The CLIC vertex detector

Pixel 2014
Niagara Falls, Canada
September 1st, 2014

Dominik Dannheim (CERN-LCD)
on behalf of the
CLIC detector and physics (CLICdp) collaboration

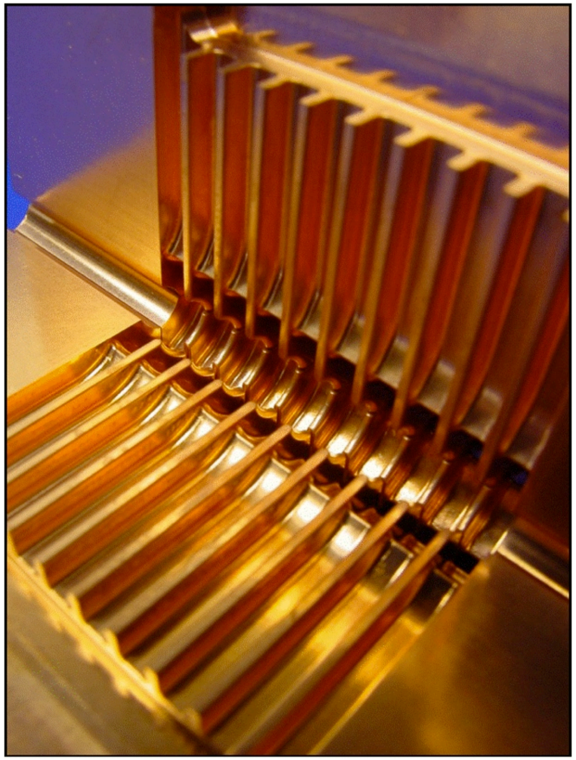
Outline

- Linear Collider concepts and physics goals
- Physics performance and vertex-detector requirements
- Detector optimization studies
- R&D on sensors and readout
- Powering, cooling and detector integration
- Summary / Conclusions

ILC and CLIC

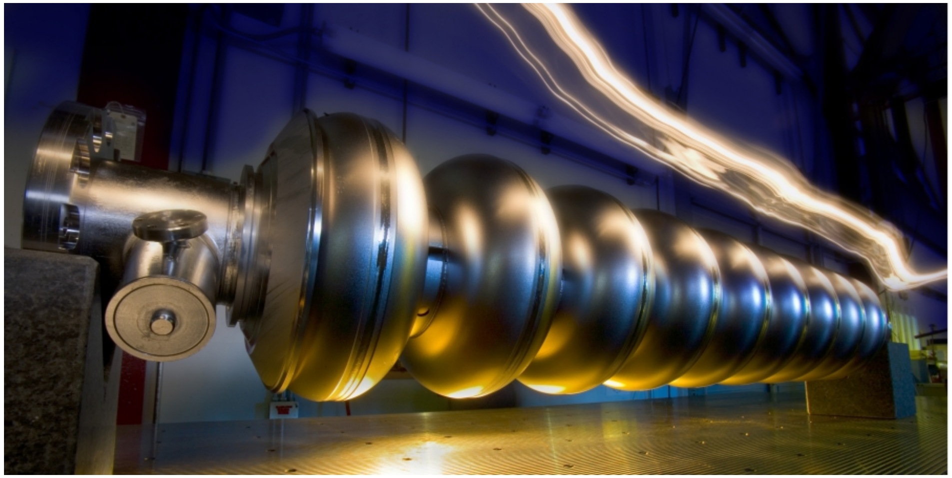
- linear e^+e^- colliders
- luminosities: few 10^{34} $cm^{-2}s^{-1}$
- length: up to ~48 km

CLIC



•2-beam acceleration scheme operated at room temperature
•gradient 100 MV/m
•√s up to 3 TeV
•physics + detector studies for 350 GeV - 3 TeV

ILC



•superconducting RF cavities (like XFEL)
•gradient 32 MV/m
•√s ≤ 500 GeV (1 TeV upgrade option)
•focus on ≤ 500 GeV, physics studies for 1 TeV

Focus of this talk is on the 3 TeV CLIC case

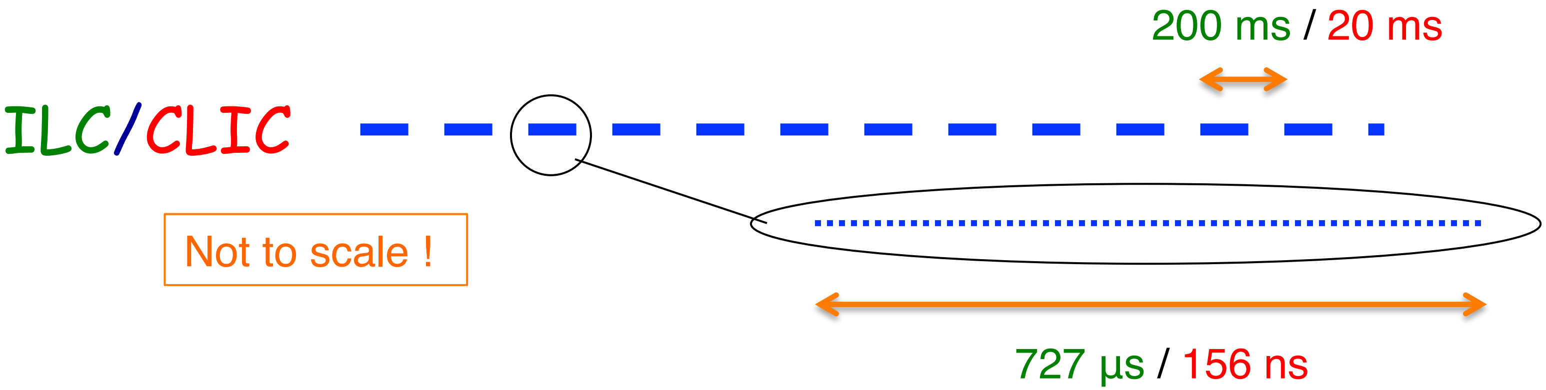
ILC and CLIC machine environment

	ILC at 500 GeV	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	$2x10^{34}$	6×10^{34}
BX separation	554 ns	0.5 ns
#BX / train	1312	312
Train duration	727 µs	156 ns
Train repetition rate	5 Hz	50 Hz
Duty cycle	0.36%	0.00078%
σ_x / σ_y (nm)	474 / 6	≈ 45 / 1
σ_z (µm)	300	44

ILC ESD-2012/2 / CLIC CDR

drives timing requirements for detectors

very small beam sizes → high rates of e^+e^- and hadronic backgrounds



200 ms / 20 ms

ILC/CLIC

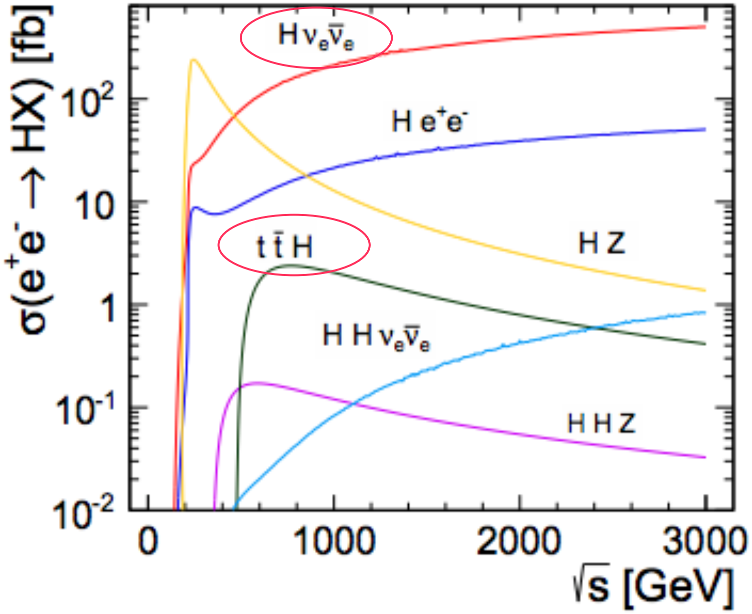
Not to scale !

727 µs / 156 ns

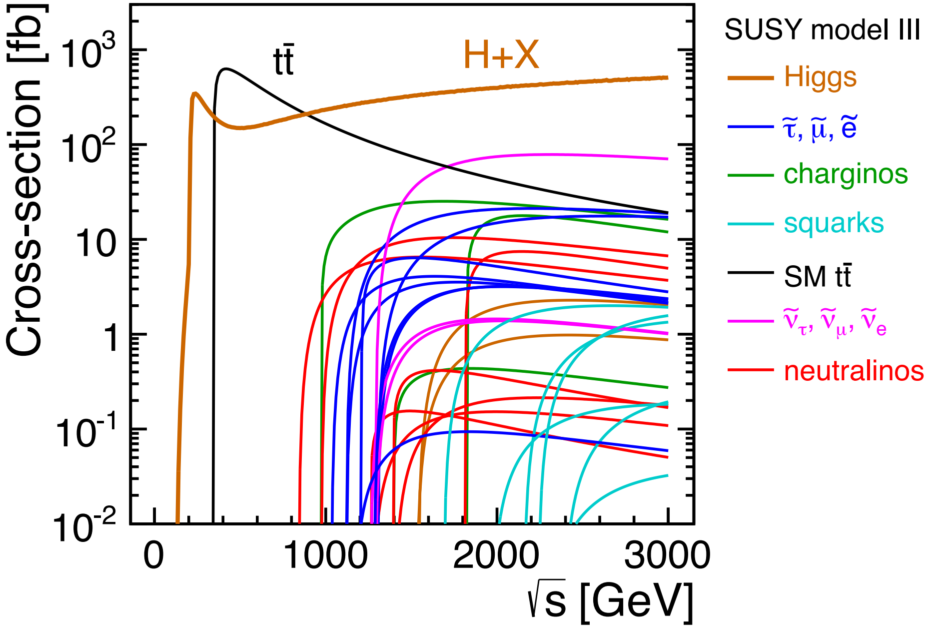
LC physics program

- Precision measurements of SM processes (Higgs, top, electroweak)
- Precision measurements of new physics potentially discovered at 14 TeV LHC
- Search for new physics: unique sensitivity to particles with electroweak charge

Higgs



SUSY example scenario

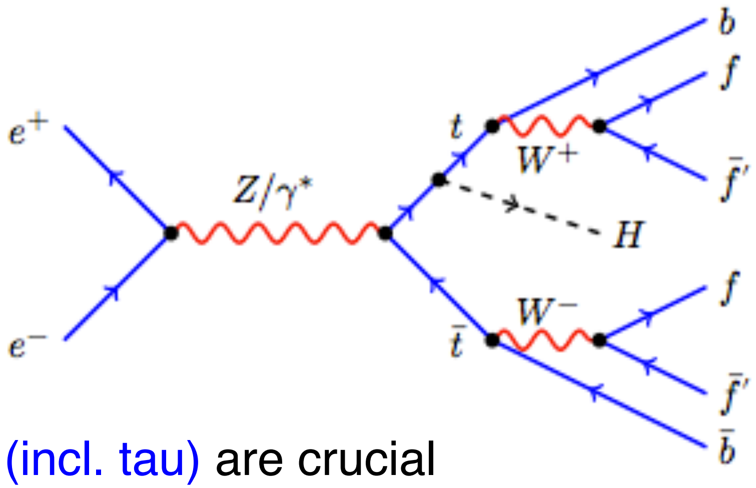


- Flavor tagging essential:
  - Separation of b, c and light jets, e.g. measurement of H→bb,cc,gg
  - Accurate reconstruction of top quarks in the decay t→Wb, e.g. for ttH

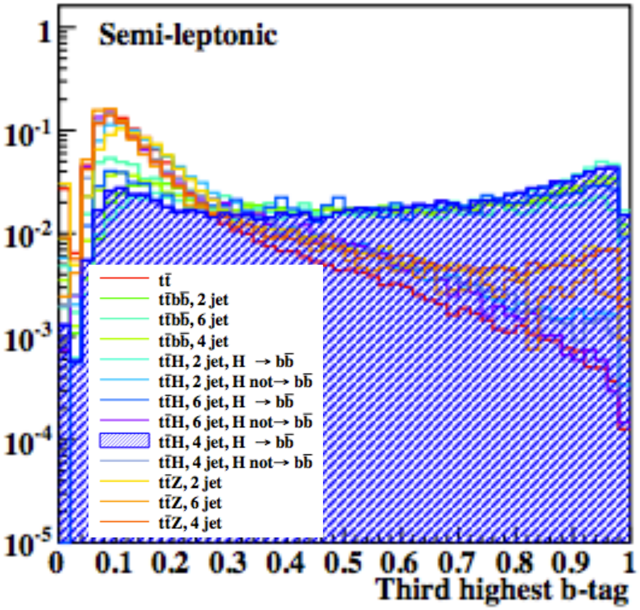
→need high-precision vertex detectors

Measurement of top Yukawa coupling

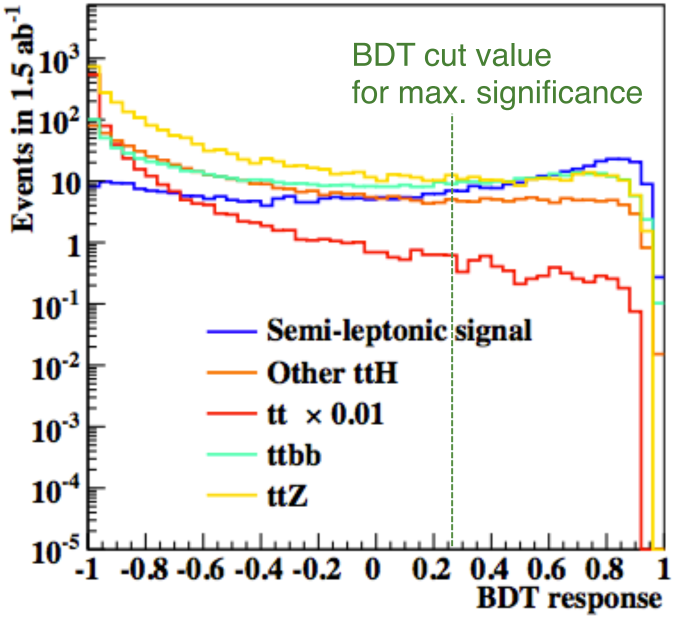
- Linear Collider allows for direct measurement of top Yukawa coupling through e^+e^- → ttH
- Full-simulation study for CLIC:
  - $\sqrt{s}$=1.4 TeV, L_{int}=1.5 ab^{-1}, unpolarised beams
  - γγ→hadrons pileup overlaid
  - consider H→bb, t→Wb
    → complex 6/8-jet final states
  - jet clustering, missing energy reconstruction, flavor tagging (4 b-jets), lepton reconstruction (incl. tau) are crucial



Third-highest b-tag value



multi-variate event selection

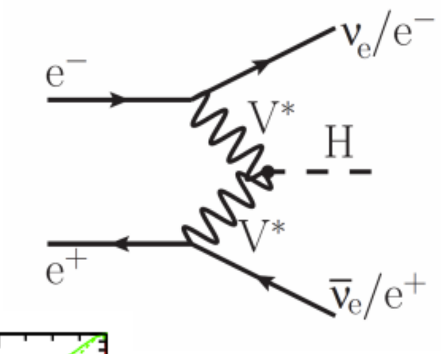


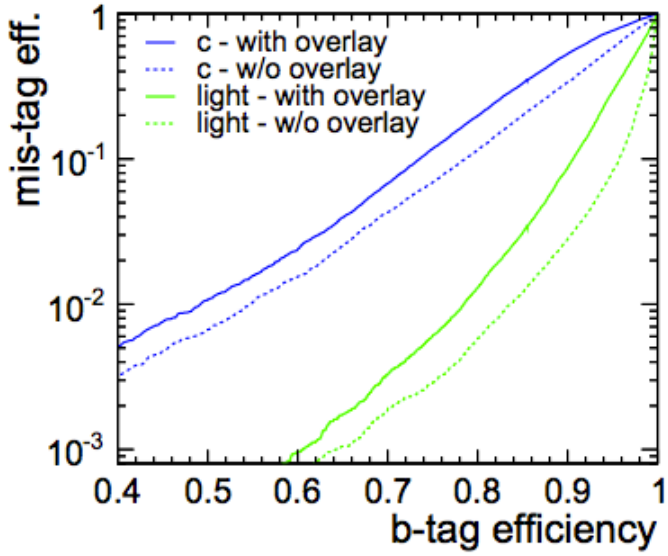
- Δ(σ(ttH)):
  12.0% (semi-lept.),
  10.9% (hadr.),
  8.1% combined
  → $\Delta(g_{ttH})$~4.3% (comb.)
- systematic uncert. negligible
- At LHC14, 3 ab^{-1}:
  $\Delta(g_{ttH})$~7-10%

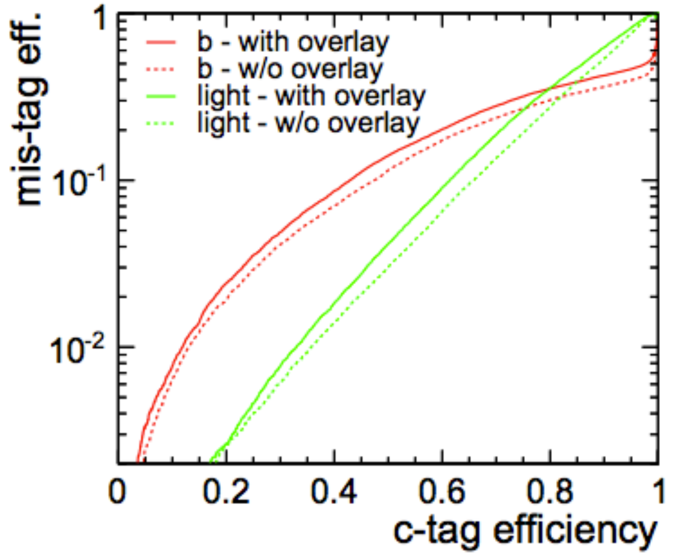
CLICdp Note-2014-001

Flavor tagging: impact on physics performance

- $e^+e^- \rightarrow H\nu\nu$: dominating Higgs production process at $\sqrt{s}$=3 TeV
- $\sigma \times$ BR measurement for the decays to bb and cc
- flavor tagging crucial for achievable precision







$\sqrt{s}$=3 TeV
L_{int}=2 ab^{-1}

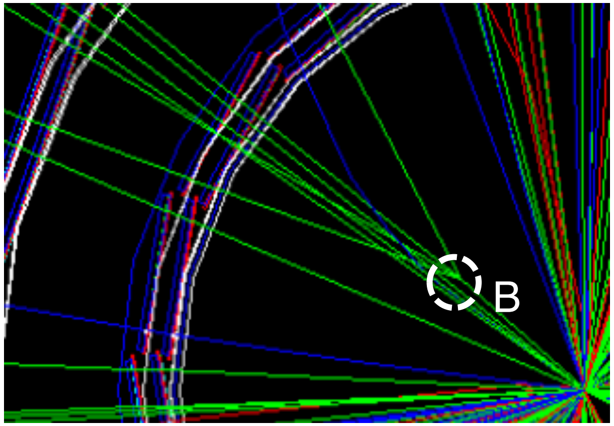
$p_{T,jet}$~70 GeV
E_{jet}~130 GeV

channel	**stat. unc. on σxBR**	**change for +/-20% fake r.**
H→bb	0.23%	0.24% / 0.21%
H→cc	3.1%	3.6% / 2.6%

LCD-Note-2011-036, CLICdp Note-2014-002

- consider ±20% change in fake rates
- sizeable effect, in particular for H→cc: 30% more integ. luminosity required for same precision when increasing fake rate by 20% (>1 year of additional running!)

LC vertex-detector requirements



- efficient tagging of heavy quarks through precise determination of displaced vertices:

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot \mathrm{GeV}^2/(p^2 \sin^3\theta)}$$

a~5 μm, b~10-15 μm

  - → good single point resolution: σ_{SP}~3 μm
    - → small pixels <~25x25 μm^2, analog readout
  - → low material budget: X ≲ 0.1-0.2% X_0 / layer
    - → corresponds to ~100-200 μm Si, including supports, cables, cooling
    - → low-power ASICs (~50 mW/cm^2) + gas-flow cooling

- 20-200 ms gaps between bunch trains → trigger-less readout, pulsed powering
- B = 4-5 T → Lorentz angle becomes important

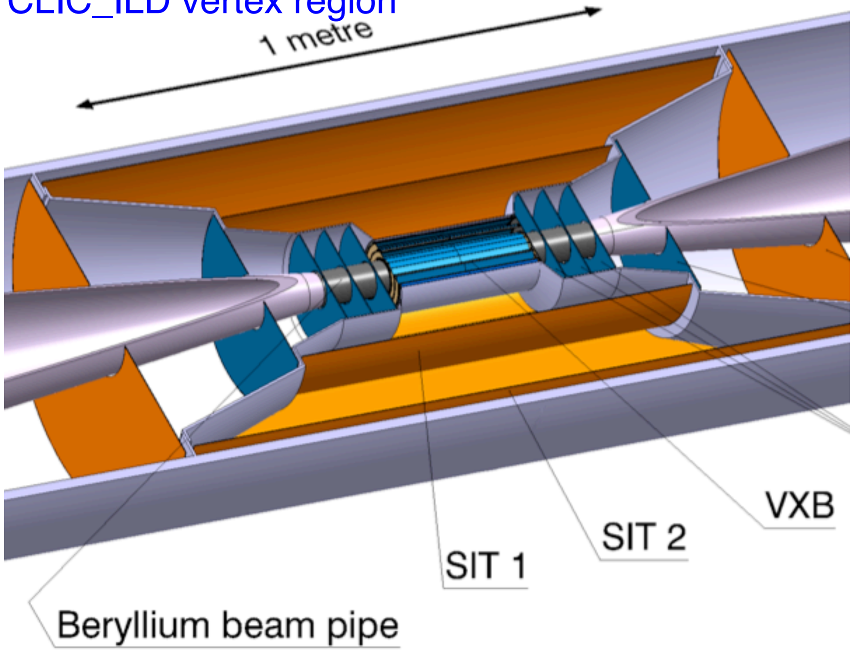
- few % maximum occupancy from beam-induced backgrounds → sets inner radius
- moderate radiation exposure (~10^4 below LHC!):
  - NIEL: < 10^{11} $n_{eq}/cm^2/y$
  - TID: < 1 kGy / year

- for CLIC: Time stamping with ~10 ns accuracy, to reject background
  → high-resistivity / depleted sensors, readout with precise time stamping

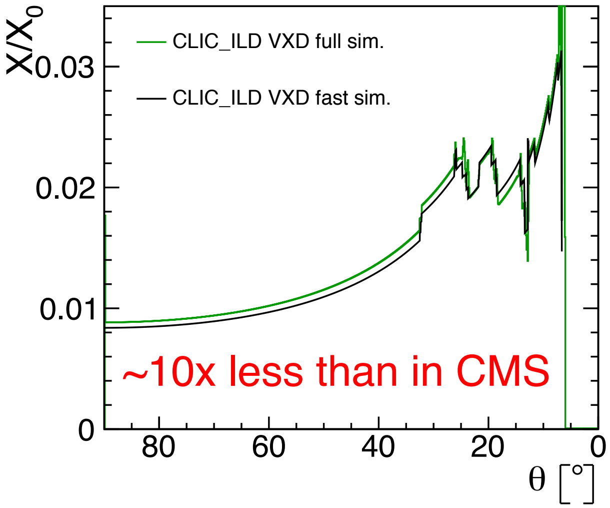
CLIC vertex-detector concept

- systematic optimization of geometries:
  - background occupancies
  - detector performance
- large coverage: $\theta > 7^{o}$ ($|\eta| < 2.8$)
- 3 double layers or 5 single layers
- $\sim 1\ m^2$ area, ~2G pixels
- $R_i \sim 30$ mm background-occupancies
- beam pipes with conical sections

CLIC_ILD vertex region

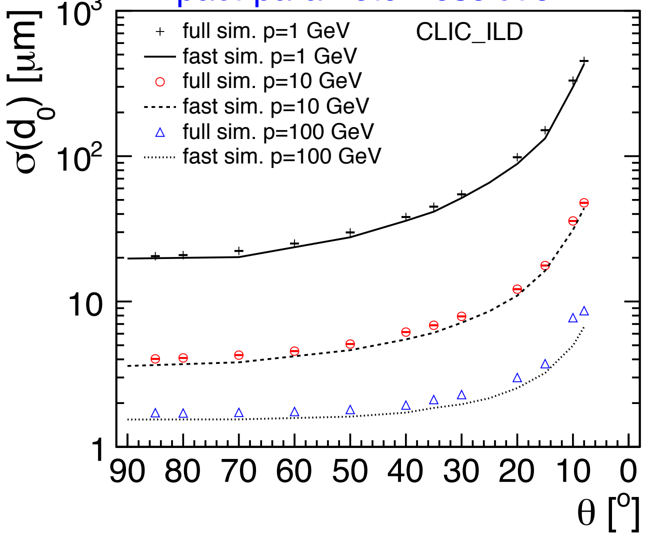


Vertex-detector material budget



~10x less than in CMS

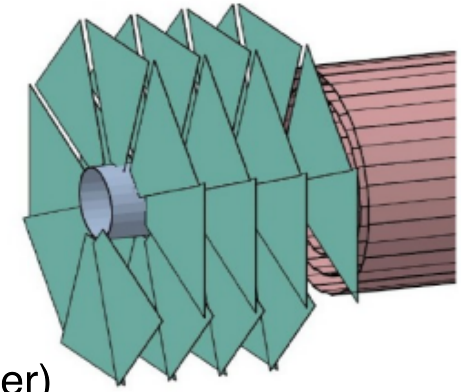
Impact-parameter resolution



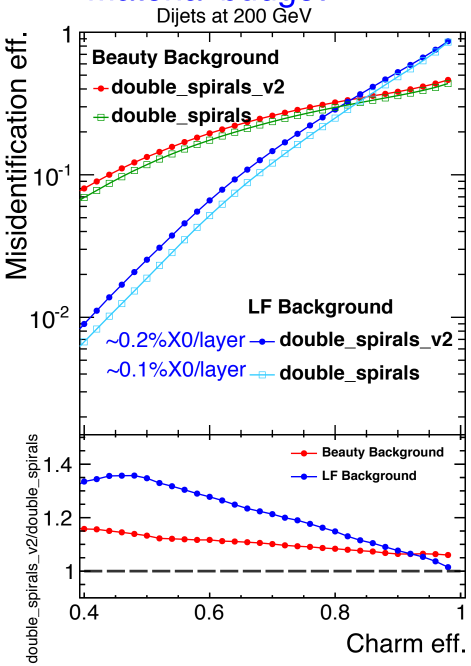
Flavor-tagging performance

- Use b- and c-tagging performance as benchmark for detector designs
- Challenging full-simulation study (multivariate analysis)
- Implementations following engineering studies:
  - Geometry with 2x more material in vertex layers
    → 5% - 35% degradation in performance
  - Spiral end-cap geometry (air-flow cooling)
    → few problematic regions with reduced coverage,
    otherwise similar performance as for disk geometry
  - 3 double layers vs. 5 single layers
    → small improvement for lower-energy jets (less material per layer)

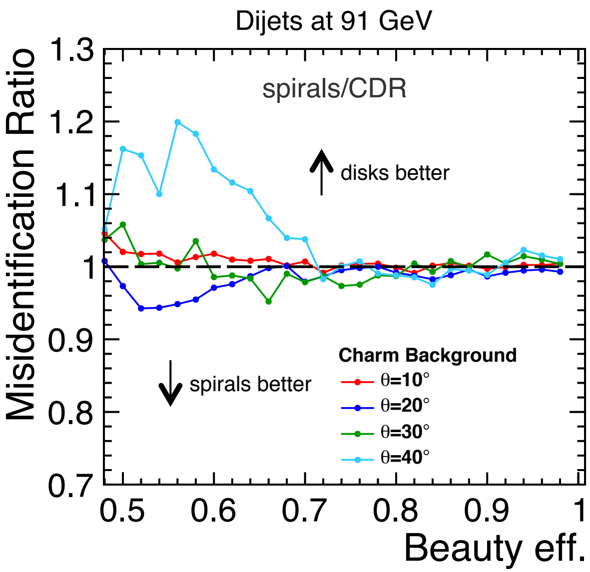
CLIC_SiD spiral end cap



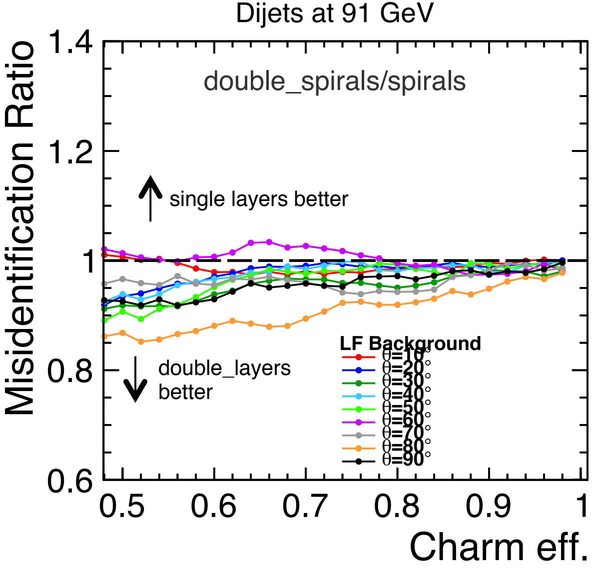
Material budget



Spiral end caps vs. disks

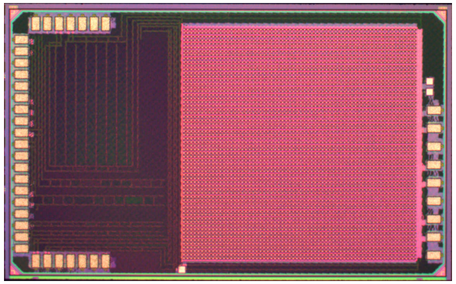


Double vs. single layers

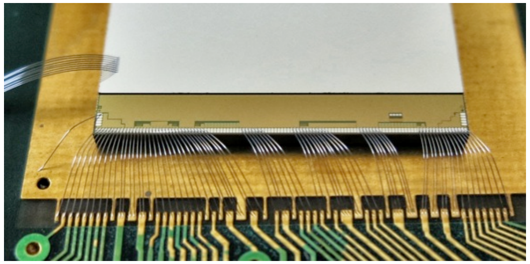


Vertex-detector technology R&D

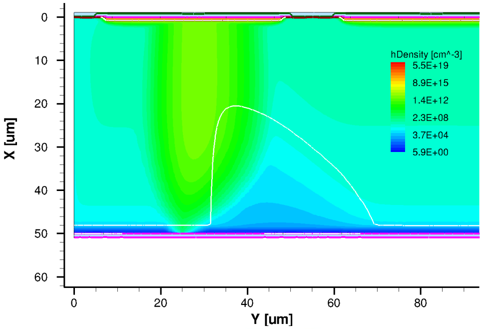
Readout ASICs



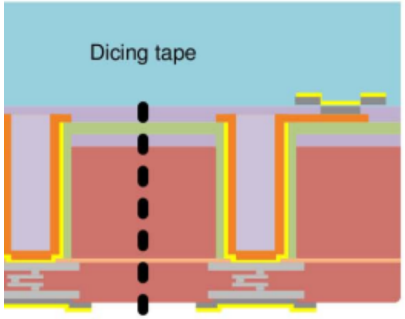
Sensors



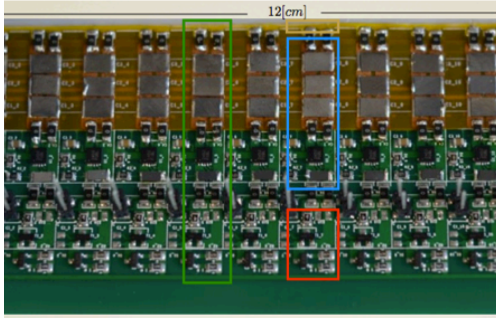
Simulations



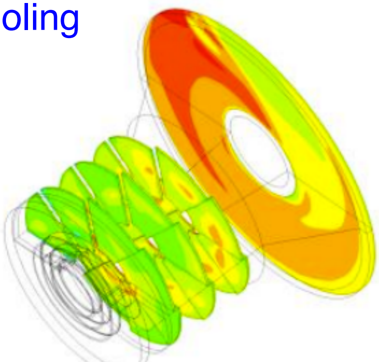
Interconnects



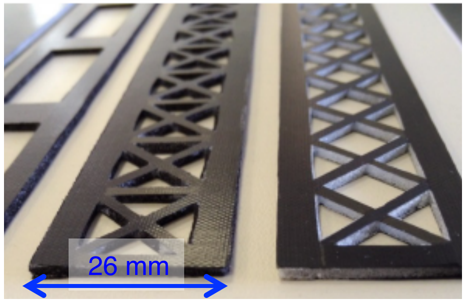
Powering



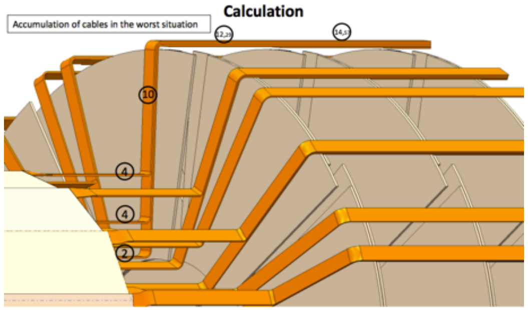
Cooling

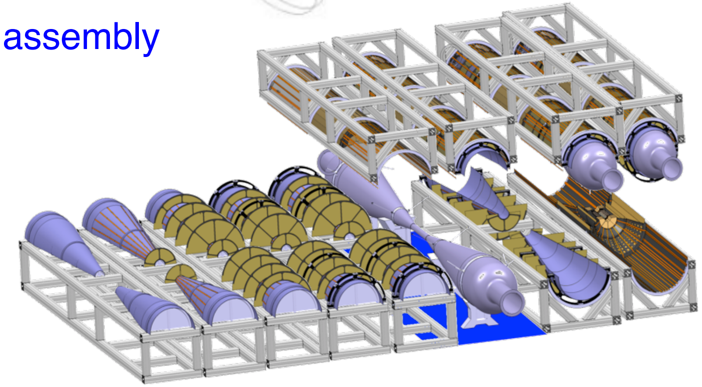


Light-weight supports



Detector integration + assembly





- Integrated R&D effort, simultaneously addressing CLIC vertex-detector challenges
- Examples for recent developments on the following slides

Medipix/Timepix hybrid r/o chip family

Chip	**Year**	**CMOS Process**	**Pitch [μm²]**	**Pixel operation modes**	**r/o mode**	**Main applications**
Timepix	2006	250 nm	55x55	∫ToT or ToA or γ counting	Sequential (full frame)	HEP (TPC)
Medipix3RX	2012	130 nm	55x55	γ counting	Sequential (full frame)	Medical
CLICpix demonstrator	2013	65 nm	25x25	ToT + ToA	Sequential (data comp.)	Test chip with 64x64 pixel matrix
Timepix3	2013	130 nm	55x55	ToT + ToA, γ counting + ∫TOT	Data driven	HEP, Medical
Velopix	2015	130 nm	55x55	ToT + ToA, γ counting + ∫TOT	Data driven	LHCb (10x Timepix3 rate)
Smallpix/ Timepix4	2016	65 nm (t.b.c.)	~35x35	ToT + ToA, γ counting + ∫TOT	Data driven	HEP, Medical
CLICpix	tbd	65 nm	25x25	ToT + ToA	Sequential (data comp.)	CLIC vertex detector

ToT: Time-over-Threshold
→ Energy
ToA: Time-of-Arrival
→ Time

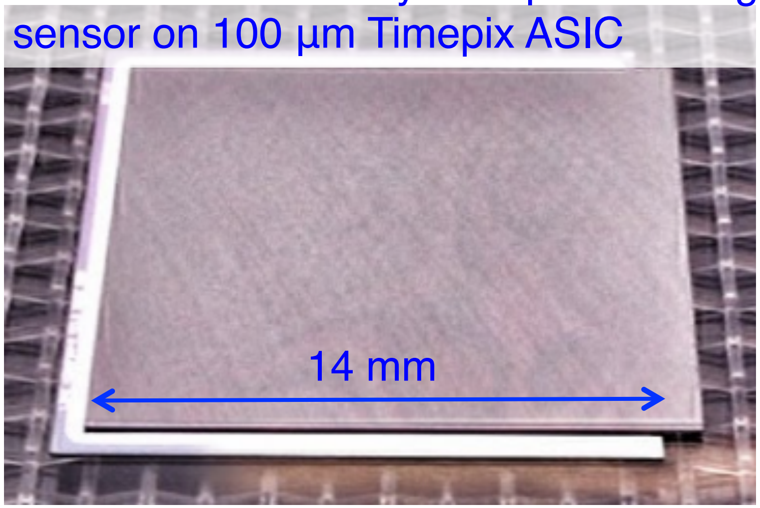
- Taking advantage of smaller feature sizes:
  - Increased functionality and/or
  - Reduced pixel size
  - Improved noise performance

Thin-sensors with Timepix r/o

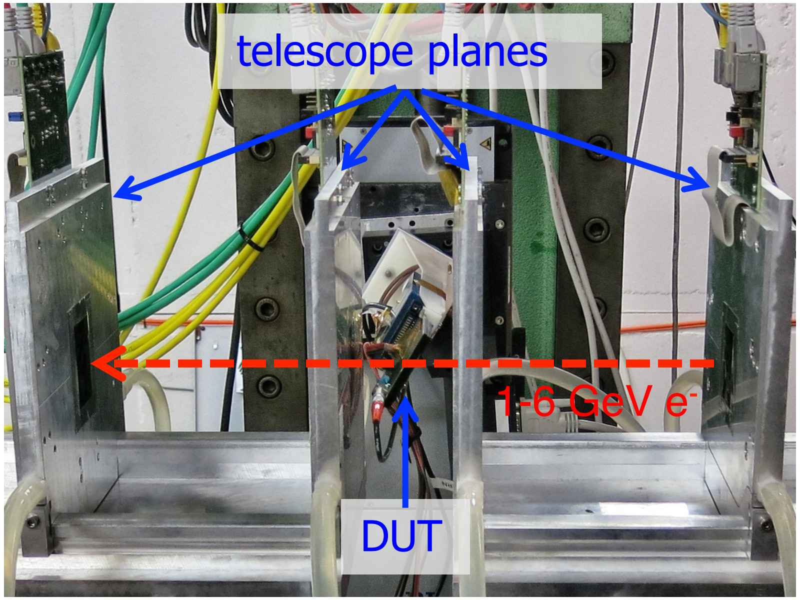
Micron + IZM and VTT/Advacam

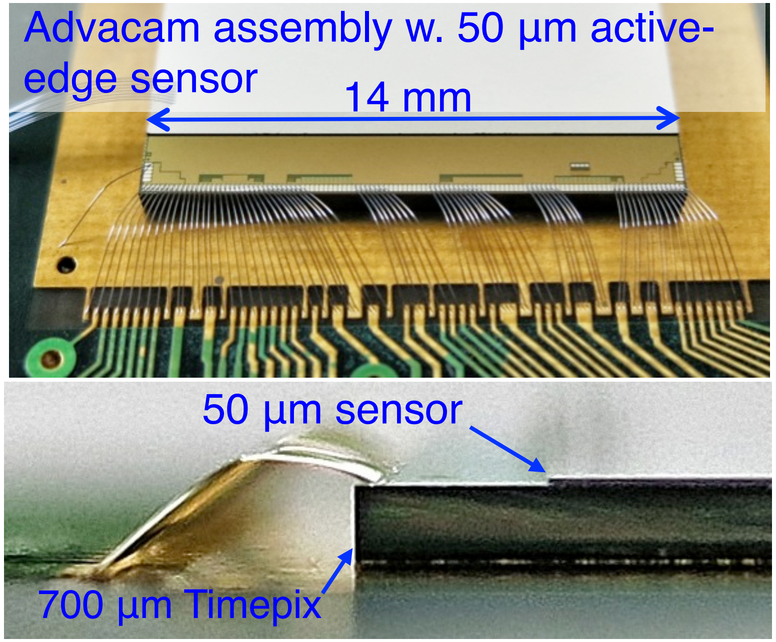
Timepix planar sensor assemblies (55 µm pitch)

- Test feasibility of ultra-thin sensors
- 50-300 µm sensor,100-750 µm ASIC thickness
- thinnest assembly: 100 µm sensor on 100 µm ASIC
- ultimate goal: 50 µm sensors on 50 µm ASICs
- Test-beam campaign at DESY II in 2013/14
  → **talk by M. Benoit on Tuesday**
- sensors with 25 µm² pitch for CLICpix: Sep.2014
  bump-bonding trials at SLAC (C. Kenney)


Micron/IZM assembly: 100 µm slim-edge sensor on 100 µm Timepix ASIC

DESY II test-beam setup




Advacam assembly w. 50 µm active-edge sensor

Timepix3

Timepix3 high-rate hybrid pixel readout ASIC:

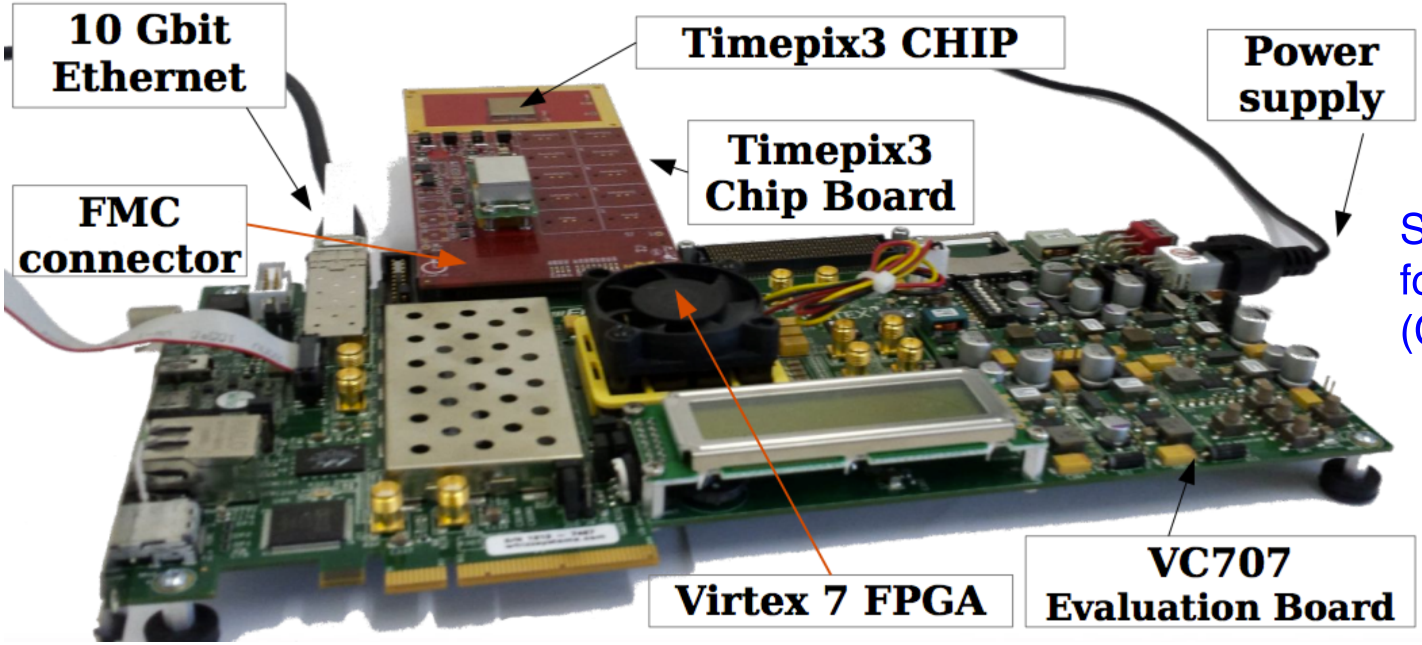
- 256x256 pixels, 55 um pitch
- implemented in 130 nm CMOS technology
- simultaneous ToT (10 bit) and ToA (18 bit), event counting, integr. ToT
- fast time stamping (1.6 ns precision)
- data-driven readout up to 40 Mhits/cm^2/s
- power-pulsing functionality

- assemblies with Advacam 300 μm sensors produced
- test-beam campaign in CERN-PS (August 2014) with AIDA/EUDET telescope

→ first results in **talk by M. Benoit on Tuesday**

- later this year: thin-sensor assemblies

Timepix3 in AIDA/ EUDET telescope



SPIDR r/o system for Timepix3 (CERN/NIKHEF)

S. Kulis

Hybrid r/o technology: CLICpix

- **65 nm CMOS hybrid r/o chip**, targeted to CLIC vertex detectors
- based on **Timepix/Medipix** chip family, synergy with HL-LHC pixel r/o projects (**RD53** collaboration on 65 nm r/o)

- **demonstrator chip** with 64 x 64 matrix
- **25 µm** pixel pitch
- simultaneous **4-bit time (TOA) and energy (TOT)** measurement per pixel

→ front-end **time slicing < 10 ns**

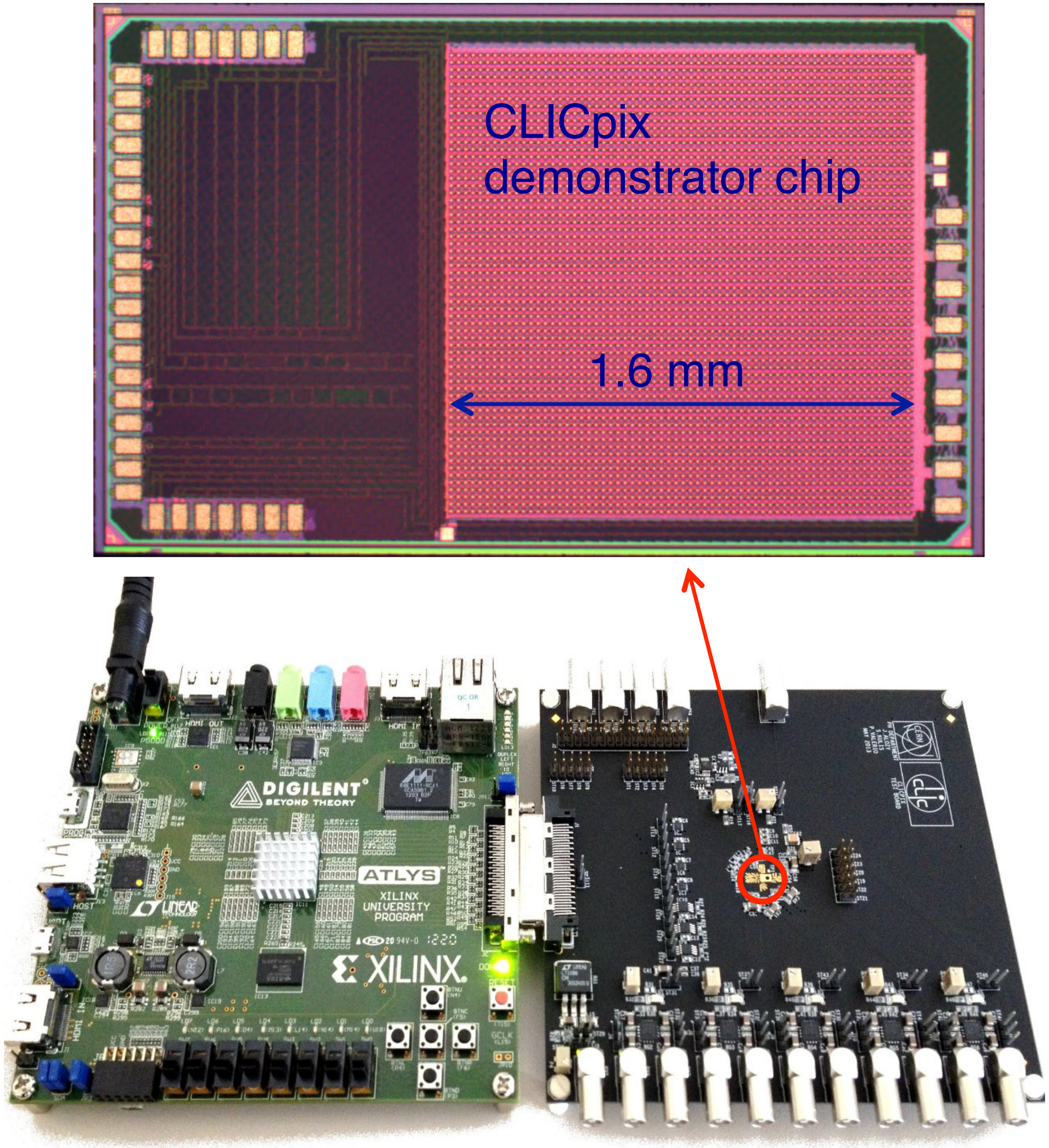
- selectable **compression** logic: pixel, cluster + column-based

→ full chip r/o in < 800 µs (at 10% occup., 320 MHz r/o clock)

- **power pulsing scheme**

→ $P_{avg} < 50$ mW/cm^2

- **r/o tests** on prototypes:
  - chip fully functional
  - agreement with simulations



S. Kulis, P. Valerio

CLICpix: summary

Parameter	**Unit**	**Simulation**	**Measurement**
Rise time	[ns]	50	-
TOA accuracy	[ns]	<10	<10
Gain	[mV/ke$^-$]	44	40 *
Dynamic range	[ke$^-$]	44 (configurable)	40 * (configur.)
Integr. nonlinearity (TOT)	[LSB]	<0.5	<0.5
ENC (w/o sensor)	[e$^-$]	~60	~55 *
DC spread σ (uncalibrated)	[e$^-$]	160	128 *
DC spread σ (calibrated)	[e$^-$]	24	22 *
Power consumption	[µW/pixel]	6.5	7

* results obtained with electrical test pulses

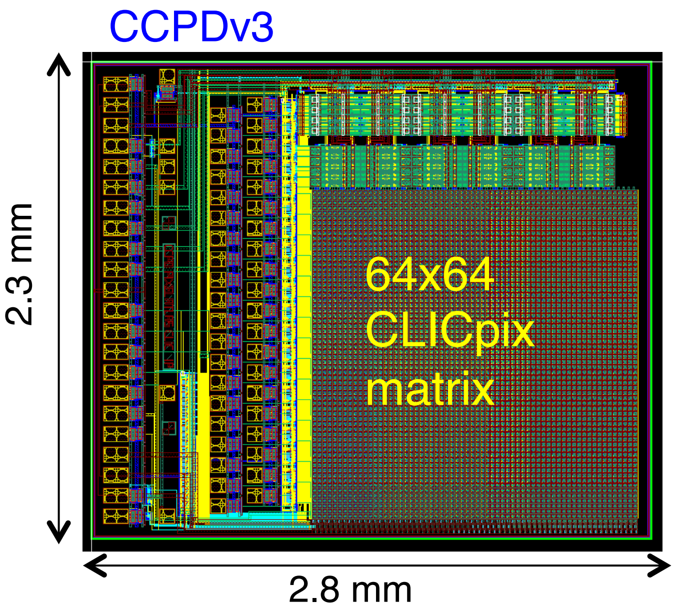
S. Kulis, P. Valerio

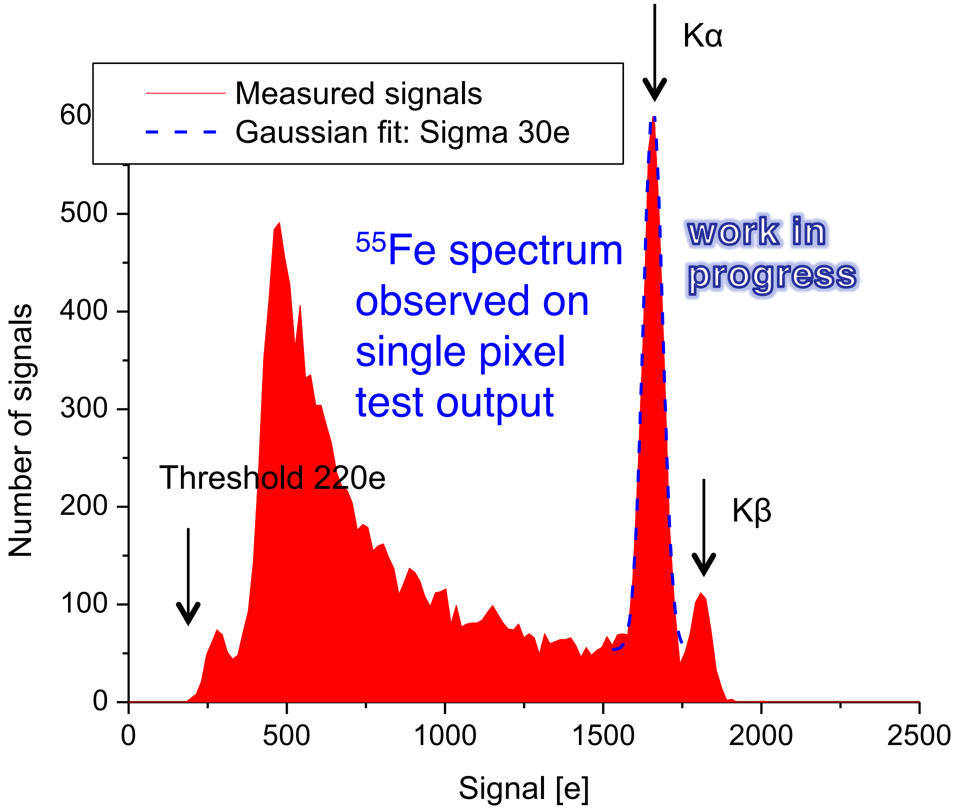
- good agreement between simulations and measurements
- power pulsing works according to specifications (~100x reduction of average power)
- programmable power on/off times, front-end wake up within ~15 µs
- Radiation test: chip functional up to ~250 MRad

HV-CMOS active sensor with capacitive coupling

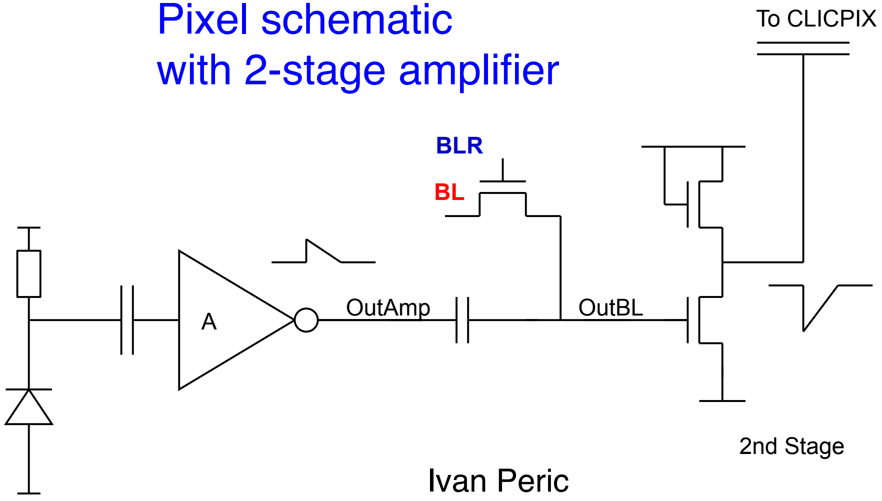
Capacitive Coupled Pixel Detector (CCPD)

- Prototype for ATLAS (FEI4) and CLIC: CCPDv3
- AMS H18 180 nm HV-CMOS process
- Vbias~30-100 V → depletion layer ~10-20 µm
- 2-stage amplifier, capacitive coupling to readout ASIC
- CLICpix 64x64 matrix (25 µm pitch)
- first tests with ^{55}Fe source: chip functional, good S/N
- more in **talk by I. Peric on Tuesday**

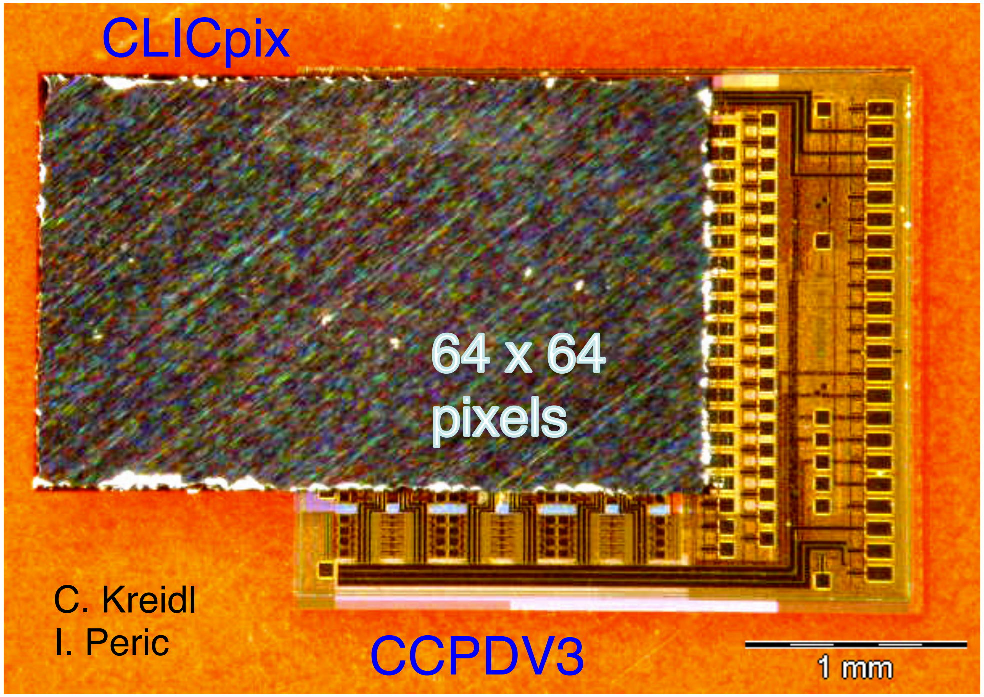


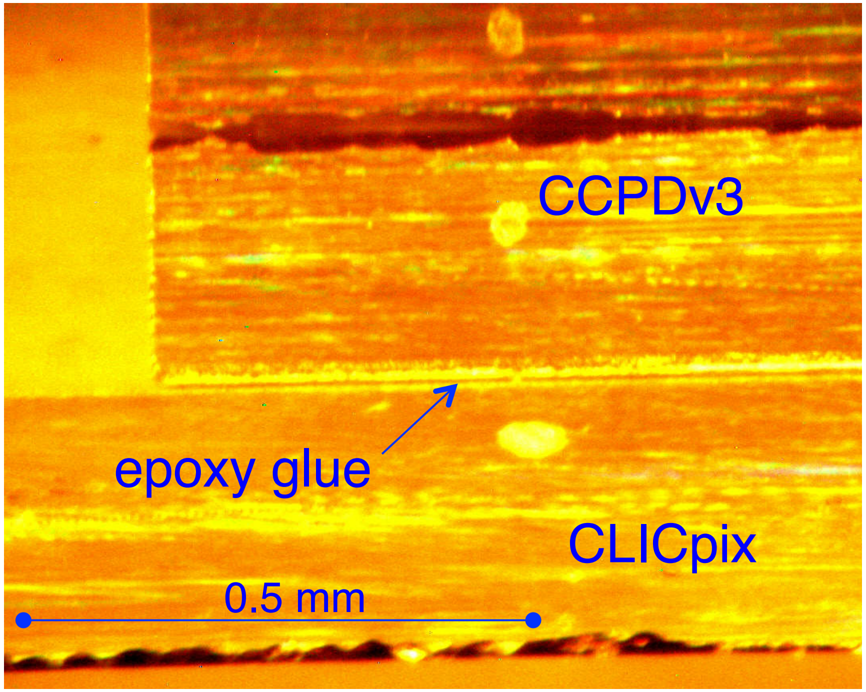


Pixel schematic with 2-stage amplifier

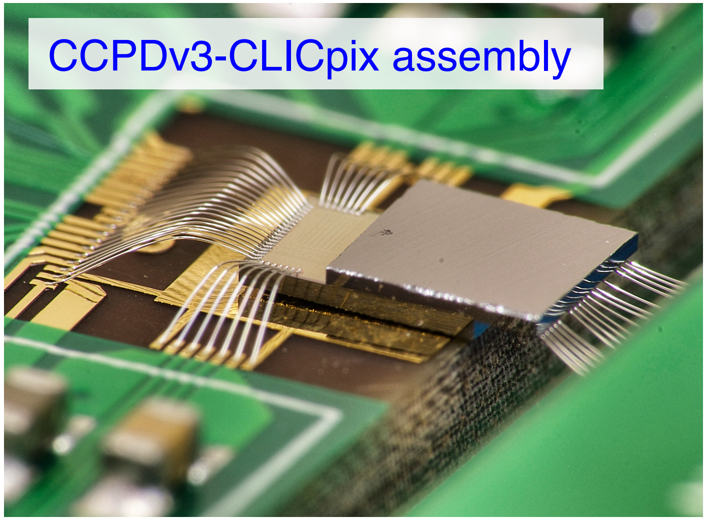


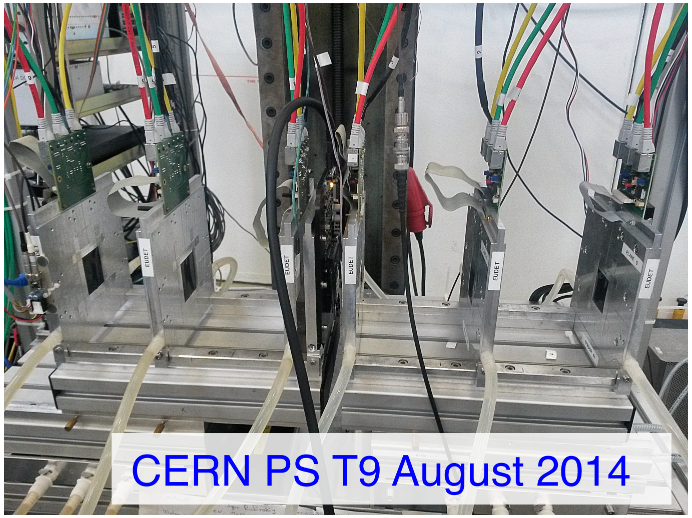
CCPDv3-CLICpix assemblies





- Capacitive coupling CCPDv3 - CLICpix through few µm of glue
- complex double-sided wire bonding
- successful test-beam integration in CERN PS with AIDA telescope


CCPDv3-CLICpix assembly

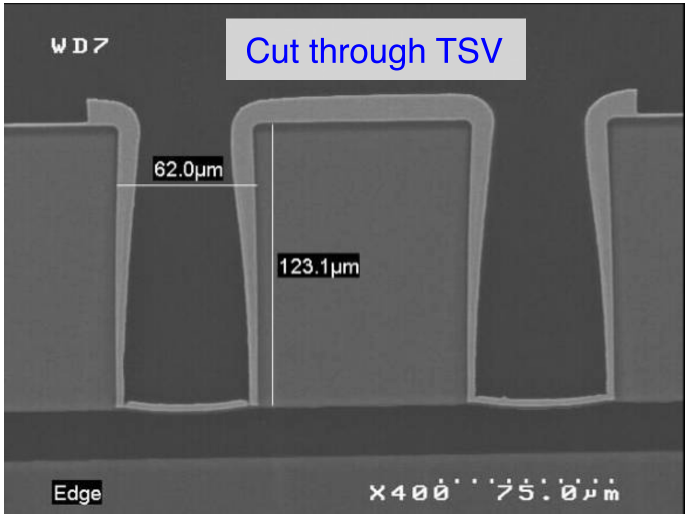

CERN PS T9 August 2014

Through-Silicon Vias (TSV)

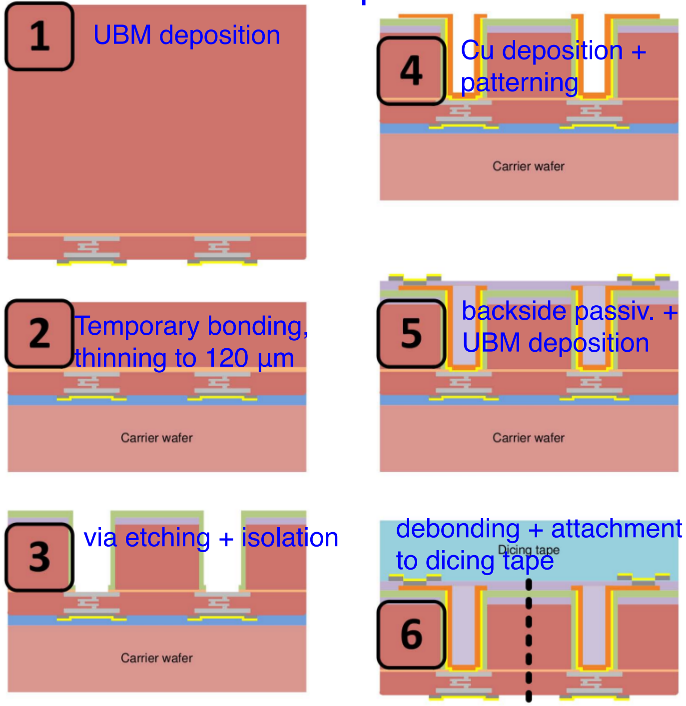
Through Silicon Via (TSV): vertical electrical connection
→ eliminates need for wirebonds
→ 4-side buttable chips
→ increased reliability, reduced material budget

TSV project (ALICE, CLIC, ACEOLE, AIDA) with CEA-Leti

- 130 nm Medipix(RX) wafers, via-last process
- first phase: demonstrated feasibility
- on-going second phase: demonstrate good yield
- launched third phase: TSV with Timepix3 50 μm thickness



CEA-Leti via-last process flow



1 UBM deposition

2 Temporary bonding, thinning to 120 μm

3 via etching + isolation

4 Cu deposition + patterning

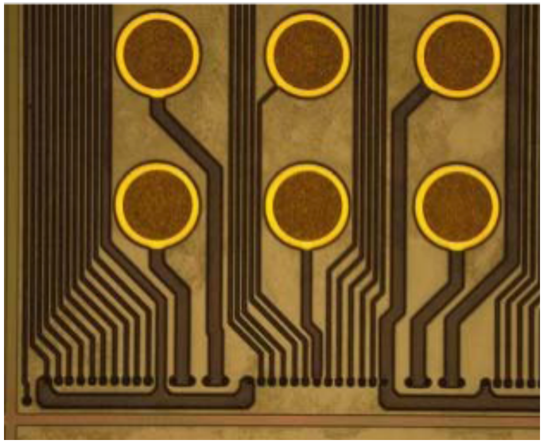
5 backside passiv. + UBM deposition

6 debonding + attachment to dicing tape

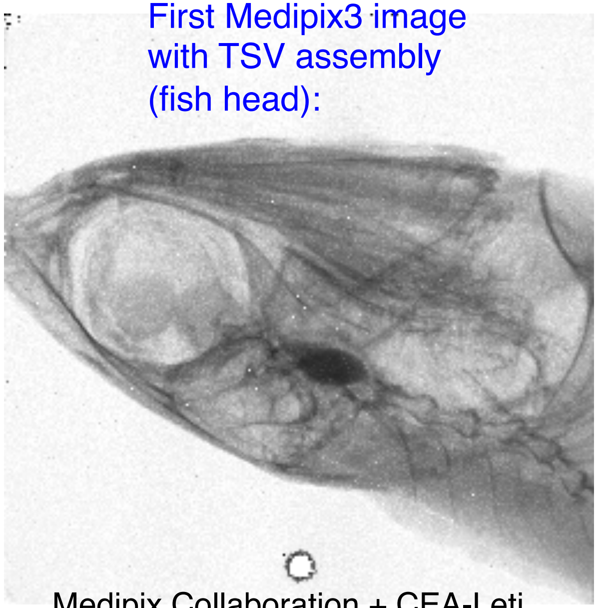
http://iopscience.iop.org/1748-0221/6/11/C11018/pdf/1748-0221_6_11_C11018.pdf

- 60 μm TSV diameter
- wafers thinned to 120 μm
- 5 μm copper layer for TSV

Medipix3 redistribution layer



First Medipix3 image with TSV assembly (fish head):



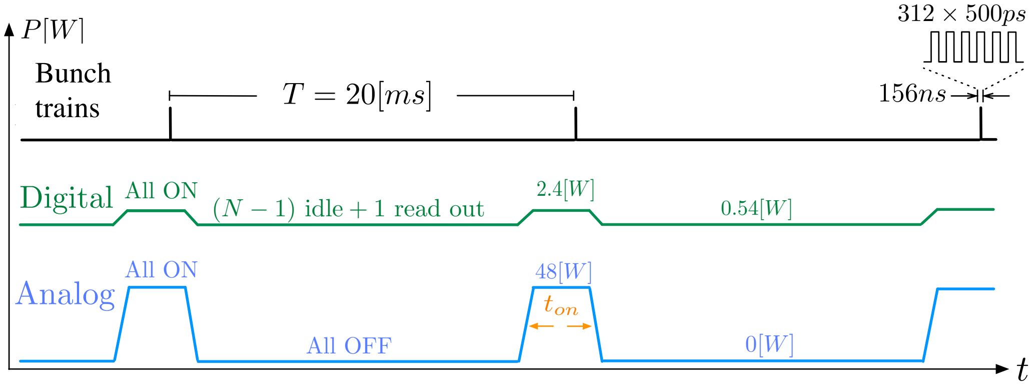
Medipix Collaboration + CEA-Leti

CLICpix power-pulsing + delivery concept

Small duty cycle of CLIC machine
→ turn off front end in gaps between bunch trains, to reduce avg. power

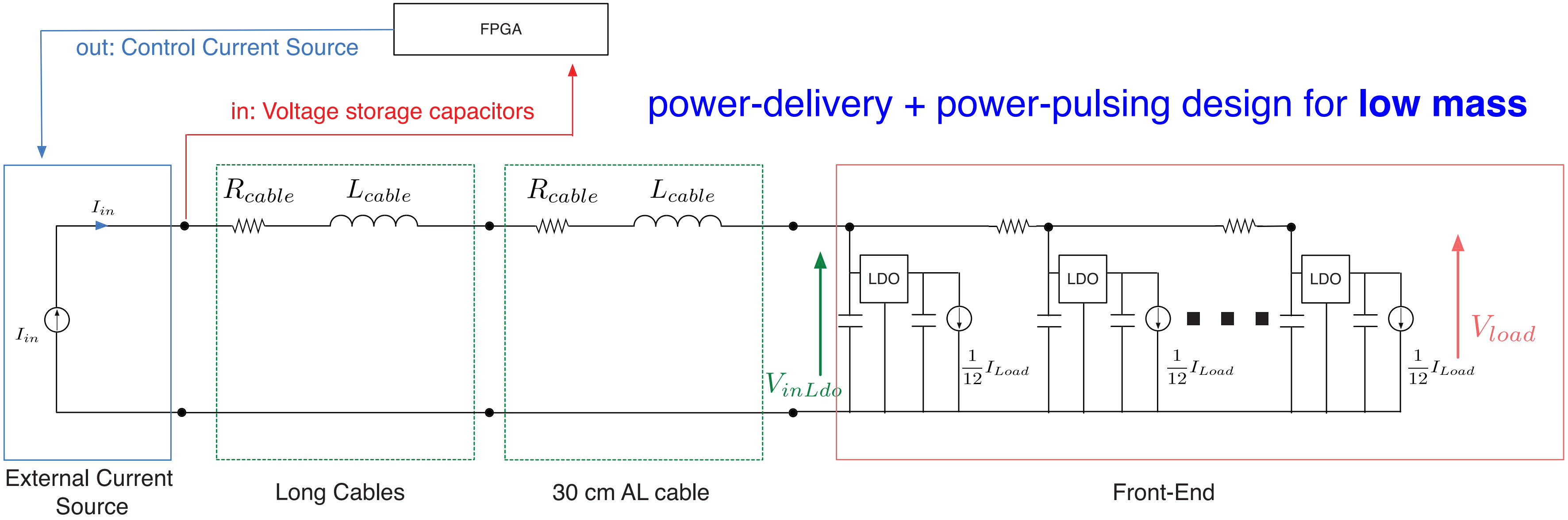
- Power pulsing with local energy storage in Si capacitors and voltage regulation with Low-Dropout Regulators (LDO)
- FPGA-controlled current source provides small continuous current
- Low-mass Al-Kapton cables

Vertex-detector power consumption



C. Fuentes

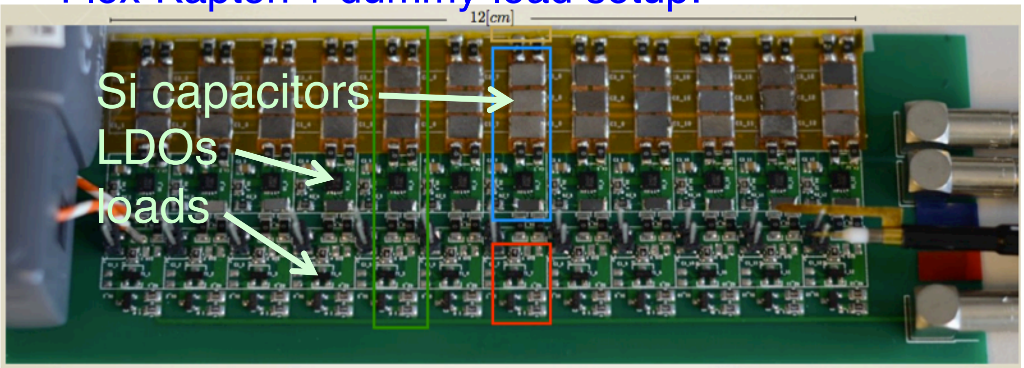
power-delivery + power-pulsing design for **low mass**



CLICpix power-pulsing + delivery results

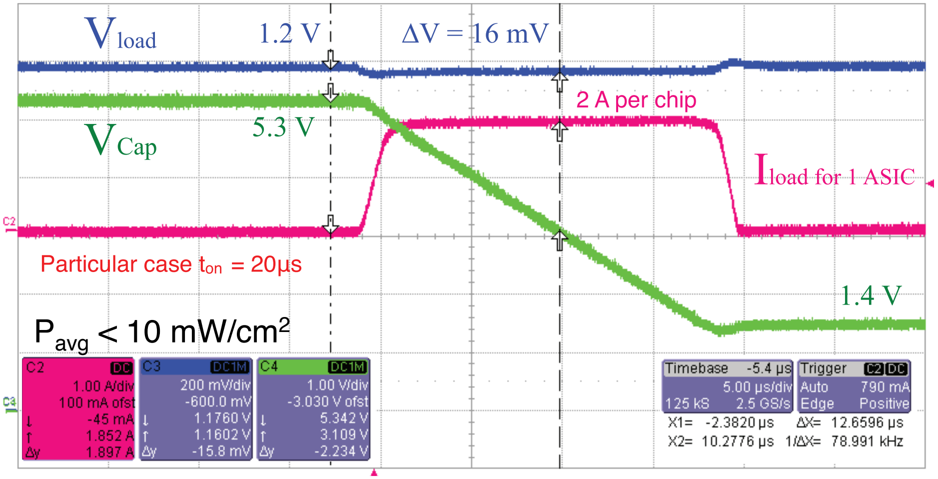
- Measurements on prototypes for digital and analog powering of ladders:
  - I_{ladder}<300 mA; P<45 mW/cm²
  - Voltage stability: ΔV~16 mV (analog), ~70 mV (digital)
  - ~0.1% X_0 material contribution, dominated by Si capacitors
  - Can be reduced to ~0.04% X_0 with evolving Si capacitor technology: 25 µF/cm² → 100 µF/cm²

Flex-Kapton + dummy-load setup:



C. Fuentes

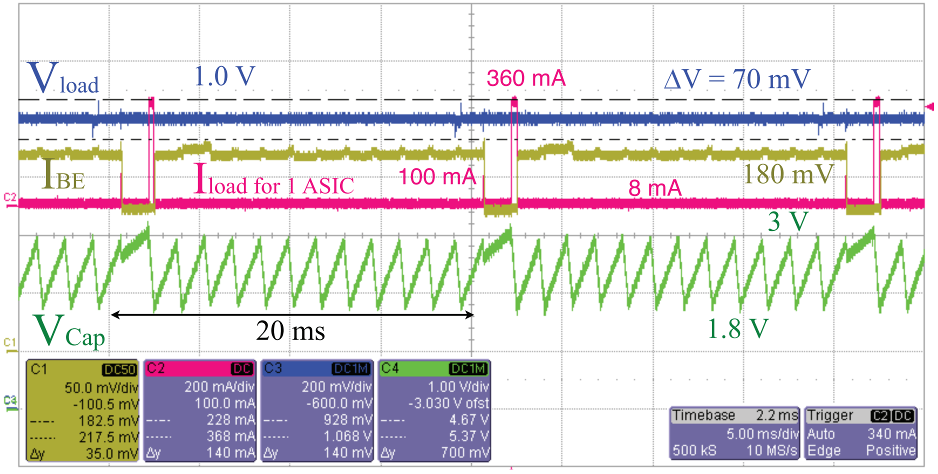
analog power



Particular case t_{on} = 20µs

P_{avg} < 10 mW/cm²

digital power



Cooling: simulations

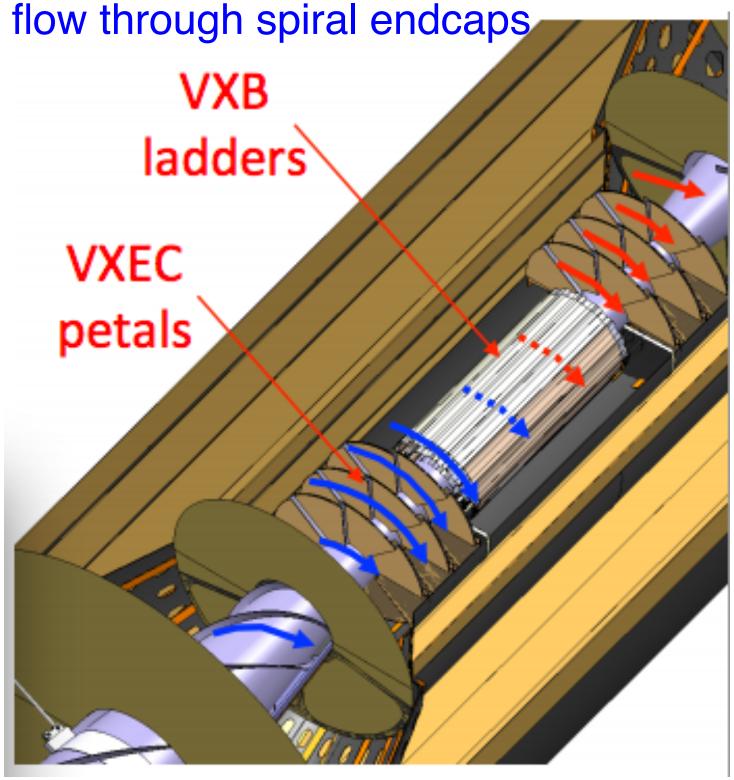
Cooling studies for CLIC vertex detector

- ~500 W power dissipation in CLIC vertex area
- spiral disks allow air flow through detector
- ANSYS Computational Fluid Dynamic (CFD) finite element simulation

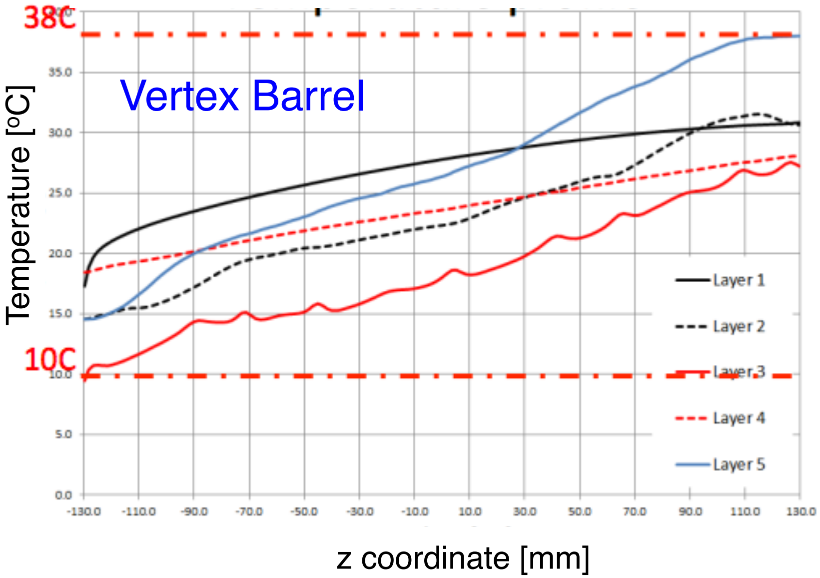
→ air cooling seems feasible

- 5-10 m/s flow velocity, 20 g/s mass flow

Air flow through spiral endcaps

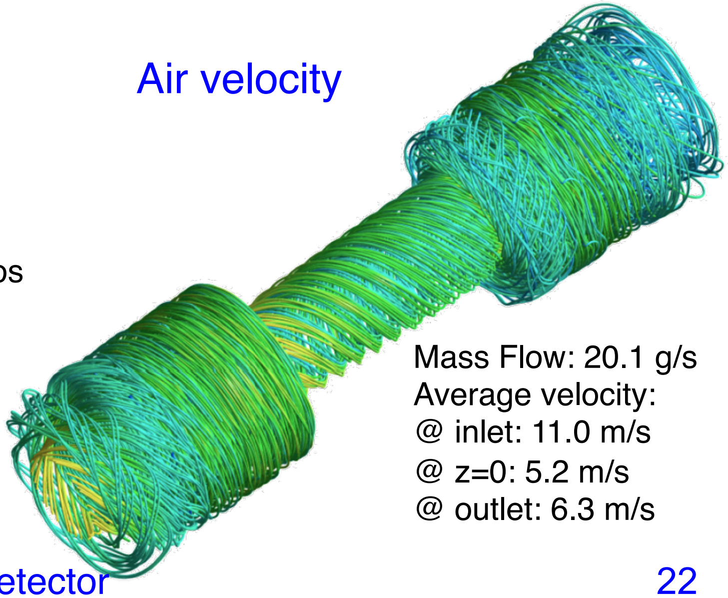


Temperature profile (FE simulations)



F. Duarte Ramos

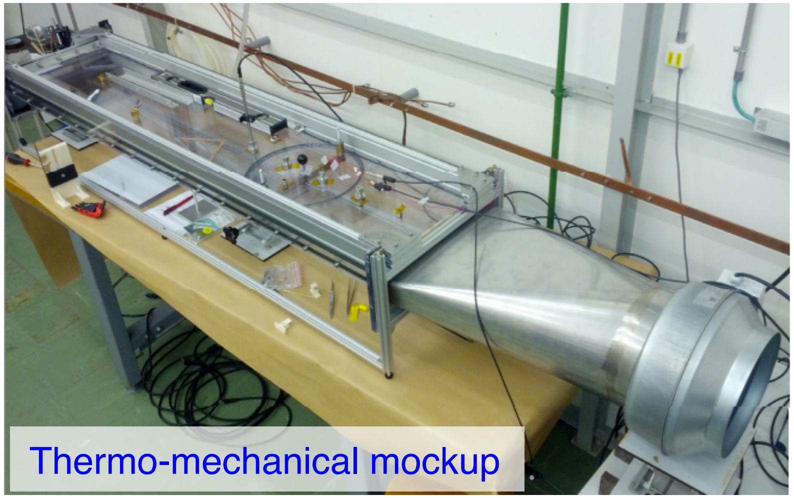
Air velocity



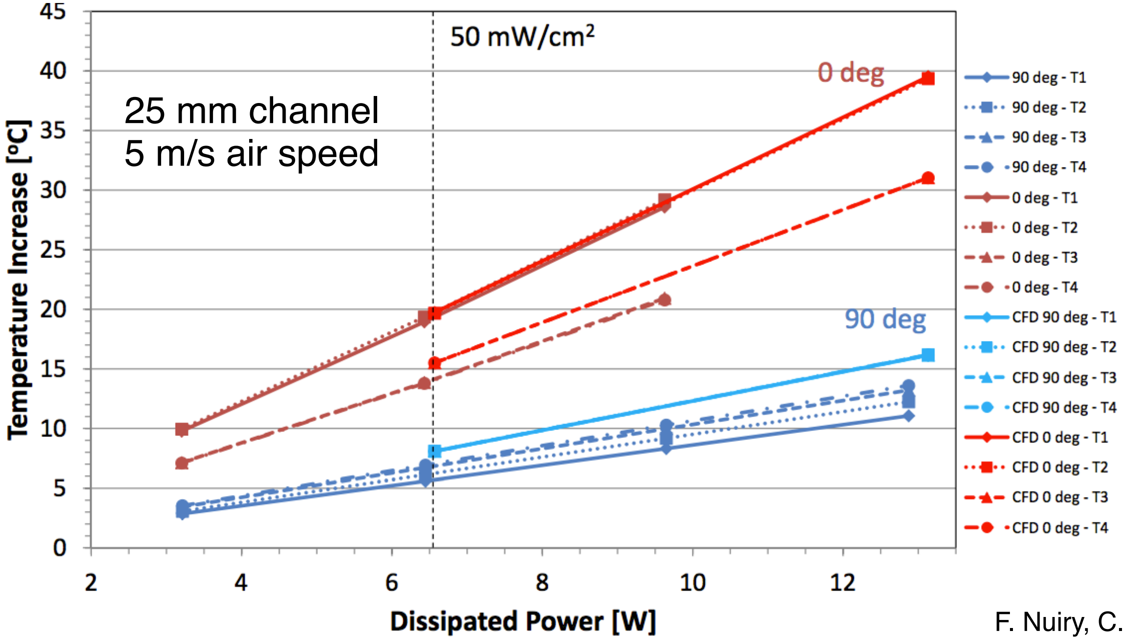
Mass Flow: 20.1 g/s
Average velocity:
@ inlet: 11.0 m/s
@ z=0: 5.2 m/s
@ outlet: 6.3 m/s

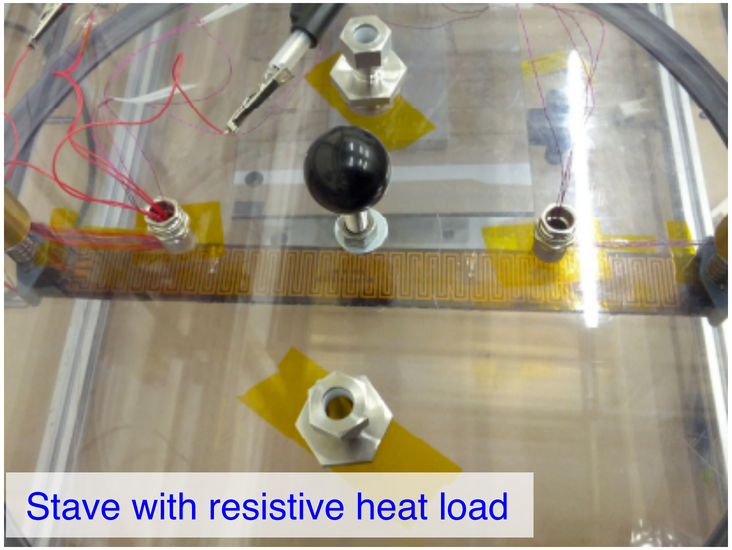
Cooling: experimental verification

- built mock-up to verify simulations (temperature, vibrations)
- measurements on single stave equipped with resistive heat loads:
  - air flow
  - temperature
  - vibrations (laser sensor)
- comparison with simulation


Thermo-mechanical mockup

Temperature increase: measurement + CFD simulation




Stave with resistive heat load

F. Nuiry, C. Bault, F. Duarte Ramos, M.-A. Villarejo Bermudez, W. Klempt

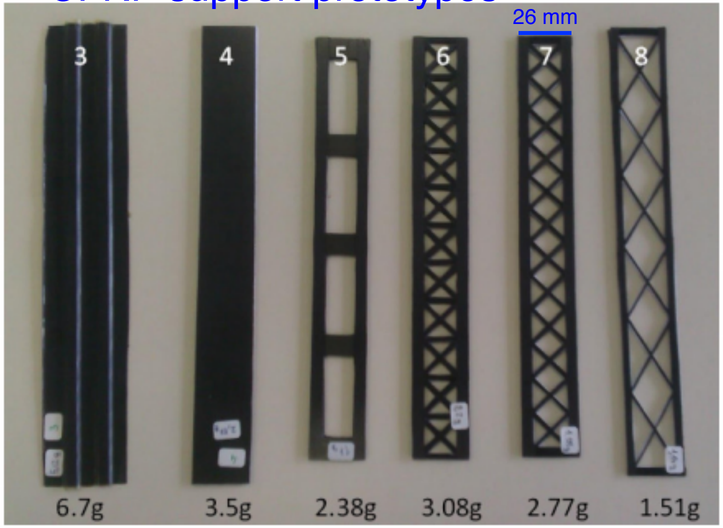
Low-mass supports

- Aim for only ~0.1% X0 per layer for powering + supports

→ ~0.05% X0 for supports

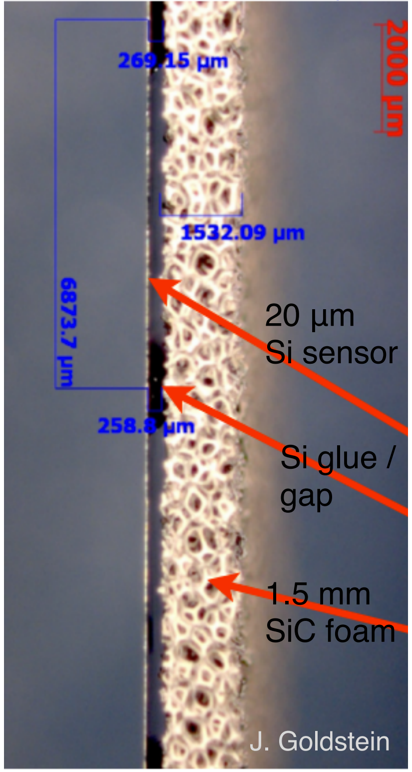
- Evaluating various designs and materials based on:
    - Carbon-Fiber-Reinforced Polymers (CFRP)
    - Silicon-Carbide (SiC) foams
- Bending stiffness validated with calculations, finite-element simulations and measurements

CFRP support prototypes

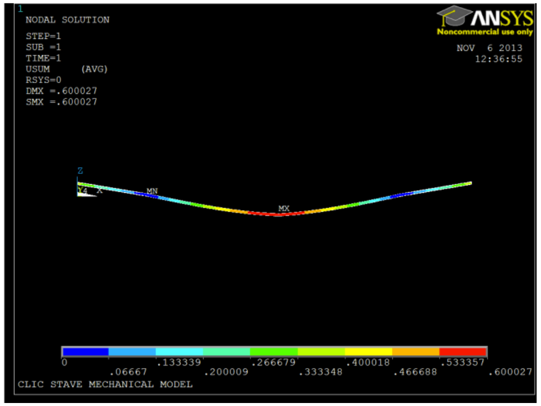


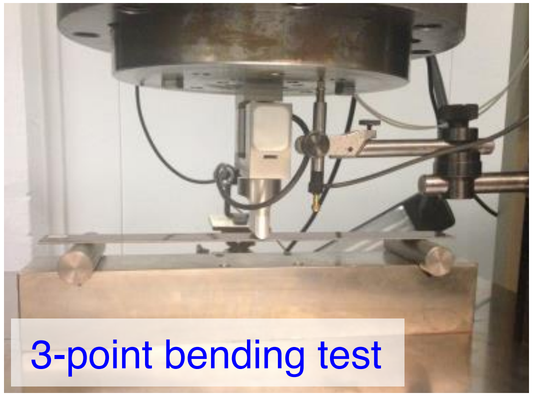
X/X0					
0,156 %	0,134 %	0,091 %	0,118 %	0,106 %	0,058 %

SiC foam assembly



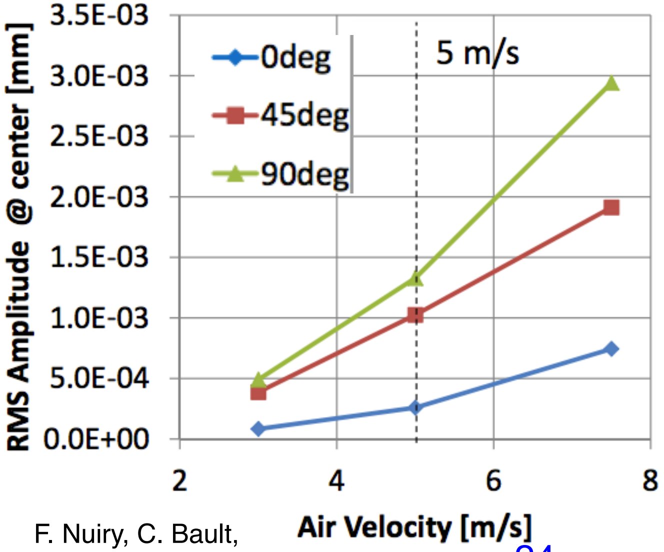
ANSYS FE simulation for CFRP





3-point bending test

Vibration-amplitude measurement for Rohacell stave

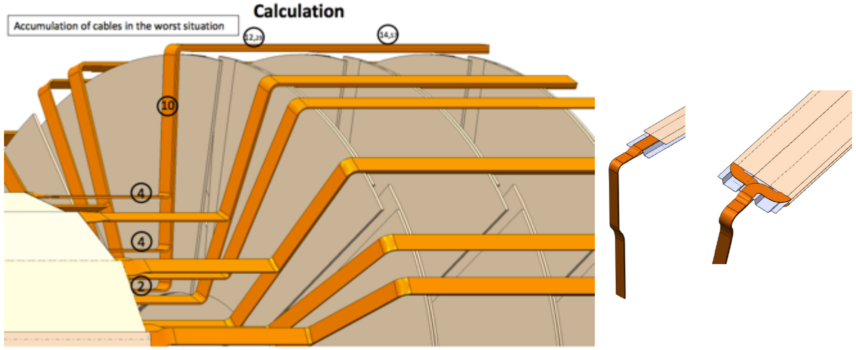


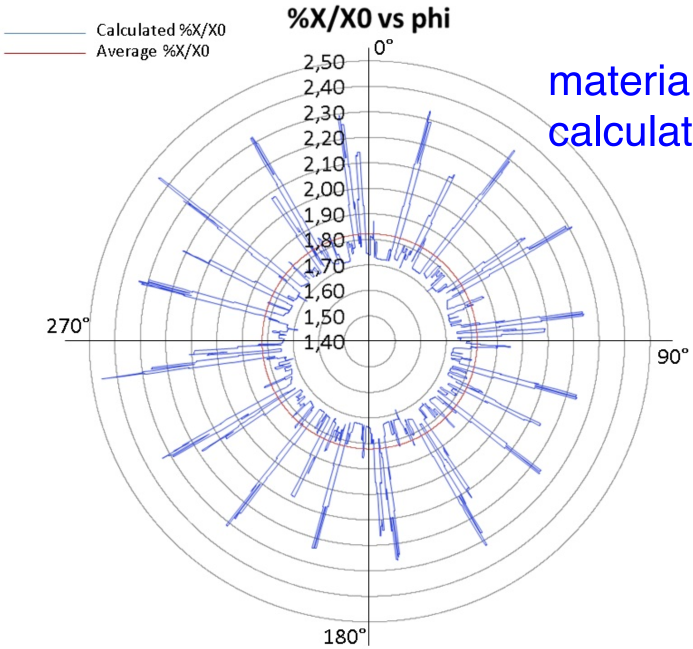
F. Nuiry, C. Bault,
F. Duarte Ramos, W. Klempt

Mechanical integration

- Detector integration: low-mass supports, services, assembly
- Taking into account constraints from powering and cooling
- Detailed material-budget calculations, comparison with simulation models

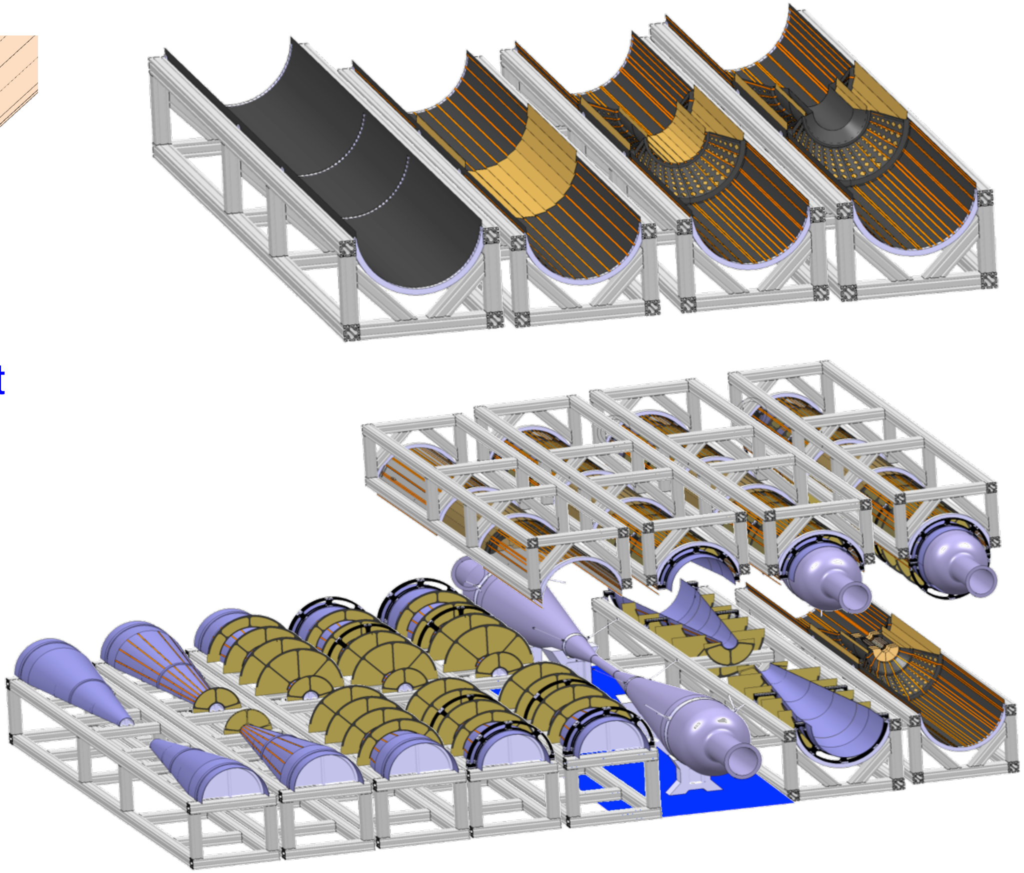
vertex-detector services





material-budget calculation

assembly scenario



F. Duarte Ramos, M.-A. Villarejo Bermudez

Summary and Conclusions

- High-energy linear lepton colliders provide:
  - unique potential for discovery and precision physics at the TeV scale
  - challenging requirements for vertex detectors
- Examples from an integrated R&D program on the CLIC vertex detector:
  - Detector layout optimization with flavor tagging
  - Hybrid pixel-detector technology with planar and active HV-CMOS sensors
  - Power delivery and power pulsing
  - Detector cooling and mechanical integration
- Synergy with other vertex-detector R&D projects

- More on sensors and simulation on Tuesday at 15h30:

  M. Benoit, *Calibration, Simulation and test-beam characterization for hybrid-pixel readout assemblies with ultra-thin sensors*

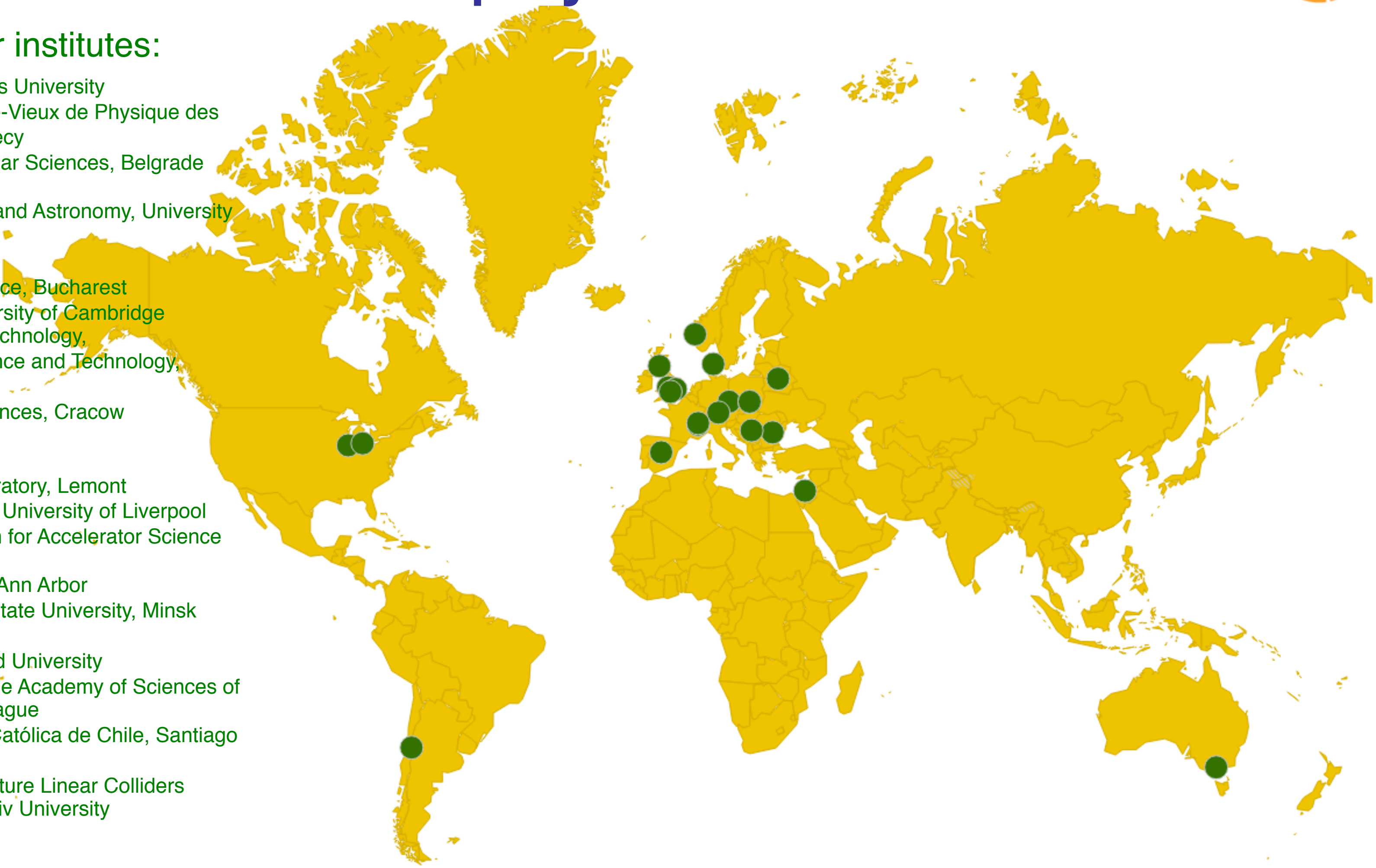
Thanks to everyone who provided material for this talk!

Additional material

CLIC detector & physics collaboration

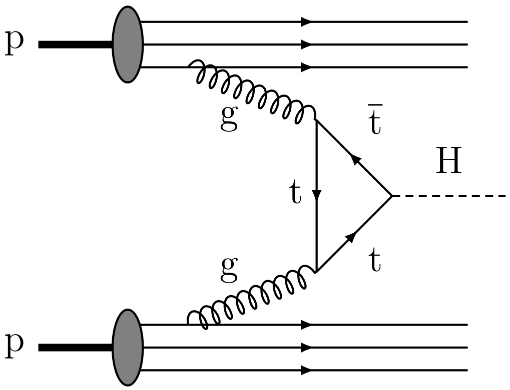
CLICdp member institutes:

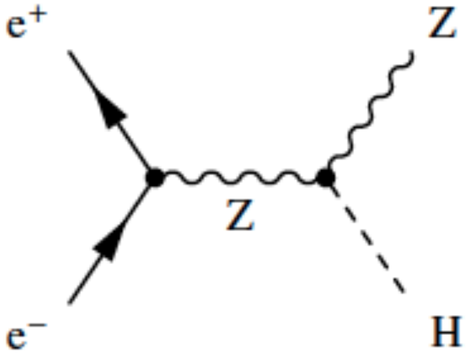
- Dept. of Physics, Aarhus University
- Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Annecy
- Vinca Institute for Nuclear Sciences, Belgrade
- University of Bergen
- The School of Physics and Astronomy, University of Birmingham
- University of Bristol
- Institute of Space Science, Bucharest
- Dept. of Physics, University of Cambridge
- Dept. of Physics and Technology, AGH University of Science and Technology, Cracow
- Polish Academy of Sciences, Cracow
- CERN, Geneva
- University of Glasgow
- Argonne National Laboratory, Lemont
- Department of Physics, University of Liverpool
- Australian Collaboration for Accelerator Science (ACAS), Melbourne
- University of Michigan, Ann Arbor
- NC PHEP, Belarusian State University, Minsk
- MPI Munich
- Dept. of Physics, Oxford University
- Institute of Physics of the Academy of Sciences of the Czech Republic, Prague
- Pontificia Universidad Católica de Chile, Santiago de Chile
- Spanish Network for Future Linear Colliders
- Dept. of Physics, Tel Aviv University



- The CLICdp collaboration is addressing detector and physics issues for the future Compact Linear Collider (CLIC) http://clicdp.web.cern.ch/
- CERN acts as host laboratory
- Currently 23 institutes from 16 countries
- The CLIC accelerator R&D is being conducted in collaboration with ~48 institutes

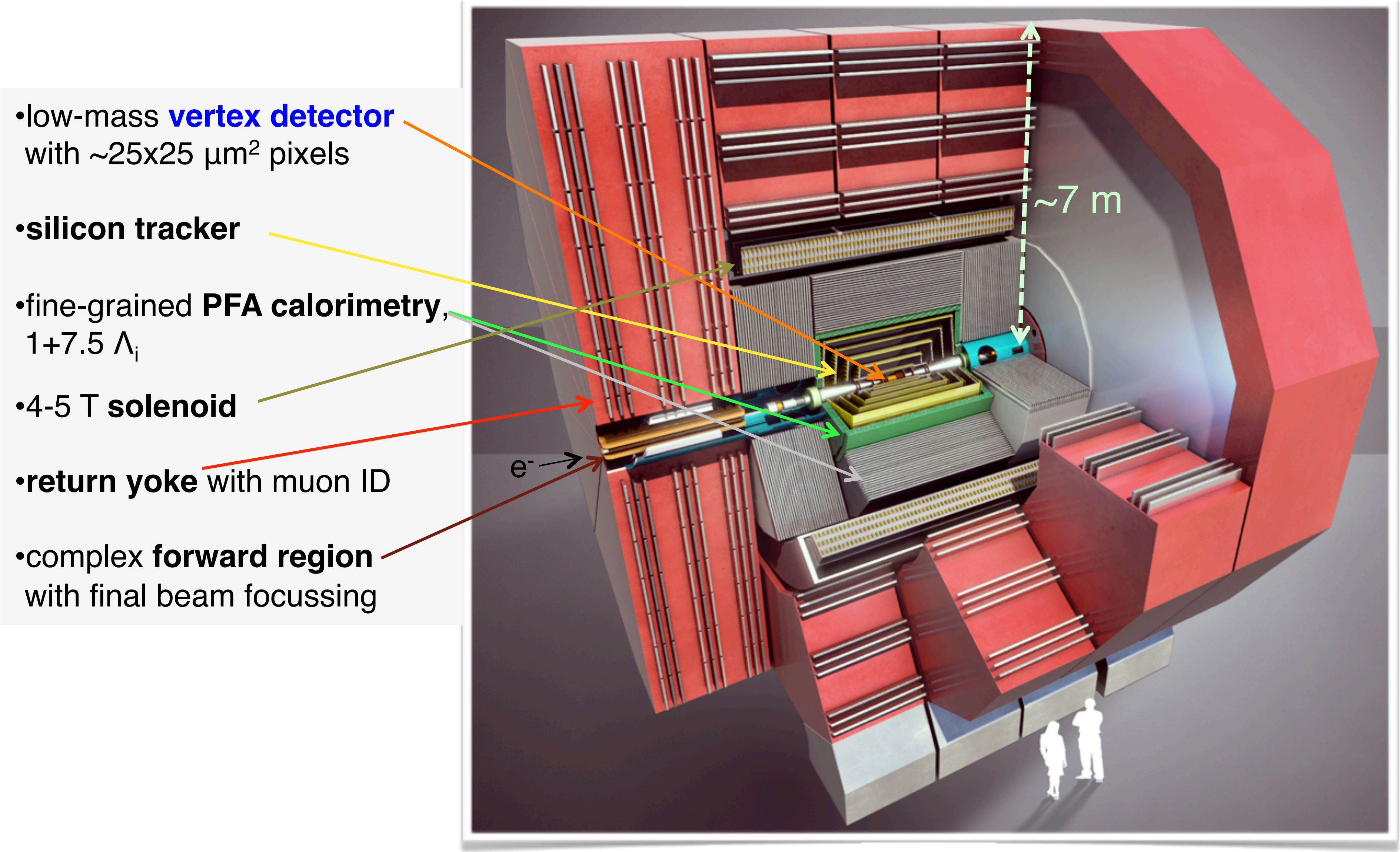
Hadron vs. lepton colliders





p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	e^+/e^- are point-like → Initial state well defined ($\sqrt{s}$ / polarization) → High-precision measurements
Circular colliders feasible	Linear Colliders (avoid synchrotron rad.)
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	Cleaner experimental environment → trigger-less readout → Low radiation levels
$\sqrt{s}$ constrained by design	$\sqrt{s}$ can be tuned → Threshold scans
High cross-sections for colored-states	Superior sensitivity for electro-weak states

CLIC detector concept



- low-mass **vertex detector** with ~25x25 μm^2 pixels
- **silicon tracker**
- fine-grained **PFA calorimetry**, 1+7.5 Λ_i
- 4-5 T **solenoid**
- **return yoke** with muon ID
- complex **forward region** with final beam focussing

Beam-induced backgrounds

small beam profiles at IP
→very high E-fields

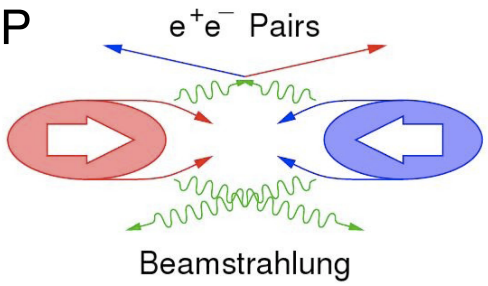
Beamstrahlung

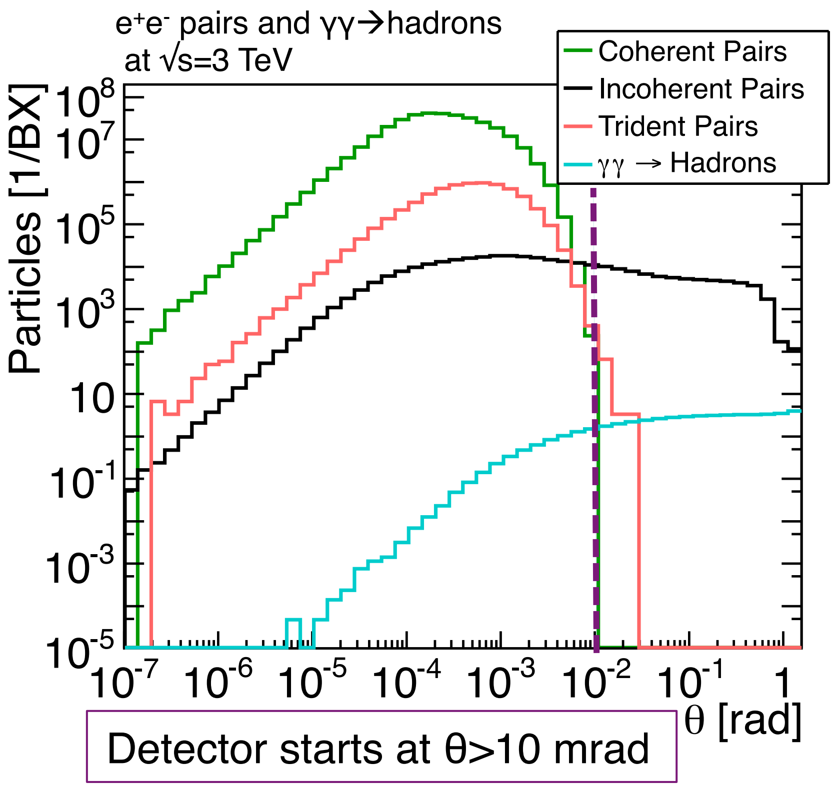
leads to:

- e^+e^- pairs
- hadronic events

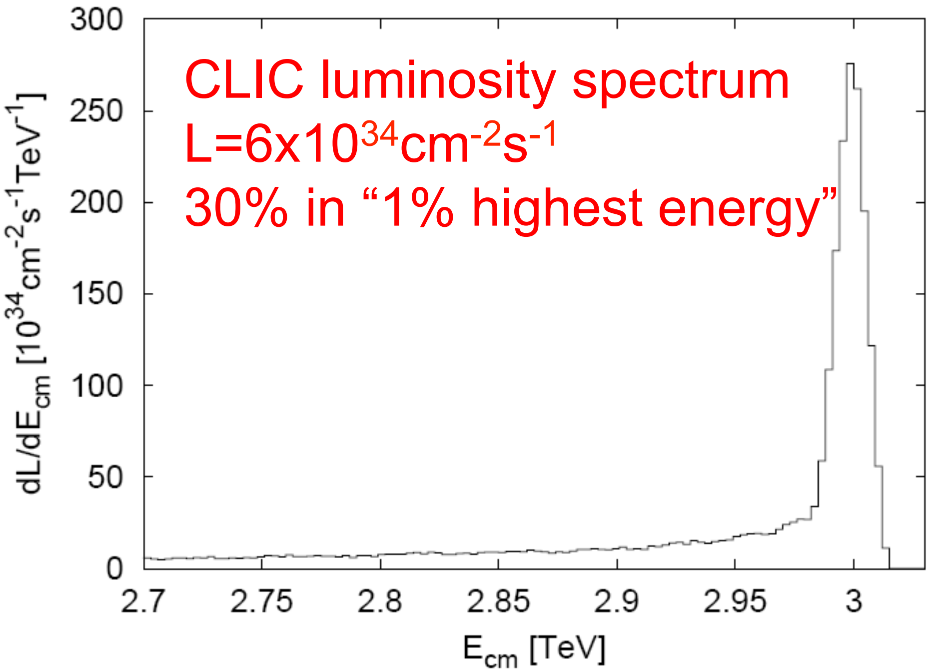
→ Reduces E_{cm}

→ Background particles





Detector starts at θ>10 mrad



CLIC luminosity spectrum
$L=6\times10^{34}cm^{-2}s^{-1}$
30% in “1% highest energy”

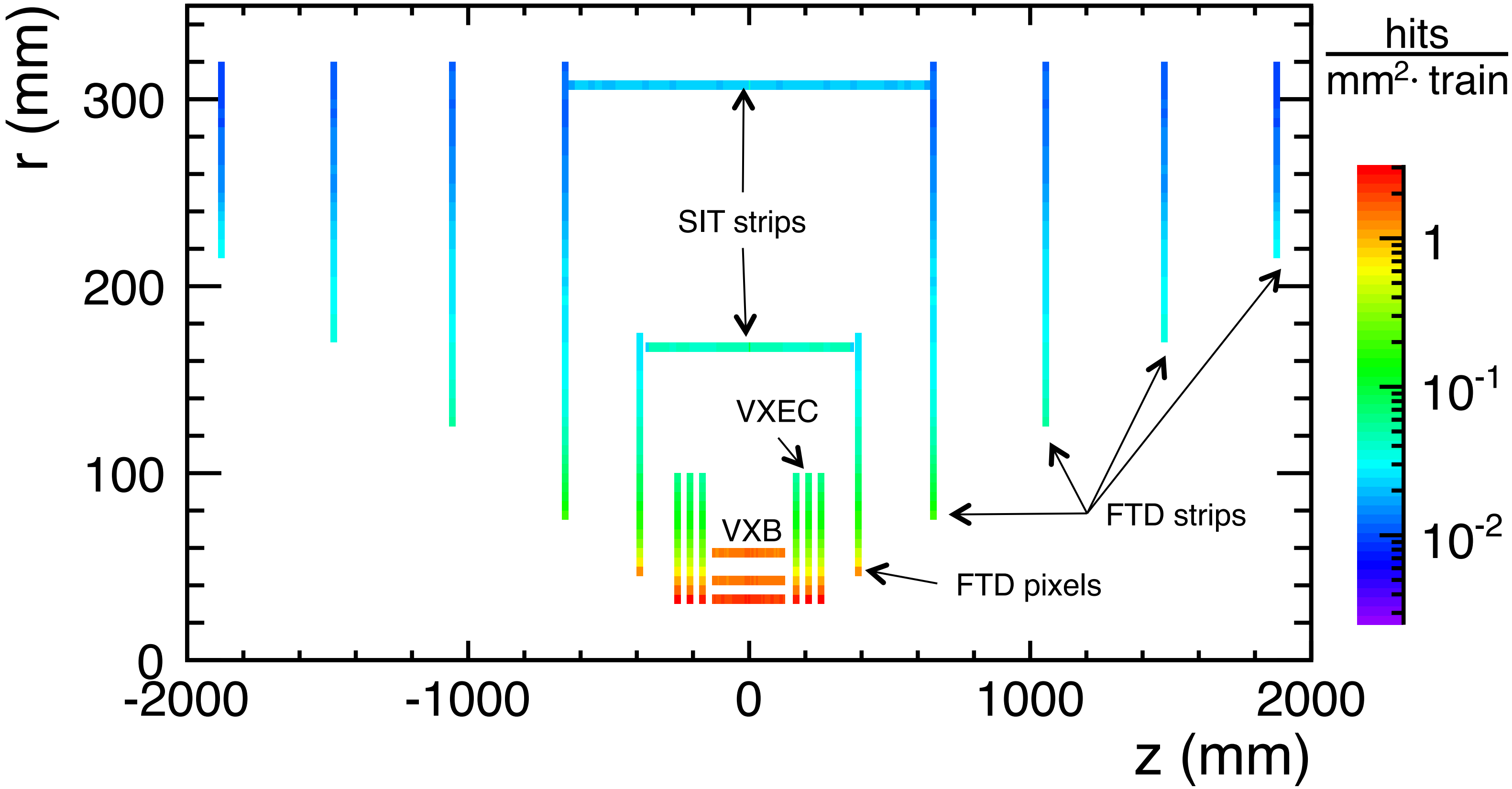
Main backgrounds in detector:

- **Incoherent e^+e^- pairs**: 60 particles / BX detector design issue (occupancies)
- **γγ→hadrons**: 54 particles / BX impacts physics

→ Need **pile-up rejection**

Backgrounds in inner tracking region

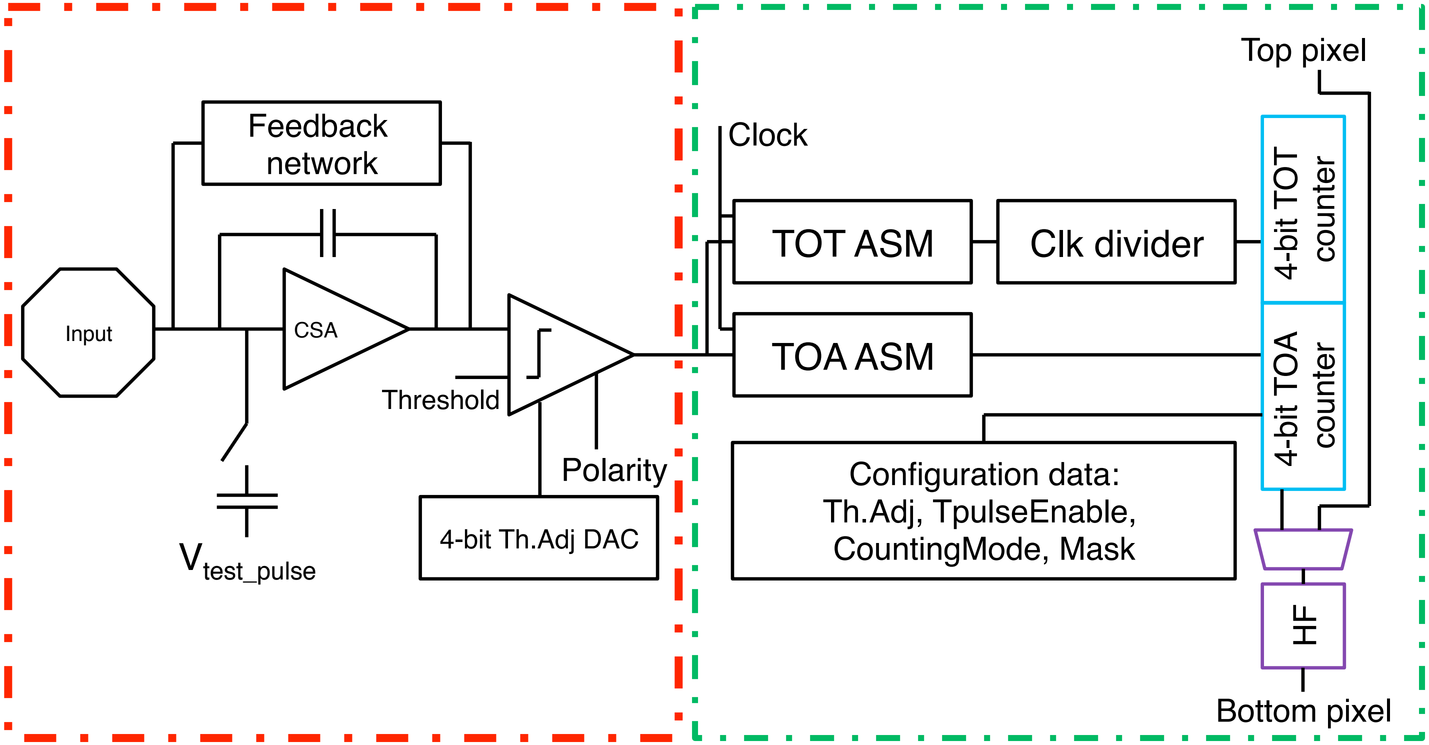
CLIC_ILD incoherent pairs + γγ → hadrons: silicon hits, no safety factors



- Train occupancies up to 3% in vertex region (including clustering and safety factors)
- moderate radiation exposure, ~10^4 below LHC

Region	Readout granularity	Max. occup.	NIEL [$n_{eq}/cm^2/y$]	TID [Rad/y]
VXB	20 µm x 20 µm	1.9 %	4×10^{10}	20k
VXEC	20 µm x 20 µm	2.8 %	5×10^{10}	18k
FTD pixels	20 µm x 20 µm	0.6%	2.5×10^{10}	5k
FTD strips	10 cm x 50 µm	290 %	1×10^{10}	700
SIT	9 cm x 50 µm	170 %	2×10^{9}	200

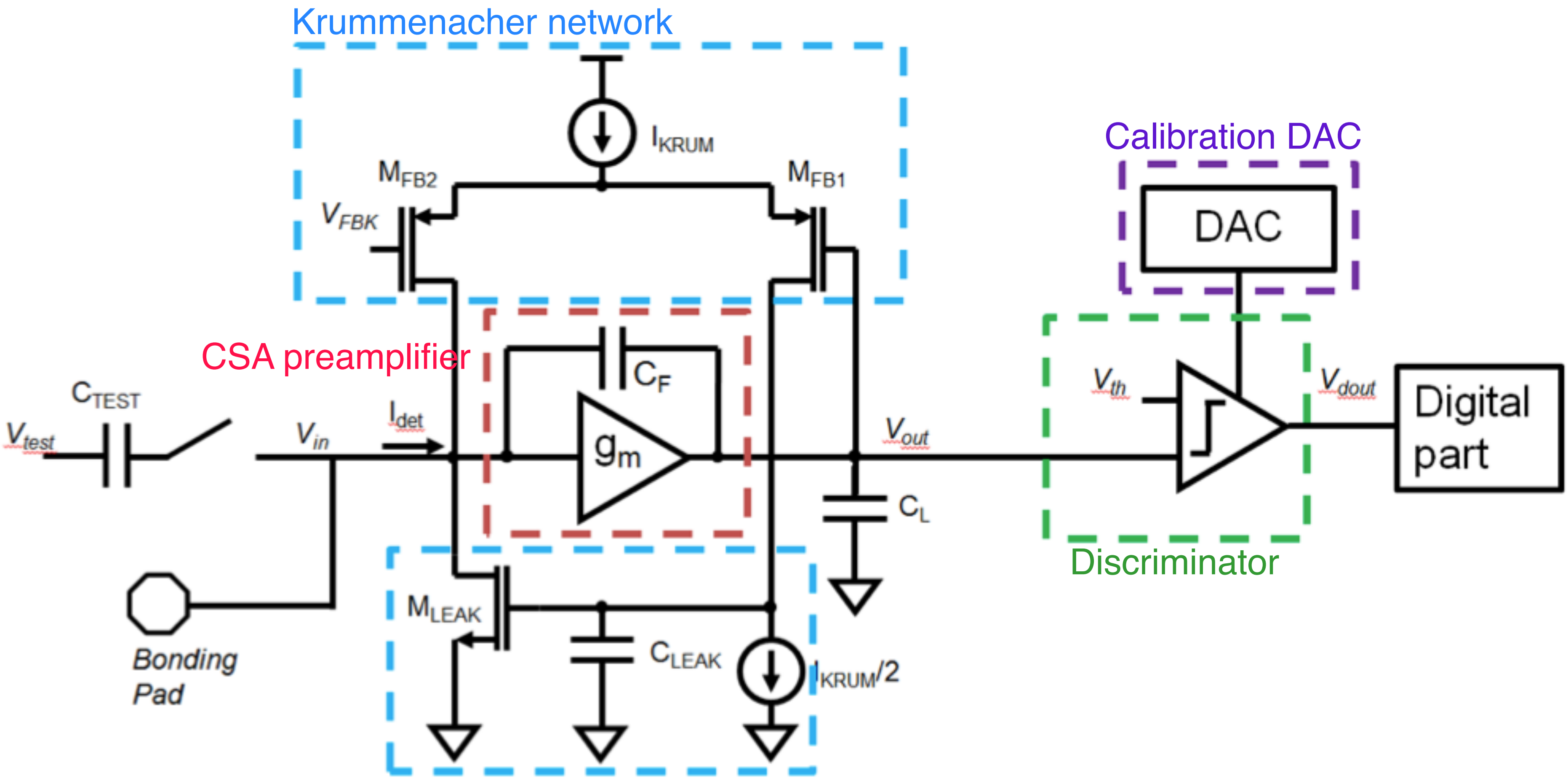
CLICpix pixel architecture



- The analog front-end shapes photocurrent pulses and compares them to a fixed (configurable) threshold
- Selectable polarity (positive / negative signals)
- Digital circuits simultaneously measure Time-over-Threshold and Time-of-Arrival of events and allow for zero-compressed readout

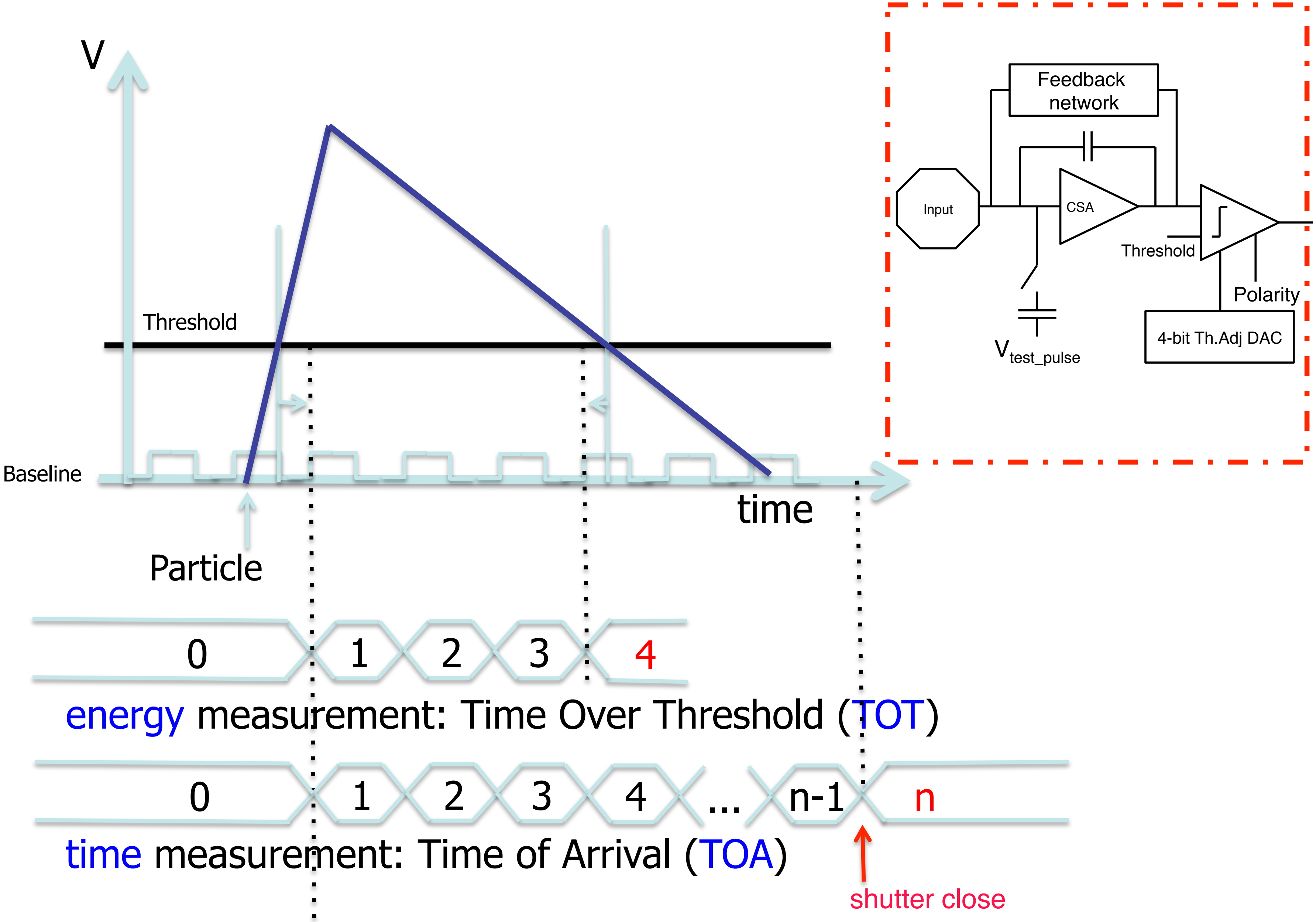
P. Valerio et al.

CLICpix analog frontend



P. Valerio et al.

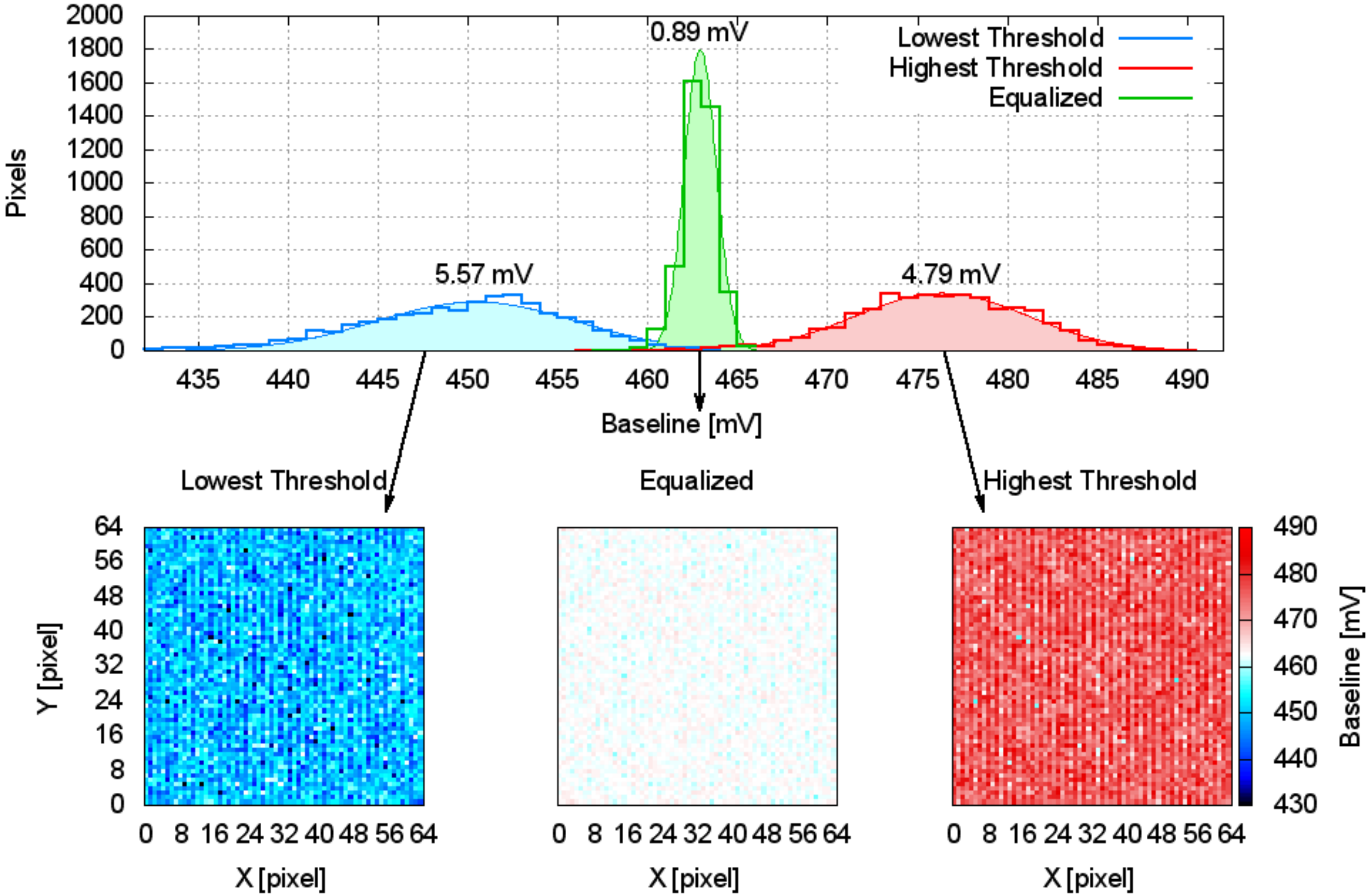
CLICpix: time and energy measurement



energy measurement: Time Over Threshold (TOT)

time measurement: Time of Arrival (TOA)

CLICpix: baseline equalization

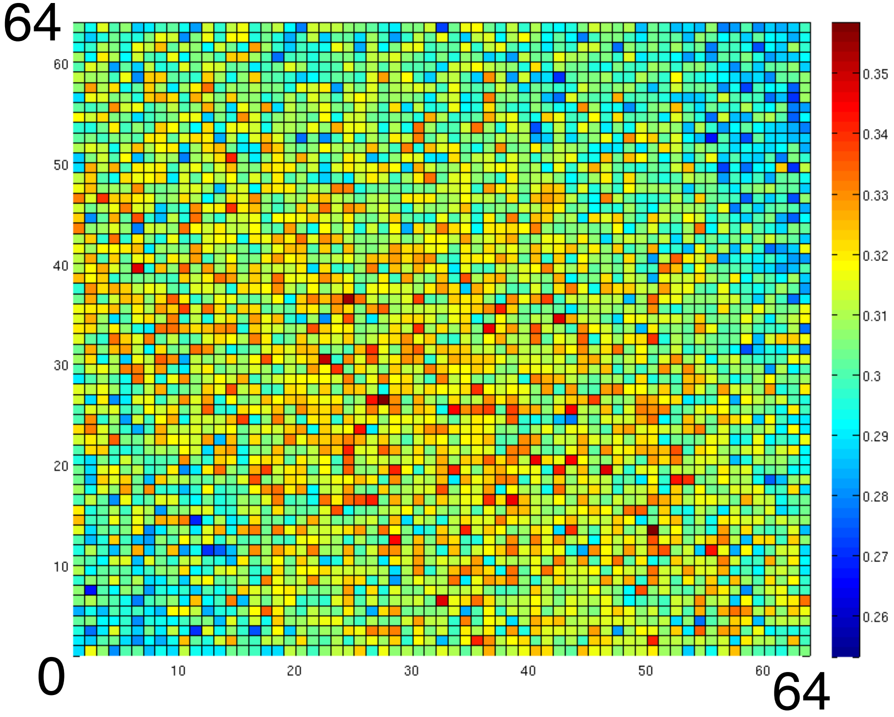


Calibrated spread across the whole matrix is 0.89 mV RMS (~22 e^-)
For comparison: MIP signal in 50 µm silicon ~3700 e^-

S. Kulis, P. Valerio

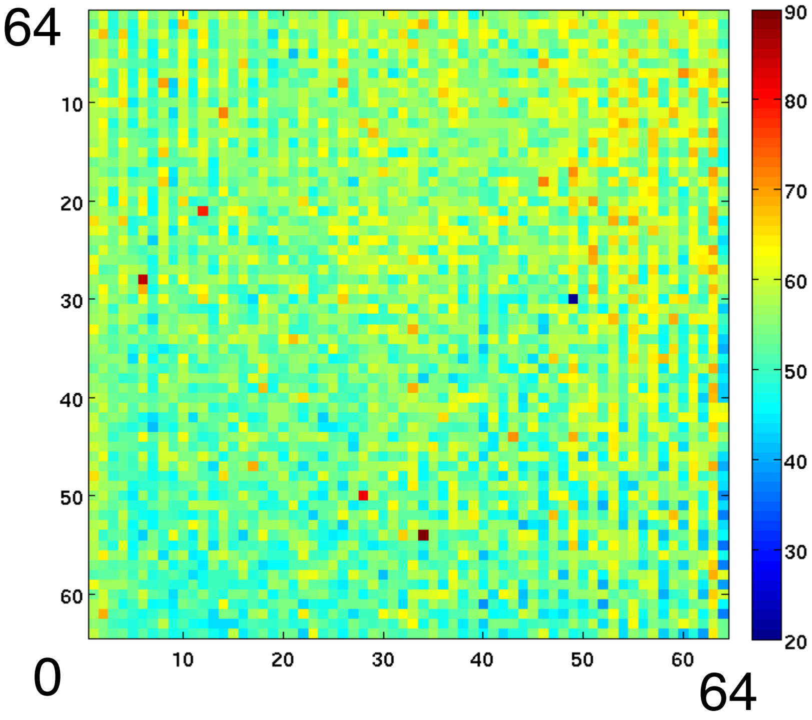
CLICpix: uniformity of gain and noise

TOT Gain Distribution



- Uniform gain across the matrix
- Gain variation ~4.2% r.m.s. (for nominal feedback current)

Equivalent Noise Charge



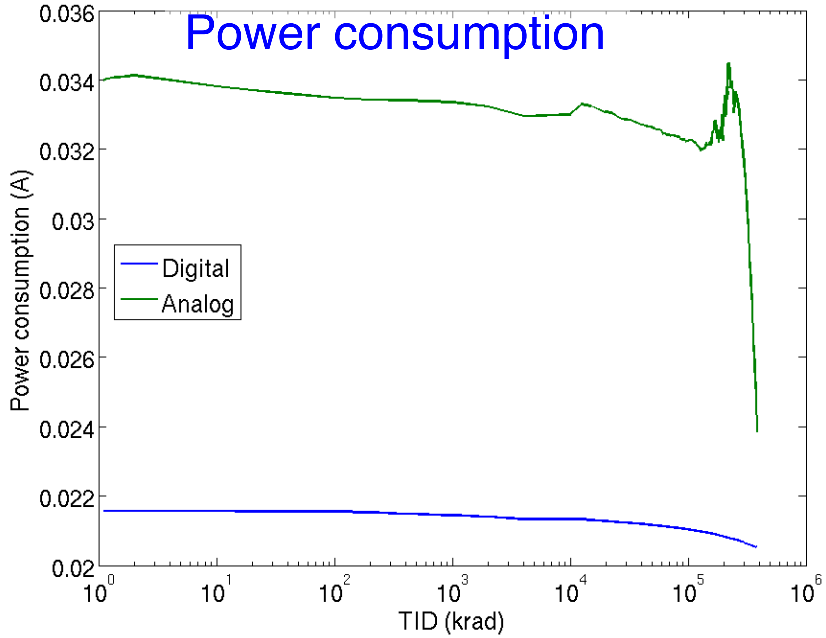
- Uniform ENC across the matrix
- Mean ENC: 55 e^-, SD: 5.7 e^- (without sensor)

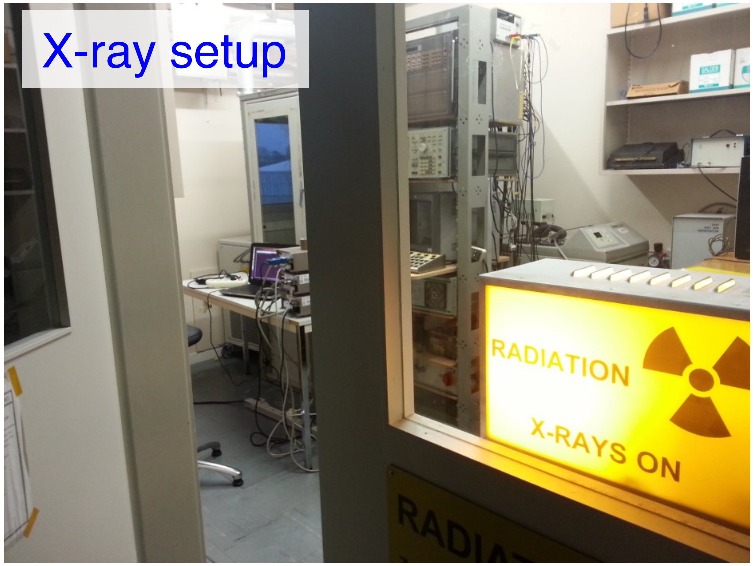
S. Kulis, P. Valerio

CLICpix: radiation qualification

- Moderate radiation-tolerance requirements at CLIC: <100 kRad TID
- However: building blocks can be re-used for RD53 (~1 GRad required)
- Results of radiation testing useful for gaining deeper understanding of the chip

→ performed radiation test up to 1 GRad (up to 150 kRad/minute) in calibrated X-ray setup





- No significant changes observed in sub-MRad range relevant for CLIC
- For >250 MRad: PMOS switches in current mirror fail

→ Break-down of analog power (note: band gap foreseen for final chip, instead of current mirror)

- digital components kept working normally

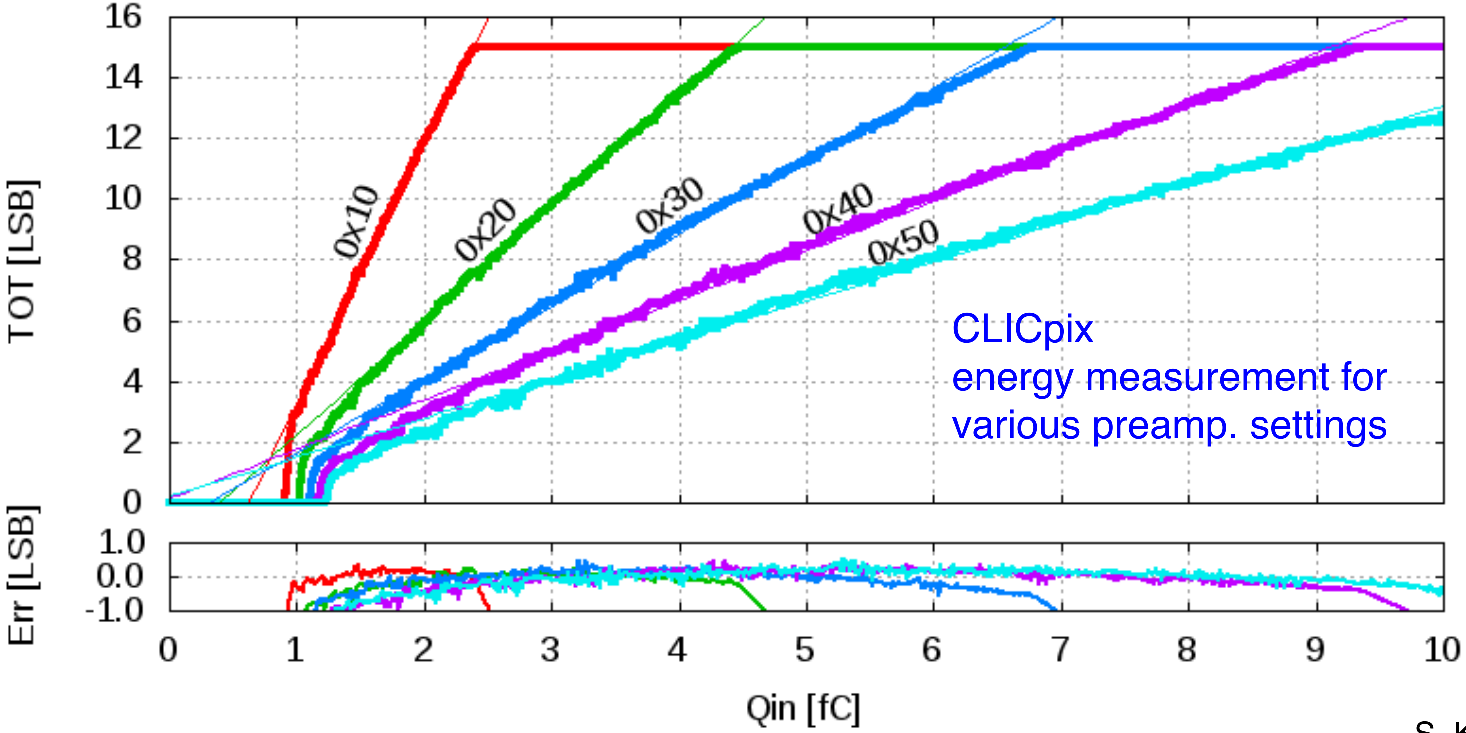
S. Kulis, P. Valerio

CLICpix: energy measurement

- Measure charge released in each pixel
  → Improve position resolution through interpolation

- Time-Over-Threshold (TOT) measurement (4-bit precision)

- Calibration measurement using external test pulser:



CLICpix
energy measurement for
various preamp. settings

S. Kulis, P. Valerio

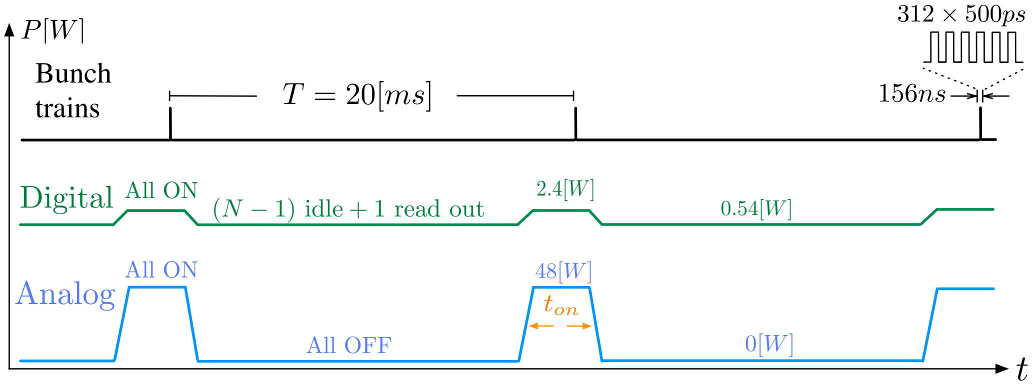
CLICpix power-pulsing + delivery requirements

Small duty cycle of CLIC machine allows for power reduction of readout electronics: turn off front end in gaps between bunch trains

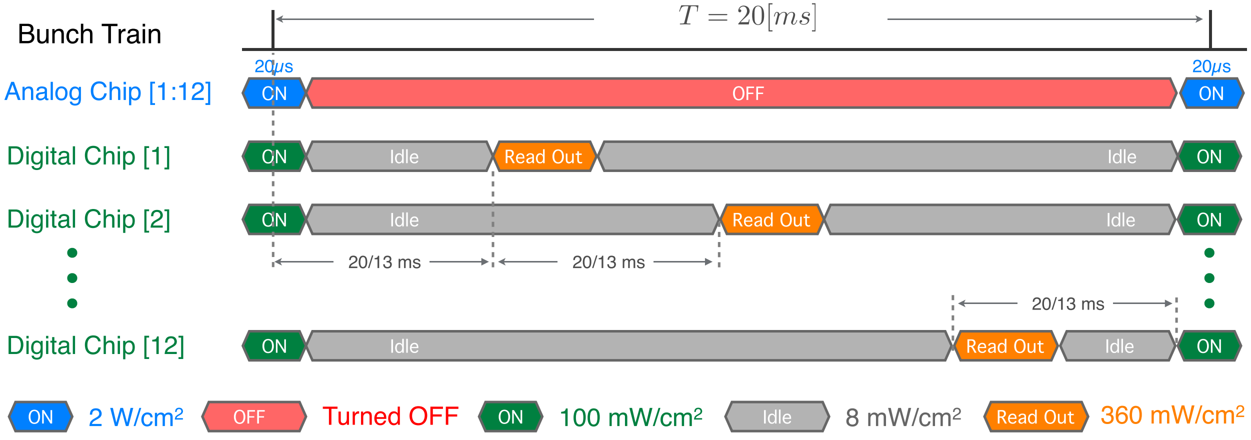
Challenging requirements:

- Power budget **<50 mW/cm^2** average (air-flow cooling limit)
- High peak current **> 40A/ladder**
- Different timing **analog/digital** electronics
- High magnetic field **4-5 T**
- Material budget **< 0.1% X_0** for services+supports
- Regulation **< 5% (60 mV)** for analog part

Vertex-detector power consumption



CLICpix powering states



C. Fuentes, X. Llopart, P. Valerio

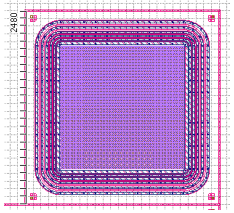
CLICpix v2

First ideas for new version of CLICpix:

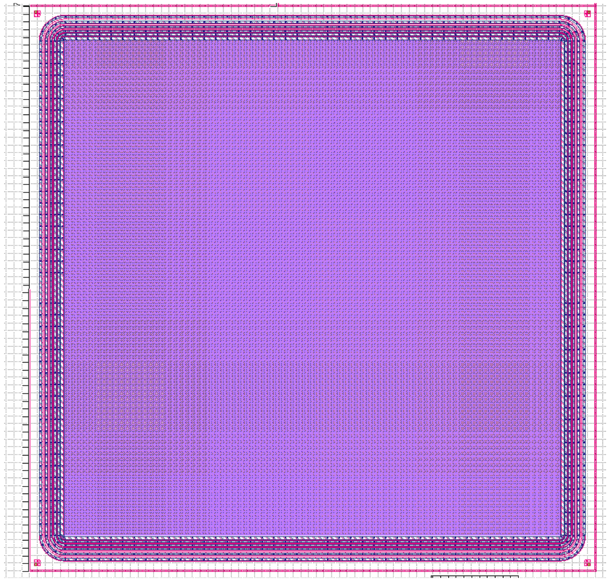
- larger pixel matrix (256x256)
- analog front-end re-design:
  sharing between adjacent pixels, to save space
  → allows for increased counter depth:
  - 5 bit TOA (instead of 4)
  - 7 bit TOT (instead of 4)
- share TOA between adjacent pixels
  (to be discussed)
  → would make space for 10 bit TOT
- on-board LDO
- PLL, band-gap blocks (RD53)
- features for daisy-chain
- bug fixes

- Launched sensor production
  for 256 x 256 CLICpix
  (in anticipation of new chip version)

CLICpix sensor 64x64



CLICpix sensor 256x256

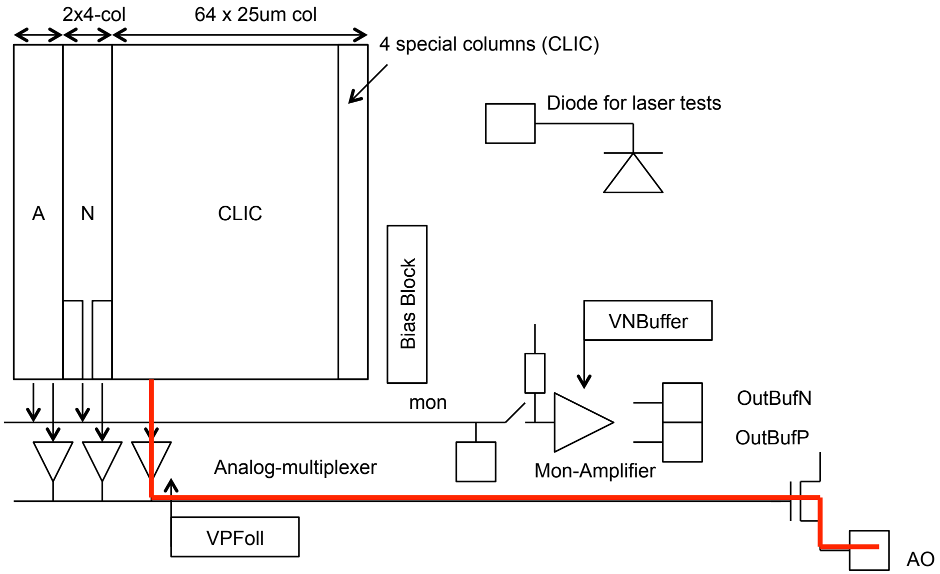


P. Valerio, M. Benoit, et al.

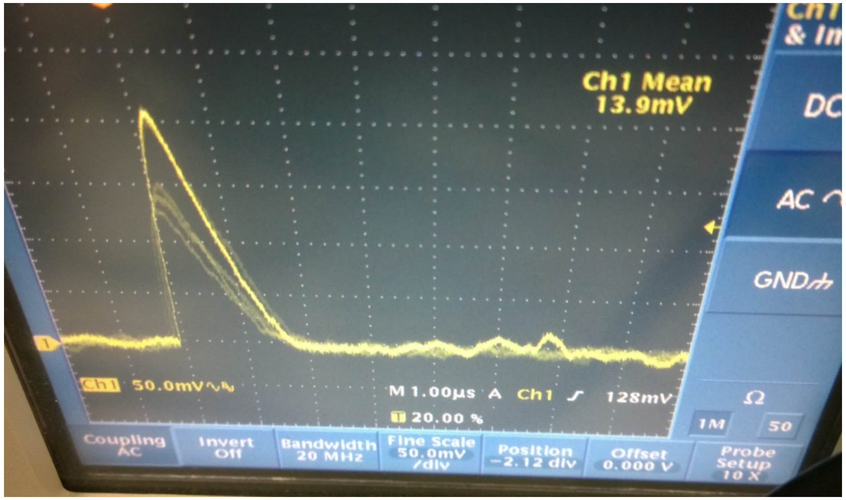
CCPDV3: first tests

- Measured signal at test output for 1st and 2nd amplification stage
- X-rays froms ^{55}Fe source
- V_{bias}=30 V
- no baseline adjustment performed
- chip is functional, signal as expected

- Assemblies with CCPDV3 glued to CLICpix and corresponding test board are in production



After 1st stage: amplitude ~200mV (~1200 e$^-$)



After 2nd stage: amplitude ~300mV