PixFEL

Enabling technologies, building blocks and architectures for advanced X-ray pixel cameras at FELs

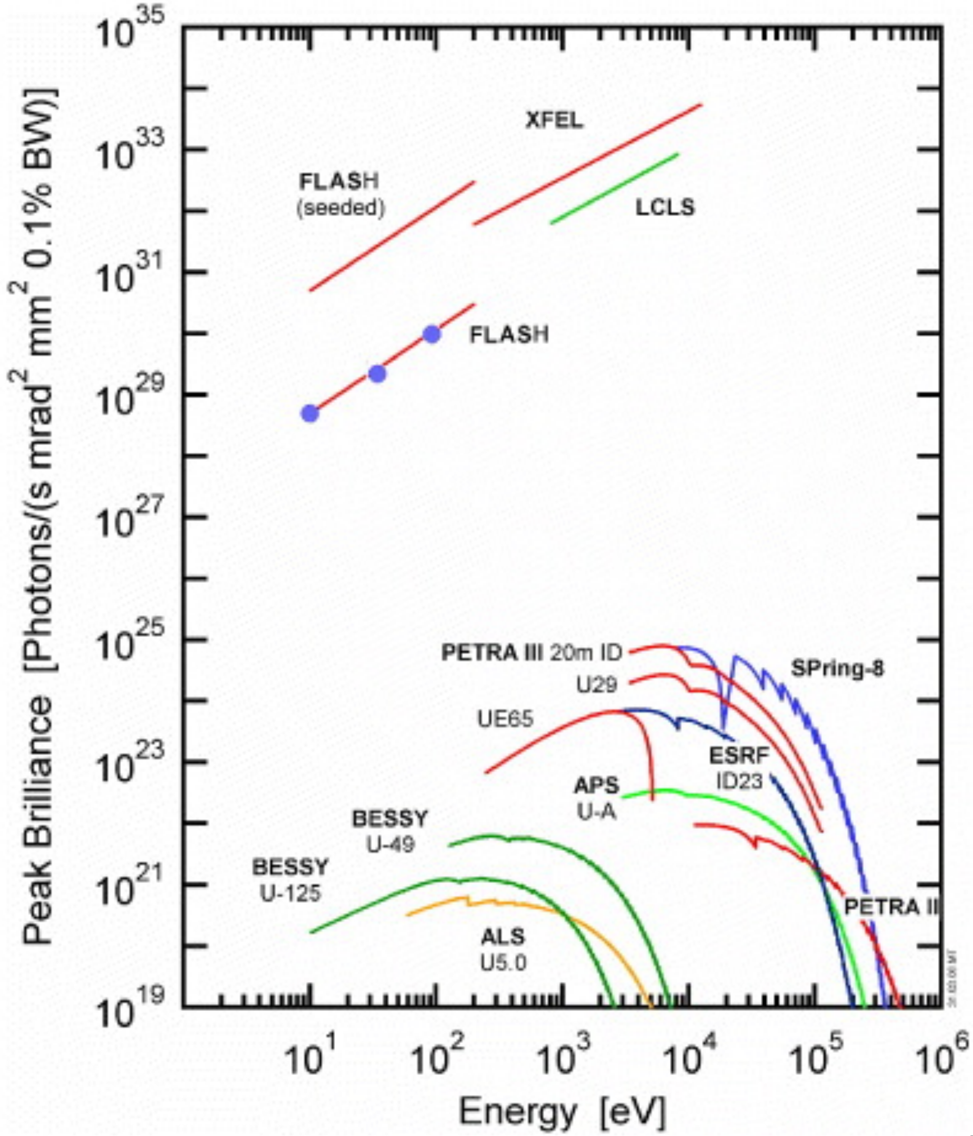
Presentazioni CSN5, INFN Sezione di Pisa 1/7/2013

Outline

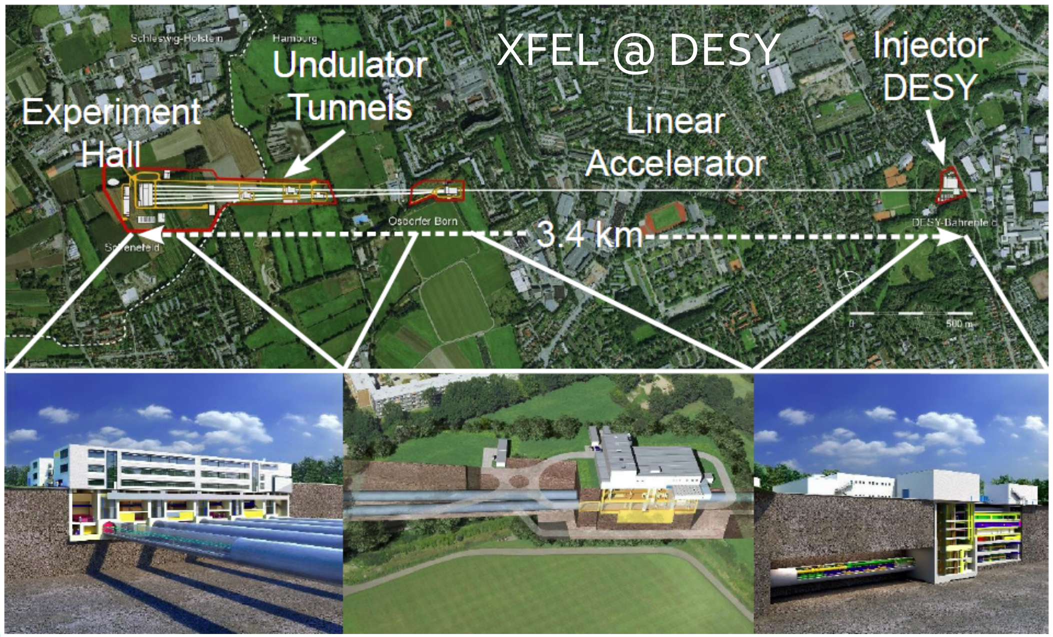
- Motivazioni
  - Macchine FEL e misure
  - Rivelatori
- Progetto PixFEL
  - Punti salienti
- Partecipazione di Pisa
  - Attività e manpower
- Conclusioni

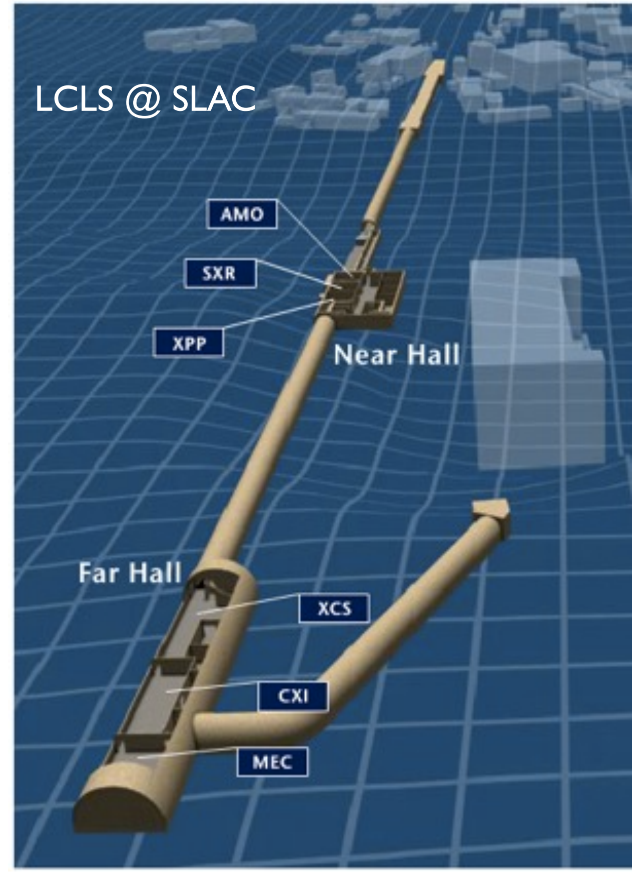
FEL Machines

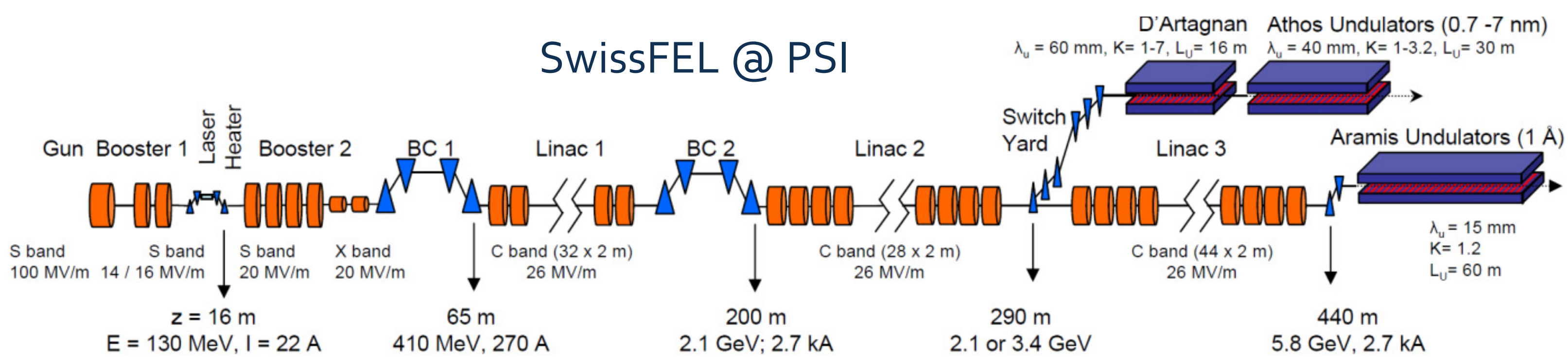
- FEL facilities provide high intensity beams of ultrafast X-rays
- Science program accessible at FELs is quite broad:
  - Structural biology: solve structures of large macromolecular biological systems
  - Chemistry: understand catalytic mechanisms (efficient conversion of light into electrical/chemical energy)
  - Material science: study transport and storage of information on increasingly smaller length- and faster time-scales.
  - Atomic and molecular science (AMO): study the fundamental interactions among electrons and between electrons and nuclei; explore the frontiers of light-matter interactions



Various FELs







FELs in operations or under construction

Project	**Status**	**First Lasing**	**T_{e-}**	**λ_{min}**	**Main Linac technology**	**Overall length**
FLASH	running	2005 (2000 TTF)	1.2 GeV	45 Å	Pulsed SC 1.3 GHz	315 m
LCLS	running	2009	14. 3GeV	1.5 Å	Pulsed NC 2.85 GHz	1700 m
FERMI@ELETTRA	running	2010	1.5 GeV	40 Å	Pulsed NC 3.0 GHz	375 m
SACLA@RIKEN	running	2011	8 GeV	1 Å	Pulsed NC 5.7 GHz	750 m
European XFEL	construction	2015	17.5 GeV →14 GeV	1 Å →0.5 Å	Pulsed SC 1.3 GHz	3400 m

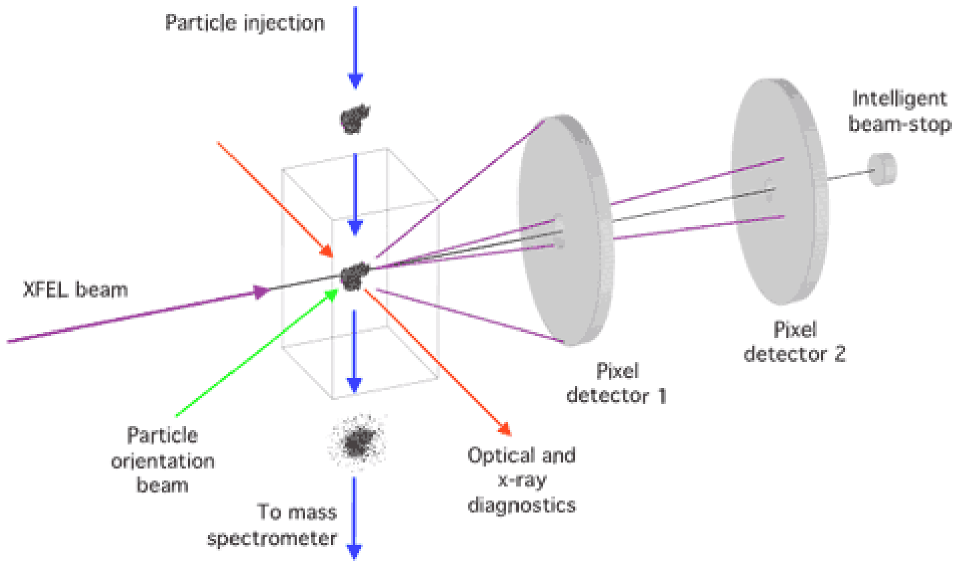
Proposals for new X-FEL facilities

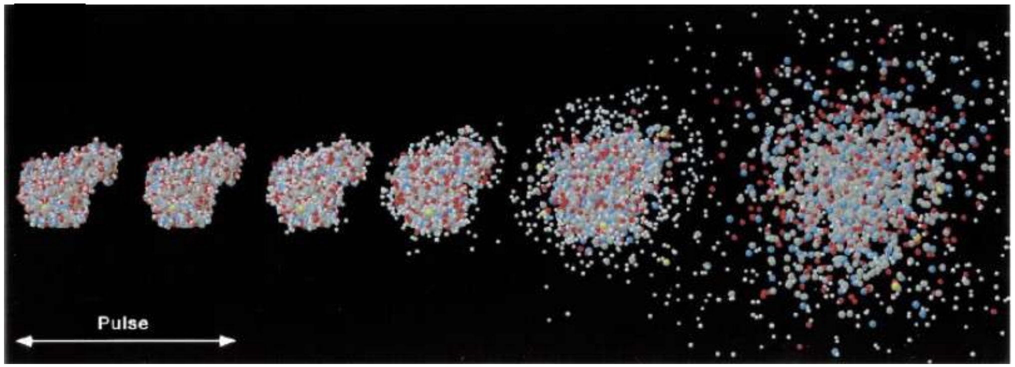
Project	Status	T_{e-}	λ_{min}	Main Linac technology	Overall length
SPARX	design report	2.4 GeV	5 Å	Pulsed NC 2.85 or 5.7 GHz	500 m
SwissFEL	design report	5.8 GeV	1 Å	Pulsed NC 5.7 GHz	715 m
PAL XFEL	design in progress	10 GeV	0.6 Å	Pulsed NC 2.85 or 5.7 GHz	900 m
Shanghai XFEL	design in progress	6.4 GeV	1 Å	Pulsed NC 5.7 GHz	600 m
MAX IV FEL	optional extension of MAX IV 3.5 GeV linac	?	?	Pulsed NC 2.85 GHz	?
NLS	design report	2.25 GeV	12 Å	C.W. SC 1.3 GHz	700 m
NGLS	design in progress	2.4 GeV	12 Å	C.W. SC 1.3 or 1.5 GHz	?
BESSY soft X-ray FEL	design report	2.3 GeV	12.4 Å	C.W. SC 1.3 GHz	450 m

	LCLS	LCLS II	Eu-XFEL	SACLA	FLASH	FLASH II	FERMI	SwissFEL	PAL XFEL	Shanghai XFEL	NGLS	MaRIE
Shortest wavelength	1.5 Å	1 Å	0.5 Å	1 Å	40 Å	40 Å	40 Å	1 Å	1 (0.6) Å	1 Å	10 Å	0.3 Å
Undulator type hard X-ray.	Fixed gap	Variable gap	Variable gap	In-vacuum Var. gap	n.a.	n.a.	n.a.	In-vacuum var. gap	Variable gap	Variable gap	n.a.	?
Undulator type soft X-ray.	n.a.	Variable gap	Variable gap	n.a.	Fixed gap	Variable gap	Apple II	Apple II	Apple II	?	Var. gap & Apple	n.a.
Injector	S-band RF gun	S-band RF gun	L-band RF gun	Pulsed Diode	L-band RF gun	L-band RF gun	S-band RF gun	S-band RF gun	S-band RF gun	S-band RF gun	VHF c.w. RF Gun	?
Cathode	Cu	Cu	Cs_2Te	CeB_6 (thermionic)	Cs_2Te	Cs_2Te	Cu	Cu	Cu	Cu	K_2CsSb	?
Main linac technology	n.c. Pulsed	n.c. pulsed	s.c. pulsed	n.c. pulsed	s.c. pulsed	s.c. pulsed	n.c. pulsed	n.c. pulsed	n.c. pulsed	n.c. pulsed	s.c. c.w.	n.c. pulsed
RF frequency	S-band	S-band	L-band	C-band	L-band	L-band	S-band	C-band	S-band	C-band	L-band	S –band
RF Rep. rate	120 Hz	120 Hz	10 Hz	60 Hz	10 Hz	10 Hz	10-50 Hz	100 Hz	120 Hz	60 Hz	n.a.	60 Hz
FEL pulses/RF pulse	1	1	2700	1	2700	2700	1	2	1	1	1 MHz c.w.	100
max. bunch charge	0.25 nC	0.25 nC	1 nC	0.2 nC	1 nC	1 nC	0.5 nC	0.2 nC	0.2 nC	0.2 nC	0.3nC	0.1 nC
max. electron energy	13.6 GeV	14 GeV	17.5 GeV	8 GeV	1.2 GeV	1.2 GeV	1.5 GeV	5.8 GeV	10 GeV	6.4 GeV	2.4 GeV	12 GeV
No. RF stations	81	81	29	69	5	5	15	34	49	?	?	?
Approx. facility length	1.7km	1.7km	3.4 km	0.8km	0.32 km	0.32 km	0.5 km	0.7km	1.1 km	0.6 km	?	1.0 km
Start operation	2009	2017	2015	2011	2005	2013	2010	2016	2015	2019	2023	?

Alcune misure ai FEL

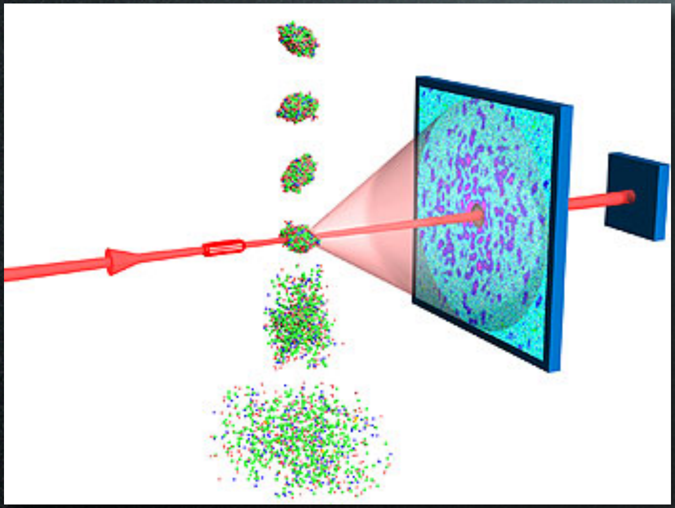
Single Particle Scattering

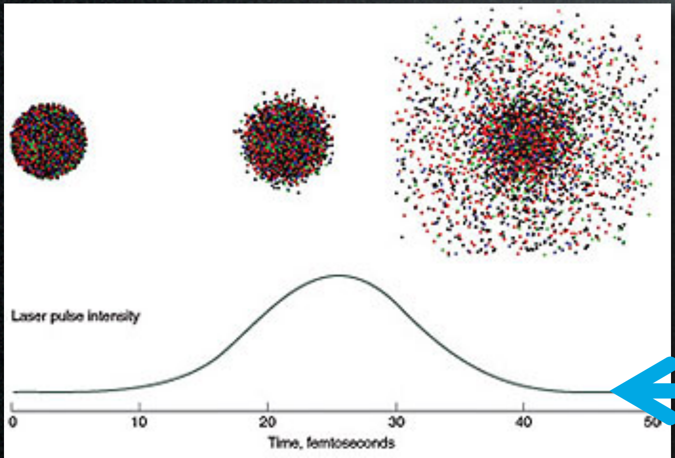




- Intense femtosecond pulses.
- 120 Hz frame rate.
- Single photon sensitivity.

Protein imaging





Lawrence Livermore National Laboratory (LLNL)

Using extremely short and intense X-ray pulses to capture images of objects such as proteins before the X-rays destroy the sample.

Single-molecule diffractive imaging with an X-ray free-electron laser.

Individual biological molecules will be made to fall through the X-ray beam, one at a time, and their structural information recorded in the form of a diffraction pattern.

The pulse will ultimately destroy each molecule, but not before the pulse has diffracted from the undamaged structure.

The patterns are combined to form an atomic-resolution image of the molecule.

The speed record of 25 femtoseconds for flash imaging was achieved.

Models indicate that atomic-resolution imaging can be achieved with pulses shorter than 20 femtoseconds.

M.Ferrario

make a movie of chemical reactions

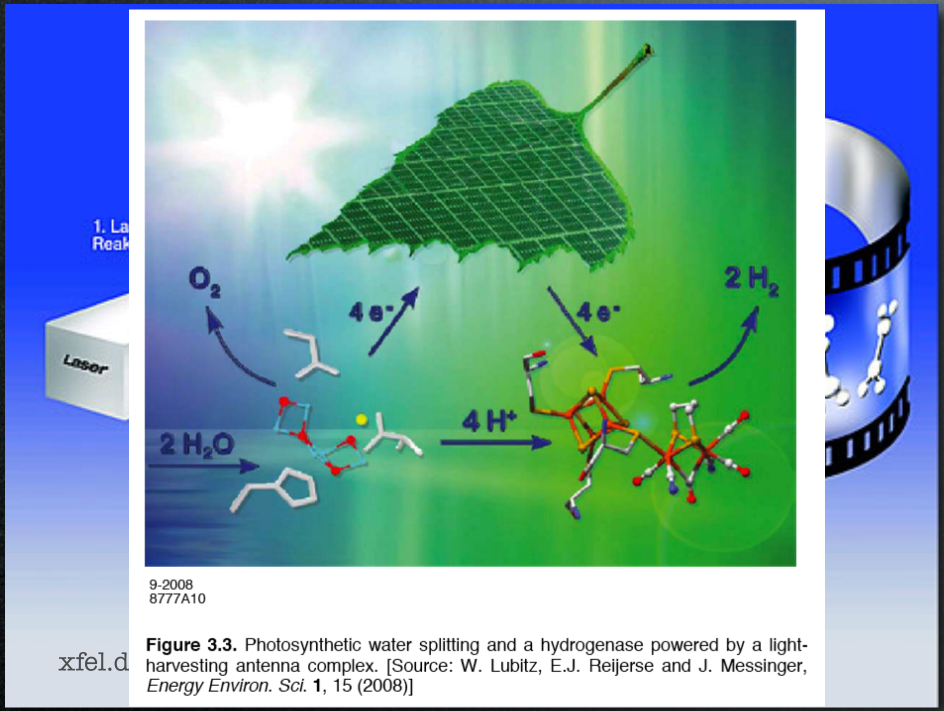


Figure 3.3. Photosynthetic water splitting and a hydrogenase powered by a light-harvesting antenna complex. [Source: W. Lubitz, E.J. Reijerse and J. Messinger, *Energy Environ. Sci.* **1**, 15 (2008)]

Chemical reactions often take place incredibly quickly: orders of magnitude of femtosecond are not rare. The atomic changes that occur when molecules react with one another take place in moments that brief.

The XFEL X-ray laser flashes make it possible to film these rapid processes with an unprecedented level of quality.

Since the flash duration is less than 100 femtoseconds, images can be made in which the movements of detail are not blurred.

And thanks to the short wavelength, atomic details become visible in the films.

To film a chemical reaction, one needs a series of pairs of X-ray laser flashes.

The first flash in each pair triggers the chemical reaction. With the second flash, a snapshot is then made.

The delay between the two flashes can be precisely modified to within femtosecond and a series of snapshots can be made at various times following the start of the reaction.

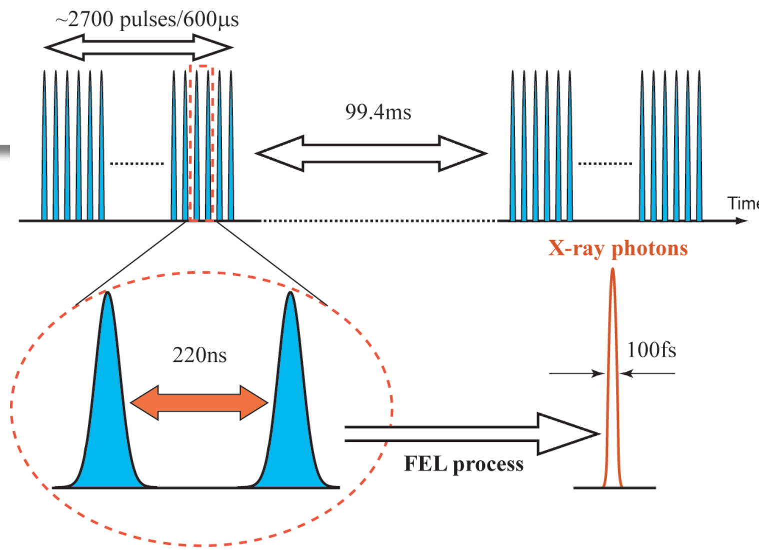
In each case, the images are of different molecules, but these images can be combined into a film.

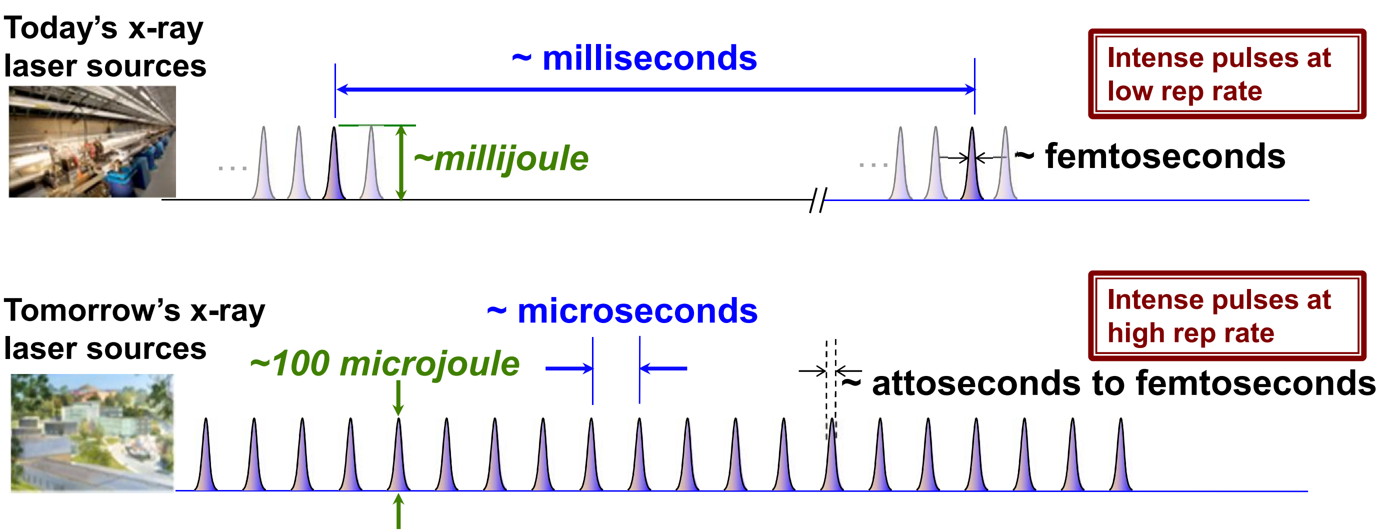
M.Ferrario

Beam time structure

- Each pulse is always very short
- LCLS: continuous operation @ 120Hz
- XFEL: 220ns spacing, with time to readout
- Future: continuos 1MHz spacing

XFEL





NLGS

Which detectors are needed for the foreseen experiments?

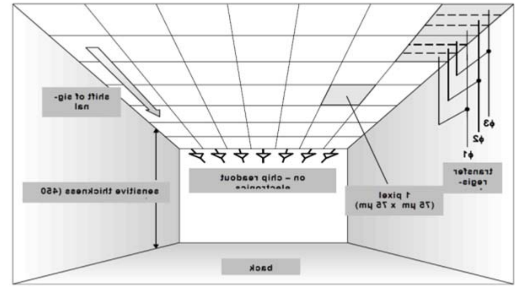
In general every experiment may require a specific detection system but we can identify two major scientific cases:

- **energy-sensitive detectors** with Fano-limited energy resolution for spectroscopic experiments, possible position-sensitivity for angular-dispersive experiments (0-D and 1-D detectors):
  - silicon drift detectors
  - high-Z detectors
  - cryogenic detectors
  - etc.

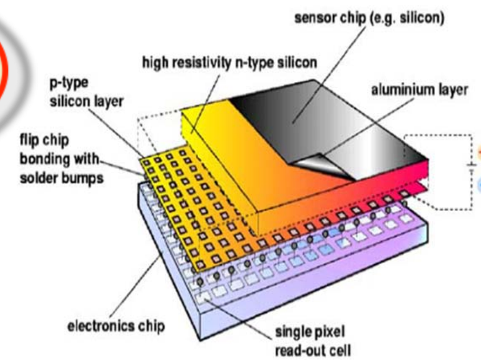
- **area detectors for imaging experiments**, diffraction (2-D detectors):
  - Charge-coupled devices
  - Hybrid Pixel Detectors
  - Monolithic Active Pixel Sensors
  - etc.

Technology options for 2D X-ray detectors

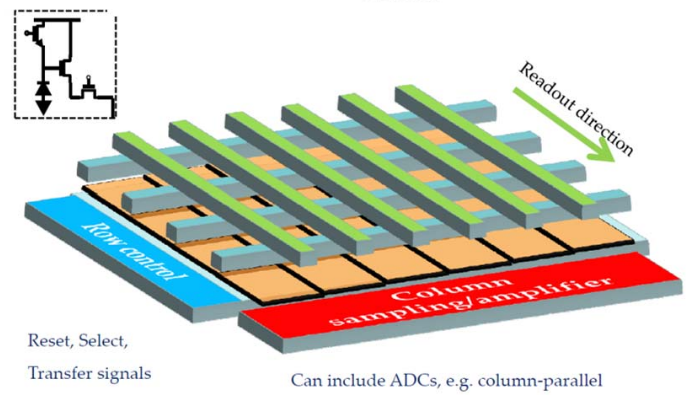
- ❑ **Fully-depleted pn-Charge-Coupled Devices (pnCCDs)**
  - very low noise (~2 el rms)
  - high QE in the range E=0.1-10keV
  - full frame rates limited to 200 Hz
  - full well capacity ~ 10^6 el. (but horizontal blooming)



- ❑ **Hybrid pixel detectors (HPDs)**
  - detector and front-end ASIC optimized separately
  - bump-bond size limits pixel size and capacitance
  - low energy X-rays critical if no on-chip transistor is available
  - issue of bump-bonding process



- ❑ **CMOS Monolithic Active Pixel Sensors (MAPS)**
  - depleted region is the epilayer (max ~20µm), poor QE for E>1keV
  - charge collection by diffusion
  - large full well capacity
  - high dynamic range (20bit?)
  - high readout speed (up to few kHz frame frequency)



and other choices under continuous development:

- ❑ MOS CCDs
- ❑ «Passive» pixel sensors
- ❑ Position-sensitive Silicon Drift Detectors
- ❑ ……

2D Imaging Detector Requirements

XFEL Pulse Structure

Single shot imaging

(recording 100 fs, read out 200 ns)

Frame storage of complete bunch train (2700 pulses)

Dynamic Range

Single photon counting

(high angle/single particle scattering)

Integration of up to 10^4 ph/pixel/pulse

High accuracy at low intensity

Low accuracy at high intensity

→ different optimization of different E ranges

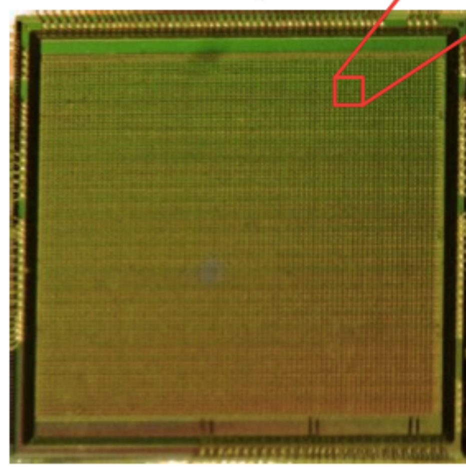
Sensitive Energy Range

0.25 (SCS, SQS) –25 keV (MID, HED)

Ideally with the same system

Vacuum and ambient pressure operation

Optimized entrance window for low E



Radiation Hardness

Integrated energy dose over 3 years operation

10 MGy - 1 GGy

Damage effects depend on energy range!

Graafsma JINST 4 (2009) pp. 12011

Angular Resolution

7 mrad for FDE experiments (worst case at 10 cm distance)

4 μrad for XPCS

Pixel size: 700 μm to 16 μm

(XPCS at 4 m distance)

Angular Coverage/ Sensor Size

Diffraction experiments require a resolution of 0.1 nm

scattering angles of 60° (120°)

(FXE, CDI, and SPB)

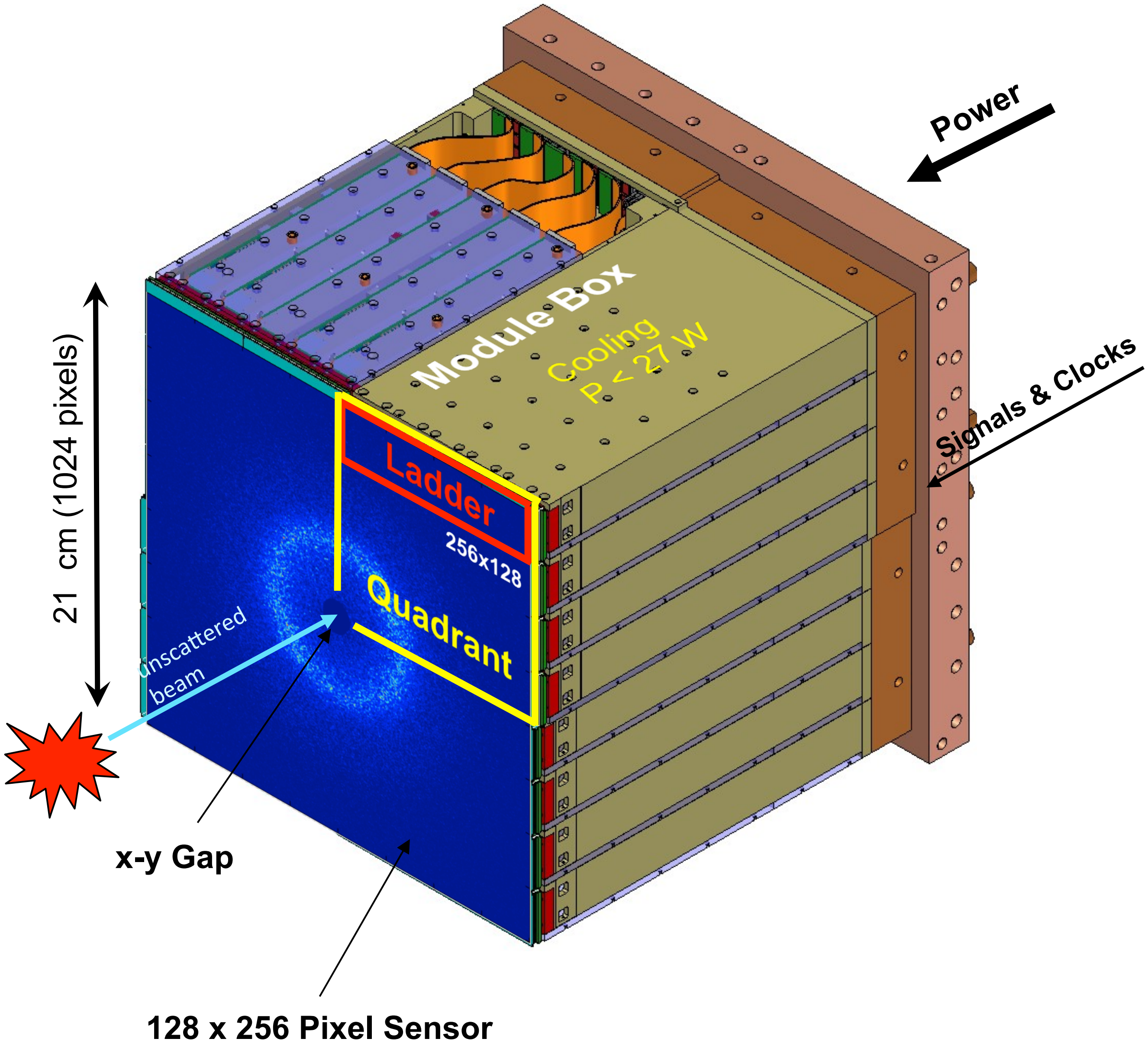
multiple detector segments

Main Scientific Applications

MID, XPCS, FXE, SPB and SQS

Match the environmental conditions of the experiment stations

DSSC Overview- Focal Plane Overview



- 1024x 1024 pixels
- 16 ladders/hybrid boards
- 32 monolithic sensors 128x256 6.3x3 cm^2
- DEPFET Sensor bump bonded to 8 Readout ASICs (64x64 pixels)
- 2 DEPFET sensors wire bonded to a hybrid board connected to regulator modules
- Dead area: ~15%

Progetto PixFEL

Nasce dall'idea di applicare gli sviluppi di rivelatori a pixel per HEP ad un sistema di rivelazione per i FEL.

Scopo finale di di costruire un sistema utilizzabile dai gruppi di ricerca nel campo della photon physics.

Nella fase iniziale ci concentremo su un dimostratore che verifichi gli elementi innovativi.

Fasi successive da realizzare anche attraverso Horizon2020

Tentativo di coinvolgere da subito le industrie per l'ingegnerizzazione del sistema (FBK, CAEN, …)

Sviluppo per: XFEL, LCLS, SwissFEL,NGLS … → necessario sviluppare contatti con le comunità degli utenti dei FEL

Concetto di PixFEL

- Sviluppo di un sistema ibrido espandibile per applicazione ai FEL
  - Due modi di operazione:
    - Burst mode – memoria locale e lettura successiva
    - Continuous mode – lettura frame per frame
- Sensore
  - inzialmente Silicio. Puo’ essere altro per energie più elevate dei fotoni.
- Front end electronics (interconnesso via bump bonding)
  - Sviluppare canale ad elevato range dinamico + ADC (65 nm)
  - Da poter leggere inizialmente in modo sequenziale frame per frame
- Digital chip (interconnesso via TSV su macro pixel)
  - Per poter fornire memoria locale e lettura successiva, o lettura a rate più elevato su link veloci

XFEL 2D imaging detectors

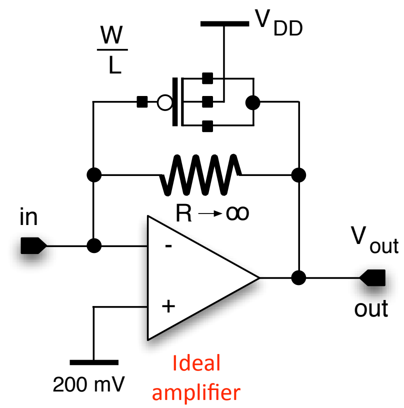
Table 1. Overview on 2D imaging detector development projects at the European XFEL. All detectors are based on Si sensor technology and will provide a spatial resolution close to the pixel size. All detectors are actively cooled and foreseen for vacuum operation, except the LPD.

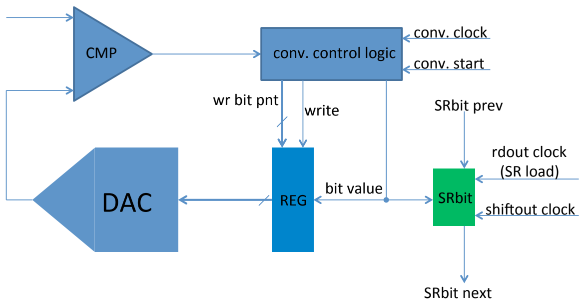
	Requirements	AGIPD	DSSC	LPD	pnCCD*	FCCD
Technology		Hybrid pixel	Hybrid pixel	Hybrid pixel	CCD	CCD
Pixel size	10...100's μm	200x200 μm^2	204x236 μm^2	500x500 μm^2	75x75 μm^2	30x30 μm^2
Detector size	1kx1k	1kx1k	1kx1k	1kx1k	256x256	1kx2k
Tiling, hole	Central, variable hole	Multiple tiles, variable hole	Multiple tiles, variable hole	Multiple tiles, variable hole	Monolithic no hole	Monolithic fixed hole
Quantum efficiency	>80%	>80%	>80% 0.5-13 keV	>80% 1-13 keV	>80% 0.3-13 keV	>80% 0.3-6 keV
Sensor thickn.		500 μm	450 μm	500 μm	450 μm	200 μm
Energy range	0.25-25 keV	3-13 keV	0.5-25 keV	1-25 keV	0.05-20 keV	0.25-6 keV
Dynamic range	10^3 … 10^4 …	10^4 at 12 keV	10^4	10^5 at 12 keV	10^3 at 12 keV	10^3 … 10^4
Noise	Single photon	300 el. rms	50 el. rms	1000 el. rms	2 el. rms	25 el. rms
Frame rate	4.5 MHz, 2700 images, 10 bursts/s	4.5 MHz, 352 images ana-logue on-chip	4.5 MHz, 640 images digital on-chip	4.5 MHz, 512 images ana-logue on-chip	200 Hz, continuous (*prototype)	200 Hz (1kx1k), continuous

Fast (AGIPD, DSSC, LPD) — Slow (pnCCD, FCCD)

Criticità ed innovazioni

- Elevato range dinamico, 1-10^4:
  → Preamplificatore a compressione di dinamica
- ADC entro 200 ns
  → Successive approx ADC 10 bit
- Tiling senza zone morte
  → Slim-edge sensors sviluppati per Alice, Atlas (FBK)
- Pitch: 100um
  →Tecnologia 65nm per aumentare la densità
- Readout e memoria: 1k frame depth
  →Uso di TSV per espandersi in profondità
- DAQ e banda di uscita
  → Critici ma non abbiamo soluzioni al momento

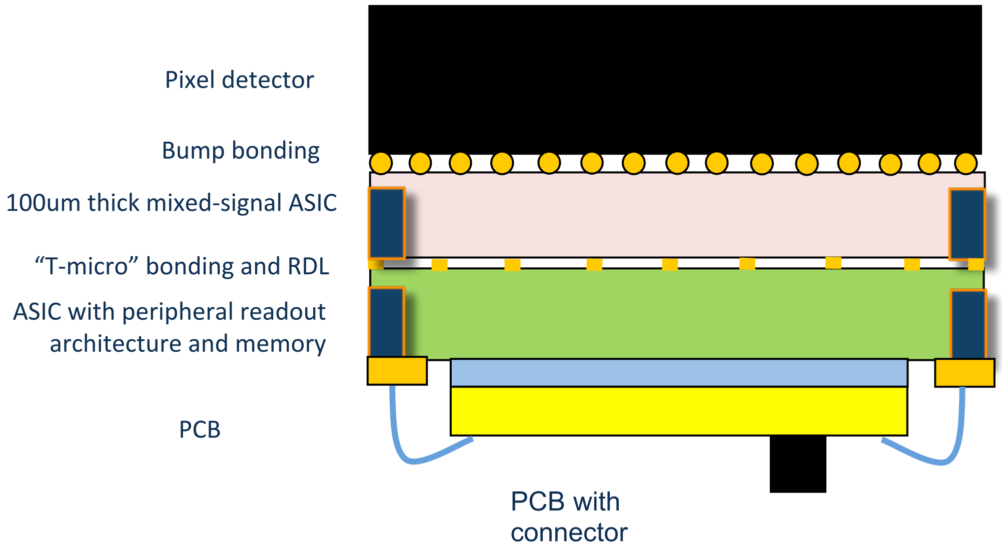




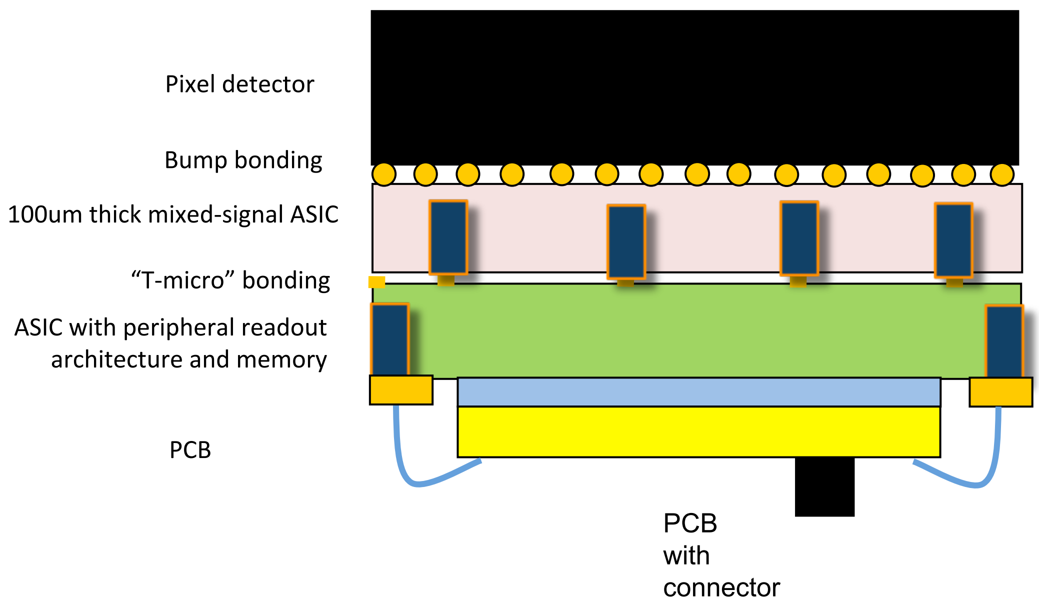
Long term activity plan

- In the long term (6+ years) the project aims at developing a 2D X-ray, pixellated camera for applications at FELs, complying with the following characteristics
  - 100 um pitch
  - 1 kFrame (?) storage capability
  - reconfigurability (?), for operation in burst and continuous mode
    - burst operation at a maximum frequency no less than 5 MHz
    - continuous operation at no less than 10 kHz (?)
  - 9 bits effective resolution
  - single photon detection capability
  - 10^4 photon @1 keV dynamic range
- To enable the integration of all the needed functionalities in a relatively small area, a 65 nm CMOS technology, in conjunction with a vertical integration process (including high density TSVs), will be adopted
- The final instrument will be based on the tiling of elementary blocks with minimum dead area to be achieved also by using low density TSV and active edge sensor technologies

Long term activity plan



- Uso di Through-silicon-vias periferici
- Lettura del chip analogico in modo sequenziale
- Chip digitale con memoria e sistema di comunicazione.



- Uso di Through-silicon-vias distribuiti
- Lettura del chip analogico in modo parellelo attraverso macro-pixel
- Chip digitale con memoria e sistema di comunicazione.

Aim of the PixFEL project

- Studying, designing and testing the building blocks (CMOS 65 nm) for the front-end electronics, complying with the application requirements
  - low noise, (reconfigurable) wide input range front-end channel with dynamic compression
  - 9 bit (effective), 5 MS/s ADC
  - circuits for gain calibration
- Investigating the enabling technologies for the design of chips with minimum dead area and high functional densities
  - standard and slim edge sensors
  - vertical integration for double tier design of the front-end
  - low density TSVs for chip interconnection to the hybrid board
  - interposers (?) for sensor to front-end pitch adaptation
- Looking into architectures for fast chip operation and readout
  - frame storage mode (memory cell, maximum memory size, readout)
  - continuous readout mode (maximum speed, accounting for DAQ limitations)
  - reconfigurability (impact on the performance)

Activities

- 2014
  - define chip specifications.
  - design of test structures with single blocks (analog front-end, ADC, circuits for gain calibration, single MOS capacitors, I/O circuits), CMOS 65 nm
  - design of a 8x8 matrix, 100 um pitch
  - design of standard pixel sensors
  - start investigation on readout electronics
- 2015
  - test the structures from the first run
  - start investigation on 3D integration processes, including low density TSVs
  - design of the 32x32 matrix (accounting for low density TSVs)
  - design of slim edge pixel sensors
  - interconnect the front-end chip to the (slim edge) pixel sensor
  - start writing VHDL and design some elementary digital block (memory cells, buffers)
  - start organizing the test beam
- 2016
  - test the 32x32 front-end chip
  - test the chip after interconnection with the detector
  - test structures including low density TSVs
  - complete VHDL design of the readout electronics
  - test the chip on a beam

Synergy with other experiments/projects

- In the framework of the WP3 (Microelectronics and Interconnection Technologies), the AIDA project is exploring 3D technologies for applications to radiation detection systems. In the same framework, people are developing microelectronics blocks in advanced technologies (including CMOS 65 nm) for chips to be interconnected by means of 3D processes

- The CMS and ATLAS collaborations have started a joint R&D activity to develop the next generation pixel detectors for the experiments at the HL-LHC. Front-end design is mostly based on 65 nm CMOS technology

- Other front-end design activities are being carried out by the two collaborations separately, again involving 65 nm CMOS technology

Gruppo

Pavia		Pisa		Trento	
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Lodovico Ratti	0.5	Giuliana Rizzo	0.5		
Valerio Re	0.1	Fabio Morsani	0.5		
Gianluca Traversi	0.3				
	3.7		**2.4**		**1.9**

TOTALE **8**

Attività a Pisa

- Collaborazione alla definizione delle specifiche
- Contatti con le facilities FEL
- Progetto convertitore SAR, logica in-pixel e architettura readout semplificata per chip prototipo singolo layer.
- Interconnessione chip-sensore
- Contributo al progetto del chip digitale per prototipo 2 layers (3D)
- Progetto e costruzione schede di test
- Caratterizzazione in lab dei vari chip prototipo
- Partecipazione al test su fascio (LCLS ?)

Budget Pisa – piano triennale

	2014		2015		2016	
Missioni	contatti con facilities FEL	6000	contatti con facilities FEL	6000		
					partecipazione a test beam	9000
	riunioni di collaborazione	2000	riunioni di collaborazione	2000	trasporto materiale	3000
			partecipazione a conferenza	2000	partecipazione a conferenza	2000
					riunioni di collaborazione	2000
	TOTALE MISSIONI	8000	TOTALE MISSIONI	10000	TOTALE MISSIONI	16000
Consumo	materiale per schede di test (PCB+carriers+componenti)	5000	materiale per schede di test (PCB+carriers+componenti)	5000		
			interconnessione chip e sensore con IZM (2 wafer sensori + 10 chip)	36000	meccanica per test su fascio	3000
			sistema di acquisizione	15000	shipping box per traporti	2000
	TOTALE CONSUMO	5000	TOTALE CONSUMO	56000	TOTALE CONSUMO	5000
Inventariabile						
totale		13000		66000		21000

Richieste servizi di sezione 2014

- Sviluppi del chip di elettronica e schede di test
  - Morsani: 50%
  - Minuti: 30%

- Assemblaggi di chip (un chip nel 2014)
  - Supporto del servizio A.T., per incollaggi, microsaldatura

Prospettive PixFEL

- Fino ad oggi nostri sviluppi focalizzati ad applicazioni di HEP
  - Anche se con attenzione ad altri campi, vedi rivelatore Radon.
- Sorgenti di finanziamento
  - INFN (CSN5) e MIUR (PRIN)
- Sempre più importante
  - Pensare ad applicazioni a campi diversi, non esclusivamente HEP
  - Trovare sorgenti alternative di finanziamento
    - FIRB
    - Progetti europei, Horizon 2020
    - Progetti regionali, fondazioni
  - Collaborazione con l'industria

BACKUP

Differences HEP vs. Photon Science Culture (slide from Peter Siddons, NSLS Brookhaven National Laboratory)

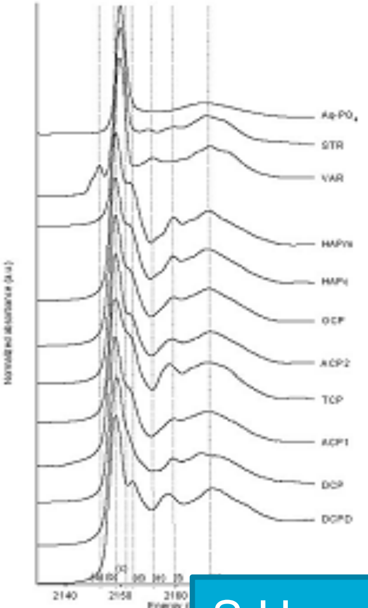
SLAC

SR and HEP are cultural opposites

- HEP: teams of hundreds for one experiment, complex detector system
- SR: teams of <10 usually,

  simple apparatus.
- HEP: Experiment takes years
- SR: Experiment takes hours or days
- HEP: Detector IS experiment
  - Scientists closely involved in design
- SR: SAMPLE is experiment:

  SR and detector a necessary evil
  - Scientists just want the result



S.Hermann

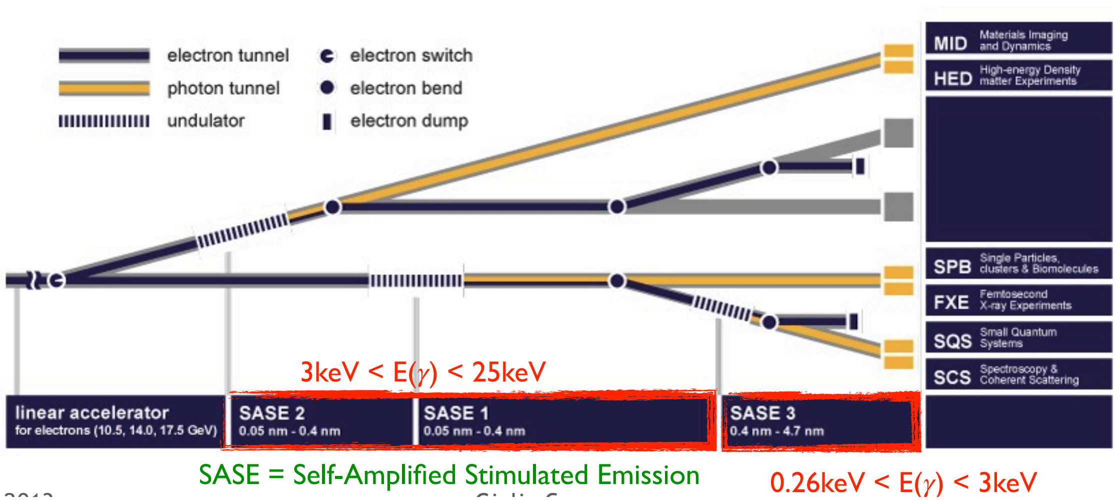
NSLS

NATIONAL SYNCHROTRON LIGHT SOURCE

BROOKHAVEN NATIONAL LABORATORY

Instrumental areas at EU-XFEL

1. Small Quantum Systems (SQS)
2. High Energy Density Matter (HED)
3. Coherent X-ray Scattering and Lensless Imaging in Materials Science (CXI)
4. X-ray Photon Correlation Spectroscopy (XPCS)
5. X-ray Absorption Spectroscopy (XAS)
6. Femtosecond Diffraction Experiments (FDE)
7. Single Particles and Biomolecules (SP
8. Research And Development (RAD)



xFEL vs LCSL

	LCLS	SACLA	European XFEL
Abbreviation for	Linac Coherent Light Source	SPring-8 Angstrom Compact Free Electron Laser	European X-Ray Free-Electron Laser
Location	California, USA	Japan	Germany
Start of commissioning	2009	2011	2015
Accelerator technology	normal conducting	normal conducting	superconducting
Number of light flashes per second	120	60	27 000
Minimum wavelength of the laser light	0.15 nanometres	0.08 nanometres	0.05 nanometres
Maximum electron energy	14.3 billion electron volts (14.3 GeV)	6-8 billion electron volts (6-8 GeV)	17.5 billion electron volts (17.5 GeV)
Length of the facility	3 Kilometer	750 Meter	3.4 Kilometer
Number of undulators (magnet structures for light generation)	1	3	5
Number of experiment stations	3-5	4	6, upgradeable to 10
Peak brilliance [photons / s / mm^2 / $mrad^2$ / 0.1% bandwidth]	$8.5 \cdot 10^{32}$	$5 \cdot 10^{33}$	$5 \cdot 10^{33}$
Average brilliance [photons / s / mm^2 / $mrad^2$ / 0.1% bandwidth]	$2.4 \cdot 10^{22}$	$1.5 \cdot 10^{23}$	$1.6 \cdot 10^{25}$

DSSC – Design Parameters

Parameter	
Energy range	optimized for 0.5 … 6 keV
Number of pixels	1024 x 1024
Sensor Pixel Shape	Hexagonal
Sensor Pixel pitch	~ 204 x 236 μm^2
Dynamic range / pixel / pulse	~5000 ph @ 0.5 keV > 10000 ph @ E≥1 keV
Resolution	Single photon detection also @ 0.5 keV
Frame rate	0.9-4.5 MHz
Stored frames per Macro bunch	≥ 640
Operating temperature	-20˚C optimum, RT possible

1 Mpixel camera with:

- Single photon sensitivity event at 0.5 keV
- high-dynamic range (>10000 ph/pixel)
- Frame rate up to 4.5 MHz (1 image every 220 ns)

All the properties have to be achieved simultaneously

DSSC will be the first instrument to fulfill this requirement

Camera integration from four side buttable