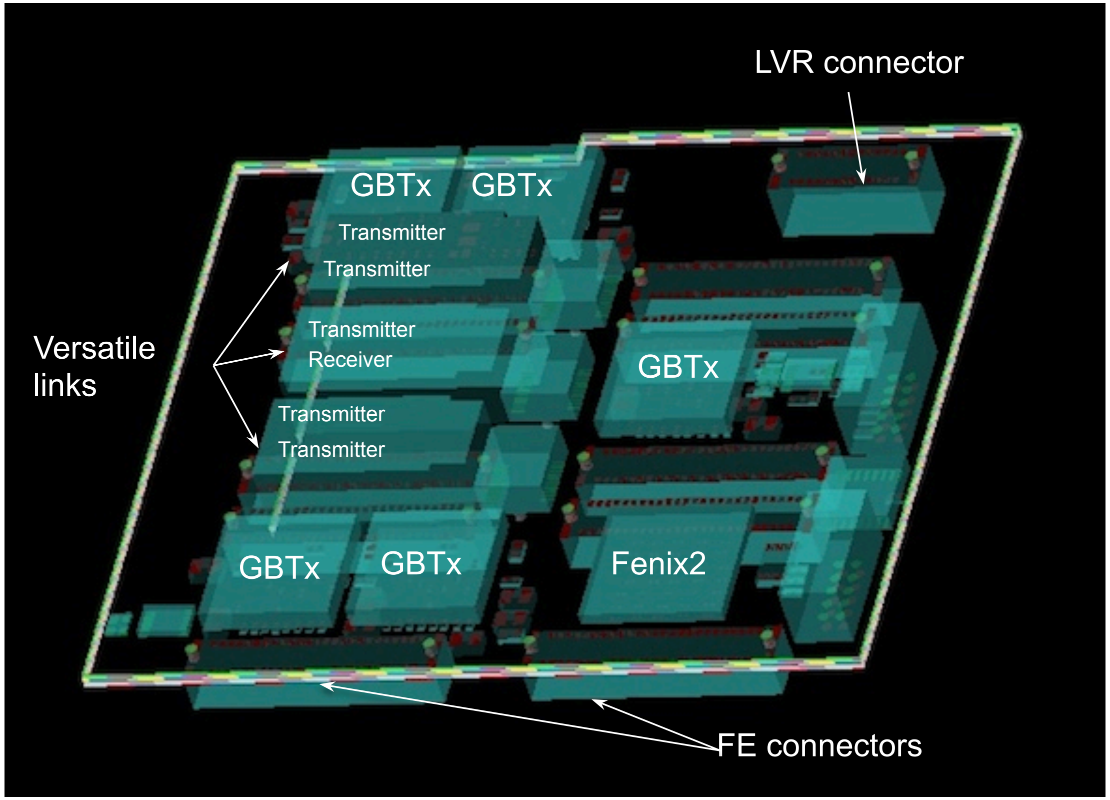
- Modularity
  - 1 channel for readout and trigger. Trigger Tower mechanical modularity.
  - As legacy for services (bias, LV)
- Features
  - Trigger-less
  - Streaming
  - >16 Gbps user data rate per Trigger Tower
- Requires 5 Gbps GBT1 (current version, available now)
  - 6 fibers/readout unit
  - Can be produced from the existing components



Upgraded FE card, conservative design

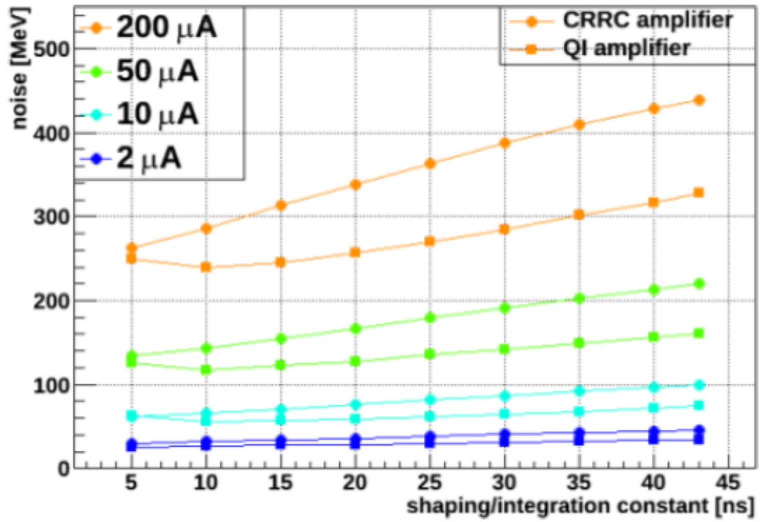
- Demonstrator board
- Can replace legacy FE board
- Fit to HL-LHC specs
- Can be produced mostly from the existing components
  - New FENIX2 chip should be developed

Sketch of the possible Upgrade FE implementation with the existing components

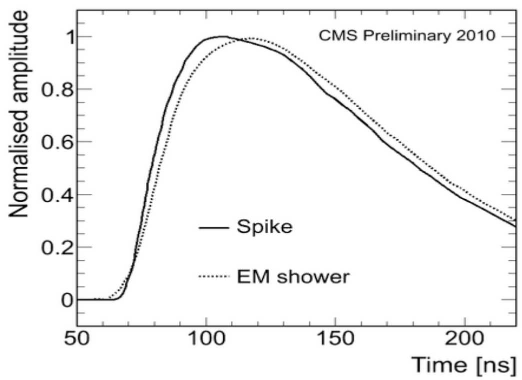


Upgrade of preamplifier and shaping

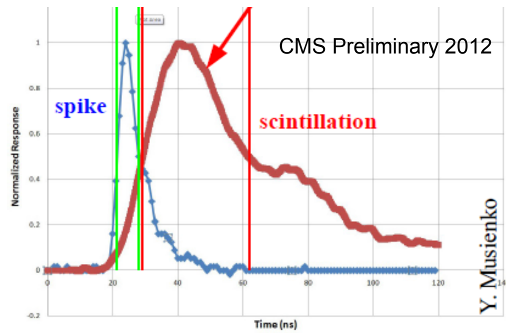
- Possible re-optimization of the pre-amplifier
  - Higher clock frequency: 80MHz, … : shorter shaping time to integrate less noise and less pile-up
  - Alternative approach
    - Integrate charge on one clock (25ns): a'la QIE chip, developed for CMS HCAL (Fermilab)
    - Complement with a precise time measurement
  - Spikes rejection by timing



CMS data: after preamp. and 40MHz digitizer.

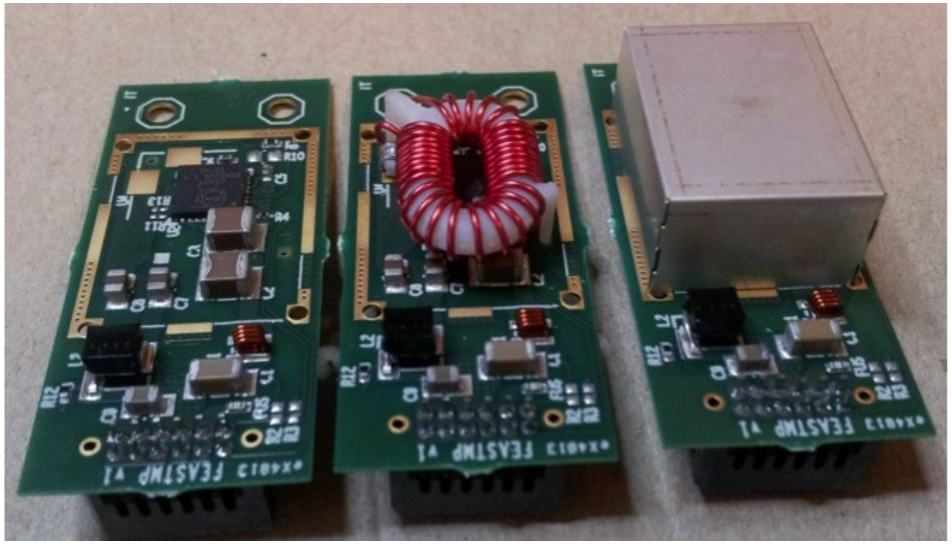


Test beam data: APD output, measured with 2GHz oscilloscope



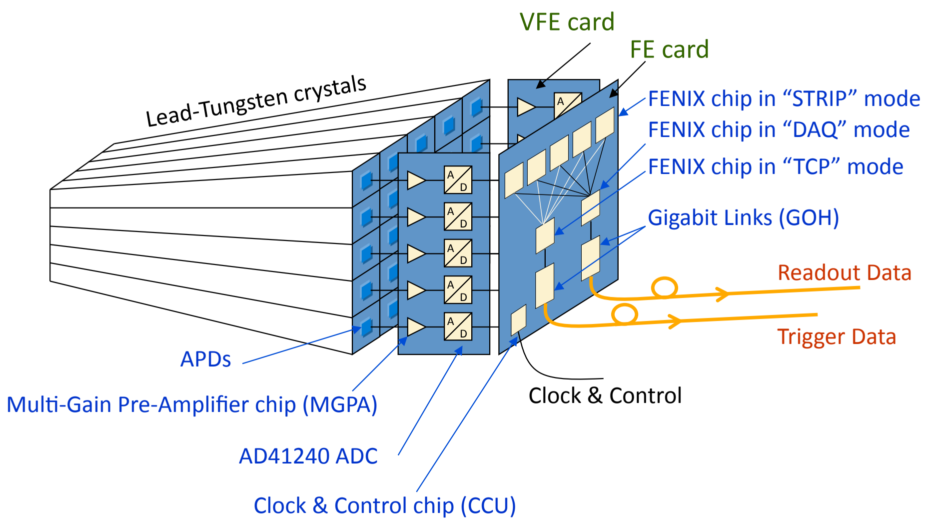
Low Voltage Regulators card

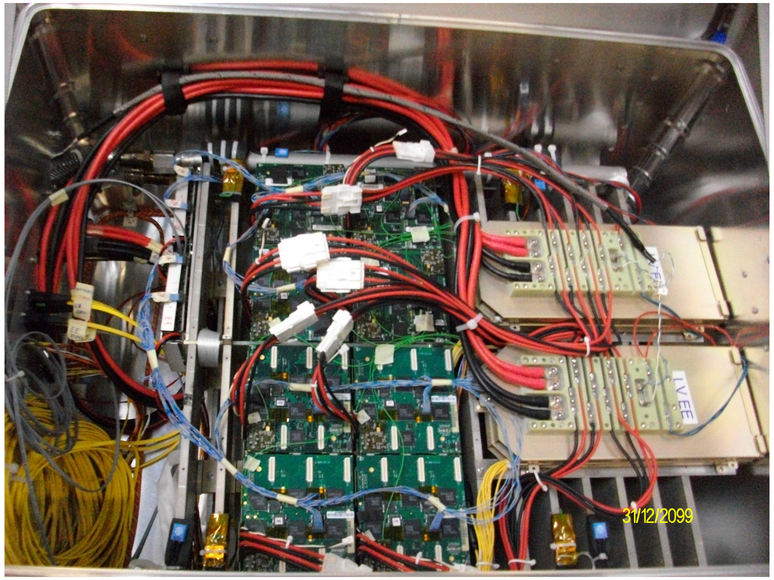
- Service card, depend on VFE and FE design
  - Possibly will supply several voltages
- CERN R&D project for new rad. hard and magnetic field tolerant DC-DC converter
  - Recent status described in ACES2014 by Federico Faccio, CERN. https://indico.cern.ch/event/287628/session/1/contribution/14/material/slides/0.pdf
  - Step-down conversion: 12V → 2.5V
  - Higher efficiency
  - ~2 times less current to deliver
  - Current design is optimized for ATLAS tracker. The form-factor is not suitable for ECAL. Customization is required



Longevity Study

- Some of the EB on-detector electronic components will be re-used in the upgraded version
  - APD + kapton cables
  - Motherboards (MB)
- Accelerated aging test of MB,VFE, FE, LVR and TRLB to 40 years (climatic chamber)
- No failures seen after 16 years equivalent ageing

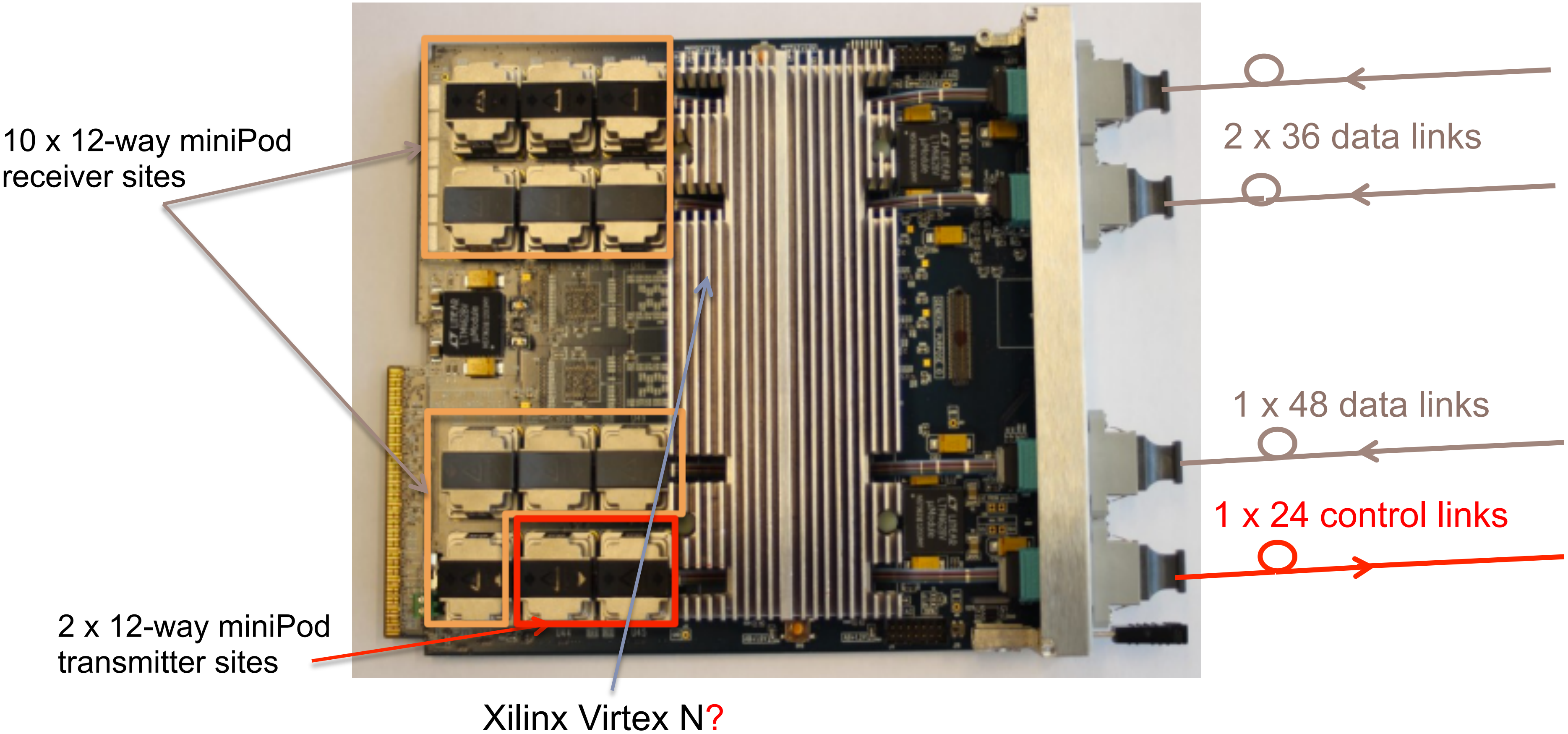




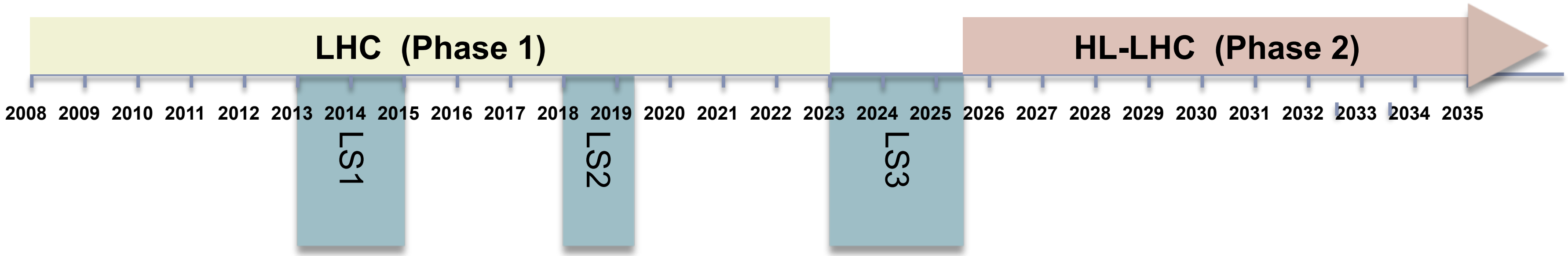
Front End Tester in Bat. 904

Off-detector electronics

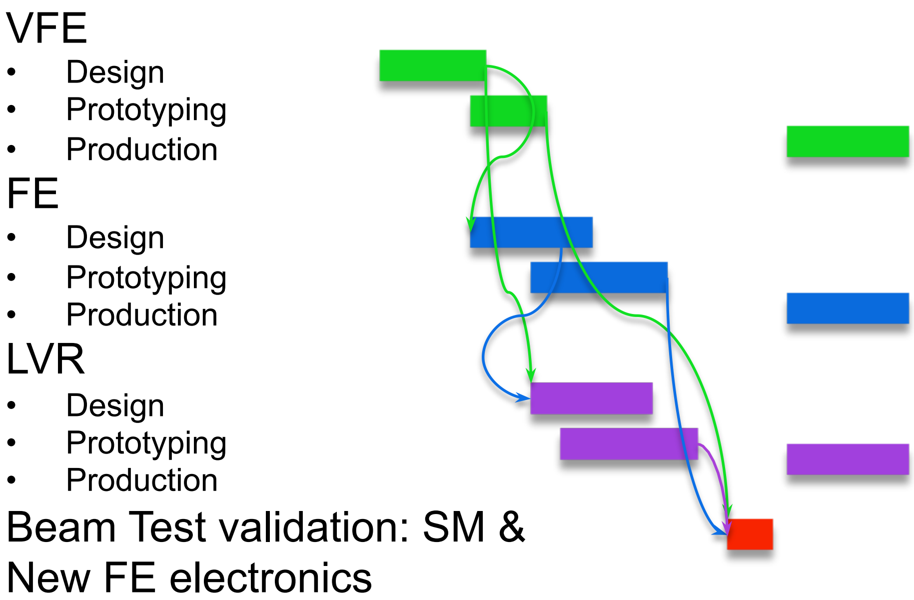
Option for Off-detector Control/Readout: Build new MP7' more suited to ECAL FE requirements



Schedule



LHC (Phase 1)
HL-LHC (Phase 2)
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
LS1
LS2
LS3



VFE
• Design
• Prototyping
• Production
FE
• Design
• Prototyping
• Production
LVR
• Design
• Prototyping
• Production
Beam Test validation: SM & New FE electronics

On-detector electronics upgrade logistics

- EB electronics upgrade will require extraction-installation-commissioning of 36 SuperModules
  - Required time – 18 months

Summary

- HL-LHC ECAL on-detector electronics upgrade is required by the trigger
- $PbWO_4$ crystals, APDs, Mother Boards, and 5x5 Trigger Tower structure will **not** be replaced
- Minimal upgrade would be replacement of the Front-End card
  - Can be implemented with the already existing components
  - Will benefit from the on-going CERN GBT2 and Versatile link-2 R&D projects
- Very-Front-End card can be optimized to better mitigate pileup and anomalous events in APD. R&D is on-going
- Low Voltage Regulator card will be upgraded to supply new VFE and FE cards
- Laser monitoring will be upgraded for better performance in HL-LHC environment
- Crystal ECAL EndCap will not survive in the HL-LHC environment , hence should be replaced. Two options are under study. One of which, Shashlyk calorimeter, can also use the upgraded EB VFE-FE electronics