The PixFEL project: progress towards a fine pitch X-ray imaging camera for next generation FEL facilities

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on behalf of the PixFEL Collaboration

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The PixFEL Collaboration

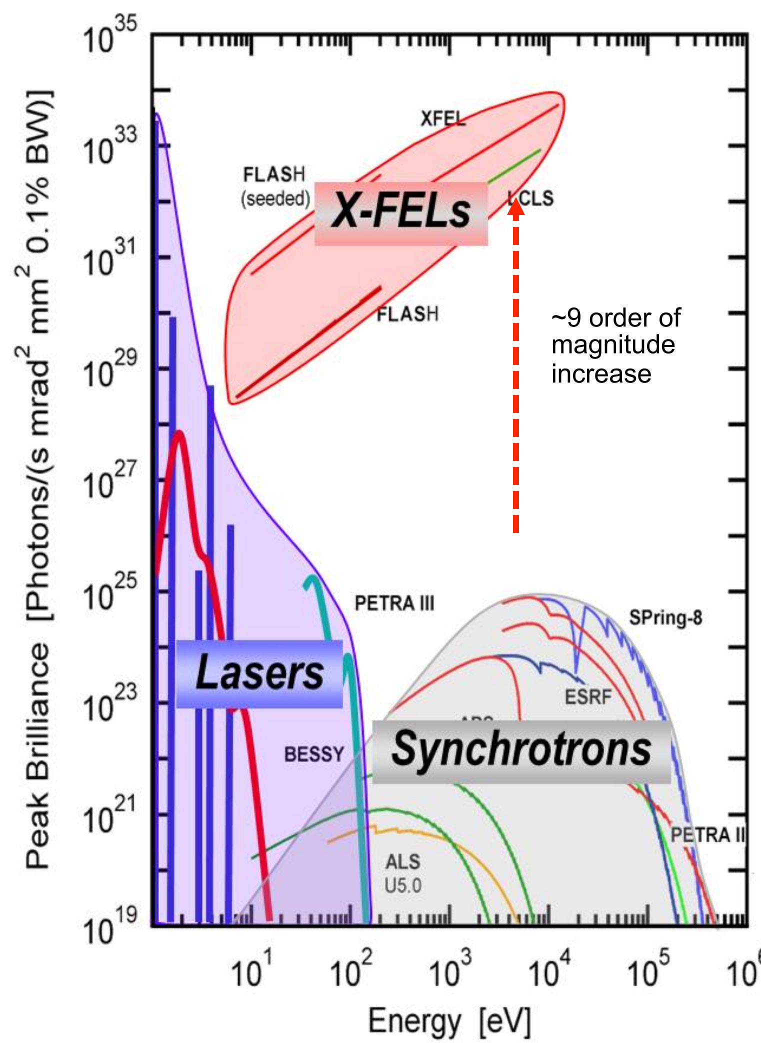
- Develop high performance X-ray imaging instrumentation for experiments at the next generation Free Electron Laser facilities
- Use innovative solutions & technology, now explored in HEP comunity, to improve performance of pixel device for photon science.
- Key technologies: active edge sensors, 65 nm CMOS process, vertical integration
- Important synergy with other activities of the groups involved: LHC upgrade (65 nm, active edge sensor), AIDA (3D vertical integration).

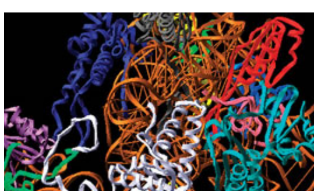
Participating groups

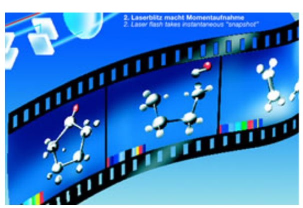
- INFN & University Pavia-Bergamo (L. Ratti, M. Manghisoni, V. Re, G. Traversi, D. Comotti, M. Grassi, P. Malcovati, L. Fabris, L. Lodola)
- INFN & University Pisa (G. Rizzo, G. Batignani, S. Bettarini, G. Casarosa, F. Forti, M. Giorgi, F. Morsani, A. Paladino, E. Paoloni)
- INFN & University Trento (L. Pancheri, G.F. Dalla Betta, R. Mendicino, H. Zu, G. Verzellesi, M. A. Benkechkache)

X-FELs as probing tool

- X-rays have been a fundamental probing tool in many fields since their discovery
- The advent of free electron laser (FEL) facilities opens up new possibilities to probe matter with X-ray beams of unique features:
  - very high intensity, coherent, ultrafast pulses, large energy range
- Broad science program accessible at FELs:
  - Structural biology, Chemistry, Material science Atomic and molecular science (AMO)
- A number of facilities already operational (LCLS, FLASH, SACLA, FERMI), other being built (Eu-XFEL, SwissFEL) or upgraded (LCLS!LCLSII)



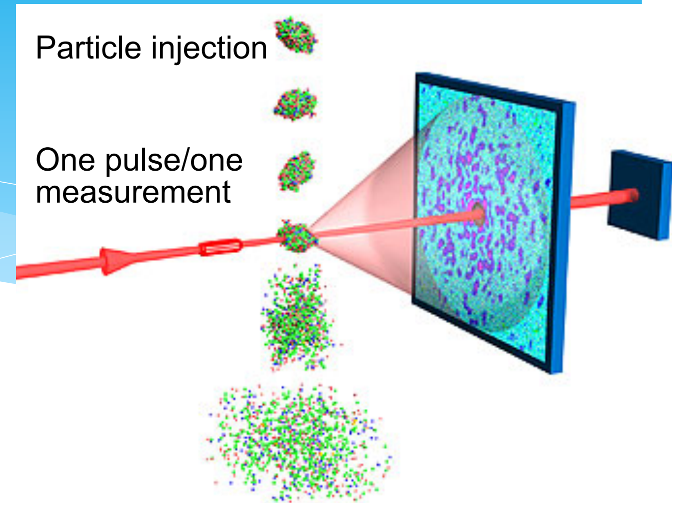

Deciphering the structure of biomolecules…


Filming chemical reactions…

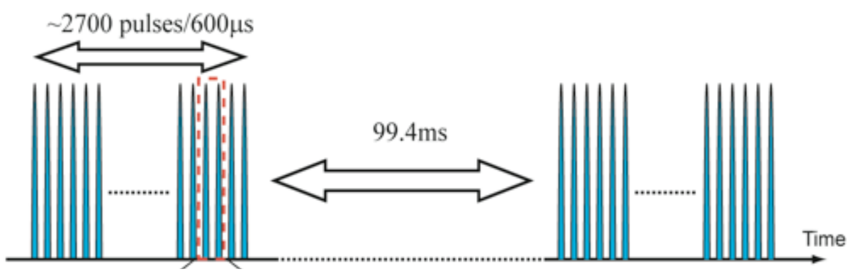

Investigating extreme states of matter…

2D Imaging X-ray FEL detector challenges

- Many measurements based on scattering of coherent X-ray pulses and detection of diffraction pattern with a large pixel camera.



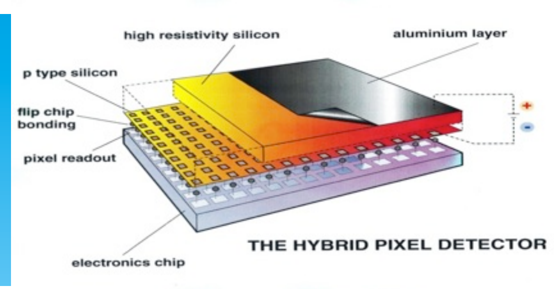
Eu-XFEL-Pulse structure



- FEL Pulse Structure
  - Single shot imaging within 220 ns (4.5MHz-pulse repetition rate Eu-XFEL)
  - Burst operation mode (Eu-XFEL)
  - Continous operation mode (LCLSII up to 1MHz!)
- Dynamic Range
  - Single photon counting
  - Up to 10^4 ph/pixel/pulse

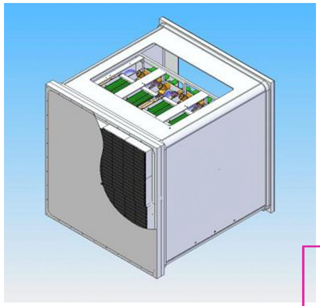
- Sensitive Energy Range
  - 0.25-25 keV ideally with the same system
- Radiation Hardness
  - 10 MGy-1 GGy over 3 years operation
- Pixel size:
  - 700-20 μm, depending on distance & angular resolution required
- Large area coverage:
  - multiple tiles with no dead area

Overview of Eu-XFEL 2D imaging detectors



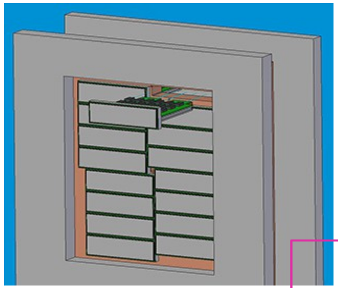
- Well advanced projects based on high Ω hybrid pixels
- Modular detectors with dead area ~ 15%
- PixFEL aims to improve on dead area, pixel size, storage cells with new technologies & adopts an innovative solution for a dynamic signal compression in the front-end

Large Pixel Detector (LPD)



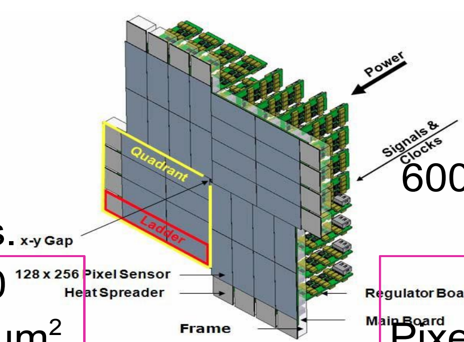
Energy range
5 (1) - 20 keV (25 keV)
Dynamic range
10^5@12 keV
Single Photon Sens.
Storage Cells ≈ 512
Pixel Size 500 x 500 μm^2

AGIPD Adaptive Gain Integrating Pixel Detector (AGIPD)



Energy range
3 - 13 keV
Dynamic range
10^4@12 keV
Single Photon Sens.
Storage Cells ≈ 300
Pixel Size 200 x 200 μm^2

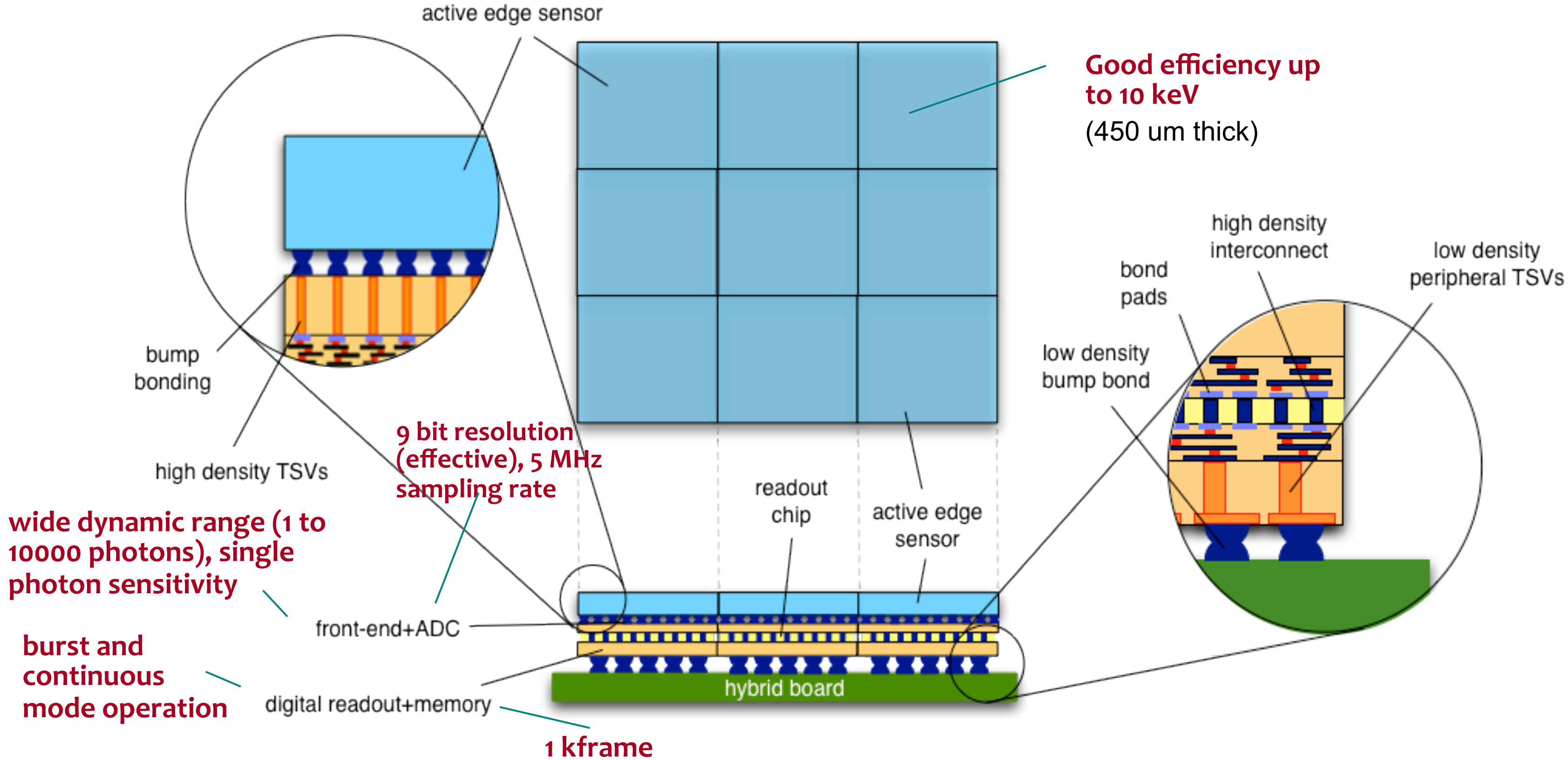
DEPFET Sensor with Signal Compression (DSSC)



Energy range
0.5 - 6 keV (25 keV)
Dynamic range
6000 ph/pix/pulse@1 keV
Single Photon Sens.
Storage Cells ≈ 640
Pixel Size ≈236 x 236 μm^2

Long term goal of PixFEL

- Develop a four side buttable, multi-layer module for the assembly of a large area X-ray detector with minimum dead area
  - active edge thick pixel sensor, two tiers CMOS readout chip (analog+digital/memory), low/high density TSV, 65 nm to increase memory and functionality, smaller pixel pitch of 100 μm.



PixFEL target specifications

Single tile (2014-2016)

Time, complexity

- Pitch: 100x100 μm^2
- Tiling "without" dead area
  - → active edge sensors ~ 2% dead area
  - → low density TSV to connect I/O chip PAD to hybrid board
- Single photon counting & Wide dynamic range, 1-10^4 photons (1-10 keV)
  - → Preamplifier with dynamic signal compression
- A/D conversion in 200 ns (Eu-XFEL)
  - → Successive approximation 10 bit ADC (SAR ADC)
- Memory: 1k frame depth
- Readout:
  - Burst mode: Eu-XFEL 4.5 MHz frame rate, 1% duty cycle
  - Continuous mode: 15 kHz frame rate or better?

Not covered in presentation

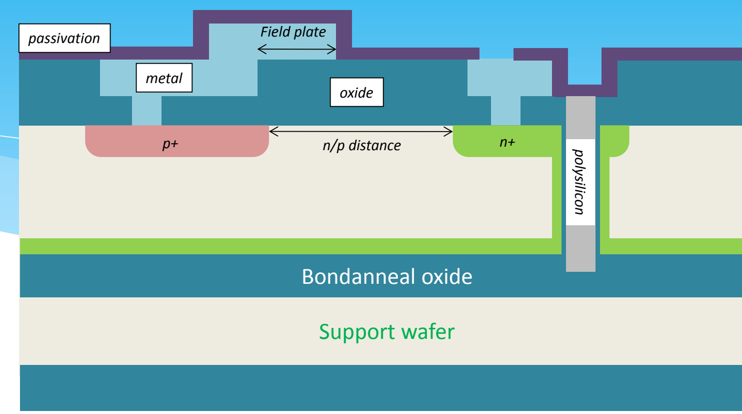
System (>2016, still to be optimized)

- Tot. area ~20x20 cm^2
- Chip 64x64 pixel, ladder=sensor=2.56x5.12 cm^2, 4x8 chips/ladder
- Bandwidth: 0.6 Gb/s/chip & 20 Gb/s/ladder

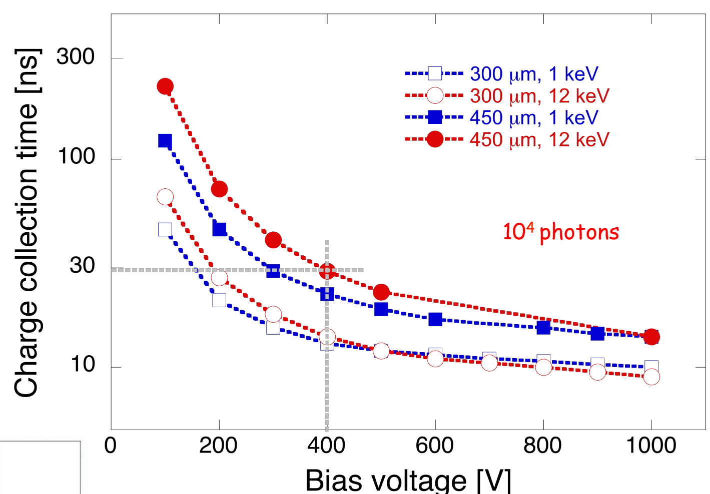
Active edge sensors

- Active edge to minimize the gap between the last active element and edge of the sensor but avoid high leakage current injection from the damaged cut region.

  → Cut lines not sawed but etched with DRIE & doped to act as electrodes



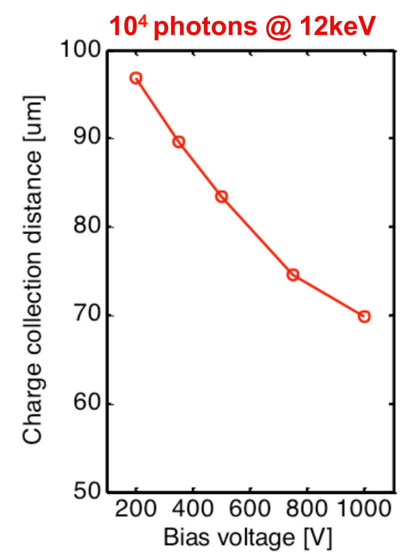
- **Main issues for FEL applications**
- Plasma effect: high charge concentration from huge signal (10^4 photons 1 keV → 2.8×10^6 e-/h > 100 MIP), reduces collection field & deteriorate charge Collection Distance (CD) and Collection Time (CT)
- Thick sensor (450 μm) for good efficiency @ 10 keV
- Thin entrance window for good efficiency @ 1 keV



TCAD simulation campaign

→ High Bias voltage mitigates plasma effect: with Vbias=400 V fast collection time (<30 ns) & collection distance < 100 μm

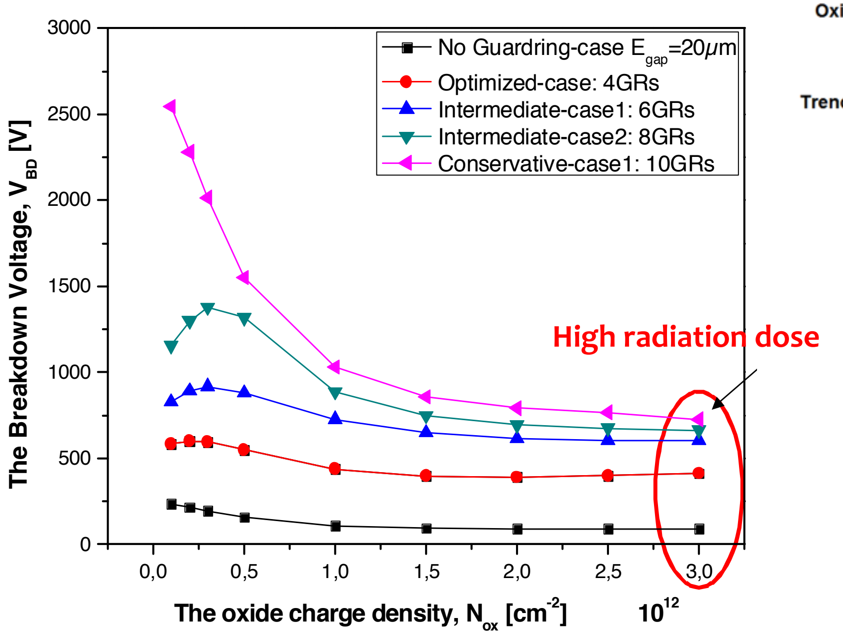
→ Edge geometry optimized to increase breakdown voltage

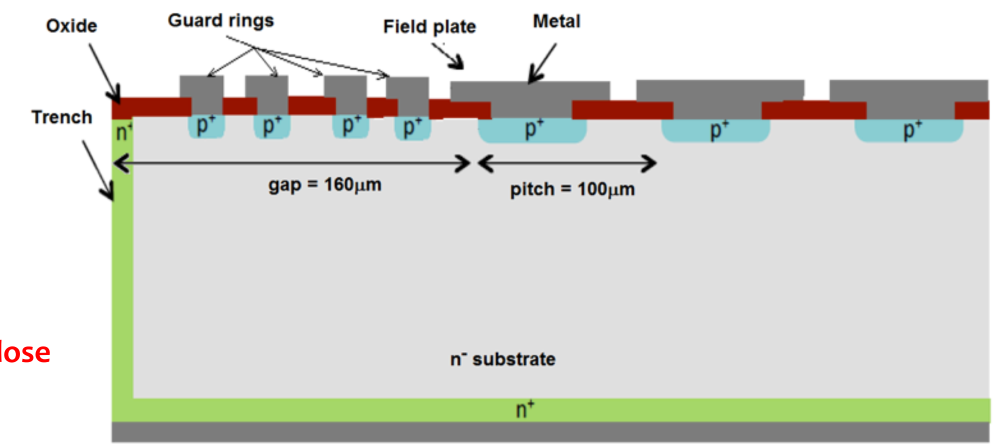


Sensor optimization for FELs

- Edge geometry optimized to increase breakdown voltage:
  - Edge distance, floating guard rings, field plate
  - Oxide thickness, junction depth
- With present optimization $V_{breakdown}$ > 400V for entire operation lifetime:
  - 4 guard rings with external field plate
  - 2.4 µm junction depth
  - 300 nm oxide thickness
  - max Q_{OX}=3e12 cm^{-2} (=high radiation dose)

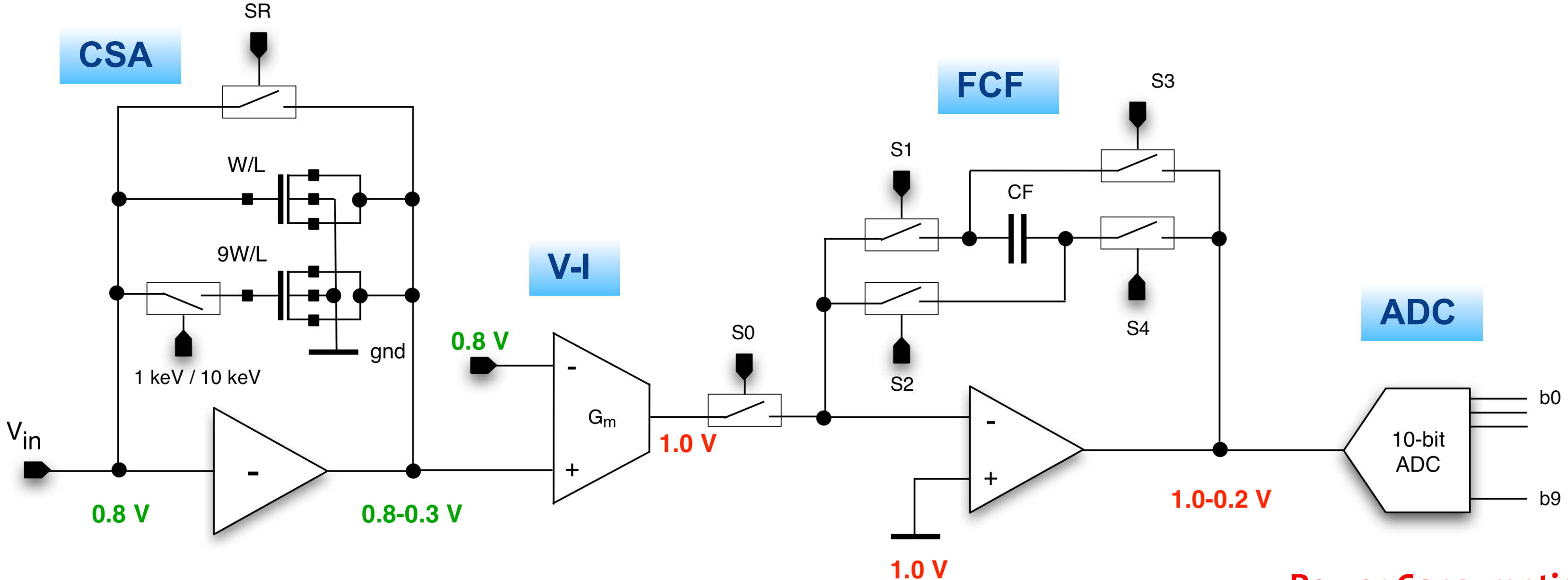
- First pixel at 160 um from the edge ~2% dead area





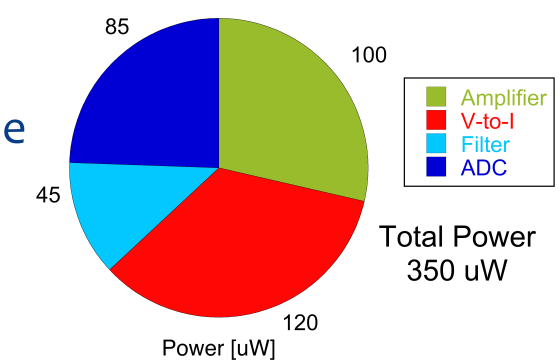
- The first PixFEL sensor batch is now in fabrication @ FBK (Trento, Italy)
- More details in G. F. Dalla Betta's Poster

Readout Channel



- Charge Sensitive Amplifier – dynamic signal compression
- Transconductor – voltage to current convertion
- Flipped Capacitor Filter – variable gain and integration time
- Analog-to-digital conversion – 10 bit SAR ADC
- Technology – 65 nm CMOS (TSMC)
- Two test chips realized now under test:
  - single blocks + 8x8 matrix with 110 um pixel cell
- Post Layout Simulation ENC=60 e- rms → SNR=4.7 for 1 keV (280 e-)

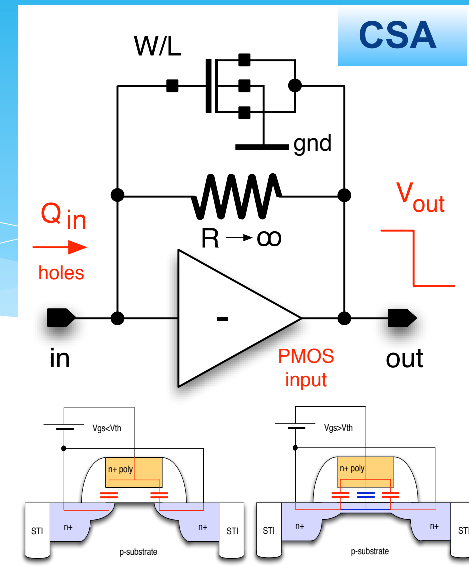
Power Consumption



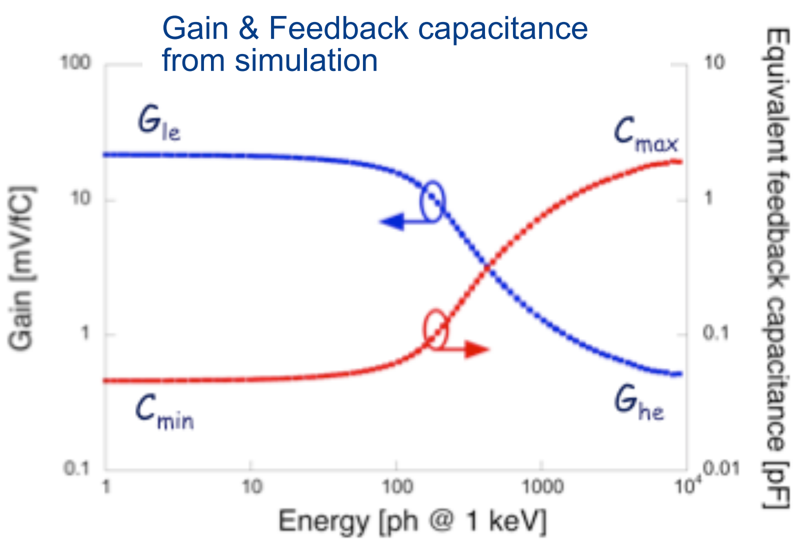
Dynamic Compression

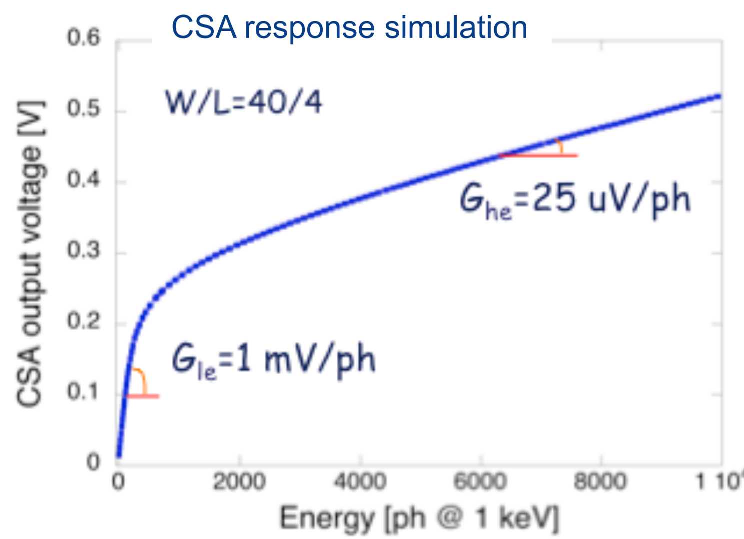
- Wide dynamic range front-end channel
- $1\text{-}10^4$ photons between 1-10 keV
- Bilinear Amplifier: use the non-linear features of MOSFET capacitor, in inversion mode, to dynamically change the gain with the input signal amplitude
  - For low energy → High gain & For high energy → Low gain

$|\Delta V_{OUT}| << V_{TH} \rightarrow C_f = C_{min}$, $Gain = 1/C_f = G_{le}$ $|\Delta V_{OUT}| >> V_{TH} \rightarrow C_f = C_{max}$, $Gain = 1/C_f = G_{he}$



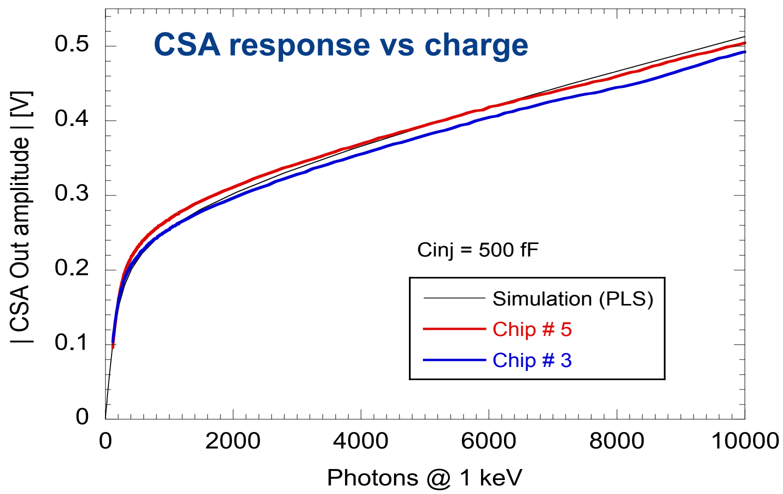
$C_{f,min} \approx C_{gs,ov} + C_{gd,ov} = 2W\Delta L C_{ox}$ $C_{f,max} \approx C_{gc} = WLC_{ox}$

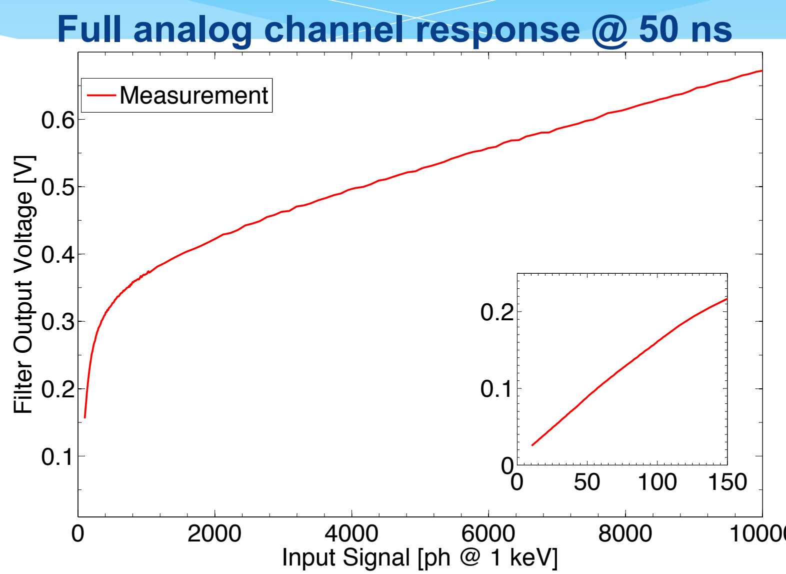


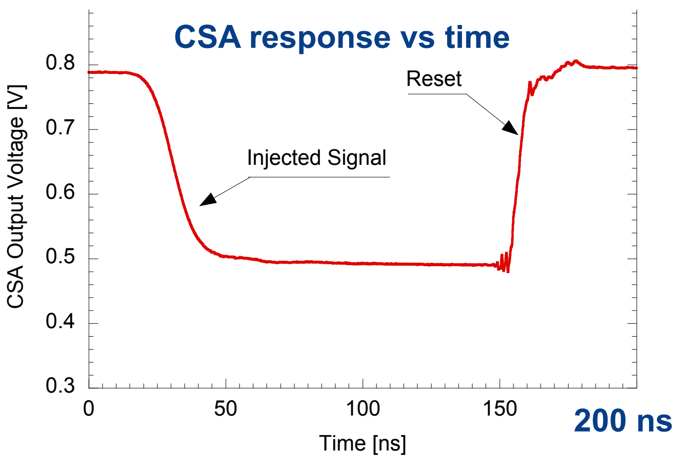


Preliminary Measurements on test chips

- Full analog channel operated successfully with 50 ns integration time compatible with Eu-XFEL time structure



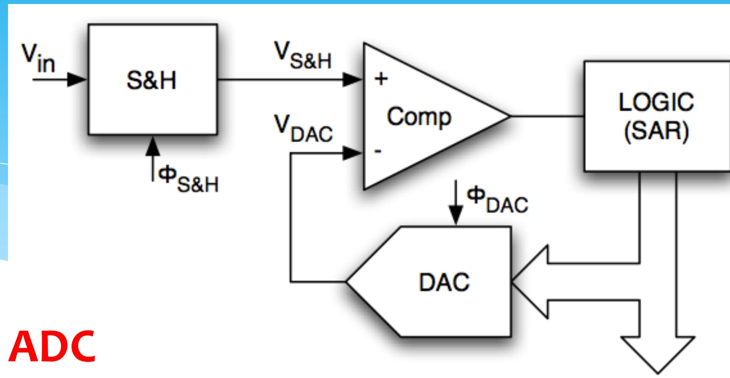




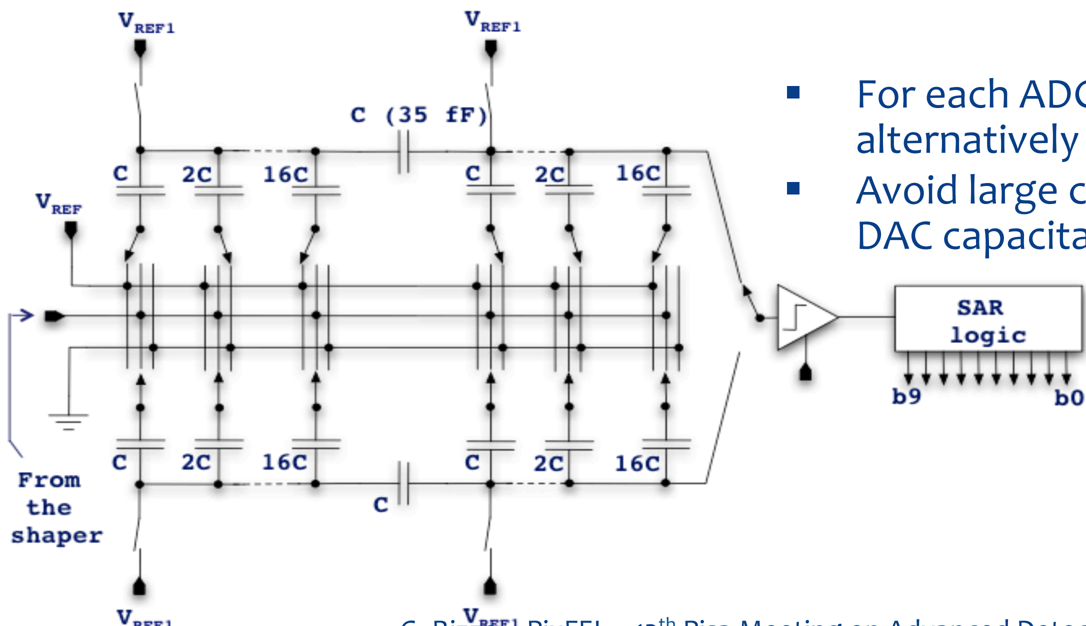
- Charge amplifier (CSA) shows the expected bilinear feature in the gain, in agreement with simulation (PLS).
- Fast transition and reset time measured (<30 ns), compatible with 4.5 MHz operation of Eu-XFEL
- Full channel response measured with the filter operated successfully @ 50 ns integration time.

In pixel ADC

- **Requirements:**
  - Wide dynamic
  - Large number of bits
    - guarantee single photon resolution at small signal
    - small quantization noise in Poisson-limited regime
  - 5 MHz sampling rate (for Eu-XFEL)
- **10 bit SAR (Successive Approximation Register) ADC**
  - good compromise between clock frequency and resolution.
  - Clockfrequency=5MHz×11=55MHz



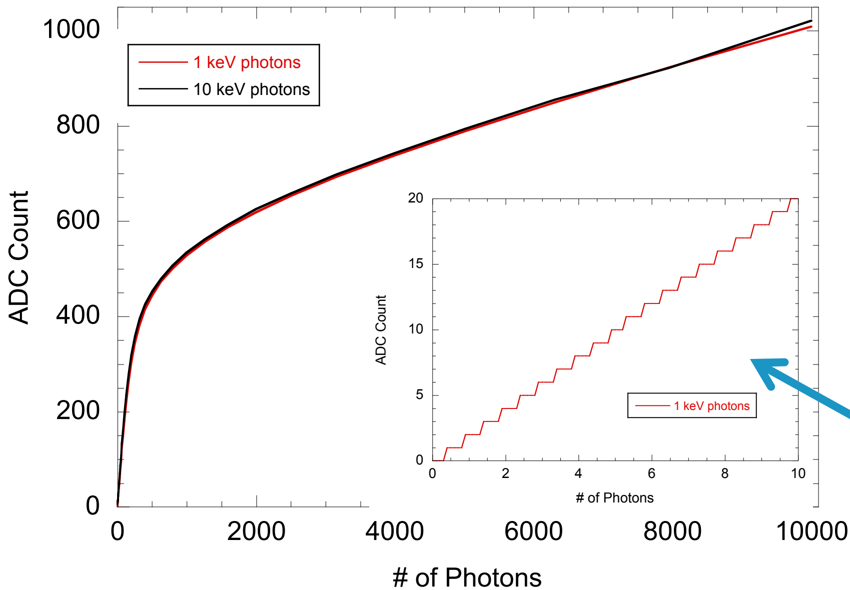
$$V_{in} = b_1 \frac{V_{ref}}{2} + b_2 \frac{V_{ref}}{4} + b_3 \frac{V_{ref}}{16} + \cdots$$



- For each ADC use **2** split capacitive DACs that work alternatively in a time interleaved structure
- Avoid large current peaks due to fast charge of the DAC capacitance (~2.5 pF)
  - Precharge of the DAC input capacitance during one entire sampling period
  - Conversion during the following sampling period

10-bit SAR ADC Performance

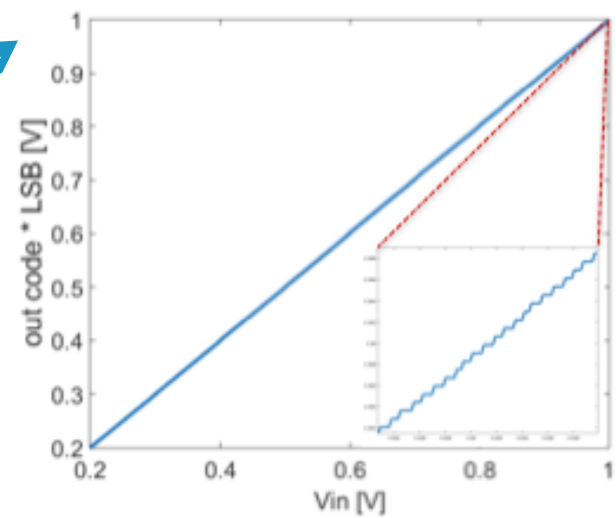
Full channel + ADC response - Simulation



- ADC Simulated performance
  - 0.2V-1V input dynamic range
  - INL and DNL < 0.5LSB
  - SNR 60 dB (ENOB=9.6)
  - Power ~ 70+15 μW
- ADC Area ~ 5000 μm²

- ADC dynamic range well covered
- Well detectable bilinear response of CSA
- First 10 photons well detectable

ADC measured response @ 20 MHz



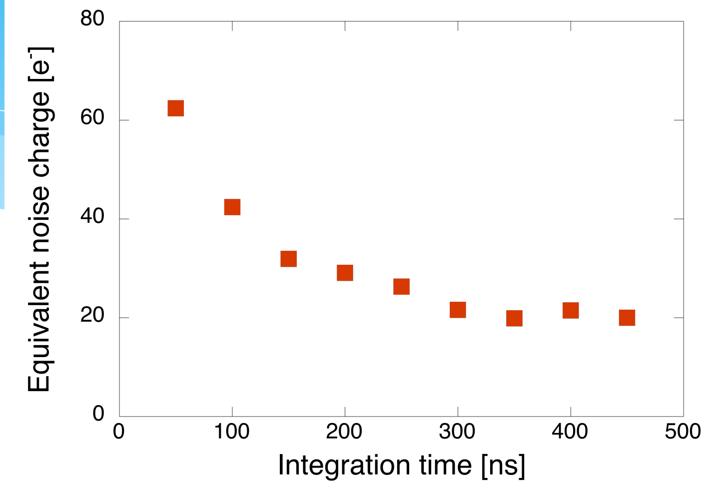
- Preliminary measurement of the ADC-only response shows good linearity over the full range (0.2V-1V)

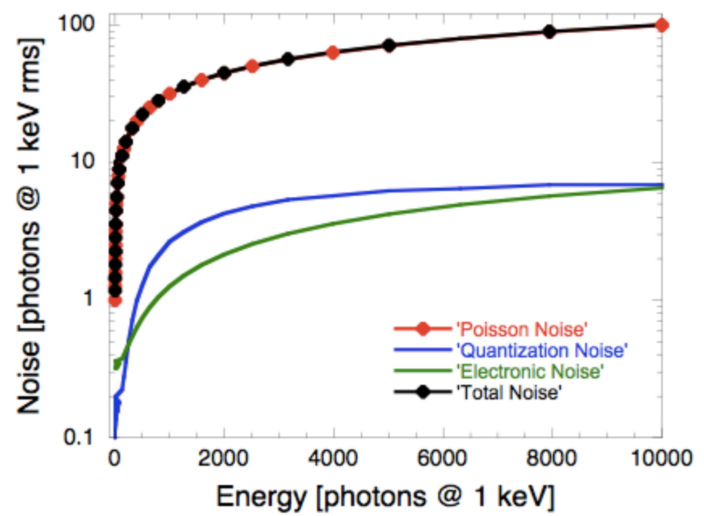
- See L. Lodola's Poster for details on ADC design & measurements

System Noise Analysis

- Electronic noise
  - due to analog front-end
  - ENC=60 e^- rms @ t=50ns (1 keV = 280e-)
  - Increases with increasing signal (Gain decreases)
- Quantization noise
  - due to ADC
  - negligible for small number of photons
  - #photons per bin/sqrt(12) for larger signal
  - Increases with increasing signal (Gain decreases)
- Poisson noise due to fluctuation of the number of photons that hit a pixel
  - irreducible

→ System performance dominated by the Poisson noise

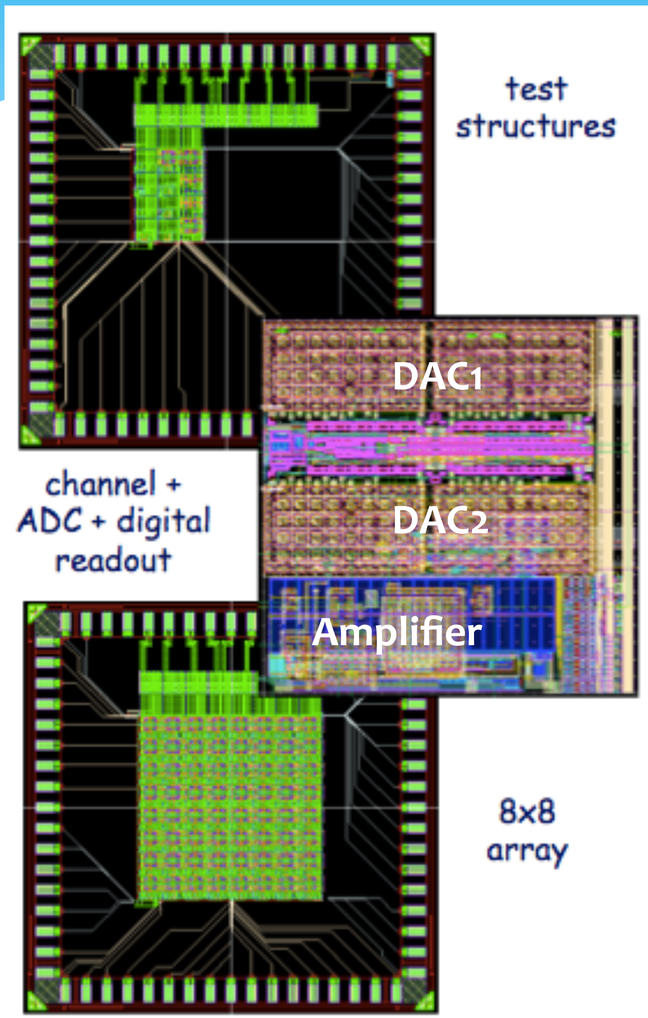




Conclusions & Perspectives

- The PixFEL project is adopting several new technologies to build a fine pitch, rad tolerant, multi-layer, fast detector with minimum dead area for X-ray imaging at future at FELs
  - active edge sensors, 65 nm CMOS, TSV, 3D integration
- First prototypes (sensors and front-end chips) realized to evaluate the proposed innovative aspects
  - Encouraging results from preliminary tests on the front-end chips
  - Full characterization and rad tolerance test (sensor & electronics) in 2015
- In 2016 build a small module with sensor and front-end chip
- Longer term ambitious plan to develop full instrument

Conclusions & Perspectives



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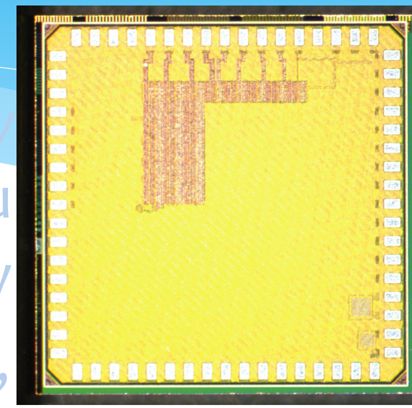

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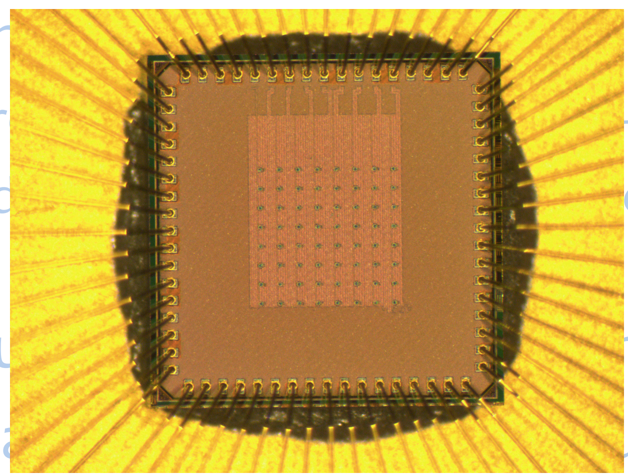
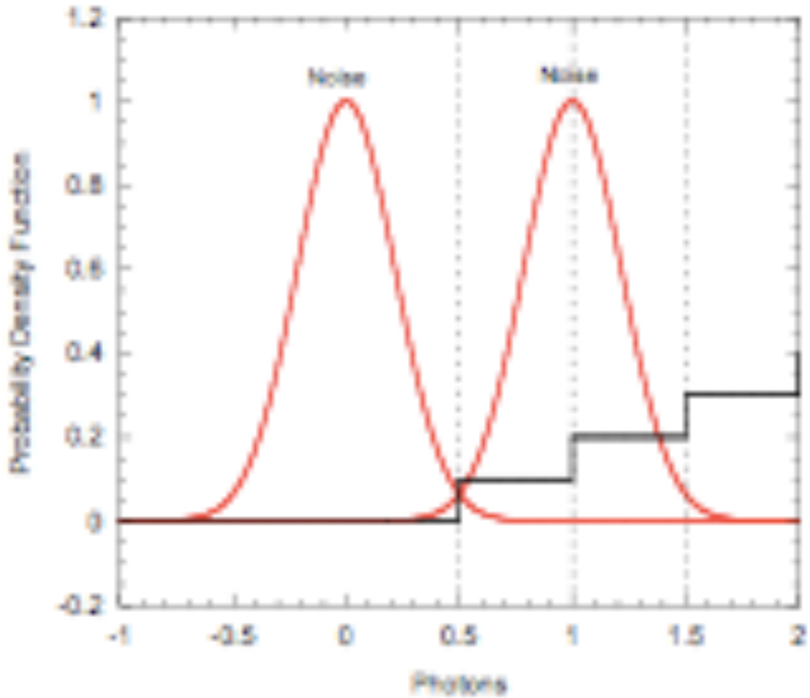


backup

Single photon detection



Assume

- Gaussian distribution for the electronic noise with

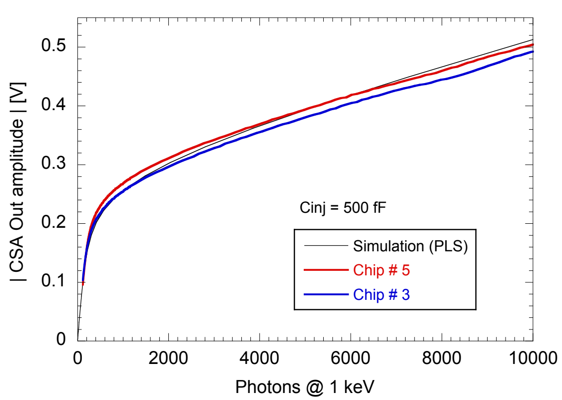
$$ENC = 60e - rms$$

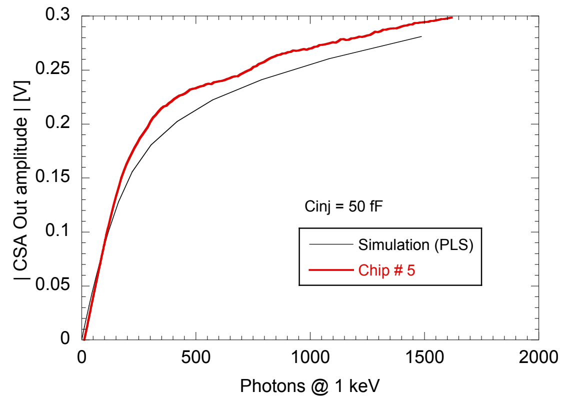
- ADC threshold of the 2nd bin placed @ 1st photon

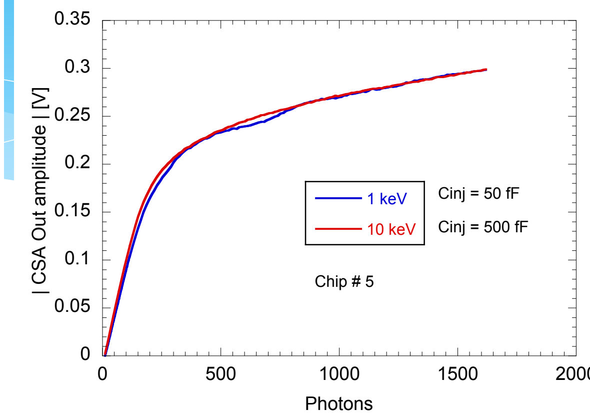
- The probability that a zero signal is misinterpreted as a one photon signal is 1%
- The probability that 1 photon signal is correctly attributed to the first 2 bins is 98%

Preliminary Measurements on test chips

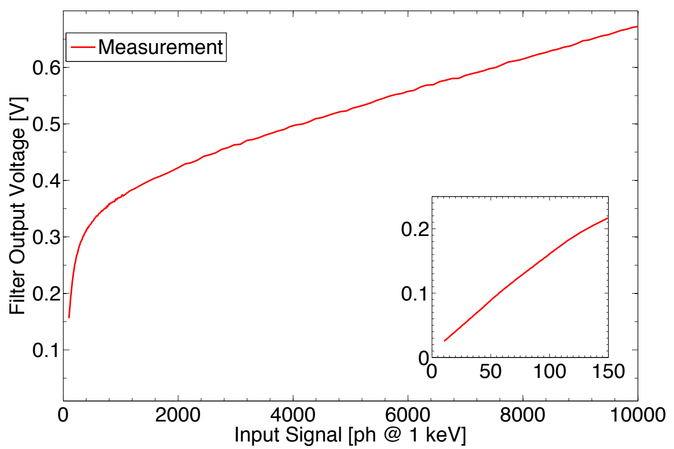
CSA response

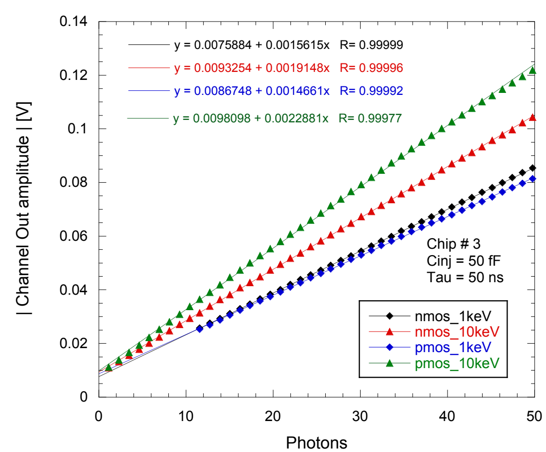






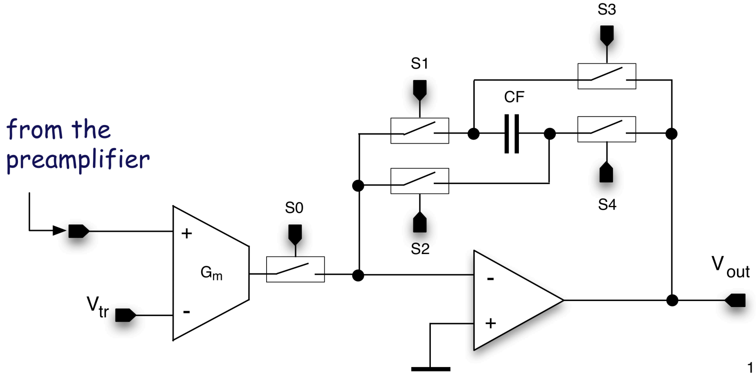
Full channel response with 50 ns integration time



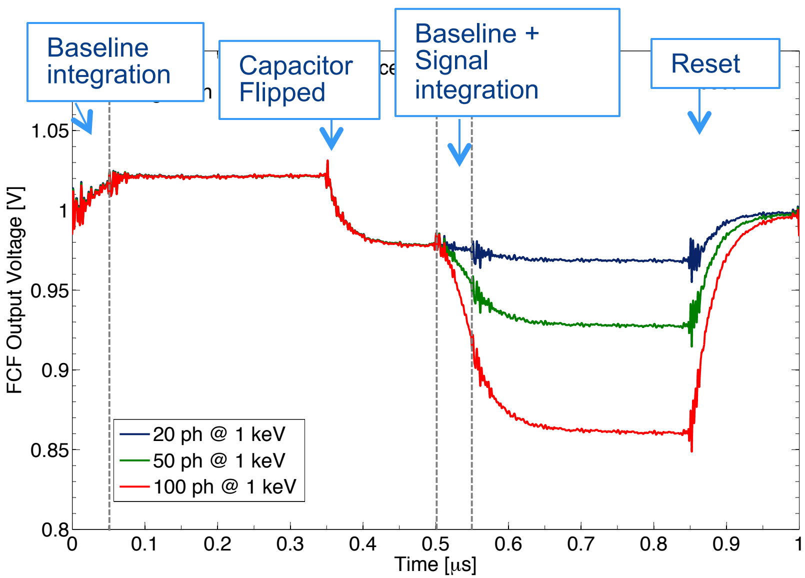


Preliminary Measurements on test chips

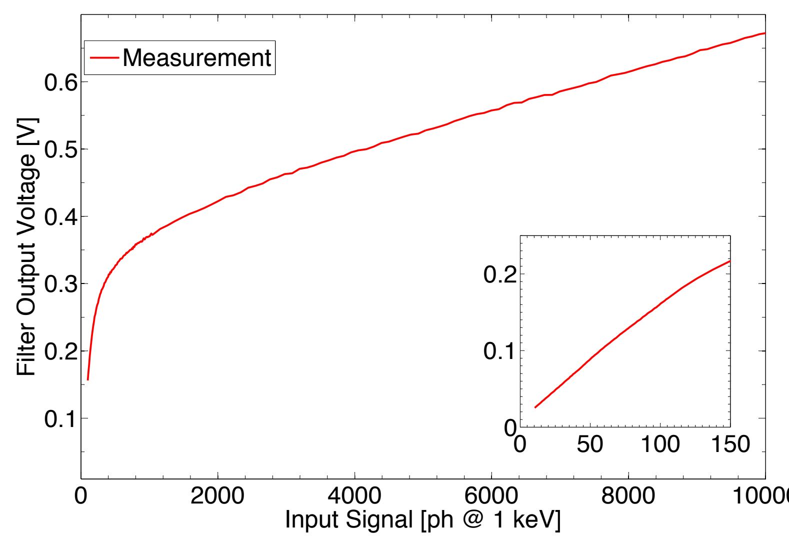
Full analog channel operated successfully with 50 ns integration time compatible with Eu-XFEL time structure



- Flipped Capacitor Filter (FCF) performs correlated double sampling (CDS)
  - X-ray pulse arrives after first integration (Baseline)
  - During second integration (Baseline + signal) filter capacitor has been flipped and baseline is subtracted

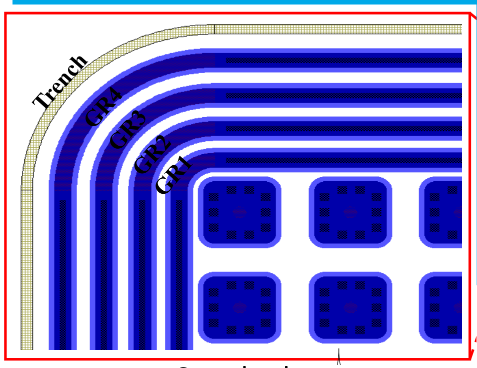


Full channel response @ 50 ns



PixFEL wafer layout

6-inch wafer including active edge & slim edge pixel sensors & test devices, to be fabricated at FBK (Trento, Italy)



Standard test structures

15x15 arrays for capacitance extraction

Large diode w/o Active Edge (6GRs)

8x8 arrays with Active Edge

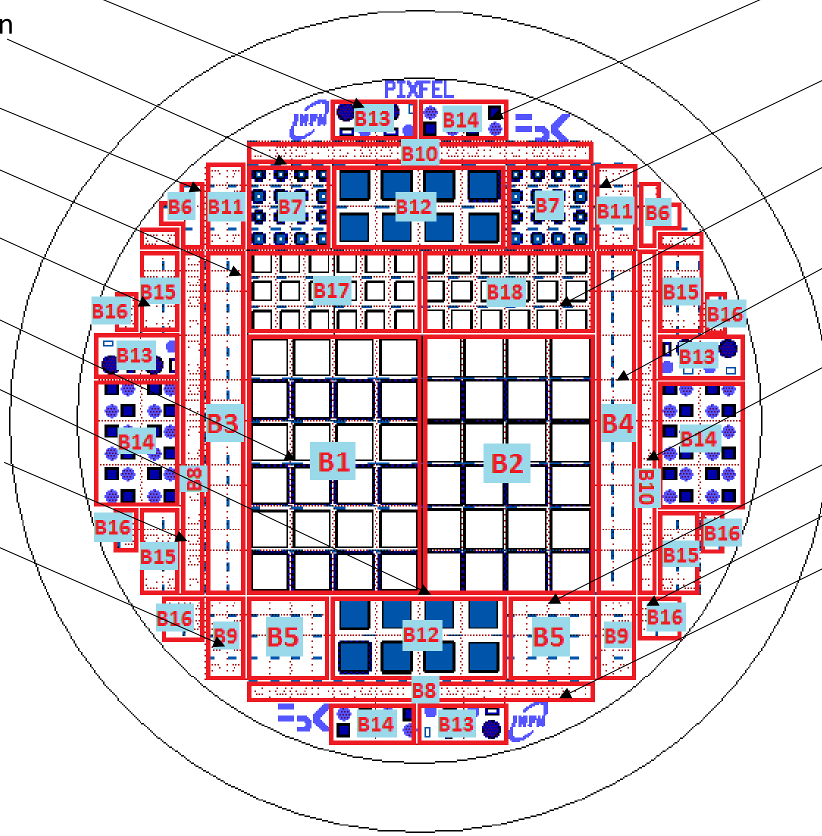
8x8 arrays with column trenches

64x64 Pixel array

Strip Sensors with Active Edge

Large diodes with column trenches

8x8 arrays with Slim Edge



Test structures for irradiation

8x8 arrays with overlapped slim Edge

32x32 Pixel array

8x8 arrays with Active Edge

Large diodes with overlapped Slim Edge

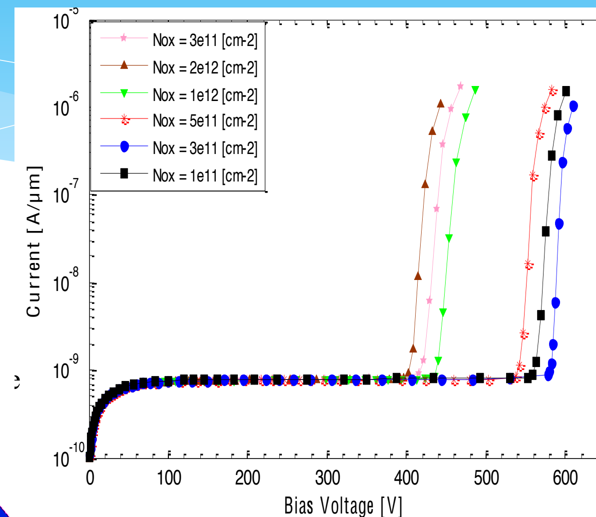
Large diodes with Active Edge

8x8 arrays with Slim Edge

Large diodes with Slim Edge

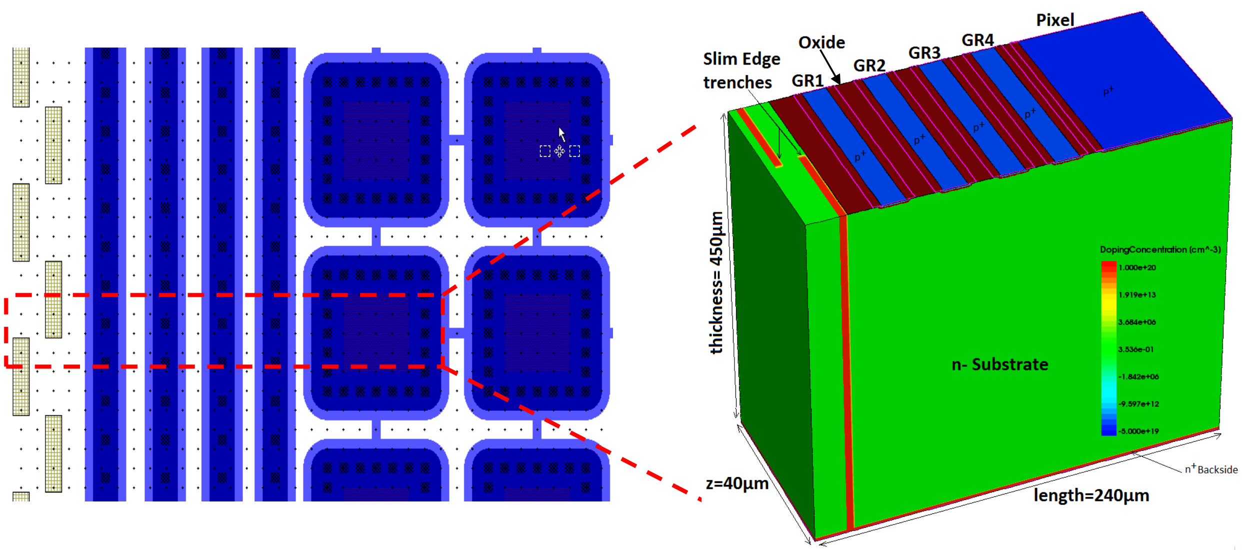
Slim edge approach

- Advantages w.r.t active edge
  - get rid of the support wafer
  - Entrance window at low energy can be optimized
- Disadvantges & risks
  - Additional dead space at the border
  - Possible reduction of breakdown voltage



Structure Layout

TCAD 3D structure



Problem of missing data

Modules of limited size and gaps between modules

➔ lots of missing data ➔reconstruction may become ambiguous

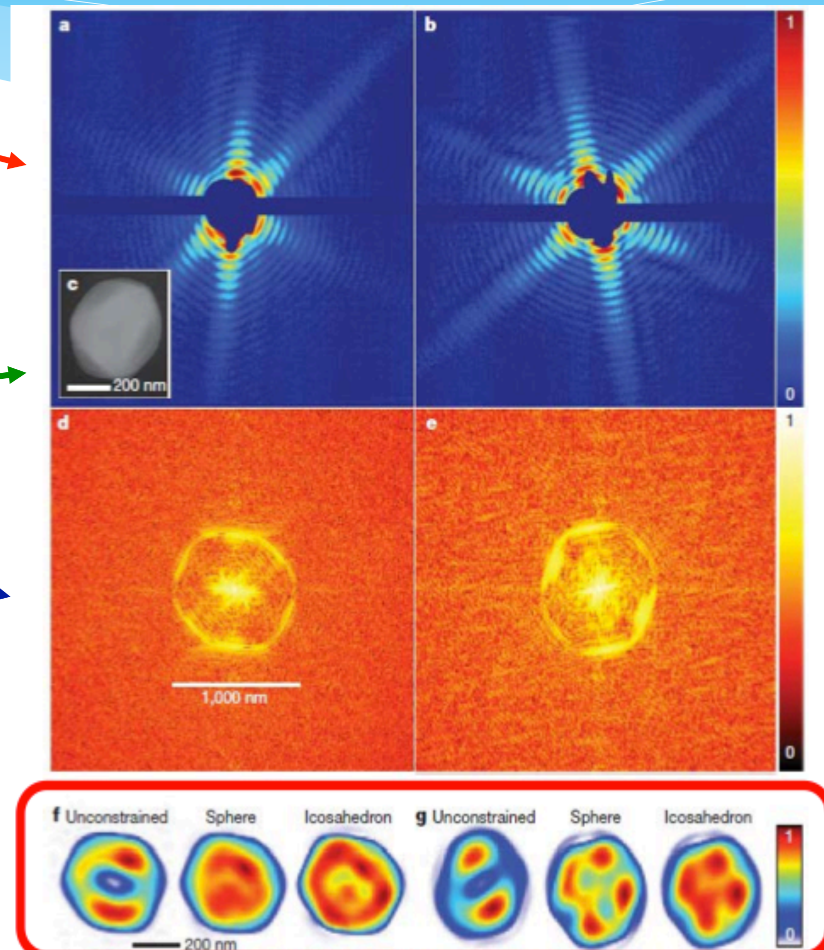
2 single shot diffraction pattern images of a large virus, 0.75 μm diameter, taken with pnCCD detector at LCLS.

As a comparison the virus picture taken with a transmission electron microscope (30000 images averaged)

Autocorrelation function for the 2 diffration patterns

Possible reconstructed images of the virus with ambiguities coming from missing data:

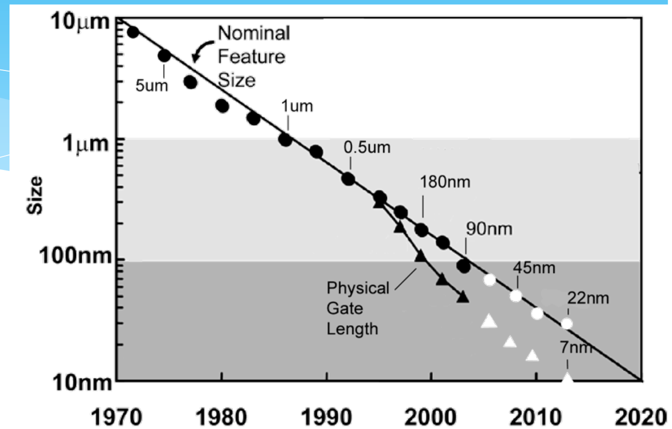
- dead area
- saturation of pixel in the central region.

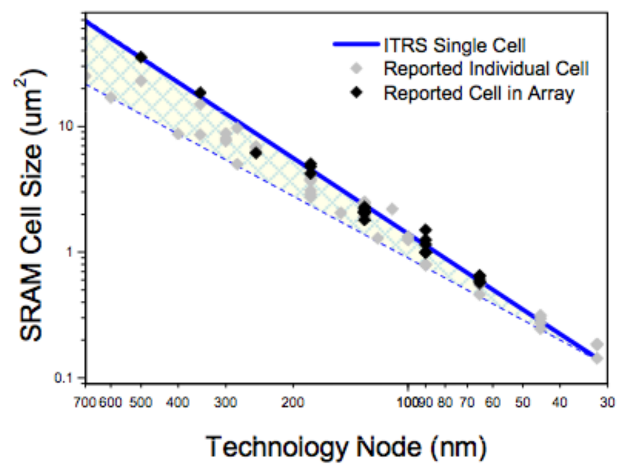


Nature **470**, 78 (2011)

PixFEL technologies: 65 nm CMOS readout electronics

- Mature technology:
  - available since 2007
- High density and low power
  - High density vital for smaller pixel and increased data buffering during bunch trains
  - Low power tech critical to maintain acceptable power for higher pixel density and much higher data rates
- Long term availability
  - Strong technology node used extensively for industrial/automotive
- Significantly increased density, speed and complexity compared to previous generations
- Important sinergy with R&D activities for LHC upgrade





Readout architectures

- No sparsification possible for these imaging detectors
  - large amount of data to be read out in a relatively short amount of time, also depending on the structure of the X-ray beam
- Burst mode operation: data need to be stored locally and read out in the interval between two bursts;
  - 65 nm CMOS technology to increase storage capacity
  - Bandwidth needs for XFEL: 4.5 MHz frame rate, 1% duty cycle, 1k frames stored over 3k frames → 0.6 Gb/s/chip & 20 Gb/s/ladder
- Continuous operation: data are read out as soon as they are collected, frame by frame;
  - With low repetition rate (i.e. 120 Hz @ LCLS) continuous readout within reach of present technology: 5 Mb/s/chip & 160 Mb/s/ladder.

    → XFEL bandwidth needs much higher: equivalent to continuous operation @ 15 kHz frame rate
  - Readout for future LCLS II at high repetition rates (up to 1 MHz) very challenging!
- Capability of switching from one mode of operation to the other may be an important asset for a 2D imager

FELs in operation or under construction

Project	Start of operation	Electron beam energy [GeV]	Photon energy [keV]	Frame/Burst repetition rate [Hz]	Number X pulses/burst
FLASH@DESY	2005	1.25	0.03-0.3	5	800@1us
LCLS@SLAC	2009	14.5	0.3-10	120	1
SACLA@RINKEN	2011	8	4.5-15	60	1
Fermi@ELETTRA	2010	2.4	0.01-0.06	10	1
European-XFEL	2016	17.5	0.4-20	10	2700@220 ns
SwissFEL	2016	5.8	1/12	100	2@50 ns
LCLS II	>2020	4-14.5	0.2-25	120 - 10^6	1

After the success of first FELs, new facilities & upgrades are in design phase in many countries (i.e. LCLS II)

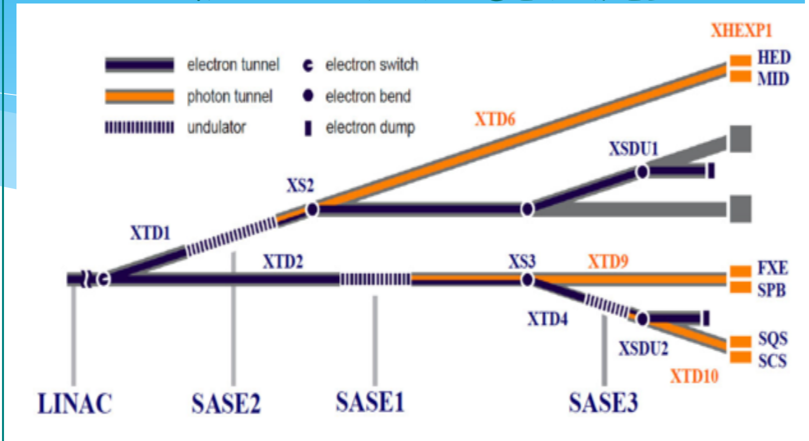
Beam line and beam-time structure

Beam lines with different photon energies available at each facility

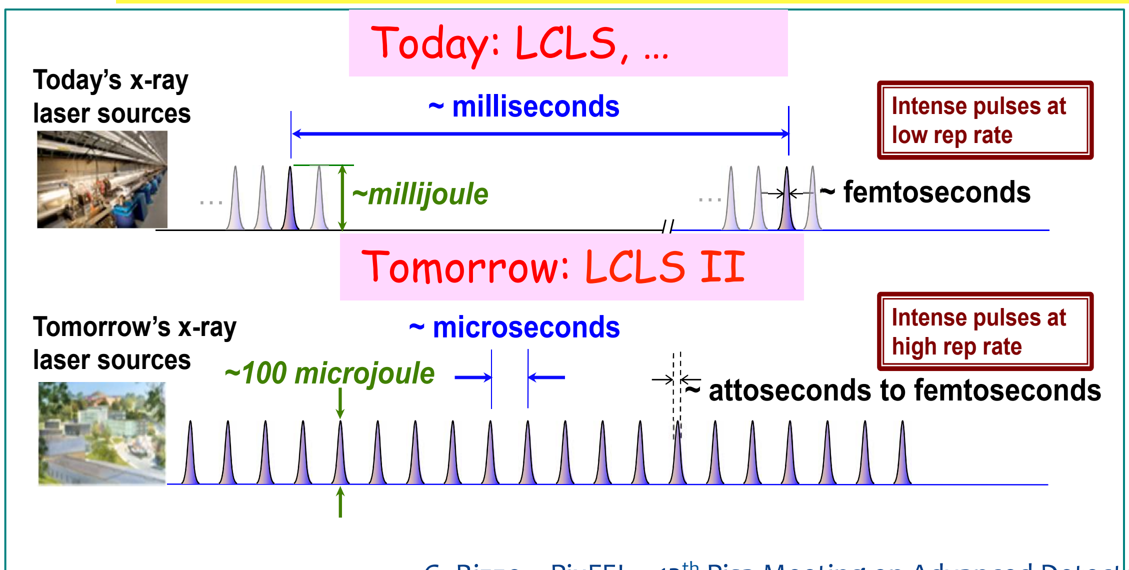
Very different beam time structure from one FEL facility to the other

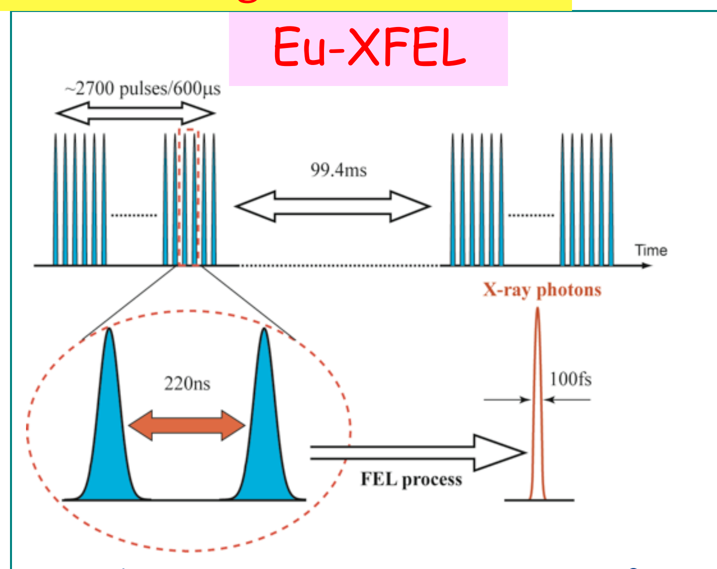
- Each X-ray pulse is always very short
- Continuous mode: LCLS @ 120Hz
- Burst mode: Eu-XFEL 220ns spacing, with time to readout
- Future (i.e. LCLS II): continuous 1MHz spacing

Beam-line structure @Eu-XFEL



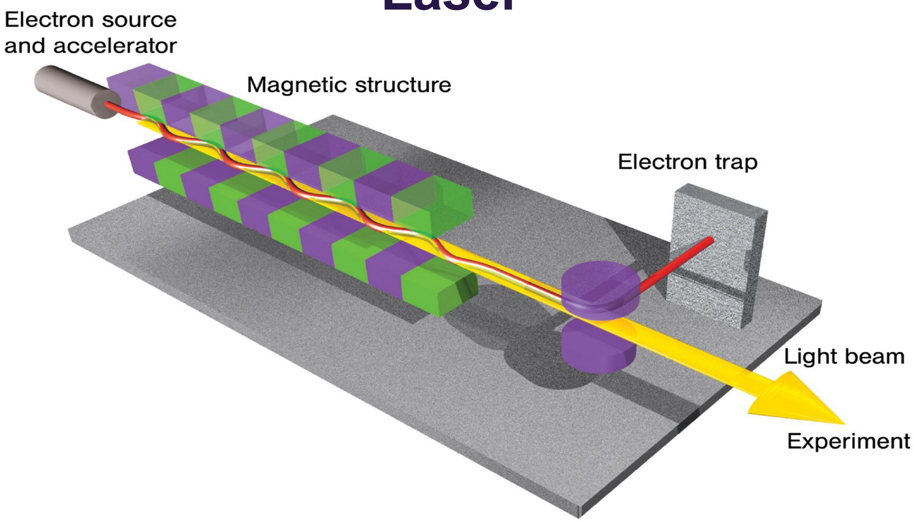
Most challenging for detectors Eu-XFEL & LCLS II, taken as target for PixFEL

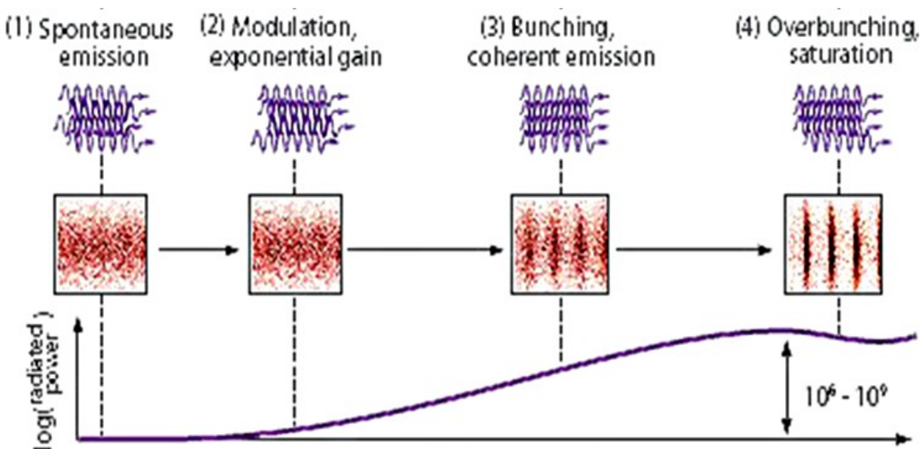




Free Electron Laser – How does it work?

Principle of an X-ray Free Electron Laser





Courtesy LANL

Wiggler

- No constructive interference of out-going radiation
- Broad spectrum
- Intensity proportional to N (N: Period)

SASE Undulator

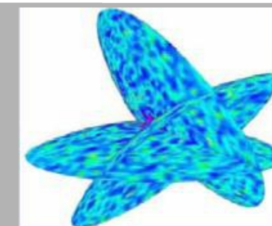
- Longer, narrower emission cone
- Micro-bunching
  - Electrons interact with electro-magnetic field and reorganize to bunches
  - Constructive interference
    - ➔ Sharp energy, coherent and high brilliance
  - Intensity proportional to N^2 and n_e^2

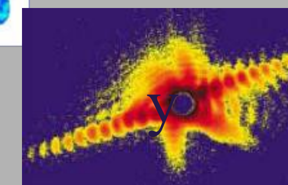
European XFEL

Scientific Instruments at XFEL.EU

SASE 1 | **SASE 2** | **High E**

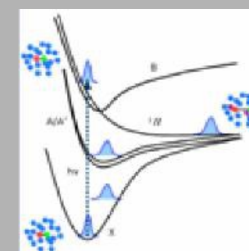
Ultrafast Coherent Diffraction Imaging of Single Particles, Clusters and Biomolecules (SPB)
Structure determination of single particles: atoms, clusters, bio-molecules, viruses and cells



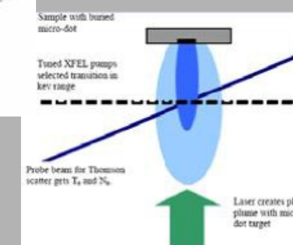


Materials Imaging & Dynamics (MID)
Structure determination of nano-devices and dynamics at the nanoscale

Femtosecond X-ray Experiments (FXE)
Time-resolved investigations of the dynamics of solids, liquids and gases.

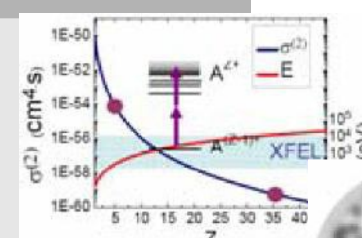


High Energy Density Matter (HED)
Investigation of matter under extreme conditions using hard X-ray FEL radiation, e.g. probing dense plasmas.



SASE 3 | **Low E**

Small Quantum Systems (SQS)
Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena.



Spectroscopy and Coherent Scattering (SCS)
Structure and dynamics of nano-systems and of non-reproducible biological objects

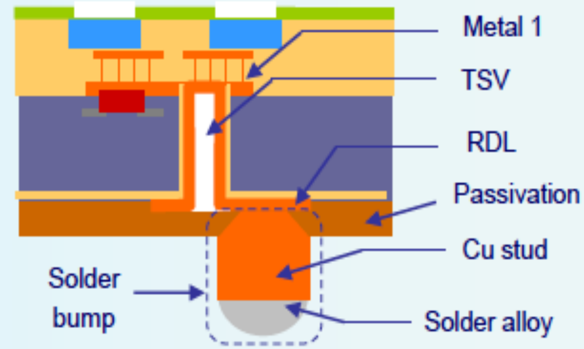
Enabling technologies for a 4-side buttable module

- Low density TSVs for chip to PCB bump-bonding

CEA-LETI

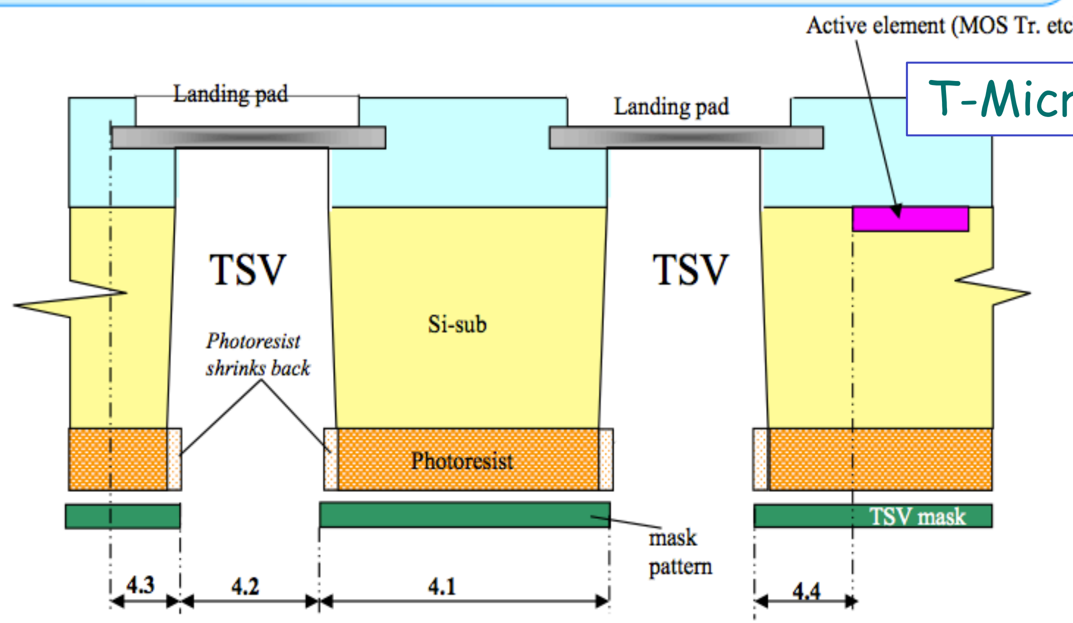
Solder bumps DRM & schematic

- Wafer size : **200 & 300 mm**
- Solder bumps material : **Cu stud / SnAg solder**
- Minimum pitch : **120 µm**
- Solder pillar diameter : **60-80 µm**
- Solder pillar thickness : **Cu 35-40 µm / SnAg 25-30 µm**



- No gaps, no need for complicate tiling (provided that the detector has minimum dead area)

T-Micro



200 ns operation mode