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# The PixFEL Project: development of advanced X-ray pixel detectors for application at future X-FEL facilities

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The PixFEL project aims to develop an advanced X-ray camera for imaging suited for the demanding requirements of next generation free electron laser (FEL) facilities. The deployment of new technologies and innovative solutions, already under study for future pixel detectors for tracking, can also boost the performance of imaging instrumentations.

In the first phase of the PixFEL project, recently approved by the INFN, the focus will be on the development of the microelectronics building blocks, carried out with a 65 nm CMOS technology, implementing a low noise analog front-end channel with high dynamic range and compression features, a low power ADC and high density memory.

At the same time the collaboration will investigate and implement some of the enabling technologies to assembly, in a second phase of the project, a seamless large area X-ray camera composed by a matrix of multilayer four-side buttable tiles. In order to minimize the dead area on the sensor tiles, a pixel matrix with active edge will be developed.
Vertical interconnection of two CMOS layers, with low density and high density through silicon vias, will be explored to build a four-side buttable readout chip with small pixel pitch and all the on-board required functionality.

The ambitious target requirements of the pixel device under development are: single photon resolution, 1 to $10^4$ photons @ 1 keV to 10 keV input dynamic range, 10-bit analog to digital conversion up to 5 MHz, 1 kevent in-pixel memory and 100 um pixel pitch.
The final goal of a longer term research program will be the construction of a versatile X-ray camera for application to high frame rate X-FEL operated either in burst mode, up to 5 MHz, like at the European X-FEL, or in continuous mode with the high repetition rates foreseen for the upgrade phase of the LCLS-II at SLAC.

## Summary

After the success of first generation free electron lasers (FEL) in the investigation of the microscopic structure of organic and inorganic materials in many fields (i.e. biology, chemistry, material science, atomic and molecular science), many reaserch centers worldwide have started studying, designing and building new FEL facilities with unique X-ray beam proprerties, in term of peak brilliance, short pulse duration, high repetition rates.
To fully exploit the potential of next generation X-FEL facilities new X-ray imaging detectors need to be developed in order to match the very demanding requirements like space and amplitude resolution, input dynamic range, frame rate and frame storage capability.

The PixFEL Collaboration, formed by several groups from INFN and University of Bergamo, Pavia, Pisa and Trento, has been recently approved by the INFN to carry on a research program for the development of a two-dimensional pixelated imaging camera for application at future FELs facilities, with advanced performance with respect to the state-of-art imaging instrumentation.
The most innovative solutions and new technologies, now beeing investigated in the HEP comunity for new pixel detectors for tracking, will be explored by our collaboration to improve the performance of pixel device for photon science.

As a reference for the target requirements of the PixFEL developments the operability in the European X-FEL experiments has been taken as benchmark, since with its 4.5 MHz maximum pulse rate, in burst operation

mode with 1\% duty cycle, this is one of the most challenging environments.
The possibility to operate the device in continuous mode FEL facilities will be also considered, in particular to cope with the high repetition rates foreseen for the upgrade phase of the LCLS at SLAC, where frame rates as high as 1 MHz have been proposed.

The main requirements set as a target in PixFEL include: a wide dynamic range, from 1 to $10^4$ photons at fixed energy, that may vary from 1 keV to 10 keV depending on the specific experiment; pixel pitch of 100 um; single photon resolution up to 100 collected photons; capability to record one image every 200 ns and to store on chip as many images as possible to read them during the pulse down time typical of burst operation (with the goal to store up to 1000 images on chip); tolerance to very high radiation dose, up to 10 MGy.

A large area seamless X-ray camera with these tight specifications can be realized as a matrix of four-side buttable tiles. Each tile consists of a multilayer device made of a high resistivity pixel sensor, with active edge technology to minimize the dead area at the physical edge of the sensor tiles, interconnected to several two tiers CMOS front-end chips, realized with high density and low density through silicon vias (TSV) to obtain a four-side buttable readout chip with a small pixel pitch and all the needed on board functionality.

The three main goals of the first phase of the PixFEL project are: the development of the microelectronics building blocks, the exploration of the enabling technology for the multilayer tile, and the study of readout architectures for application in burst mode and in continuous mode operation.

The development of the front-end chip, will be carried out with a 65 nm CMOS technology to take full advantage of the synergy with similar activities starting in the HEP comunity for future detector development and at the same time to get increased in-pixel functionality and storage capability while reducing the pixel pitch.
The very challenging design of a front-end channel with the wide input dynamic range and single photon resolution at small signal, has already started: a dynamic compression of the signal is based on non-linear features of a MOS capacitor used in the feedback network of the charge preamplifier. With respect to other solutions proposed to this issue by other collaborations, the PixFEL channel has the advantage of being based on standard CMOS technology and on a single channel with dynamically changing gain, instead of a parallel cofiguration with different switchable gains.
The analog to digital conversion will be in-pixel with a 10-bit successive approximation register (SAR) ADC, now being designed. This solution provides an acceptable compromise between clock frequency and resolution; with 10 bits it may garantee single photon resolution at small signal and quantization noise smaller than the Poisson noise for large signals, retaining some margin for parameters dispersion and noise.
A first small prototype chip, with an 8x8 pixel matrix with the basic functionality of the front-end channel, 100 um pitch and a simple readout architecture will be submitted in Autumn 2014.

The minimization of the dead area in the sensor layer will be pursed in PixFEL by adopting planar active edge pixel sensors. In this technology, to extend the sensitivity of the sensor up to a few micron from its physical edge, the cut lines of each detector tile are realized with etched and heavily doped deep trenches, to act as wall (ohmic) electrodes.
For the specific application for FEL instrumentation, in the energy range between 1 to 10 keV, the development of relatively thick (about 450 um) pixel sensors with active edge,
needs anyway to be optimized.
One important aspect for this application is the impact of plasma effect, possible in case a high number of photons (up to $10^4$) hit a single pixel, resulting in high charge density that could affect charge collection, point spread function and response time. Specific TCAD device simulations, performed
to investigate this issue, indicate that this effect can be mitigated by increasing the bias voltage, with results in good agreement with experimental data reported by other collaborations.
Furthermore to deplete these relative thick sensors a large bias voltage is needed.
Since in active edge sensors early breakdown voltage could become a limiting factor, specific TCAD simulation of different edge terminations are now underway to optimize the pixel sensor design and find the best trade off between the minimization of the edge region and the sensor breakdown voltage.

A detailed description of the PixFEL project plans, and a summary of the main results from circuit and device simulations will be presented at the time of the conference.

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