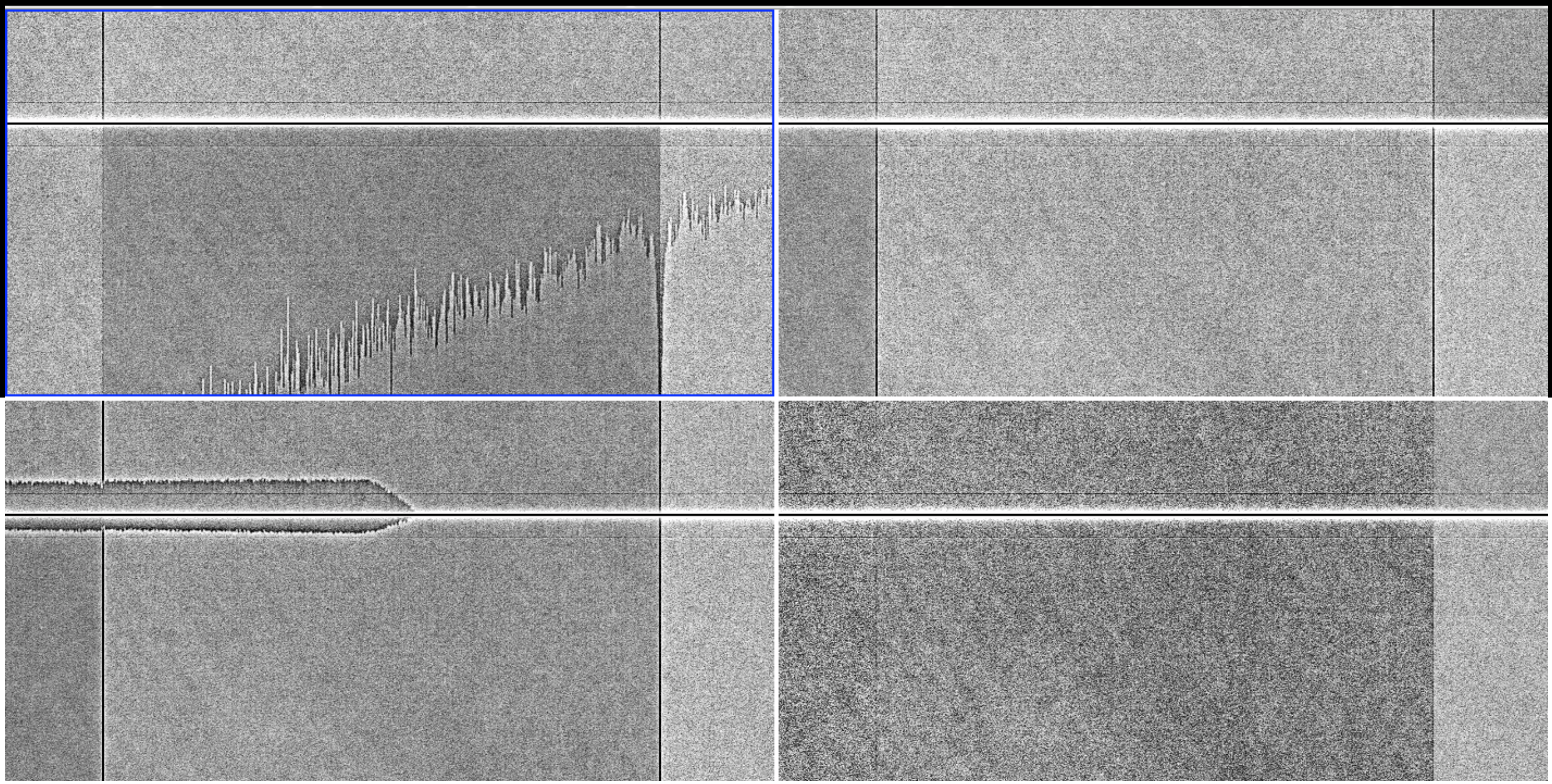
Tearing and related field distortions in deep-depletion CCDs



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LPNHE PARIS

LSST

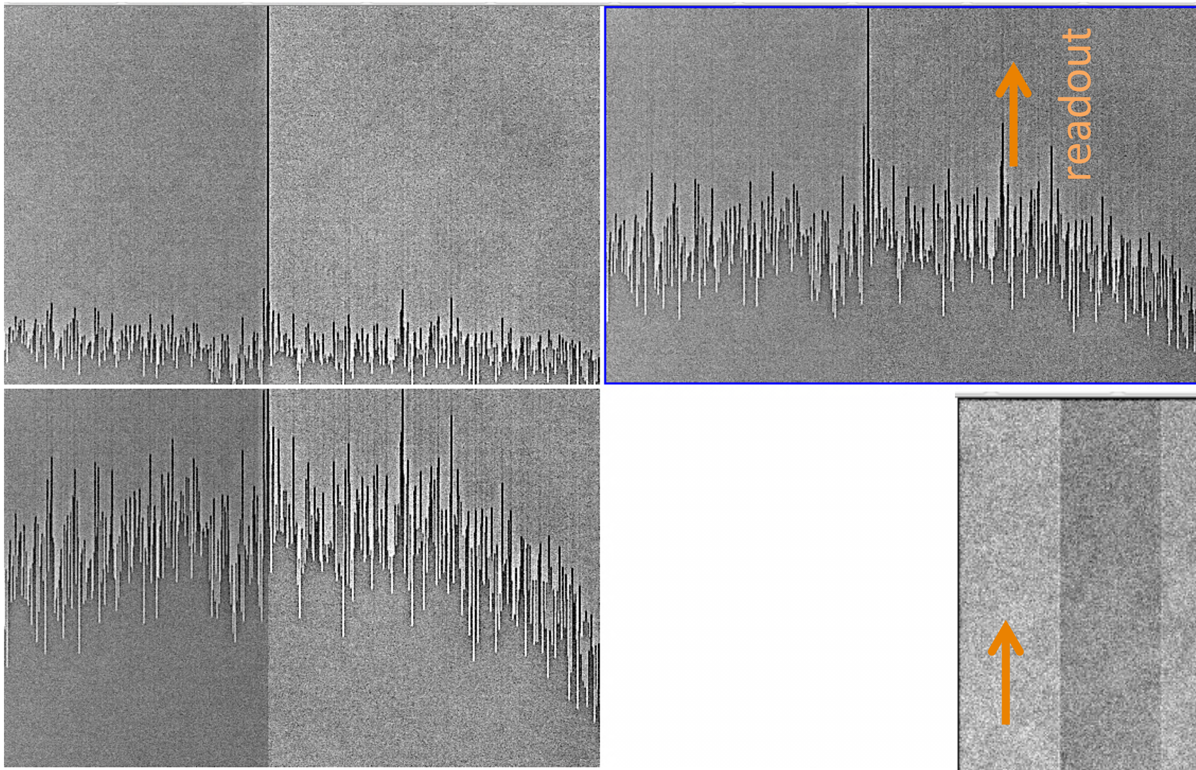
ISPA2018

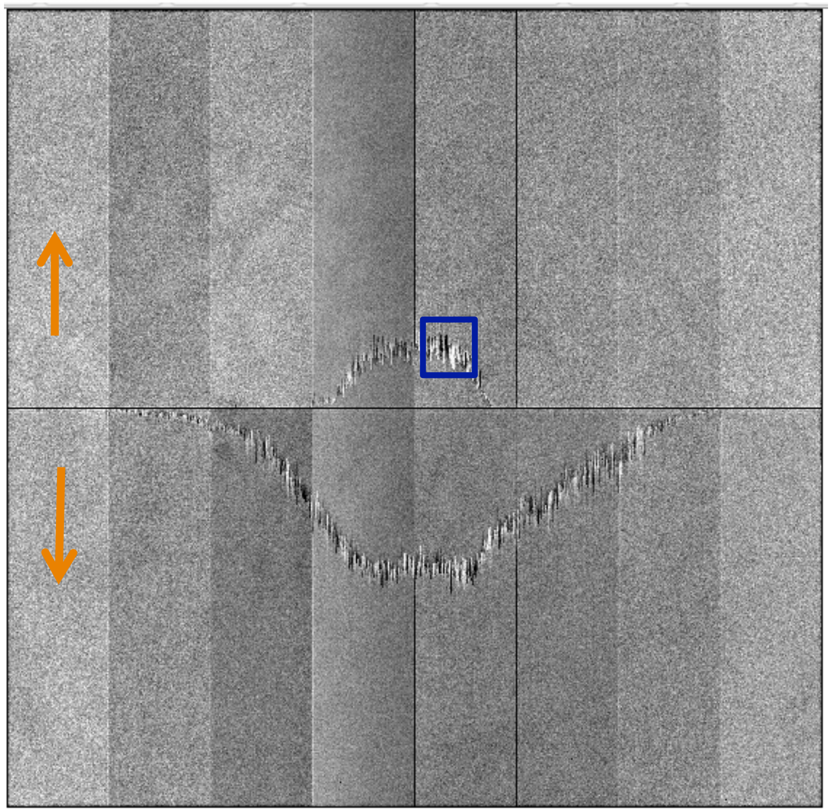
Tearing issue in LSST

- LSST e2v-250 CCD, operated in unipolar mode (all biases and clocks ≥ 0V, except Back Substrate Bias)
- Tearing patterns are seen in flat field frames, cause strong local Pixel Response Non-Uniformity and astrometric distortions
- Tests carried out at LPNHE in Paris with single CCD and LSST control and readout electronics, matching LSST raft data

➢ Observed patterns and experimental fixes
➢ Tearing as field distortions
➢ Generation and amplitude of the field distortions
➢ Conditions for a tearing fix in unipolar mode
➢ A working model for the tearing patterns

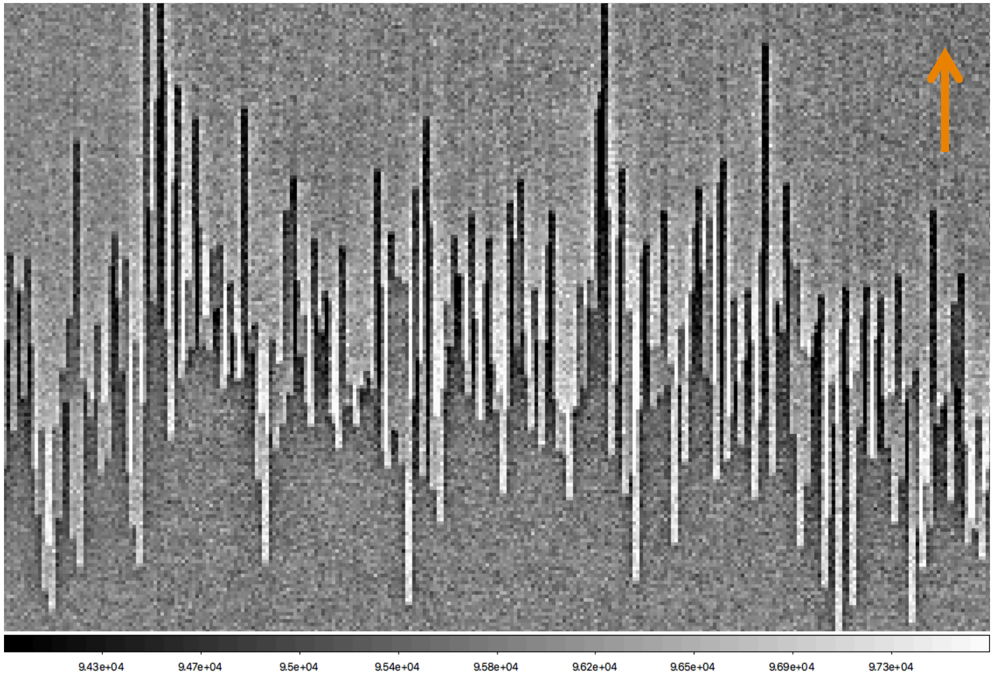
Wide tearing pattern

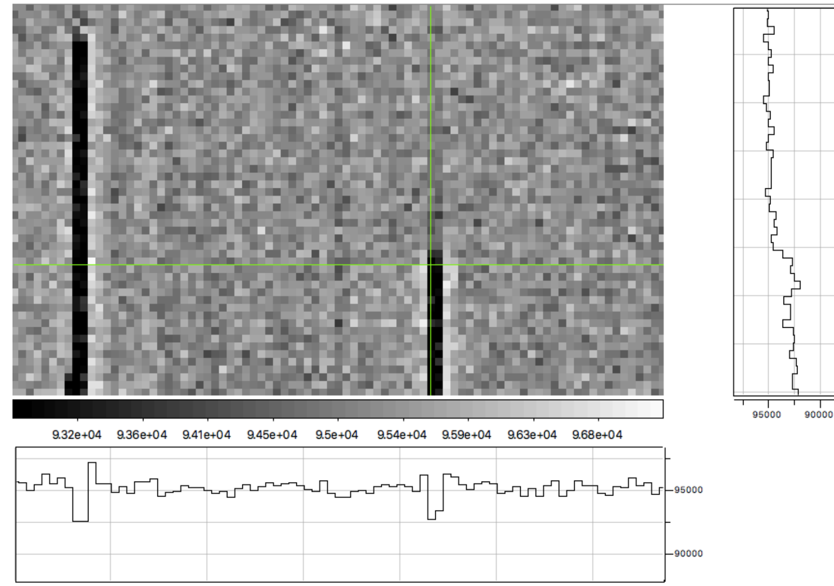


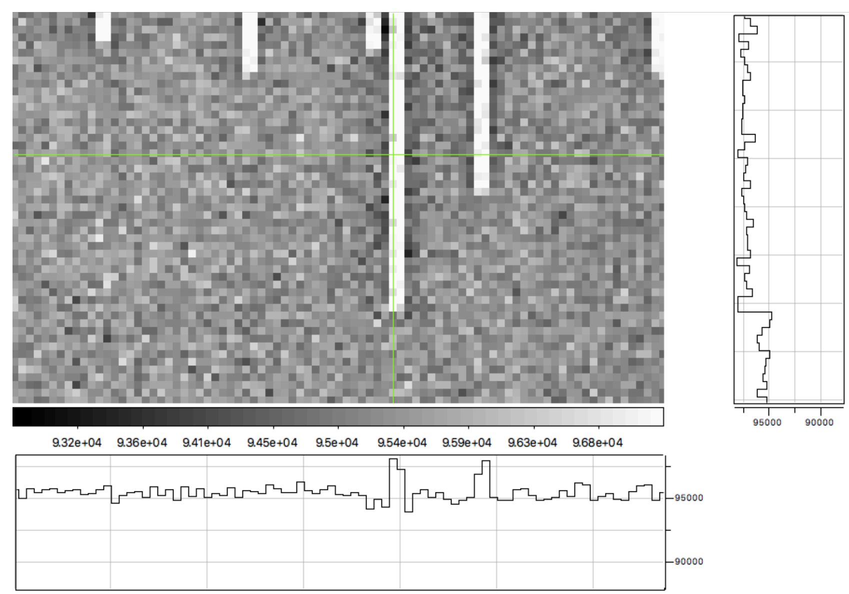


- Three consecutive frames: pattern moves in readout direction
- Tearing conditions: high Parallel Up clock voltage (PU > 9.5 V)
- Semi-stable over later frames

Field distortions from channel stops



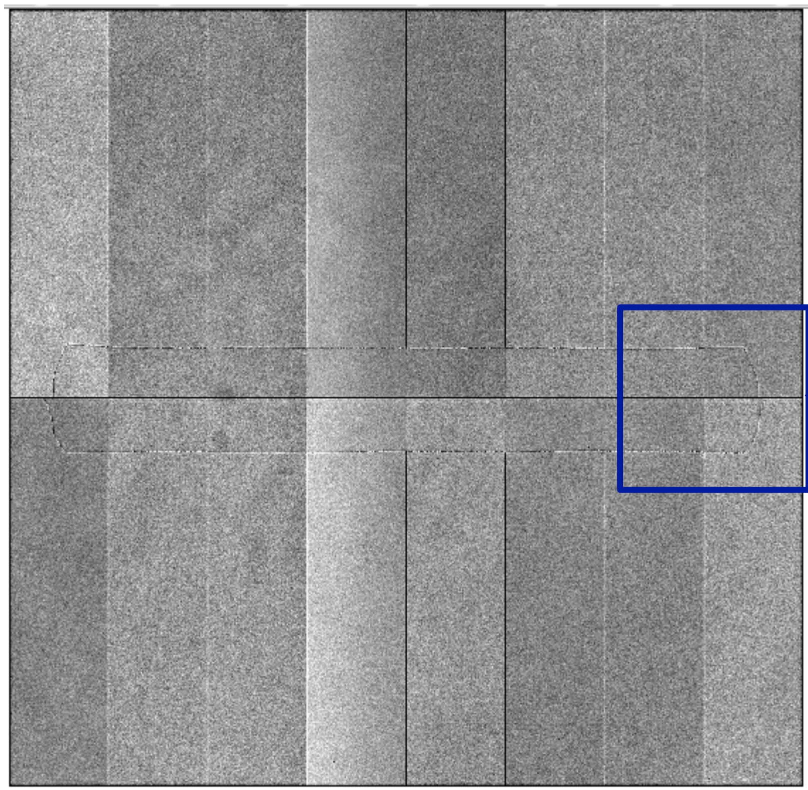


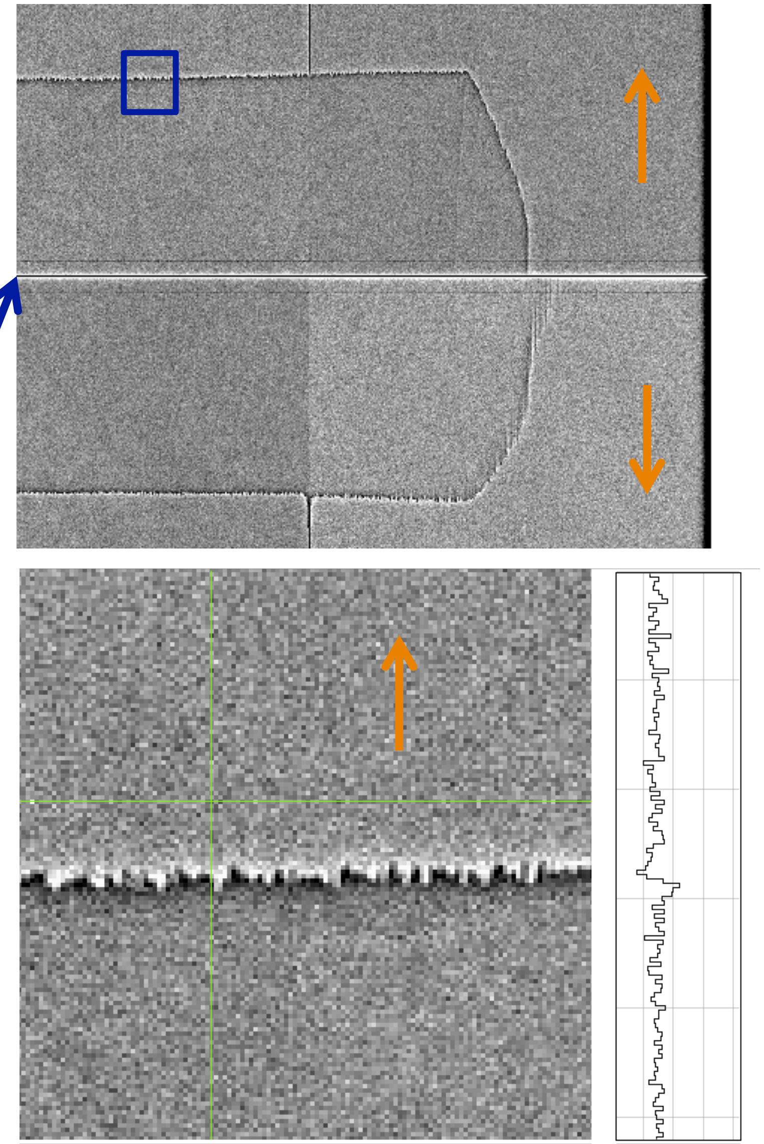


- Isolated darker and lighter columns are in fact paired, surrounded by excess/ deficit respectively
- Field distortions from holes accumulated in the channel stops between columns, affect incoming photoelectrons
- Amplitude of local distortions: up to 7%

Thin tearing pattern

- Lower PU voltage, improved parallel transfer sequence: thin tearing around mid-line

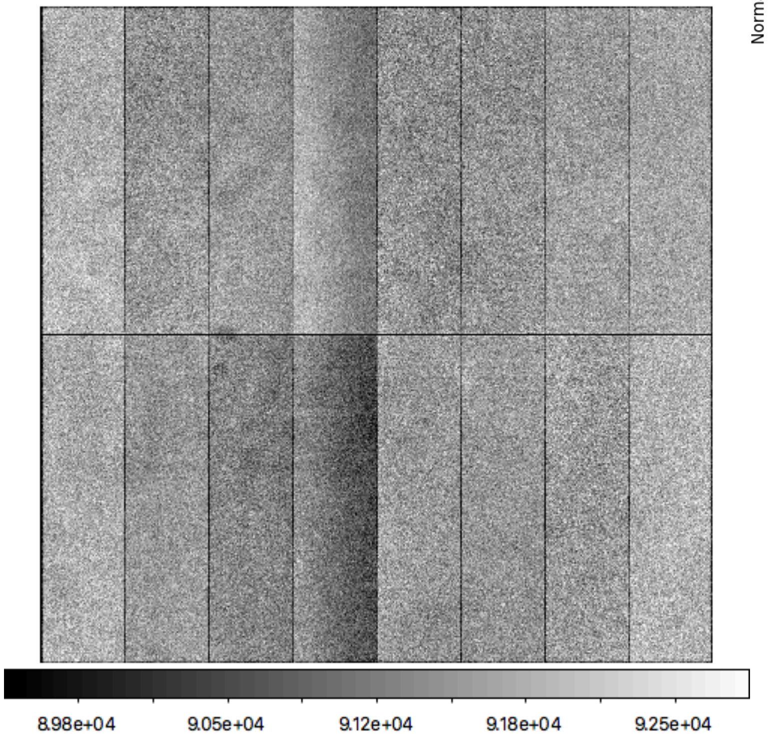




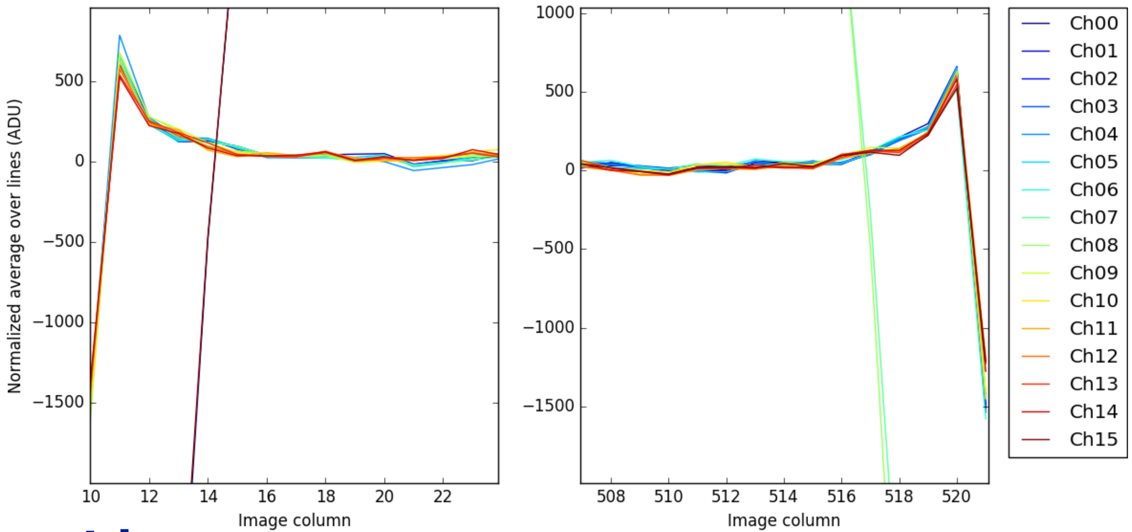
- Excess comes first in readout direction: not a transfer issue, again a distortion

Tearing fix?

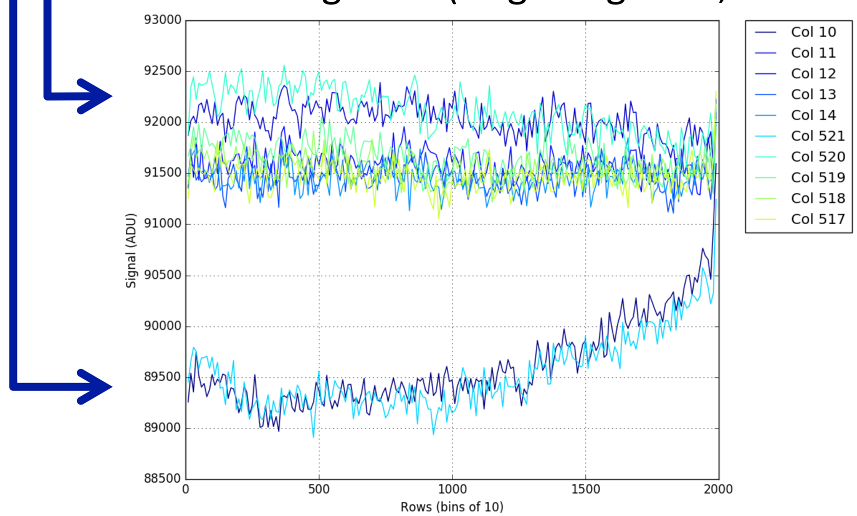
- Doubled speed of fast parallel clear (Tp = 2.5µs instead of 5µs)
- Remaining pattern: “rabbit ears”, 3% deficit, symmetrical across segment edges



Profile along columns near edges (averaged)

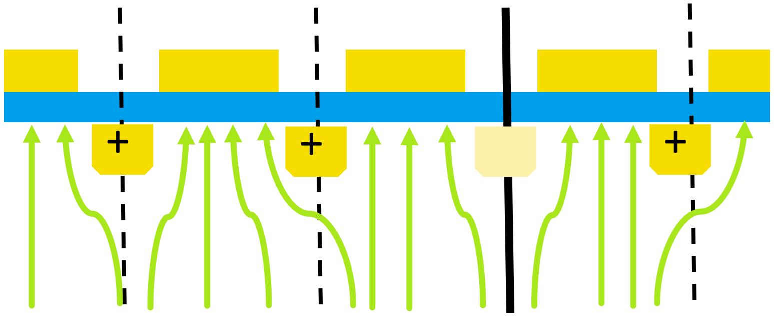


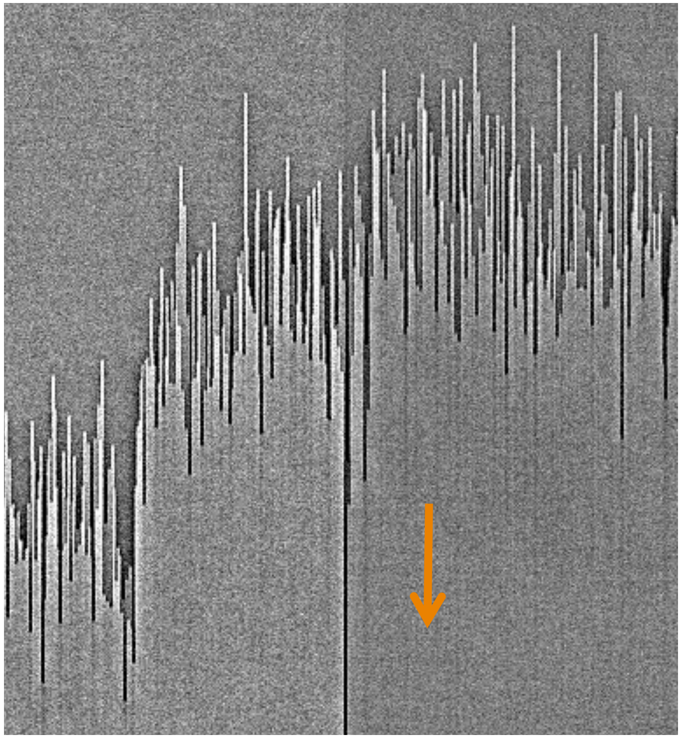
Profile along rows (single segment, binned)

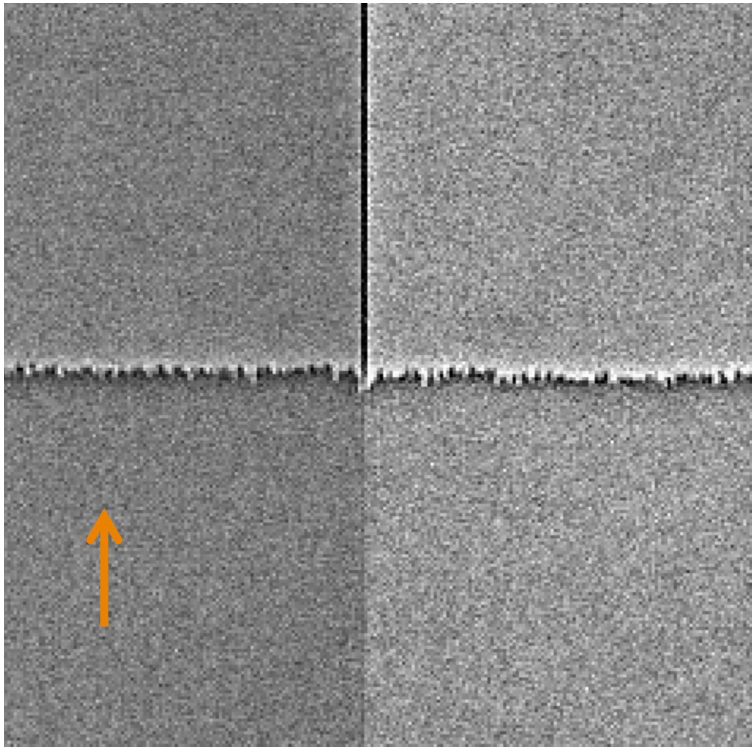


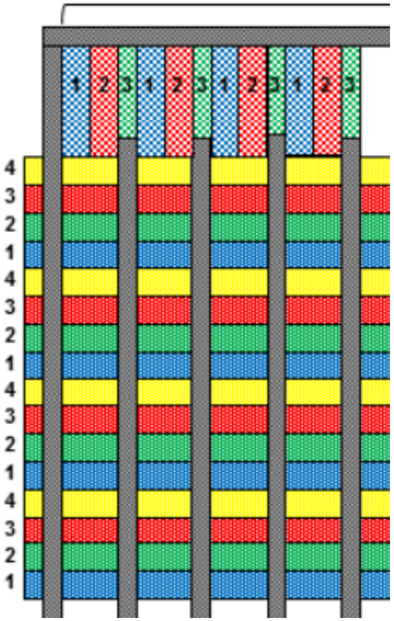
Segment edge distortions

- “Rabbit ears” are continuous with classical tearing patterns, stop after tearing edge
- Channel stop at the edge between segments: lower concentration of holes
- Physical difference at the junction with the serial register



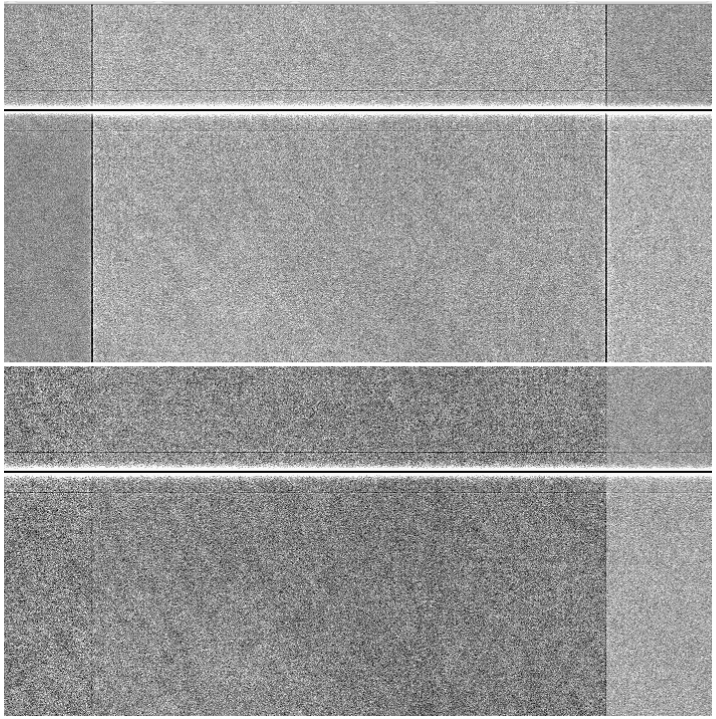


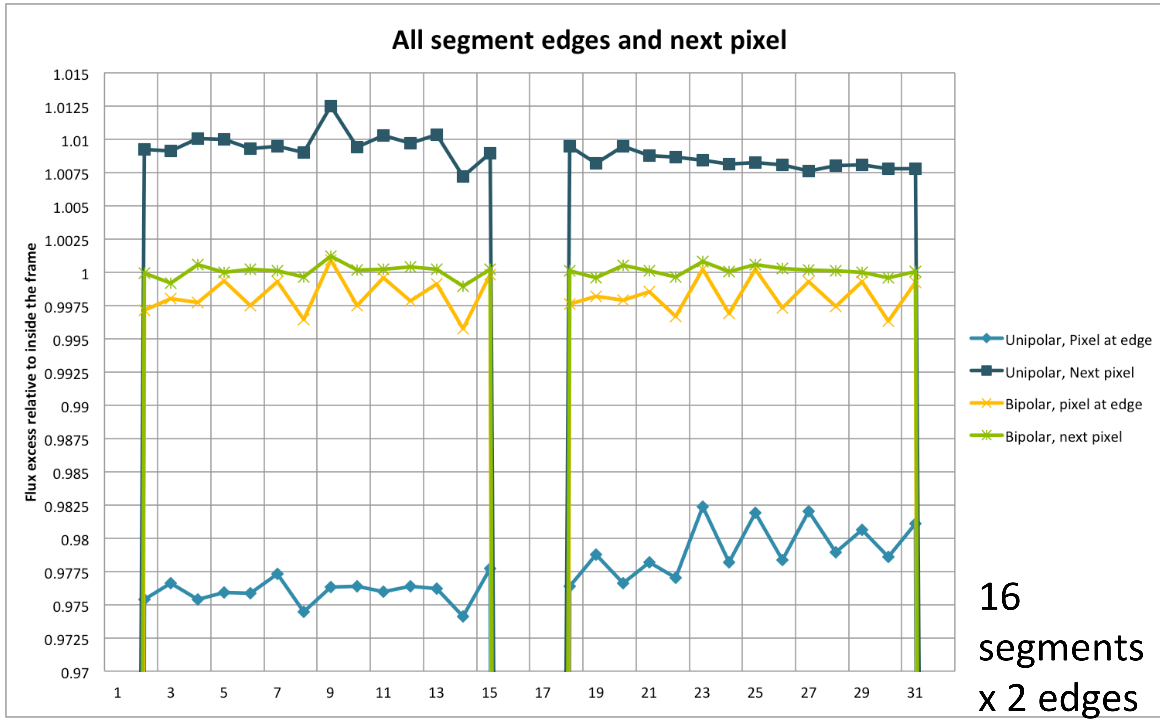




source: T-e2v

Partially-inverted parallel clocking

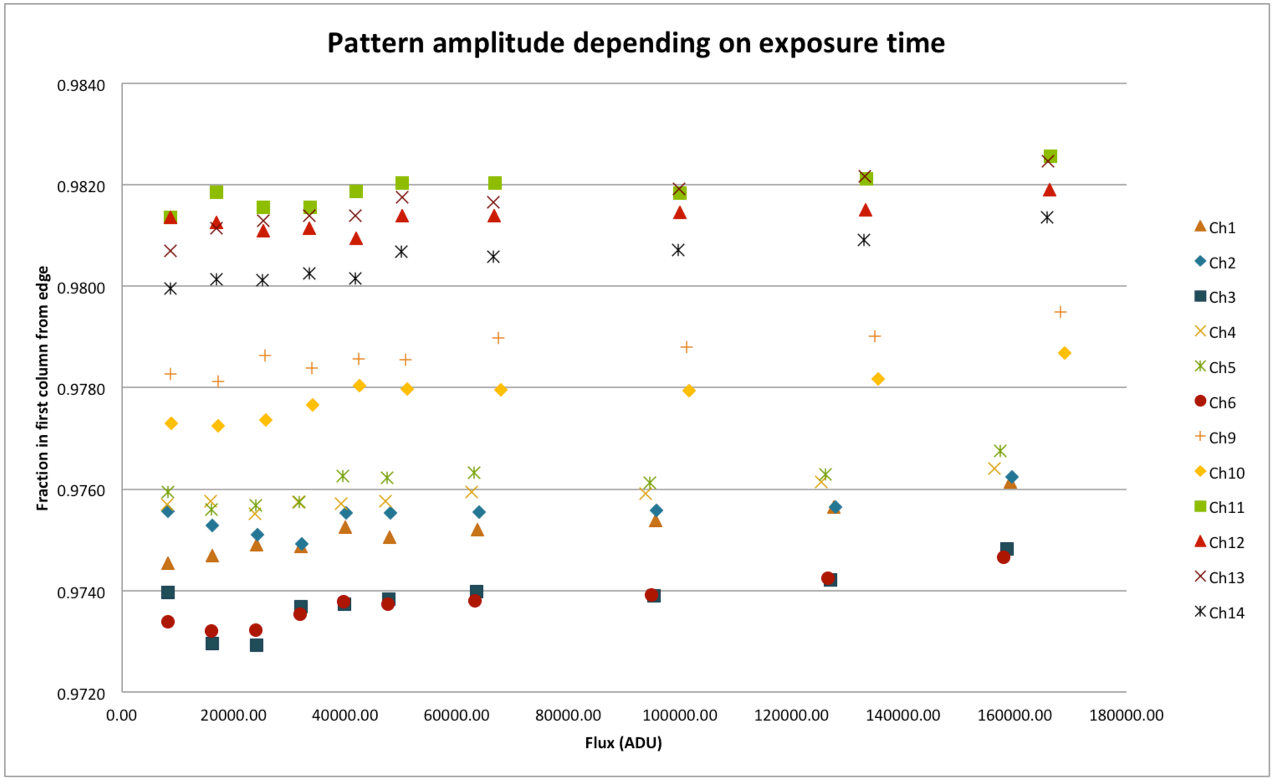




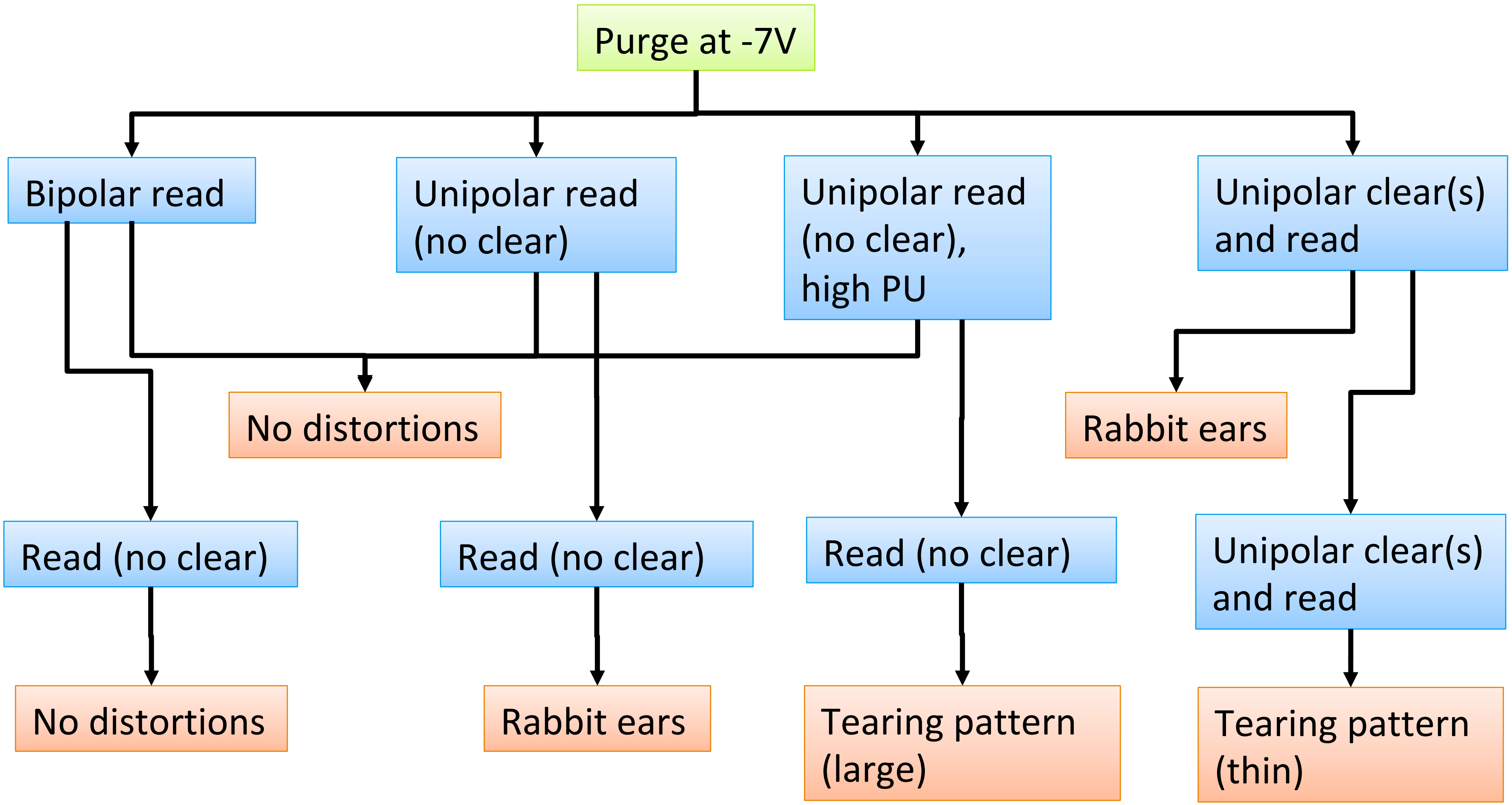
- Shifting operation to a bipolar mode with Parallel Low clock voltage PL ≤ -6.5V removes the tearing and the “rabbit ears” pattern
- Inversion: holes are attracted away from channel stop regions
- Test on raft at SLAC: even with PL= -6.5V, one sensor with a strong bright defect required a purge right before exposure (= all four phases of parallel clocks set to low at the same time) to remove the tearing pattern.

Observing the field distortions

- Generate field distortions in a reliable manner: purge at -7V, expose and read a 4s frame in unipolar mode, then observe distortion with the next frame (all with λ = 650 nm)
- Decrease by ≤1‰ when Parallel Up (PU) is increased from 8.3 to 9.5V during observation frame: drift field increases by 2%, field distortion ≈ 3%
- Dependence on flux: compatible with brighter-fatter at high flux

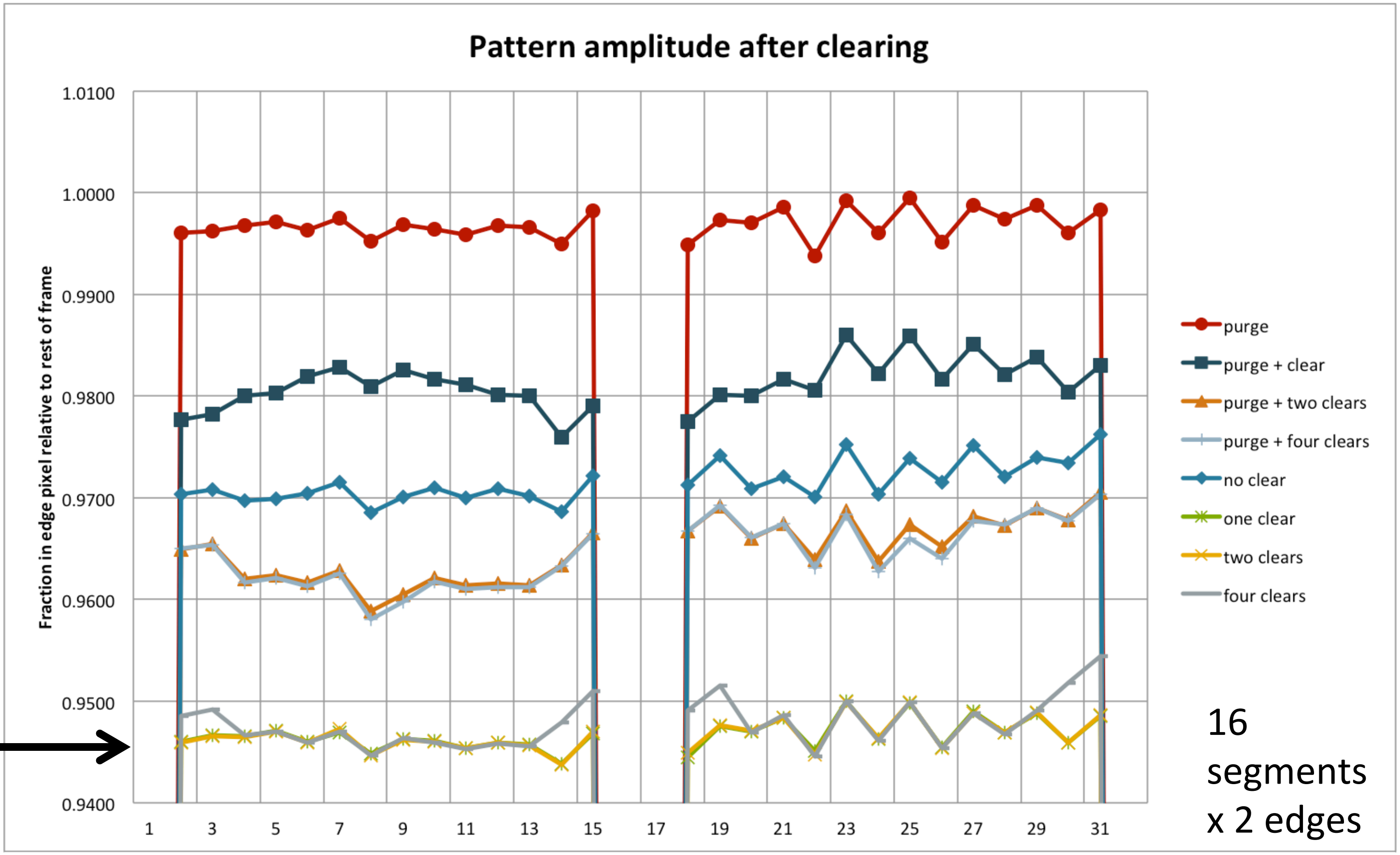


Generating field distortions



- Distortions in one frame depend on the readout mode in the previous frame, and on whether there is a clear, but not on the readout mode of the current frame

Amplitude of field distortions



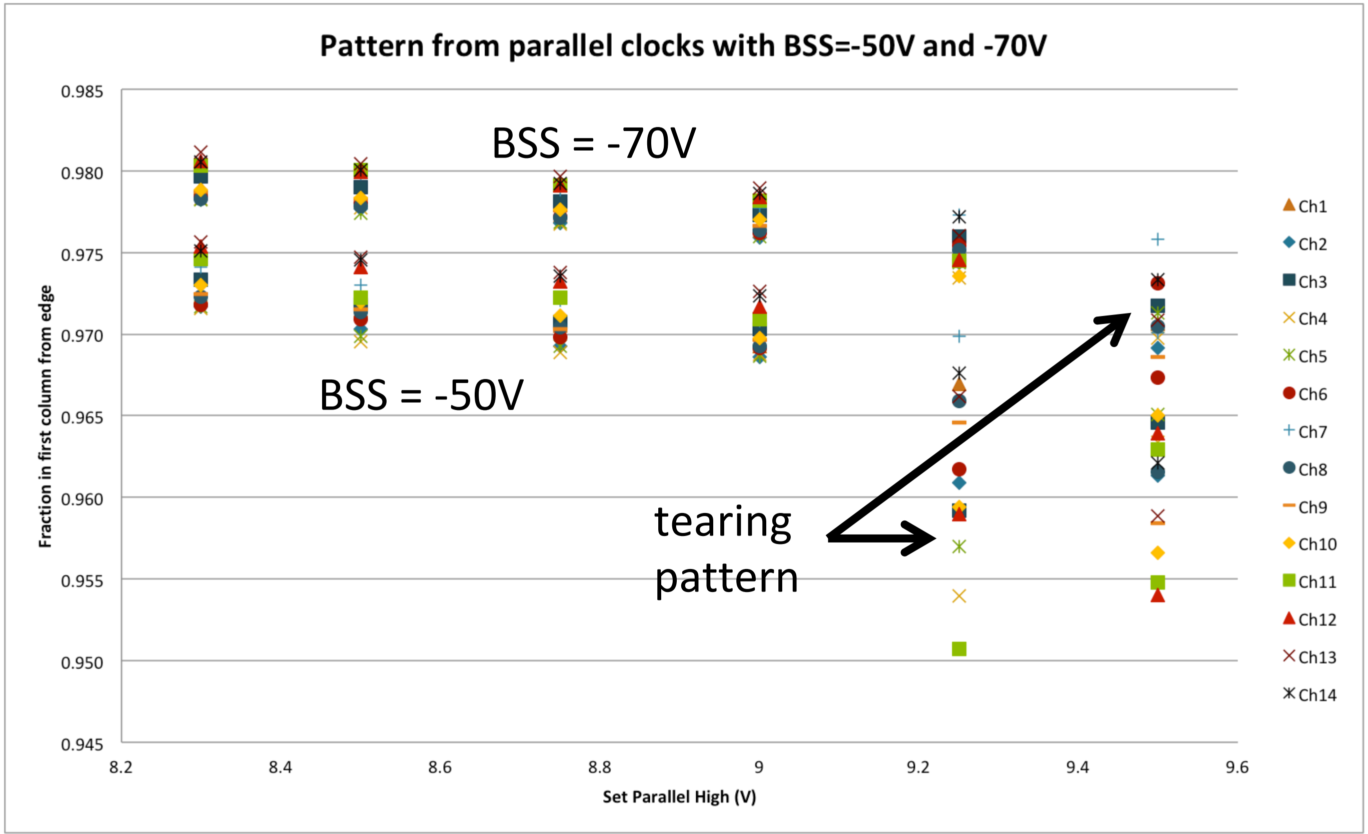
tearing pattern

16 segments x 2 edges

- The deficit in the first and last columns of segments measures the difference in hole density between the edge channel stops and their neighbors
- Caused either by holes emptying from the edge channel stop, or accumulating in the neighbors, or both

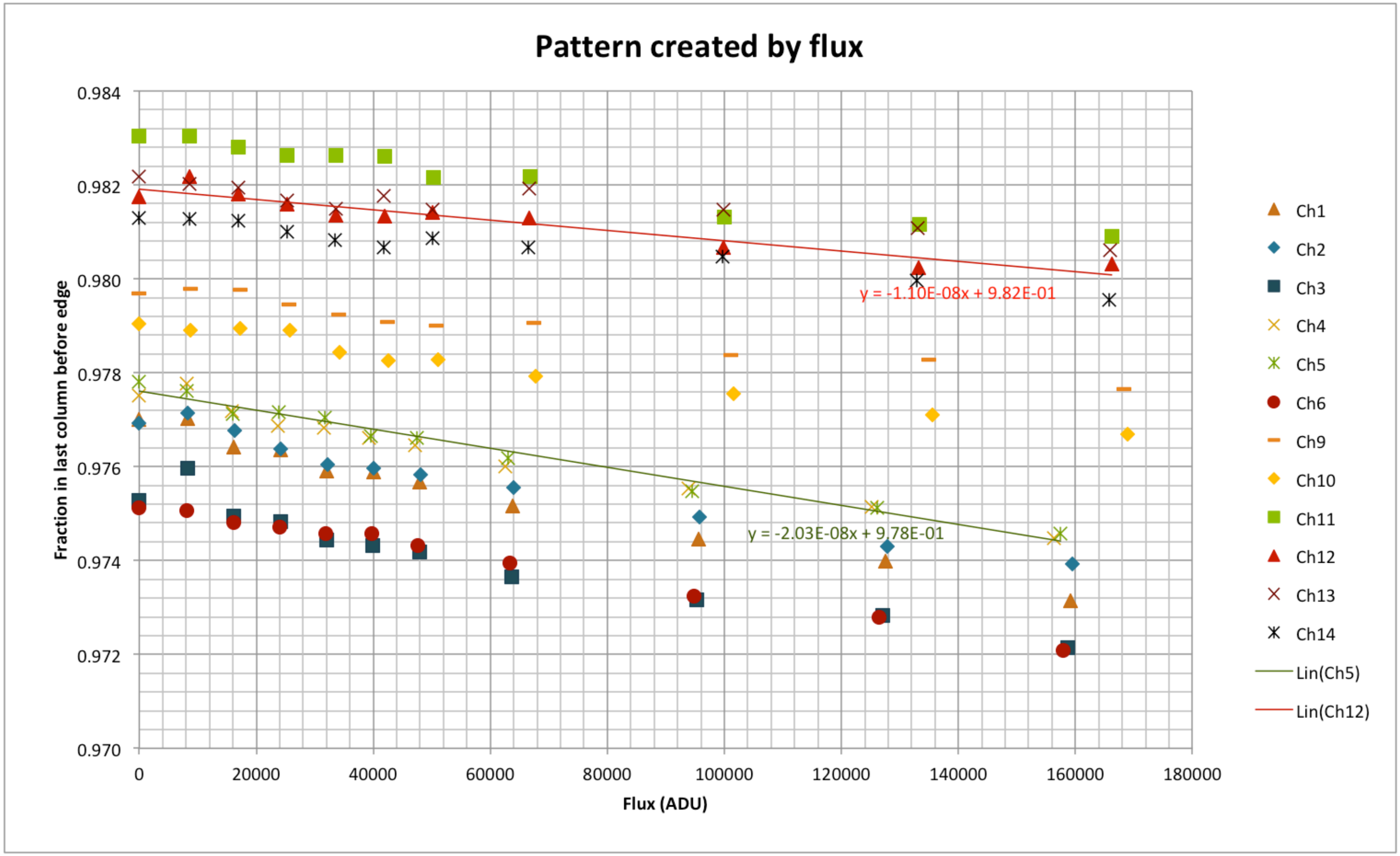
Parallel clocks settings

- Timing of the clear and readout: the amplitude changes, and the height of the tearing pattern when there is one
- Amplitude increases with PU in the previous frame, until tearing
- Change to Back Substrate (BSS) is applied during both frames: amplitude could be dominated by drift field, but tearing starts at lower value of PU



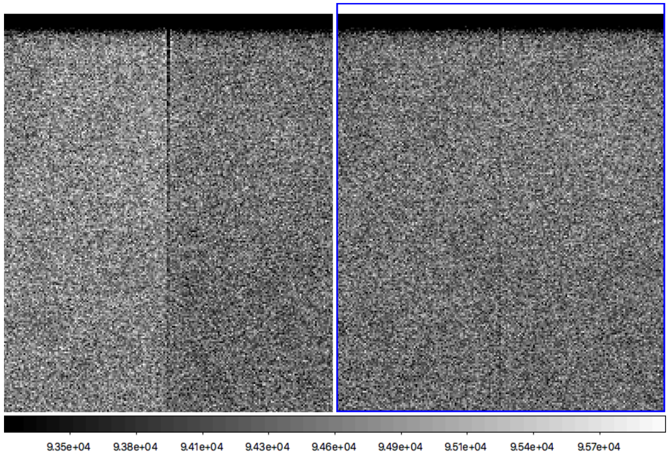
Generating field distortions: other effects

- Dark time (up to 20s) in unipolar mode after purge, before exposure: pattern increases <2‰ (independent of time)
- Pattern depending on flux in the previous frame: second order (≤3‰)

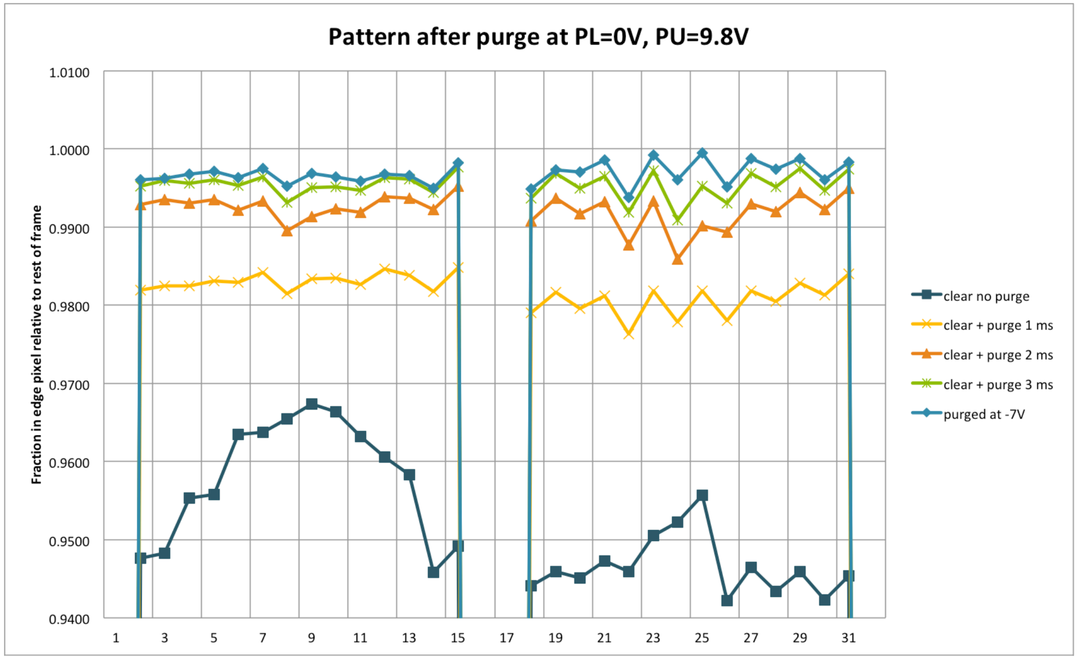


Purging in unipolar mode

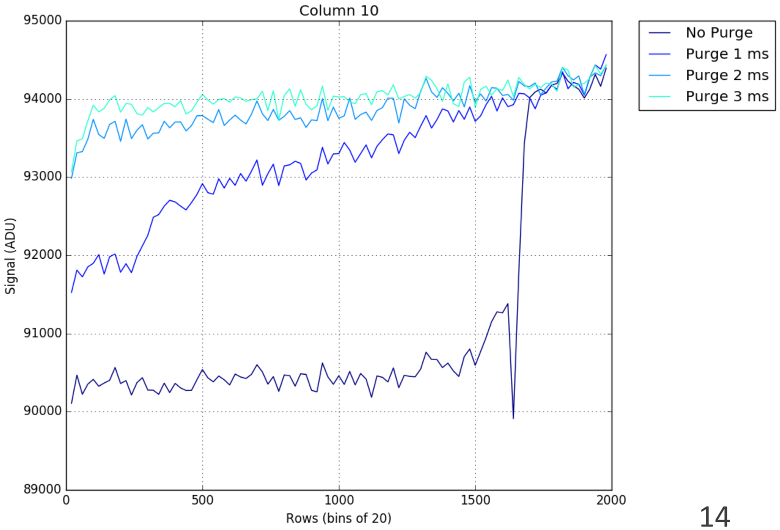
- Pulling all clocks to PL=0 V can remove the tearing and most of the field distortions, if:
  - Long enough (≥ 3ms)
  - Last operation before taking frame (after clearing)
  - Serial clocks S1+S2 are set high at the same time
  - Done before each frame
- "Purging" = flattening out the hole distribution



purged at 0V purged at -7V

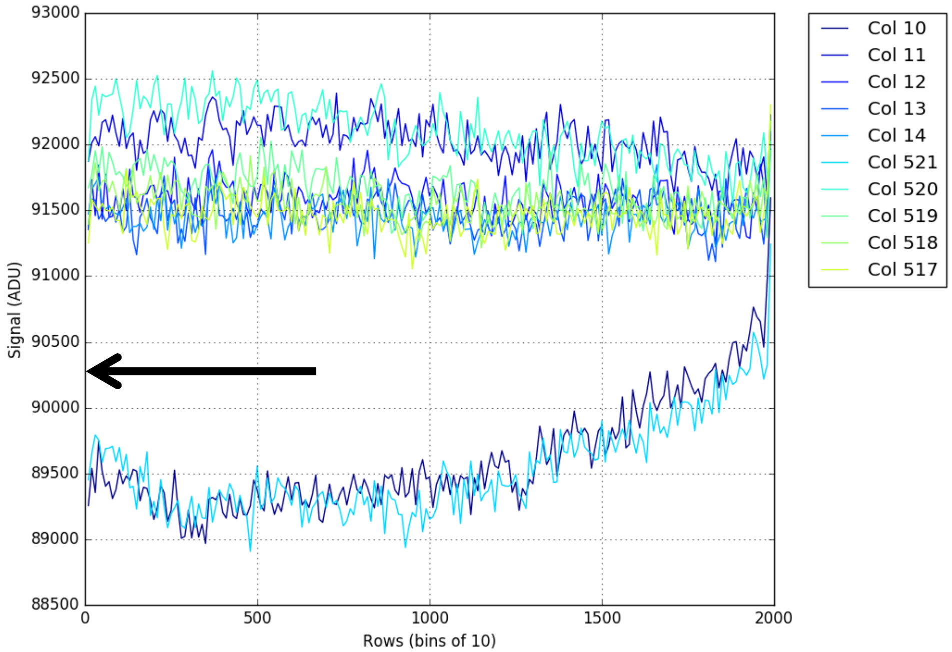


Remaining "rabbit ears" pattern near serial register (< row 200)



A working model for the tearing patterns

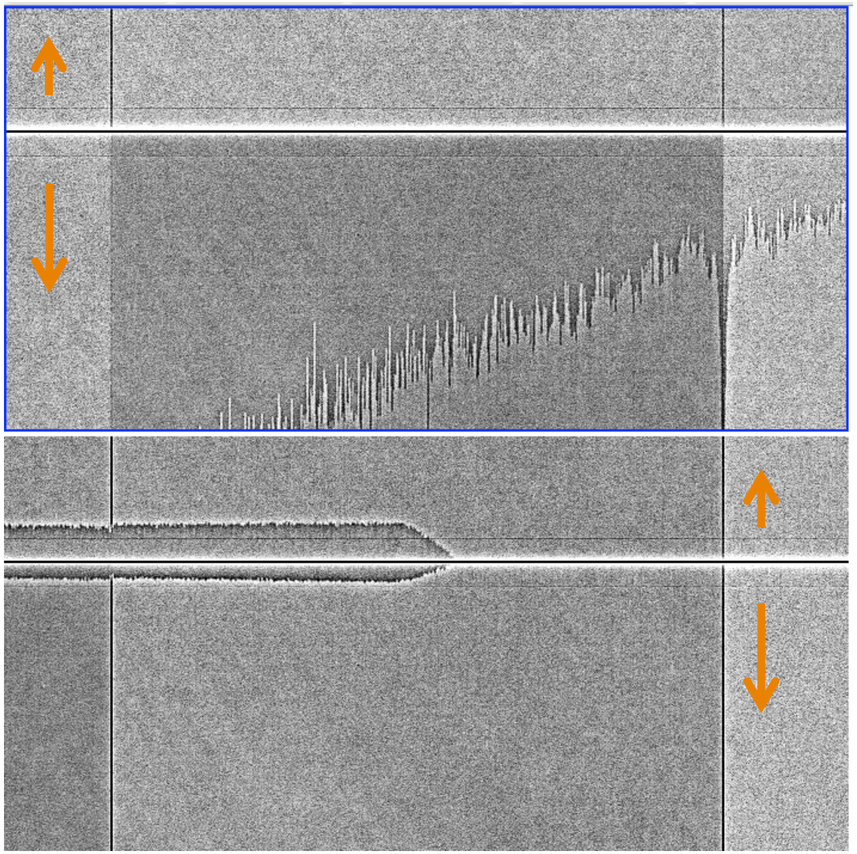
- Simple model: in unipolar mode, there is a number of holes confined to each channel stop.
- Purge at -7V + shift back to unipolar voltages: holes settle into the channel stops with a flat distribution along the rows.
- Mechanism to move holes: parallel clocking for clearing/readout
- Efficiency depends on the PU voltage, the exact sequence of the transfer, and the repulsive effect of the holes present in the next row.
- In the channel stops at the segment edges, holes arriving at the serial register can get out.



- In the other channel stops, holes accumulate towards the serial register side until clocking cannot beat the charge repulsion.
- These two effects cumulate to create the “rabbit ears” pattern.

A working model for the tearing patterns

- Transition from “rabbit ears” to tearing patterns: clocking moves the holes efficiently enough along the channel stops to empty them, starting from the mid-line.
- Wide tearing pattern at high PU: the edge of the hole density moves in the clocking direction, until it is blocked by the accumulated holes, and the tearing pattern stabilizes.
- Thin tearing pattern caused by clearing (and not readout): clearing sequence is more efficient at moving the holes.
  - Size of pattern depends on the exact timing of the sequence



- Non-uniformity vs columns: difference in total hole content or in hole capacity between channel stops, or non-uniformity of clocks over sensor surface.

Conclusions

- Tearing and the “rabbit ears” pattern are long-standing issues in LSST rafts with E2V sensors
- Both are lateral field distortions caused by holes accumulated in the channel stop regions
- The parallel clocking of the frame for readout and clearing is the most likely source for the distortions, but there is evidence for additional effects at play
- The “purging” with the unipolar voltage set clears the tearing and most of the rabbit ears, if executed correctly
- Moving to a bipolar voltage set would allow to remove the issue entirely (and has other beneficial effects, re: CTE, dark current, full well)