Particam: A fully digital sensor for sub micron resolution

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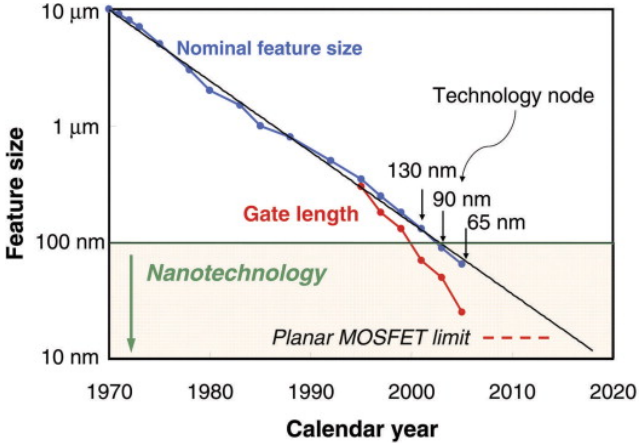
Particles and Imaging
(Pixel2024)

Motivation

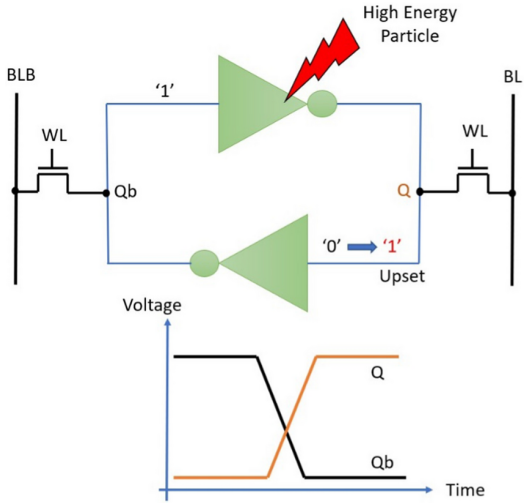
- Adoption of smaller feature sizes for particle physics has slowed down over the last years
- Design becomes much more expensive and complex
- Limitations due to bump bonds and transistor size for analogue circuits
- Need a new concept for further miniaturisation to go below $\mathcal{O}(10\,\mu\text{m} \times 10\,\mu\text{m})$ pixel pitch



Source:10.1016/S1369-7021(06)71539-5

Concept

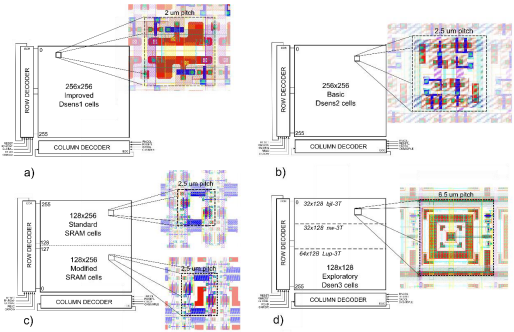
- Enter the Single Event Upset (SEU)!
- Ionising radiation can flip the content of memory cells
- Normally bad because it can break the configuration of the ASIC
- Much effort is spent minimising the rate and effects of SEUs
- What if we can harness the lightning?



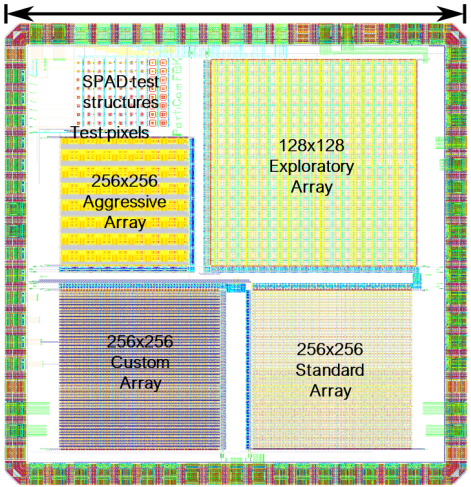
Source:10.1007/s00542-023-05500-2

Particam1

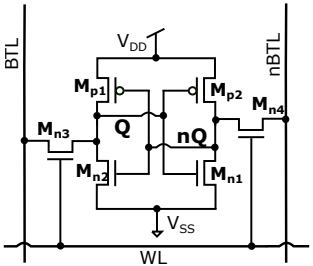
- Generic R&D project
- Demonstrator in UMC 65nm node designed by FBK
- Many different RAM cell designs

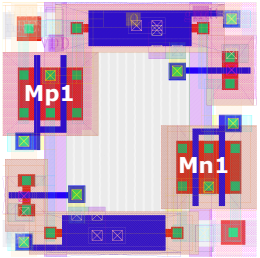


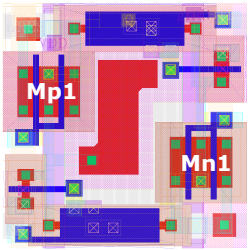
≈ 2.1mm!



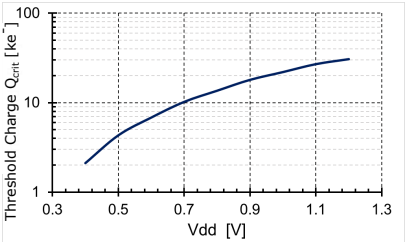
Standard Array



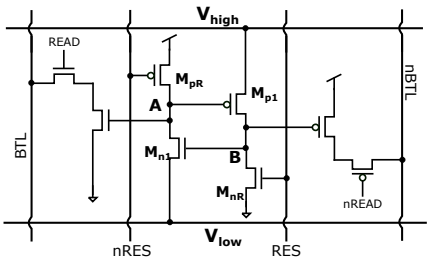


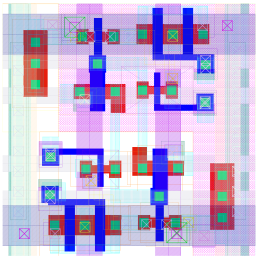


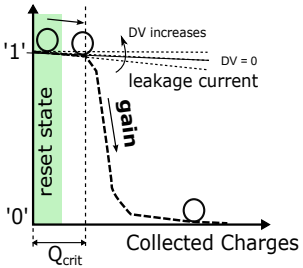
- Standard 6T SRAM cell as reference
- 2.5 µm × 2.5 µm pitch
- 2nd version with enlarged junction
- Very high threshold charge Q_T at nominal $VDD = 1.2V$



Custom Array



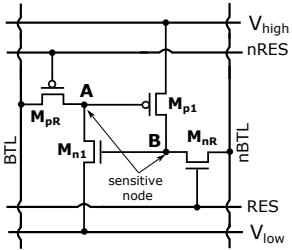


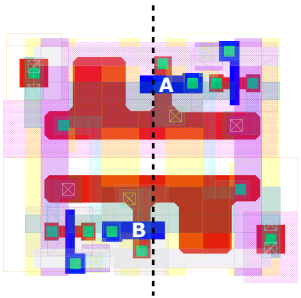


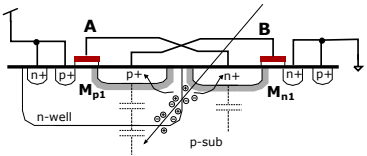
- RAM cell implemented as imbalanced flip-flop
- 2.5 µm × 2.5 µm pitch
- Cell is precharged to meta-stable state '1'

- Charge or leakage current flip cell to '0'
- Can't flip "back" without reset
- Leakage can be reduced by increasing $DV = VDD - V_{high} = V_{low} - VSS$

Aggressive Array





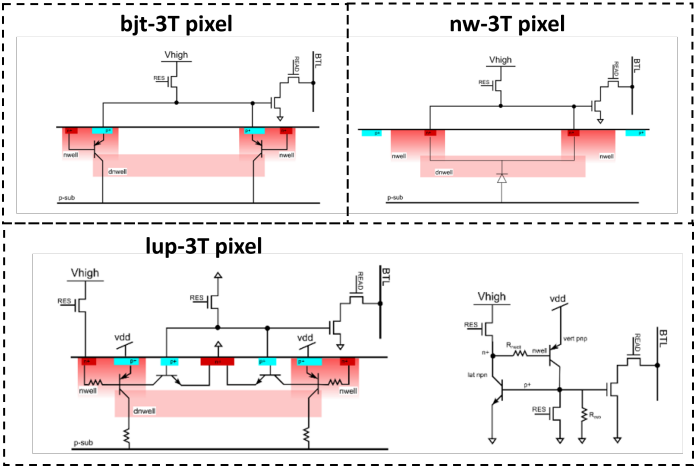


- Same concept as Custom Array without driver and reset
- $2\,\mu m \times 2\,\mu m$ pitch

- Reset thought bitline
- Enlarged junction for more charge collection

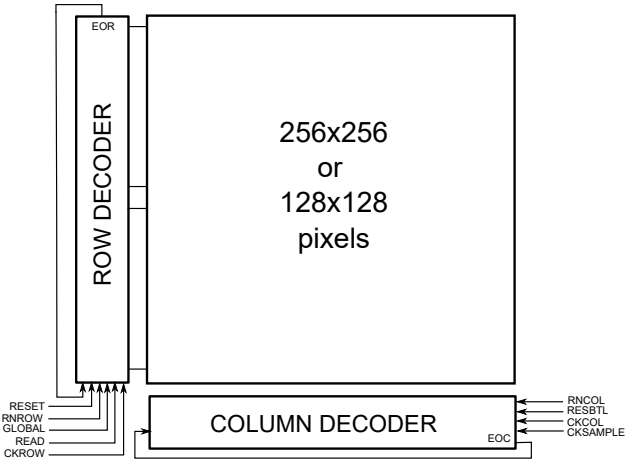
Exploratory Array

- Exploring "passive" and parasitic structures
- 6.5 µm × 6.5 µm pitch
- Based on 3T pixel:
  - Photo-transistor (BJT) in well structure
  - Deep n-well charge collection
  - Latch-up



Readout

- Simple decoder based readout
- Decoders implemented as circular shift registers
- Data is connected in groups 8 columns to output pads
- Can be operated in either global or rolling shutter
- Exploratory array has 128×128 pixel, other arrays have 256×256

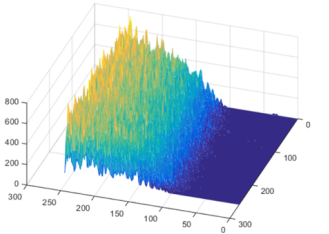


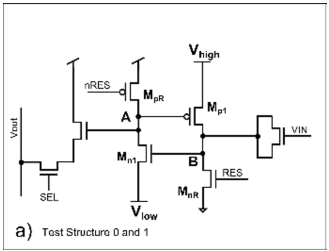
Measurement Results

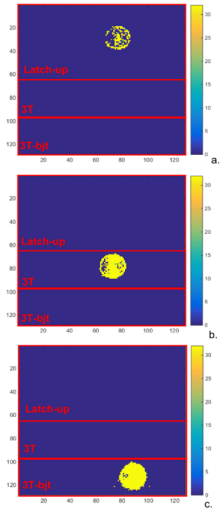
- Sensor was produced on standard resistivity substrate
- Design rules don't allow for substrate bias

→ Charge collection only in $\mathcal{O}(100\,\text{nm})$ shallow junctions

- Only pixels with large junctions and low Q_{crit} are sensitive to alphas
- Intense laser light works on all but the standard SRAM cells
- Have to rely on test pixels to find Q_{crit}

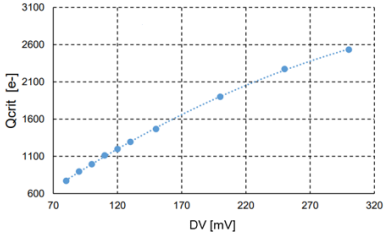




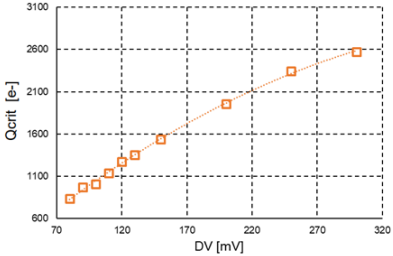


Measurement Results II

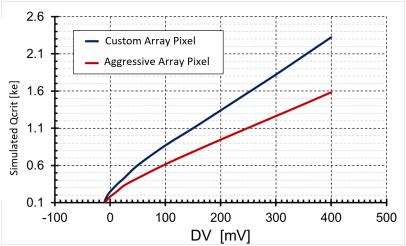
Custom Array



Aggressive Array

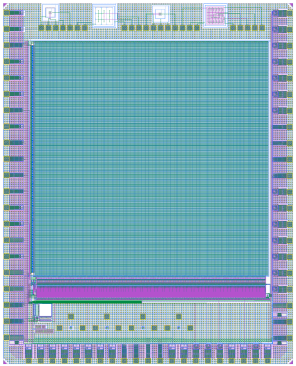


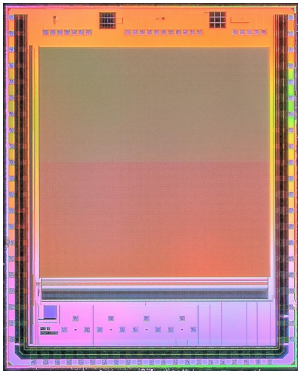
- Test pixels have similar Q_{crit}
- Results agree with simulation
- Large variation between test pixels of the same design due to leakage
- Detailed studies ongoing



Particam2

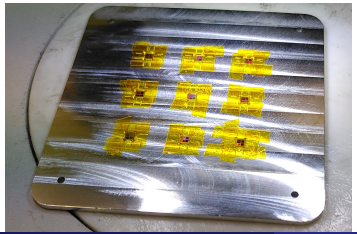
- Produced in LFoundry 110nm node, an epi-layer imaging process
- Triple well, so only NMOS logic in the pixel
- 12.6 µm × 12.6 µm pitch with 3T and ADC readout
- Produced with 2 epi configurations:
  - Standard ≈7.5 µm with low res
  - Thick ≈15 µm with >1 kΩ cm
- VBD ≈ 70 V for thick epi
- Testing ongoing

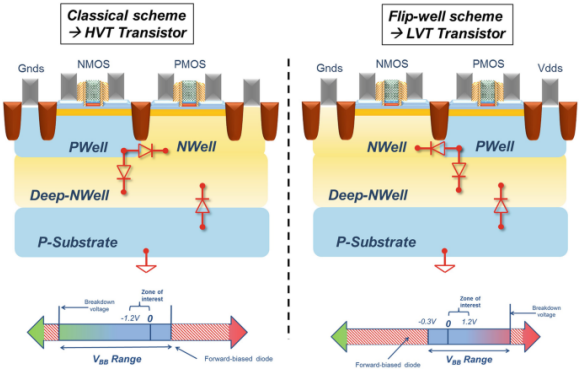




Quo Vadis?

- Test Particam1 with converter coating as detector for ultra-cold neutrons with PSI
- Evaluating different small process nodes for further submissions:
  - TPSCo 65nm
  - GlobalFoundries FD-SOI: 22nm and 45nm
- Looking for possible applications and collaborators



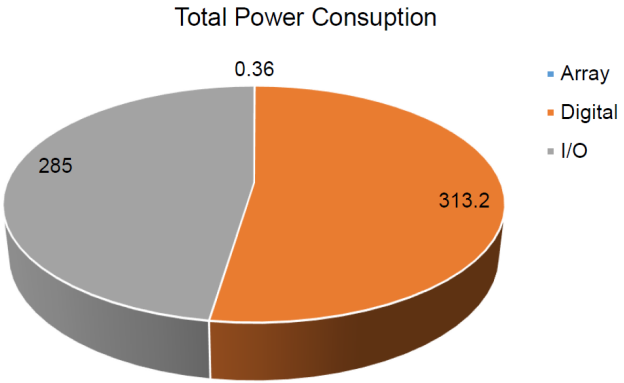


Source:10.1007/978-3-030-39496-7_2

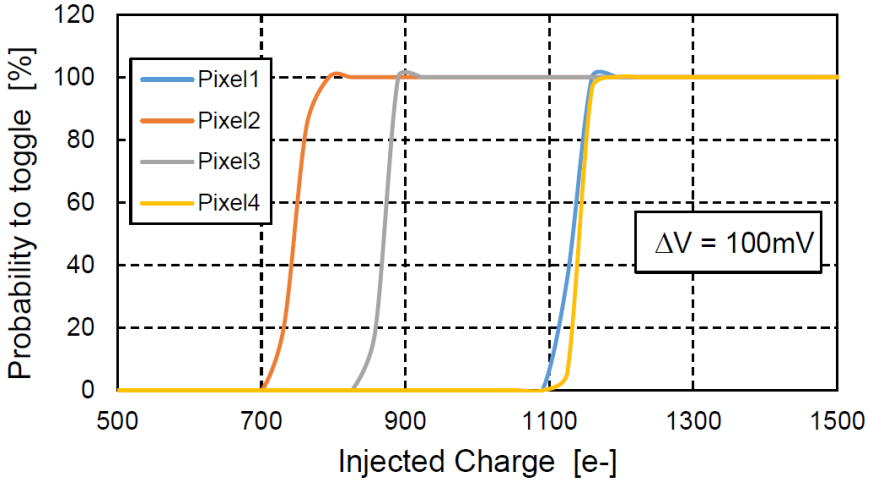
Backup

Power Consumption

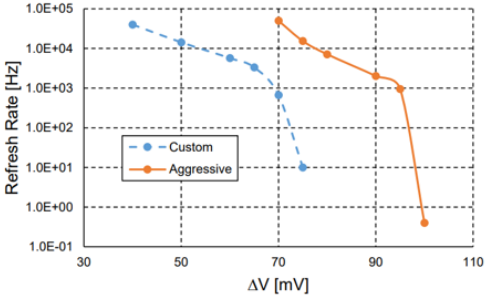
- Simulated power in µW
- 1.8 kfps @ 1% activity
- 100 µm × 100 µm sensitive area

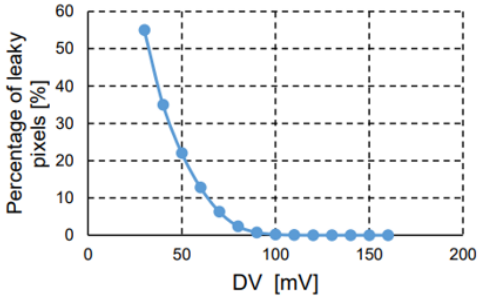


Threshold Scan

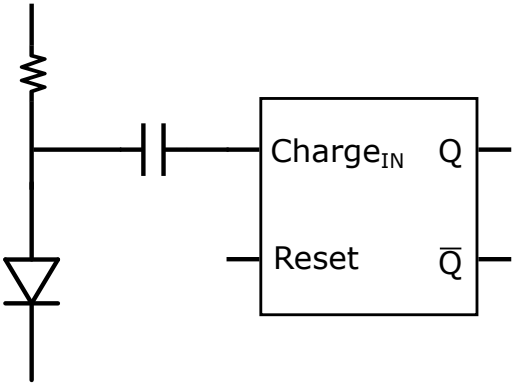


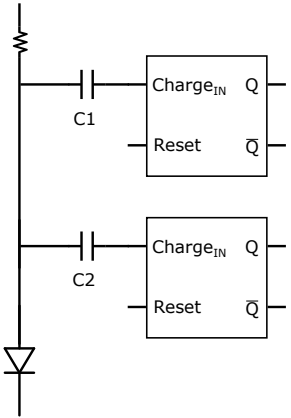
Noise


1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
Refresh Rate [Hz]
Custom
Aggressive
30
50
70
90
110
ΔV [mV]


60
50
40
30
20
10
0
Percentage of leaky pixels [%]
0
50
100
150
200
DV [mV]

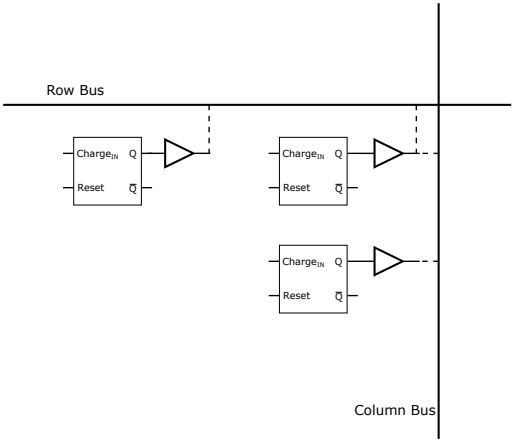
AC-coupling

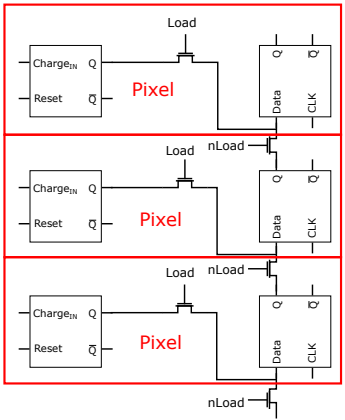




- AC-couple charge to remove leakage from the diode
- Allows for different sensitivity/thresholds with $C_1 \neq C_2$
- Needs to be implemented in a way the flipping doesn't feed back into the other elements in the pixel

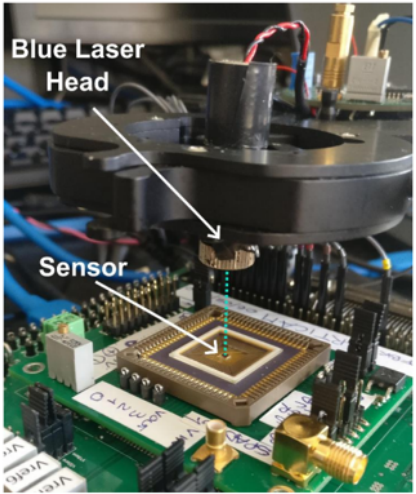
Readout



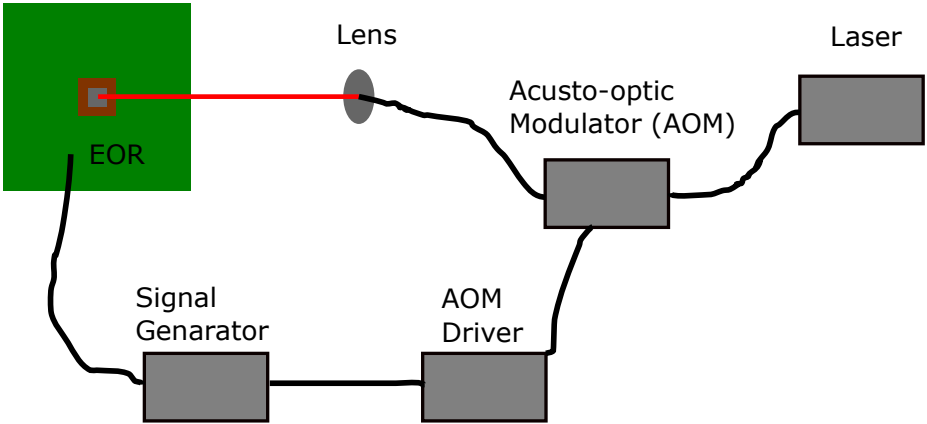


- Add bus lines to only read columns/rows with hits
- Implement RO as shift register chains?

Laser Setup FBK



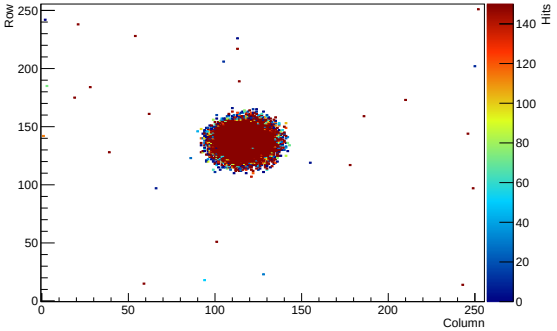
Laser Setup UoL



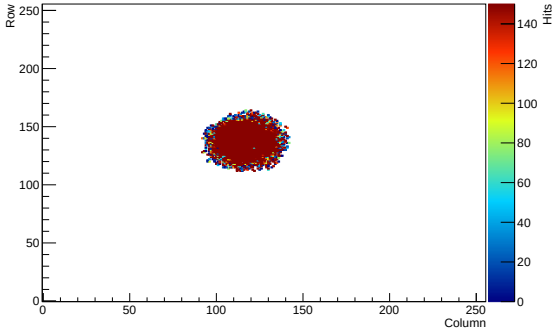
- Colleagues of the atom interferometry group kindly set something up for me
- 780nm (infrared) continuous laser
- Acousto-optic modulator (AOM) gates the laser
- Vary pulse length for more energy

Laser Analysis I

Raw



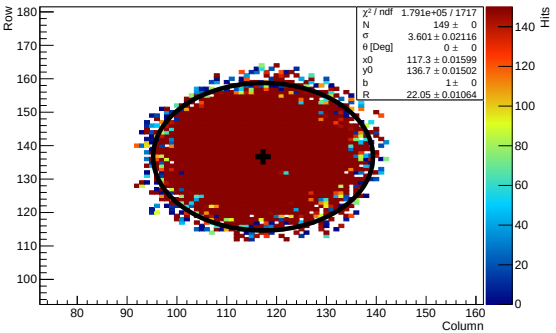
Cleaned



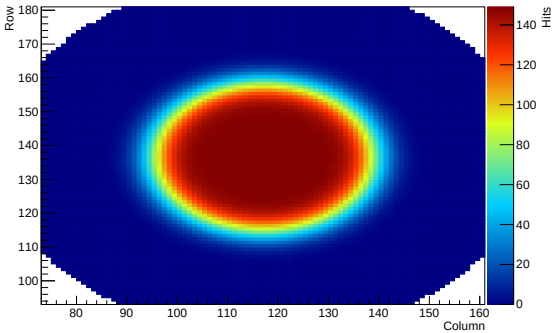
- Remove all pixels that have no neighbour within +-1 with hits to remove noise

Laser Analysis II

Fit results

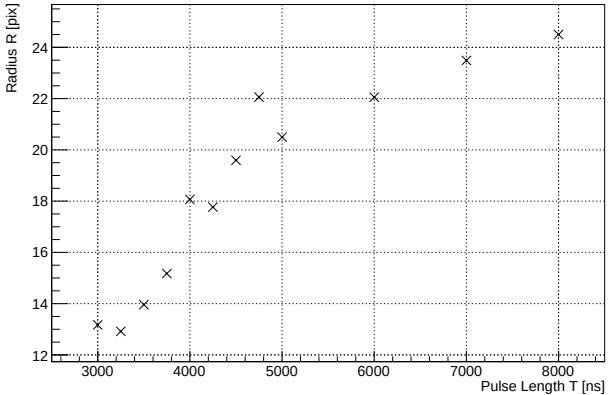


Fit function



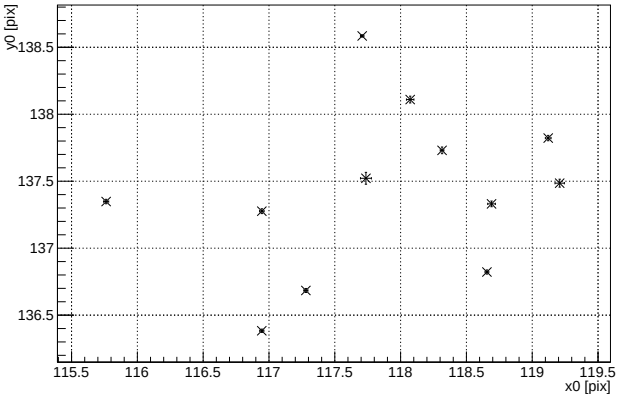
- Fit hit map with circular s-curve (Gaussian error function erf)
- Extract centre points x0/y0, radius R for a given pulse length T
- (implemented generalised rotated ellipse but circle works better)

Laser Radius



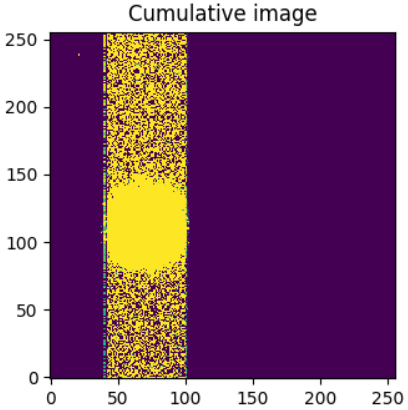
- Beam is Gaussian so radius grows slower for longer pulses

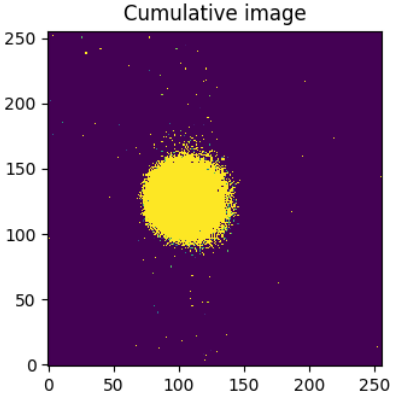
Laser Spot Position



- x0 within 4 pixels = 8um!
- y0 within 3 pixels = 6um!

Streaking





- Large beam spots cause streaking along the column
- Hypothesis: Leakage through the BTL into the non-flipped pixels
- Reduced by holding BTL-reset during the exposure state