PixFEL: Sviluppo di rivelatori a pixel per applicazioni a macchine Free Electron Laser

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Abstract

Il progetto PixFEL ha lo scopo di sviluppare un rivelatore per il piano focale per la rivelazione di raggi X alla prossima generazione di macchine Free Electron Laser, con la funzione di ricostruire le immagini di diffrazione prodotte dai fasci coerenti ad alta brillanza. Le applicazioni sono molteplici, e spaziano dalla fisica dei materiali alla biologia.

Nel progetto PixFEL si vogliono migliorare le prestazioni dei rive-latori esistenti utilizzando tecnologie avanzate, come elettronica CMOS a 65nm, integrazione verticale, e sensori di silicio edgeless, puntando a realizzare degli elementi di rivelazione con cui costruire un mosaico di grandi dimensioni e zone morte ridottissime, in grado di rivelare fotoni tra 1 e 10 keV con un range dinamico di 10^4 fotoni per pixel.

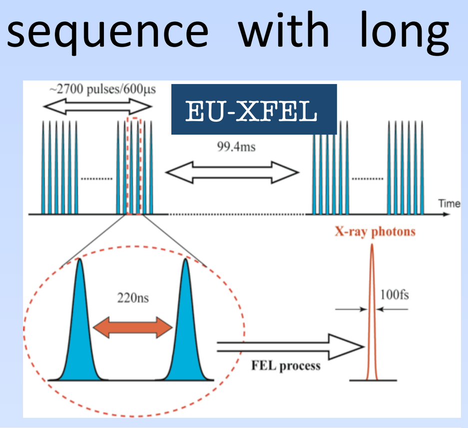
Nel lungo periodo la collaborazione PixFEL vuole sviluppare una X-ray camera versatile che possa essere operata sia in modo impulsato che in modo continuo alle future macchine FEL come Eu-XFEL o LCLS-II

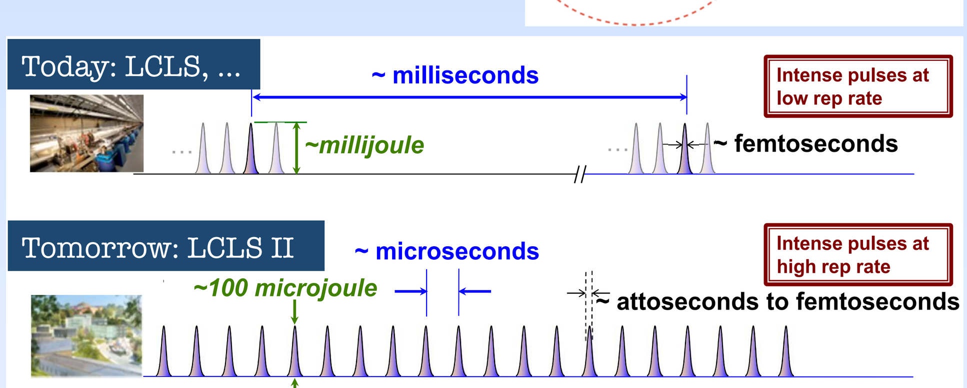
1. Free Electron Lasers

Coherent X-Ray beams with very high intensity and large energy range.

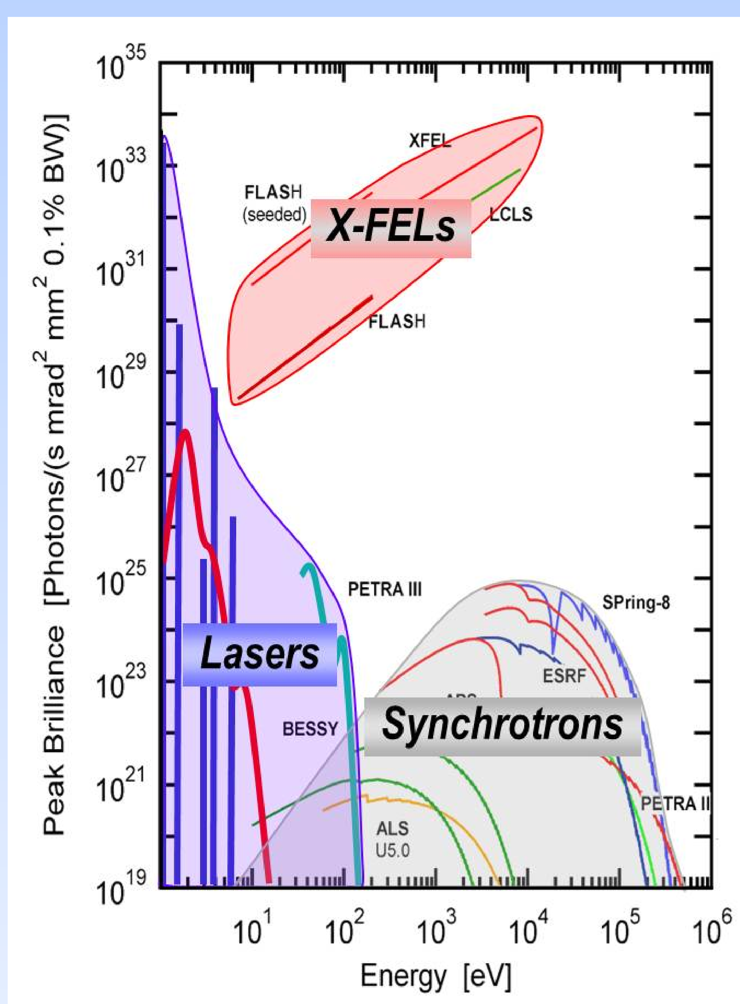
Very short (fs-as) and brilliant pulses:

- Burst mode: rapid sequence with long interval for readout.
- Continuous mode: up to 1 MHz pulses.





Burst and continuous mode beam time structure



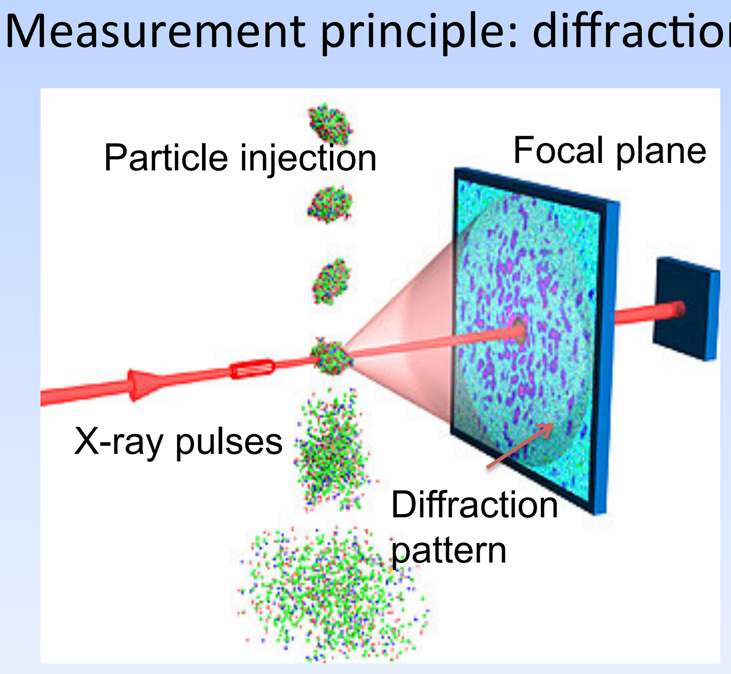
Peak brilliance vs. Energy for sources

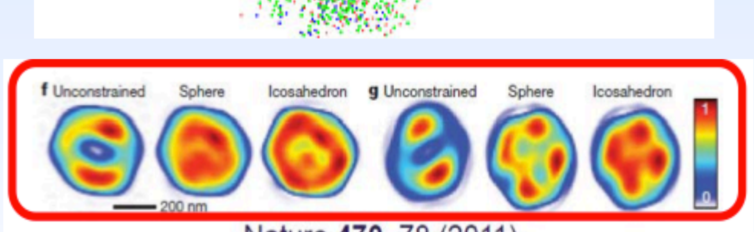
Project	Start of operation	Electron beam energy [GeV]	Photon energy [keV]	Frame/Burst repetition rate [Hz]	Number X pulses/burst
FLASH@DESY	2005	1.25	0.03-0.3	5	800@1us
LCLS@SLAC	2009	14.5	0.3-10	120	1
SACLA@RINKEN	2011	8	4.5-15	60	1
Fermi@ELETTRA	2010	2.4	0.01-0.06	10	1
European-XFEL	2015	17.5	0.4-20	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

FELS in operation or under construction

2. X-Ray FEL Detectors Challenges

Measurement principle: diffraction





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Ambiguity in reconstructed images of a virus coming from missing data due to dead area or saturation of pixel.

Frame rate
- Single shot imaging (<100fs pulse, 200 ns readout)
- Frame storage of complete bunch train (2700 pulses) for Eu-XFEL or fast readout for continuous machine (up to 1MHz)

Dynamic Range
- Single photon counting
- Up to 10^4 photons/pixel/pulse

Sensitive Energy Range
- 0.25-25 keV ideally with the same system

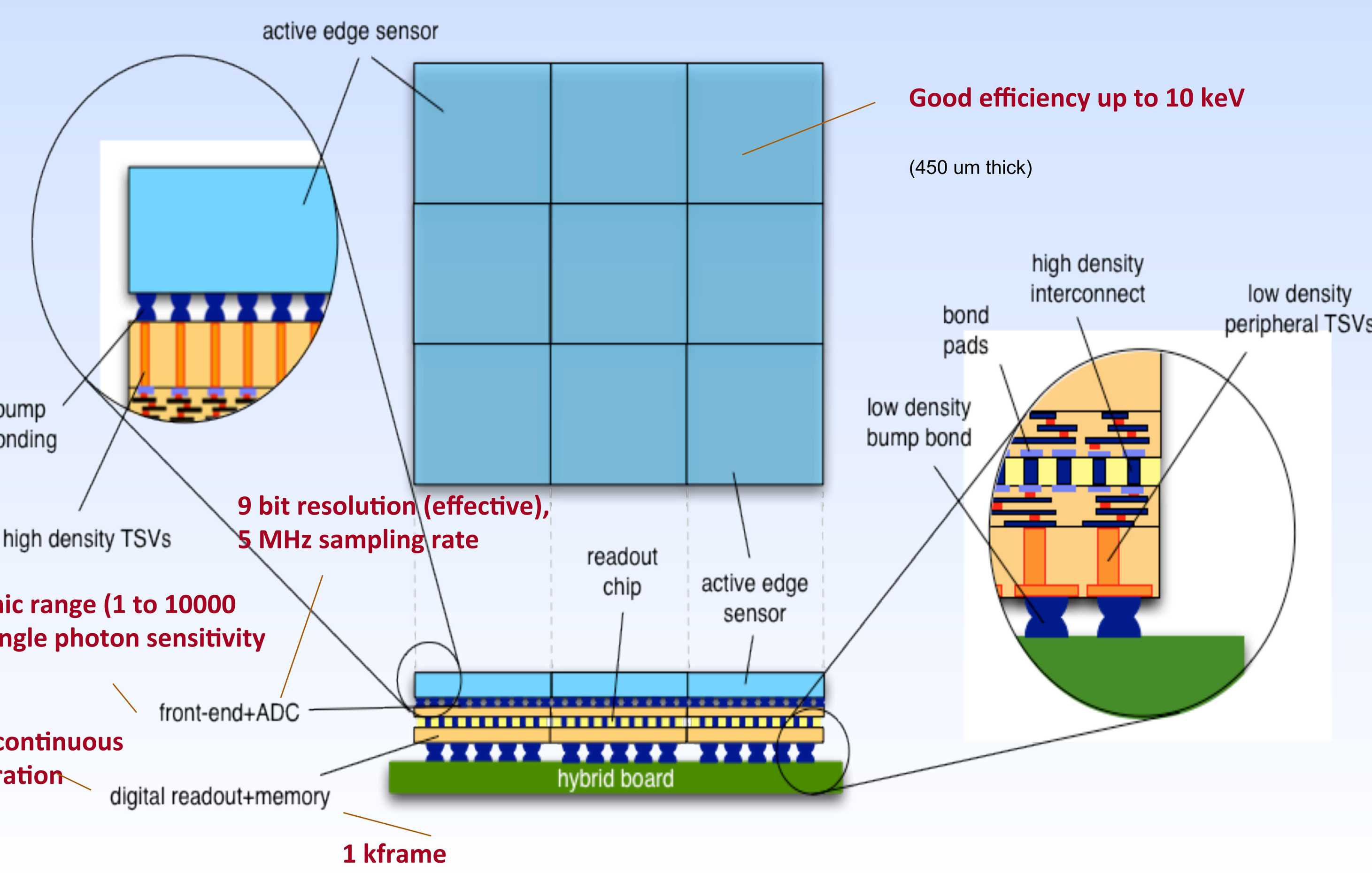
Radiation Hardness
- 10 MGy-1 GGy over 3 years operation

Pixel size:
- 700-20 μm, depending on distance & angular resolution required

Large area coverage:
- multiple tiles with no dead area

3. PixFEL Long Term Goals

Develop a four side buttable module for a large area X-ray camera for FELs using a multilayer device: active edge thick pixel sensor, two-tier CMOS readout chip (analog+digital/memory) with low/high density TSV, 65 nm technology to increase memory and functionality, in a small pixel pitch of 100 μm.



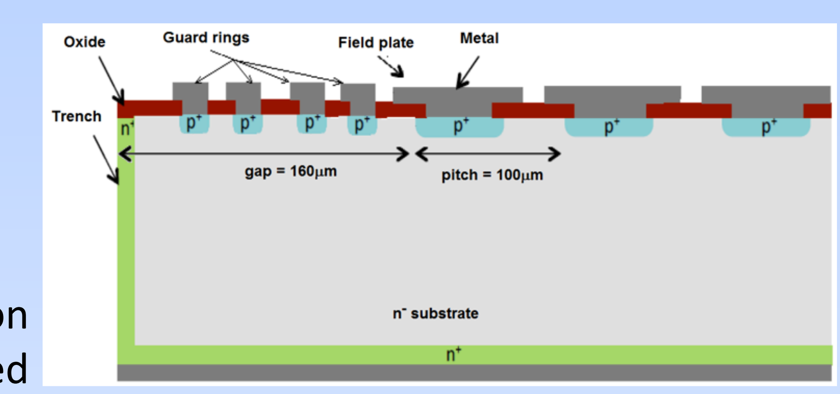
4. PixFEL Technologies

Silicon pixel sensors

Active edge, to allow tiling

450 μm thickness for efficiency

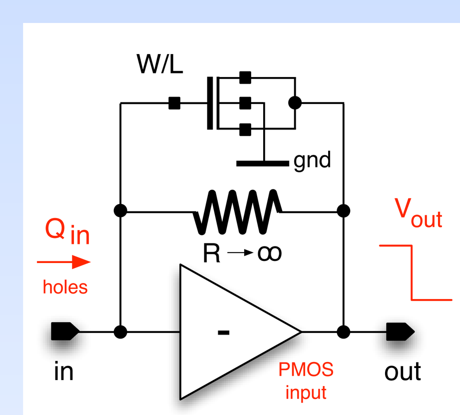
Optimized edge geometry:
- High voltage needed to have good collection efficiency even with the plasma effect caused by the large number of photons.



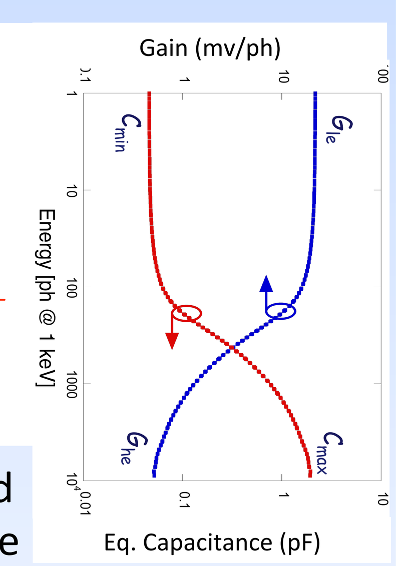
65nm CMOS readout

Dynamic compression amplifier
- Non-linear MOS caps for high dynamic range
- ENC = 60 e-RMS @ 50ns shaping
- Power = 350 μW/pixel

In-pixel 10 bit SAR ADC @ 5MHz sampling



Preamp schematic and simulated performance



Readout architecture

Burst mode operation
- 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
- With low repetition rate, OK. At 1MHz, very challenging.

Interconnections

Bump-bonding for sensor to preamp connection

Through-silicon vias for chip to chip connection
- Both high and low density TSV

5. Perspectives

- The PixFEL 3-year demonstrator project has been approved by INFN
  - explore application of innovative technologies to an X-ray FEL imaging camera: active edge sensors, 65 nm, Through Silicon Vias, 3D integration
- Great potentiality and synergy in cross-field fertilization
  - group mostly coming from HEP, learning its ways in X-ray imaging
- Longer term ambitious plan to develop full instrument
  - need to interact with user community and existing detector development groups

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