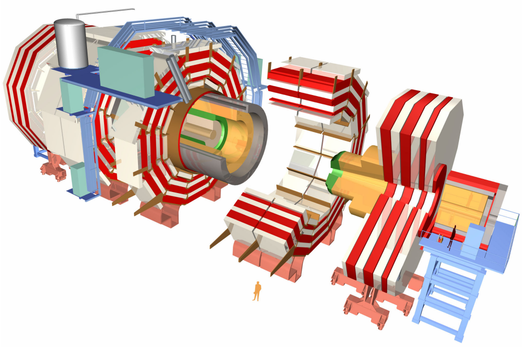
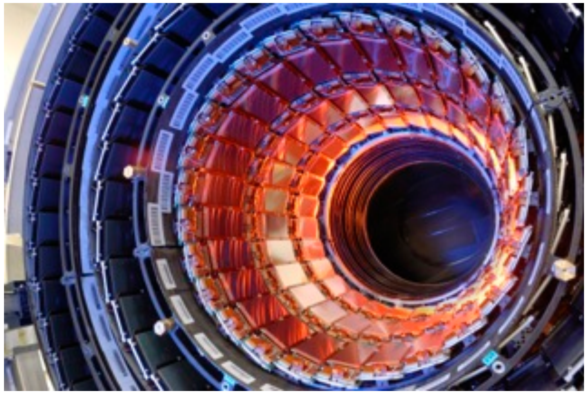




CBC2: CMS microstrip readout for HL-LHC

[D. Braga], G. Hall , M. Pesaresi, M. Raymond (Imperial College)

D. Braga, L. Jones, P. Murray, M. Prydderch (RAL)

D. Abbaneo, G. Blanchot, A. Honma, M. Kovacs, F. Vasey (CERN)

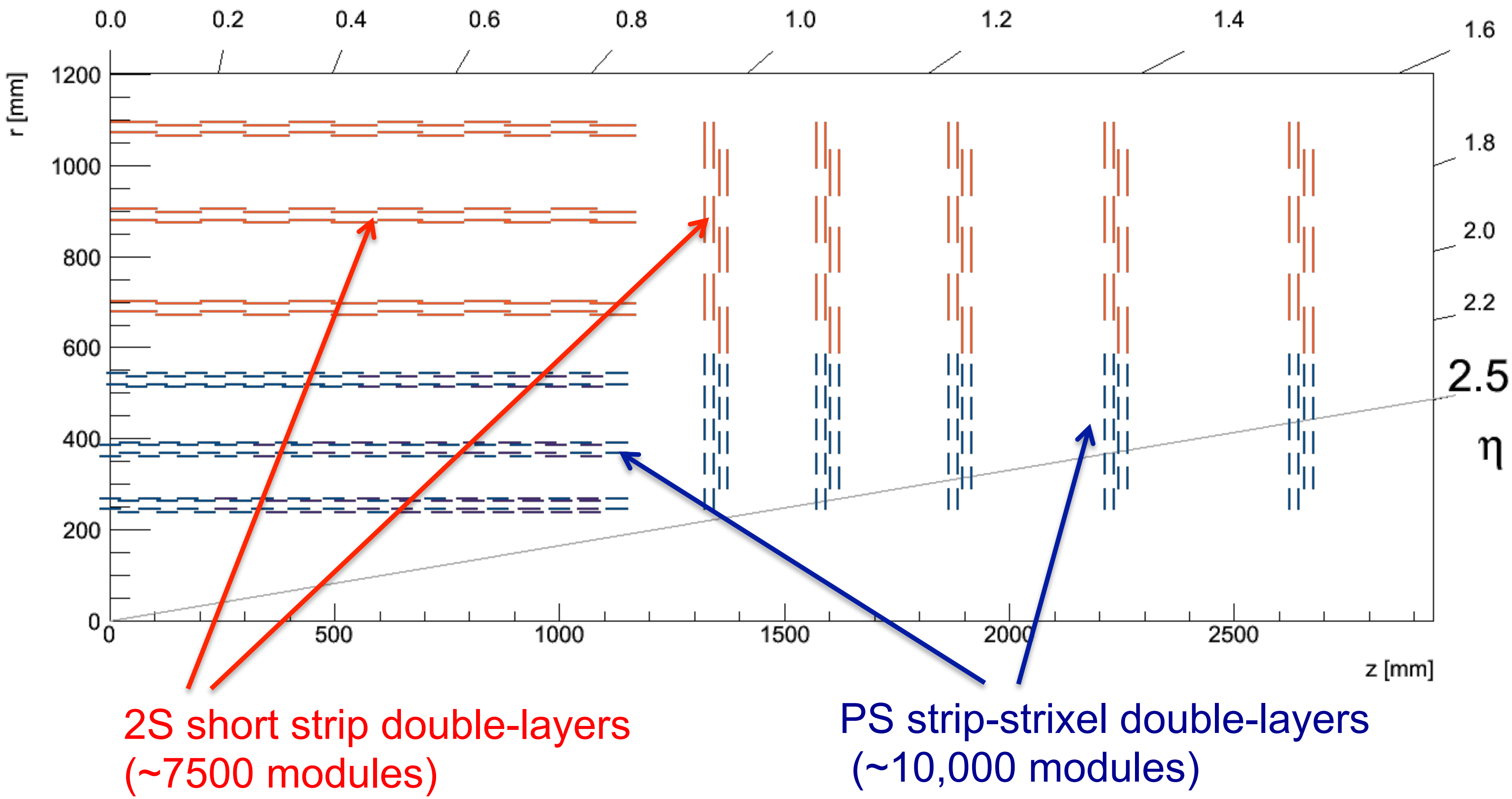
Background

- CMS upgrade under consideration for many years
  - objective to reach 3000 fb^{-1} in next decade or so
  - High Luminosity LHC (Phase II) requires new Tracker around 2023
  - Requirements:
    - lower material budget
    - increased granularity
    - enhanced radiation tolerance
    - tolerable power consumption
    - affordable cost
    - all compatible with physics objectives –some of which remain uncertain
      - e.g. will new physics be discovered in next running period?
      - but solid long term programme of Higgs & top studies, searches, etc…

Evolution of objectives

- Original goal
  - new – improved - tracker with similar angular coverage, constrained by re-using existing services
  - provide some part of tracker data to L1 trigger to contain rate to 100 kHz
- More recent developments
  - Baseline Tracker design now adopted
    - "conventional" barrel-endcap layout looks optimal
  - but CMS exploring enhancing forward region physics as well as standard physics programme
  - uncertainty if L1-track triggering will reduce rate to 100 kHz in 6.4μs
    - ideas (and detector requirements) not yet validated by simulations
    - possible objective of L1 readout up to 1 MHz/10-20μs
    - both approaches require on-detector data reduction

Baseline tracker layout (pixels not shown)



- Double layer readout compatible with trigger
- Geometry compatible with forward extension

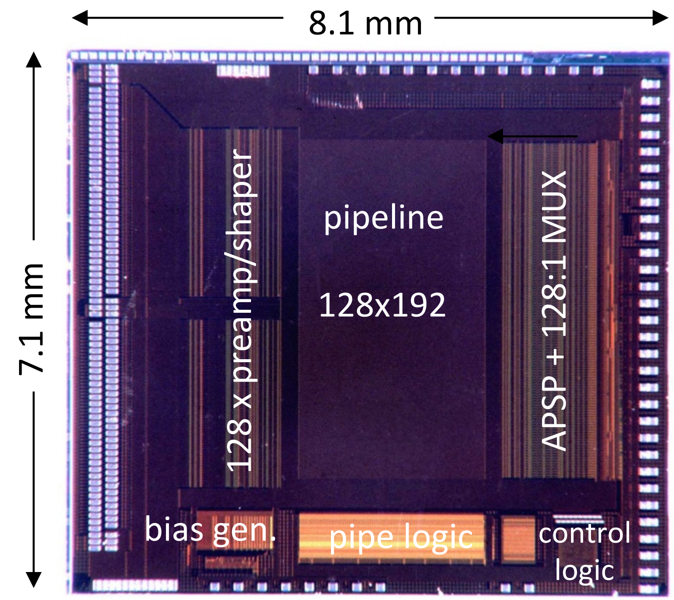
ASIC development

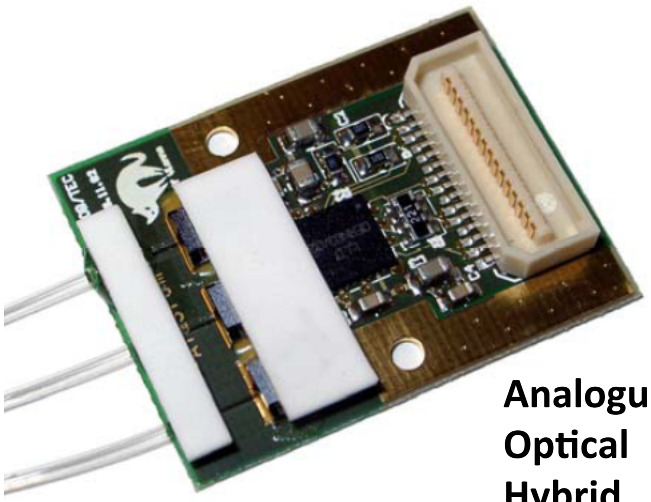
- Earliest developments foresaw conventional outer tracker, plus some dedicated trigger (and pixel) layers
  - 128 channel CMS Binary Chip (CBC) produced and proven 2011
  - Readout architecture followed original tracker, using APV25
  - Analogue data abandoned for practical reasons
    - digital optical link components now commercially standard,
    - ADC power
    - 130 nm CMOS makes analogue memory cells harder to implement
- Subsequently, outer modules with trigger capability agreed
  - 254 channel CBC2 successfully developed – delivered 2012
  - optimised for new assembly method with mass production in mind

Present CMS Tracker architecture

- Analogue unsparsified readout
  - APV25 in 0.25µm commercial CMOS
  - synchronous
  - occupancy independent data volume
  - 2.7mW/chan for 10-20cm µstrips

  - analogue data transmission to external ADC & zero-suppression, clusters
    - semi-custom optical links @ 40Msps
    - 1310 nm single-mode Fabry-Perot lasers
    - very successful
    - reflected state of technology at the time
  - benefits
    - simple and easy to debug/evaluate
    - robust against noise

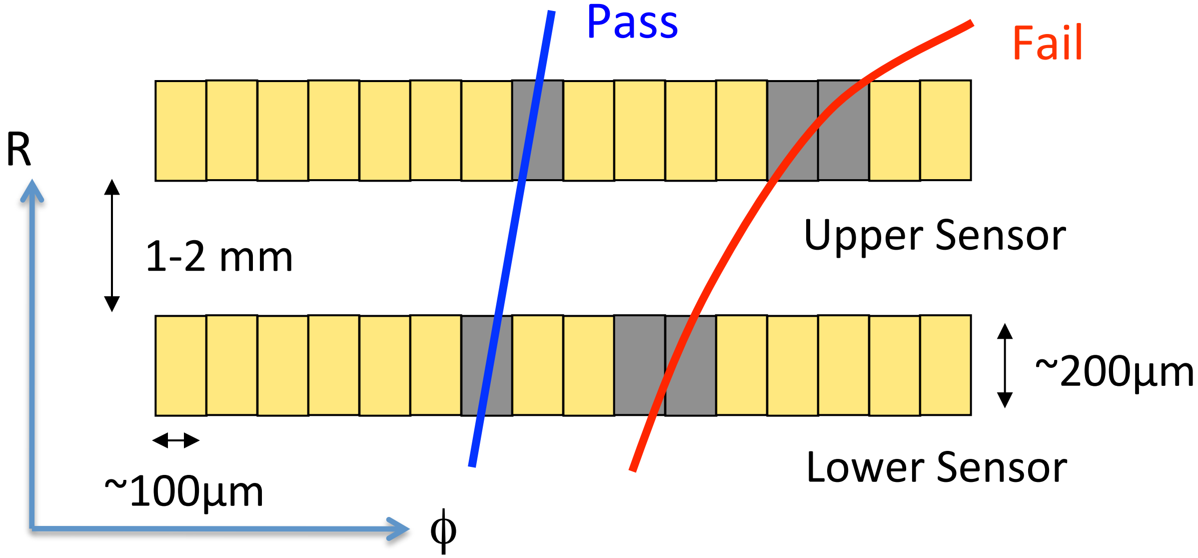




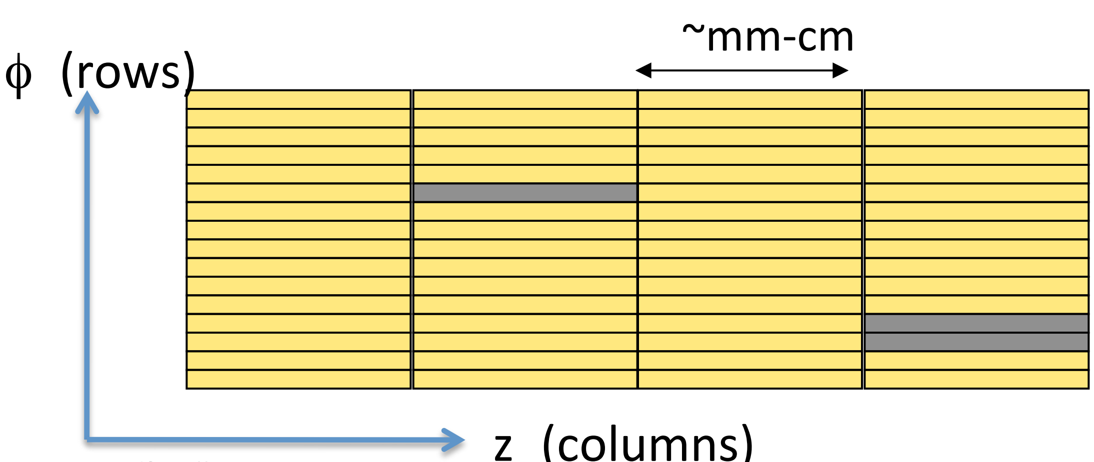
Analogue Optical Hybrid

Basic trigger module concept

- Compare binary pattern of hit pixels on upper and lower sensors



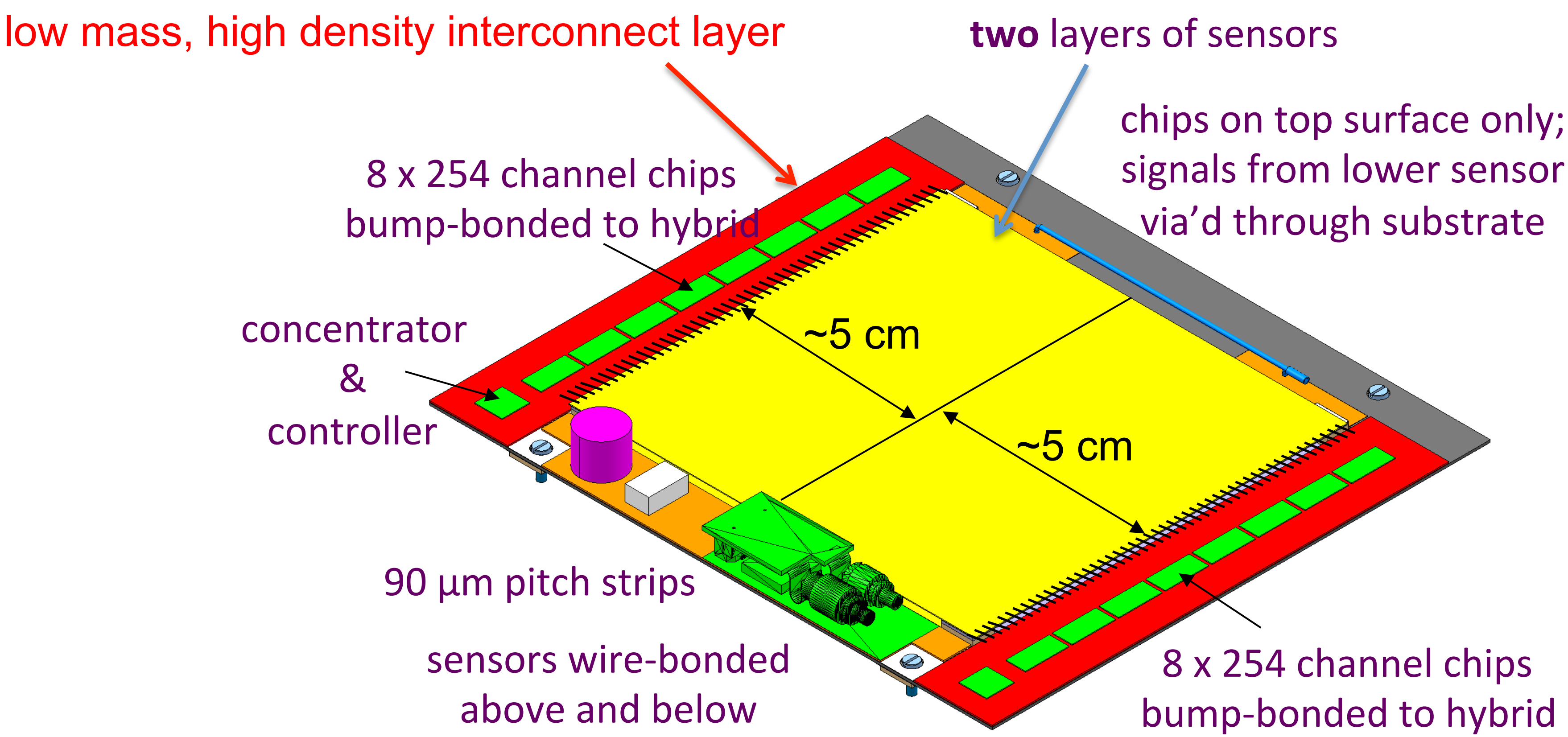
High p_T tracks can be identified if hits lie within a search window in R-ϕ (rows) in second layer



Sensor separation and search window determines p_T cut
z-segmentation determines vertex capability

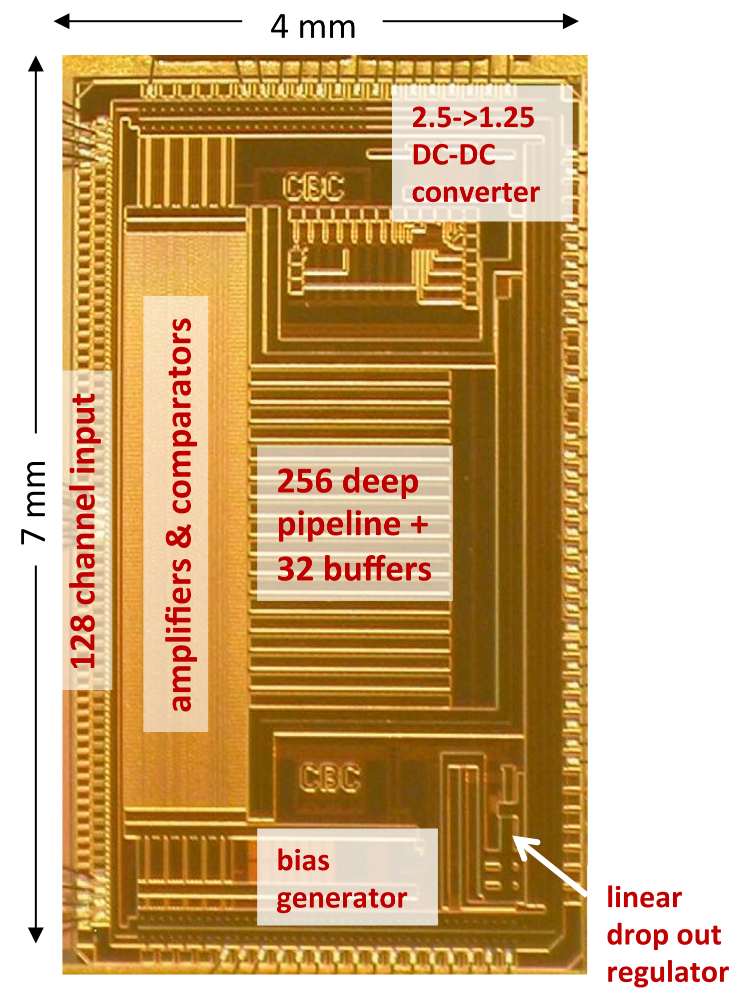
2S PT-module with CBC2

- **Track & trigger** μstrip module for outer tracker region
  - CBC2 logic correlates hits on two sensors to reject those from low p_T tracks



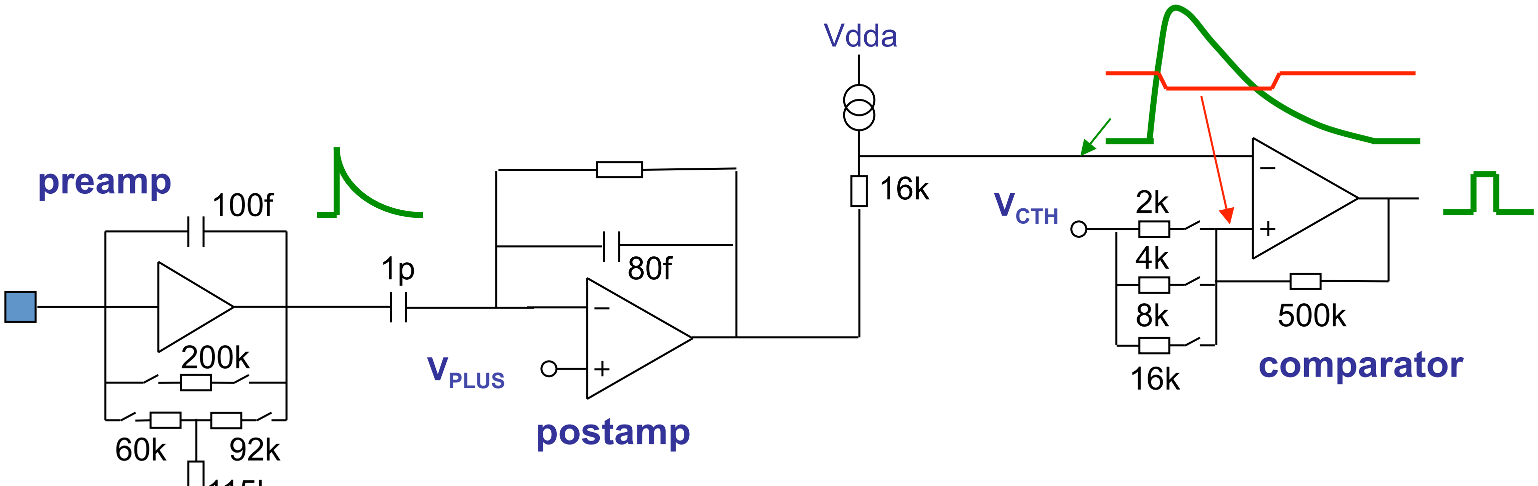
First version: CBC main features

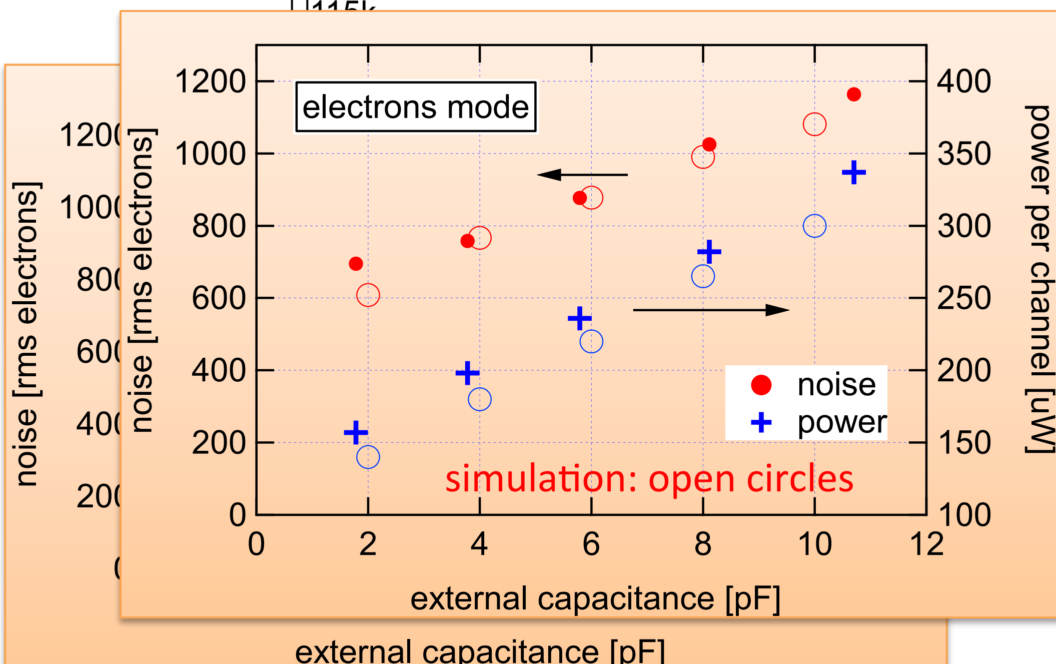
- IBM 130nm CMOS process
- binary, unsparsified architecture
  - retains chip and system simplicity
  - but no pulse height data
- designed for ~2.5 - 5cm µstrips < ~ 10 pF
- 128 channels, 50 µm pitch wire-bond
  - either polarity input signal
- **<u>not contributing</u>** to L1 trigger
- powering test features:
  - 2.5 -> 1.2 DC-DC converter
  - LDO regulator (1.2 -> 1.1) feeds analogue FE
- fast (SLVS) and slow (I2C) control interfaces



Very quick snapshot of CBC results (2011)

CBC measured performance





alogue

- 130 + (21 x C [pF]) µW/chan

gital

- < 50 µW/chan

tal

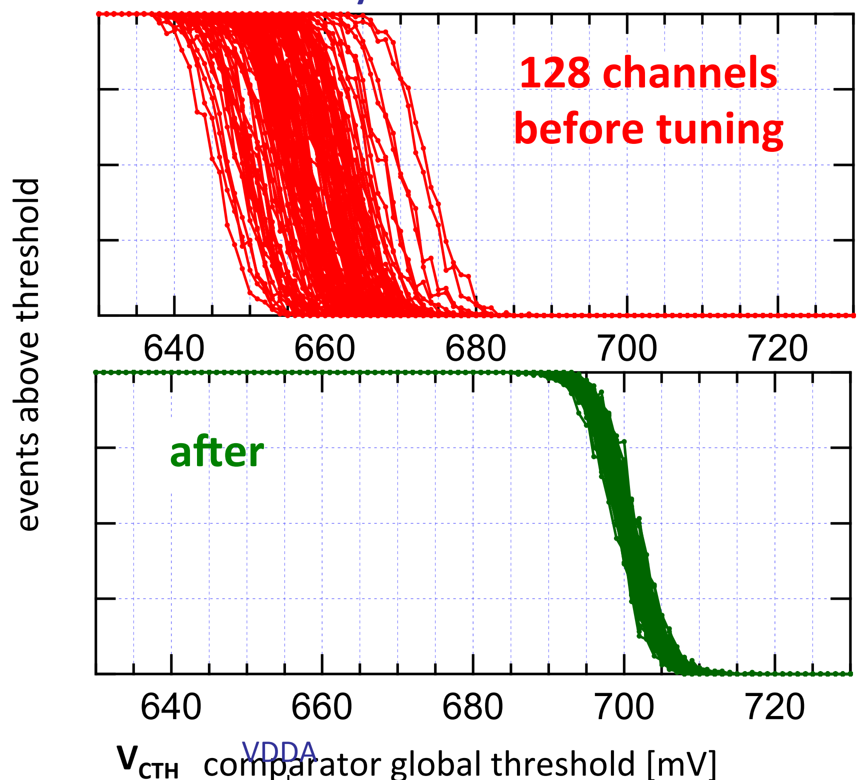
- 180 + (21 x C[pF]) µW/chan

e.g. < 300 µW /channel for C = 5 pF

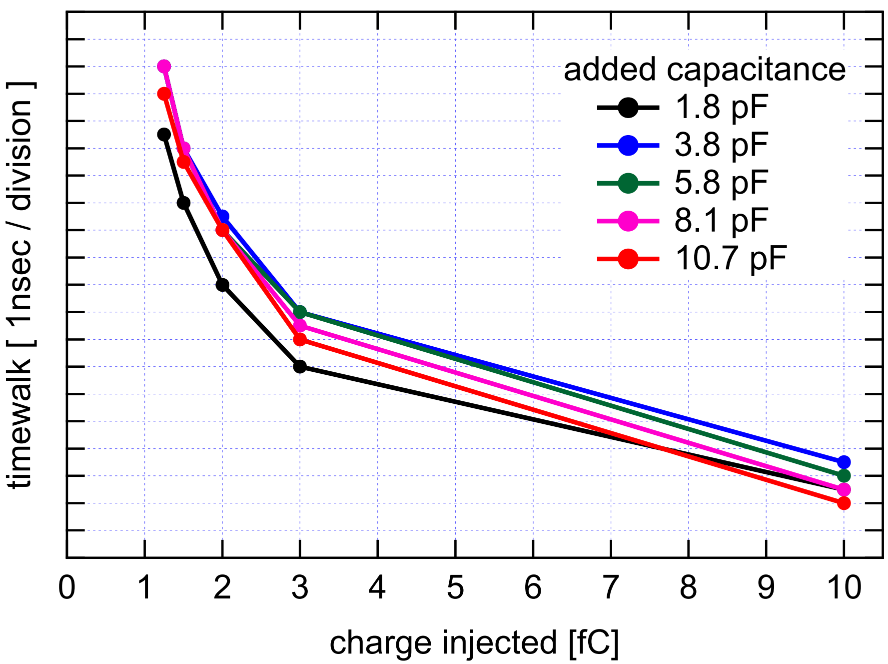
CBC comparator

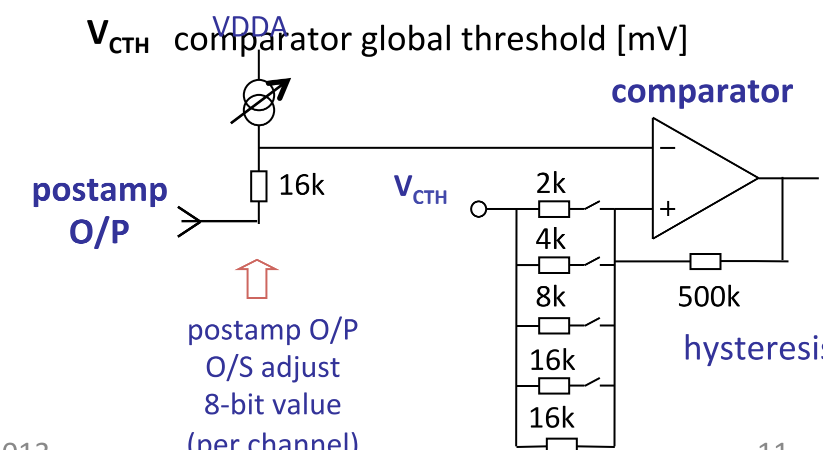
- thresholds adjusted satisfactorily
- timewalk within spec

threshold uniformity

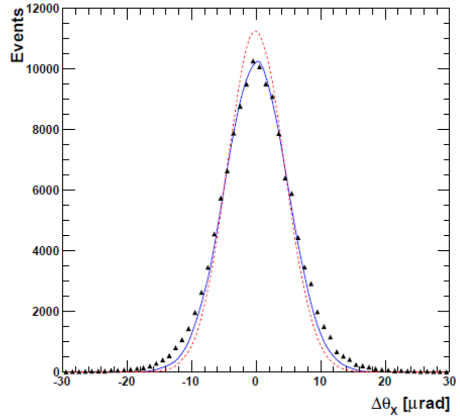


timewalk: threshold at 1 fC



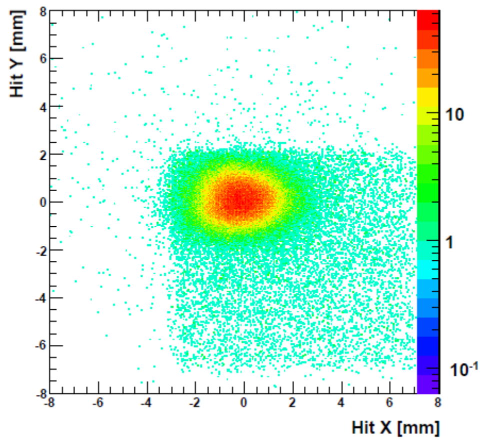


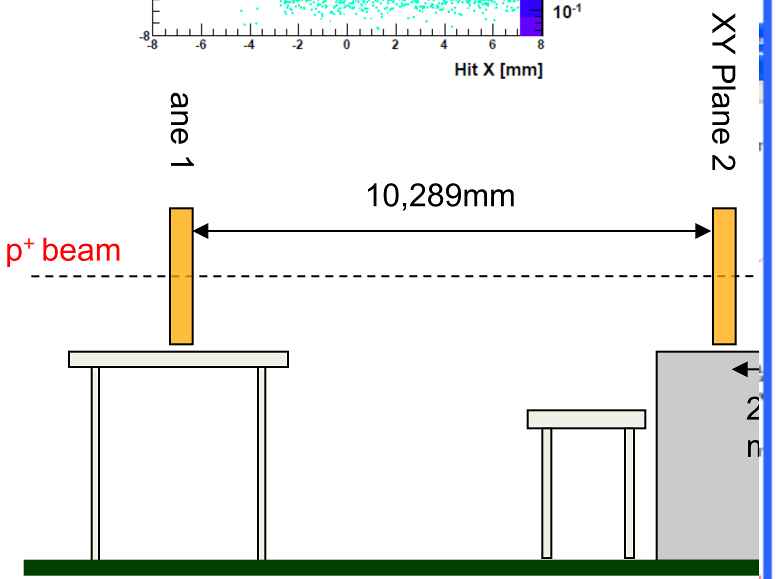
- Based on CMS Tracker DAQ readout hardware, software (used for UA9 studies)
  - FED, APV25s, 100m fibre … n, multi-core PCs
  - 50 kHz data taking durin … ,

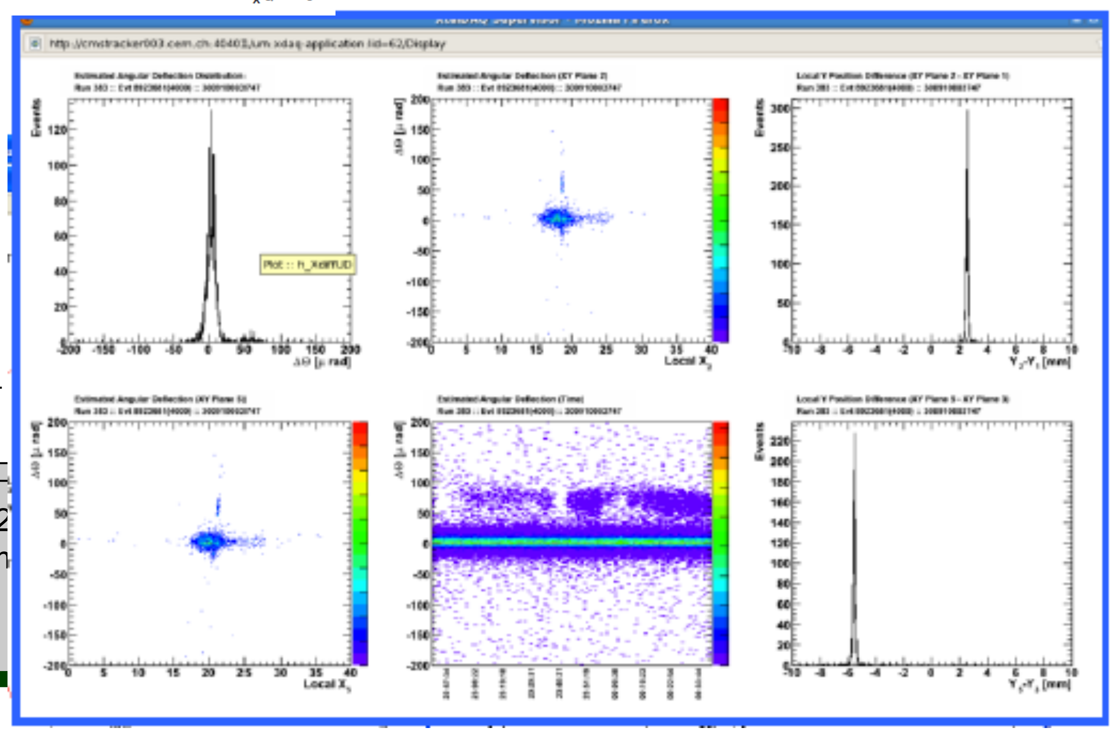


spatial resolution: 6.8-7.0 µm

angular resolution: 5.2 µrad

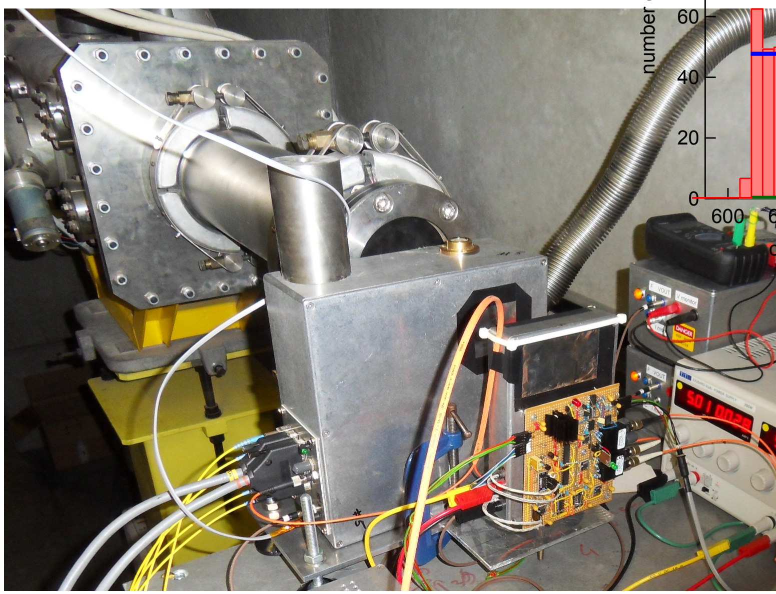


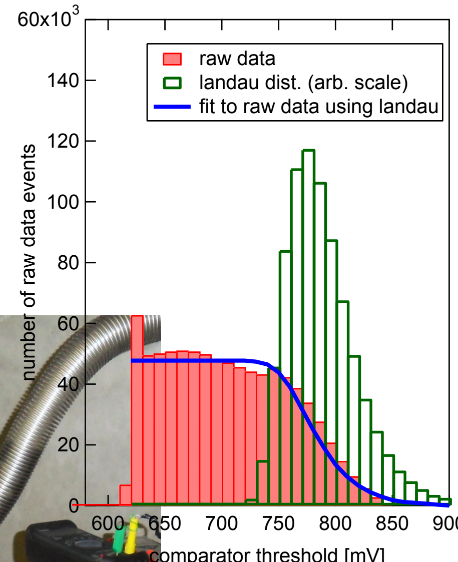




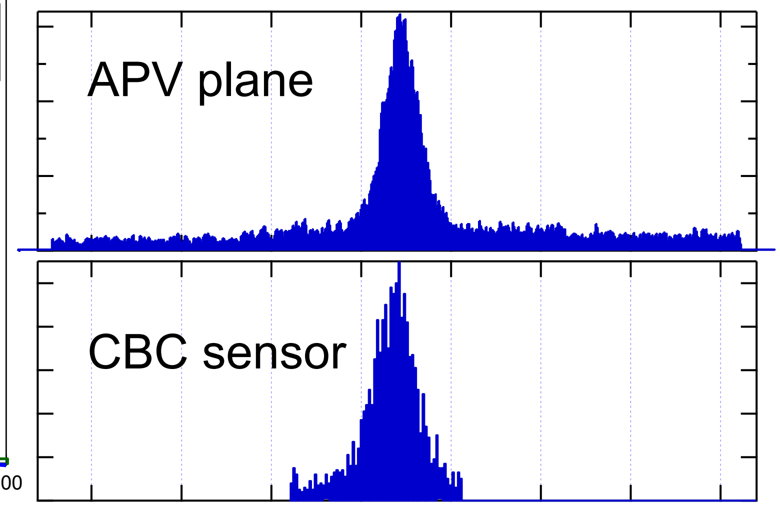
CBC beam tests 2011

- CERN H8 beam line
  - 400 GeV/c protons

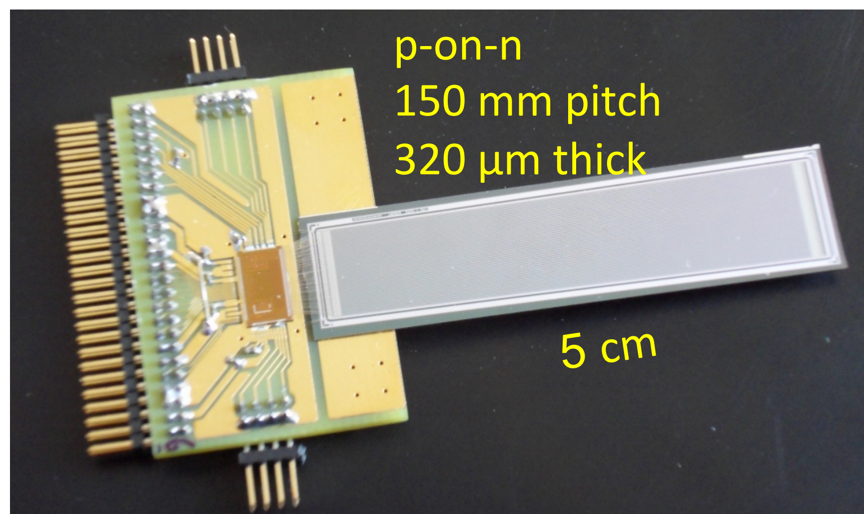




beam profile



5 mV / division

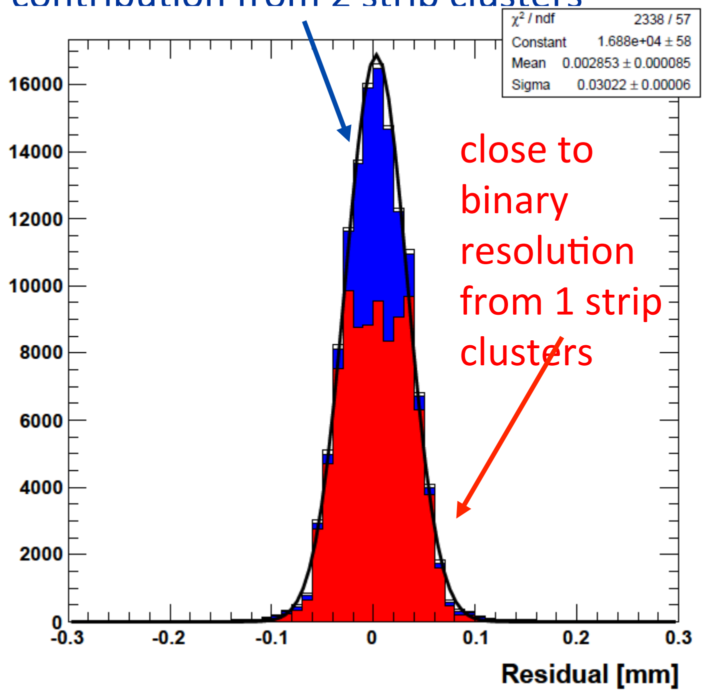


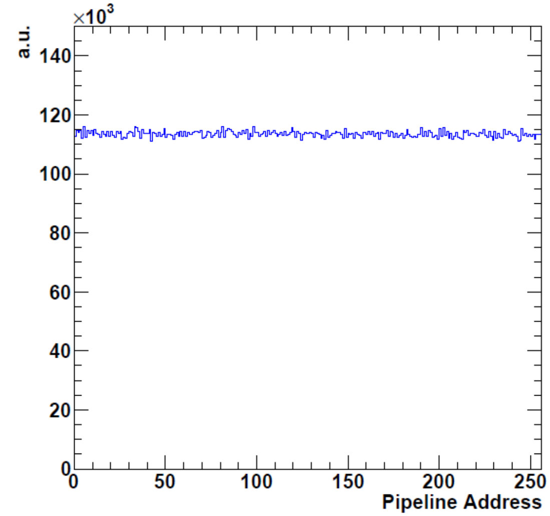
64 x 150 µm pitch strips bonded to 5 cm long, 320 µm thick fan shaped p-on-n sensor

CBC performance in beam

- Successful operation
- Digital logic works well
  - no pipeline errors
  - no CBC errors in > 30M events

better than pitch/√12 due to contribution from 2 strip clusters

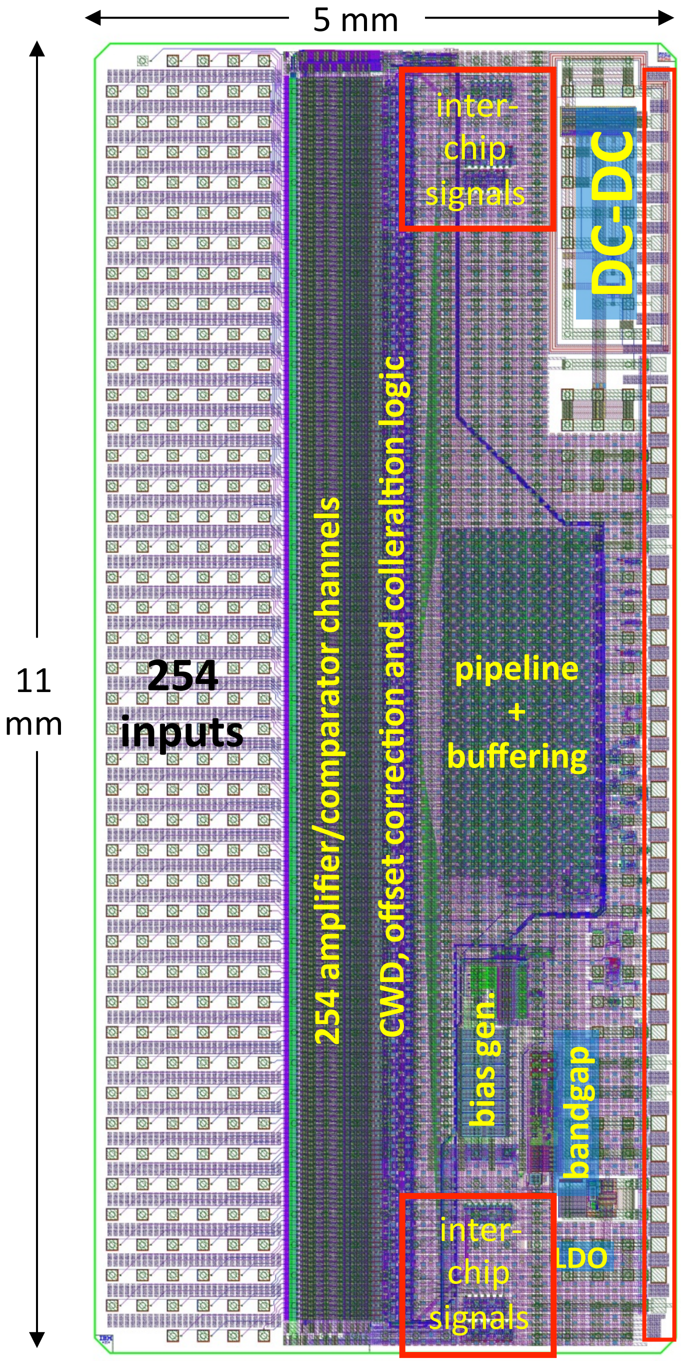




use telescope to select events at CBC module
- single track events only (pileup eliminated)
- incident on CBC sensor (transverse to strips)
- incident in 3mm along strips (const p=134um)
- events within 7ns of sampling clock

measure resolution of CBC module from residual
- using telescope for track extrapolation
- factoring out telescope spatial resolution

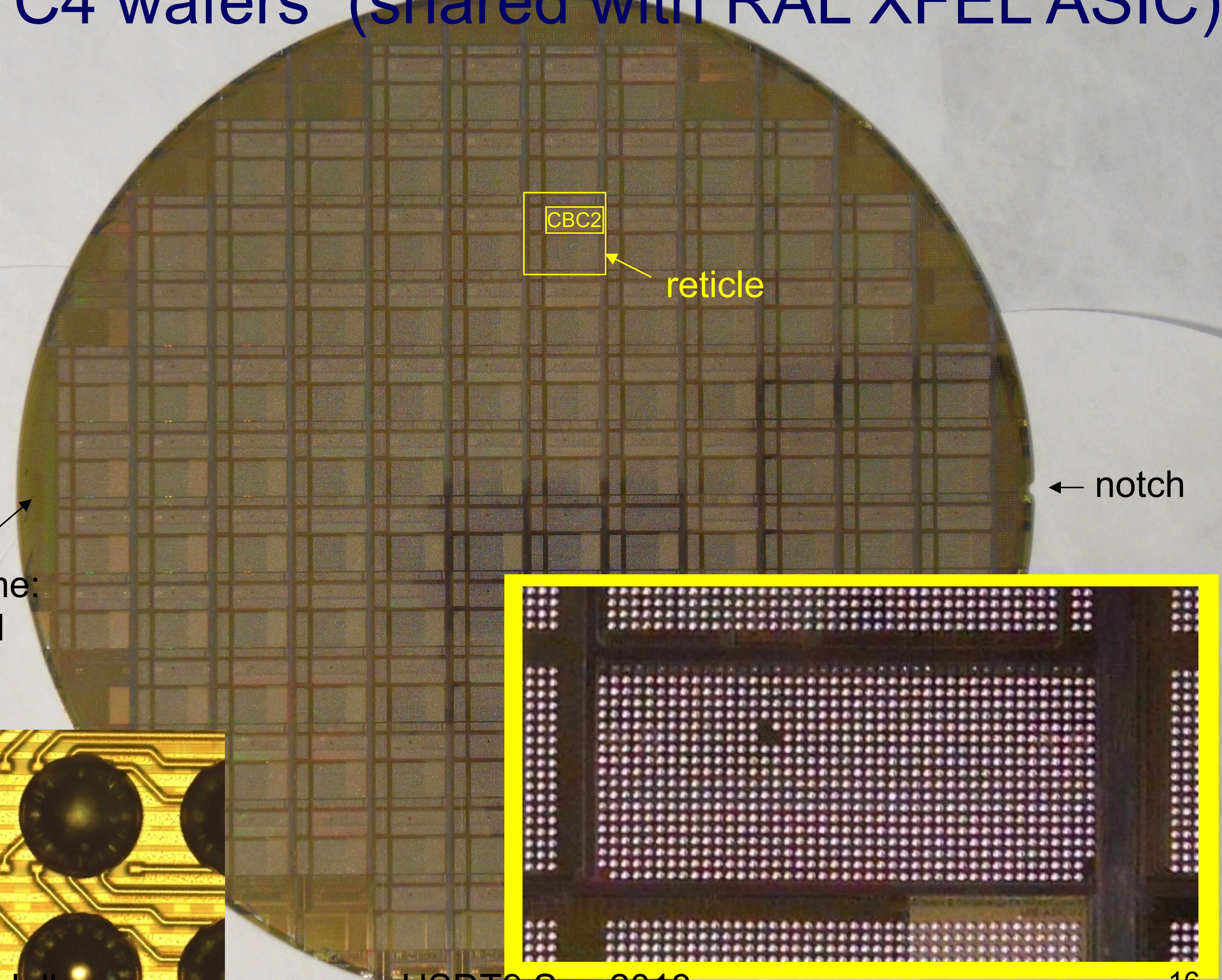
resolution: 29.4 um

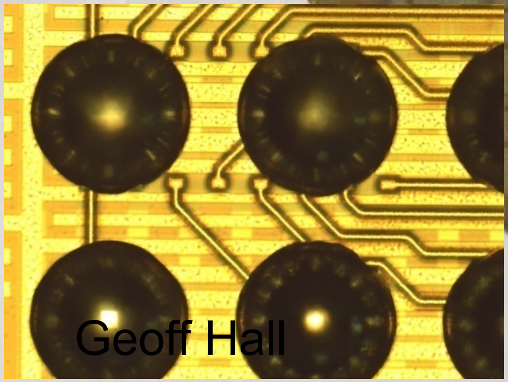


CBC -> CBC2: New features

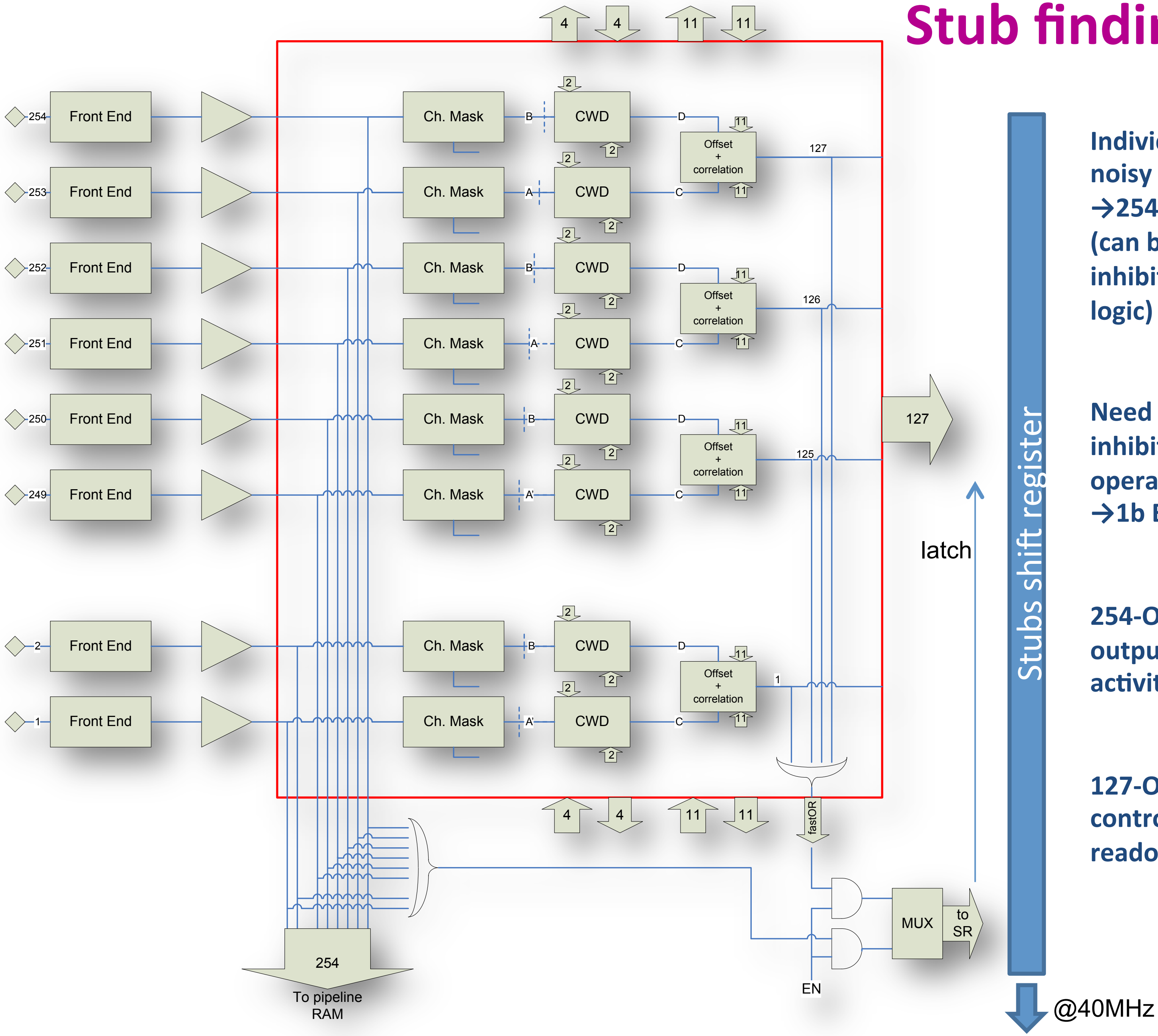
- 250µm pitch C4 layout
  - aim for commercially assembled module
  - some gains in bond inductance
  - back edge wire-bond pads for wafer probe
- 254 channels for 127 + 127 strips
- correlation logic for stub formation
  - between top & bottom strips
  - vetoes wide clusters
- Test pulse
  - no time to implement on CBC
  - & other minor circuit improvements
- Improved DC-DC (CERN)
- received Jan 2013 – fully functional

CBC2 C4 wafers (shared with RAL XFEL ASIC)





Stub finding Logic



Individual mask for noisy channels
→254b from I2C reg.
(can be also used to inhibit coincidence logic)

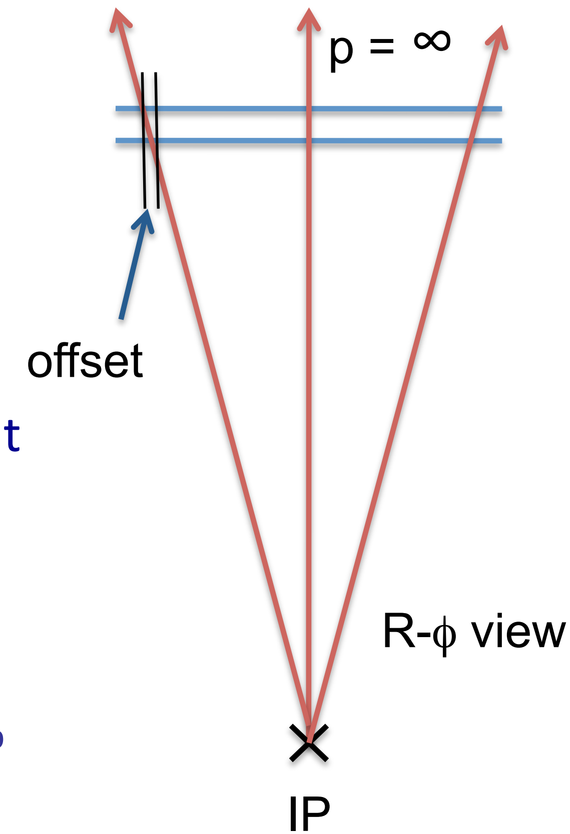
Need to be able to inhibit stub shift register operation
→1b EN from I2C reg.

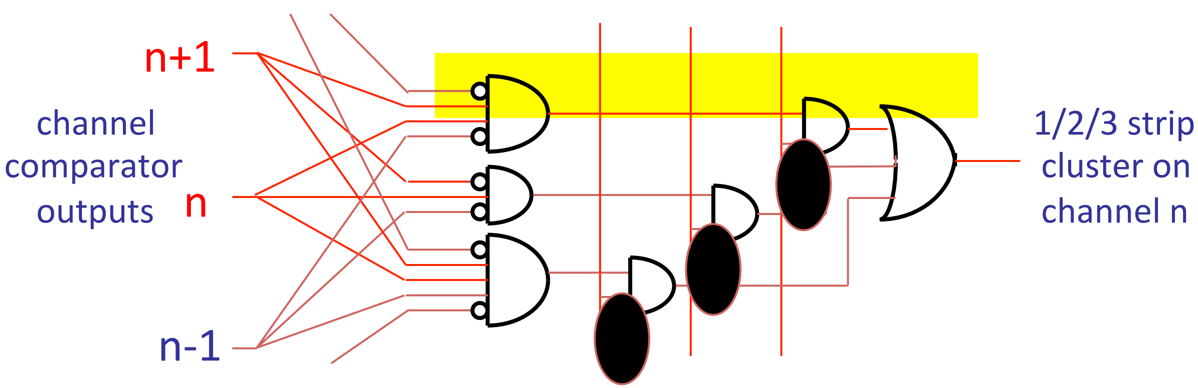
254-OR of channel outputs to signal any activity on chip

127-OR of stubs to control the stubs SR readout

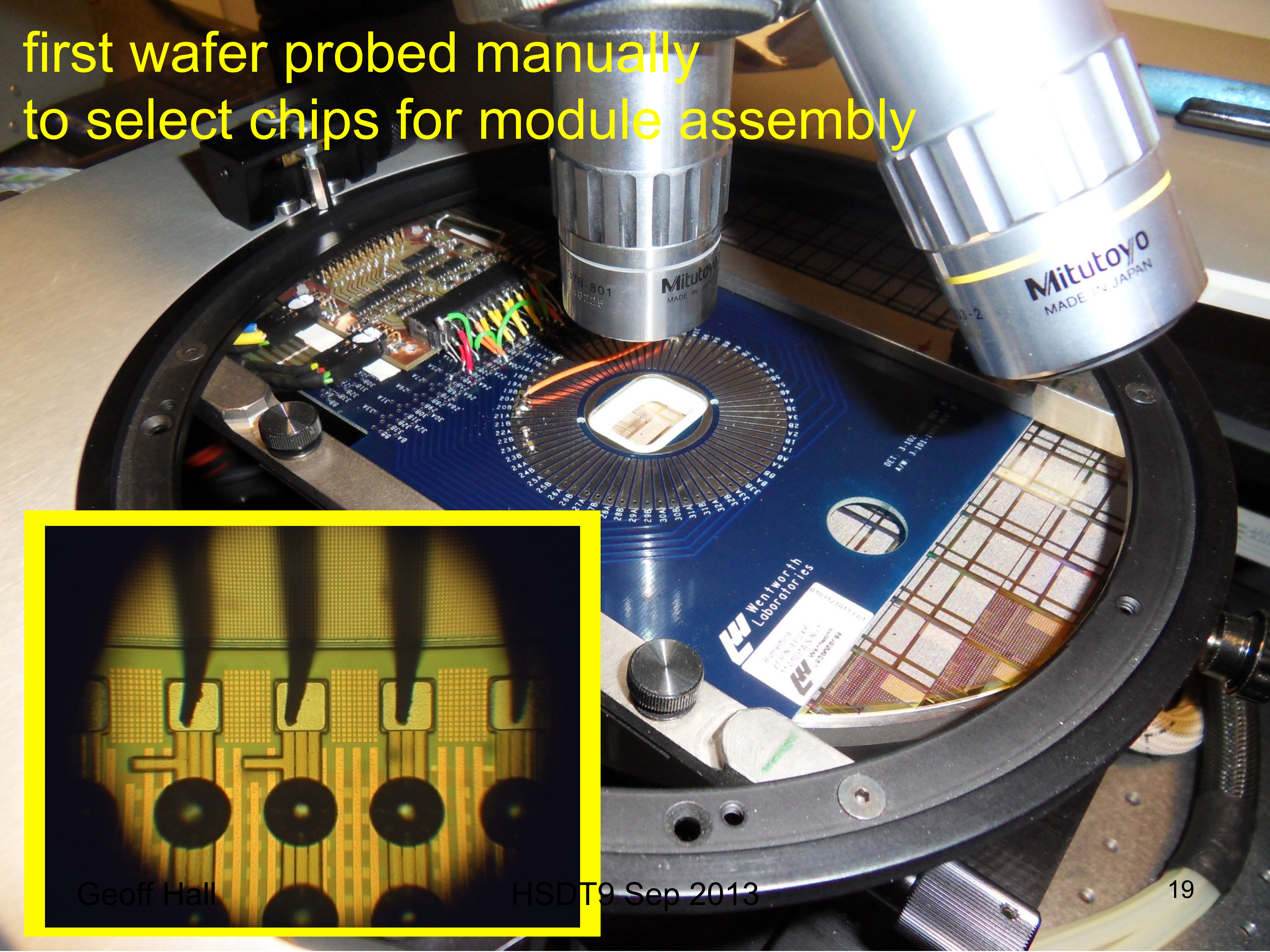
Stub logic features

- Cluster width
  - exclude clusters wider than 3 strips
- Offset correction and correlation
  - programmable window, selects pT
    - up to +/-8 channels
  - programmable offset, adjust lateral displacement
    - up to +/-3 channels





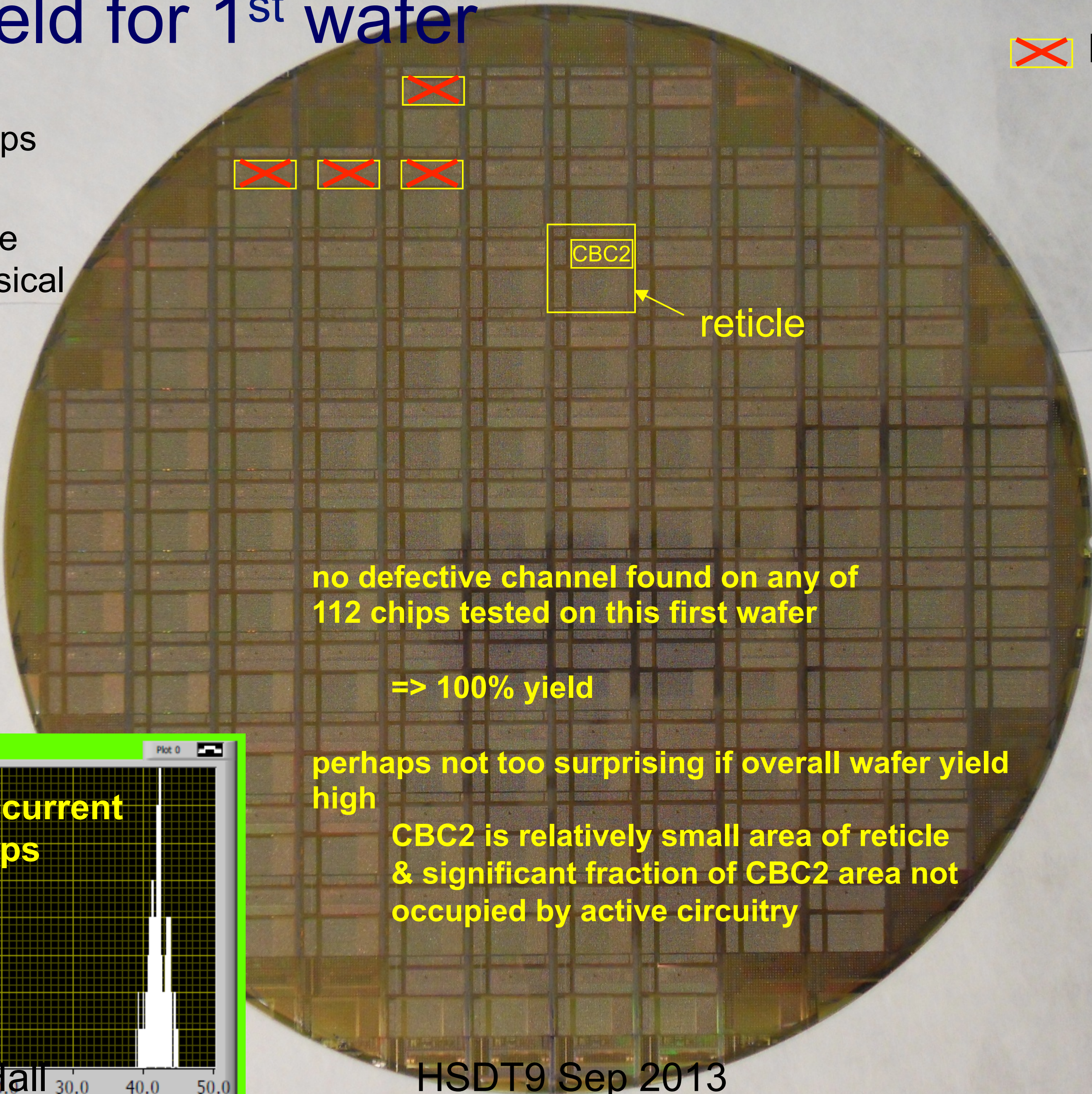
first wafer probed manually to select chips for module assembly



final yield for 1st wafer

112 reticles
108 good chips
4 bad chips

bad chips due solely to physical damage from probe card

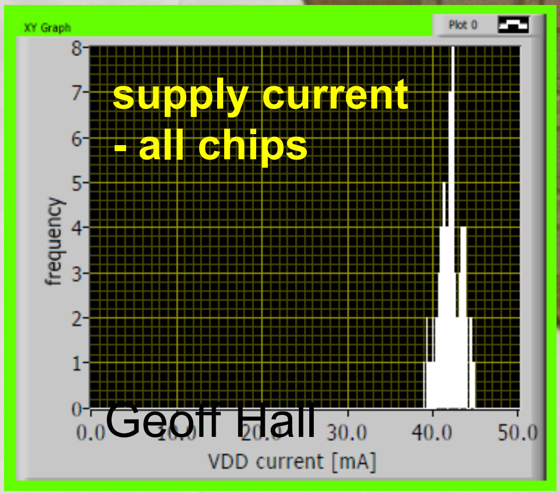


no defective channel found on any of 112 chips tested on this first wafer

=> 100% yield

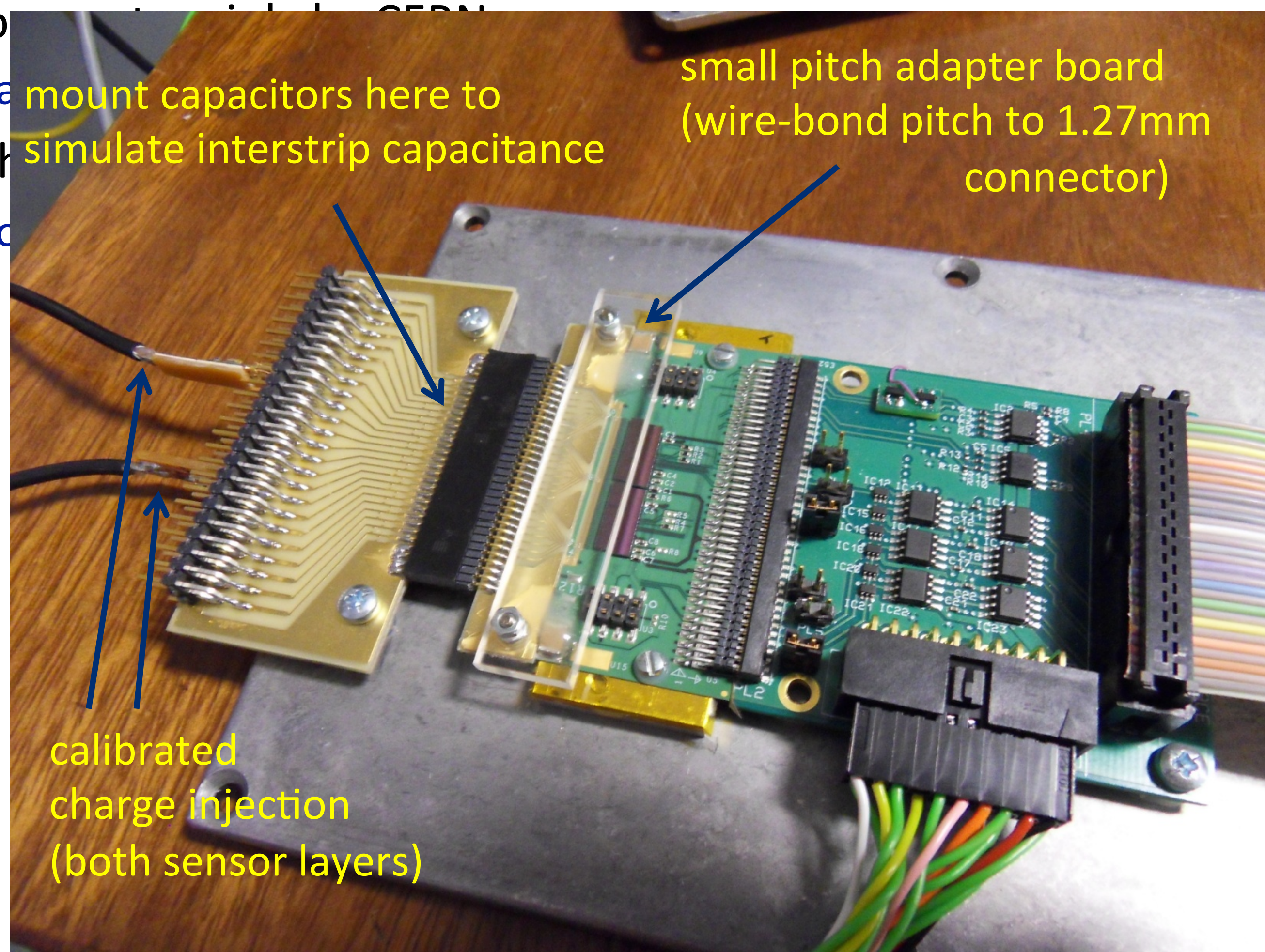
perhaps not too surprising if overall wafer yield high

CBC2 is relatively small area of reticle
& significant fraction of CBC2 area not occupied by active circuitry

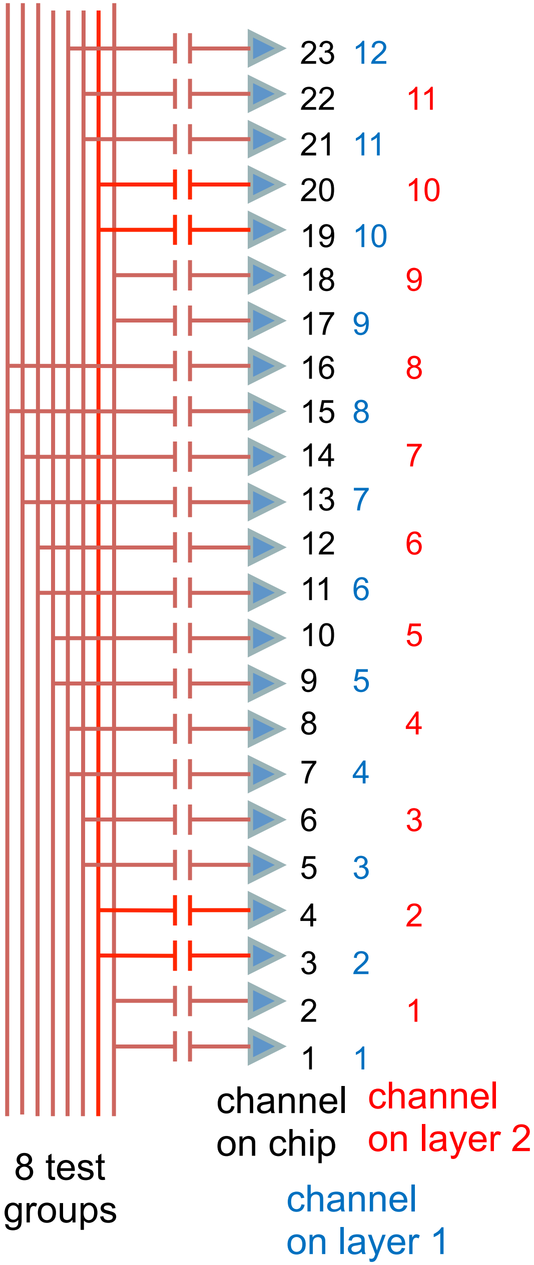


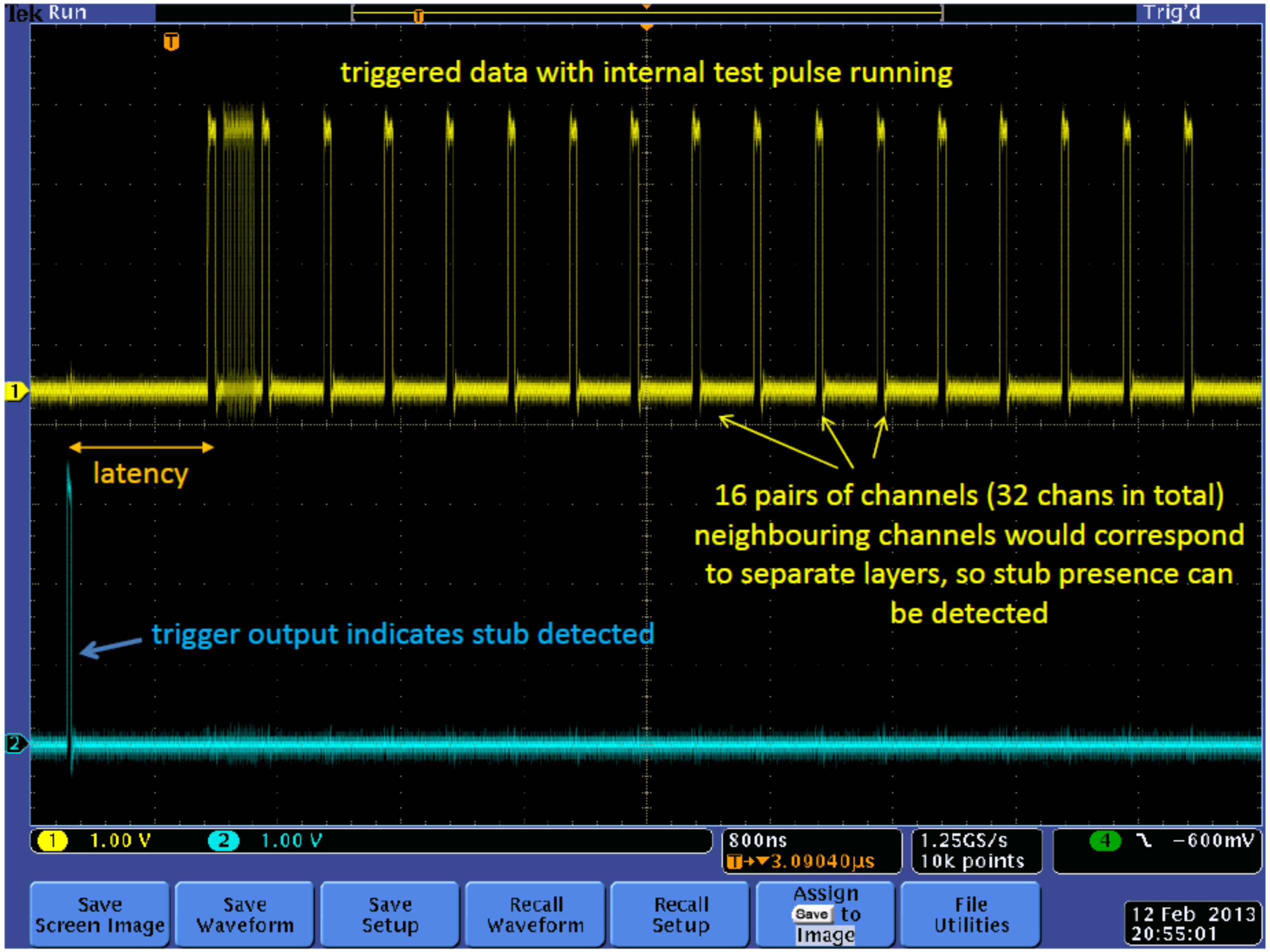
2S module

- Development with CMS team
- Substrate develo
  - Hybrid procured a
- First version: 2 ch
  - electrical validatio



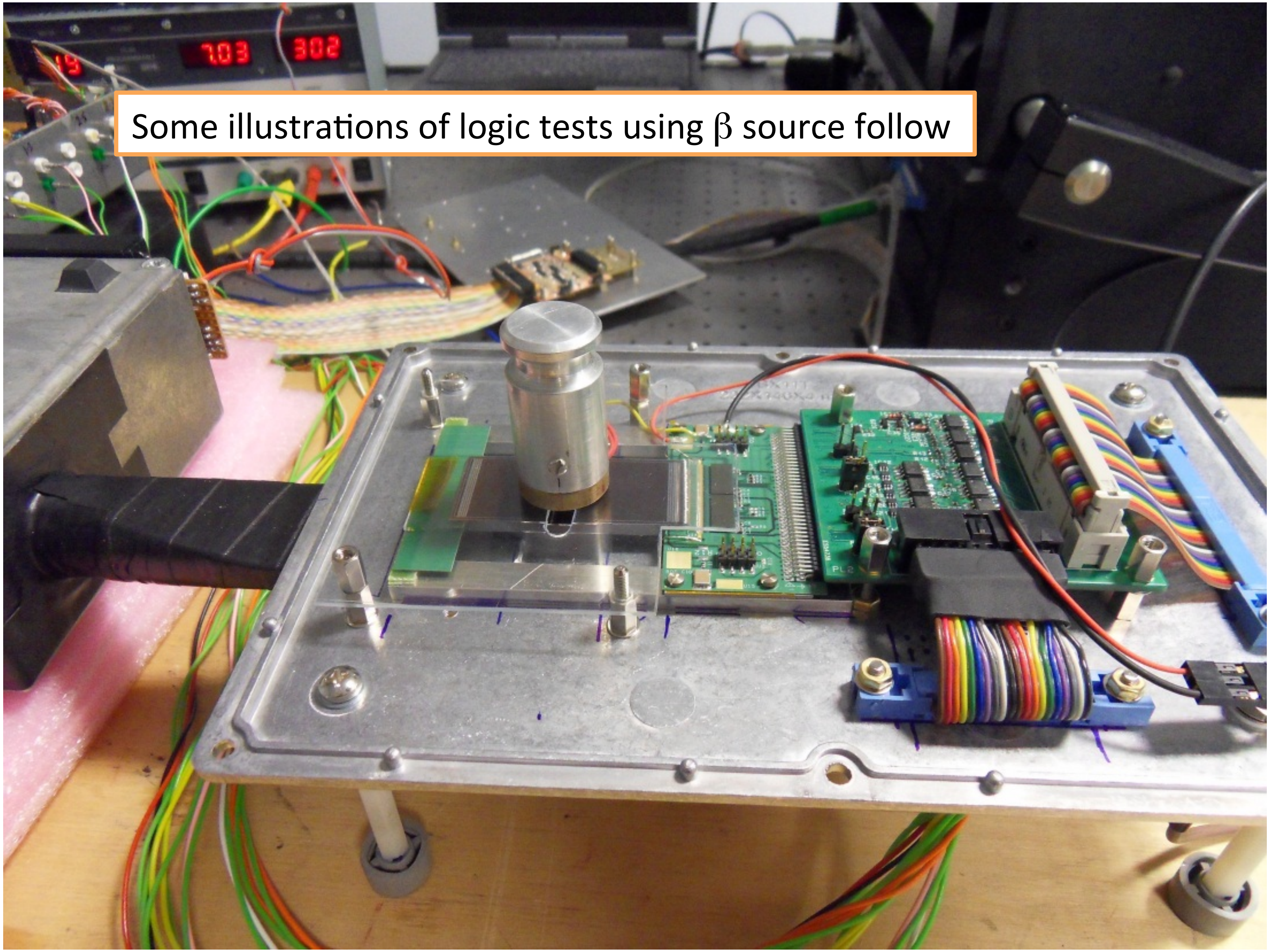
Result with test pulse

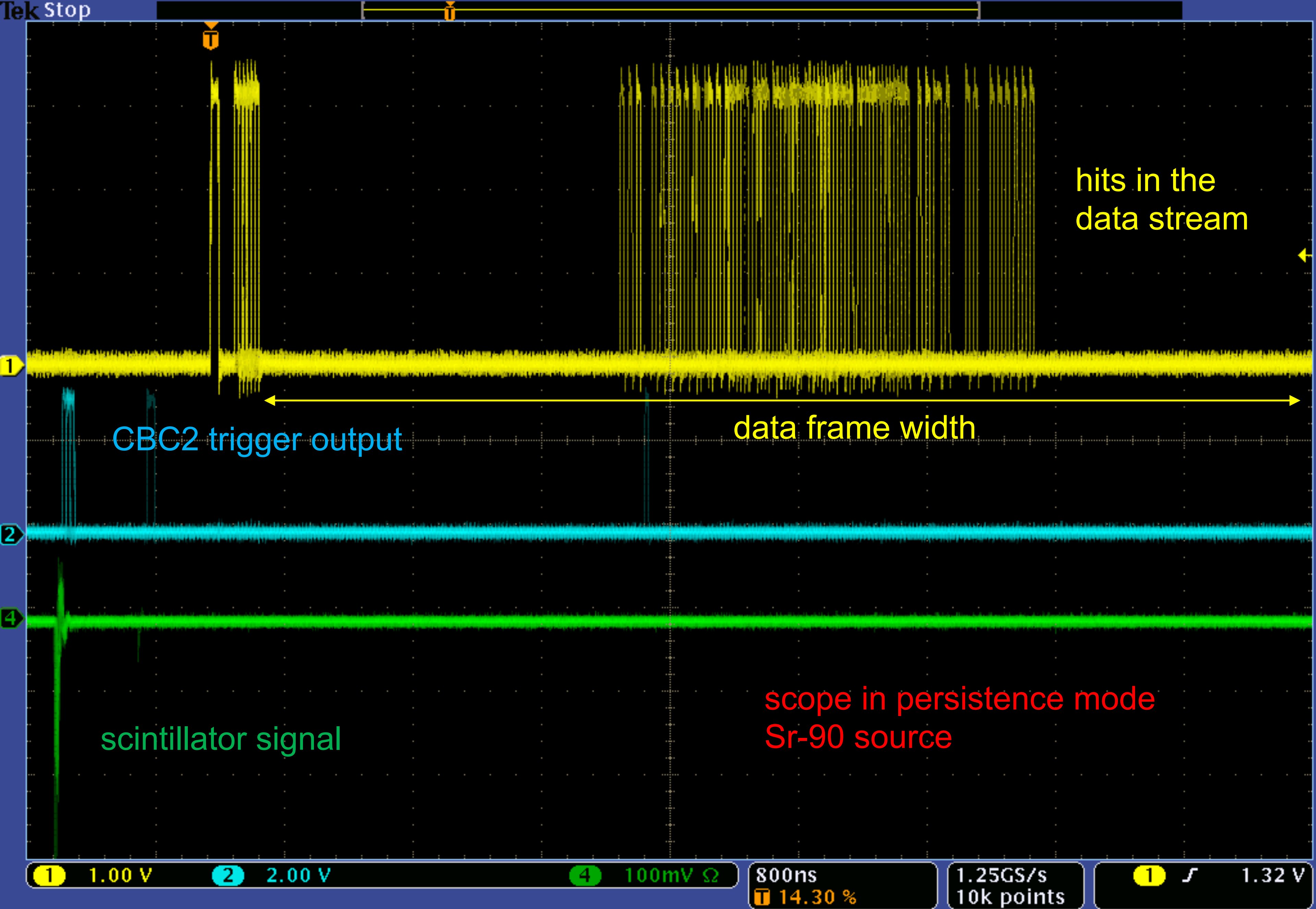


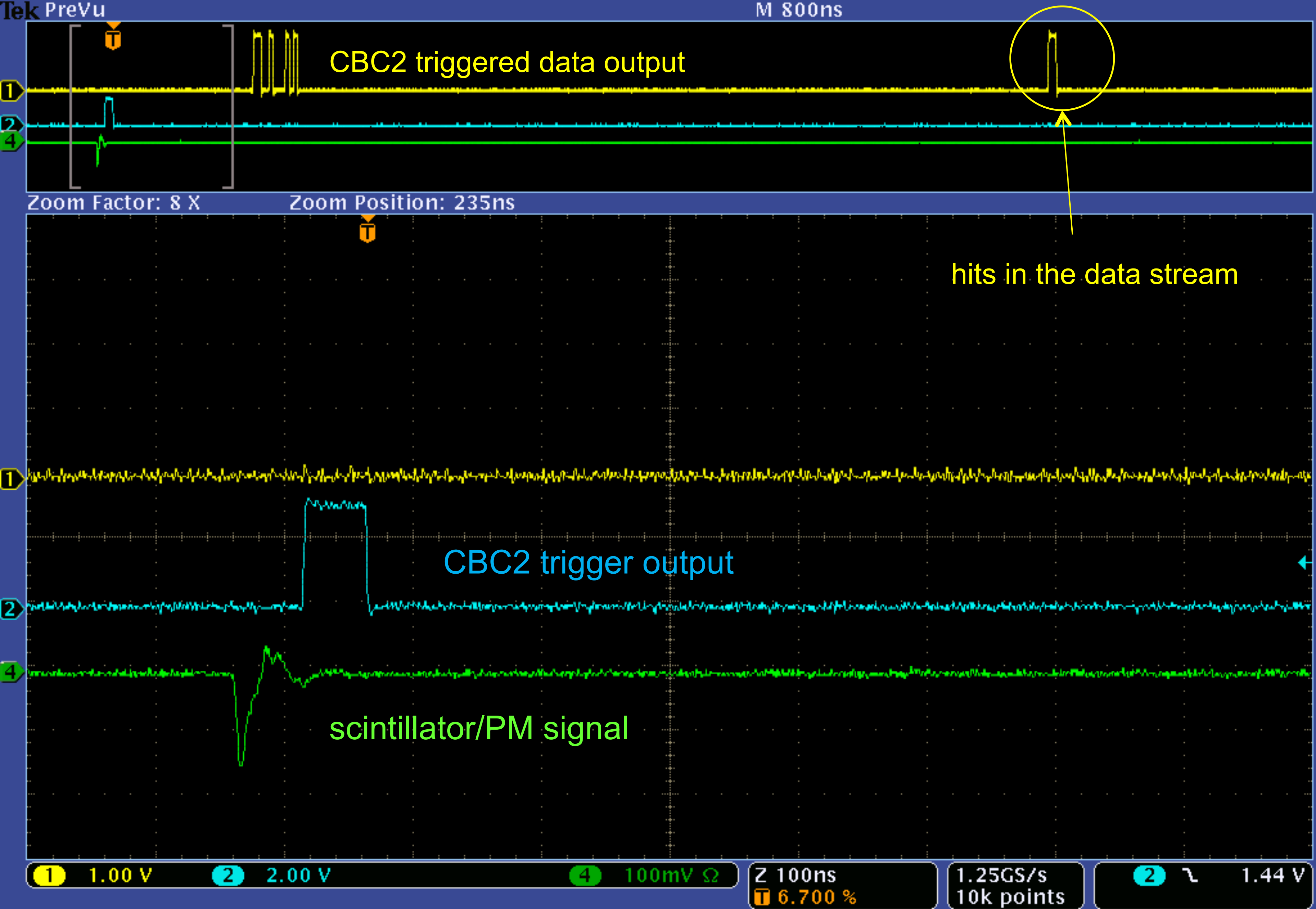


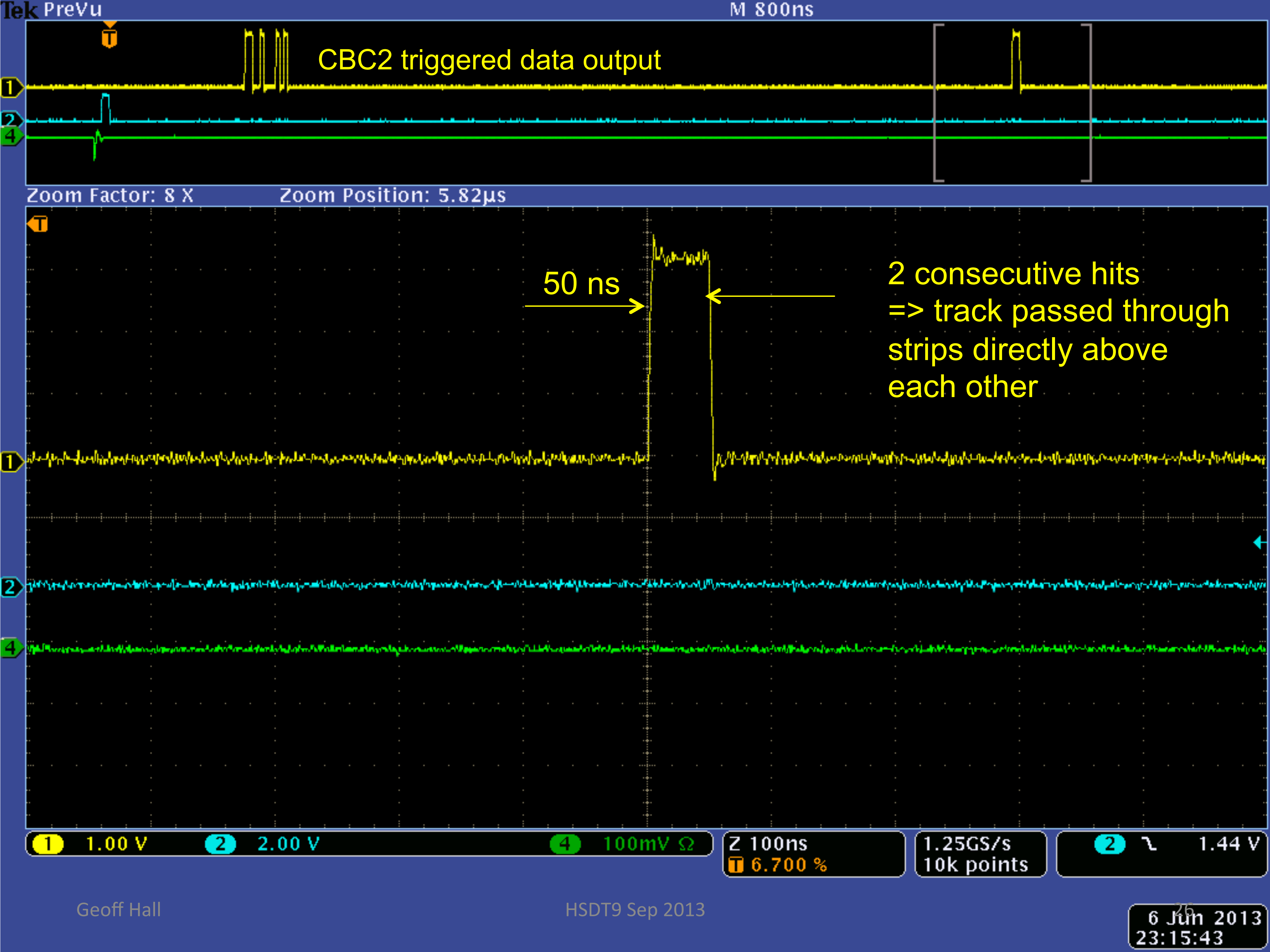
– Proves basic functionality but need real data for better test

2S mini-module

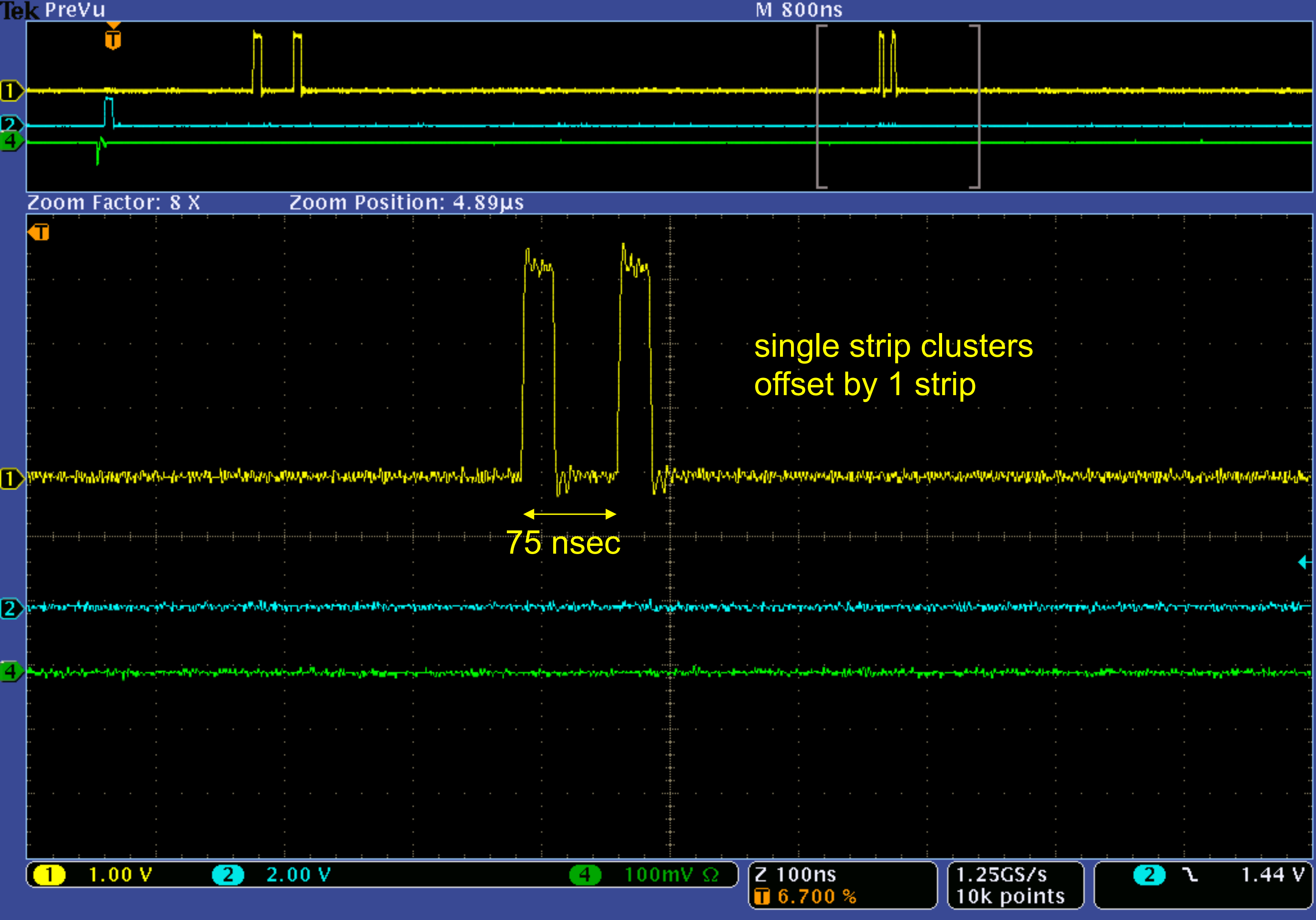


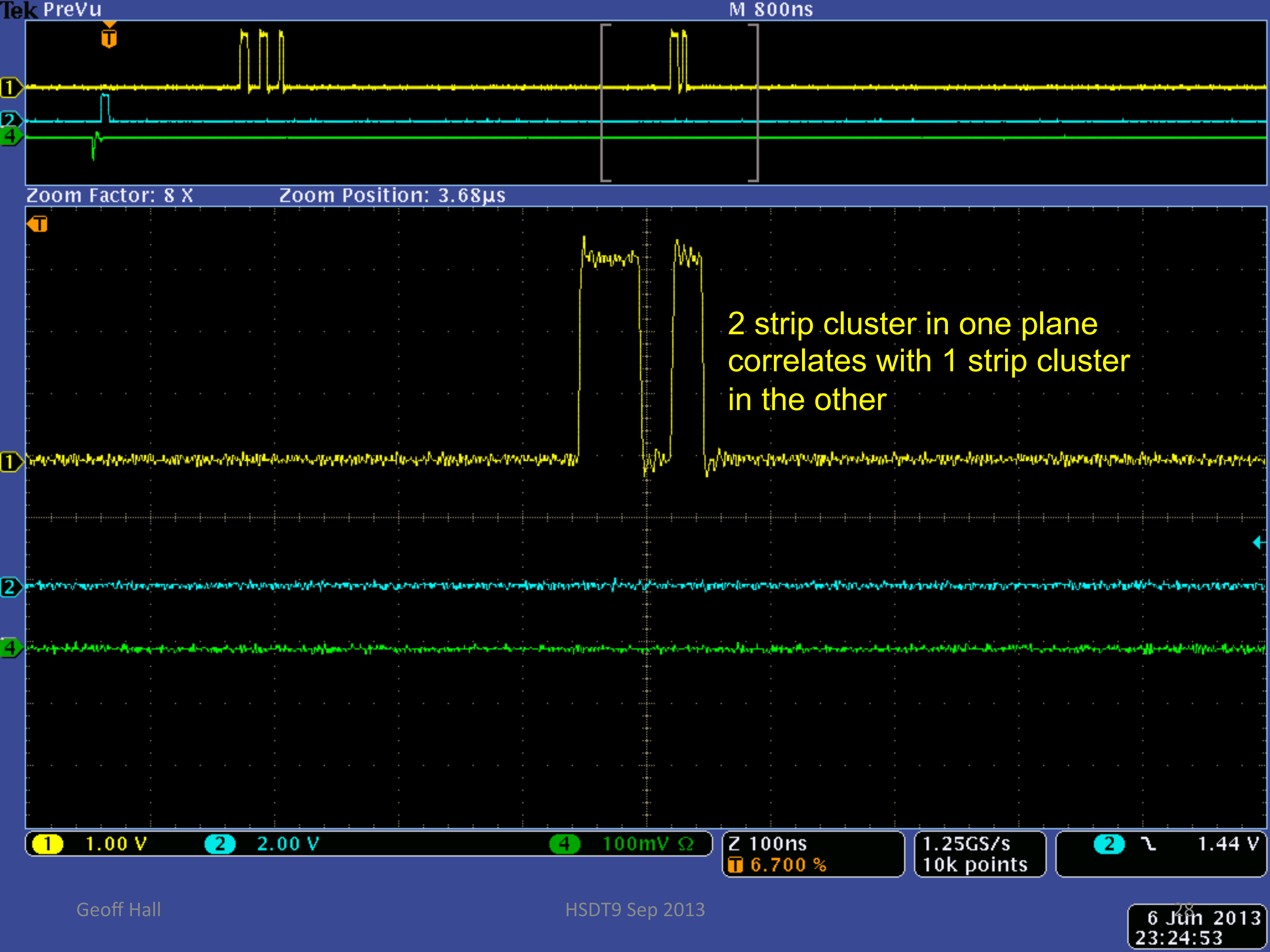

Tek Stop
hits in the
data stream
data frame width
CBC2 trigger output
scintillator signal
scope in persistence mode
Sr-90 source
1 1.00 V
2 2.00 V
4 100mV Ω
800ns
14.30 %
1.25GS/s
10k points
1 1.32 V
10 Jun 2013
21:15:53

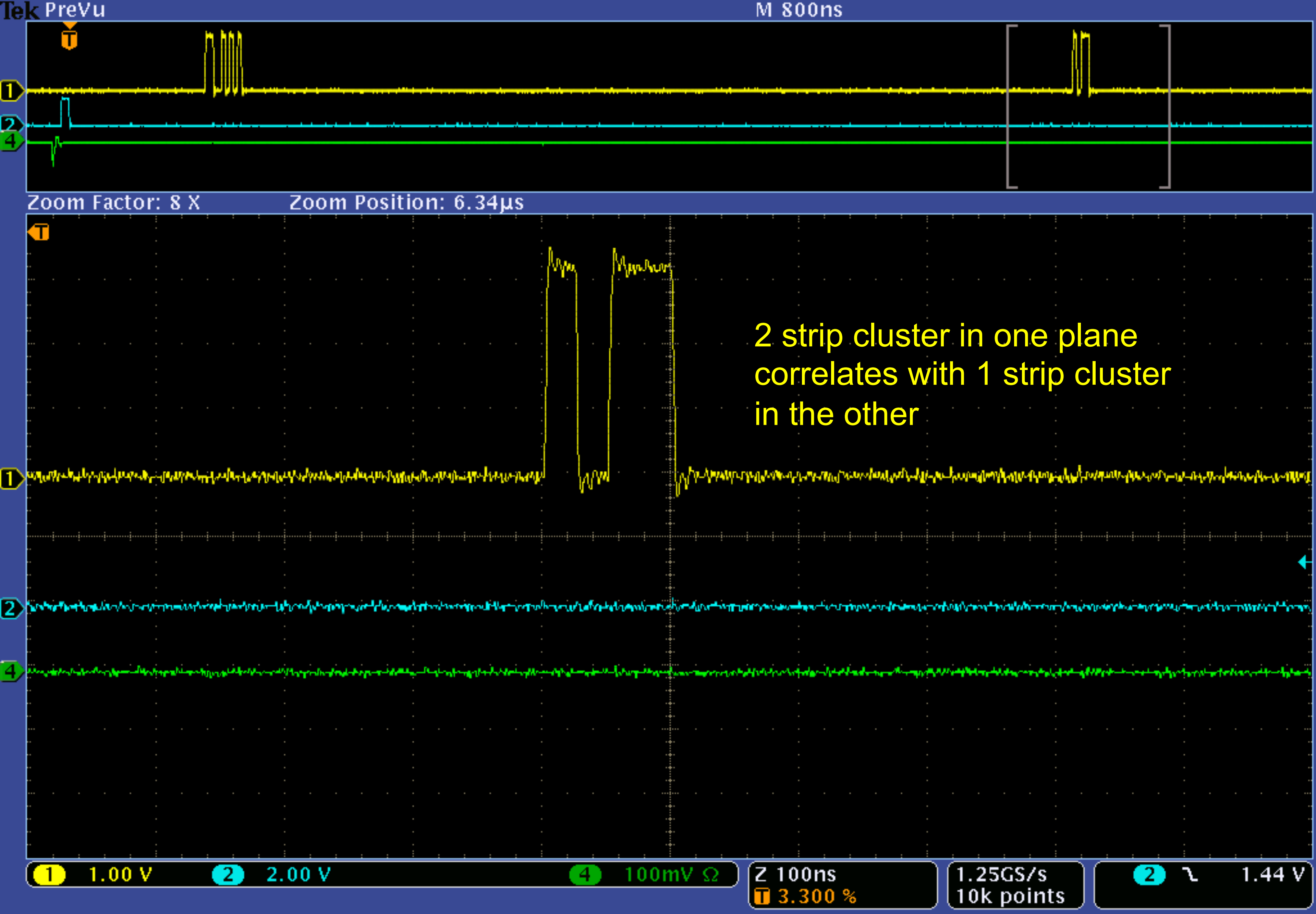

Tek PreVu
M 800ns
CBC2 triggered data output
Zoom Factor: 8 X
Zoom Position: 235ns
hits in the data stream
CBC2 trigger output
scintillator/PM signal
1 1.00 V
2 2.00 V
4 100mV Ω
Z 100ns
6.700 %
1.25GS/s
10k points
2 1.44 V
6 Jun 2013
23:14:56

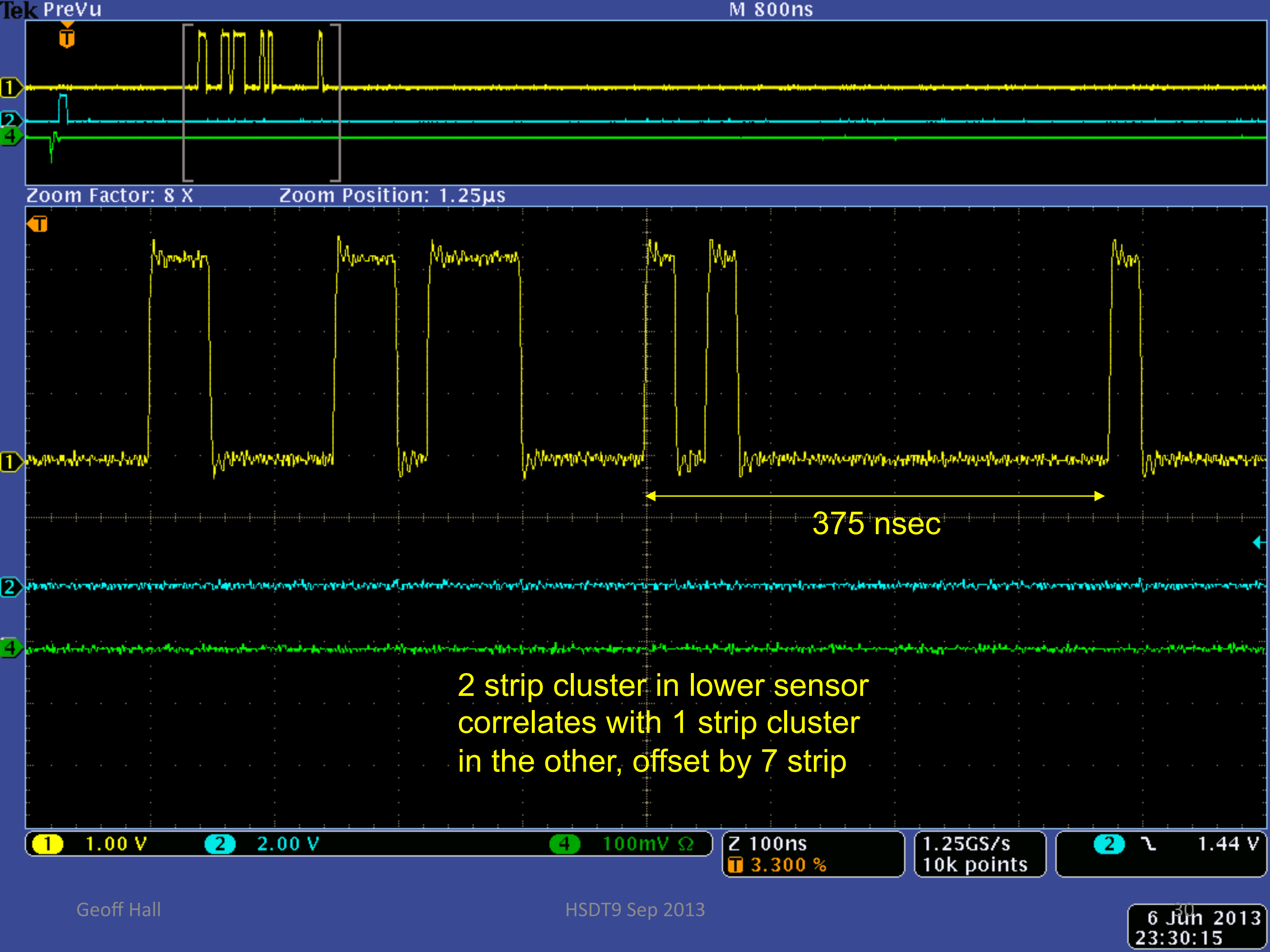


Tek PreVu
M 800ns
CBC2 triggered data output
Zoom Factor: 8 X
Zoom Position: 5.82µs
50 ns
2 consecutive hits
=> track passed through
strips directly above
each other
1.00 V
2.00 V
100mV Ω
Z 100ns
6.700 %
1.25GS/s
10k points
1.44 V
6 Jun 2013
23:15:43


Tek PreVu
M 800ns
Zoom Factor: 8 X
Zoom Position: 4.89µs
single strip clusters
offset by 1 strip
75 nsec
1.00 V
2.00 V
100mV Ω
Z 100ns
6.700 %
1.25GS/s
10k points
1.44 V
6 Jun 2013
23:23:47


Tek PreVu
M 800ns
Zoom Factor: 8 X
Zoom Position: 3.68µs
2 strip cluster in one plane
correlates with 1 strip cluster
in the other
1.00 V
2.00 V
100mV Ω
Z 100ns
6.700 %
1.25GS/s
10k points
1.44 V
6 Jun 2013
23:24:53


Tek PreVu
M 800ns
Zoom Factor: 8 X
Zoom Position: 6.34µs
2 strip cluster in one plane correlates with 1 strip cluster in the other
1.00 V
2.00 V
100mV Ω
Z 100ns
3.300 %
1.25GS/s
10k points
1.44 V
6 Jun 2013
23:29:20


Tek PreVu
M 800ns
Zoom Factor: 8 X
Zoom Position: 1.25µs
375 nsec
2 strip cluster in lower sensor
correlates with 1 strip cluster
in the other, offset by 7 strip
1.00 V
2.00 V
100mV Ω
Z 100ns
3.300 %
1.25GS/s
10k points
1.44 V
6 Jun 2013
23:30:15

Rough road map

2011
2012
2013
2014
2015
2016
2017

CBC1

- analogue front end in 130nm
- wirebonded
- binary logic
- L1 triggered readout only, non-sparsified

CBC2

- C4 bump-bonded
- full hit correlation logic
- L1 triggered non-sparsified readout, fast trigger OR

CBC3

- full readout architecture defined
- final data format
- additional correlation logic

CBC4

- optimisation
- final version

2S-Pt prototype module studies

2S-Pt final module studies

start production

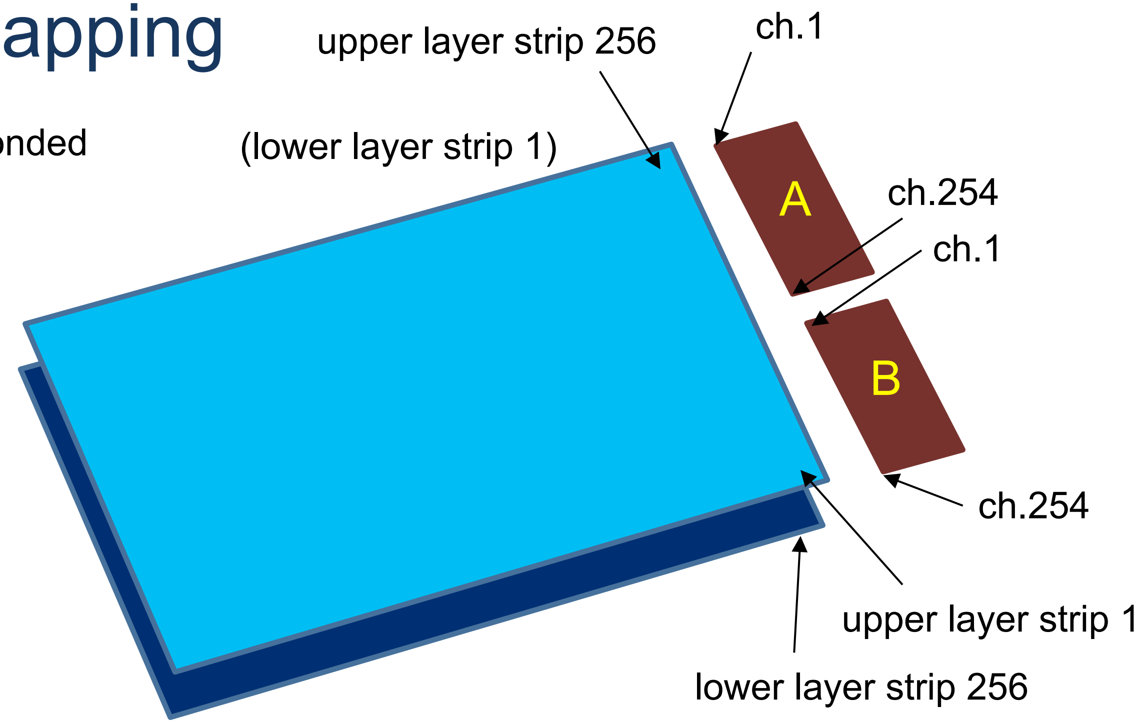
Summary & conclusions

- Two successful iterations of new outer Tracker ASIC
- First prototype version of 2S module in hand
  - functions well in lab environment
  - first beam tests foreseen late 2013
- Road map for future developments
  - detailed schedule depends on complete upgrade plan and HL-LHC approval process

Backup slides

channel to strip no. mapping

2 edge channels on each sensor not bonded
(i.e. strips 2 - 255 inclusive bonded)



chip channel vs. sensor strip #

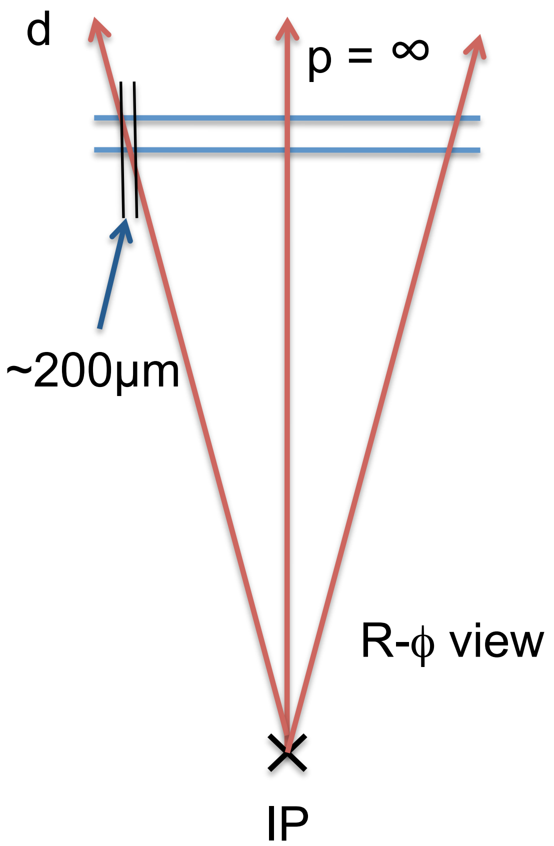
	chip A									chip B								
	2	4	6	8	.....	.....	250	252	254	2	4	6	....	....	248	250	252	254
upper sensor	255	254	253	252	.....	....	131	130	129	128	127	126	....	...	5	4	3	2

	chip A									chip B								
	1	3	5	7	.....	.....	249	251	253	1	3	5	....	....	247	249	251	253
lower sensor	2	3	4	5	...	....	126	127	128	129	130	131	...	...	252	253	254	255

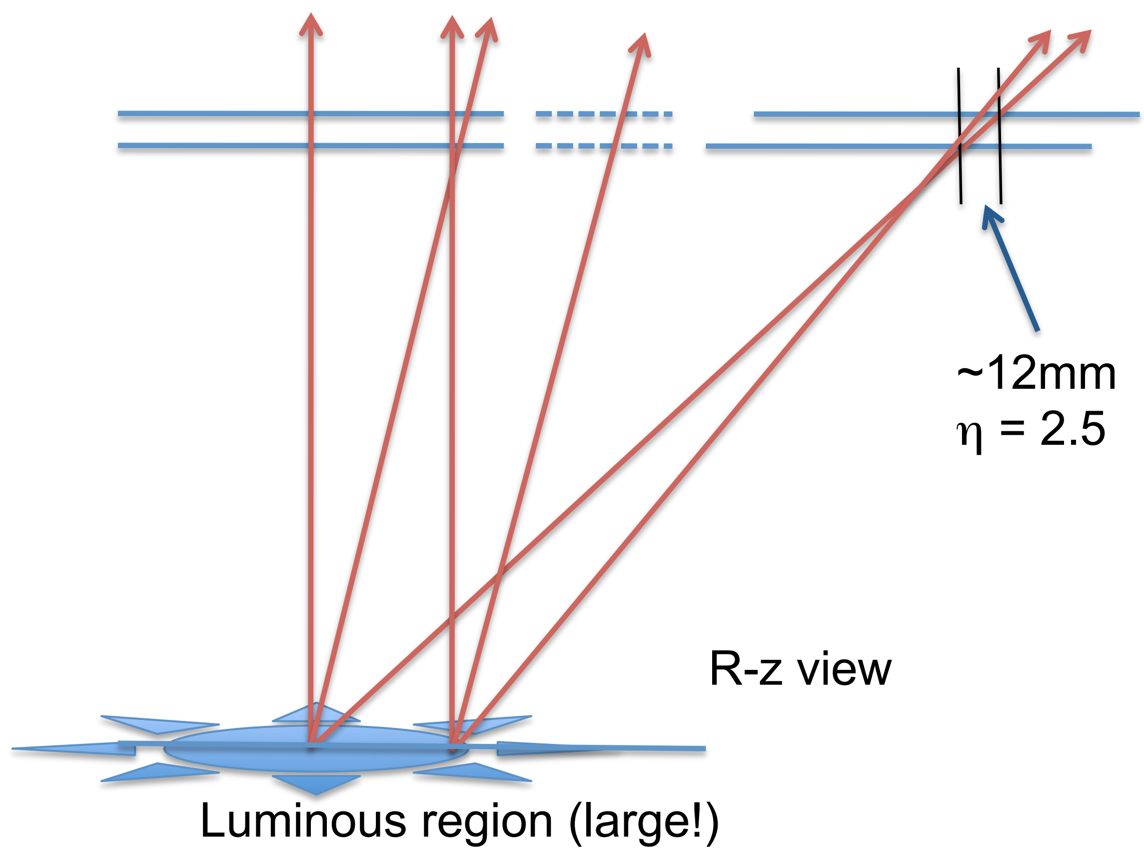
Comparison logic

- Modules are flat, not arcs
- Compensate for Lorentz drift
- Orientation of module

=> position dependent logic

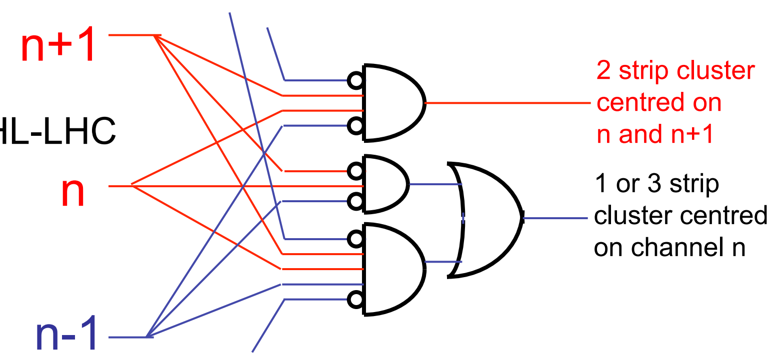


- z offset η dependent
- search window to allow for luminous region and quantization => 3 pixels (if not tiny)



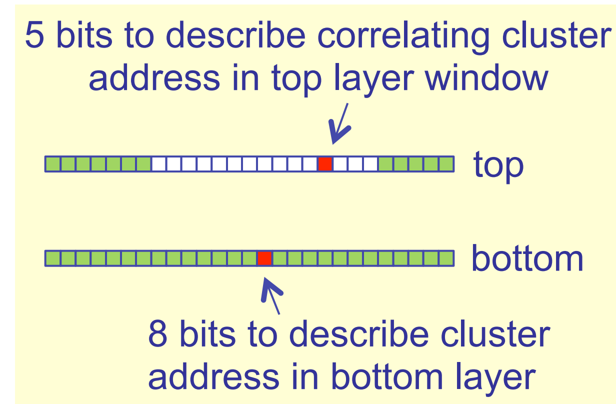
- Family of modules with offsets in z

CBC3 - the "final prototype"



next version of chip should incorporate all features required for HL-LHC

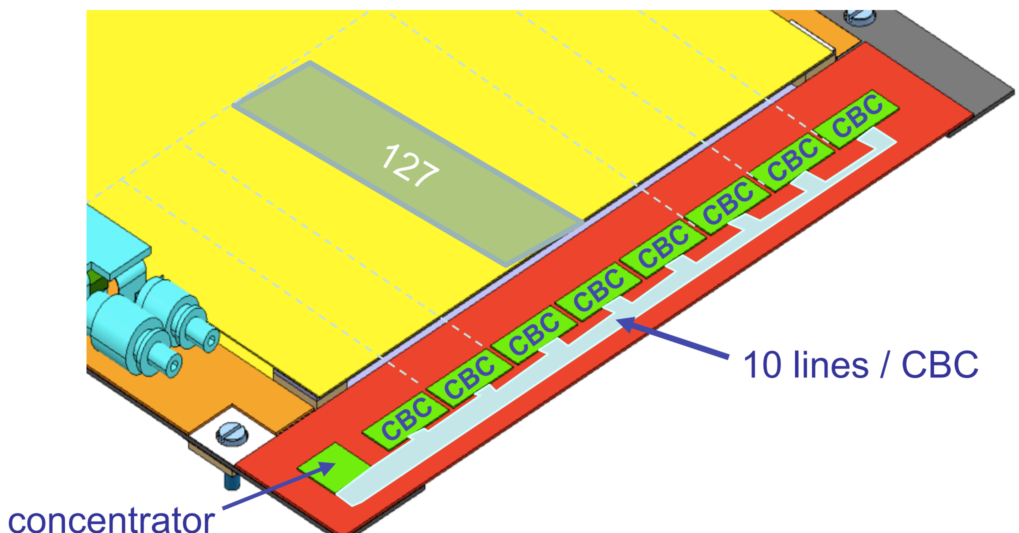
- **final choices for front end**
  - ½ strip cluster resolution
    - 2 strip cluster position assigned to mid-point
- **stub data definition**
  - 8 bits address (for ½ strip resolution) of cluster in bottom layer
  - 5 bit bend information
    - address of correlating cluster in top layer
- **stub data formatting & transmission to concentrator**
  - 13 bit / stub, up to 3 stubs/BX => 39 bits
  - +1 bit unsparsified L1 triggered readout data
  - => 40 bits / 25 nsec
    - e.g. 10 lines at 160 Mbps (per chip)
- **other useful features**
  - e.g. slow ADC to monitor bias levels
  - …



CBC data to concentrator

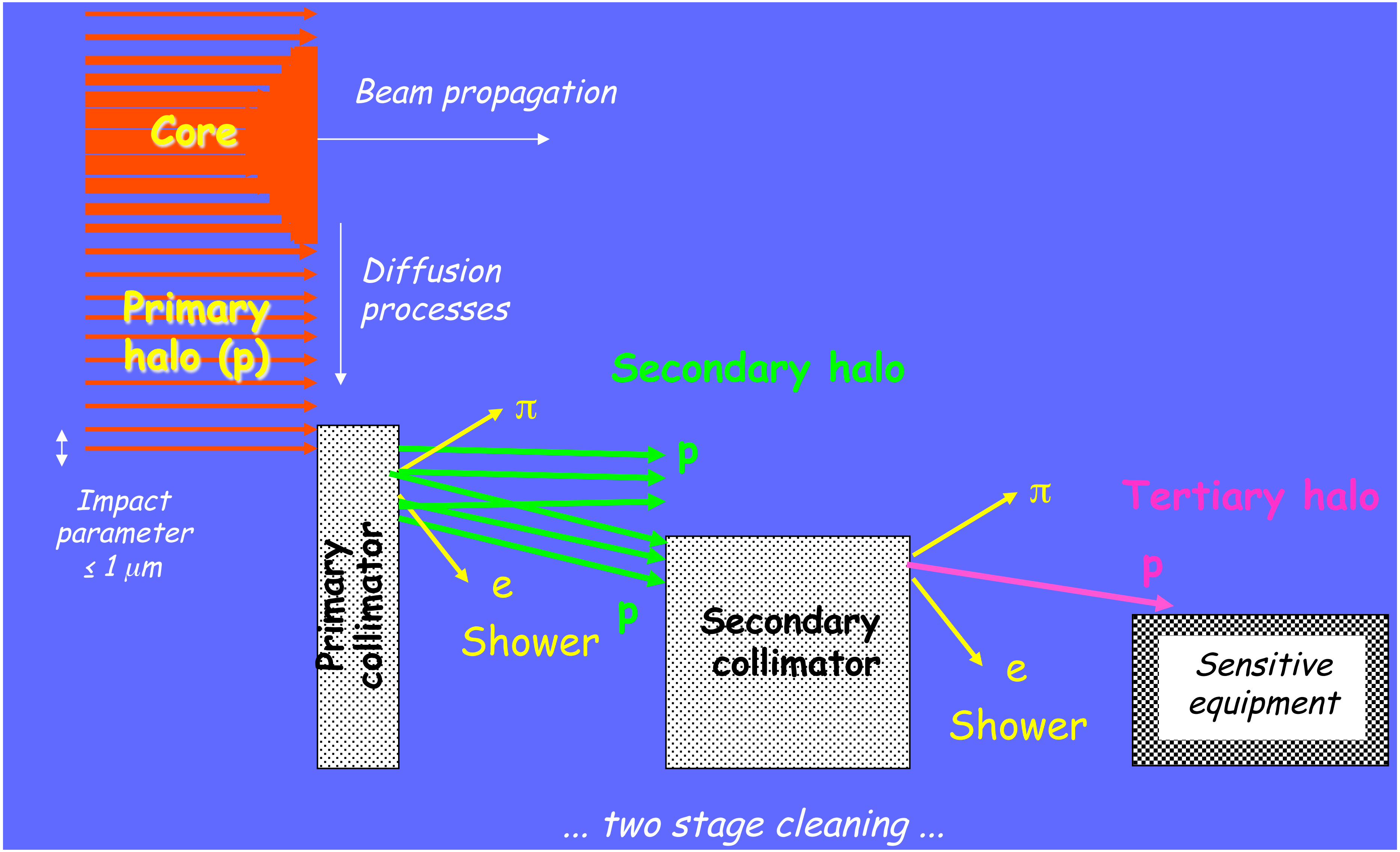
25 ns

S1	S1	S1	S1	S1	S1	S1	S1	B1	B1
B1	B1	B1	S2	S2	S2	S2	S2	S2	S2
S2	B2	B2	B2	B2	B2	S3	S3	S3	S3
S3	S3	S3	S3	B3	B3	B3	B3	B3	**R**

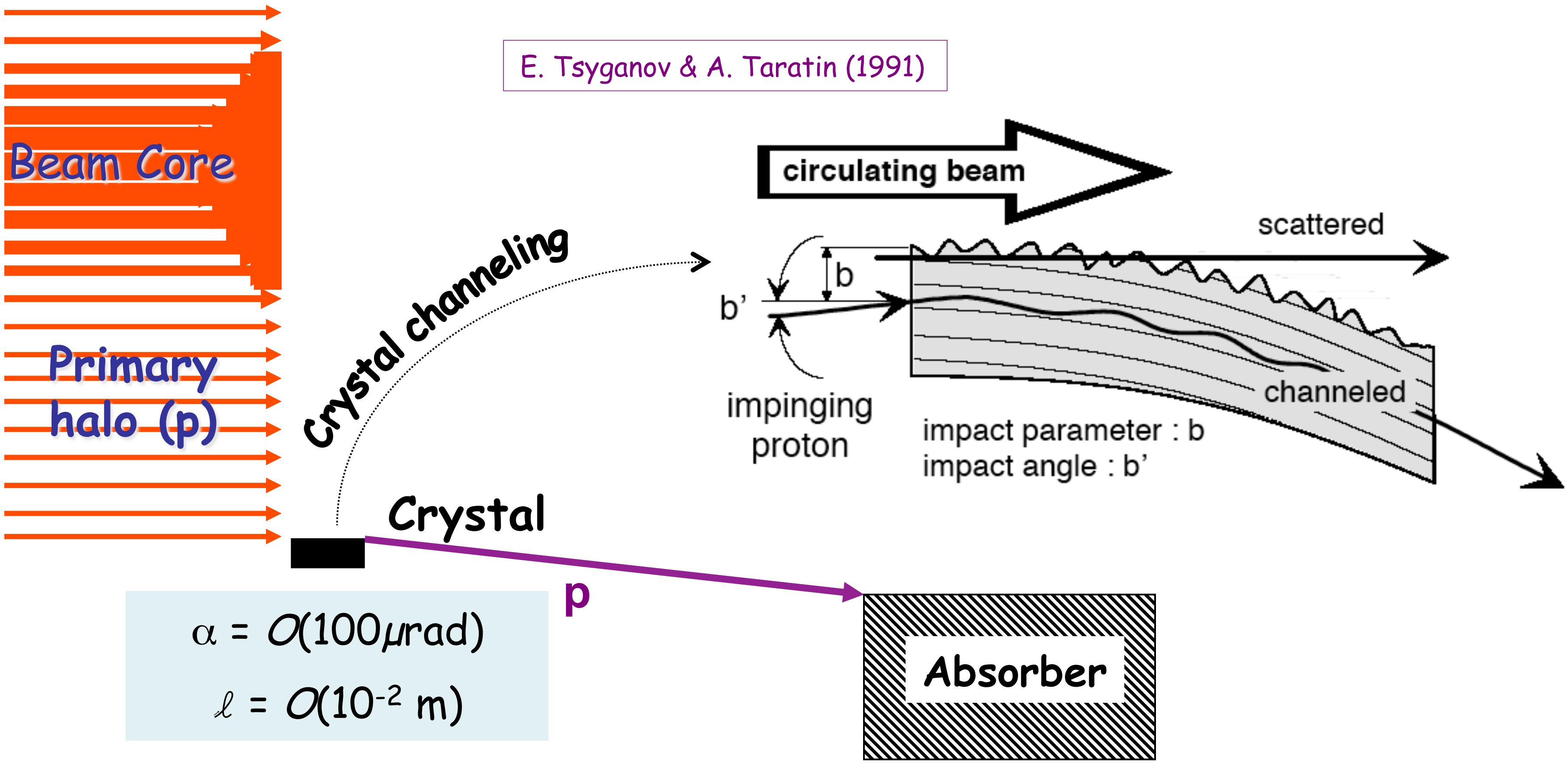


Principle of Beam Collimation

Walter Scandale, 2010



Crystal collimation

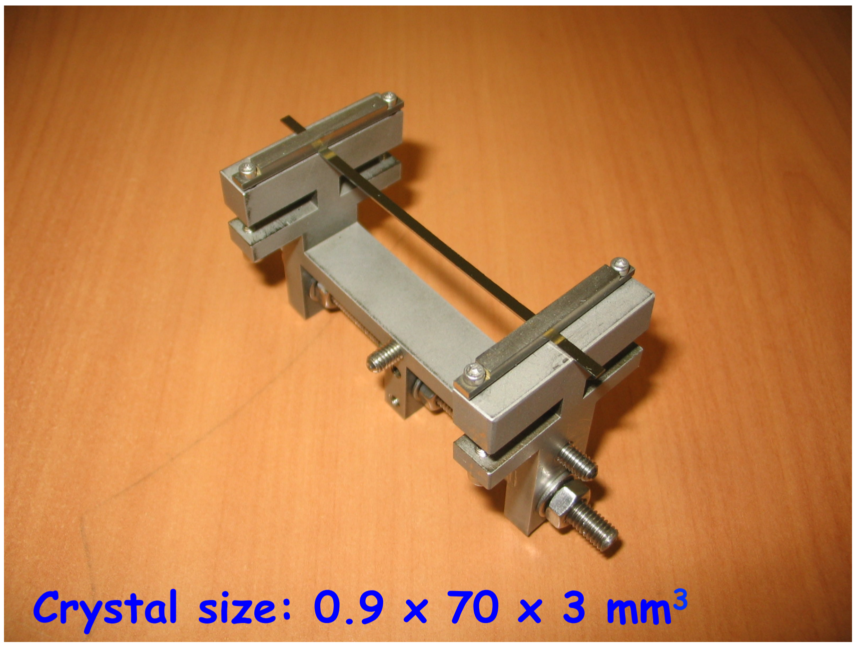


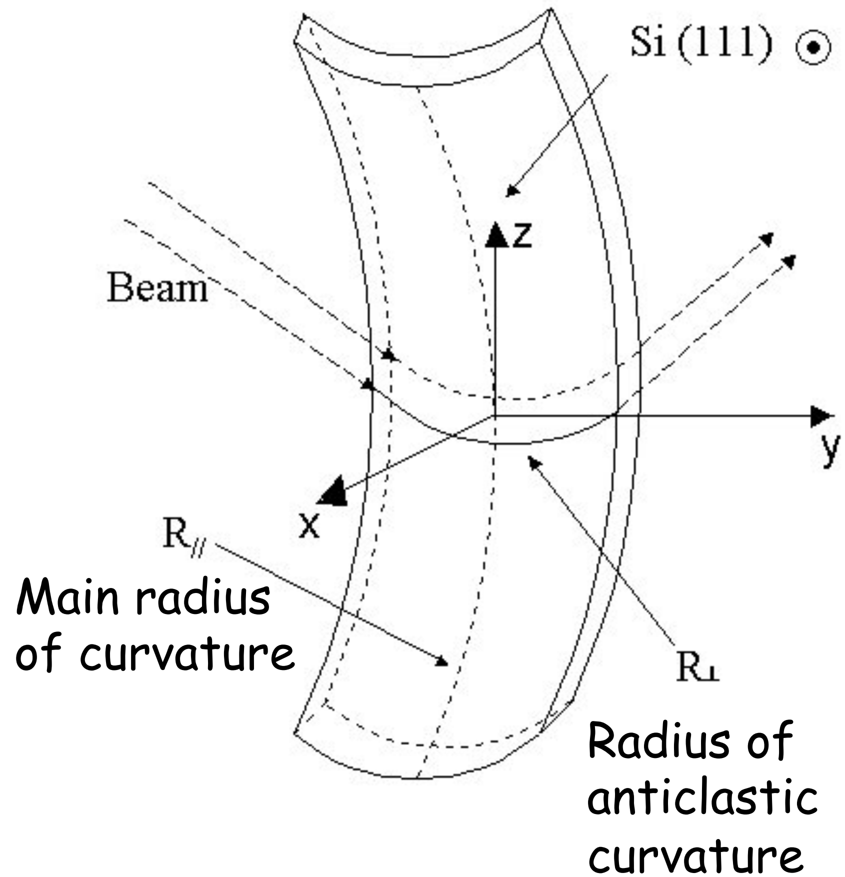
- Coherent deviation of the primary halo
- Very small probability of inelastic interaction in the crystal
- Larger collimation efficiency
- Less impedance
- Reduced tertiary halo

Strip crystals

Built at IHEP - Protvino and at INFN - Ferrara

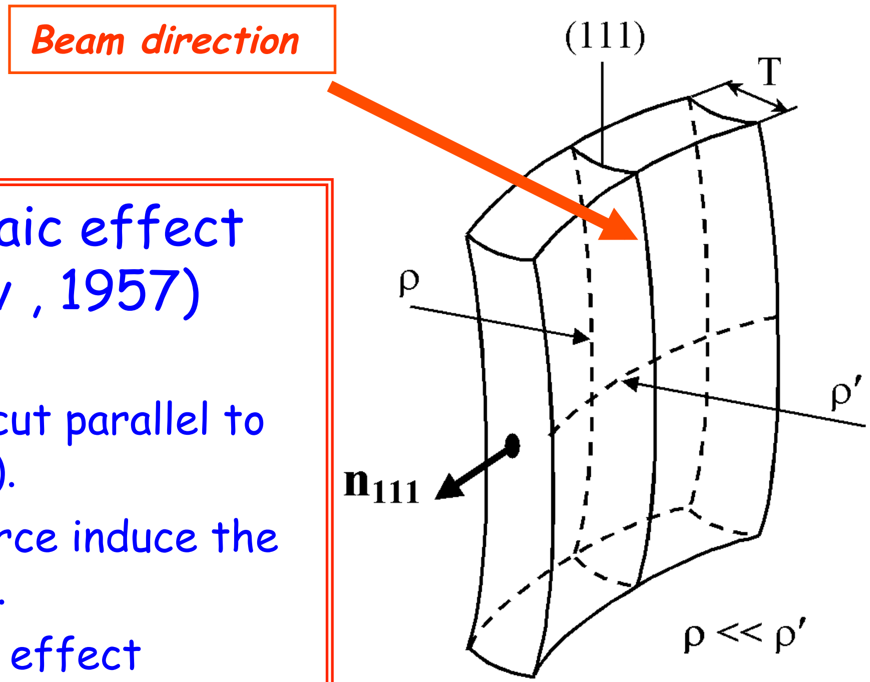
The main curvature due to external forces induces the anticlastic curvature seen by the beam

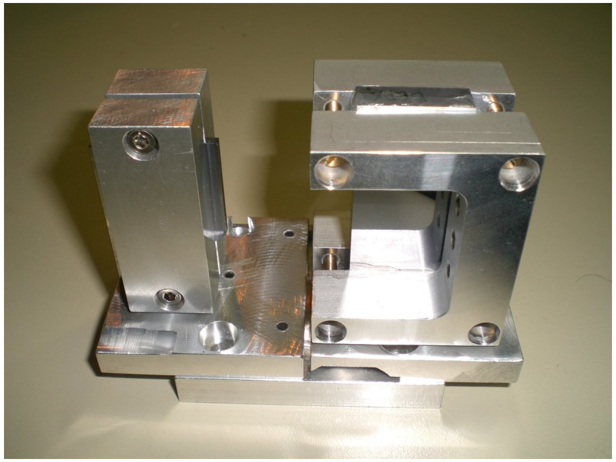


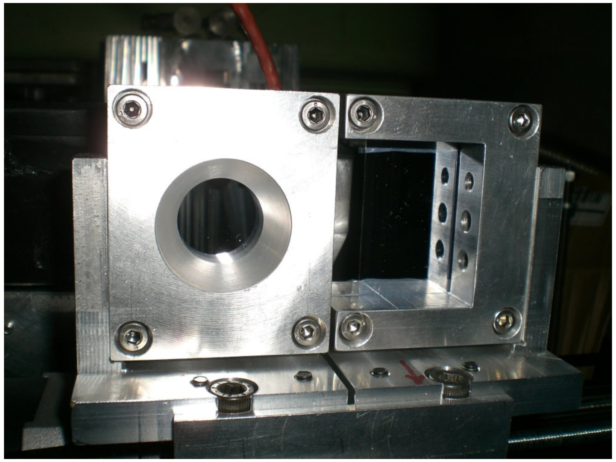


Quasimosaic crystals

Built at PNPI - Gatchina







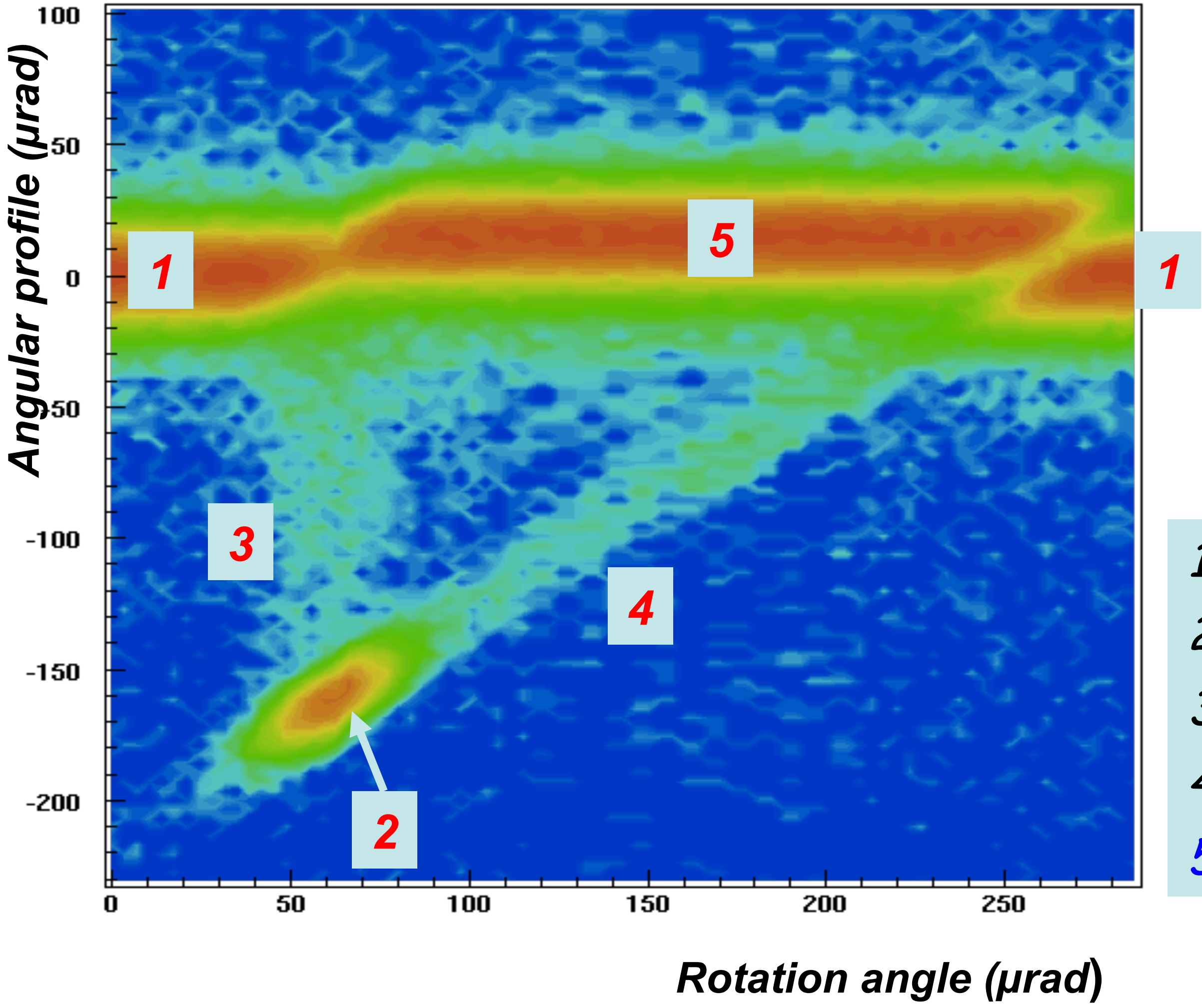
Crystal size: 0.7 x 30 x 30 mm³

Quasi-Mosaic effect (Sumbaev , 1957)

- The crystal is cut parallel to the planes (111).
- An external force induce the main curvature.
- The anticlastic effect produces a secondary curvature
- The anisotropy of the elastic tensor induces a curvature of the crystal planes parallel to the small face.

Angular beam profile as a function of the crystal orientation

9mm long Si-crystal deflecting 400GeV protons



The **angular profile** is the change of beam direction induced by the crystal

The **rotation angle** is angle of the crystal respect to beam direction

The **particle density** decreases from red to blue

1 - "amorphous" orientation

2 - channeling (50 %)

3 - de-channeling (1 %)

4 - volume capture (2 %)

5 - volume reflection (98 %)