UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Update on:
XIDer – an **X**-ray **I**ntegrating **De**tector for the ESRF-EBS Upgrade

David Schimansky

Schaltungstechnik und Simulation

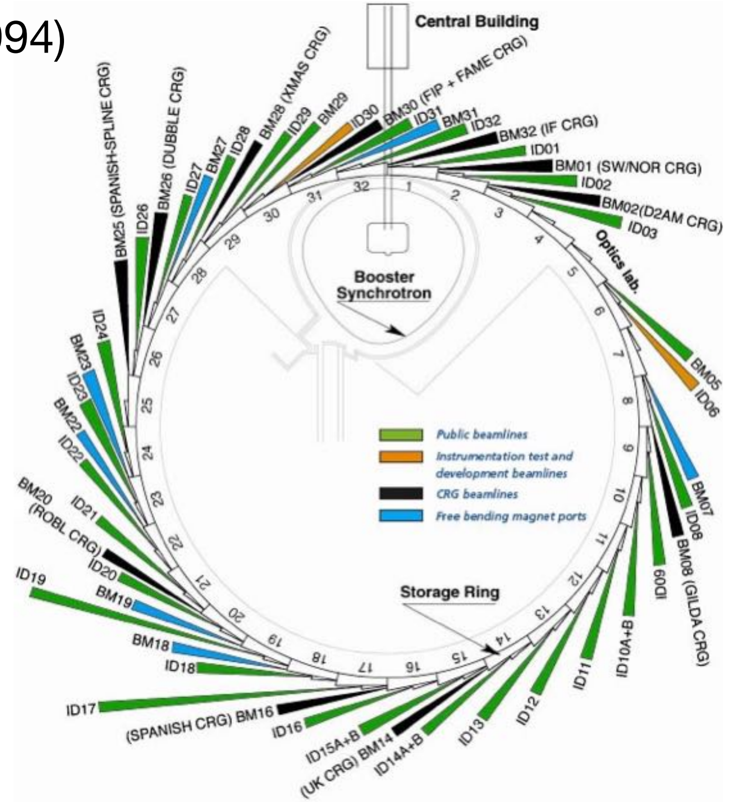
Contents

- The European Synchrotron Radiation Facility (ESRF) & its upgrade program (EBS)
- Introduction to XIDer
- Readout ASIC
  - Design
  - Characterisation Example: Frontend noise & linearity
- Sensor/ASIC assembly prototypes
- Conclusion & Outlook

European Synchrotron Radiation Facility (ESRF)

European Synchrotron Radiation Facility (ESRF)

- Joint research facility in Grenoble, France (founded in 1988)
- Funded by 22 countries (France, Germany, Italy, ..)
- Electron synchrotron x-ray source (up to ~150keV)
- First 3rd generation synchrotron (opened in 1994)
- Circumference: 844m
- 2000 publications per year
- Advertises itself as „user facility“
- Available research methods
  - X-ray spectroscopy
  - X-ray tomography
  - X-ray diffraction



ESRF Upgrade Program (EBS)


EBS electromagnets

Extremely-Brilliant Source (ESRF-EBS):

- Storage ring & instrumentation upgrade program over the period 2015-2022
- New storage ring has been finished and opened in 2020 as planned
- Improved energy efficiency (30% cost reduction)
- Increased brilliance of x-ray beam
- Needs new detectors tailored to the upgraded source

  ⇒ Reach out to external laboratories

ESRF Upgrade Program (EBS)

EBS electromagnets

Extremely-Brilliant Source (ESRF-EBS):

- Storage ring & instrumentation upgrade program over the period 2015-2022
- New storage ring has been finished and opened in 2020 as planned
- Improved energy efficiency (30% cost reduction)
- Increased brilliance of x-ray beam
- Needs new detectors tailored to the upgraded source

$\Rightarrow$ Reach out to external laboratories

XIDer: X-ray Integrating Detector

Project Outline

XIDer:

- R&D project until end of 2022
- 4-year funding: Shared 50/50 by ESRF and Heidelberg University
- HighRR members working on this project: Marin Collonge (ESRF), Christian Kreidl (HD), Michael Ritzert (HD), David Schimansky (HD)

Detector Requirements

Build detector for any kind of (time-resolved) x-ray diffraction experiment at the ESRF:

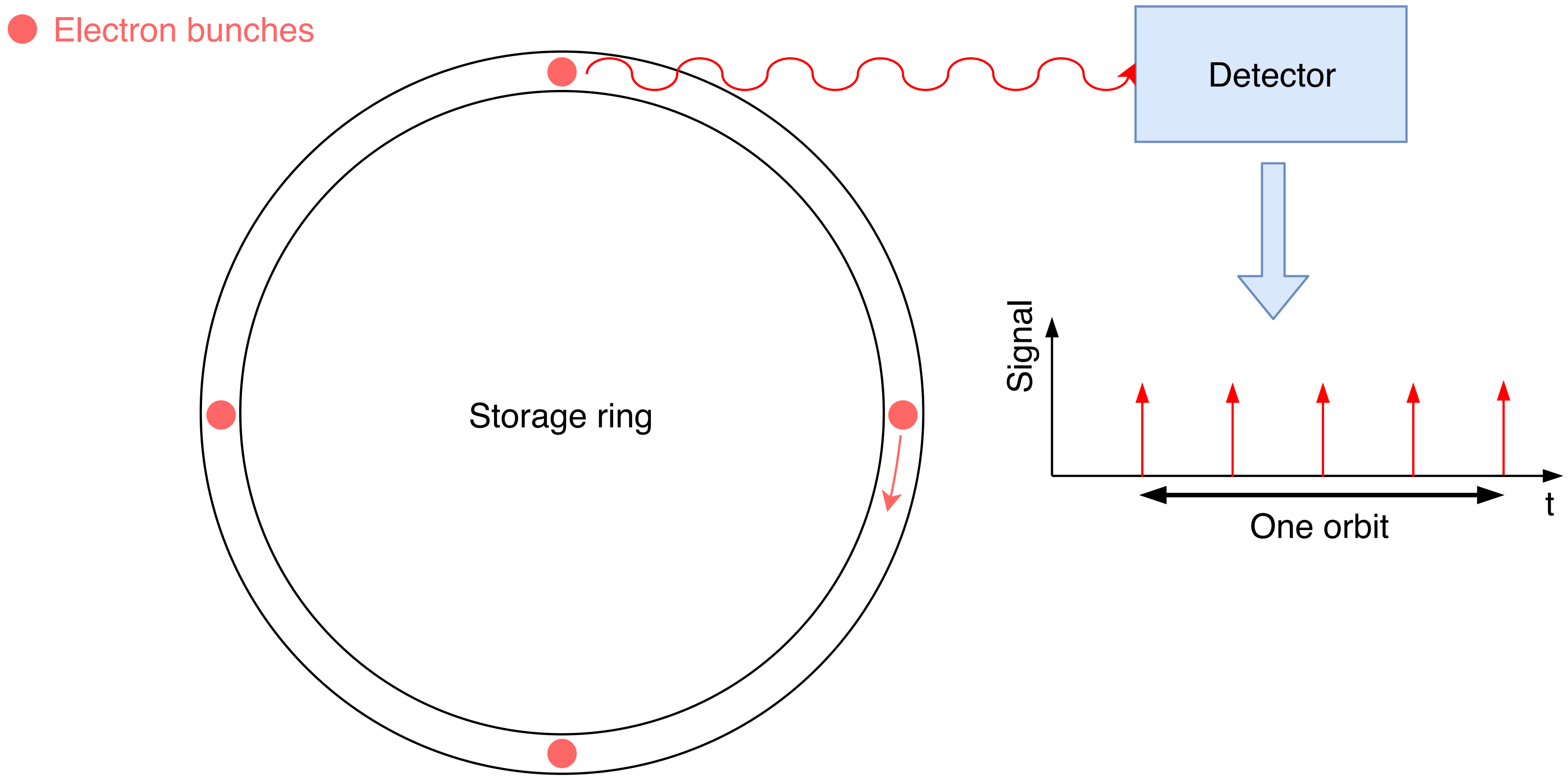
- Energy range: 30-100keV
- Different spatial resolutions: 100µm vs. 200µm pixel pitch
- Dynamic range: Single Photons up to $> 10^{11} \frac{ph}{mm^2 s}$
- Cope with different bunch filling modes for storage ring
- Time-resolved >100k frames/s
- Flexible readout schemes single frame, accumulated frames, ..

Detector Requirements

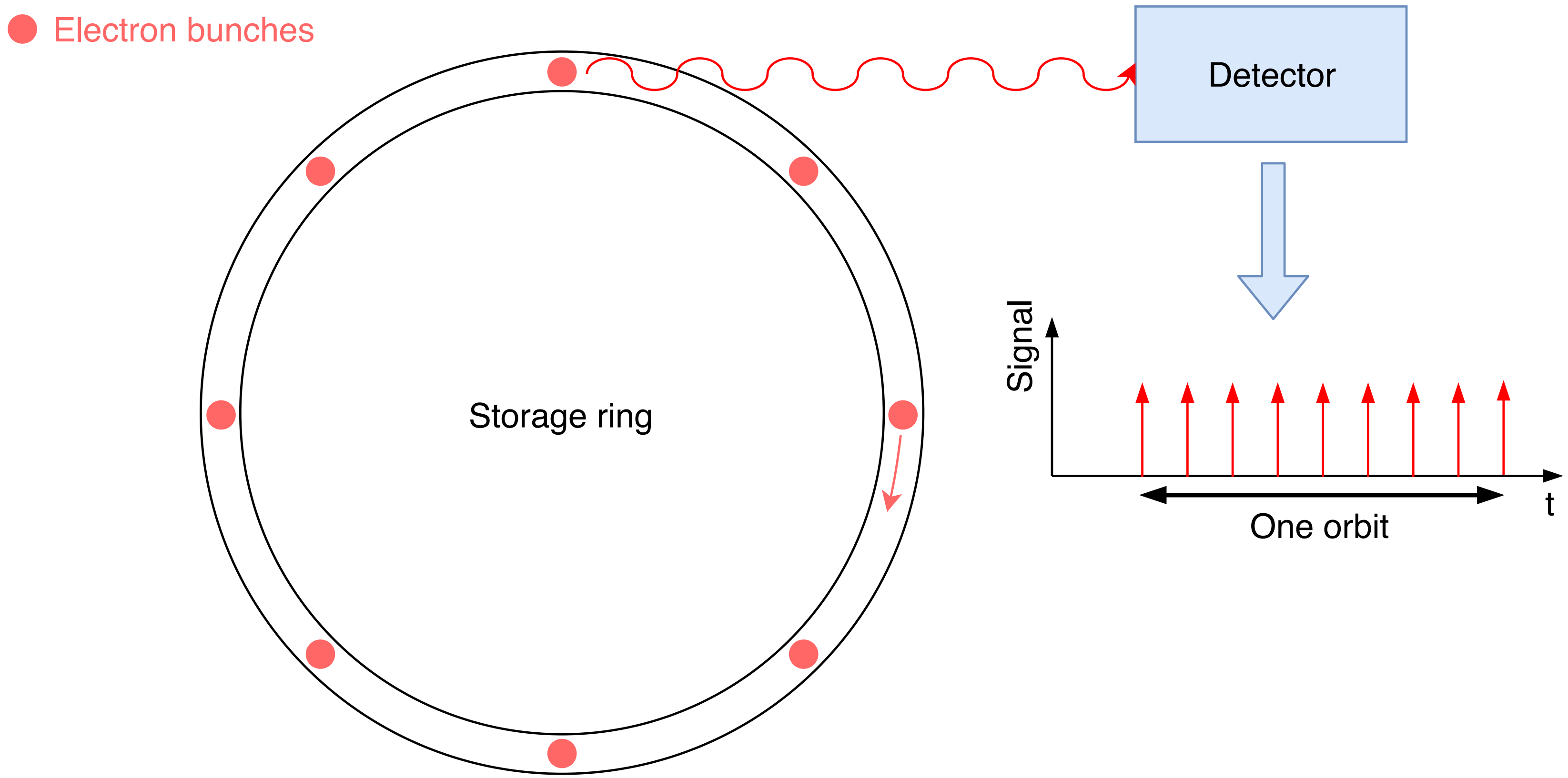
Build detector for any kind of (time-resolved) x-ray diffraction experiment at the ESRF:

- Energy range: 30-100keV
- Different spatial resolutions: 100μm vs. 200μm pixel pitch
- Dynamic range: Single Photons up to $> 10^{11} \frac{ph}{mm^2 s}$
- Cope with different bunch filling modes for storage ring
- Time-resolved >100k frames/s
- Flexible readout schemes single frame, accumulated frames, ..

Detector Requirements: Bunch modes



Detector Requirements: Bunch modes



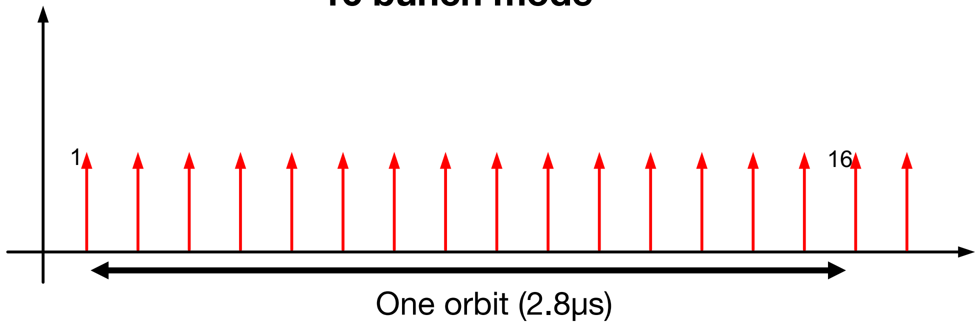
Detector Requirements: Bunch modes/ Photon Fluxes

Schaltungstechnik und Simulation

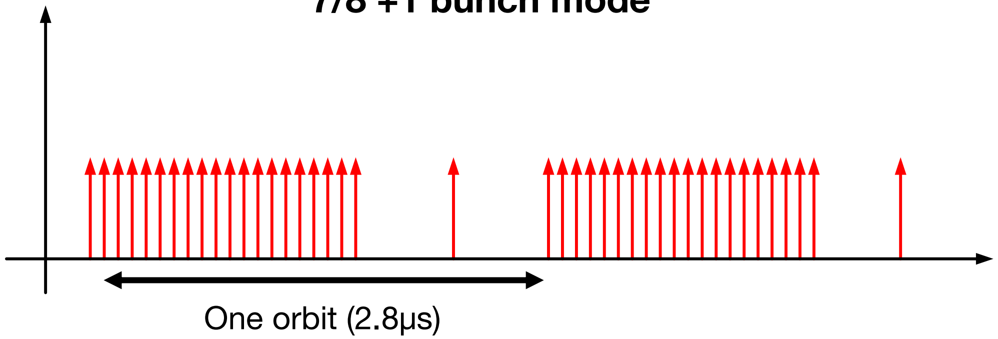
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Example cases of possible bunch modes

16 bunch mode



7/8 +1 bunch mode



- Pulsed illumination for time-resolved experiments
- Single bunches have to be recorded and processed
- Need single photon sensitivity

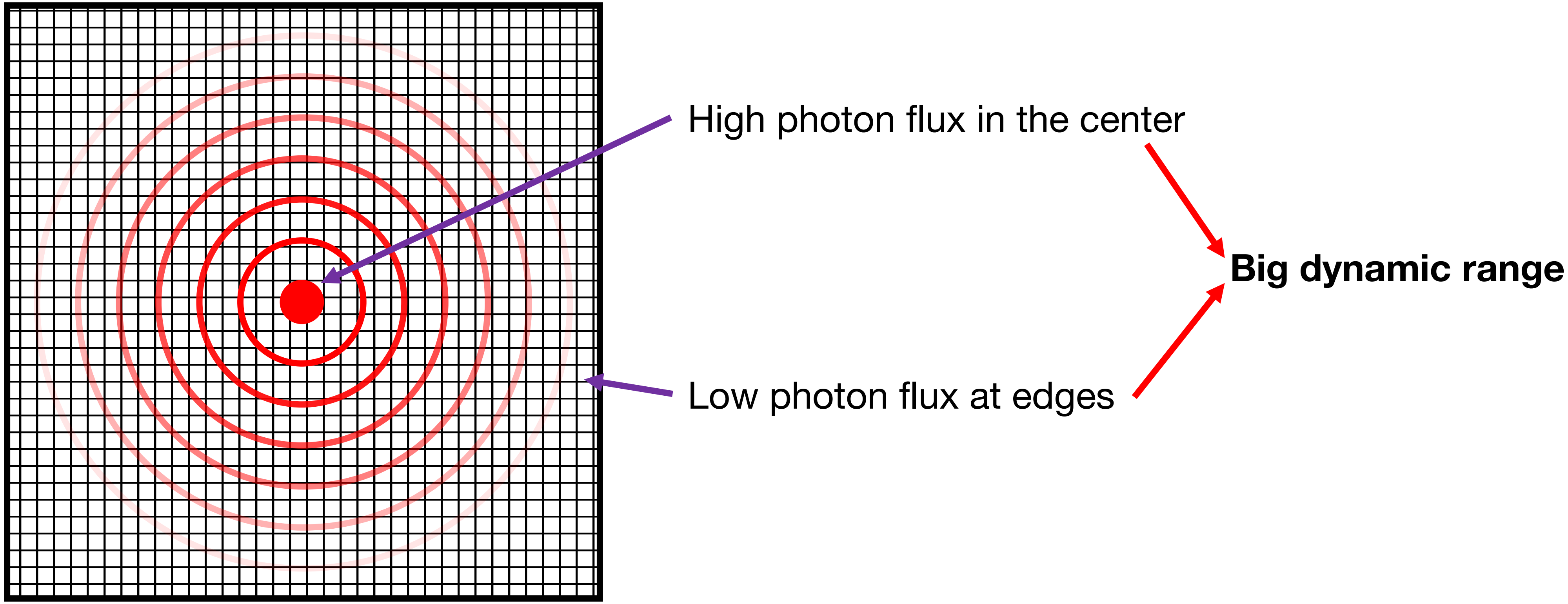
- Quasi-continuous illumination for 7/8 of the orbital period
- Integrate many bunches into one image
- Expected $> 10^{11} \frac{ph}{mm^2 s}$

Big dynamic range

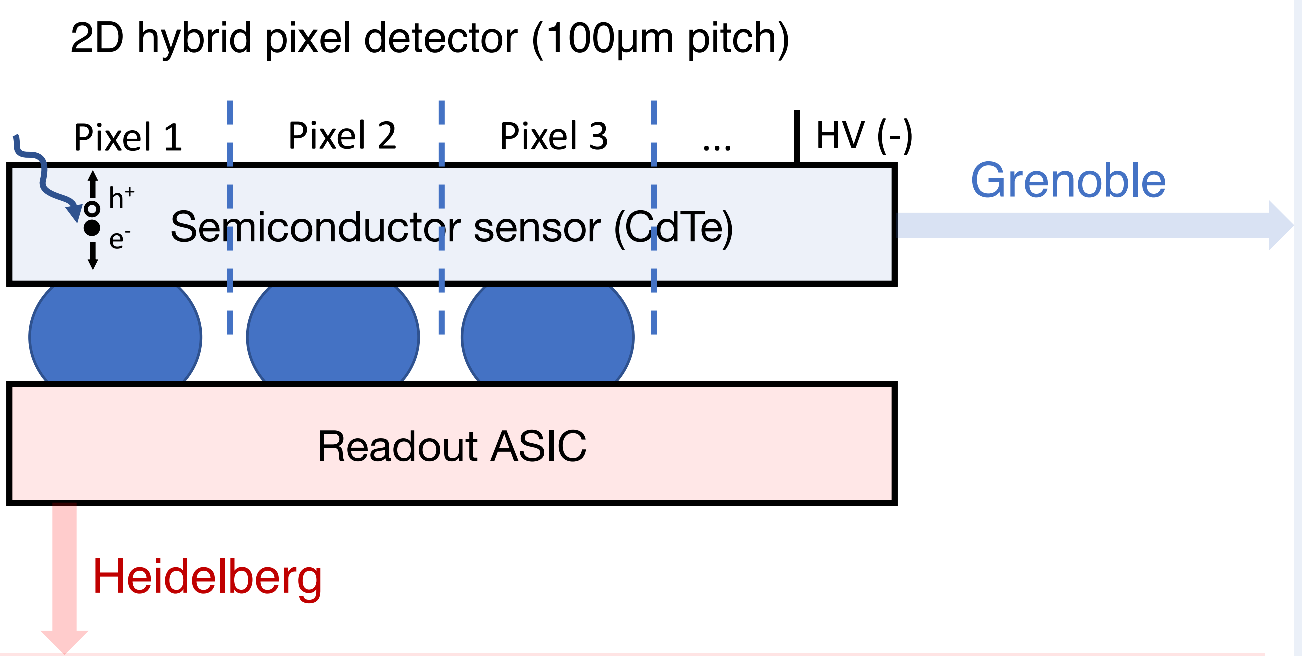
Detector Requirements: Photon Fluxes

- Requirement of big dynamic range is not only given by different bunch modes
- Even in high flux experiments, single photon sensitivity is still important:

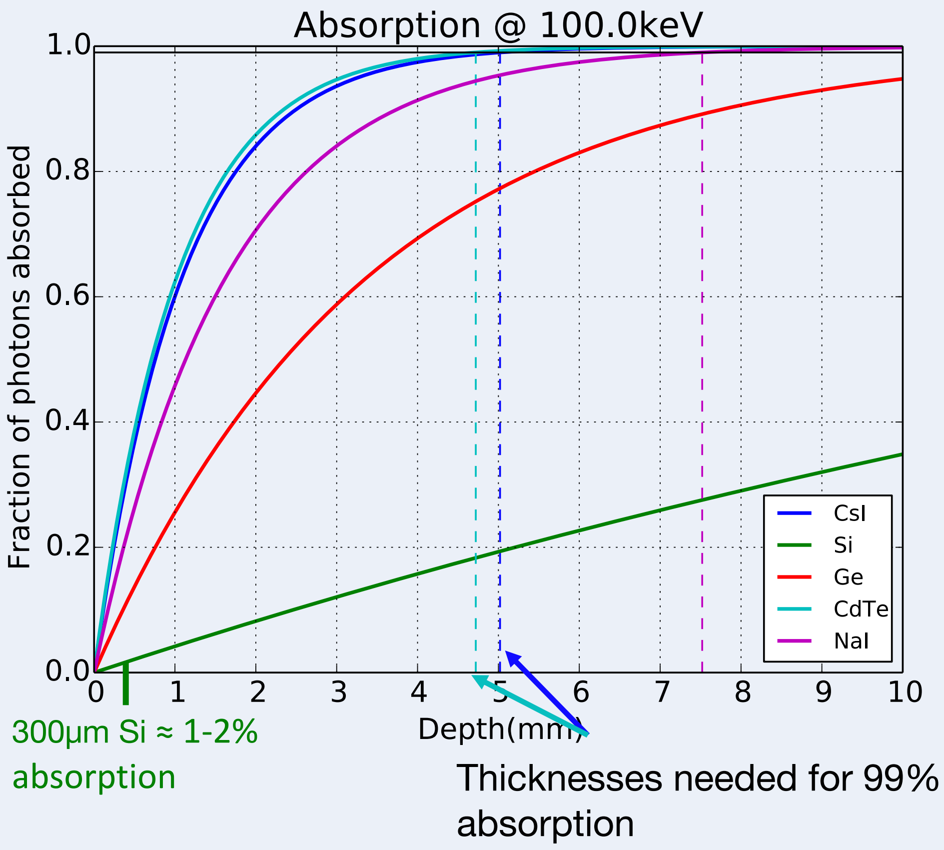
Example: Airy disk of circular aperture hits the pixelated detector



Tackling these challenges



- Every pixel is connected to its own frontend in the readout ASIC
- **Charge integrating** frontend with **continuous analog-to-digital conversion** for high dynamic range

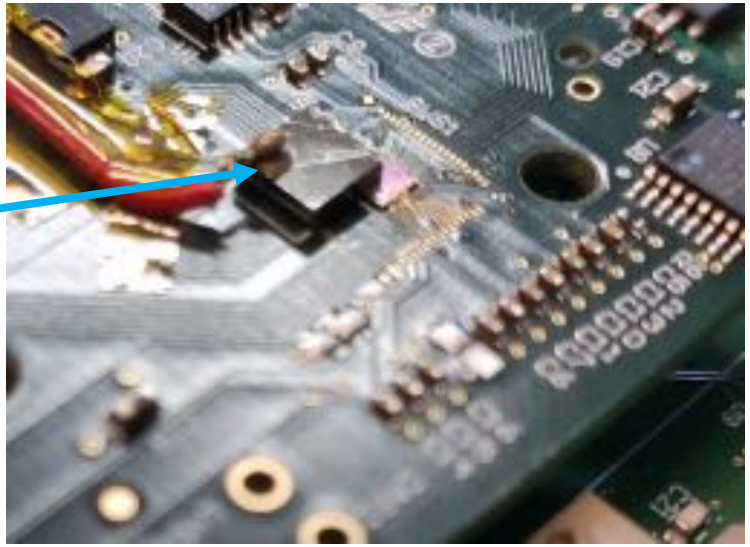


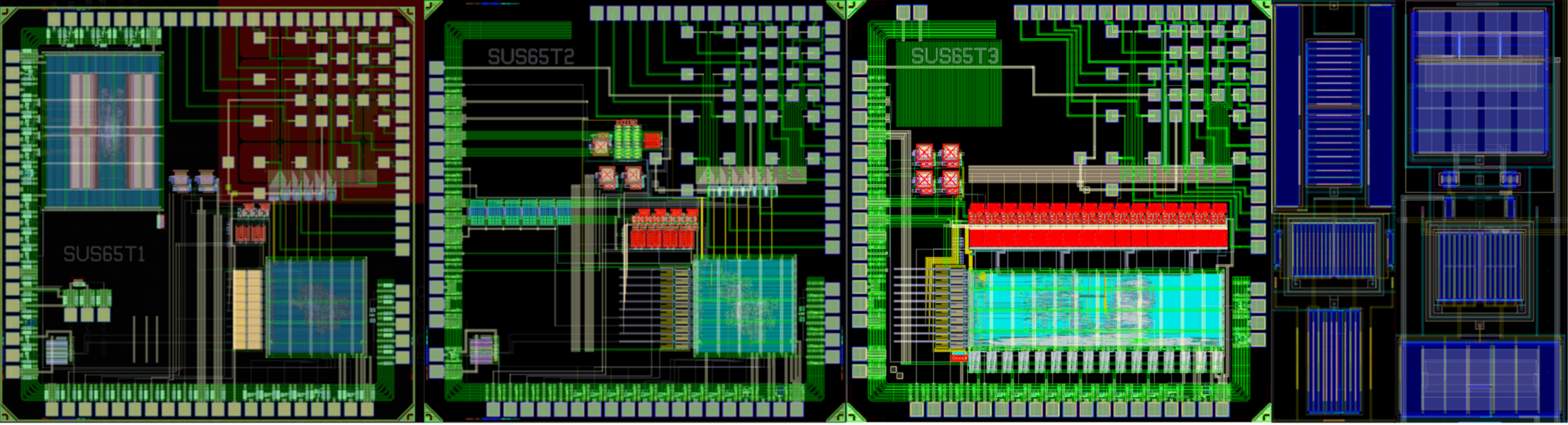
- Use **high-Z material** to get high stopping power
- Tendency: Cadmium Telluride (CdTe)

Problems with Cadmium-Telluride (CdTe)

- Expensive and only a few suppliers around the world
- Heat sensitive: Introduction of defects >80°C
- Brittle
- Low tensile strength
- Afterglow: Generated charge signals have very long tails (see sensor measurements)
- Polarisation:
  - High photon fluxes generate space charges due to trapping of holes (low mobility-lifetime product of holes)
  - Space charges then generate electric field that counteracts field of bias HV
  - Space charge field can get so strong that HV field is cancelled completely
    - ⇒ Detector becomes “blind” to incoming photons
    - ⇒ Addition of Zinc (Cadmium-Zinc-Telluride, CZT) in right amounts can solve this problem by increasing the hole mobility-lifetime product
    - ⇒ BUT: CZT is almost impossible to buy. We keep trying, though.

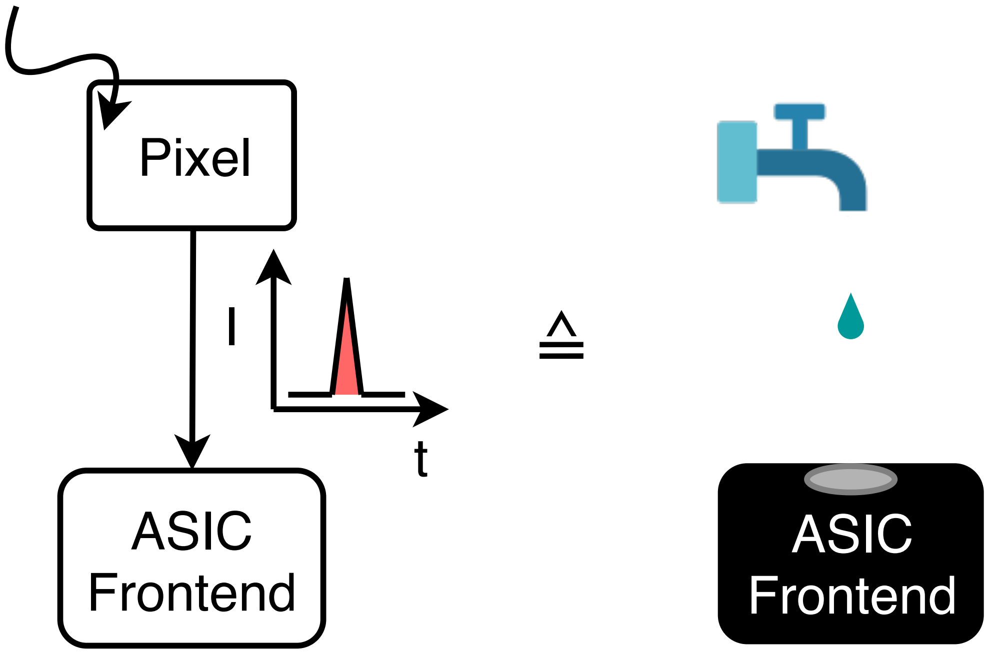
Crack in CdTe sensor prototype after shipping it from HD to the ESRF





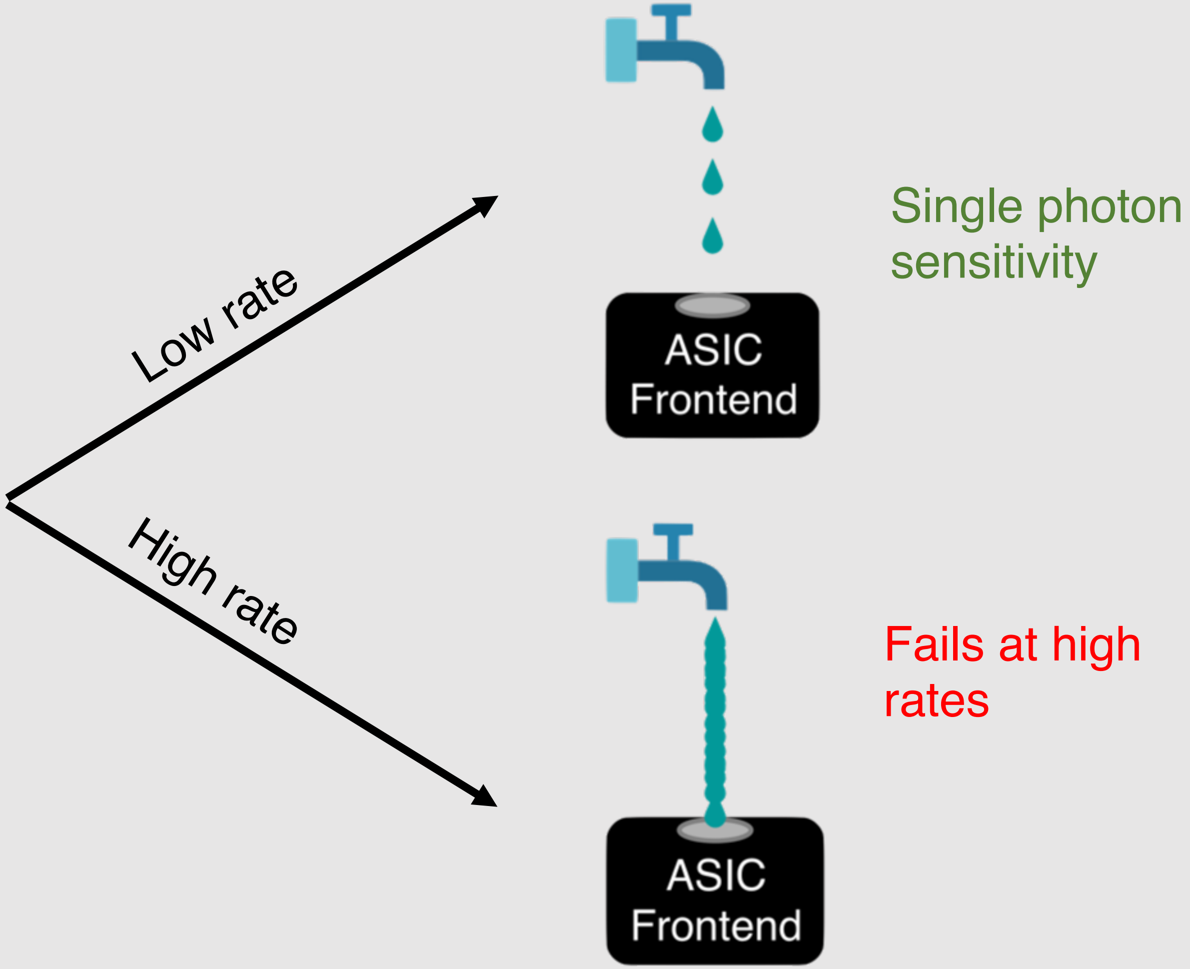
Readout ASIC

Simple Photon Counting



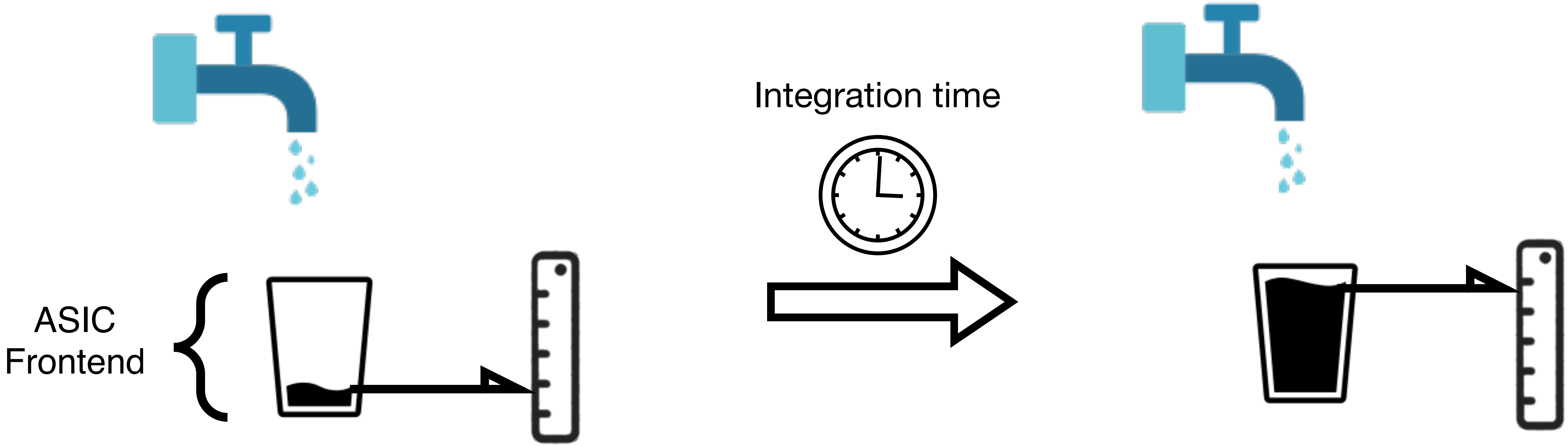
Analogy: Photons are water drops

Most basic idea: Count drops



Charge Integration

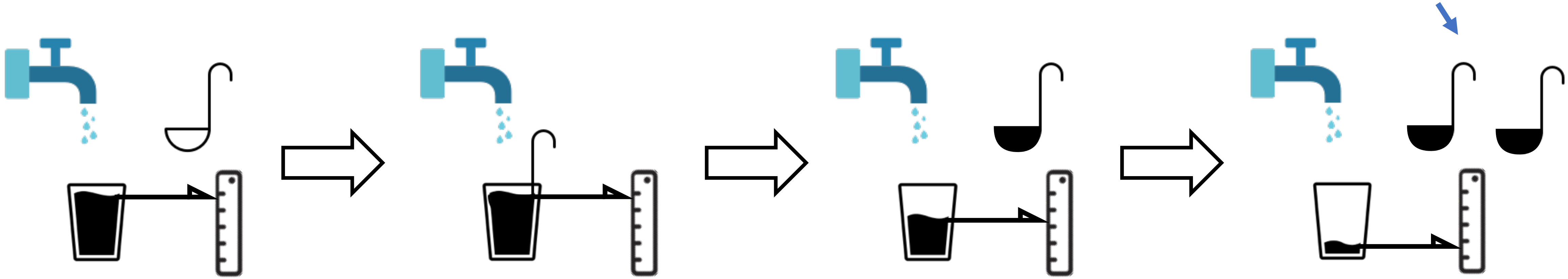
Conceptually different: Collect drops in a bucket and measure water level



Dynamic range is limited by bucket size

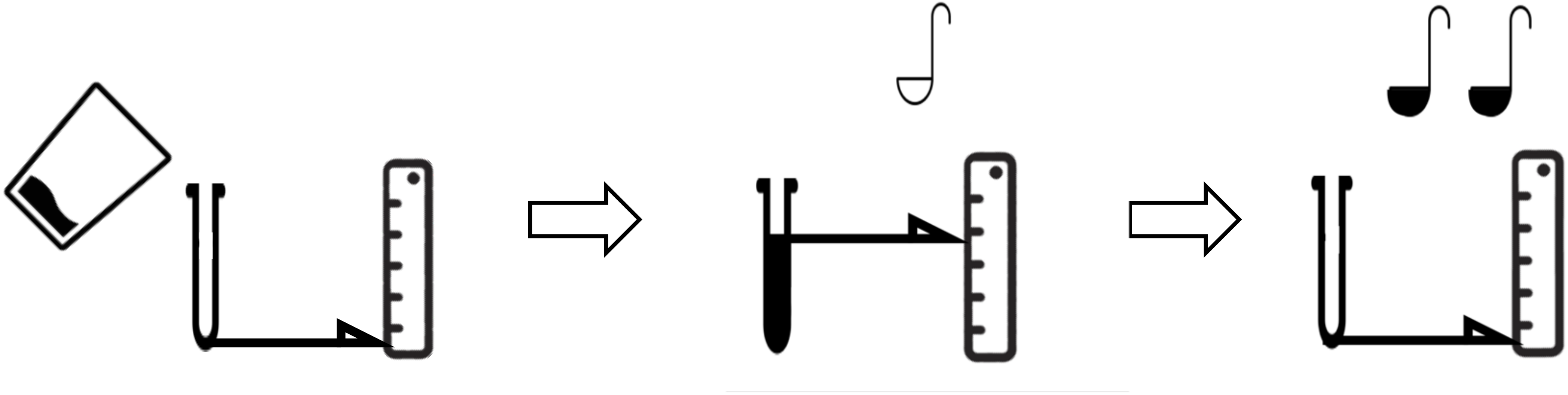
Add-on to charge integration: Prevent bucket from overflowing by emptying it with spoons

Remember amount of spoons needed



Single photon sensitivity & can handle high rates & dynamic range is not limited by bucket size

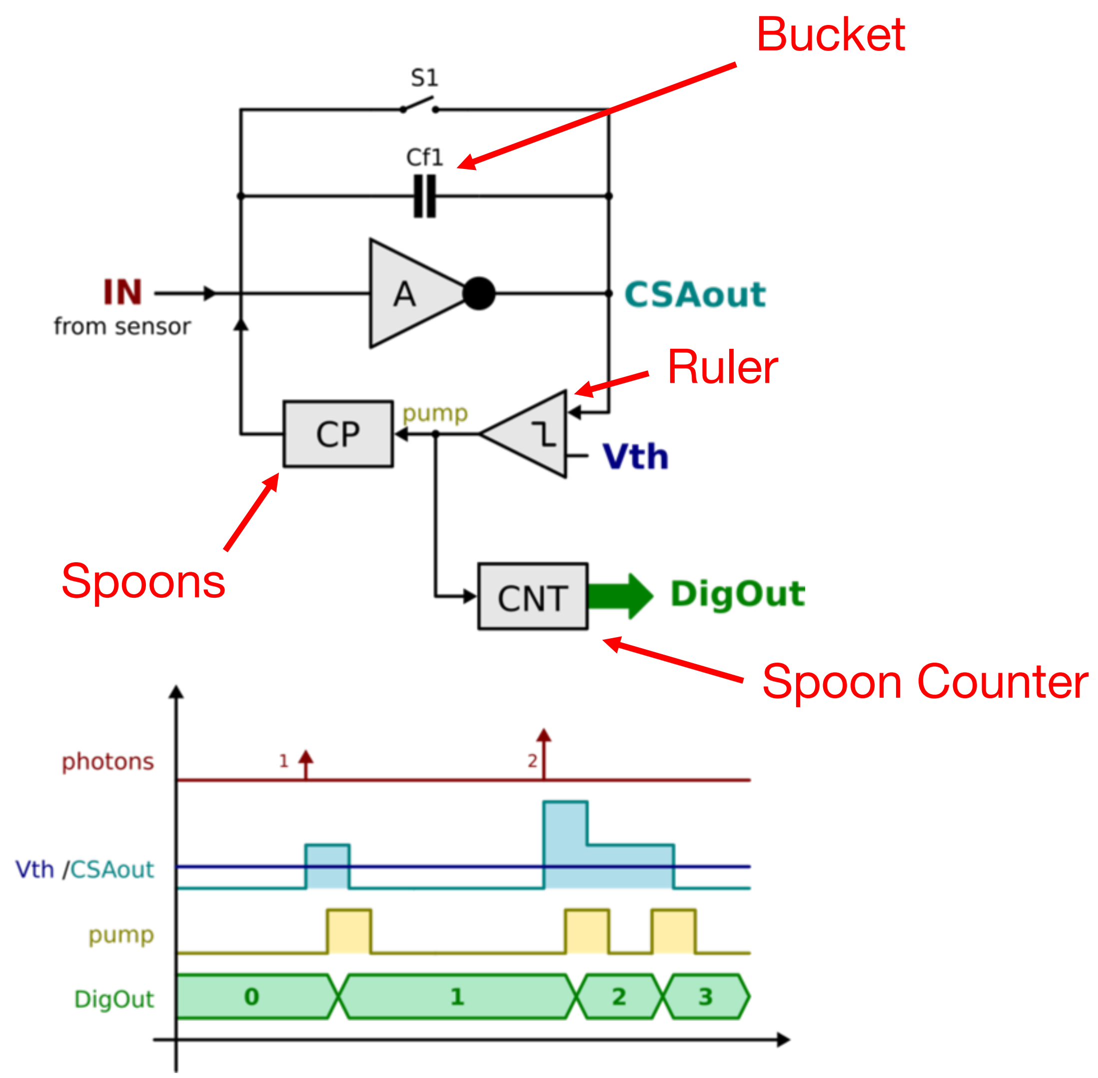
Pipelining with More Precise Second Stage



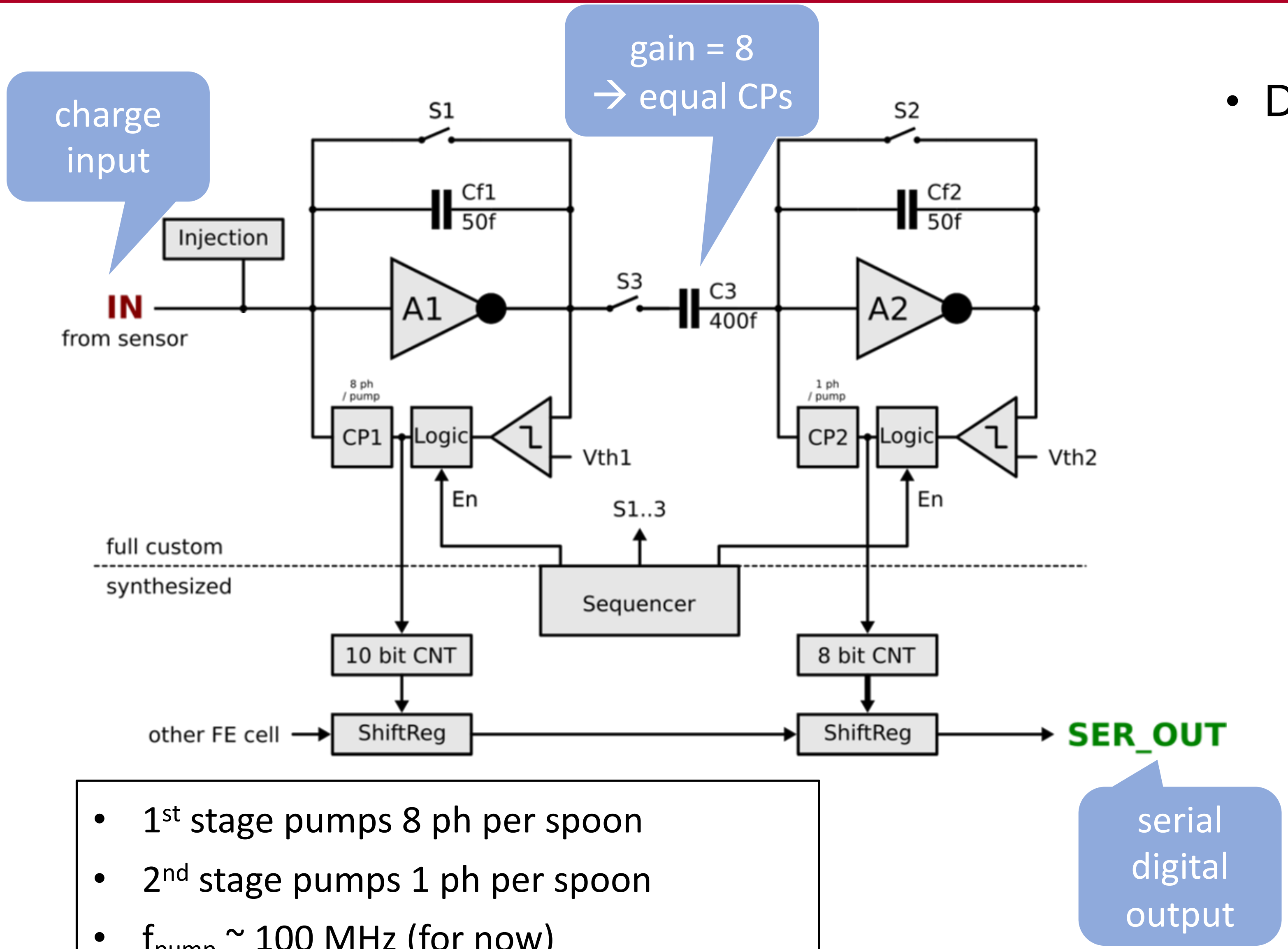
⇒ A second, smaller bucket with a smaller spoon allows for even bigger dynamic range, e.g.:

- Small spoon has size of single photon => Single photon sensitivity
- Big spoon has size of several photons => Higher rates

Continuous Conversion with Single Bucket



Continuous Conversion with Two Buckets

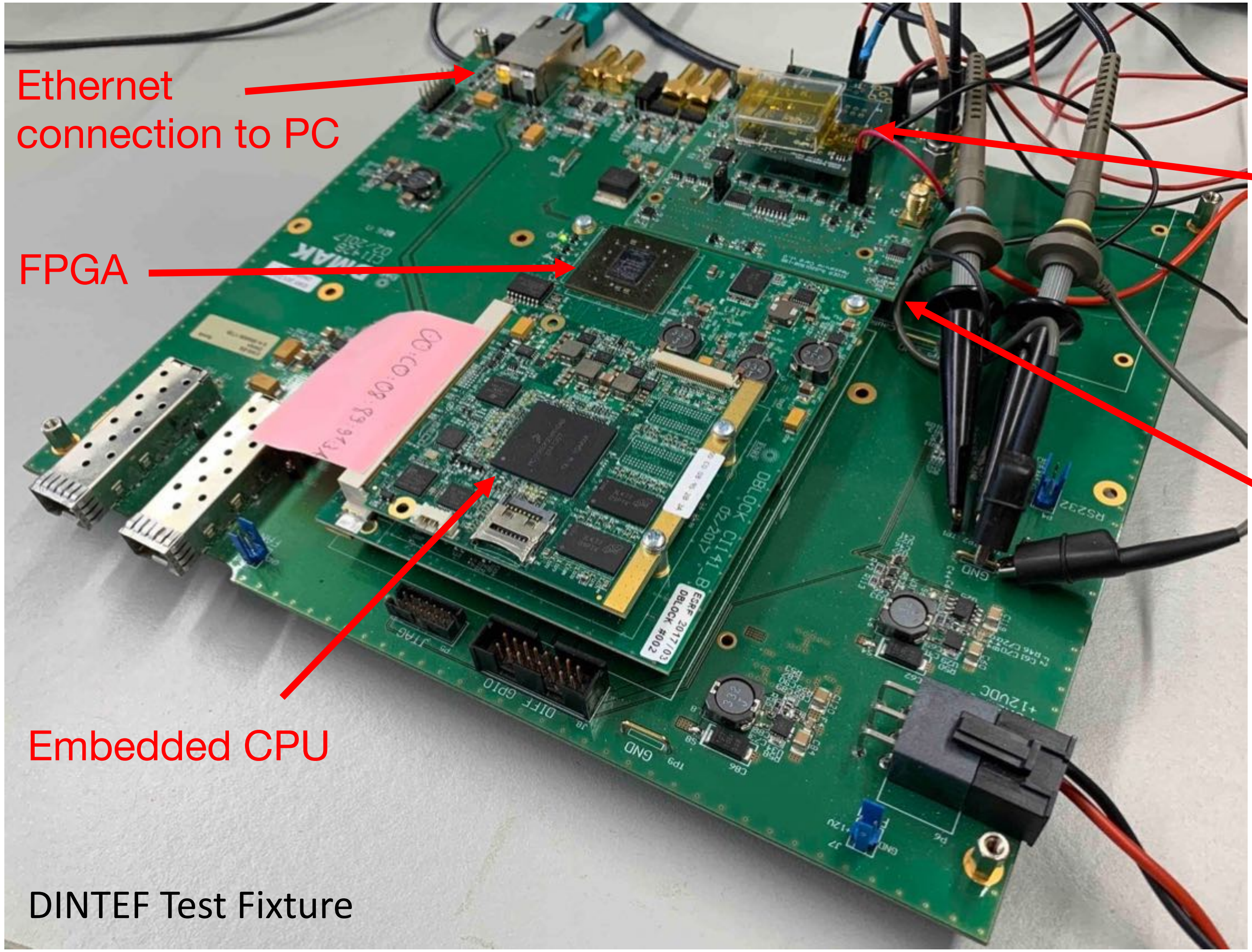


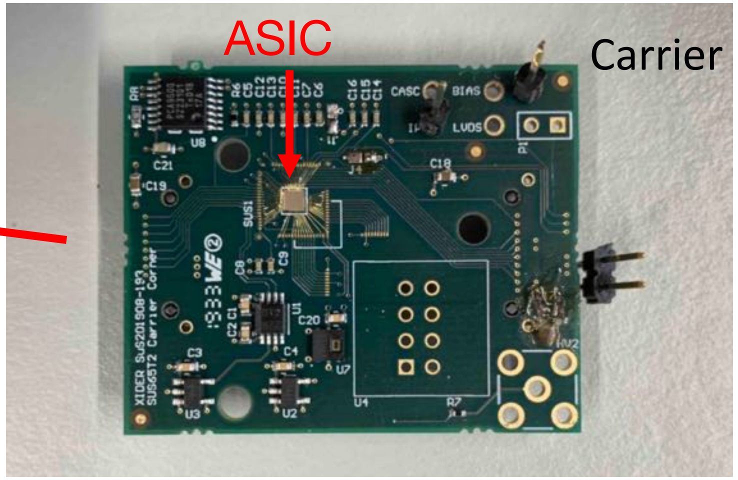
- 1^{st} stage pumps 8 ph per spoon
- 2^{nd} stage pumps 1 ph per spoon
- f_{pump} ~ 100 MHz (for now)

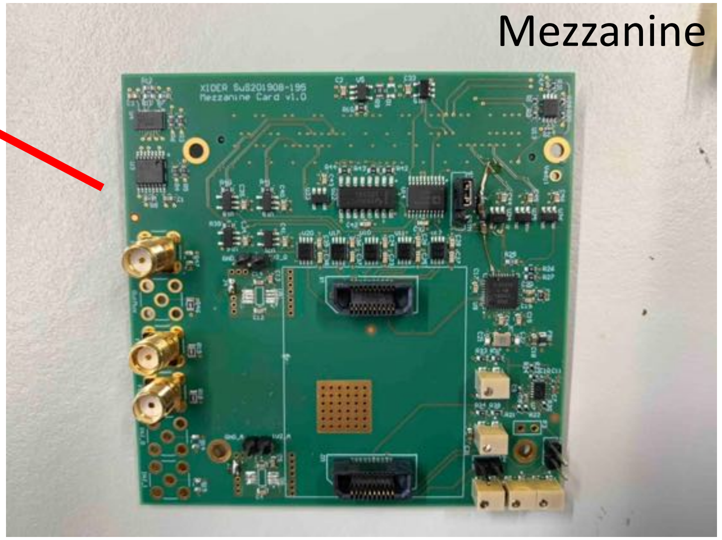
→ 1st stage: $8 \cdot 10^8 \frac{ph}{pixel \cdot s}$

- Design choices and challenges:
  - Spoon size
  - Spoon rate
  - Spoon ratio between stages
  - Bucket sizes
  - Charge pump (CP) topology
  - CP matching
  - Clean stage transition
  - Power limitation
  - Space limitation ($(100\mu m)^2$ pixels)

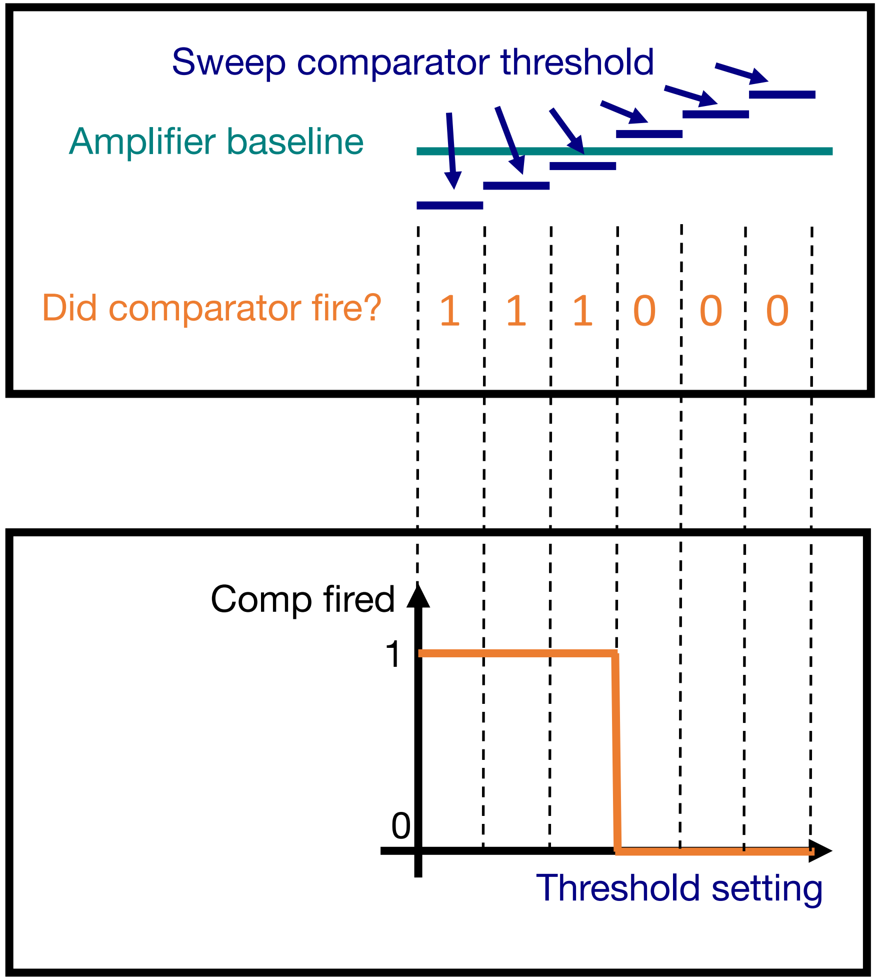
Test Setup

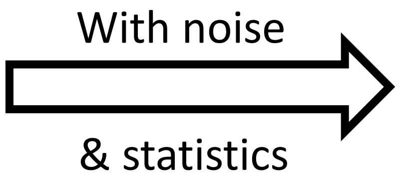

Ethernet connection to PC
FPGA
Embedded CPU
DINTEF Test Fixture

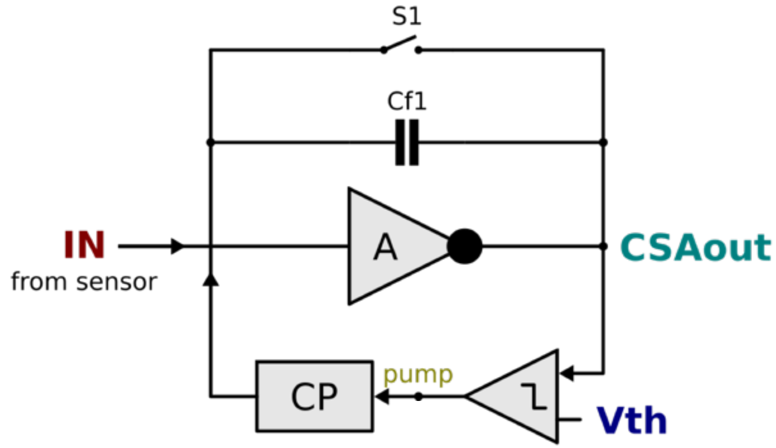

ASIC
Carrier

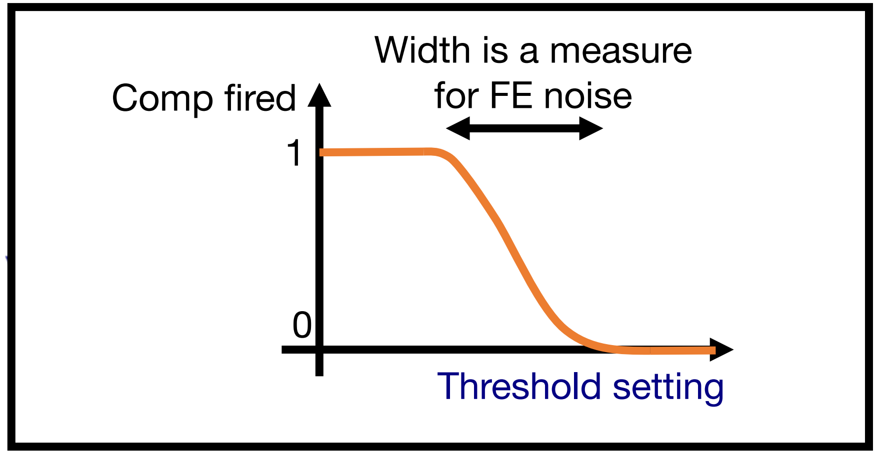

Mezzanine

Frontend Noise Measurement



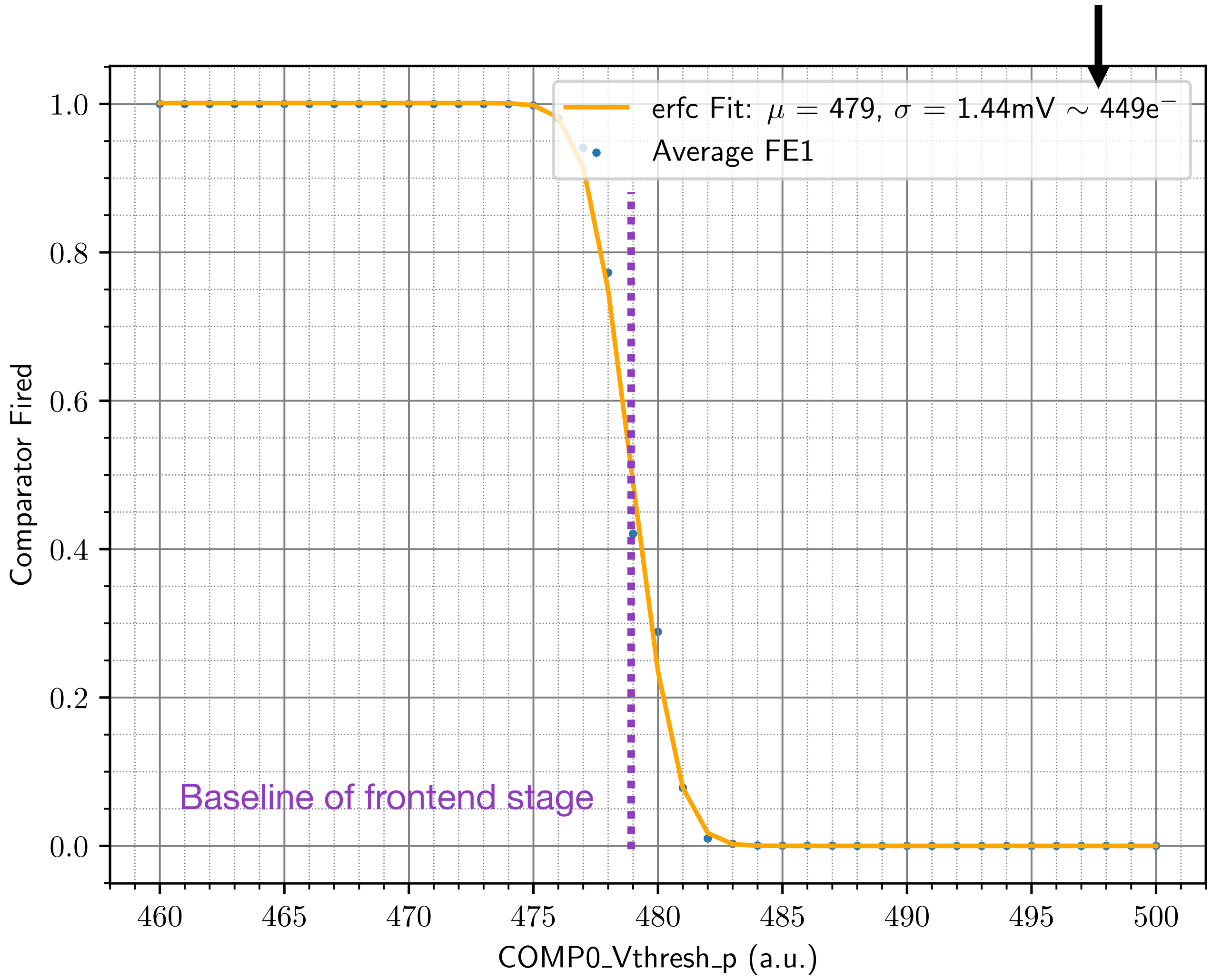






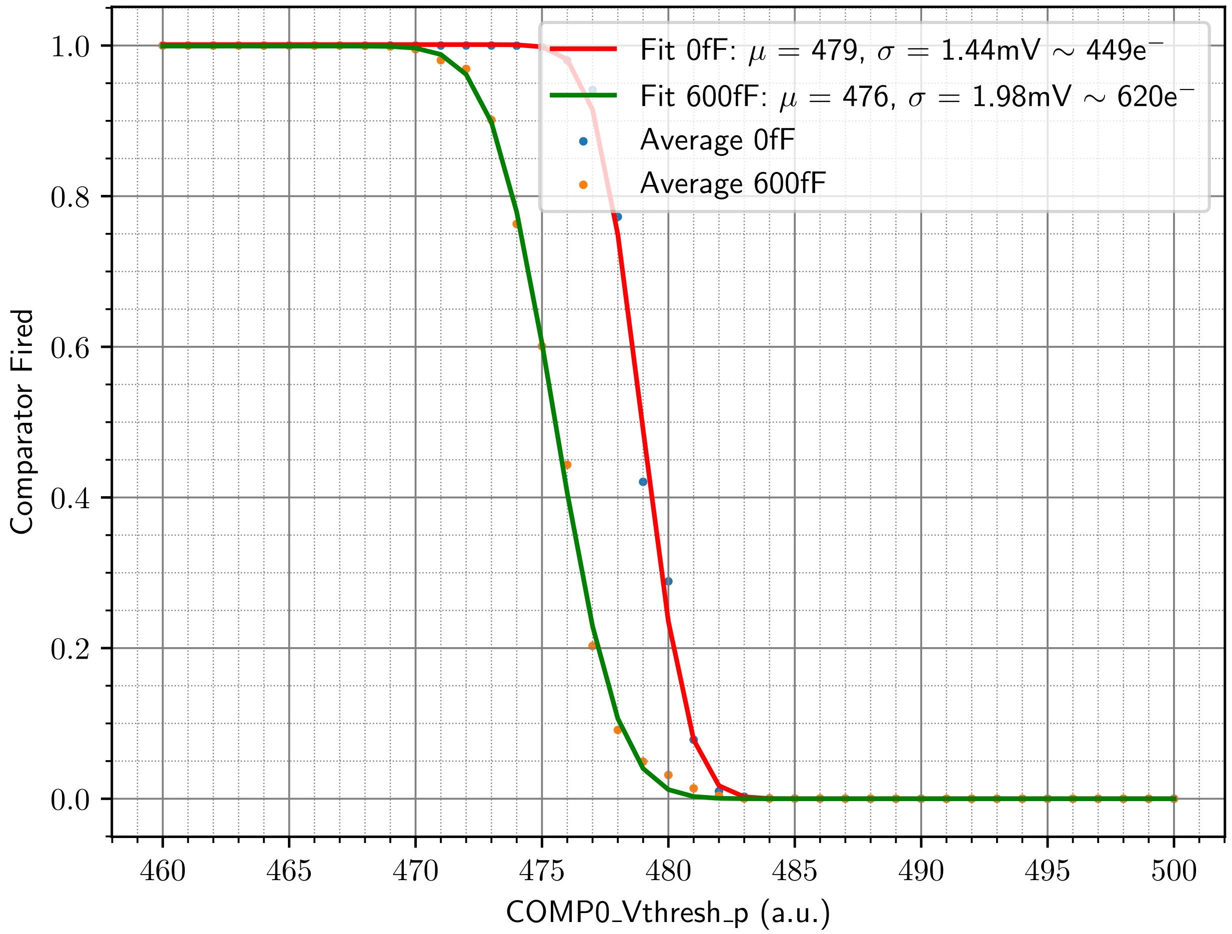
Frontend Noise Measurement

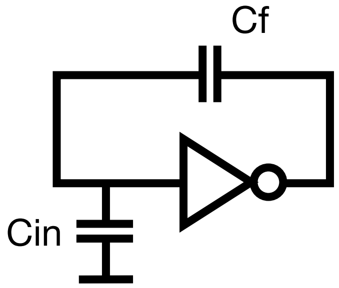
For this chip iteration, we want to be below 600e- (input referred noise)



- Blue data points: Average of 4000 measurements for same comparator threshold
- Orange curve: Error function fit

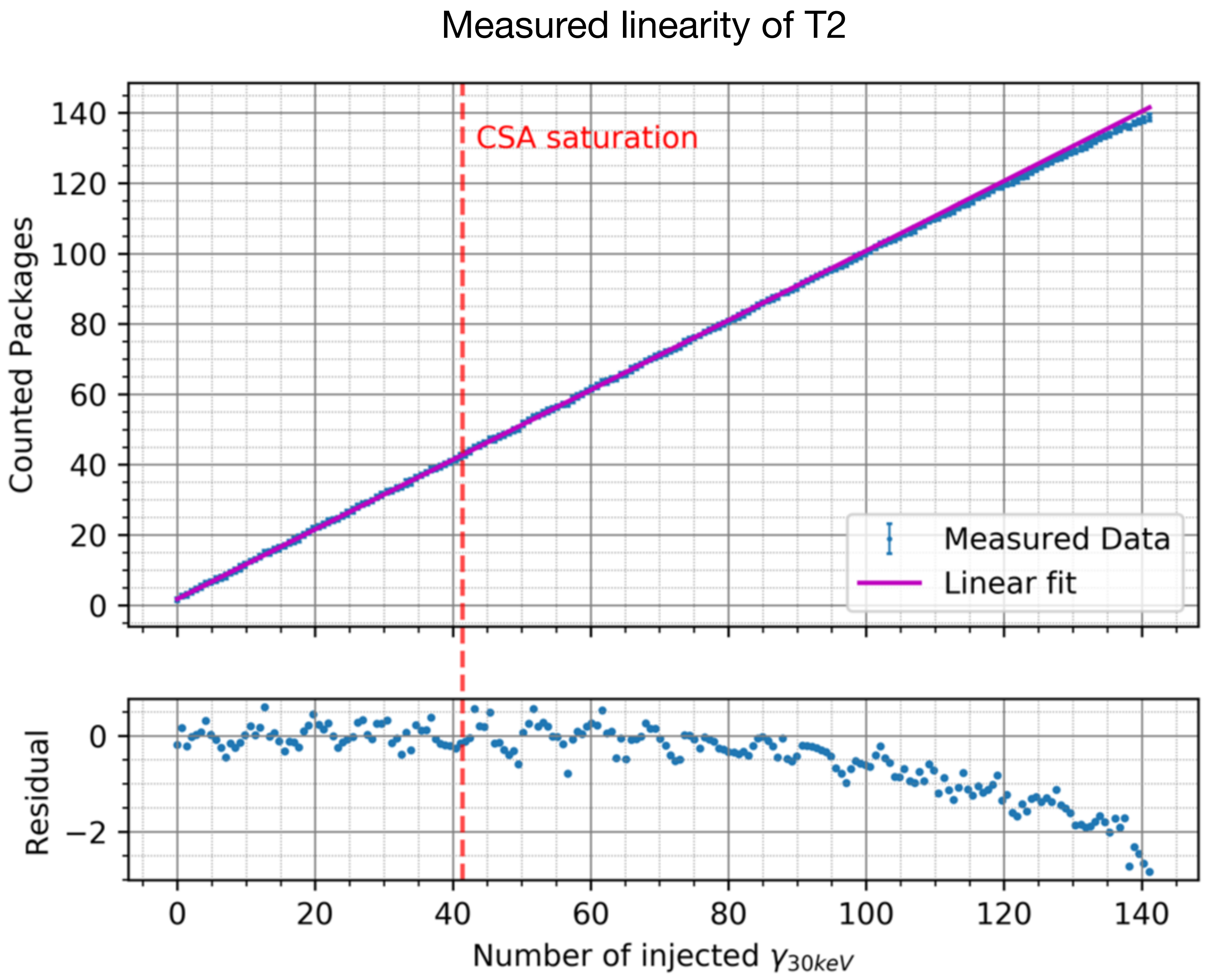
- Different input capacitances (good sanity check)

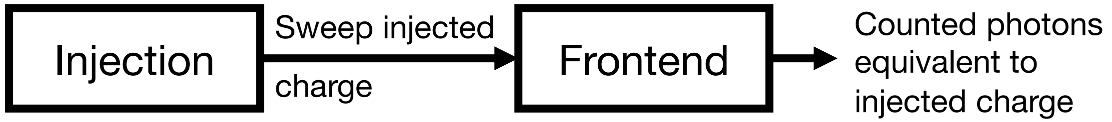




- Fits to simulation almost perfectly
- As expected: Noise rises by factor of ~1.4 (1.5 in sim) from 0fF to 600fF input capacitance

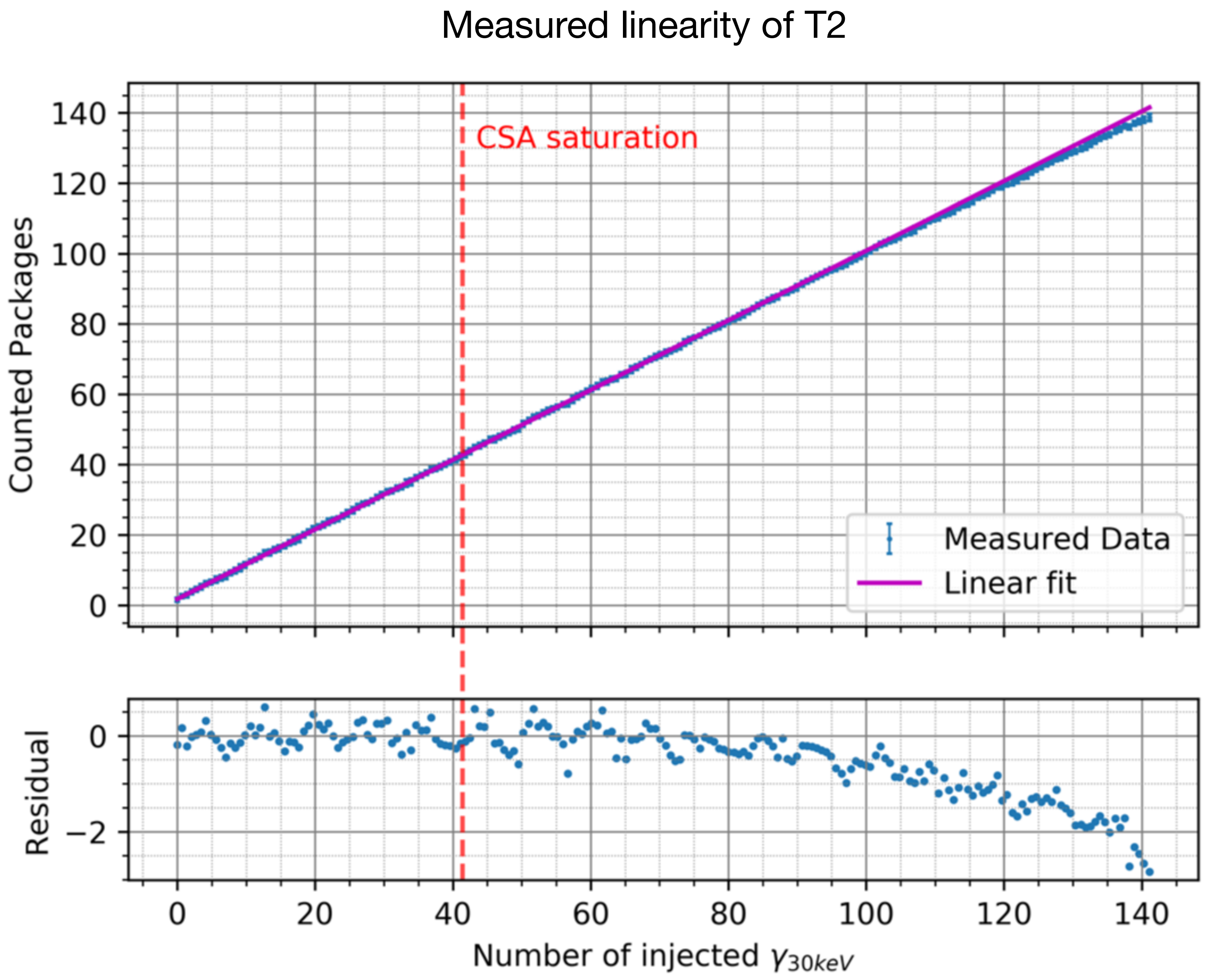
Frontend Counting Linearity Measurement

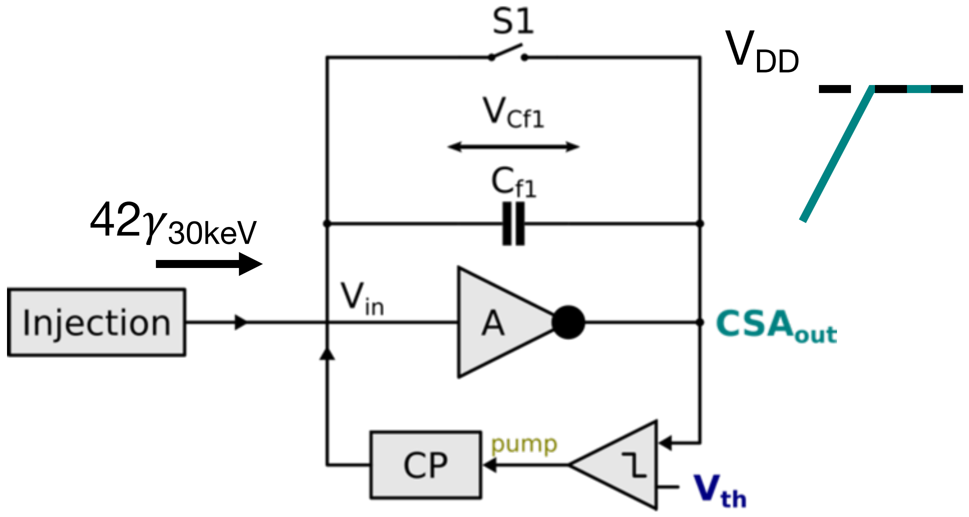




- Linear fit performed for injections <42$\gamma_{30\mathrm{keV}}$ (explanation on next slides)
- Up to a point of 80 $\gamma_{30\mathrm{keV}}$, FE shows linear behaviour, maximum deviation of less than 1 count
- Above 80 $\gamma_{30\mathrm{keV}}$ the curve bends
- At 140 $\gamma_{30\mathrm{keV}}$ the maximum deviation is roughly 3 ADUs

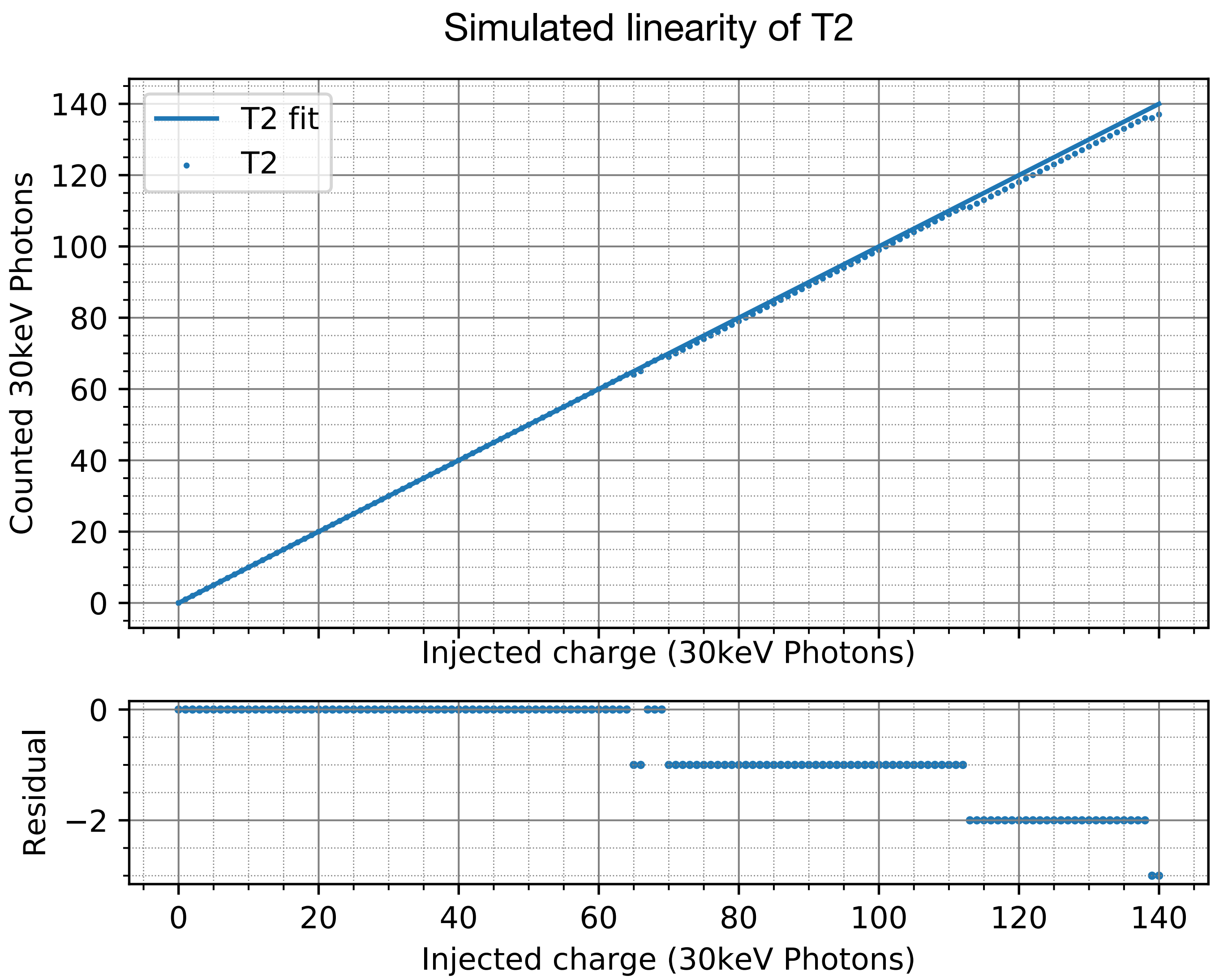
Frontend Counting Linearity Measurement





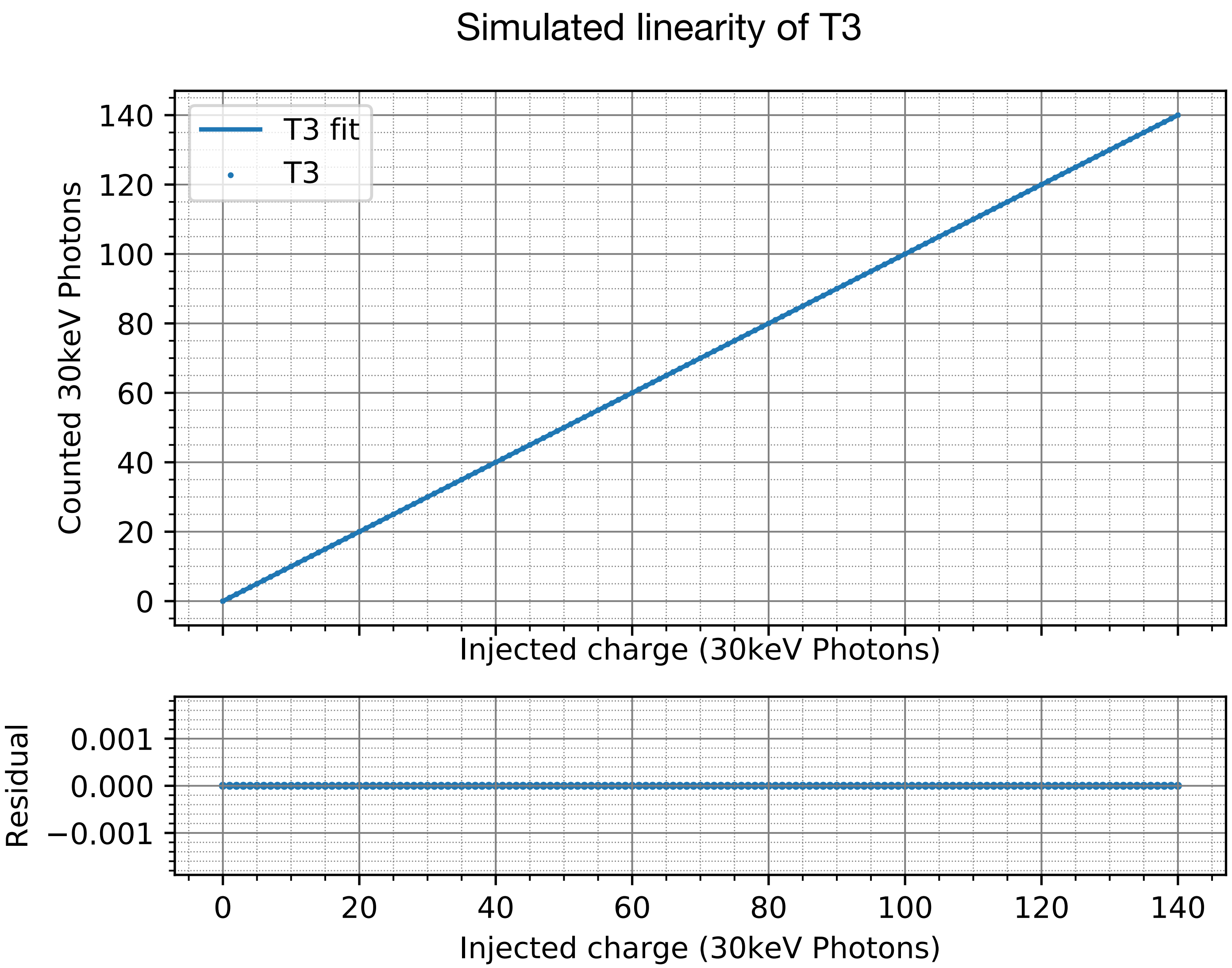
- At ~42 injected γ_{30keV} the output voltage of the first stage is at the supply voltage (saturation)
- In first order: Frontend is robust against CSA saturation because additional charge is still stored on C_{f1} (it can't go anywhere else)
- If we go too far: Nonlinearities in charge pump cause error in measurement
- **Important:** Most of the experiments will be below 42 γ_{30keV} at the same time

Frontend Counting Linearity

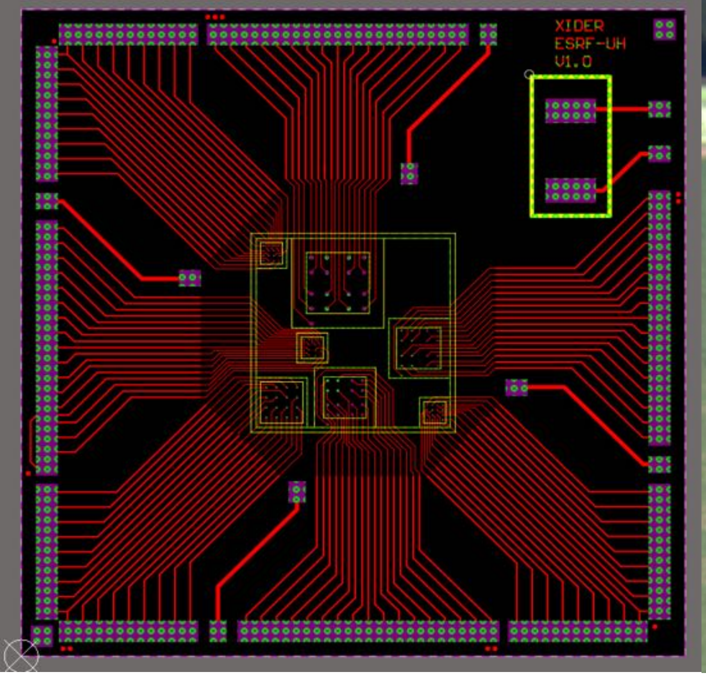


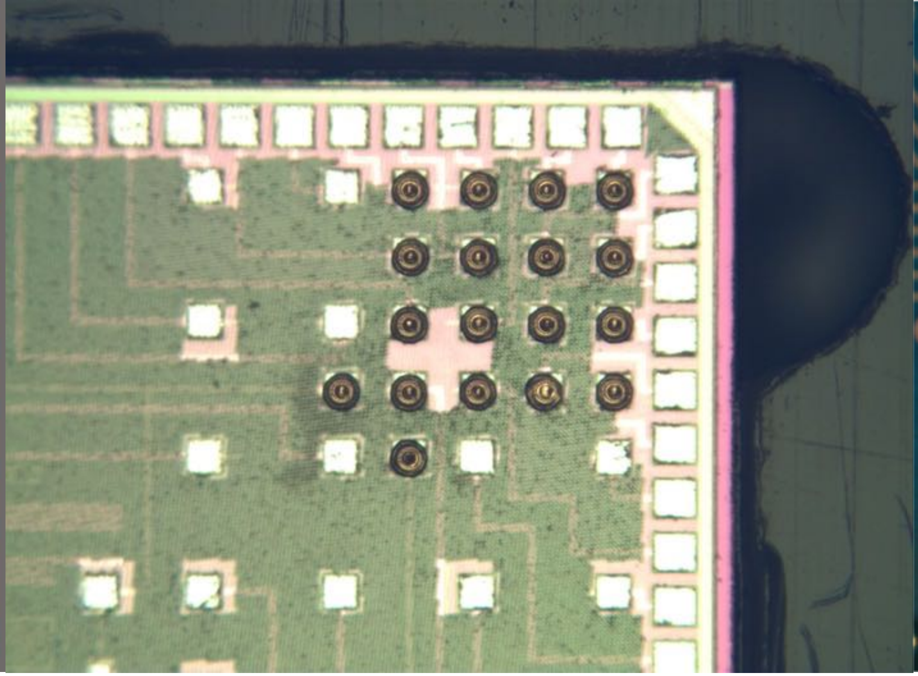
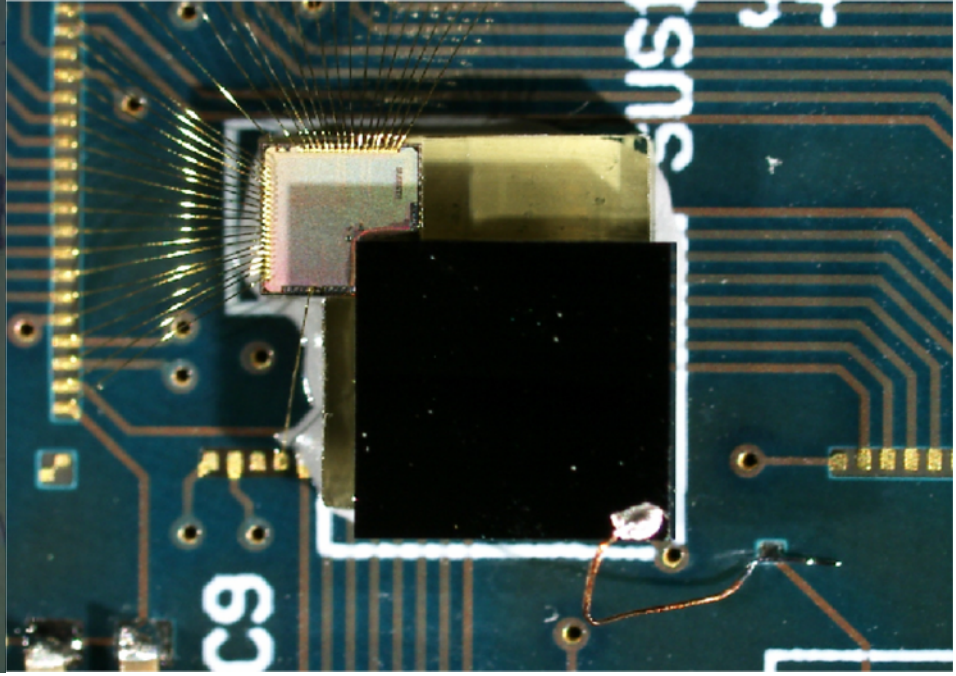
- Simulation shows similar behaviour:
  - Below $70\gamma_{30\text{keV}}$ the frontend is linear
  - For 140 injected $\gamma_{30\text{keV}}$ the deviation is 3 ADU
- Side note: This is without noise!

Frontend Counting Linearity



- Fixing parasitic effects in charge pump yields perfect linearity from 0 to 140 injected 30keV photons according to simulation (without noise!)
- Needs to be verified in lab measurement



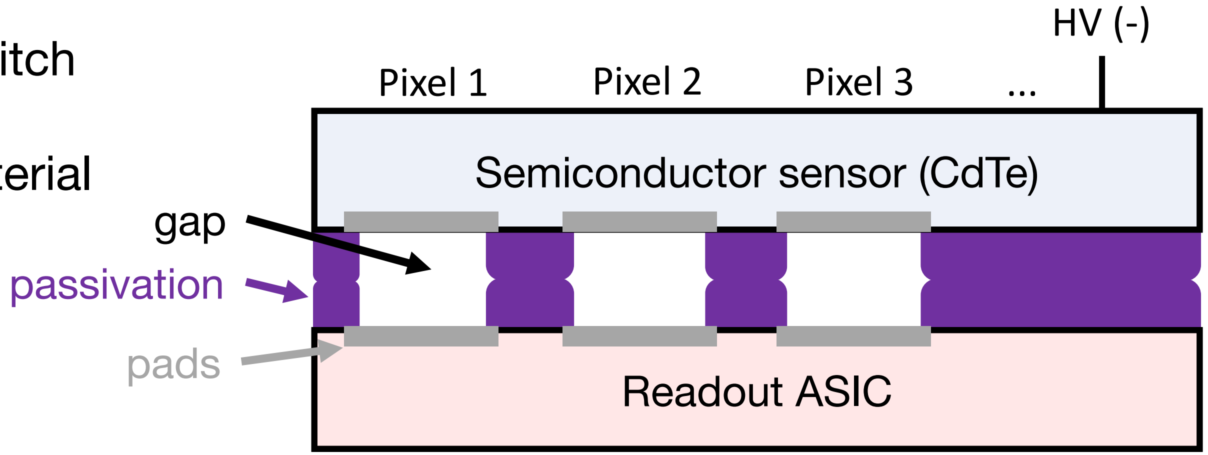



Sensor/ASIC Assembly Prototypes

Challenges for ASIC/Sensor Interconnection

- Plan: Pixelwise flip-chip interconnection with 100µm pitch
- Need to fill gaps in between pads with conductive material
- Problems with CdTe:
  - No high temperatures (>80°C)
  - No mechanical pressure

⇒ Soldering is out of question

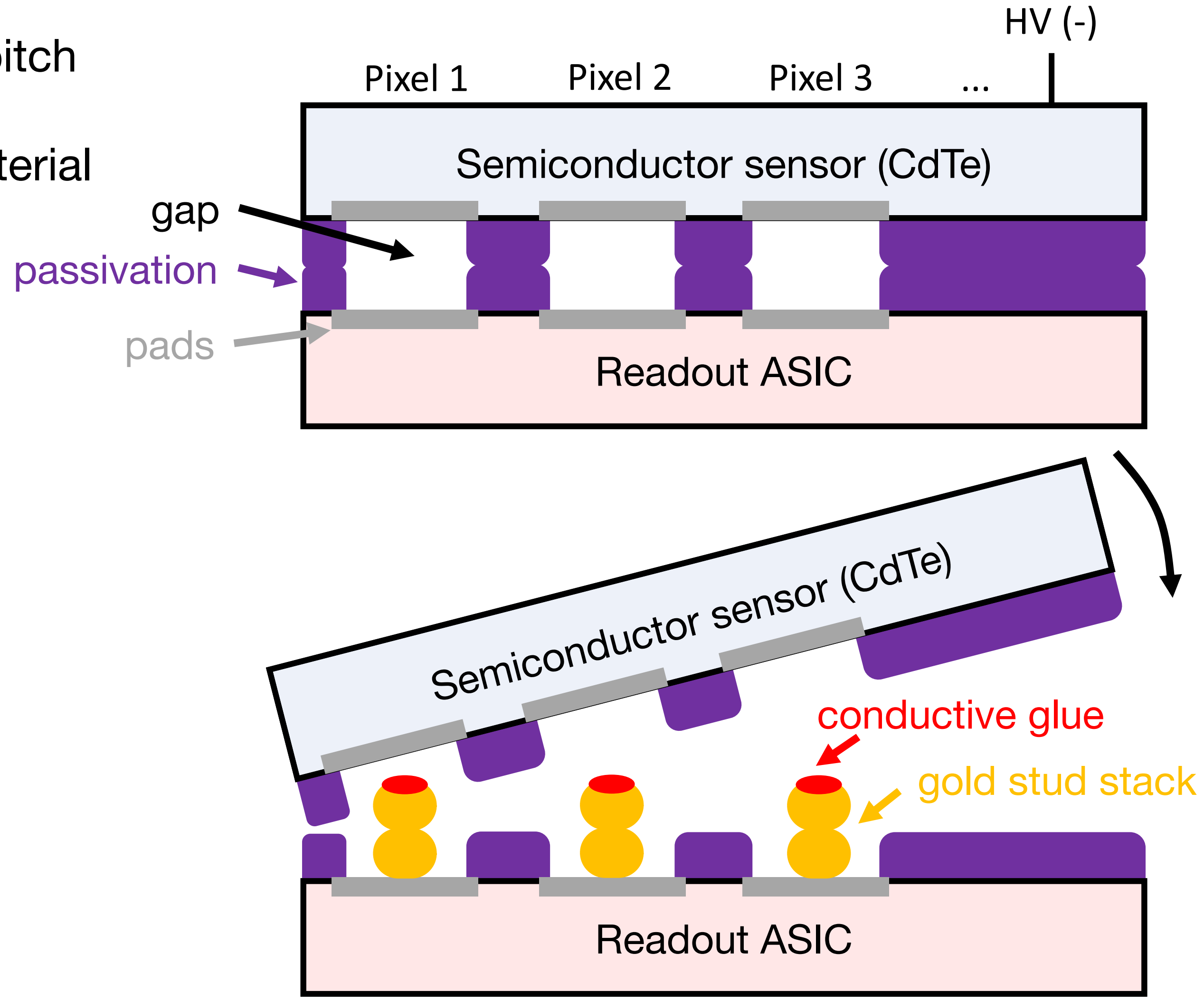


Challenges for ASIC/Sensor Interconnection

- Plan: Pixelwise flip-chip interconnection with 100µm pitch
- Need to fill gaps in between pads with conductive material
- Problems with CdTe:
  - No high temperatures (>80°C)
  - No mechanical pressure

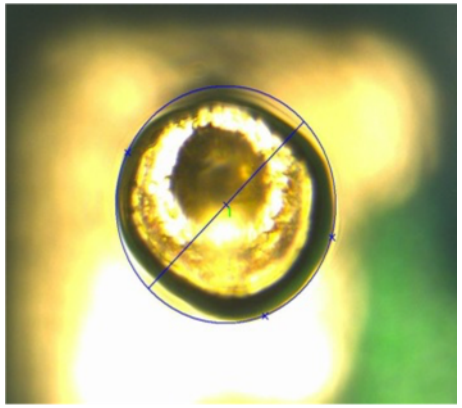
⇒ Soldering is out of question

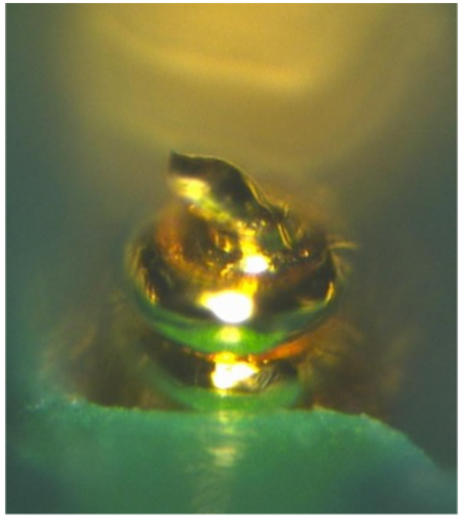
- Solution proposed and carried out by Christian Kreidl:
  - Place stack of gold studs on ASIC to fill gaps
  - Dip gold stud tips in conductive glue that cures at room temperature
  - Flip sensor on top



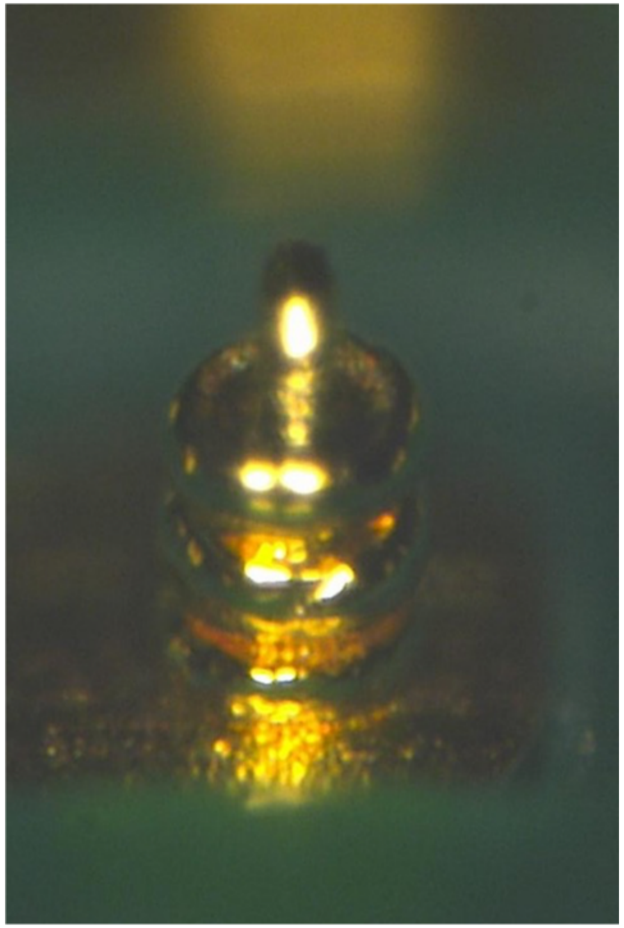
ASIC/Sensor Interconnection

top view of 2 stacked gold studs, 80μm diameter





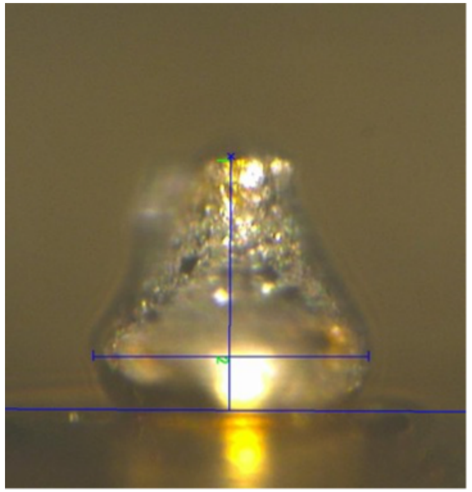
2 stacked gold studs with tail



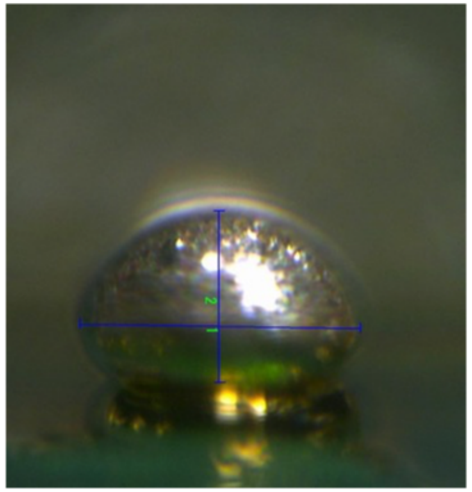
3 stacked gold studs with tail

1 gold stud with glue

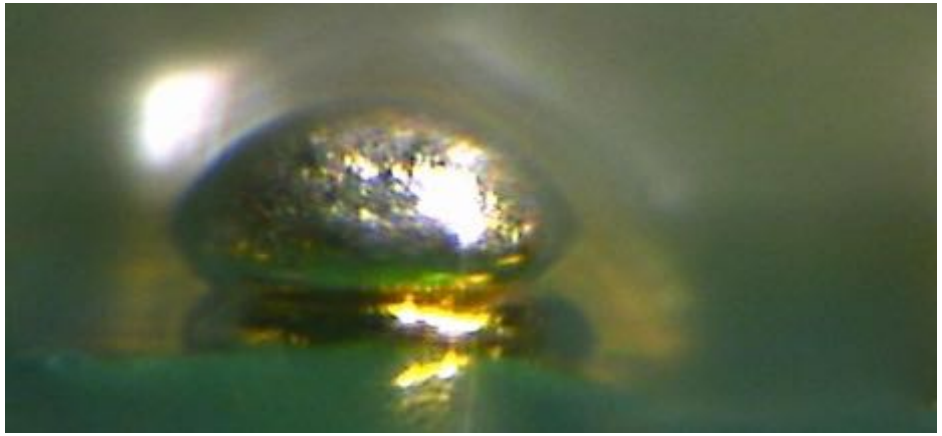
height: 80μm
width: 78μm



2 gold studs with glue

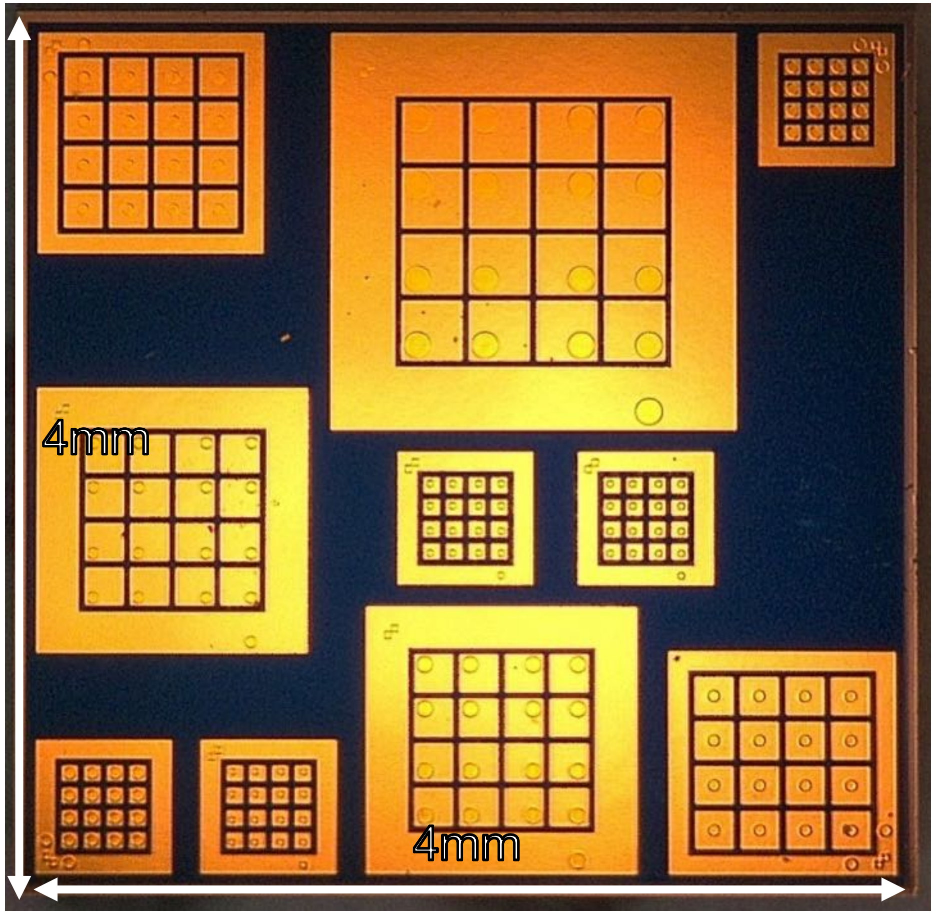


height: 83μm
width: 57μm



2 gold studs with glue

"Front" of CdTe prototype sensor

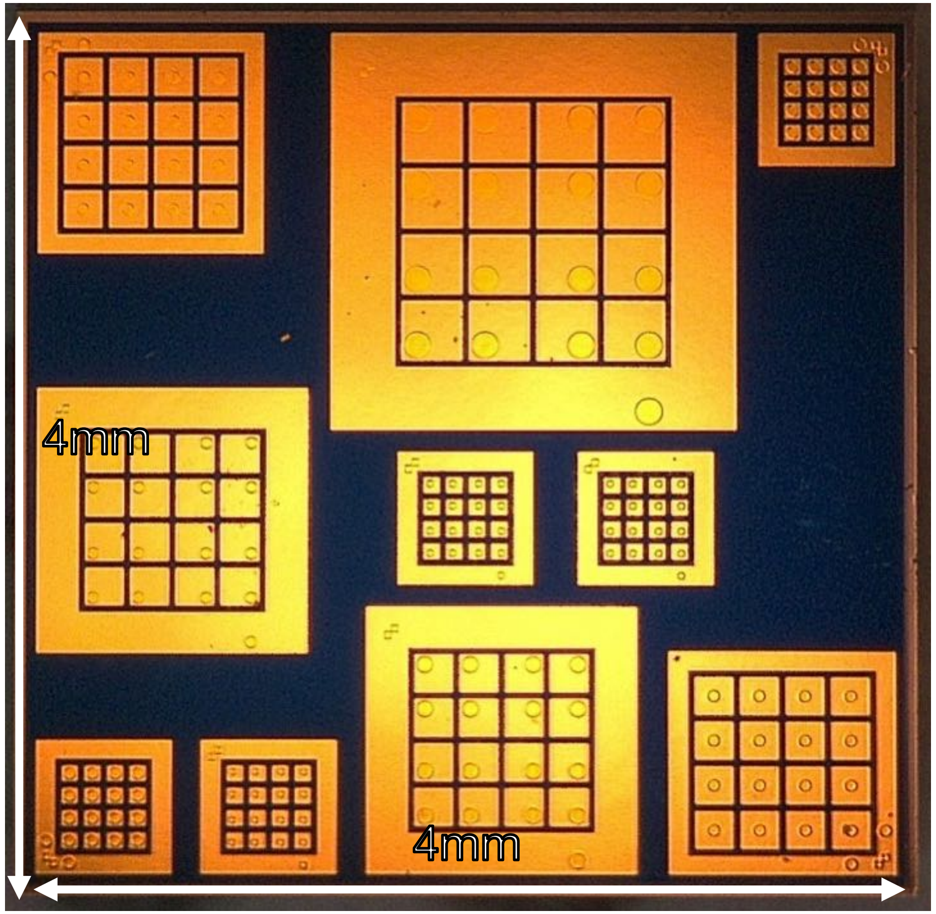


Design by ESRF, manufactured by Acrorad

4x4 pixel test structures with guard ring and different pixels sizes and pitches (100µm, 200µm & 300µm)

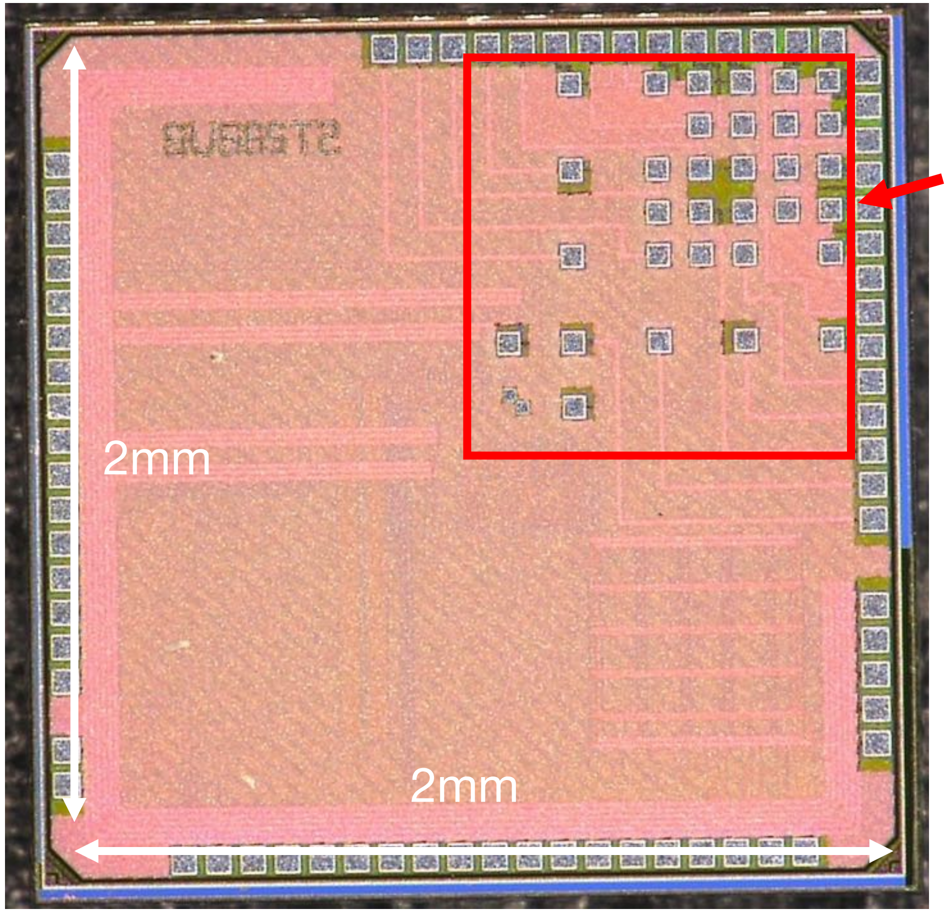
ASIC/Sensor Interconnection

”Front” of CdTe prototype sensor



Design by ESRF, manufactured by Acrorad

Top of ASIC prototype SUS65T2

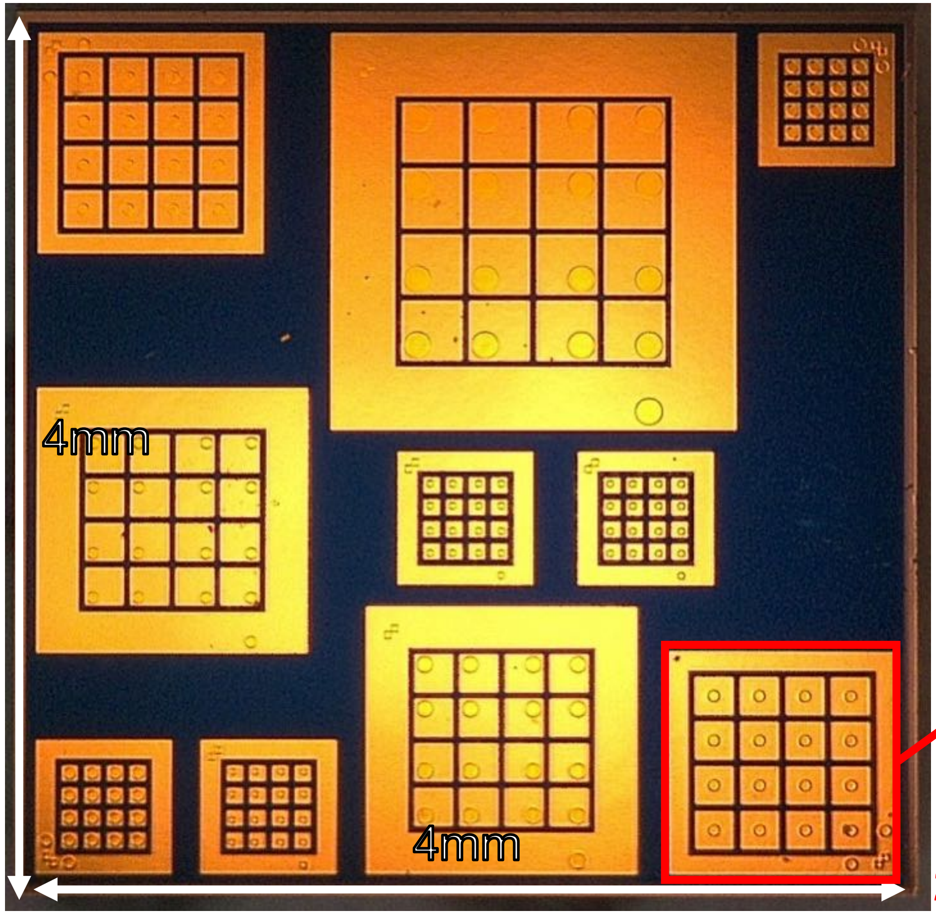


Bump-bond interconnection area for 100µm and 200µm pixel pitch

Design by HD, manufactured by TSMC

ASIC/Sensor Interconnection

”Front” of CdTe prototype sensor

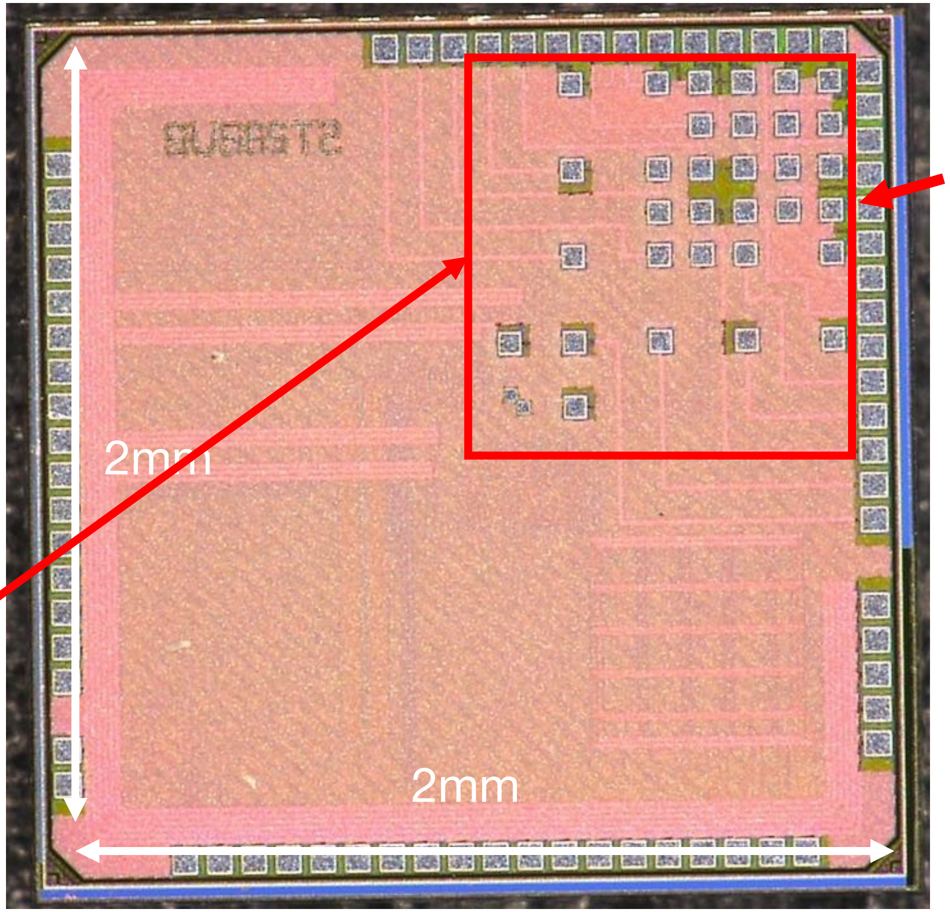


Design by ESRF, manufactured by Acrorad

Flip on top

200µm pitch

Top of ASIC prototype SUS65T2

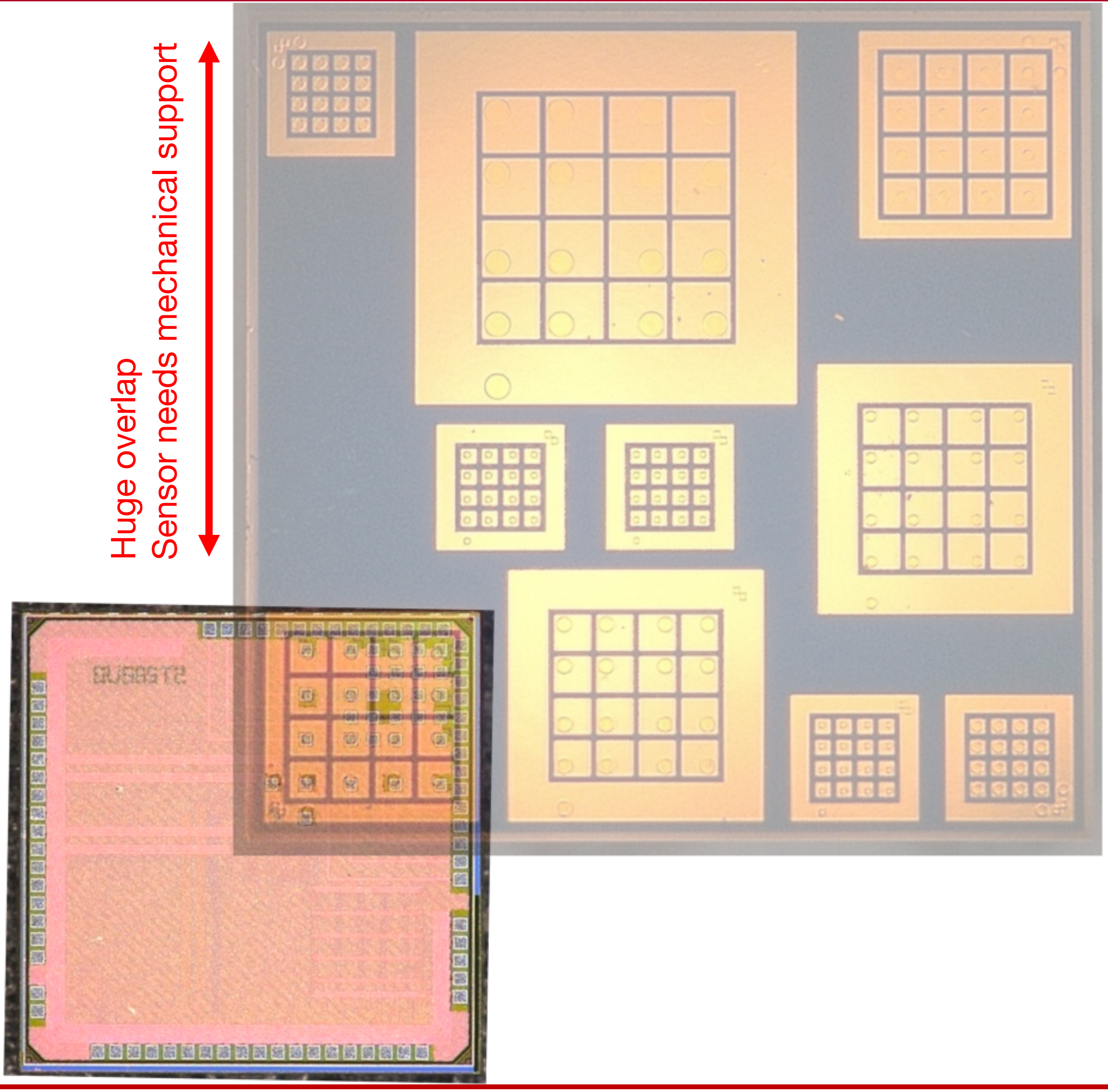


Bump-bond interconnection area for 100µm and 200µm pixel pitch

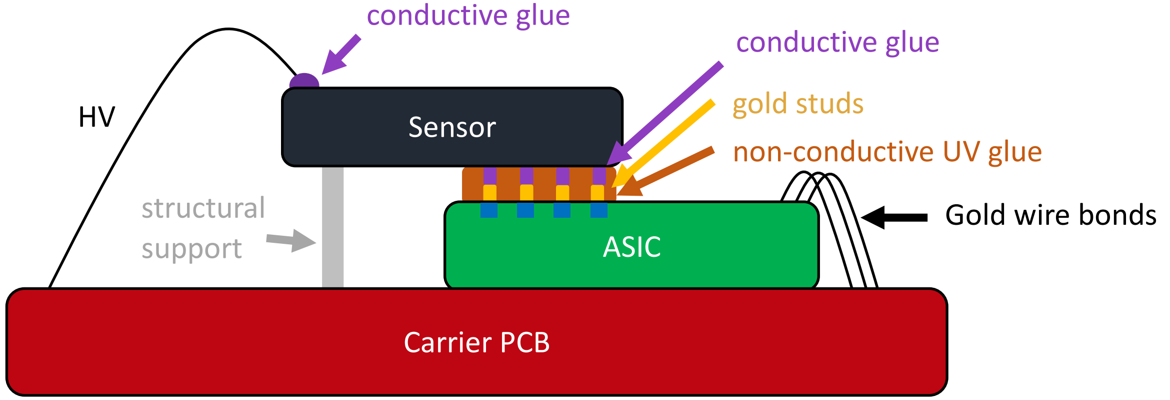
Design by HD, manufactured by TSMC

ASIC/Sensor Interconnection

Huge overlap
Sensor needs mechanical support

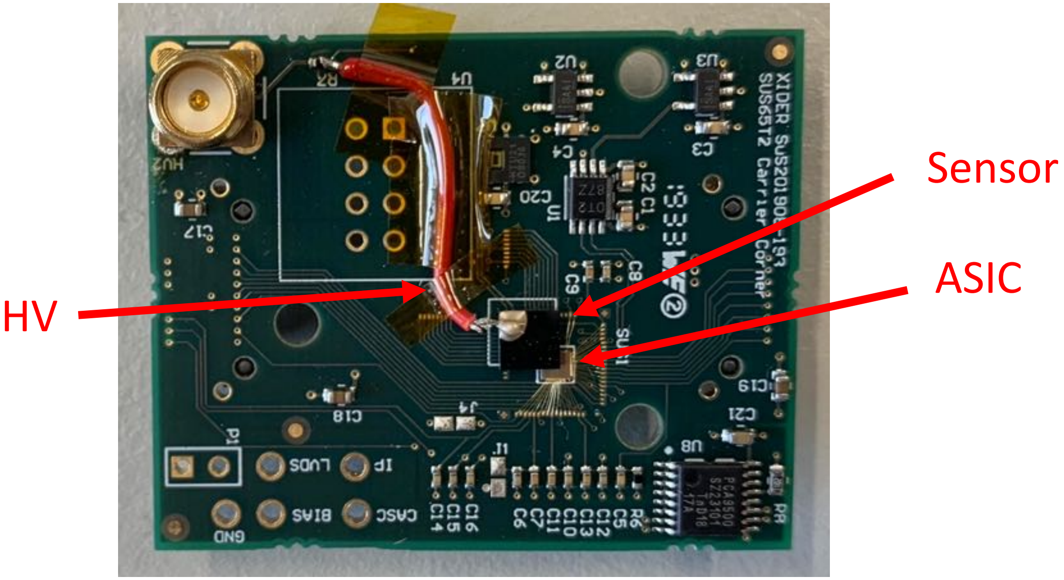


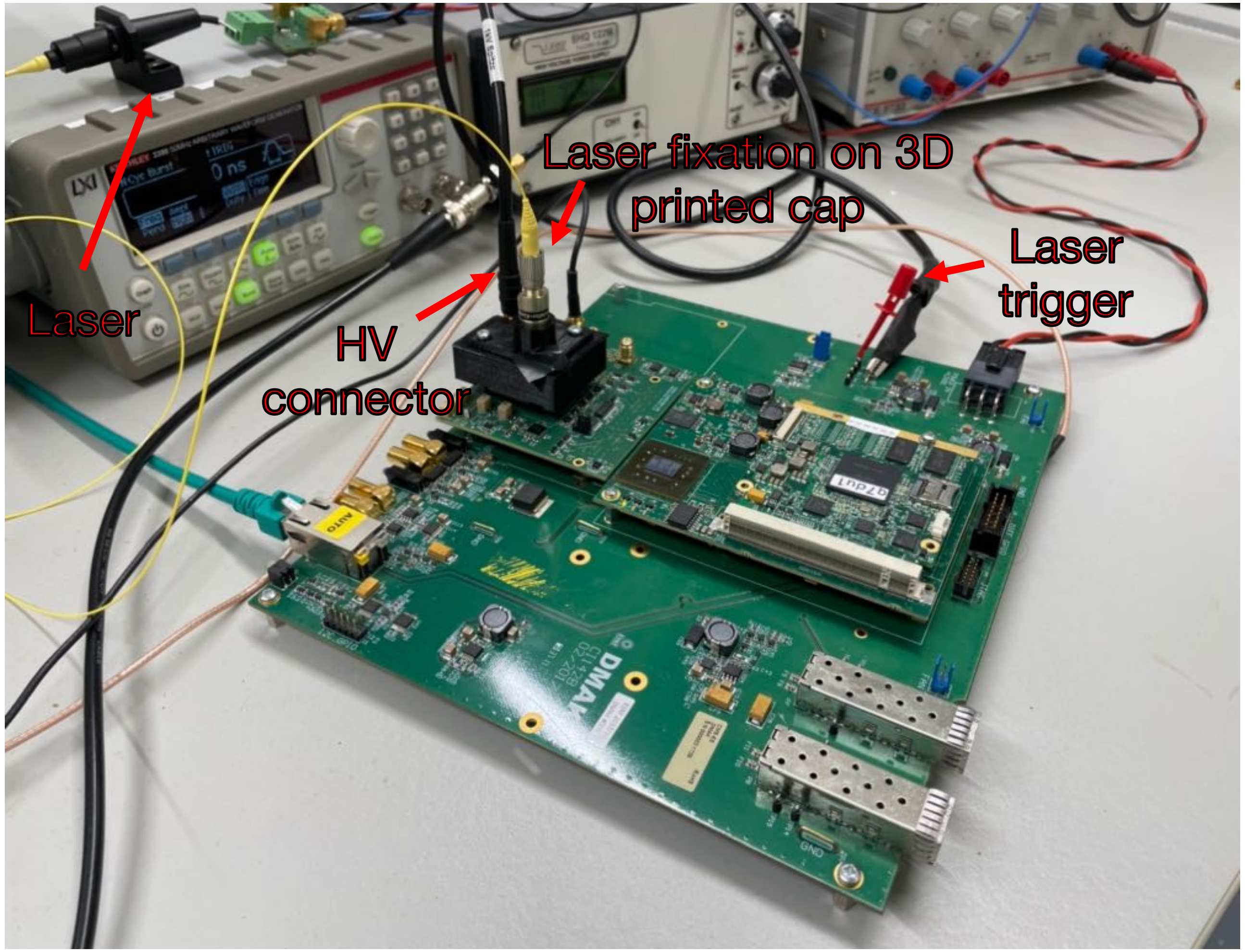
Schematic of ASIC/Sensor assembly on carrier PCB

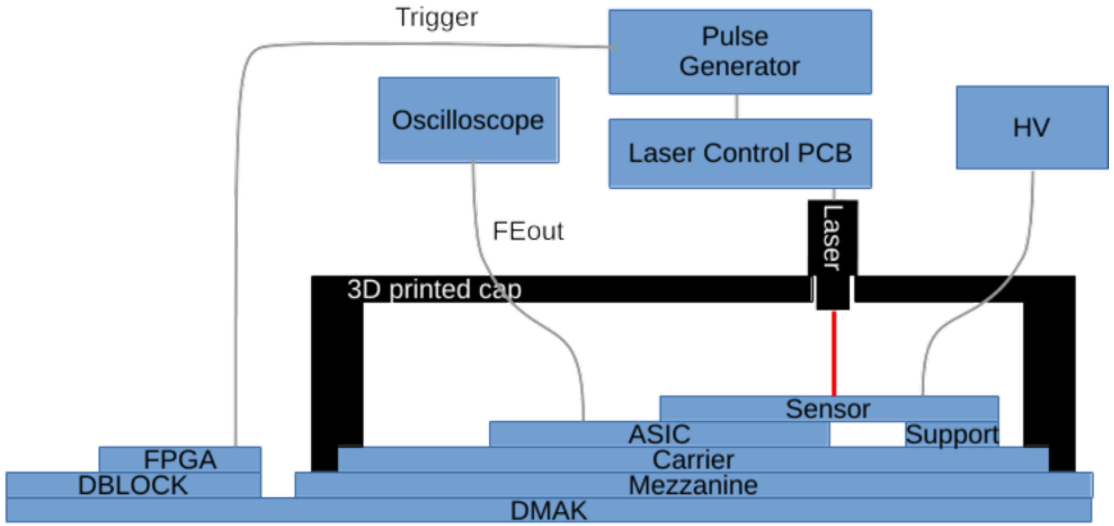


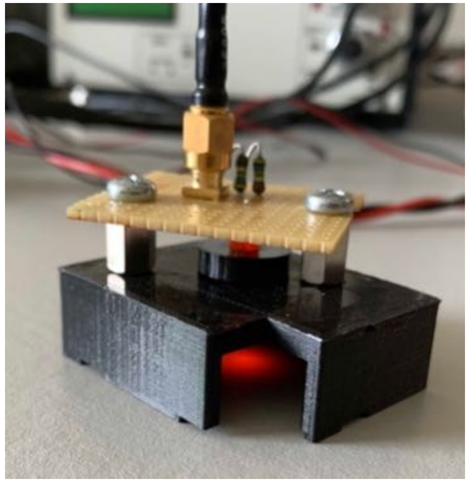
Carried out by Christian Kreidl

After almost one year of trying: Our first ASIC/Sensor assembly built in-house!







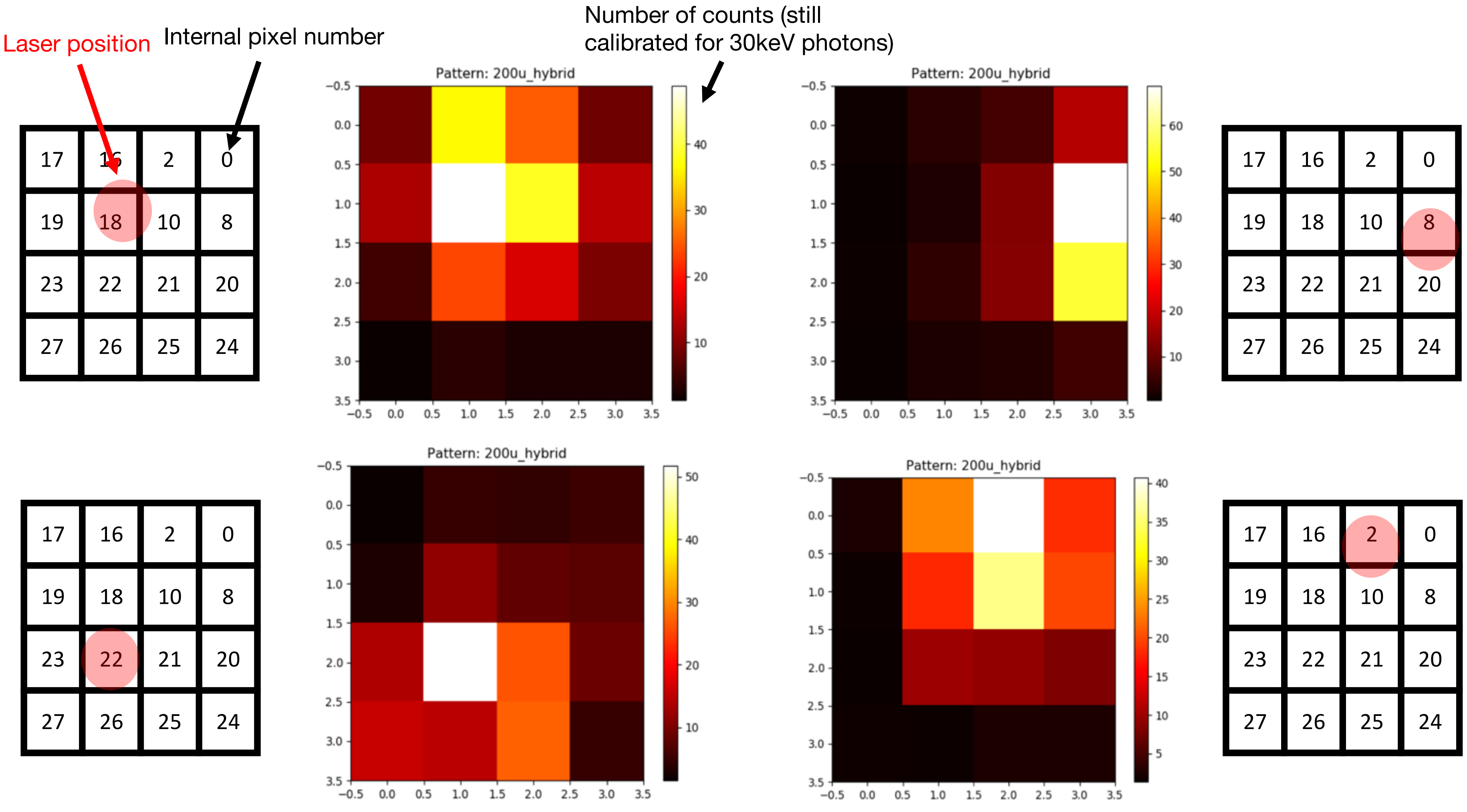


Unmounted 3D-printed cap with LED

Mounted cap on carrier PCB

Sensor Measurements: 2D Image

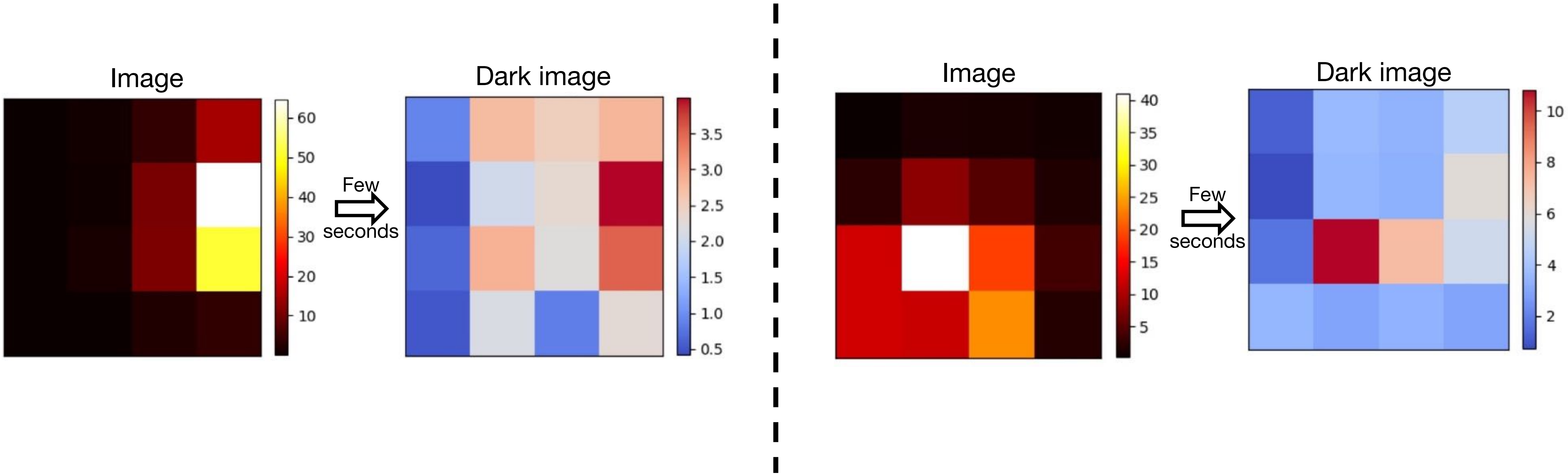
- Our first images taken with an actual CdTe sensor! (**2020 milestone**)
- Proof for basic functionality of:
  - Sensor prototype
  - ASIC/Sensor interconnection
  - ASIC (Frontend, control, data readout, ..)



Sensor Measurements: 2D Image

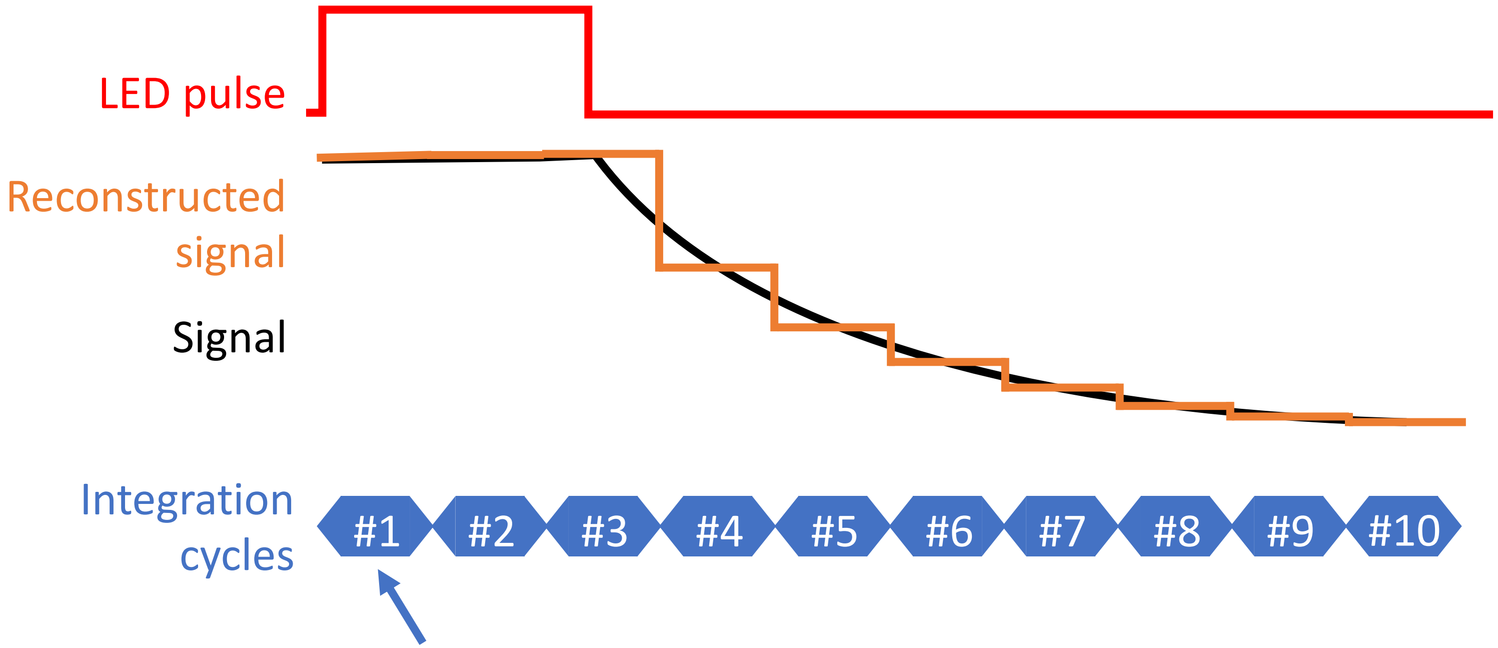
- But: Even seconds after taking an image, we still see a signal

  ⇒ Afterglow of CdTe Sensor



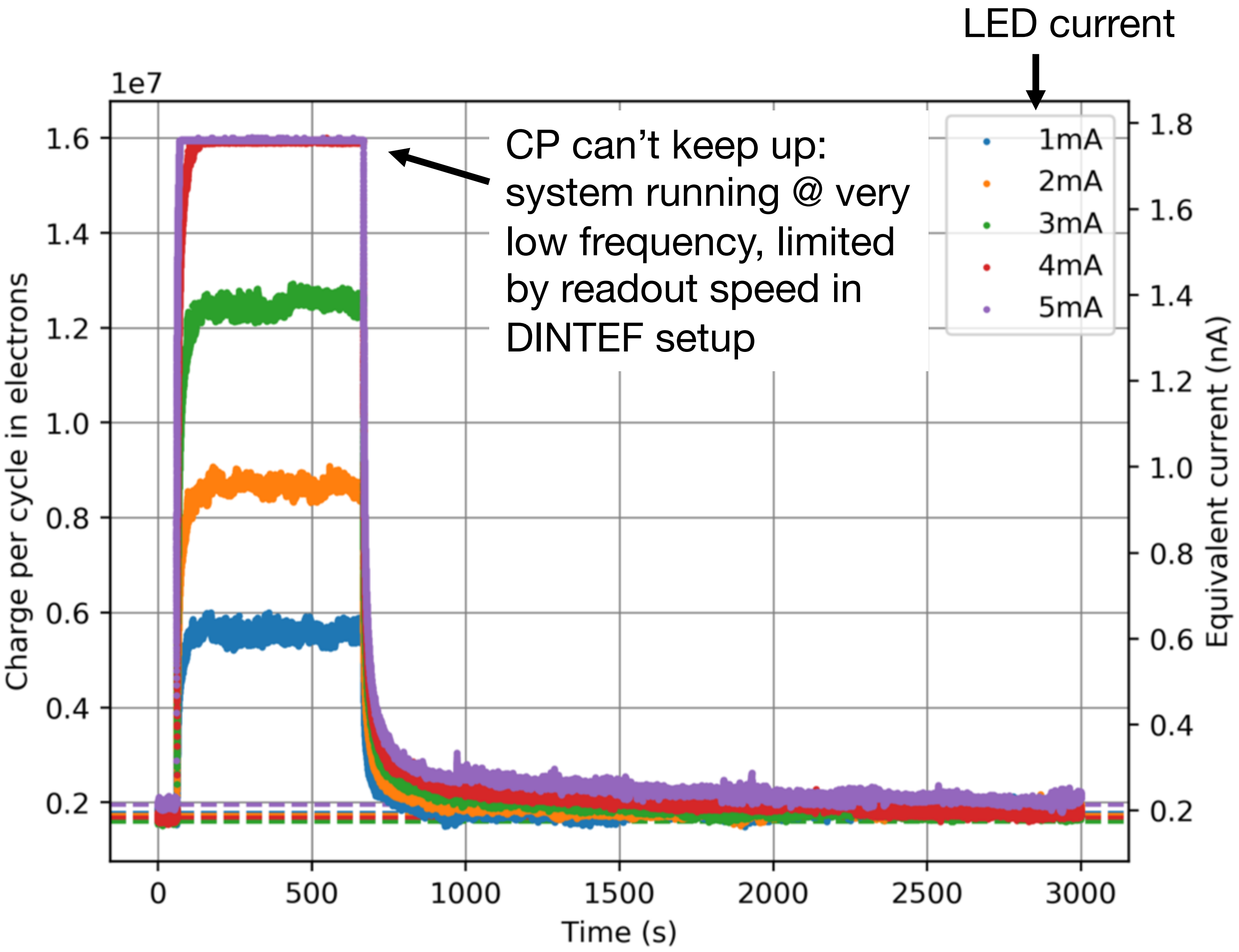
Sensor Measurements: Afterglow

- Return to single pixel measurement
- Idea:
  - Shine LED on sensor for 10 minutes
  - Turn off LED
  - Measure signal troughout LED pulse & afterglow for 5 hours
- Aim:
  - Study time dependency of afterglow (does it depend on intensity of LED irradiation?)



Size can be chosen in a wide range depending on input clock.
E.g. with 1MHz: 75us-2.2ms
In this measurement: 1.5ms

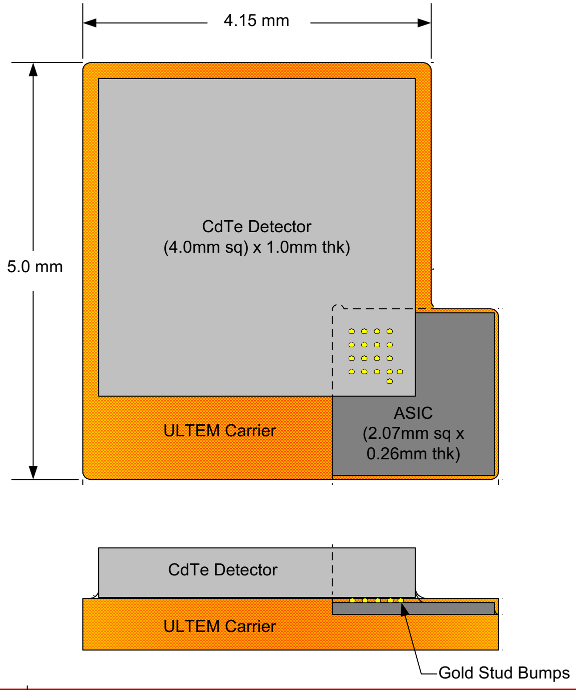
Trade-off between time resolution and signal sensitivity

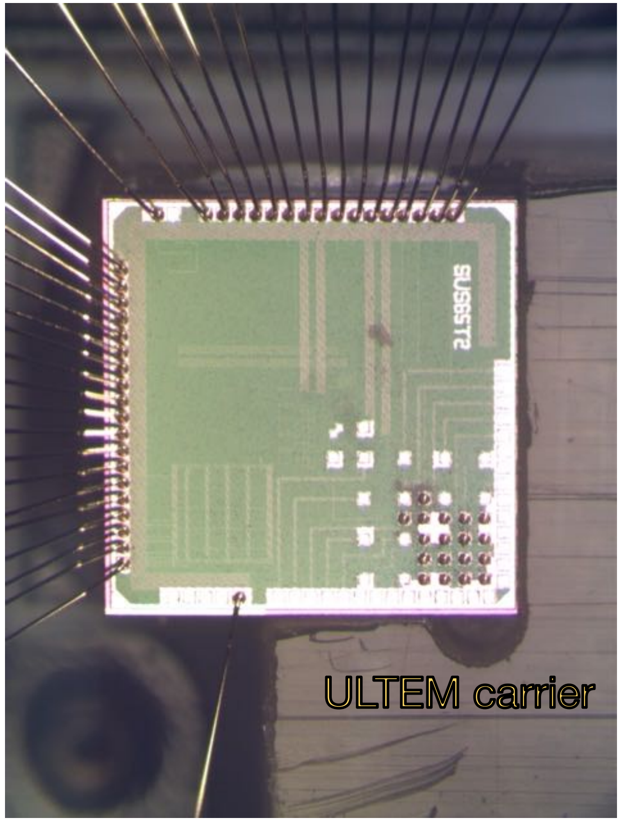


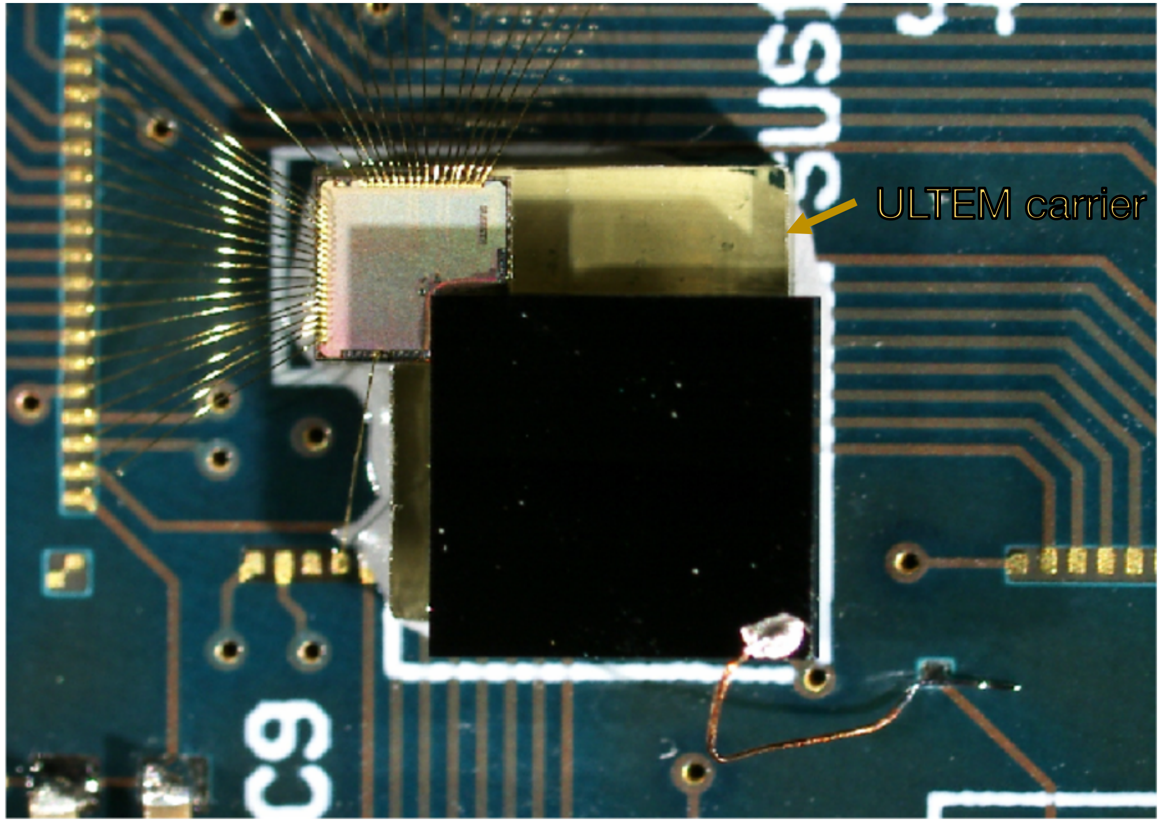
- Even 30 minutes after LED irradiation, afterglow is still visible!
- Might be a show stopper for single photon sensitivity after high photon flux
- Needs further investigation (Marin Collonge)

New ASIC/Sensor Assemblies

- After more than a year, we finally found a commercial solution (Polymer Assembly Technology) for CdTe/ASIC interconnection
  - Sensor prototype is supported by a plastic carrier
  - First tests look very promising







Summary

- XIDer is a multi-purpose detector for time-resolved x-ray experiments at the ESRF
- Uses unconventional approach to combine single photon sensitivity and high dynamic range
- My tasks:
  - Design and characterise the readout ASIC
  - Verify feasibility
  - Develop design concepts for large scale integration
- ASIC prototypes SUS65T1, SUS65T2 and SUS65T3 have been characterised and show very satisfying performance
- No show stopper on chip side (yet)
- First sensor measurements after long interconnection struggle
- Is sensor material good enough? Should we start with Silicon? Hope for CZT...

Planned Future Steps

- Solutions for large scale system integration (partially done):
  - Frame-wise frontend commands (called telegram)
  - Data storage
  - Design of output data links for high data rates (several tens of GB/s)
  - Automated frontend calibration, maybe via on-chip processor
- Array compatible layout
- Characterise sensor with new sensor/ASIC assemblies
- Perform beamline measurements at ESRF with Sensor/ASIC assemblies
- Use sensor measurement findings to further refine ASIC design
- Design first draft of final detector module
- Design ”final testchip”

Backup

Synchrotron Radiation Brilliance

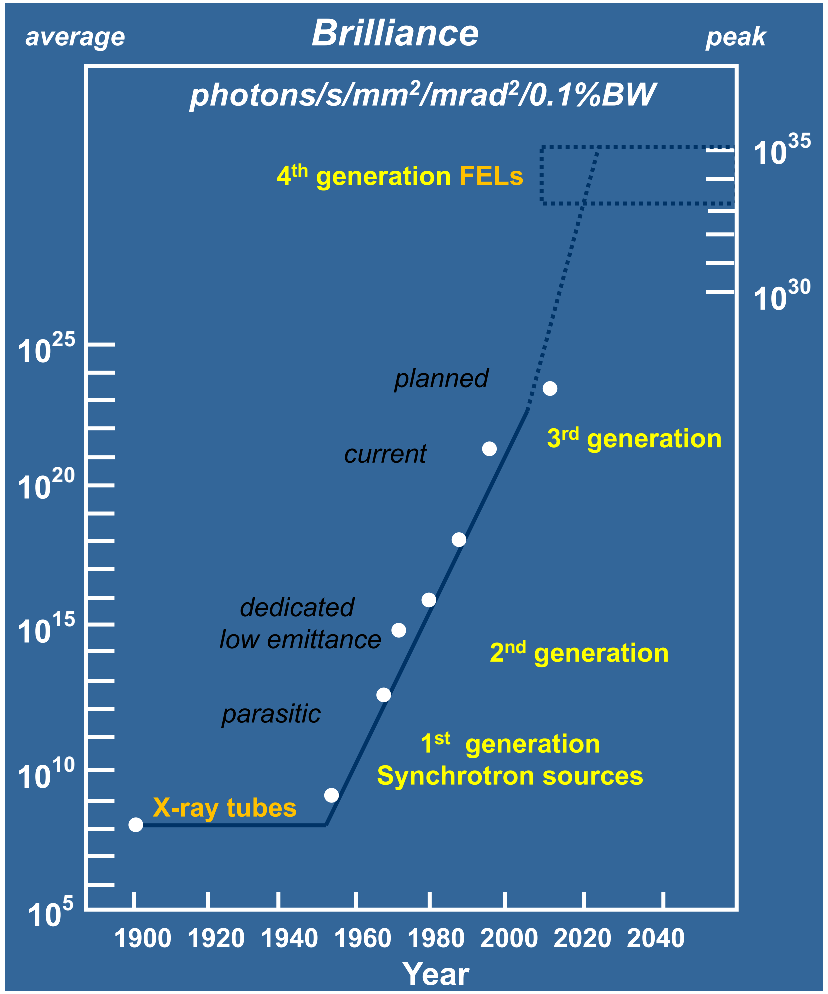
$$\textbf{SR Brilliance} = \frac{\text{photon flux}}{(\Delta A)\ (\Delta\Omega)\ (\Delta\lambda/\lambda)}$$

source area (ΔA), solid angle (ΔΩ), spectral interval (Δλ/λ)

- **The** figure of merit for a synchrotron‘s performance
- High brilliance ≙ high flux of useful photons at the sample and detector

Synchrotron Generations

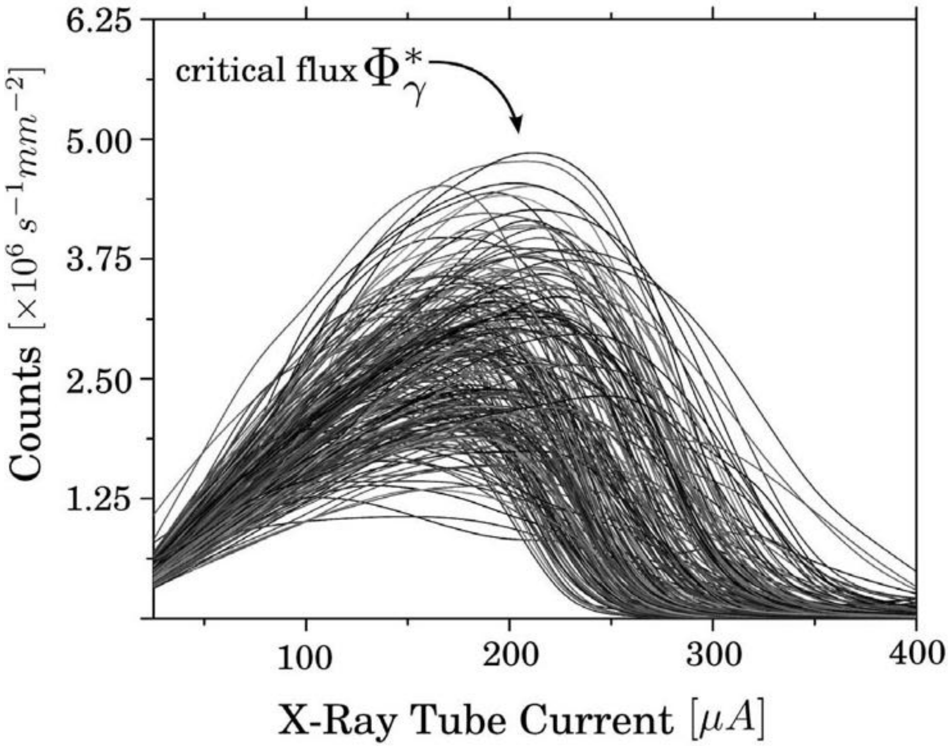
- 1st : Particle accelerators that generate synchrotron light as a parasitic effect
- 2nd : Dedicated synchrotron light production
- 3rd : Higher brilliance by introducing insertion devices (wigglers/undulators)
- 4th : Even higher brilliance and coherence



Taken from H. Shiraki et al „THM growth and characterization of 100 mm diameter CdTe single crystals“, IEEE Trans. Nucl. Sci, vol. 54, pp. 117-1723, 2009

- 100mm diameter, 300mm length

Count rate collapses for high photon fluxes:

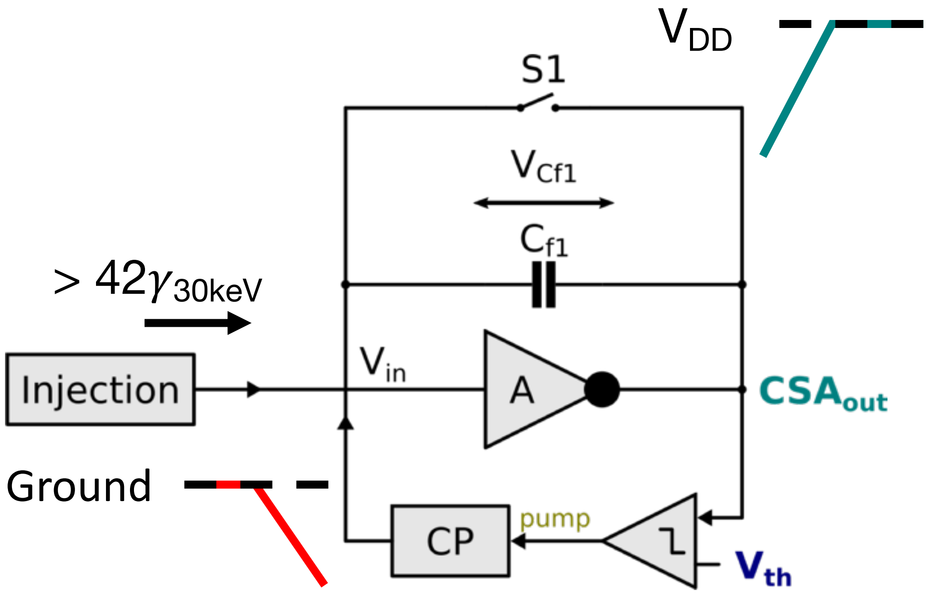


Taken from „Nature of polarization in wide-bandgap semiconductor detectors under high-flux irradiation: Application to semi-insulating $Cd_{1-x}Zn_xTe$“ (D. S. Bale, C. Szeles, Phys. Rev. B, 2008)

Frontend Counting Linearity

- Charge integration is still working due to charge conservation:
  - Injected charge has no other path to flow off
  - Charge has to be stored on C_{f1} following $Q = C_{f1} \cdot V_{Cf1} = C_{f1} \cdot (CSA_{out} - V_{in})$
  - CSA_{out} can't increase any further, so **V_{in} decreases instead**
- In first order, this does not affect the measurement:
  - The continuous conversion only cares about the actual charge, not the voltages

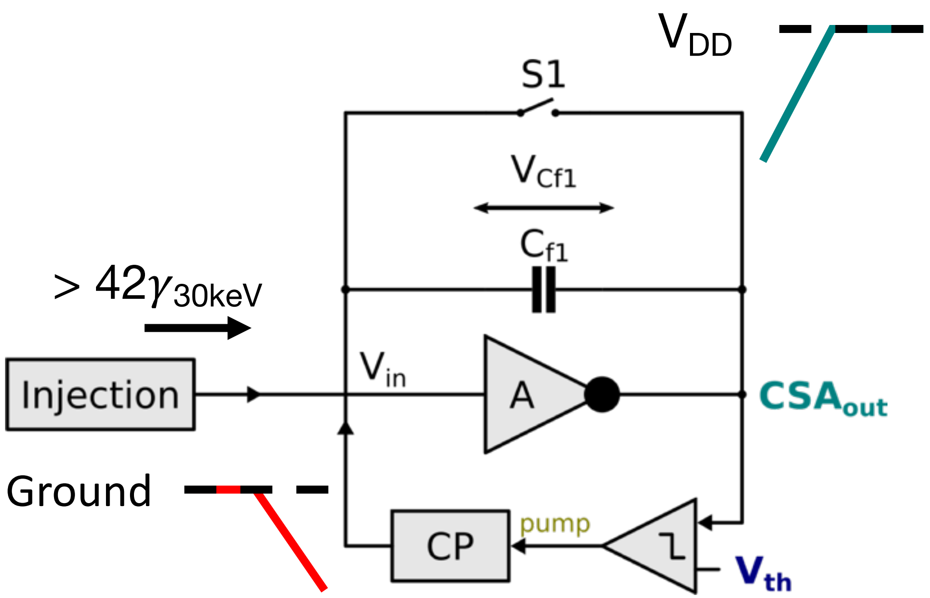
$\Rightarrow$ Frontend still linear beyond injected charge of $42\gamma_{30keV}$



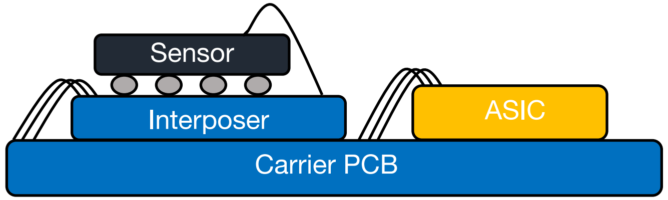
- Charge integration is still working due to charge conservation:
  - Injected charge has no other path to flow off
  - Charge has to be stored on C_{f1} following $Q = C_{f1} \cdot V_{Cf1} = C_{f1} \cdot (CSA_{out} - V_{in})$
  - CSA_{out} can't increase any further, so $\mathbf{V_{in}}$ **decreases instead**
- In first order, this does not affect the measurement:
  - The continuous conversion only cares about the actual charge, not the voltages

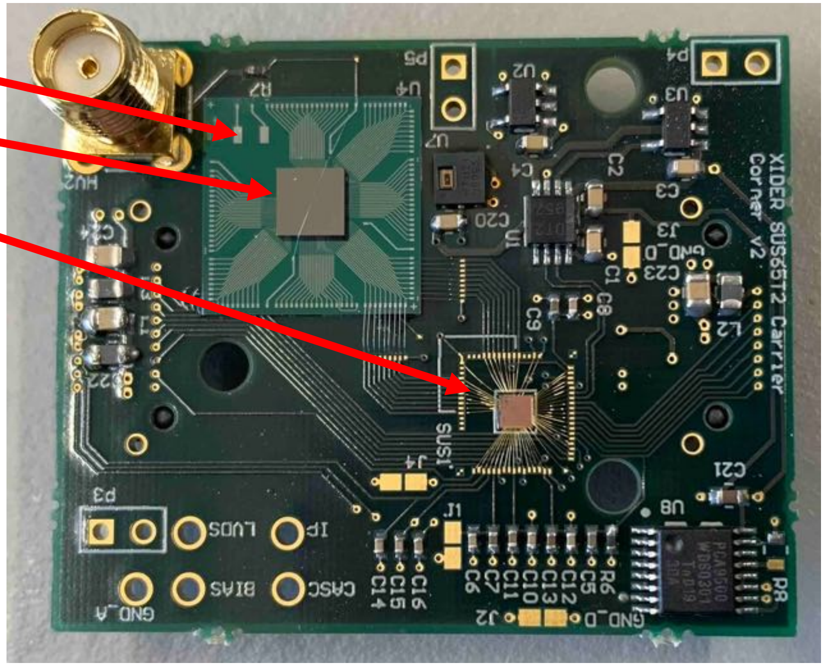
  $\Rightarrow$ Frontend still linear beyond injected charge of $42\gamma_{30keV}$
- But: If V_{in} drifts off too far, the charge package size begins to change because of parasitic charge injection effects in the charge pump

  $\Rightarrow$ Bend of the curve above roughly $80\gamma_{30keV}$

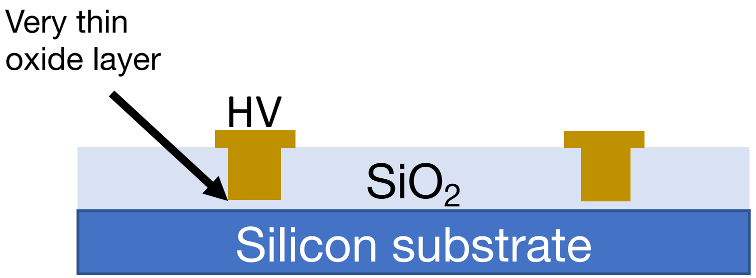


Failure Example: Sensor Interposer

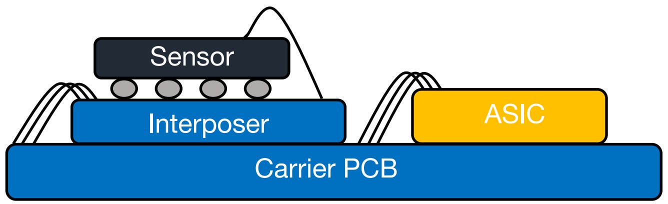


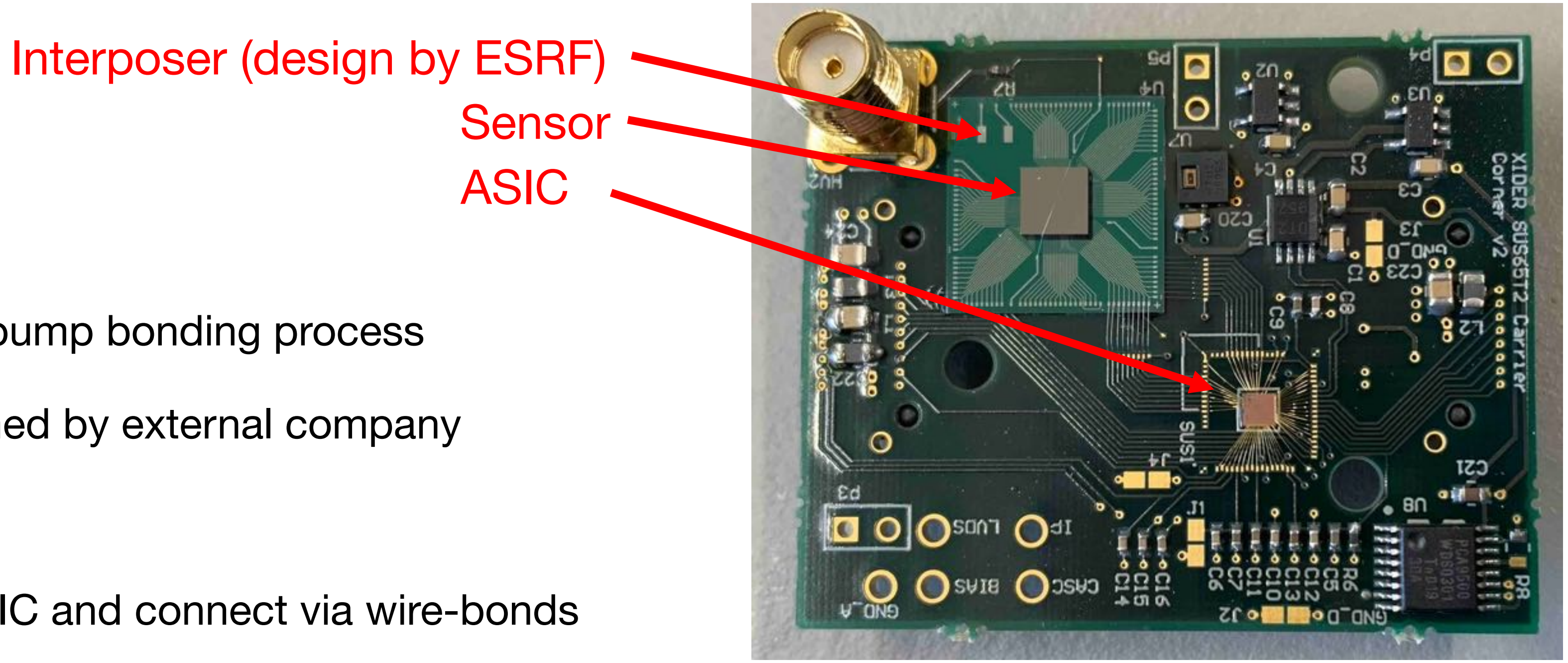


- Use sensor interposer (silicon) for easier bump bonding process
- Sensor/interposer bump bonding performed by external company
- Glue and wire bond interposer to PCB
- Route sensor pixel outputs on PCB to ASIC and connect via wire-bonds
- Interposer needed Al-bonds (which we can't do in-house)
  - ⇒ Ask Ralf Achenbach from KIP for help
- Unfortunately: The interposer pad insulation is too weak to carry sensor HV (500V), even though the manufacturer knew that we route the HV across the interposer
  - ⇒ Every interposer in use breaks down as soon as sensor HV is applied



Failure Example: Sensor Interposer





- Use sensor interposer (silicon) for easier bump bonding process
- Sensor/interposer bump bonding performed by external company
- Glue and wire bond interposer to PCB
- Route sensor pixel outputs on PCB to ASIC and connect via wire-bonds
- Interposer needed Al-bonds (which we can't do in-house)
  - ⇒ Ask Ralf Achenbach from KIP for help
- Unfortunately: The interposer pad insulation is too weak to carry sensor HV (500V), even though the manufacturer knew that we route the HV across the interposer
  - ⇒ Every interposer in use breaks down as soon as sensor HV is applied