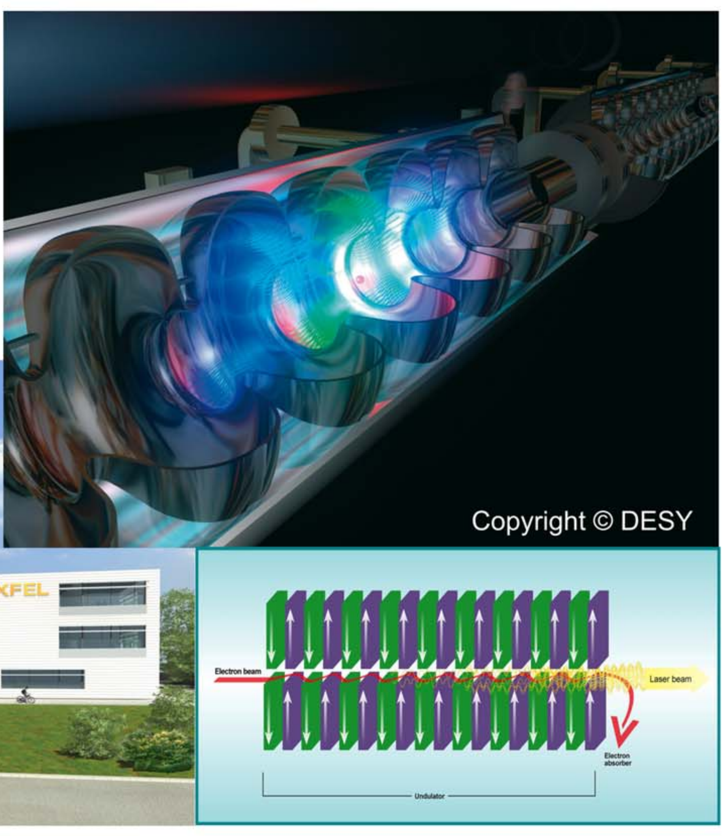
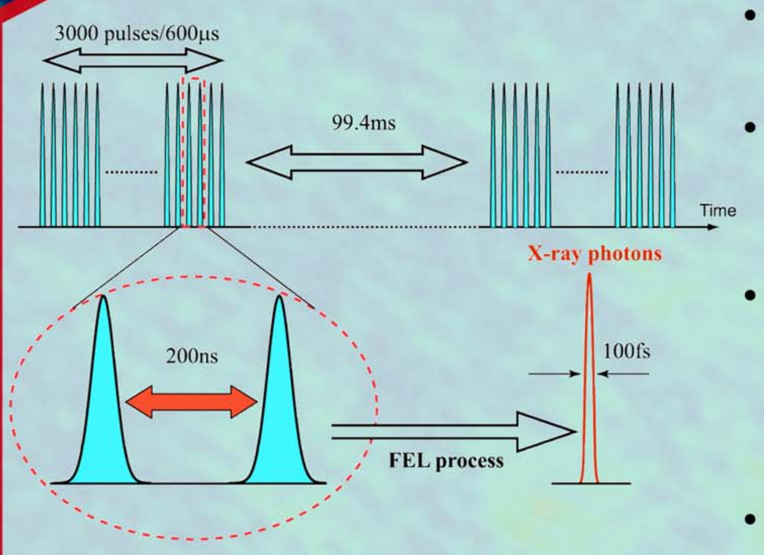
DEPFET Sensor with Signal Compression (DSSC): a Large Format X-ray Imager with Mega-Frame Readout Capability for the European XFEL

Matteo Porro **(map@hll.mpg.de)**
Max Planck Institut für Extraterrestrische Physik & MPI Halbleiterlabor, Germany
on behalf of the DSSC Consortium

We are developing a new detector system capable to fulfil the requirements of the future XFEL in Hamburg. The instrument will be able to record X-ray images with a maximum frame rate of 5MHz and to achieve a high dynamic range. The system is based on a pixel-silicon sensor with a new designed nonlinear-DEPFET as a central amplifier structure. The detector chip is bump-bonded to a set of mixed signal readout ASICs that provide full parallel readout. The signals coming from the detector, after having been processed by an analog filter, are immediately digitized by a series of 8-bit ADCs and locally stored in a custom designed memory also integrated in the ASICs designed in the 130nm CMOS technology. During the time gap of 99ms of the XFEL machine, the digital data are sent off the focal plane to a DAQ electronics that acts as an interface to the backend of the whole instrument. The pixel sensor has been designed so as to combine high energy resolution at low signal charge with high dynamic range. This has been motivated by the desire to be able to be sensitive to single low energy photons and, at the same time, to measure at other positions of the detector signals corresponding to up to 10^4 photons of 1keV. In order to fit this dynamic range into a reasonable output signal swing, achieving at the same time single photon resolution, a strongly non linear characteristics is required. The new proposed DEPFET provides the required dynamic range compression at the sensor level, considerably facilitating the task of the electronics. At the same time the DEPFET charge handling capacitance is enormously increased with respect to standard DEPFETs. The Pixel matrix will have a format of 1024x1024 hexagonal pixels with a side length of 136μm . The simultaneous implementation of the 5MHz frame rate, the single low-energy photon resolution and the high dynamic range goes beyond all the existing instruments and requires the development of new concepts and technologies.



The European XFEL Bunch Structure



- 10 Hz Macro-Bunch repetition rate
- every Macro-Bunch is composed of 3000 X-Ray pulses
- the X-Ray pulses have a temporal distance of 200 ns (this leads to 5MHz frame rate)
- Each X-Ray pulse has a temporal width of 100 fs

The system must acquire a complete 1024 x1024 image every 200 ns!

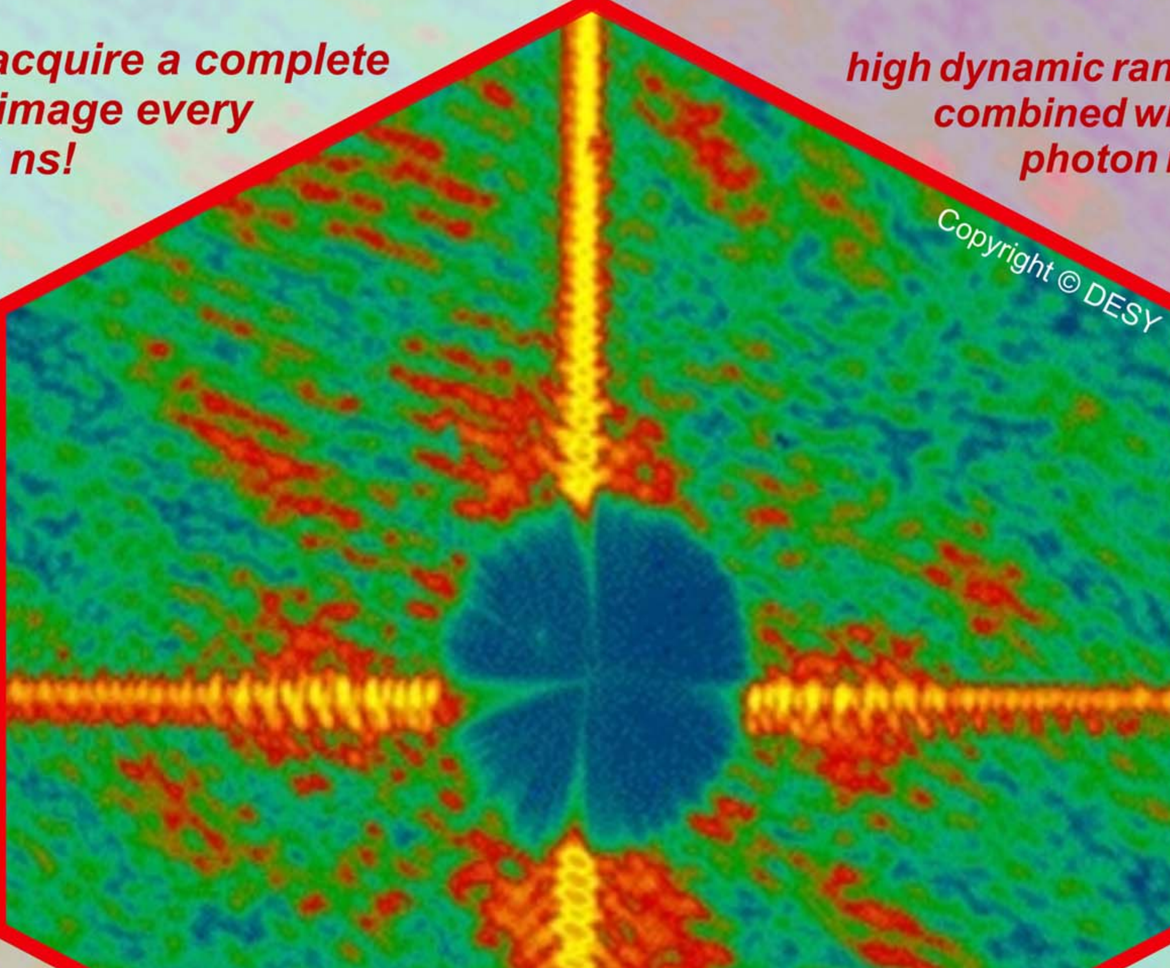
DSSC Detector Specifications

Parameter	Expected DSSC performance
Energy range	0.5 … 25 keV (optimized for 0.5 … 4 keV)
Number of pixels	1024 x 1024
Sensor Pixel Shape	Hexagonal
Sensor Pixel pitch	~ 204 x 236 μm²
Dynamic range / pixel / pulse	> 6000 photons @1 keV
Resolution (S/N >5:1)	Single photon @ 1 keV (5 MHz) Single photon @ 0.5 keV (≤ 2.5 MHz)
Electronics noise	< 50 electrons r.m.s.
Frame rate	1-5 MHz
Stored frames per Macro bunch	≥512
Operating temperature	-30°C optimum, RT possible

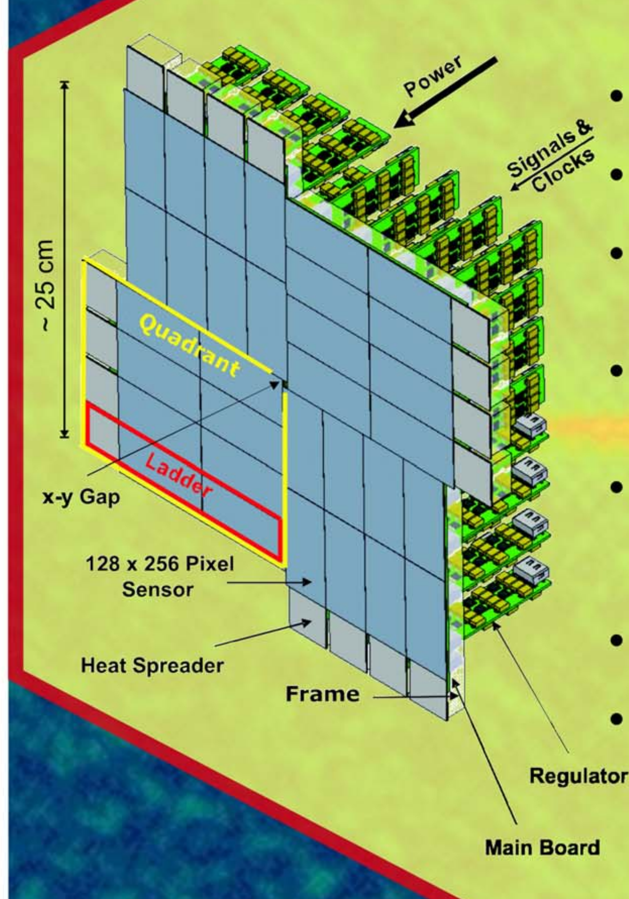
Our system can cover a variety of experiments but it is specially tailored for X-ray Photon Correlation Spectroscopy. The most striking properties are:

5 Mhz operation

high dynamic range simultaneously combined with single 1keV photon resolution

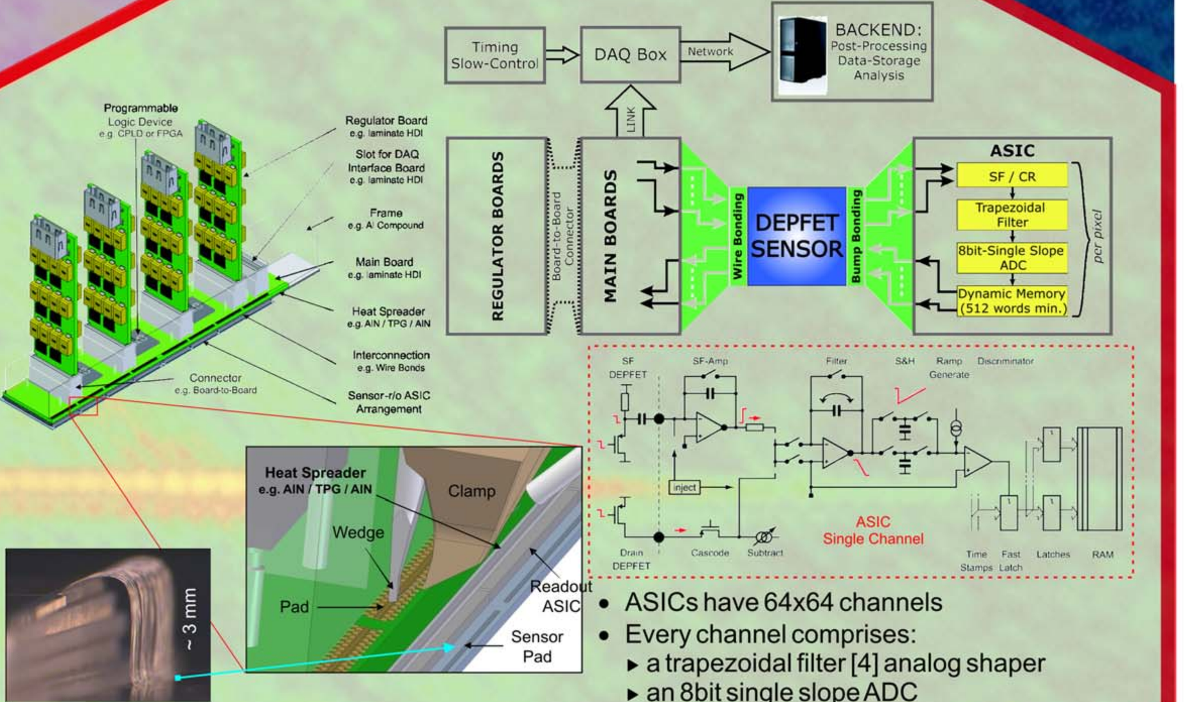


Focal Plane Overview



- 1024x 1024 pixels
- 16 ladders/hybrid boards
- 32 monolithic sensors 128x256 (6.2x3 cm²)
- DEPFET Sensor bump bonded to 8 Readout ASICs (64x64 pixels)
- 2 DEPFET sensors wire bonded to a hybrid board connected to regulator modules
- Heat spreader
- Dead area: ~15%

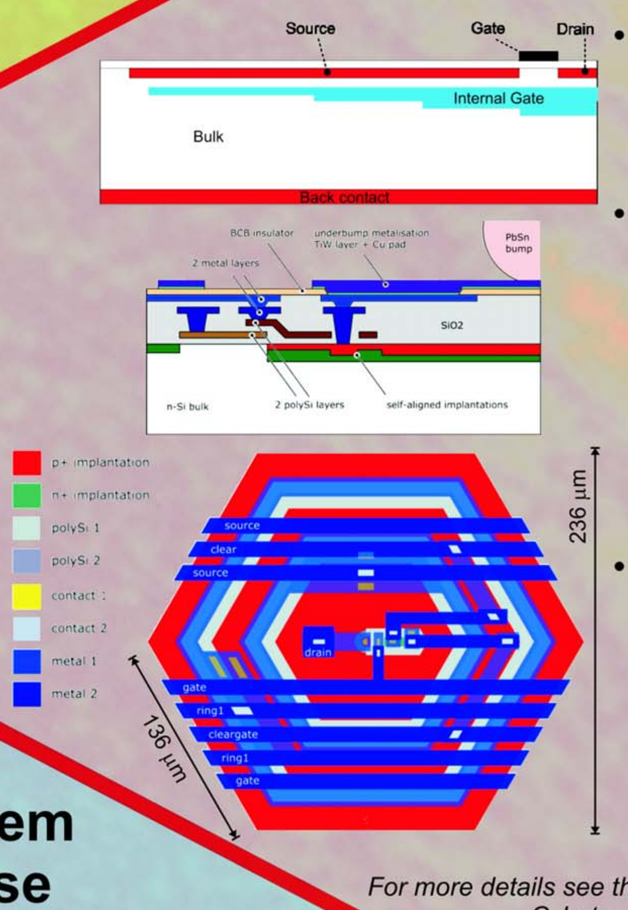
System Block Diagram



- ASICs have 64x64 channels
- Every channel comprises:
  - a trapezoidal filter [4] analog shaper
  - an 8bit single slope ADC
  - a DRAM able to store at least 512 frames

Signal coming from the sensor pixels are filtered, digitized and stored in the ASIC. Digitized data are sent off the focal plane during the bunch gap of 99ms

DEPFET Pixel Concept



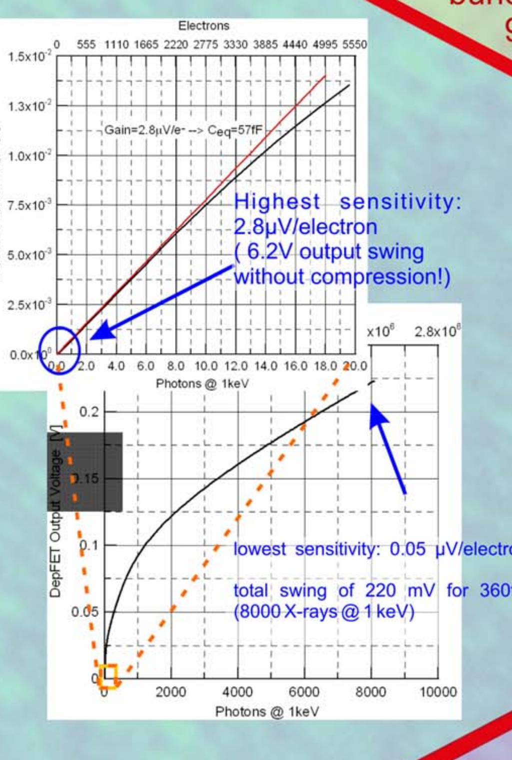
- DEPFET [1,2] consists of a p-channel FET on a n-type bulk that is fully depleted by a reverse biased backside diode.
- The signal charge is collected in a potential minimum, called internal gate, below the conductive channel of the FET. The charge collected in the internal gate modulates the transistor current (current readout scheme) or the source voltage (source follower readout)
- The DEPFET is surrounded by a small drift chamber in order to collect the charge deposited by the incoming radiation into the internal gate. The pixels will have exagonal drift rings and a DEPFET structure in the middle.

For more details see the Poster by G. Lutz in this session

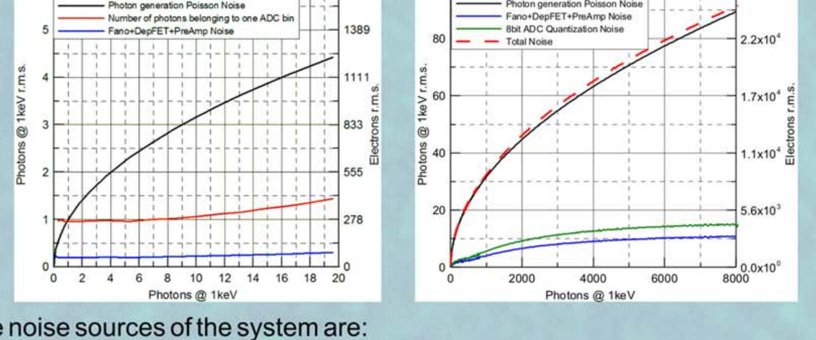
DEPFET Signal Compression

- In the DEPFET design realized for XFEL, [3] the internal gate extends into the region below the large area source. Small signal charges assemble below the channel only, being fully effective in steering the transistor current. Large signal charge spills over into the region below the source and are correspondingly less effective in steering the transistor current. This leads to a non linear outputcharacteristic of the device(signal compression).
- For small signals the DEPFET provides the maximum amplification and allows obtaining the best signal to noise ratio and therefore single 1keVphotoresolution.
- With the simulated output characteristic of the device and an 8 bit ADC it is possible to achieve a

dynamic range of at least 6000 photons @ 1 keV per pixel



System Noise

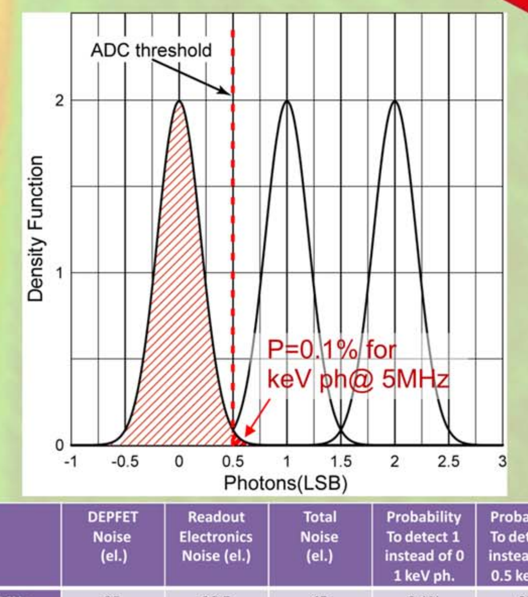


- The noise sources of the system are:
  - (a) Electronics Noise: DEPFET, Analog Front-End
  - (b) Quantization Noise introduced by the ADC
  - (c) Noise of the Poisson distributed Photon Generation Process
- The non-linear characteristic of the DEPFET makes (a) and (b), i.e. The DSSC Detector Noise components, *Signal Dependent*
- Simulations and extrapolations from measurements on DEPFET prototypes show that:

The DSSC noise is much smaller than the Poisson Photon Generation noise over the entire dynamic range already using an 8bit ADC

Single Photon Resolution

- For small signals the Quantization Noise is negligible and the Electronics Noise is about 45 electrons r.m.s at the highest operating frequency of 5MHz
- The mean charge generated by one photon at 1 keV is 278 electrons. This gives a Signal to Noise ratio of 278:45 > 6:1.
- Considering a Gaussian distribution of the Electronics Noise and placing the ADC threshold in the middle of the bin, there is a chance of only 0.1% that a zero signal is misinterpreted as a one photon signal of 1keV



	DEPFET Noise (el.)	Readout Electronics Noise (el.)	Total Noise (el.)	Probability To detect 1 instead of 0 1 keV ph.	Probability To detect 1 instead of 0 0.5 keV ph.
5MHz	35	28.5	45	0.1%	6%
2.5 MHz	18	8.2	20	~0	0.03%
1 MHz	10	4.7	11	~0	~0

Operating at 2.5 MHz single photon resolution with S/N > 6 is achievable also for 0.5 keV Photons

Conclusions

A new concept of pixel detector system, based on innovative non-linear DEPFETs, has been proposed and simulated.

Simulations have shown that, thanks to the intrinsic low noise of the pixel and the signal compression at the sensor level, it is possible to achieve simultaneously:

- Single 1keV photon resolution (S/N >6) @ 5MHz frame rate
- Single 0.5keV photon resolution (S/N >6) @ 2.5 MHz frame rate
- dynamic range of at least 6000 photons @ 1keV per pixel

REFERENCES

[1] J. Kemmer and G. Lutz, Nucl. Instr.and Meth. A, vol. 253, pp. 365–377, 1987.
[2] M. Porro, I. G. Ferrari Member, P. Fischer, O. Haelker, M. Harter, S. Herrmann, N. Hoernel, R. Kohrs, H. Krueger, P.Lechner, G. Lutz, I. Peric, R. H. Richter, L. Strueder, J. Treis, M. Trimpl, and N. Wermes, Nuclear Science, IEEE Transactions on, vol. 53, no. 1, pp. 401–408, Feb. 2006.
[3] Porro, M., Andricek, L., Castoldi, A., Fiorini, C., Fischer, P., Graafsma, H., Hansen, K., Kugel, A., Lutz, G., Pietsch, U., Re, V. and Strueder, L. (2008). IEEE Nuclear Science Symposium Conference Record, 1578-1586.
[4] M. Porro, C. Fiorini, and L. Strueder, Nucl. Instr. and Meth. A, vol. 512, pp. 179–190, 2003.

Figure in the background: diffraction image of a nanostructure sample taken in an experiment at the free-electron laser facility FLASH in Hamburg using a single ultra-short, extremely intensive and coherent laser shot of just 25 femtoseconds duration.