The PERCIVAL soft x-ray imaging detector for FERMI and SESAME.

Elettra Sincrotrone Trieste

Flavio Capotondi

(on behalf of DiProI users community, Percival and Fermi@Elettra projects)

ECSAC - International Conference on SESAME, Veli Lošinj, 01-10-2016

Topics

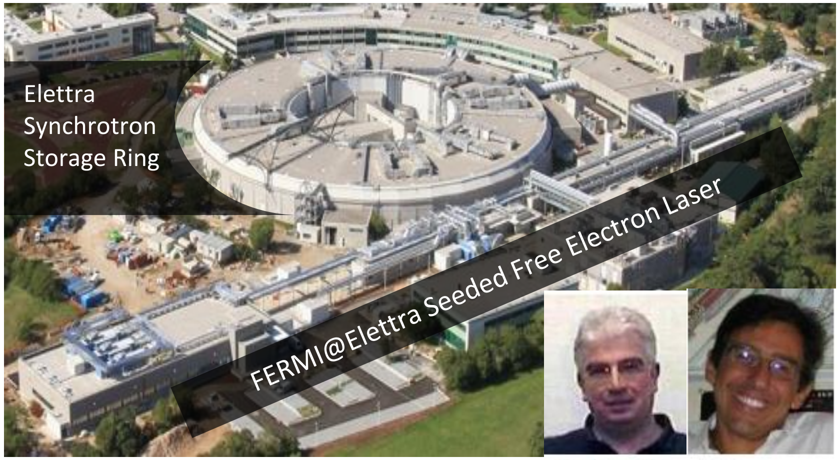
- **Introduction: seeded FERMI and DiProI beamline.**
- **CDI and detector requirements.**
- **PERCIVAL project.**
- **Research opportunities with PERCIVAL @ FERMI.**
- **Conclusions.**

Topics

- ***Introduction: seeded FERMI and DiProI beamline.***
- CDI and detector requirements.
- PERCIVAL project.
- Research opportunities with PERCIVAL @ FERMI.
- Conclusions.

Elettra Sincrotrone Trieste

FERMI the first seeded FEL source

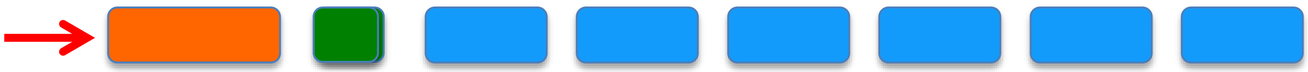


M. Svandrlik L. Giannessi

FERMI@Elettra is a single-pass seeded FEL user-facility in XUV/soft-X-ray:

- ✓ Two separate FEL amplifiers covering the spectral range from 100 to 4 nm (12-300 eV).
- ✓ FERMI-FEL1 is based on the high gain harmonic generation (HGHG) scheme.
- ✓ FERMI-FEL2 is based on double cascade "fresh" bunch scheme.

FERMI FEL-1
Single cascade

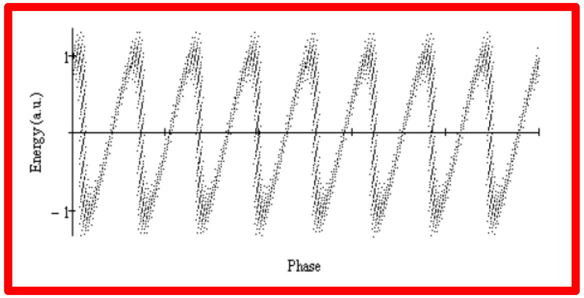


Seed
THG or
tuneable OPA

modulator

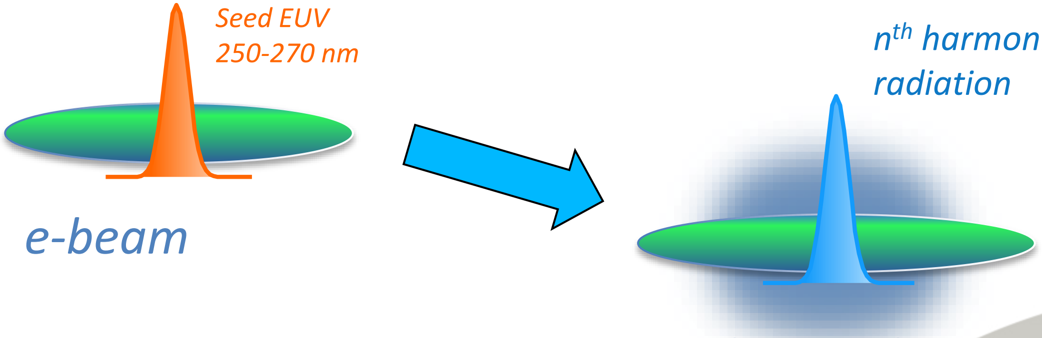
High gain radiator tuned at n^th harmonic

Dispersive section



Modulated beam

Bunched beam



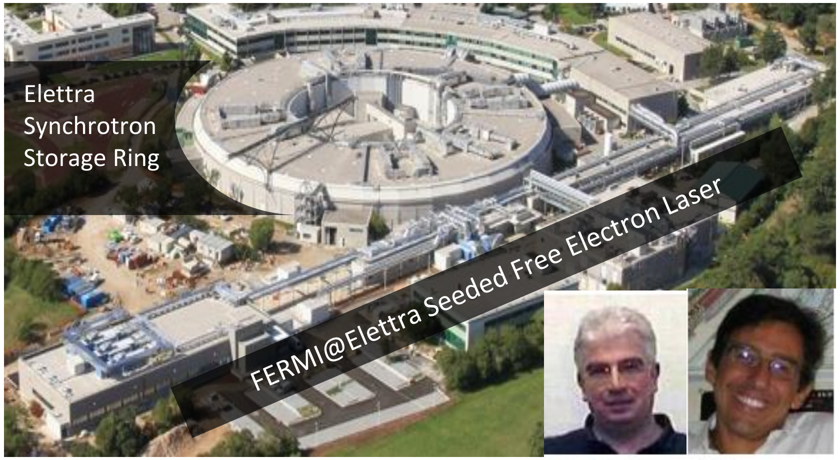
e-beam

modulated e-beam

E. Allaria et al., Nature Photonics, **6**, 699 (2012)

FERMI the first seeded FEL source

Elettra Sincrotrone Trieste



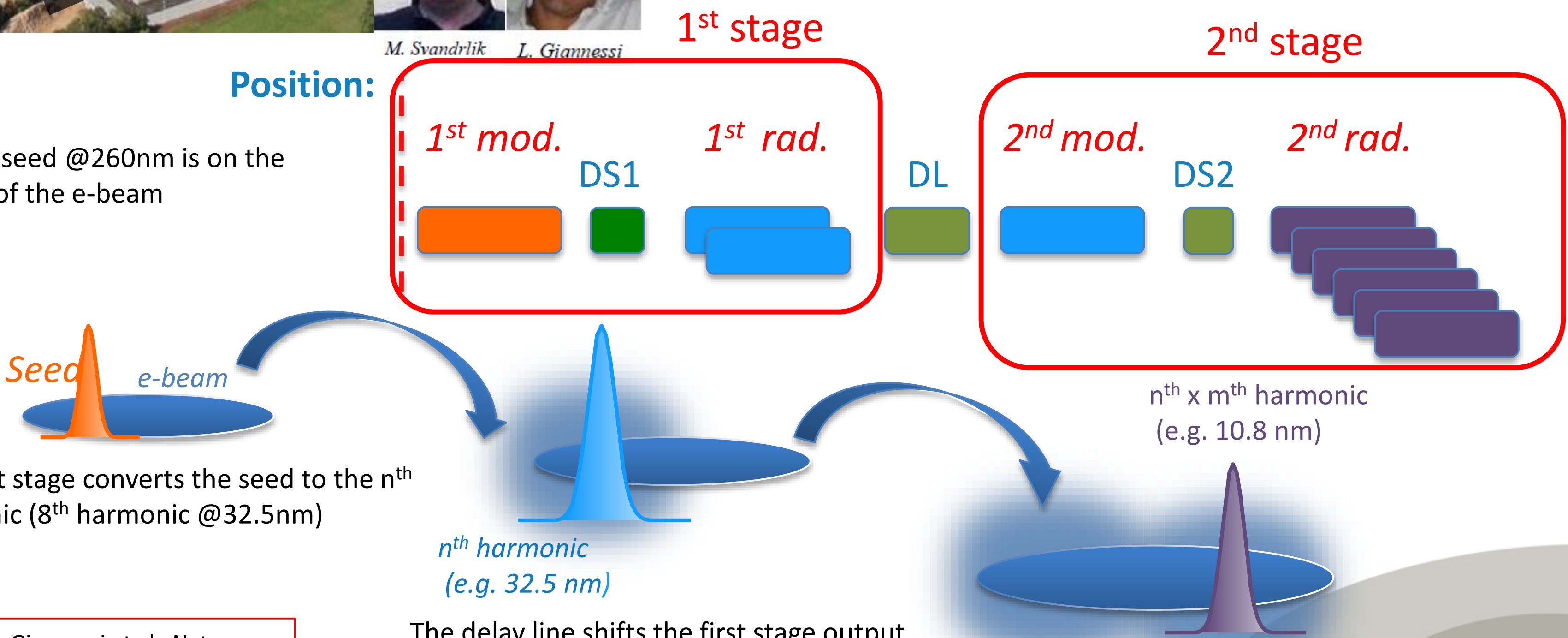
M. Svandrlik L. Giannessi

FERMI@Elettra is a single-pass seeded FEL user-facility in XUV/soft-X-ray:

- ✓ Two separate FEL amplifiers covering the spectral range from 100 to 4 nm (12-300 eV).
- ✓ FERMI-FEL1 is based on the high gain harmonic generation (HGHG) scheme.
- ✓ FERMI-FEL2 is based on double cascade "fresh" bunch scheme.

FERMI FEL-2

The fresh bunch technique



The seed @260nm is on the tail of the e-beam

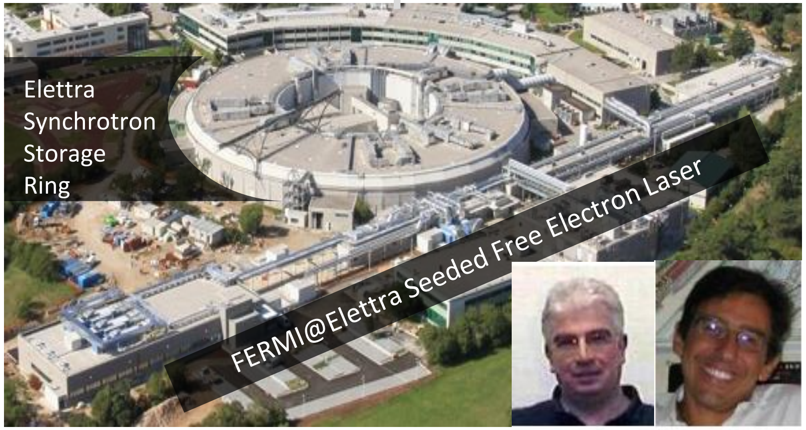
The first stage converts the seed to the nth harmonic (8th harmonic @32.5nm)

The delay line shifts the first stage output to a fresh portion of the e-beam

The second stage converts the first stage to the nth x mth harmonic of the seed

W.M.Fawley, L. Giannessi et al., Nature Photonics, **7**,913 (2013)

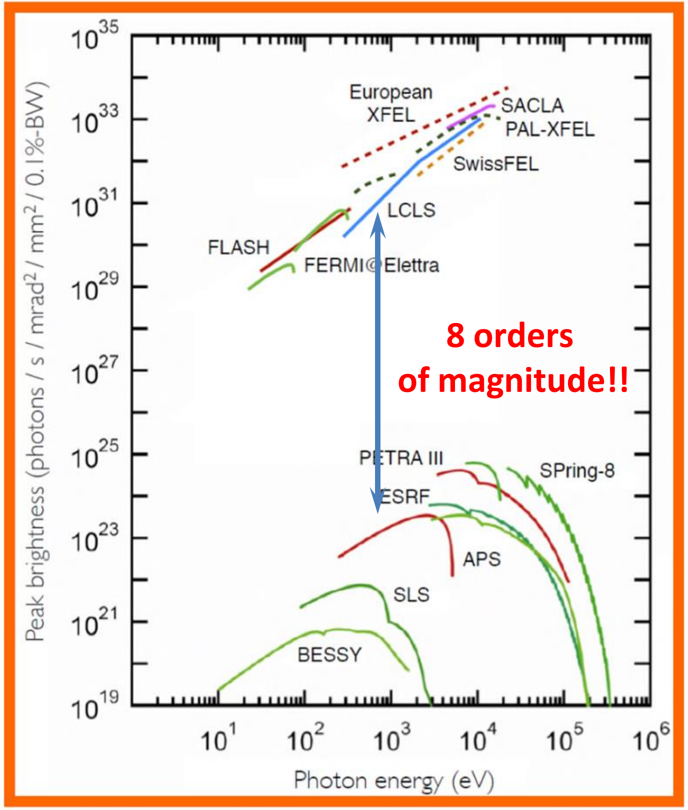
FERMI the first seeded FEL source



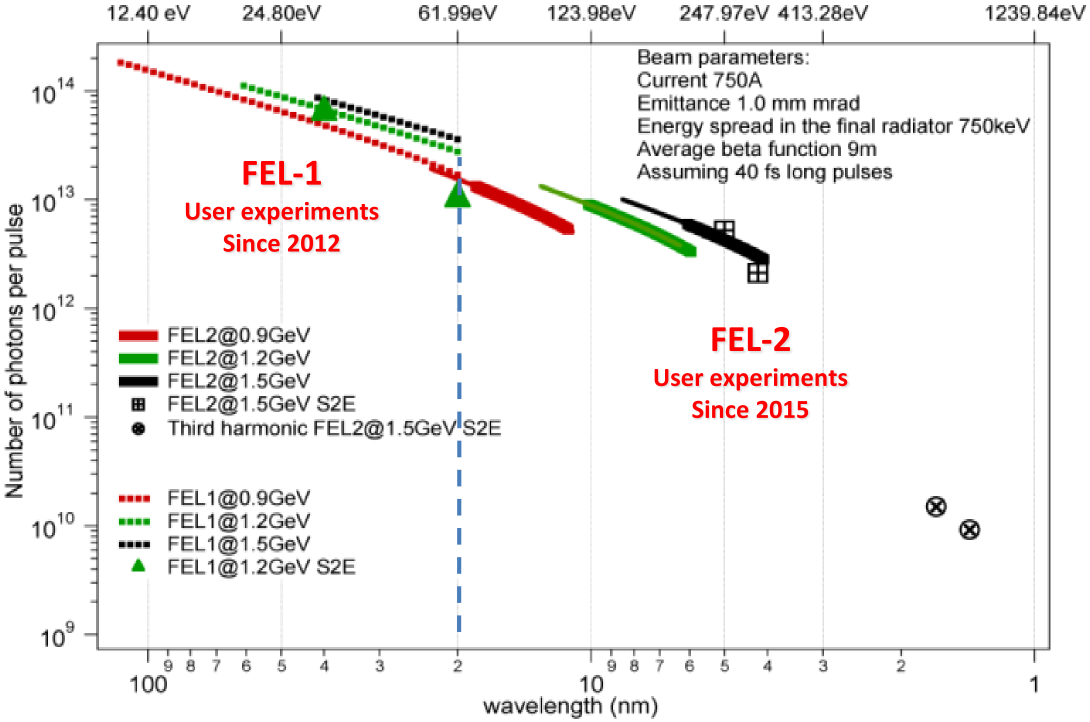
nnessi

FERMI@Elettra is an optical laser seeded FEL user-facility in XUV/soft-X-ray:

- ✓ Two separate FEL amplifiers covering the spectral range from 100 to 4 nm (12-300 eV).
- ✓ FERMI-FEL1 - based on the high gain harmonic generation (HGHG) scheme.
- ✓ FERMI-FEL2 - based on double cascade “fresh” bunch scheme.



8 orders of magnitude!!



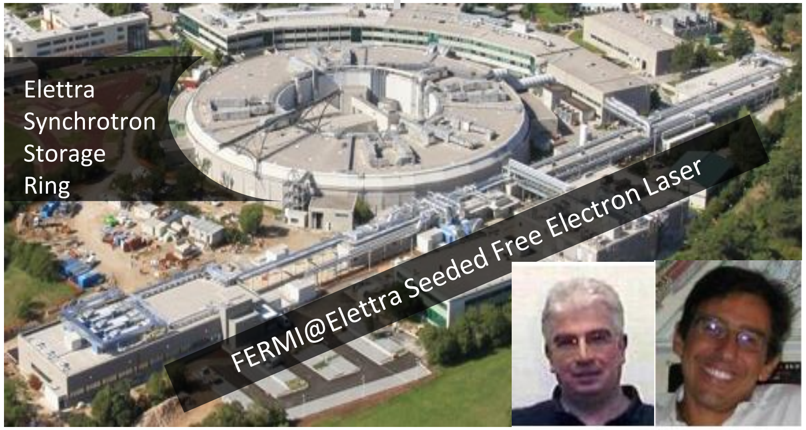
Beam parameters:
Current 750A
Emittance 1.0 mm mrad
Energy spread in the final radiator 750keV
Average beta function 9m
Assuming 40 fs long pulses

FEL-1
User experiments Since 2012

FEL-2
User experiments Since 2015

Elettra Sincrotrone Trieste

FERMI the first seeded FEL source



FERMI@Elettra is an optical laser seeded FEL user-facility in XUV/soft-X-ray:

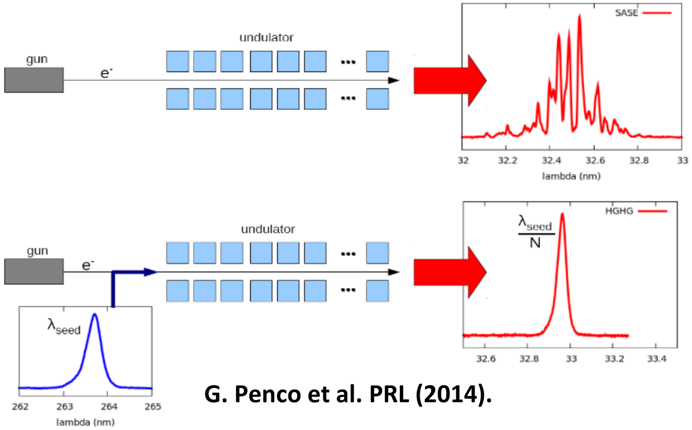
- ✓ Two separate FEL amplifiers covering the spectral range from 100 to 4 nm (12-300 eV).
- ✓ FERMI-FEL1 - based on the high gain harmonic generation (HGHG) scheme.
- ✓ FERMI-FEL2 - based on double cascade “fresh” bunch scheme.

Unique source characteristics compared to SASE FELs

High temporal coherence: pulses with defined Gaussian-like time–energy profiles - spectral purity $\Delta\lambda/\lambda \sim 10^{-4}$)

⇓

Ultrafast events with chemical sensitivity, single shot resonant CDI - **mandatory for wave mixing and phase controlled experiments**

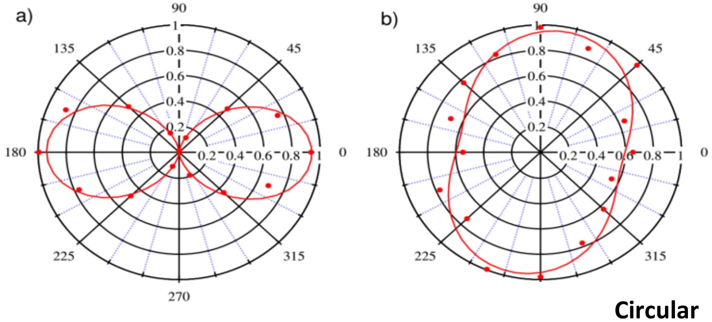


G. Penco et al. PRL (2014).

Variable polarization and fast energy tunability

⇓

Useful for near edge absorption for probing dichroic effects, such as resonant magnetic imaging



Circular Polarization ~ 95 %

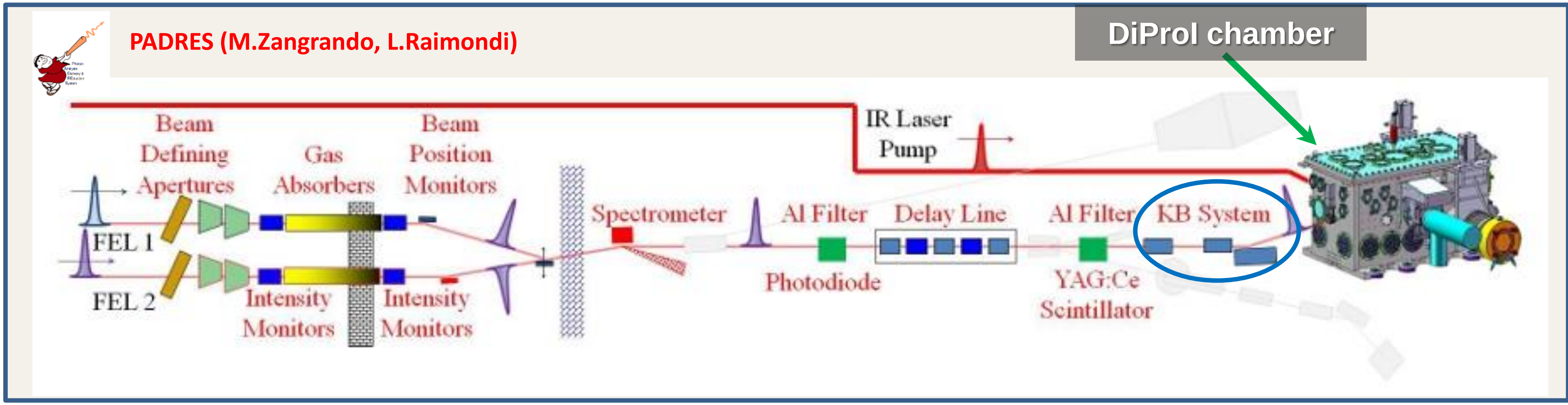
E. Allaria et al. PRX (2014).

Flavio Capotondi – ECSAC - International Conference on SESAME, Veli Lošinj, 01-10-2016

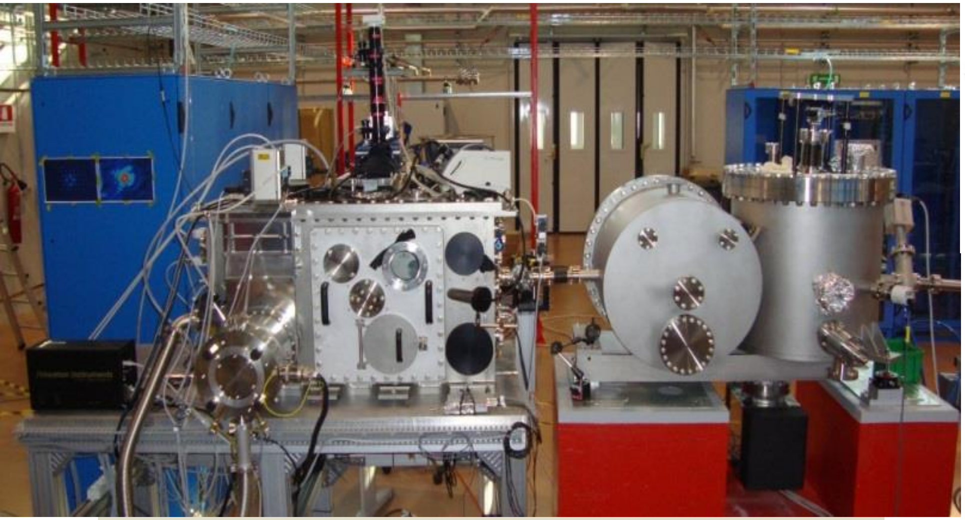
Why to use FERMI

- ✓ **Coherence** → Diffractive Imaging, holography
- ✓ **Intensity** → Matter under extreme conditions
- ✓ **Short Pulse** → fs time-resolved experiments
- ✓ **Tunability** → Resonant excitation and probe
- ✓ **Polarization** → Dichroism, magnetic scattering
- ✓ **Short λ** → Imaging, nanoscaple probing
- ✓ **Stability** → Integration, control, repeatability
- ✓ **Spectral Purity** → Monocromaticity, low time jitter

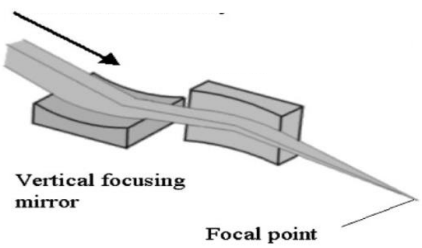
DiProI – BL Core capabilities

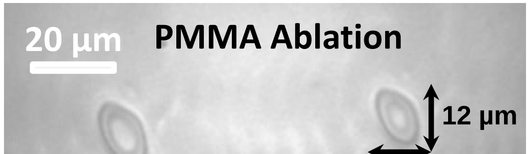


Bendable planar mirrors in Kirkpatrick-Baez configuration



Installed on dedicated FERMI beamline: June 2011
Open to User Experiments: December 2012





**Versatile modular cons
allowing exchange a
adding new compor**

May 2013 Volume 84 Number 5

AIP Review of Scientific Instruments

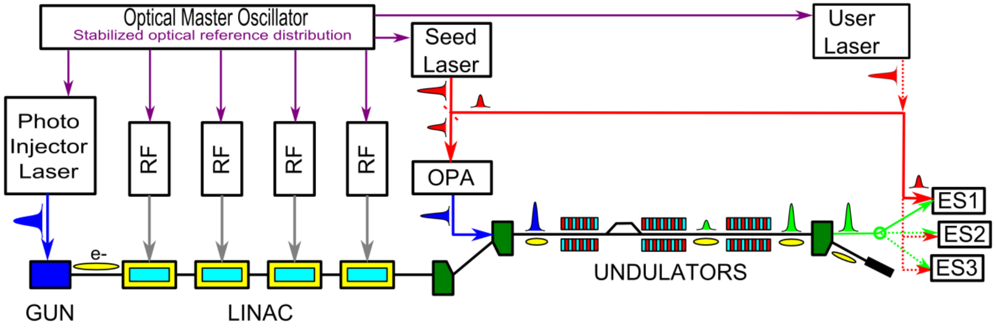
INVITED ARTICLE:
Coherent imaging using seeded free-electron laser pulses with variable polarization: First results and research opportunities
by F. Capotondi, E. Pedersoli, N. Mahne et al.

rsi.aip.org

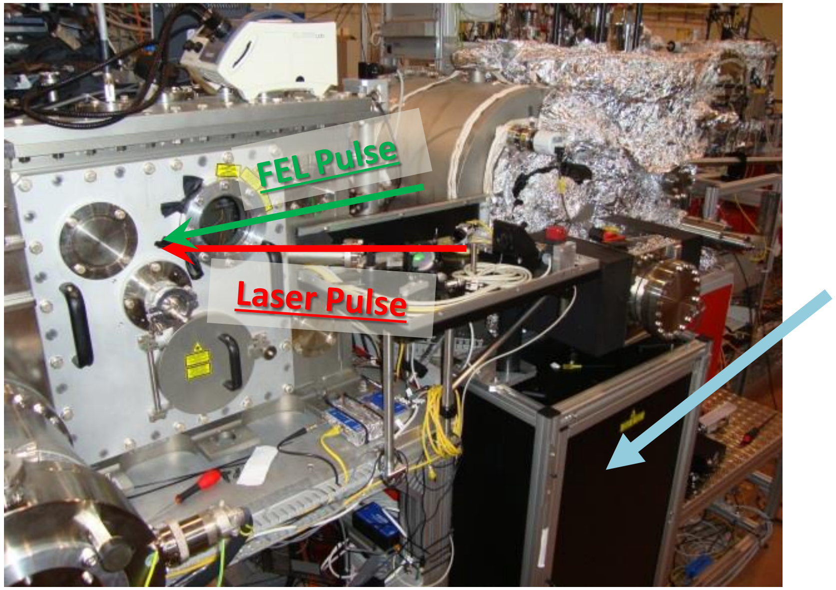
Instrument design in collaboration with:
**H.N. Chapman, S. Bajt, H. Fleckens
J. Schulz, J. Hajdu, M. Bogan**

Further info on DiProI end station:
F.Capotondi et al. RSI 84, 051301 (2013)
F. Capotondi et al. JSR 22, 544 (2015).

DiProI – P&P optical laser



P. Cinquegrana et al. Phys. Rev. STAB 17, 040702 (2014)



Optical breadboard (main features):

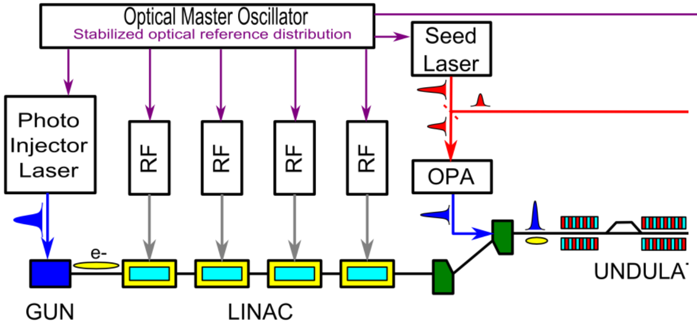
1. **Laser wavelength 780 nm (optional 2° and 3° harmonic), 750 μJ max power 150-70 fs pulse length.**
2. **Laser Polarizer.**
3. **Laser Attenuator.**
4. **Shot-to-shot pulse intensity.**
5. **Delay line +/- 660 ps.**
6. **Stabilization pointing feedback.**

Since Feb-2013 DiProI end station equipped with external user laser

In collaboration with: M.Danailov, A.Demidovich, K.Gabor, I.Nikolov, P.Cinquegrana, P.Sigalotti

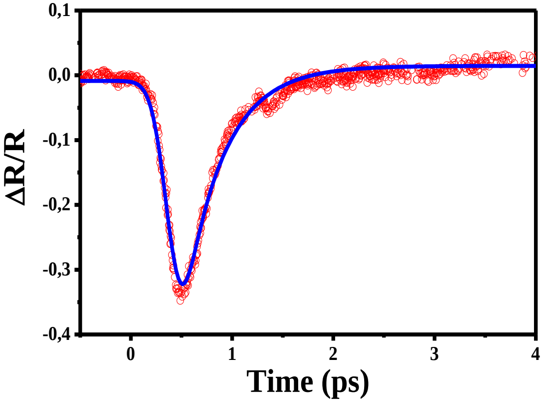
DiProl – P&P optical laser

Elettra Sincrotrone Trieste



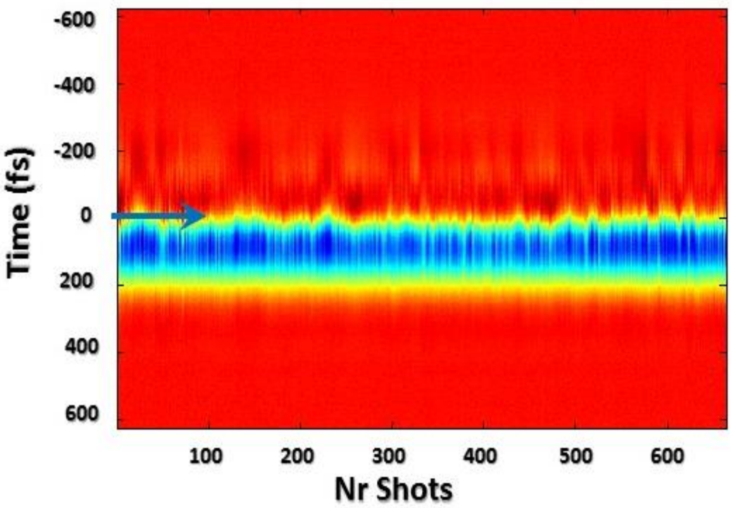
User Laser

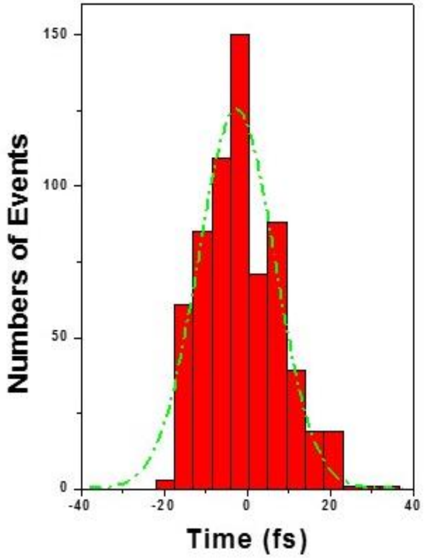
P. Cinquegrana et al. Phys. Rev. STAB 17, 0407(



nain features):

780 nm (optional 2° and 3°





Arrival time jitter between FEL and IR laser ~ 10±2 fs (RMS), i.e. 3 μm difference paths length of two beams on 100 m !!!

Measured on at the ½ drop point of the reflectivity curve.

Long term (~ 1 day) stability time zero between FEL and IR laser ~ 60 fs.

M.Danailov et al. “Towards jitter-free pump-probe measurements at seeded free electron laser facilities” Optics Exp. 22, 12869-12879 (2014).

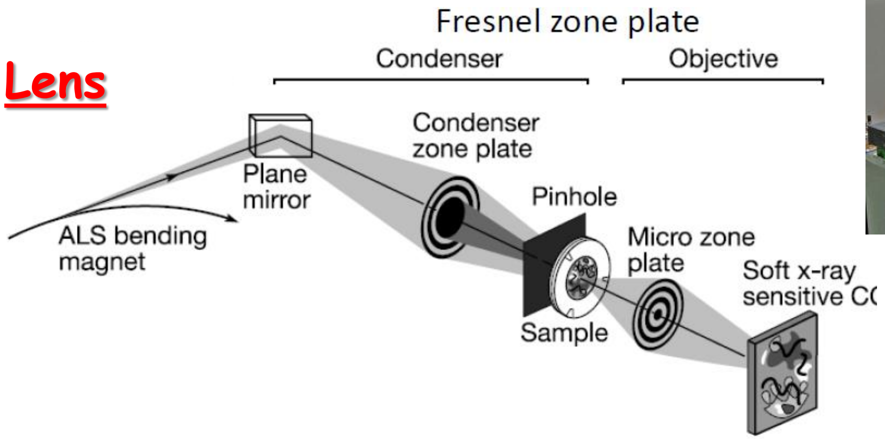
In collaboration with: M.Danailov, A.Demidovich, K.Gabor, I.Nikolov, P.Cinquegrana, P.Sigalotti

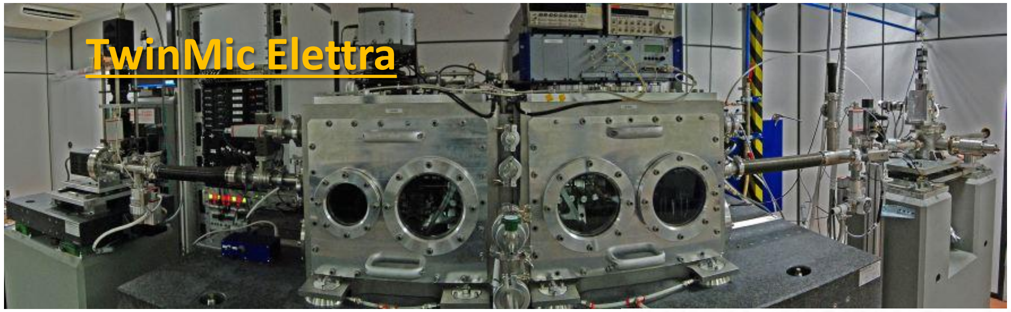
Topics

- Introduction: seeded FERMI and DiProI beamline.
- ***CDI and detector requirements.***
- PERCIVAL project.
- Research opportunities with PERCIVAL @ FERMI.
- Conclusions..

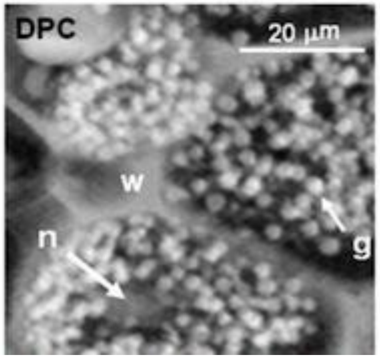
Lens vs Lensless imaging

Lens

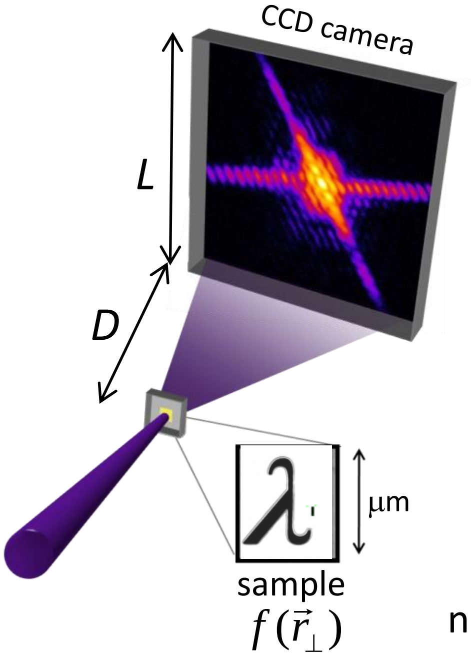




Lenses directly acquire information in real space, inverting the Fourier transformation by recombining at a given distance the scattered x-rays with correct phases making them interfere to form a replica of the object



Lensless



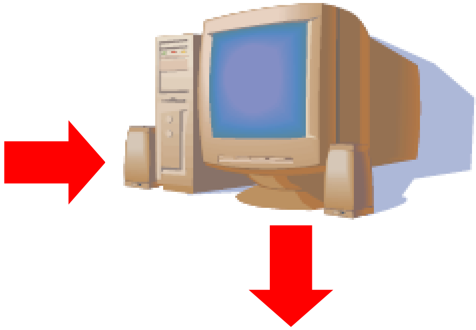
Measured diffracted intensity

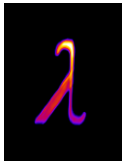
$$\left|TF\{f\}(\vec{k}_\perp)\right|^2$$

Phase lost

$$\cancel{\varphi(\vec{k}_\perp)}$$

no high quality optics for imaging!

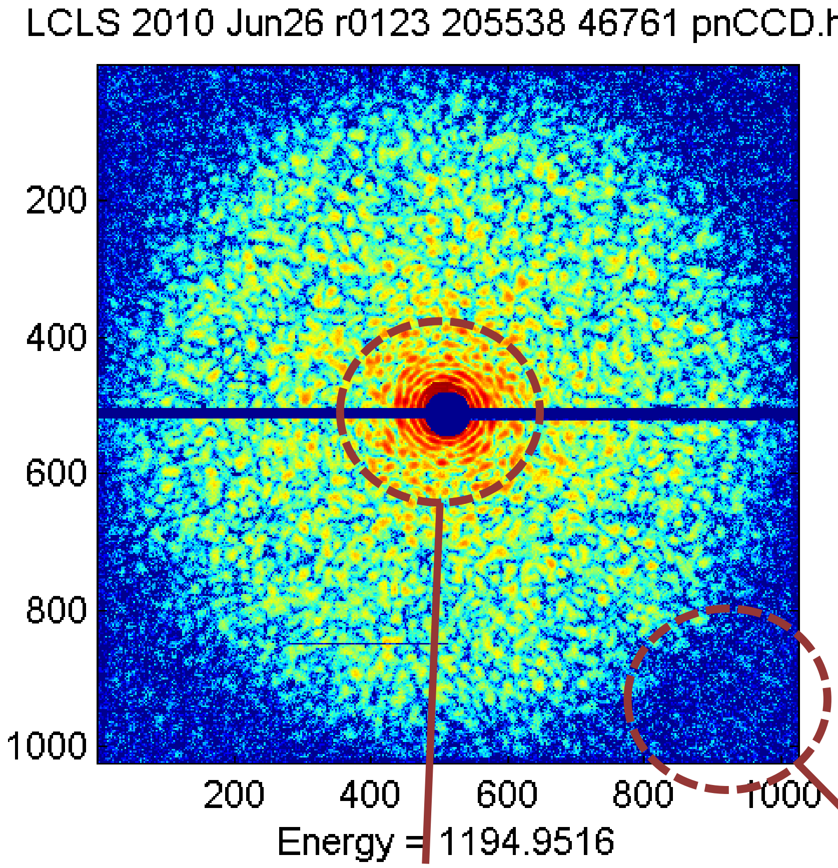


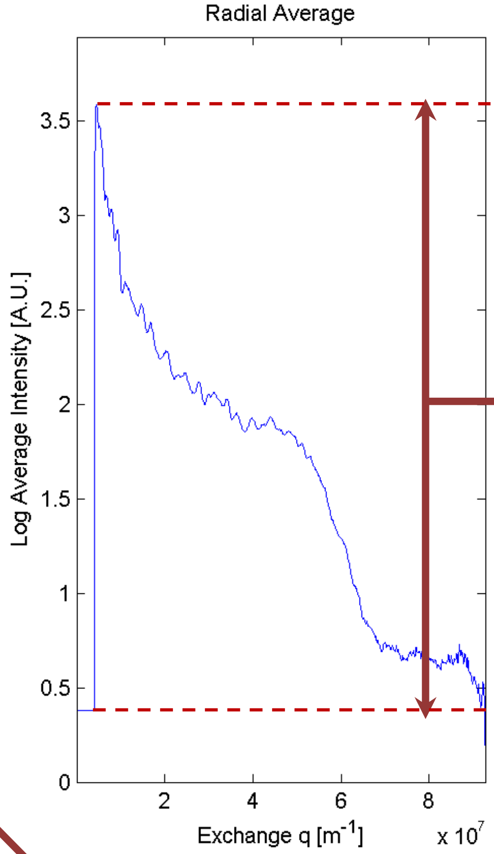


CDI acquire data in reciprocal space. In Fraunhofer approximation Diffraction pattern is related to the real-space object through a Fourier transformation, which encodes the image in propagation directions and phases of the electromagnetic field.

Typical speckle pattern

LCLS XFEL (Stanford) – Sample Culster of Core/Shell (Co/SiO_2) nanoparticles injected into FEL beam





3 - 3.5 Orders of magnitude

Low q, object dimension

High q, resolution

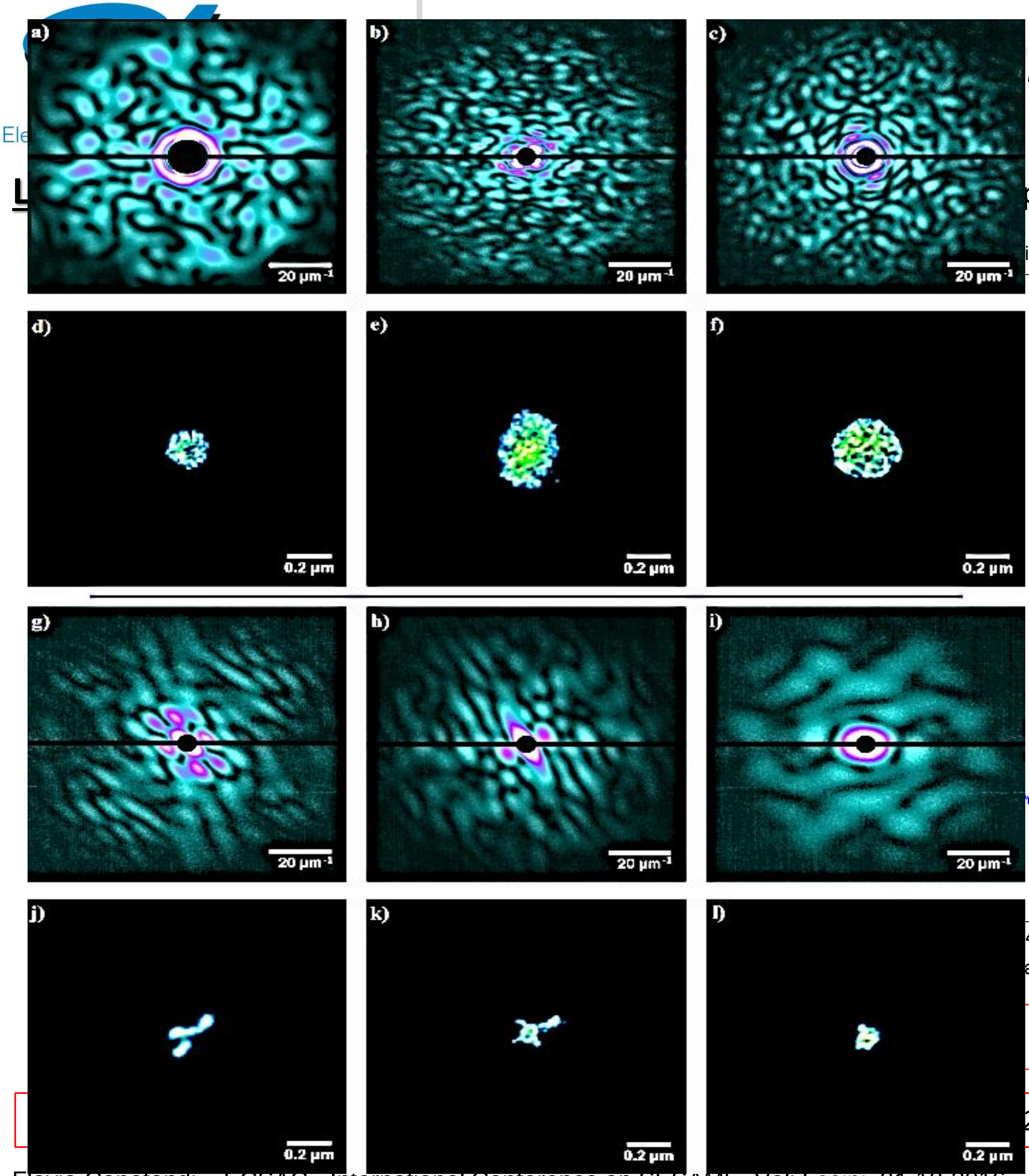
Pedersoli E. et al. *Journal of Physics B: Atomic, Molecular and Optical Physics, (2013).*

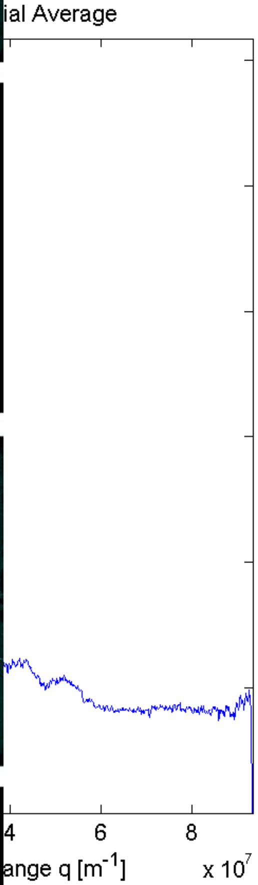
l speckle pattern

Ele

L

particles injected into FEL beam



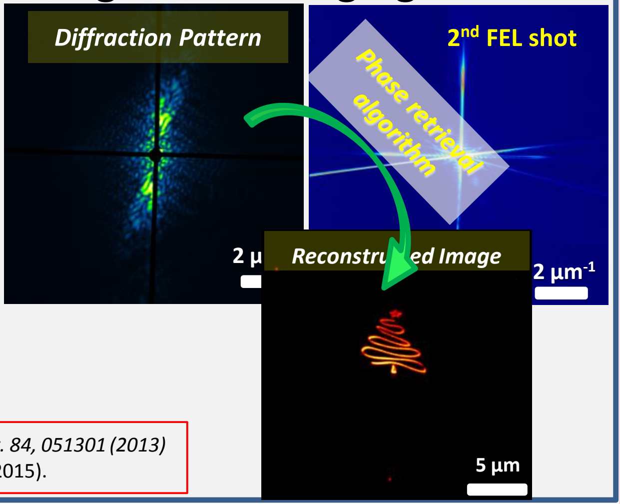


3 - 3.5 Orders of magnitude

2013).

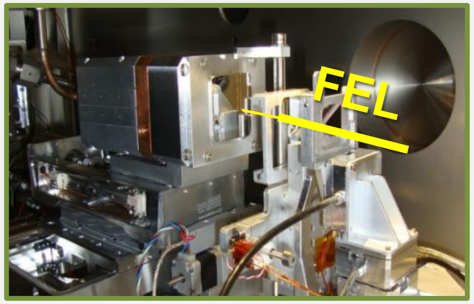
Scattering experiments @ DiProI

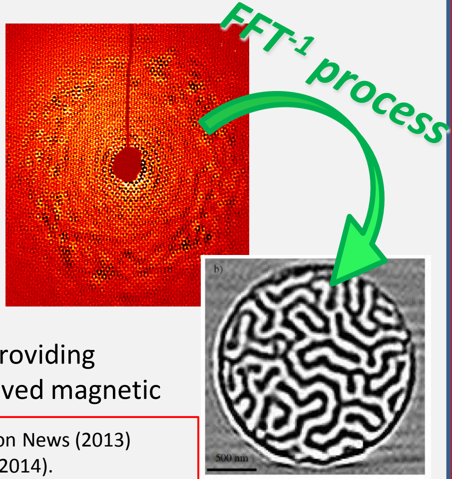
CDI-Single-shot imaging



F.Capotondi et. al. *Rev. Sci. Instr. 84, 051301 (2013)*
F. Capotondi et al. JSR 22, 544 (2015).

FT - Magnetic-holography

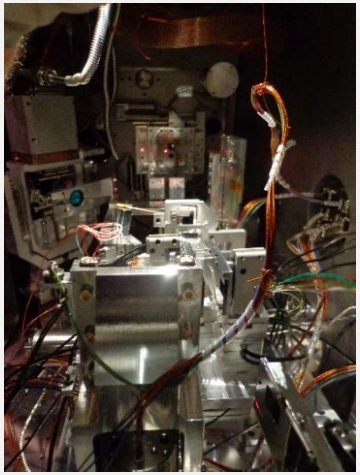




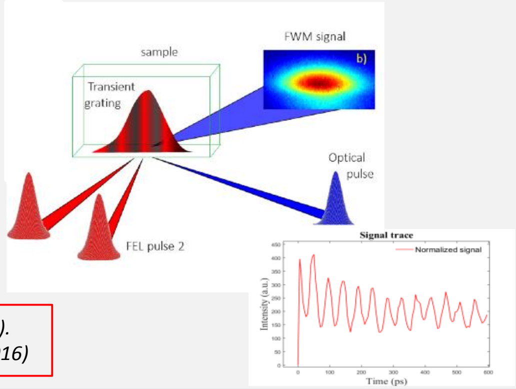
FERMI@Elettra is the only FEL source providing circular polarization ideal for time resolved magnetic imaging

L. Müller et. al. Syncrotron Radiation News (2013)
C. von Korff Schmising et. al., PRL (2014).

Four wave mixing spectroscopy

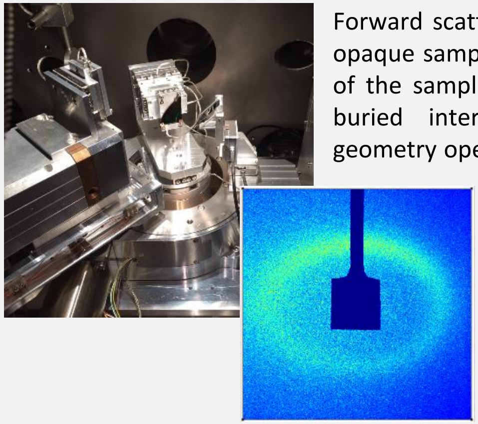


2 FEL beams are recombined on the sample at a given crossing angle. The fully coherent FERMI-FEL pulses generate EUV transient gratings probed by a third optical beam along the “phase matched” direction.



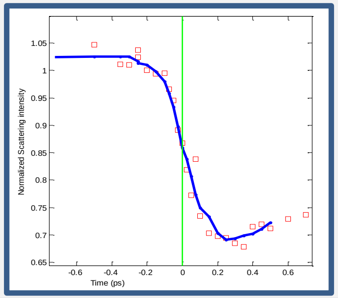
F.Bencivenga et. al. *Nature 520, 205 (2015).*
F.Bencivenga et sl. Faraday Discussion (2016)

EUV-Soft X-ray relfectivity/CDI in ref. geom



Forward scattering geometry is not applicable for opaque samples and in cases when the properties of the sample top layers are of interest, such as buried interfaces and thin films. Reflection geometry opens more experimental flexibility

Time resolved fast demagnetization curve

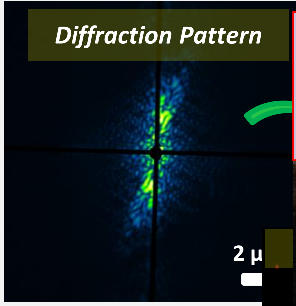


Reflected magnetic scattering signal at the Co M-edge (20.8 nm) Angle 45°.

In collaboration with C.Gutt Siegen Univ.

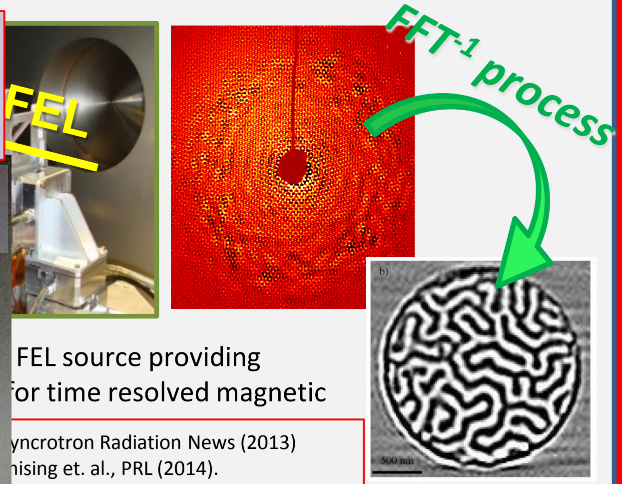
Scattering experiments @ DiProI

CDI-Single-shot imaging



F.Capotondi et. al. *Rev. Sci. Instr. 84, 051301 (2013)*
F. Capotondi et al. JSR 22, 544 (2015).

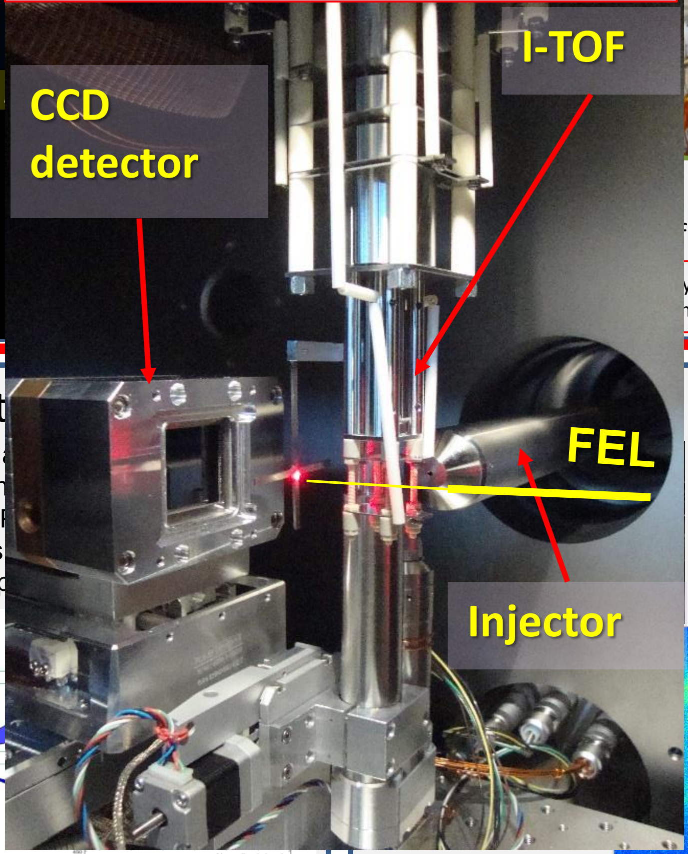
FT - Magnetic-holography



FEL source providing
for time resolved magnetic

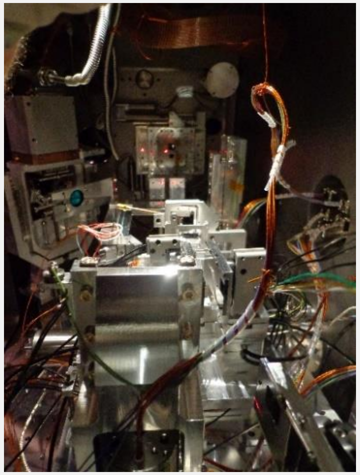
yncrotron Radiation News (2013)
nising et. al., PRL (2014).

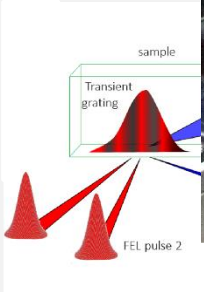
Particle Injector Under commissioning

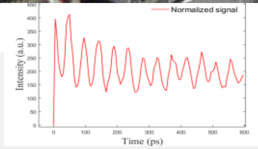


Four wave mixing spect

2 FEL beams a
sample at a given
coherent FERMI-F
transient gratings
beam along the “p



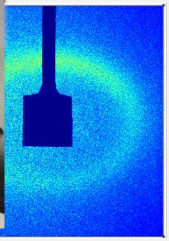




F.Bencivenga et. al. *Nature 520, 205 (2015).*
F.Bencivenga et sl. Faraday Discussion (2016)

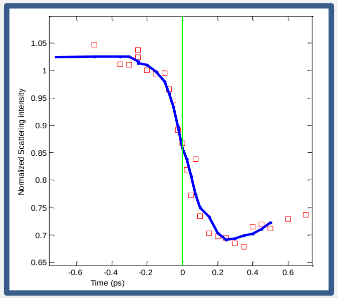
relfectivity/CDI in ref. geom

Forward scattering geometry is not applicable for opaque samples and in cases when the properties of the sample top layers are of interest, such as buried interfaces and thin films. Reflection geometry opens more experimental flexibility



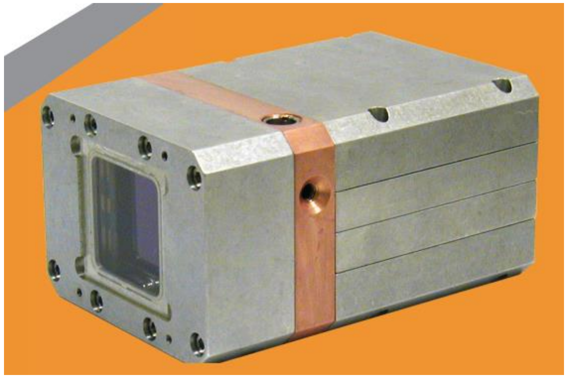
Reflected magnetic scattering signal at the Co M-edge (20.8 nm) Angle 45°.

Time resolved fast demagnetization curve



In collaboration with C.Gutt Siegen Univ.

DiProI – Current 2D detectors (status)

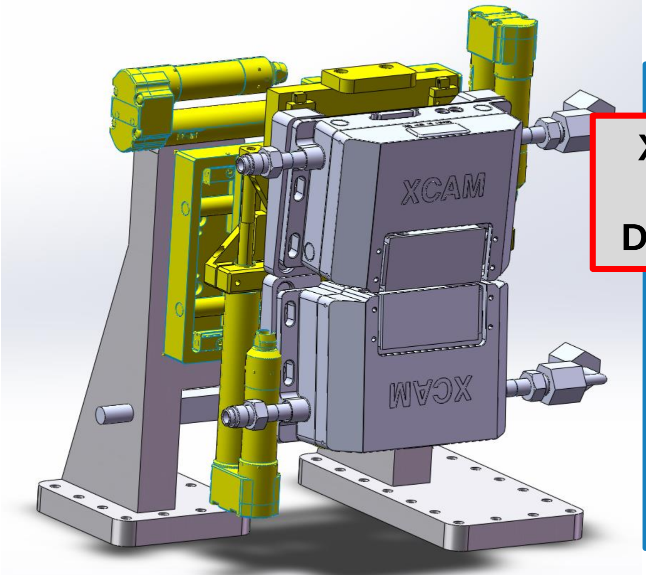


Commercial PI MTE2048B

MAIN FEATURES

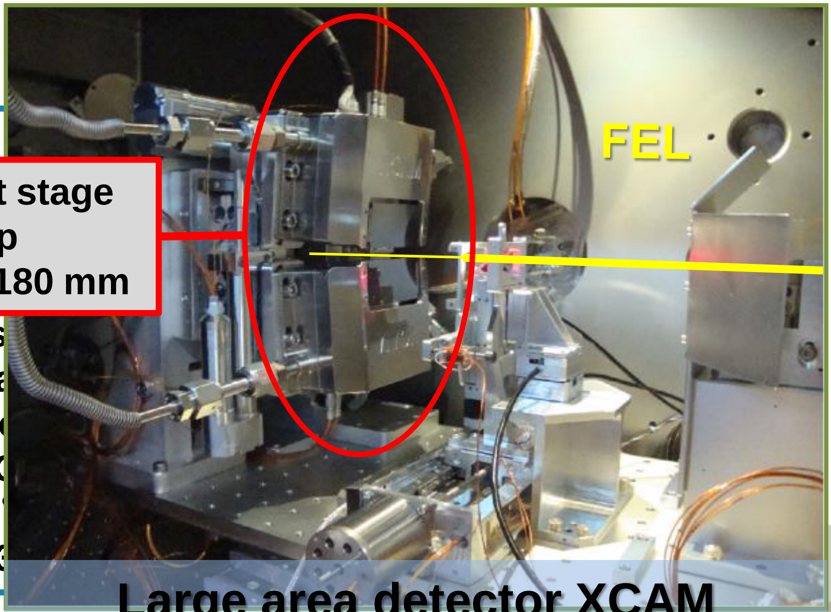
2048x2048 pxls 13.5 µm pxl size
(26x26 mm image area)
1 readout point
Upto 2MHz ADC.
Cooling -40° C
Noise about 7 ADU (15 e-) @ 1MHz

Good but SLOW for 10-50 Hz FEL
1 image each 4 sec @ 1MHz



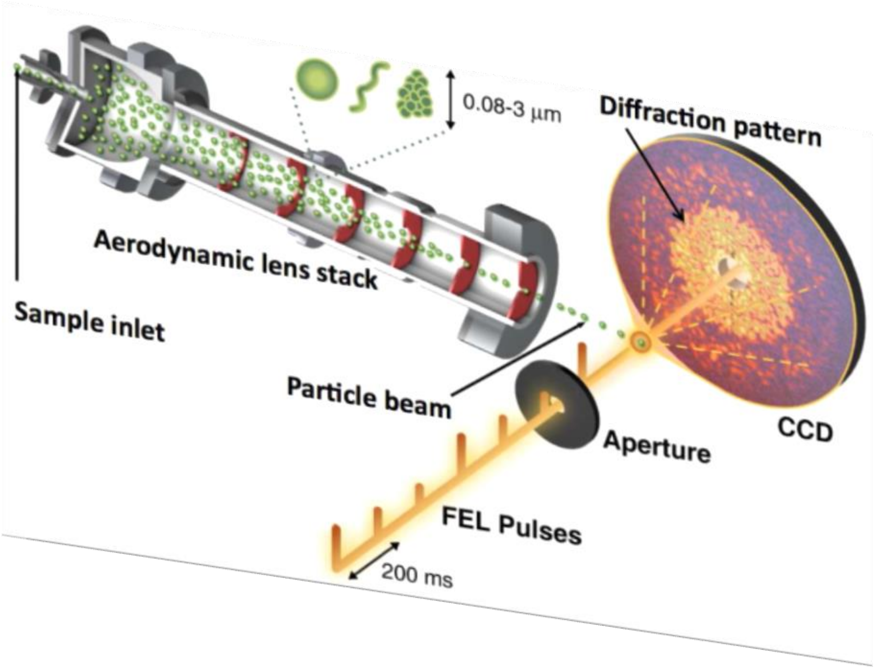
Commercial X-Cam
15 µm pxl s
(2x60x30 mm ima
4 readout p
1MHz ADC
Cooling -40
Noise about 15 ADU (

XY Large area alignment stage
With adjustable gap
Detector size about 230x180 mm



Large area detector XCAM
Inside DiProI Vacuum Vessel

Dreaming Detector for FEL experiments



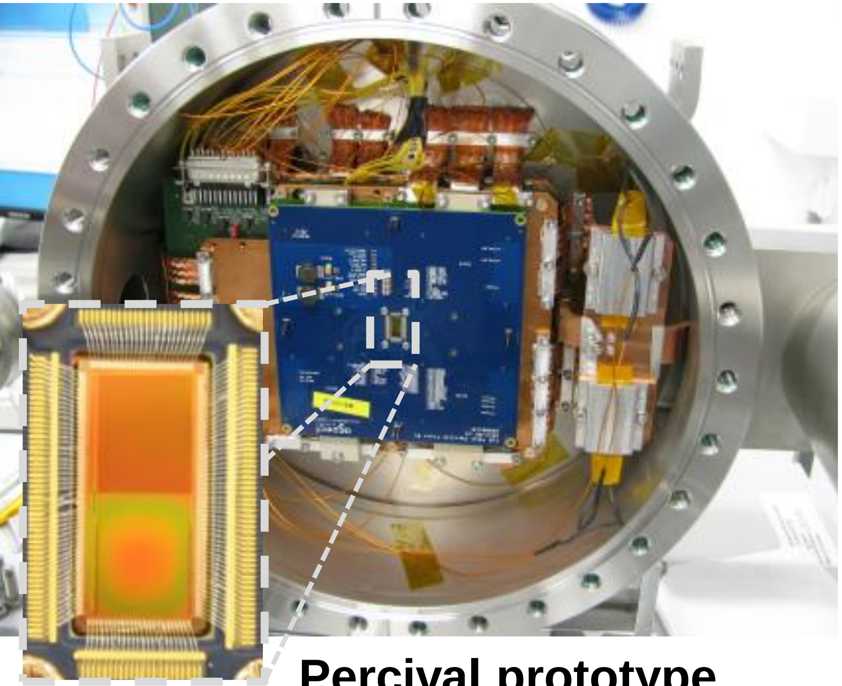
- **Energy range from 100 eV – 1KeV (III harm. FEL-2).**
- **Format size more then 1Kx1K pixels.**
- **Small pixels size between 10-50 µm.**
- **Fast frame rate (50 Hz).**
- **Large dinamic range at least 16 bits.**
- **Single shot sensitivity for hν > 200 eV. Noise ~ 15 e^-**
- **Very high and uniform over sensor quantum efficency.**

Topics

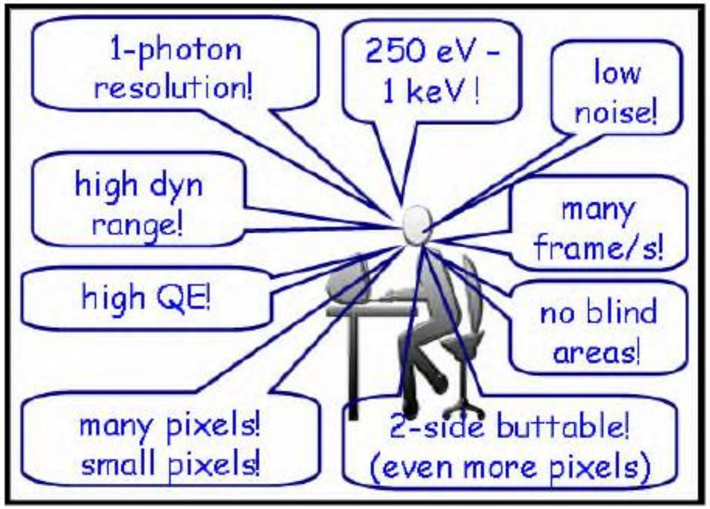
- Introduction: seeded FERMI and DiProI beamline.
- *CDI and detector requirements.*
- **PERCIVAL project.**
- Research opportunities with PERCIVAL @ FERMI.
- Conclusions..

Elettra Sincrotrone Trieste

PERCIVAL: Pixelated Energy Resolving CMOS Imager, Versatile And Large



Percival prototype



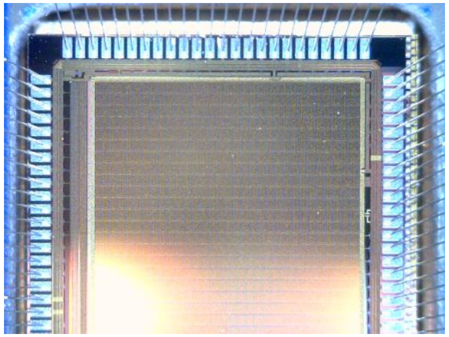
TRY TO MEET ALL THE REQUIREMENTS

The Percival collaboration

DESY - D **RAL - Gb** **Elettra - It** **Diamond - Gb** **PAL - Kr** **JPL - Usa**

Elettra Sincrotrone Trieste

Detector specification



Percival prototype chip
based on CMOS technology

PERCIVAL target specifications (ambitious)

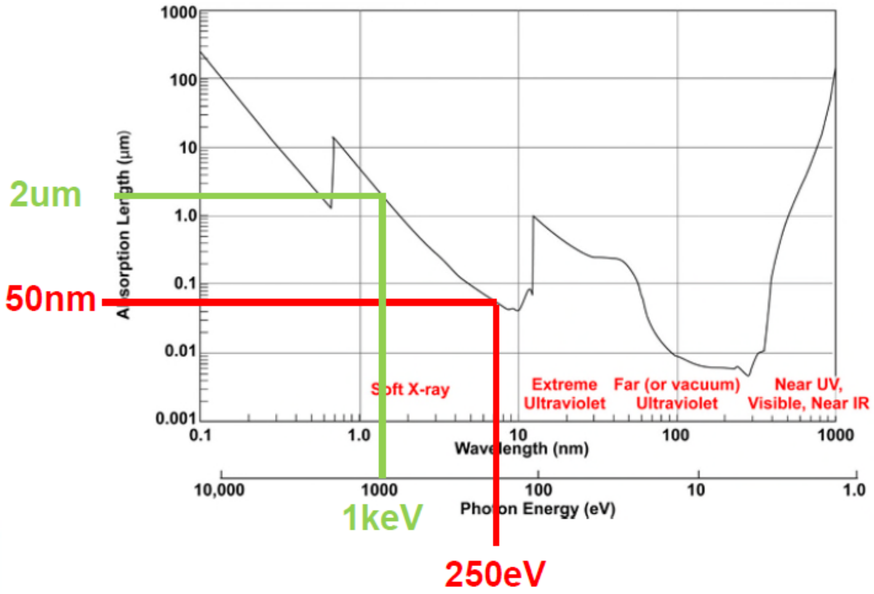
- Low energy x-ray detection from 300 eV – 1.0 KeV (ext. to 100 eV with less QE)
- High efficiency ➔ back side illumination & direct conversion
- High resolution ➔ pixels size a 27 µm pitch
- Large area ➔ Phase – 1 2 Mpixel (1400 x1480 pixels, ~ 3.8 x 3.8 cm^2) P2M
  Phase – 2 13 Mpixel (3700 x 3500 pixels, ~ 10 x 10 cm^2) P13M
- Single photon (250 eV) detection ➔ low noise
  250 eV generating ~ 70 e$^-$ in silicon => noise ~ 13 e$^-$ (Rose criteria)
- High dynamic range:
  2x10^5 photons @ 250 eV ➔ ~ 120 dB or full well > 10^7 e$^-$
- High frame rates (120 FPS)
- Fully digital – with 4 variable automatic gains.
- Data rate 38 Gb/s

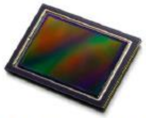
Front or back side illumination?

- Back-side illumination (BSI) with minimal 'entry' loss ⇒ low energy range
- Thick epi ⇒ high energy range

PERCIVAL

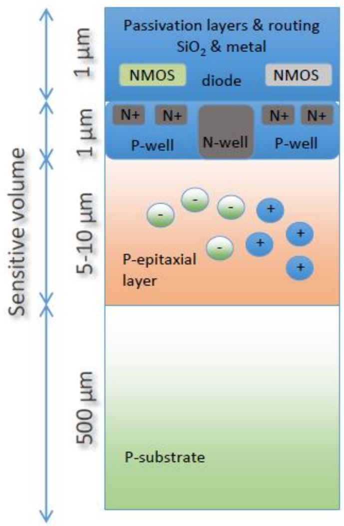
Goal: very high QE in the range from 250eV to 1keV



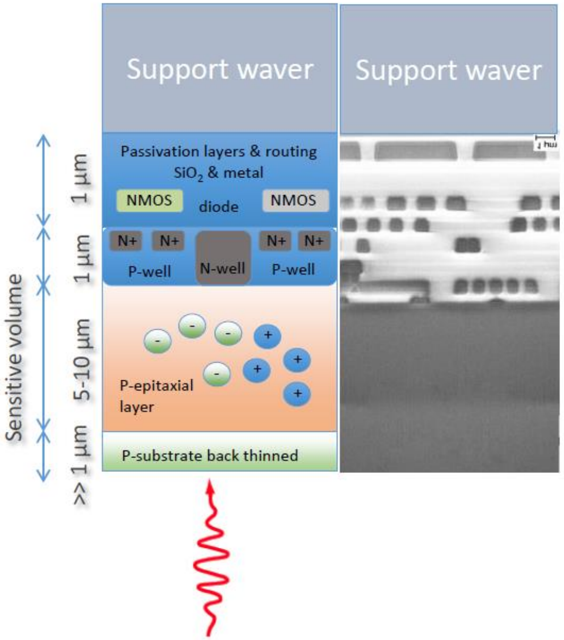


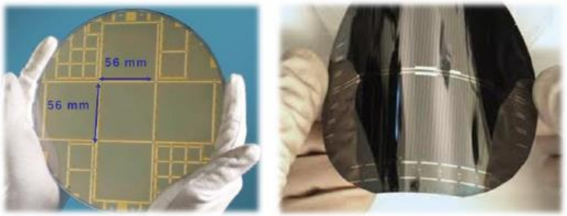
Conventional C-MOS sensor

Front illumination

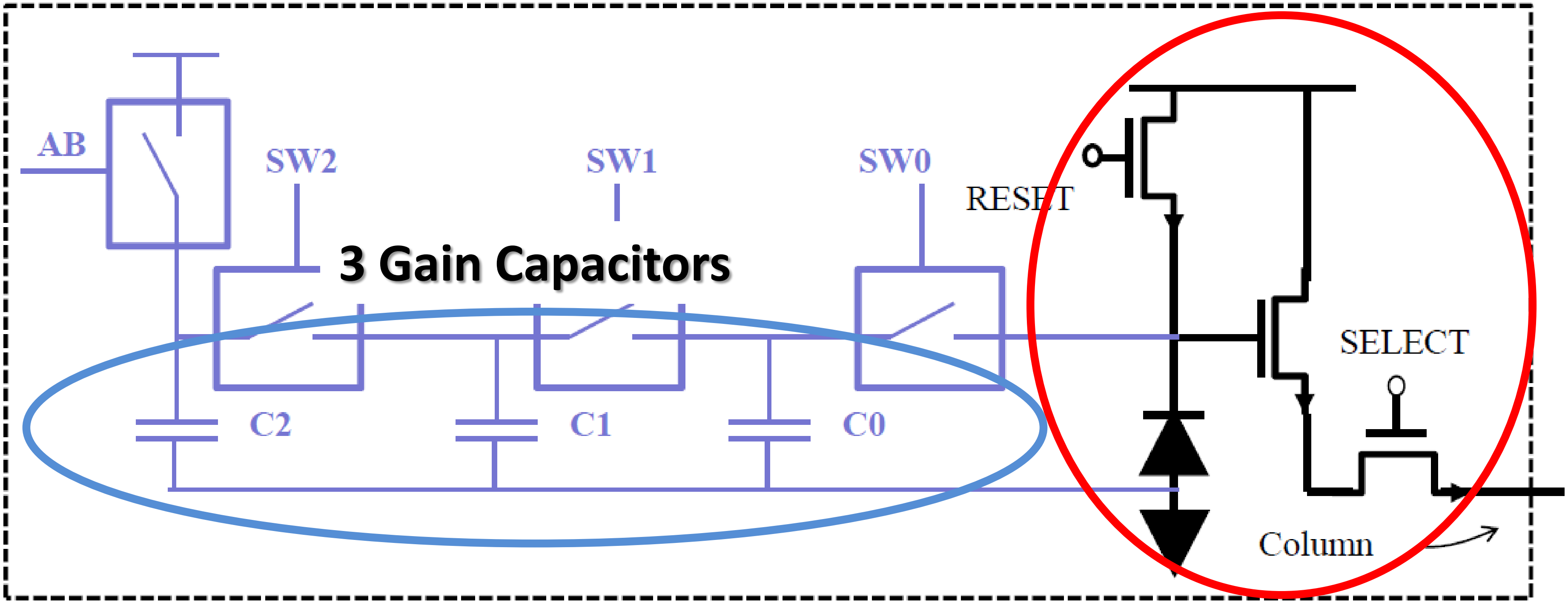


Back illuminated





The Pixel structure



3 Gain Capacitors

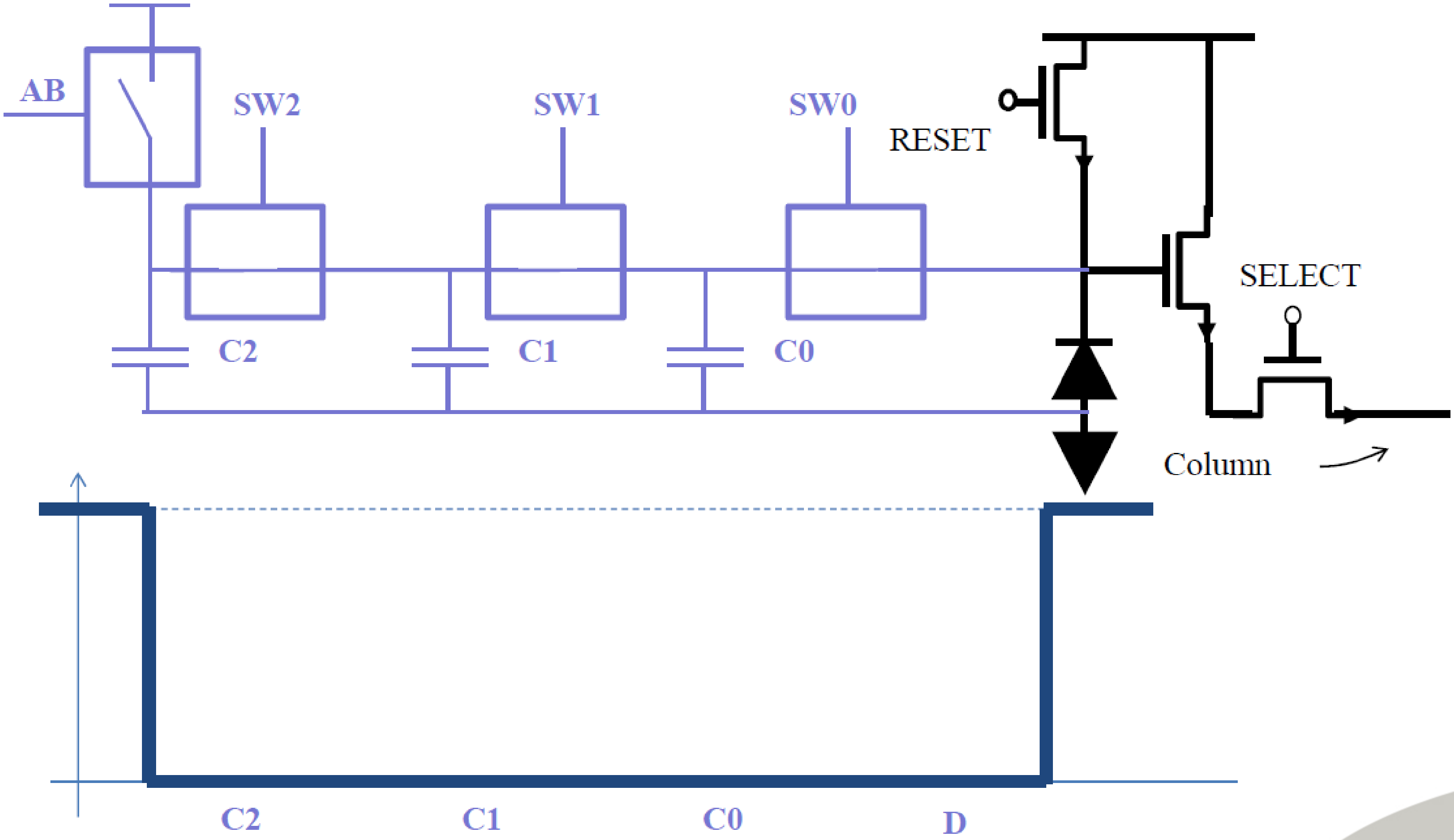
CMOS
Diode+Reset+Readout

Total capacitance → total full well
Ratios of cap's → minimise dynamic range drop at boundaries
\# of cap's → trade-off between speed and DR drop at boundaries

Key targets: ENC <~ 15 e- rms; FWC >~ 10^6 e^-

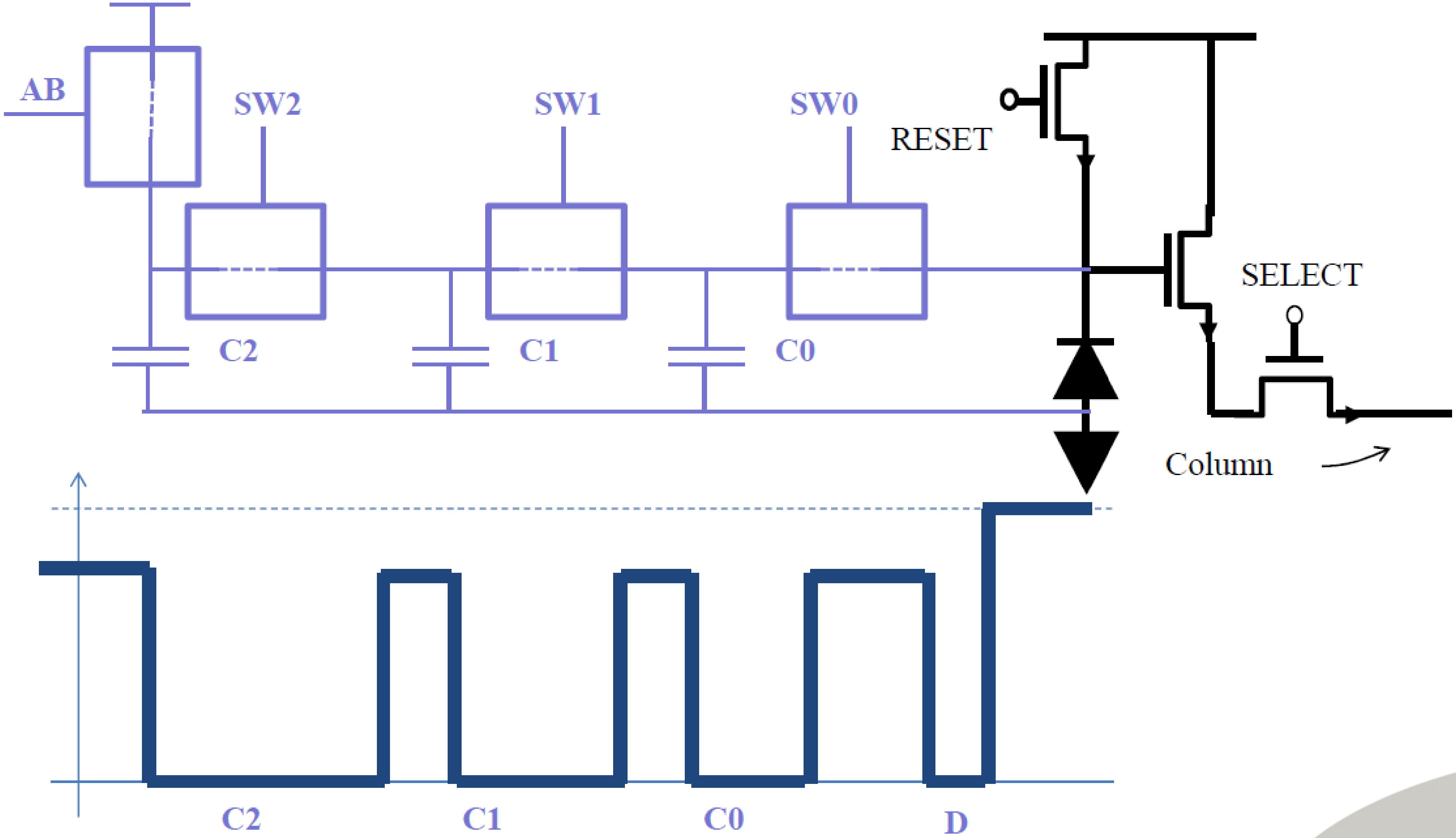
The Pixel structure

PIXEL OPERATION. Reset



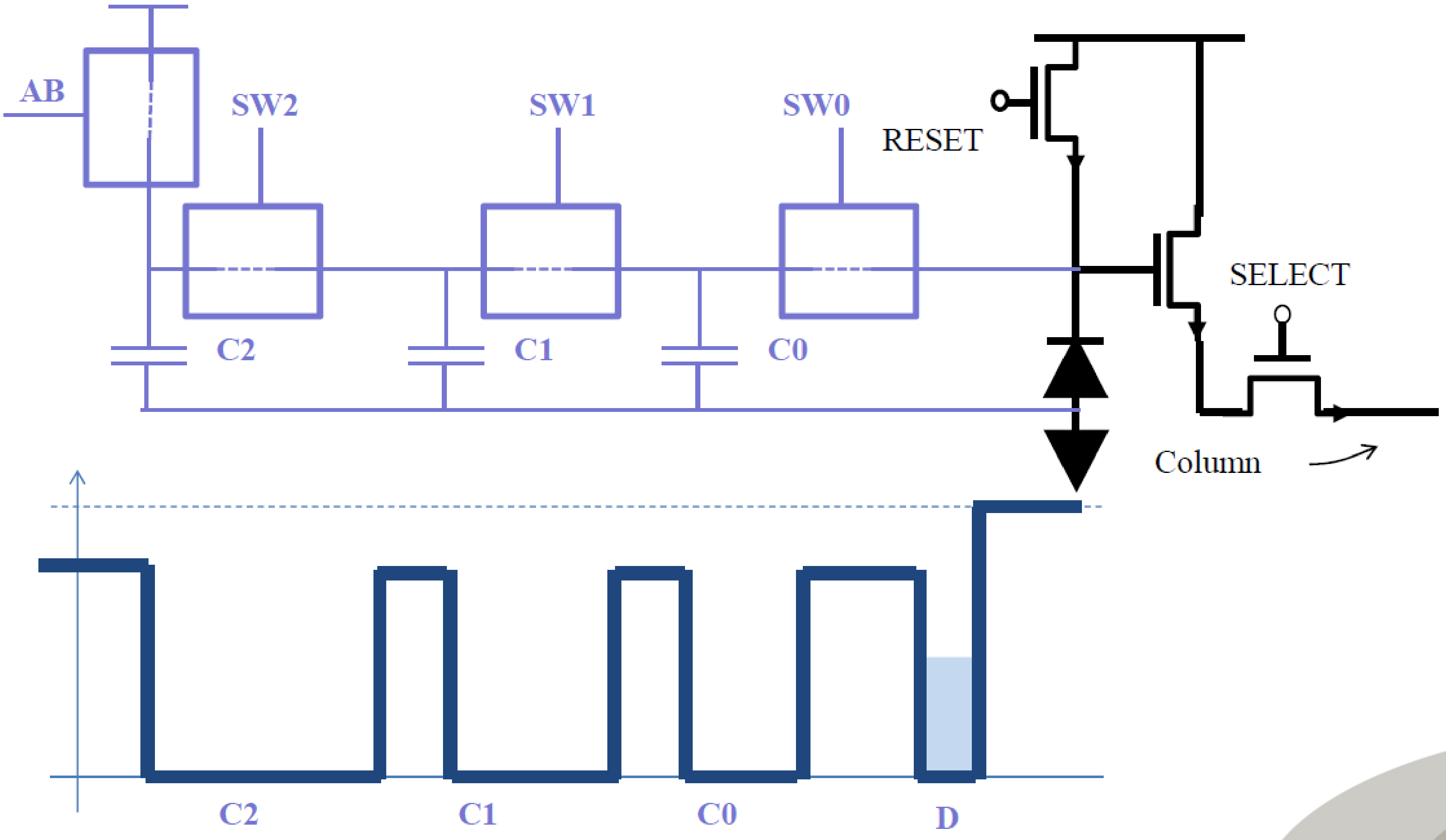
The Pixel structure

PIXEL OPERATION. Start integration



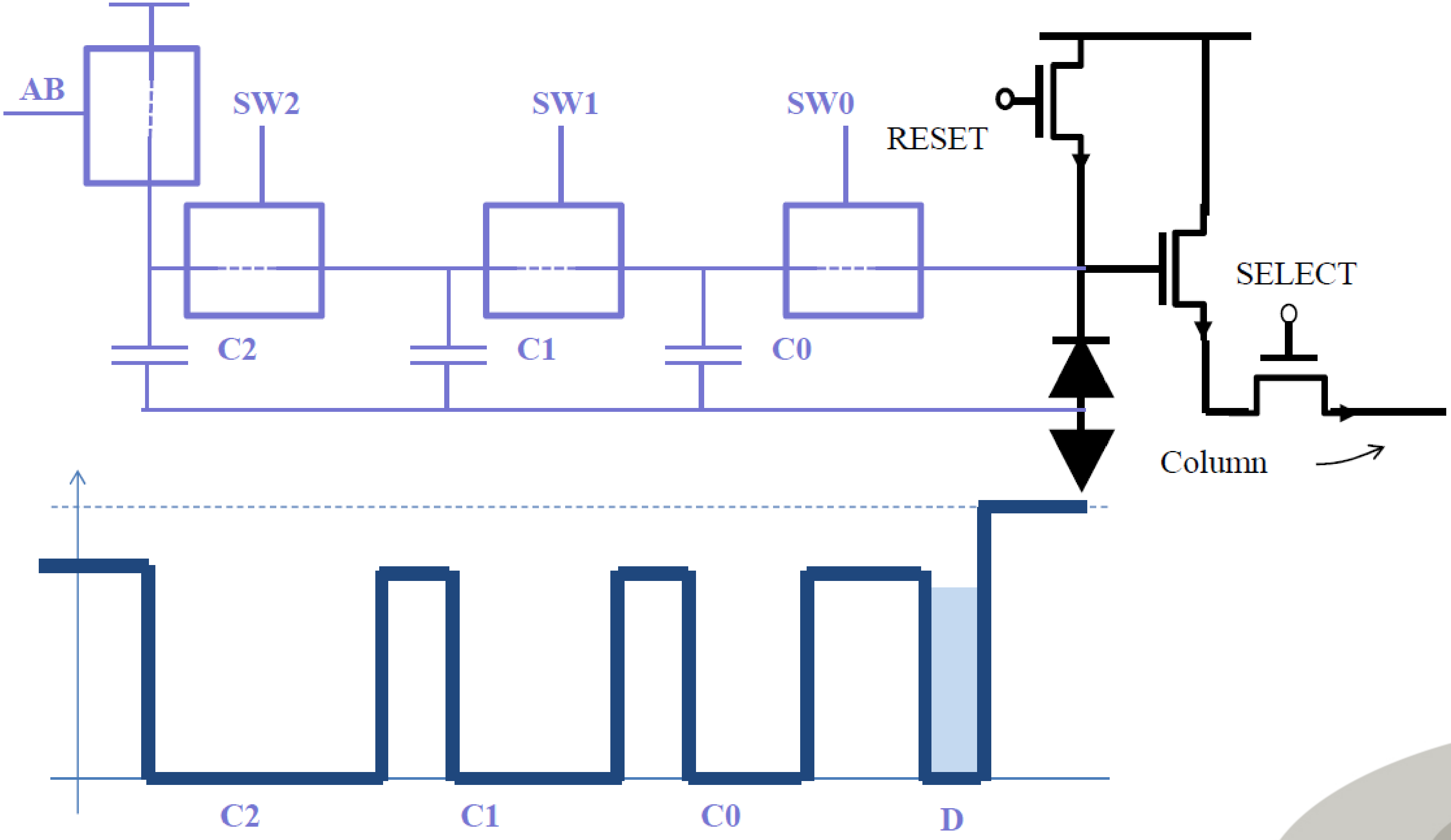
The Pixel structure

PIXEL OPERATION. Integration



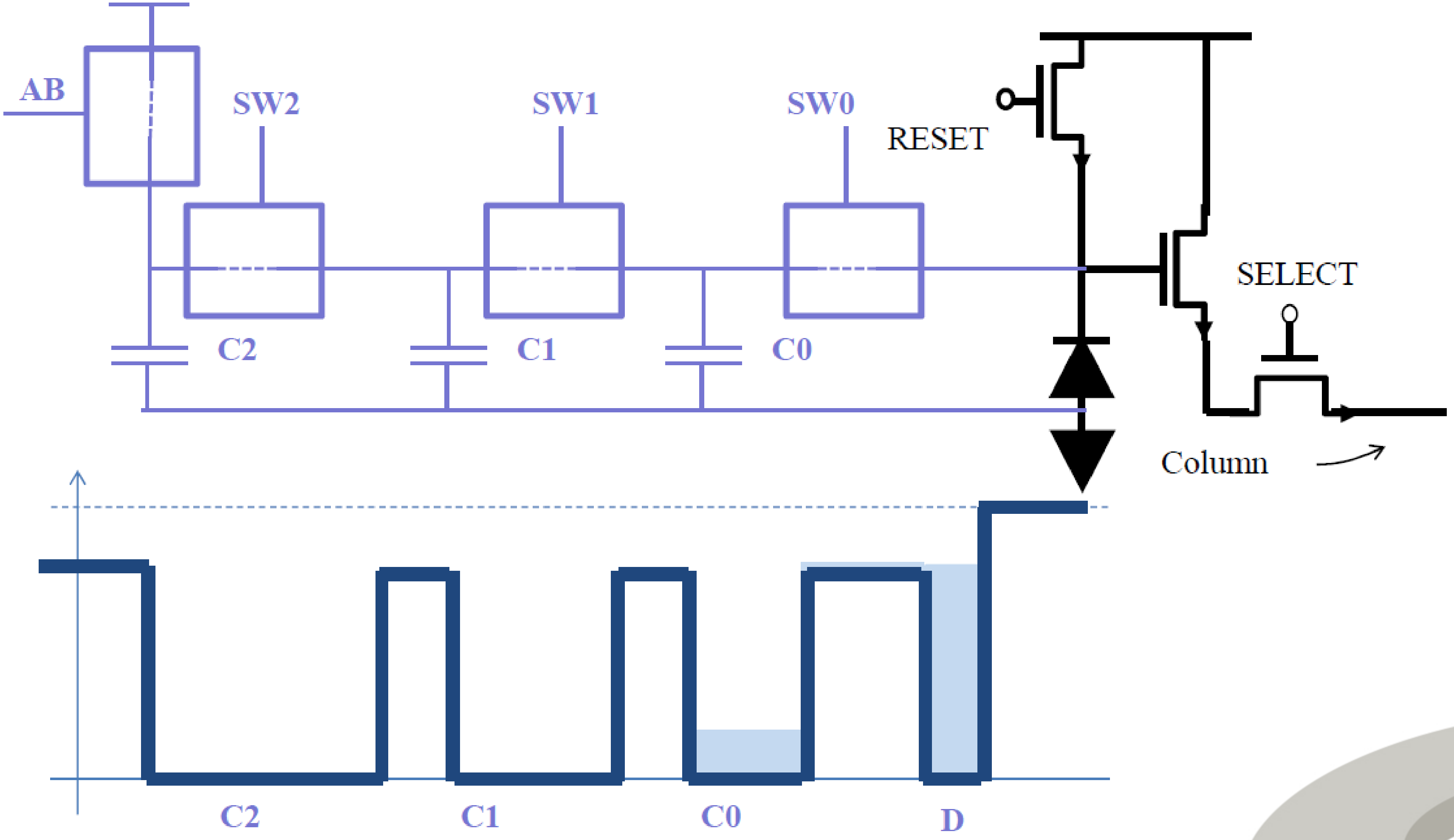
The Pixel structure

PIXEL OPERATION. Integration



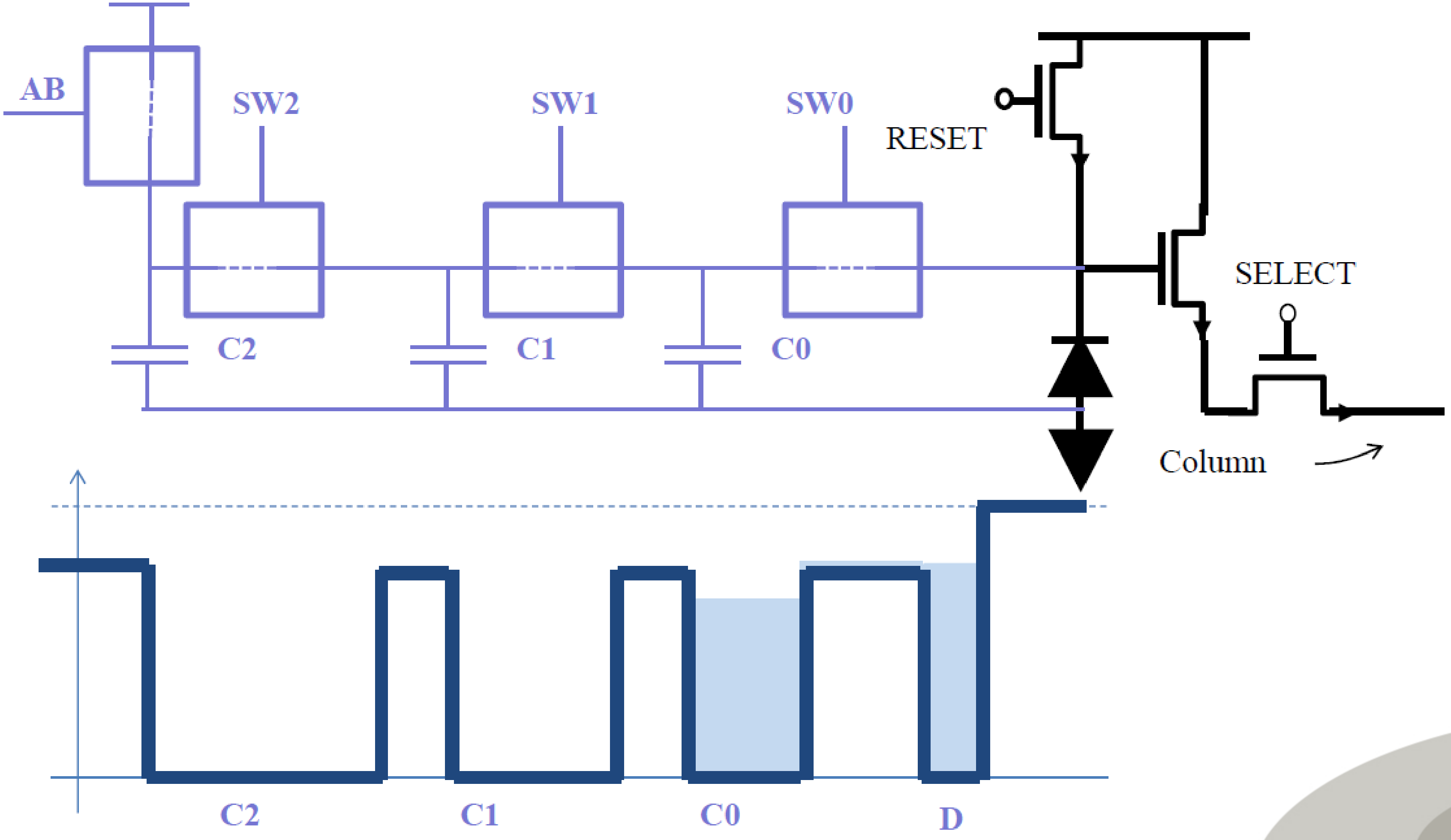
The Pixel structure

PIXEL OPERATION. Integration



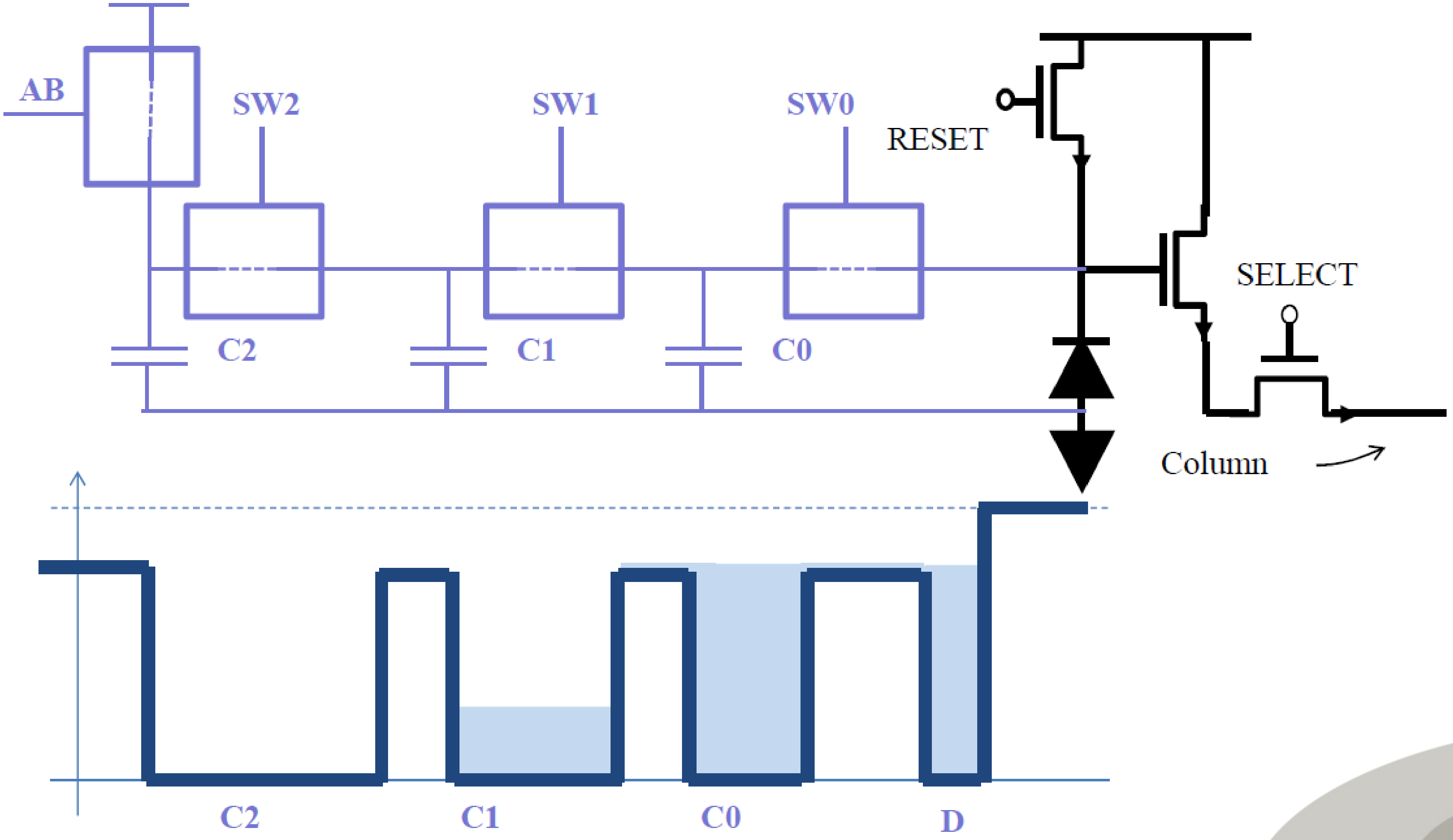
The Pixel structure

PIXEL OPERATION. Integration



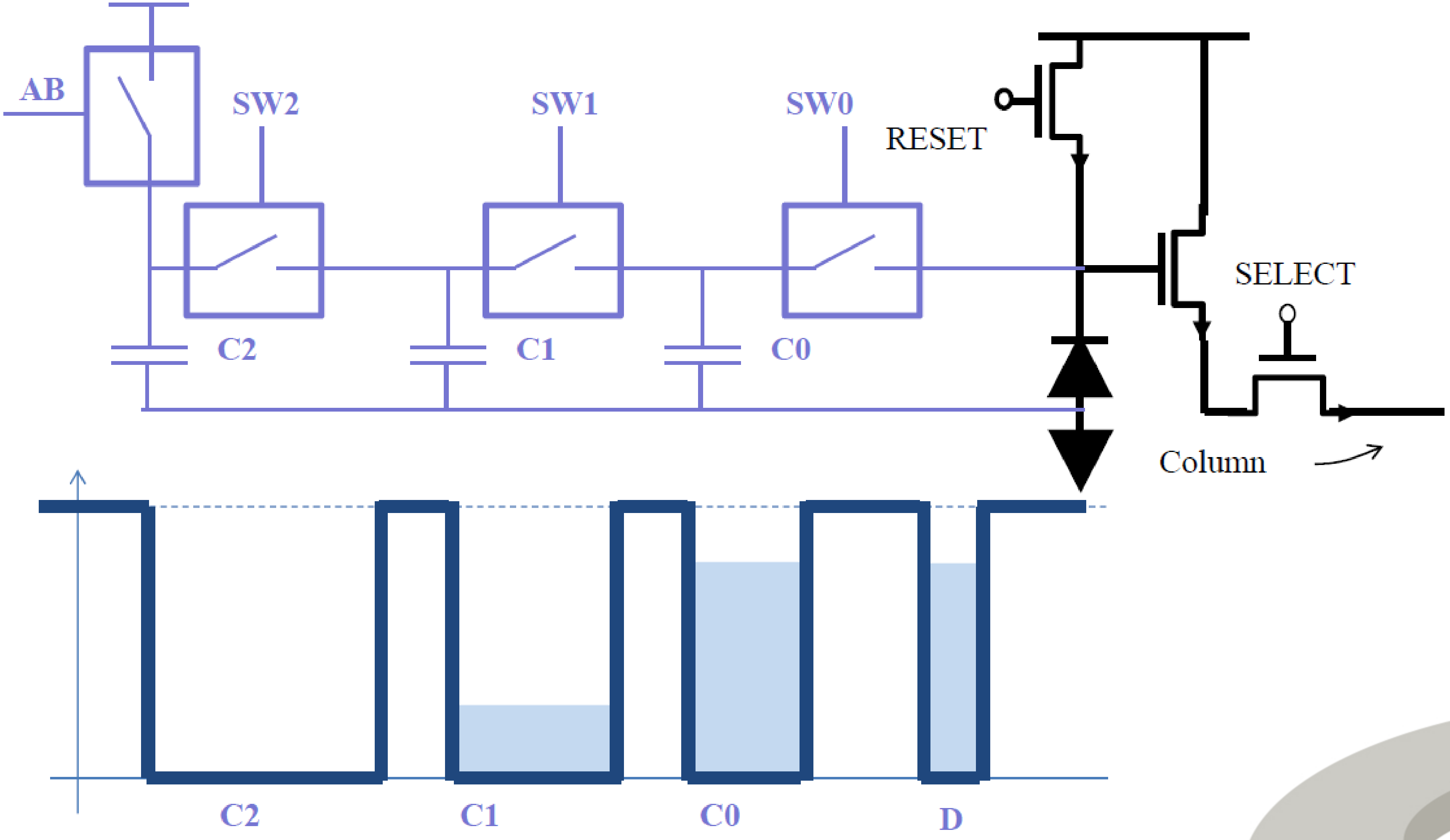
The Pixel structure

PIXEL OPERATION. Integration



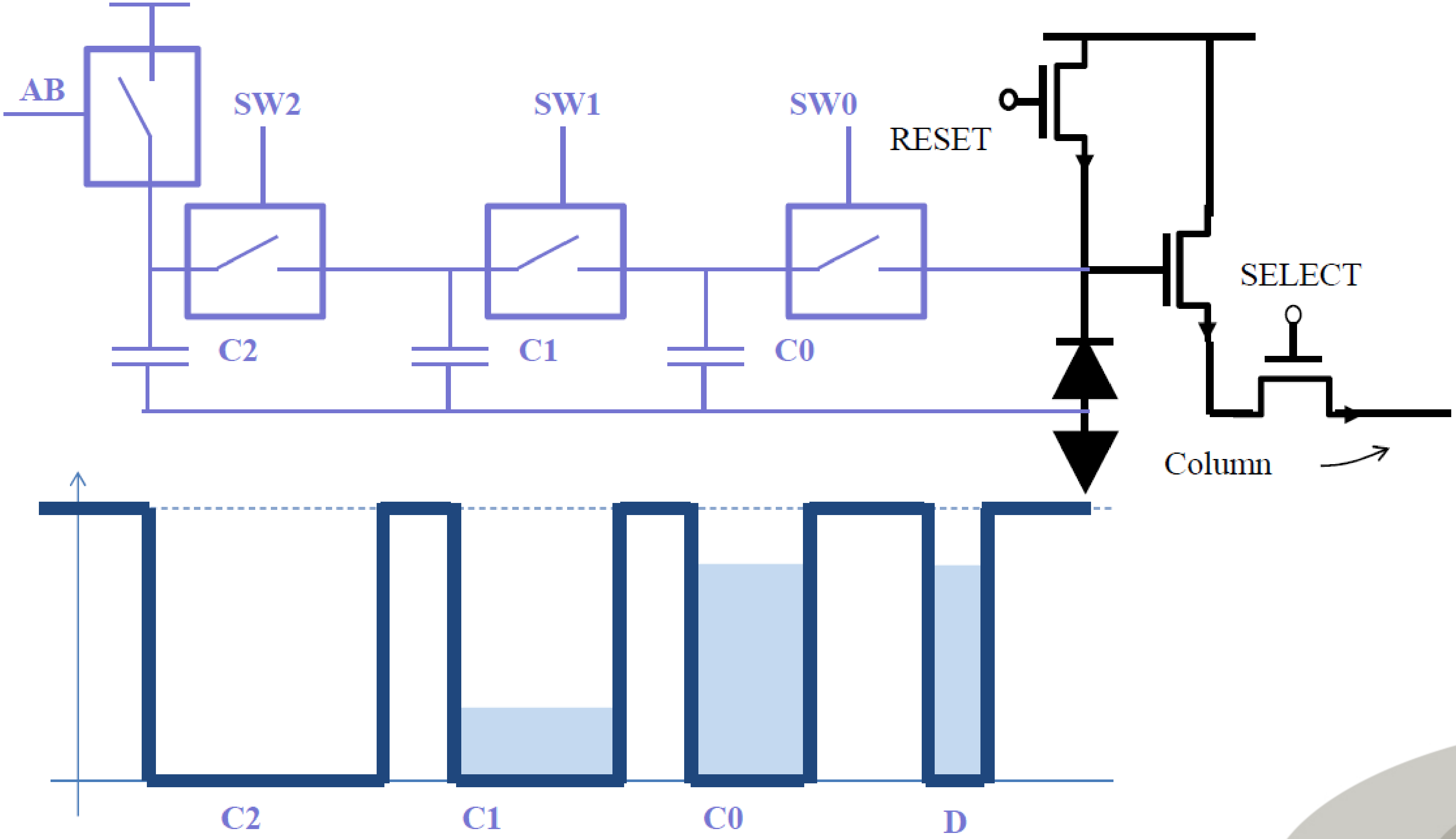
The Pixel structure

PIXEL OPERATION. Stop integration



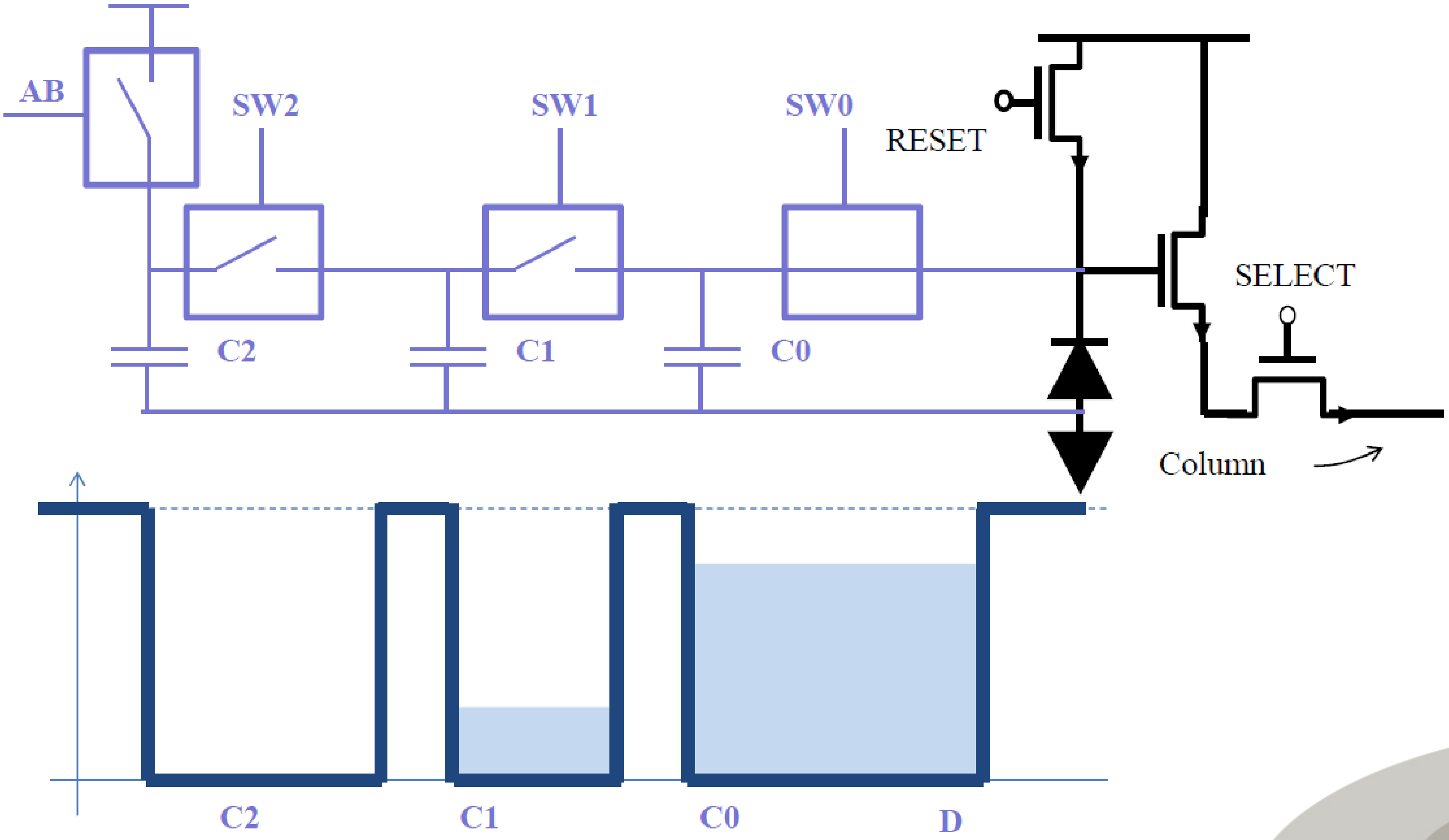
The Pixel structure

PIXEL OPERATION. Read diode



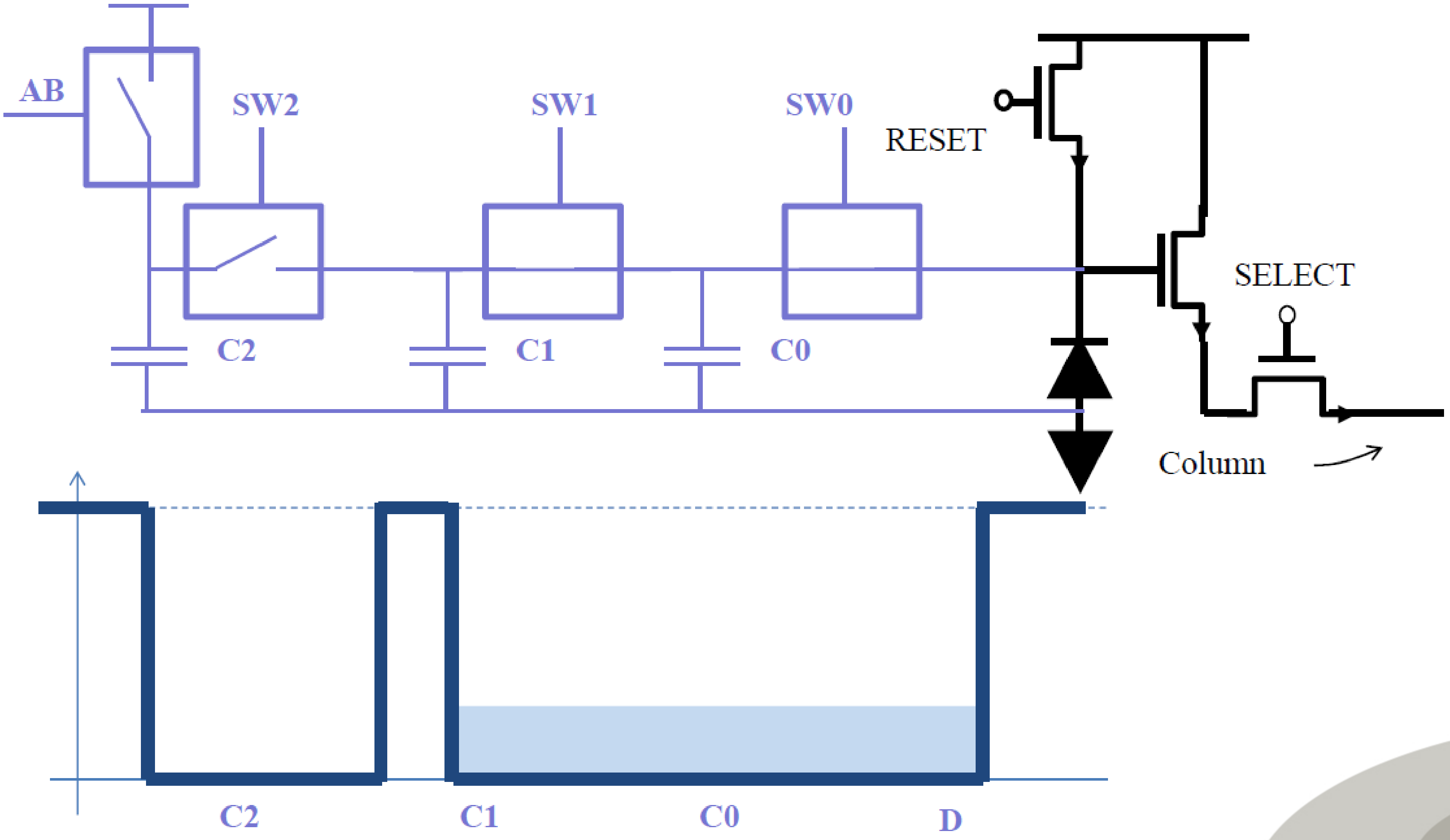
The Pixel structure

PIXEL OPERATION. Read C0



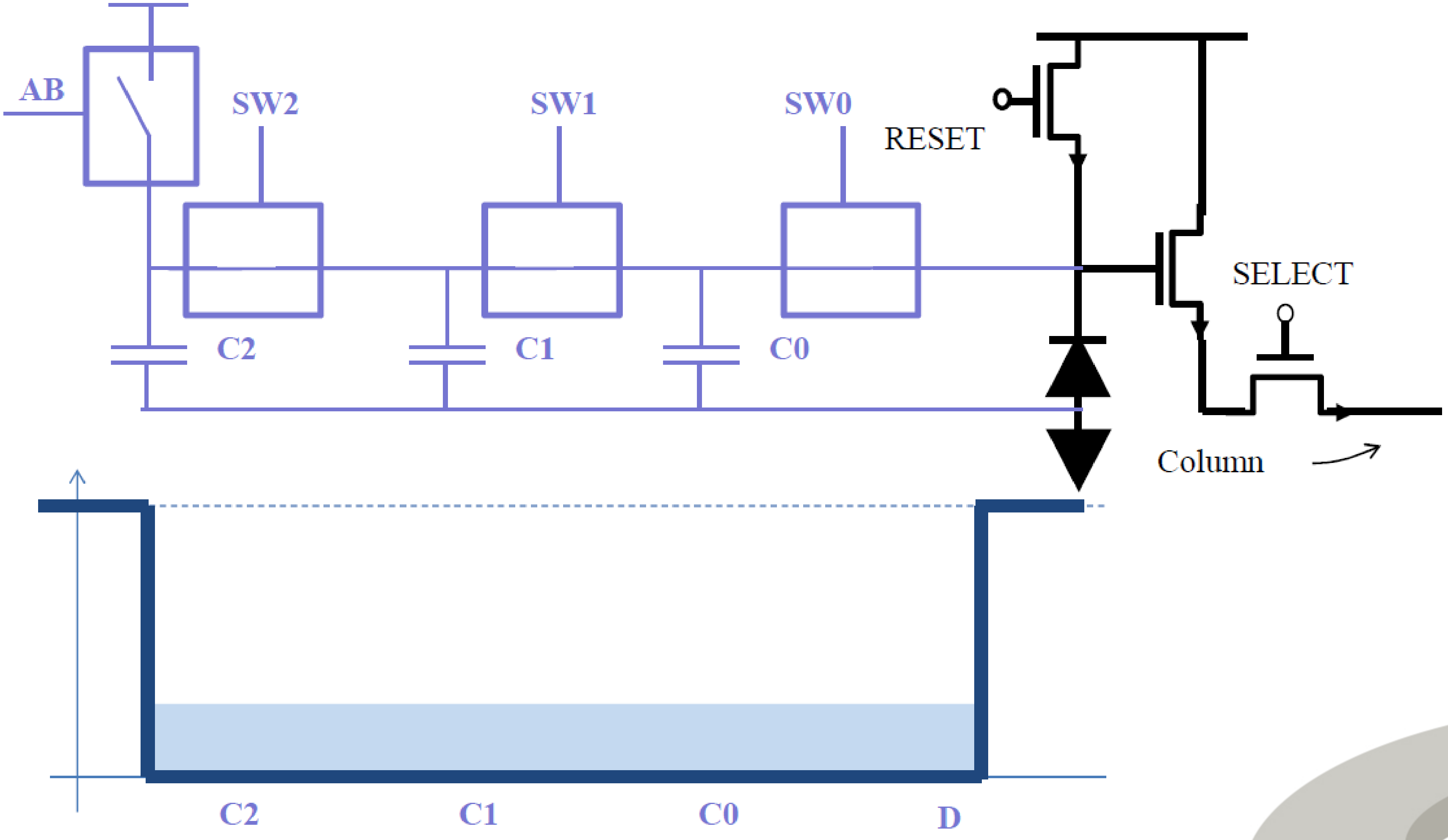
The Pixel structure

PIXEL OPERATION. Read C1

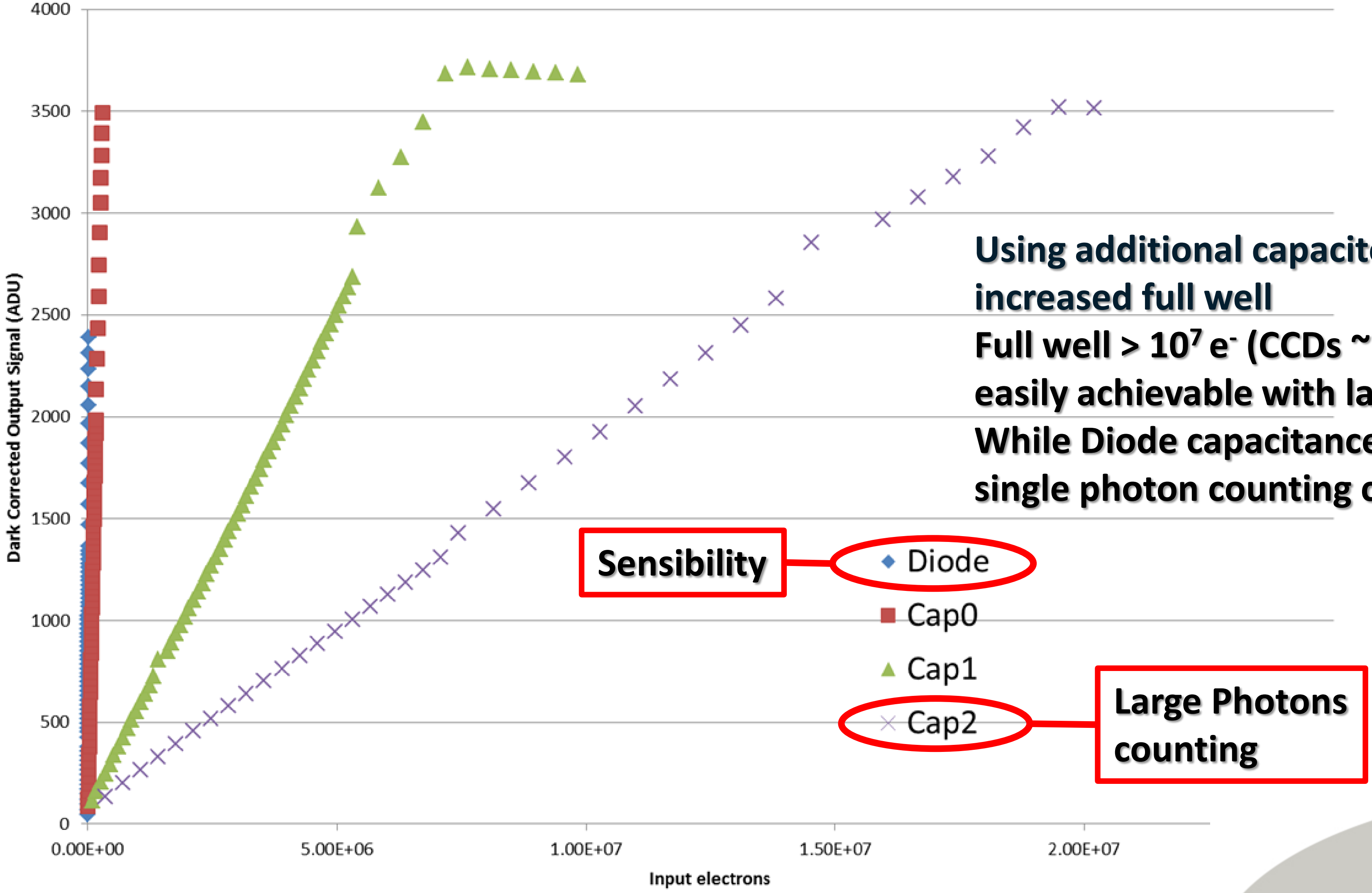


The Pixel structure

PIXEL OPERATION. Read C2



The Pixel structure



Sensibility

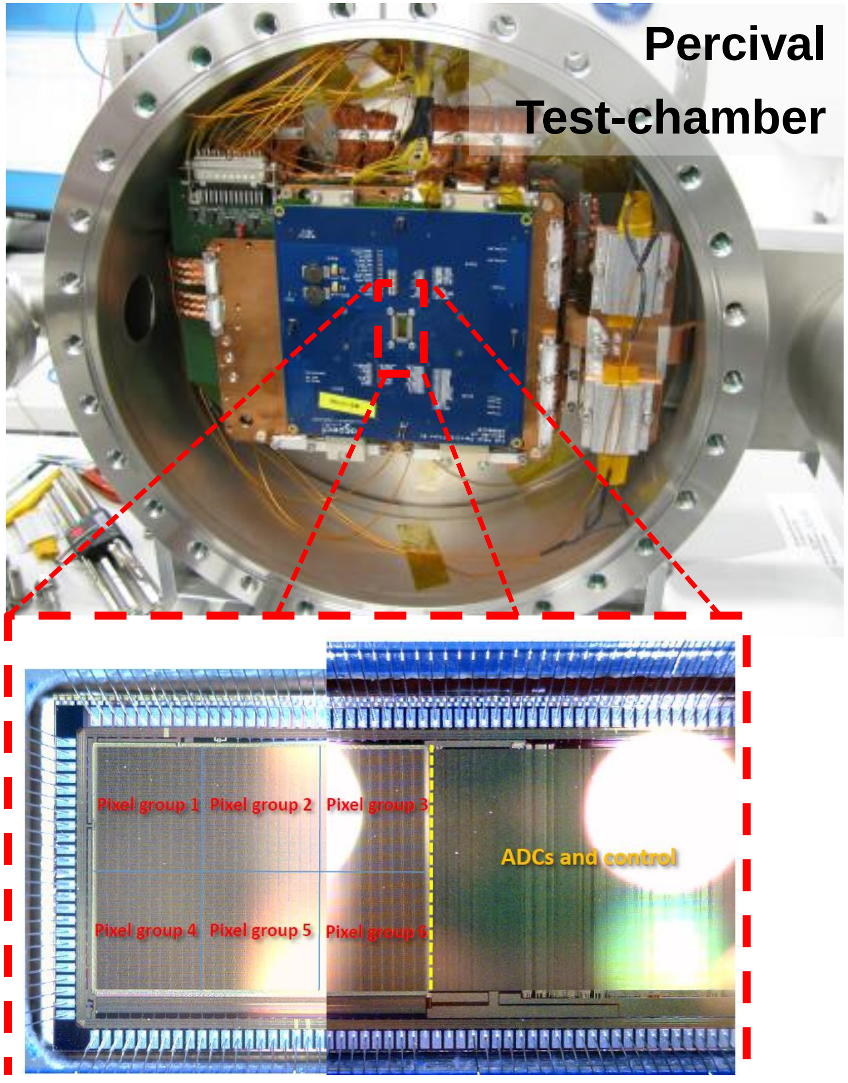
Large Photons counting

Using additional capacitors for increased full well

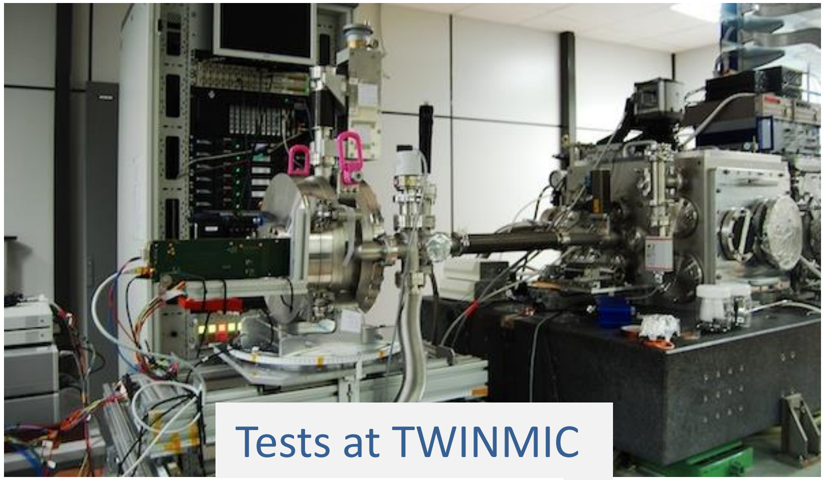
Full well > 10^7 e^- (CCDs ~ 500000) easily achievable with large diode

While Diode capacitance can keep single photon counting capability

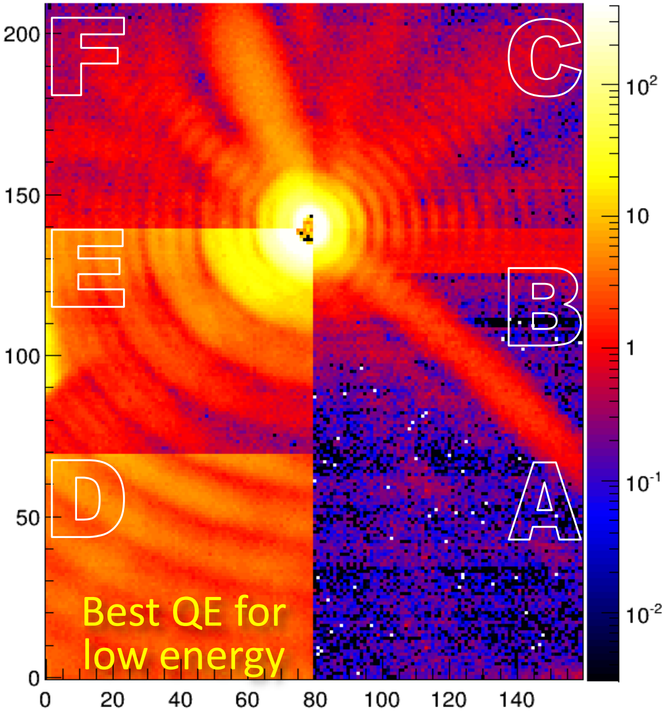
Pixels design test



Test chip with different 6 pixel structures



Tests at TWINMIC

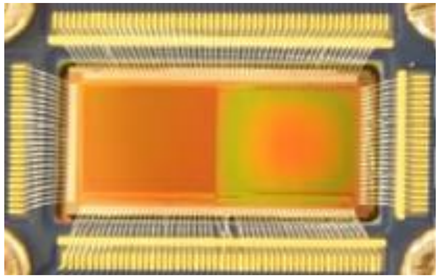


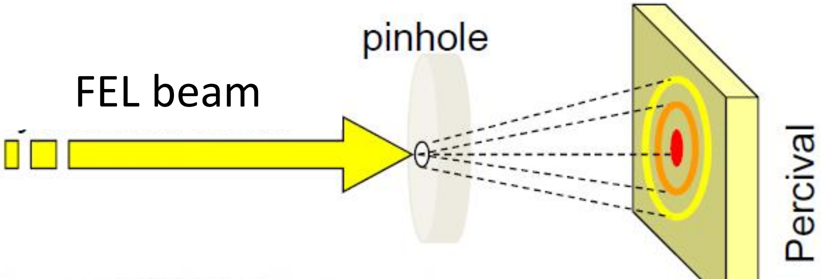
Best QE for low energy

Photon Energy
350 eV + 3rd harmonic

Elettra Sincrotrone Trieste

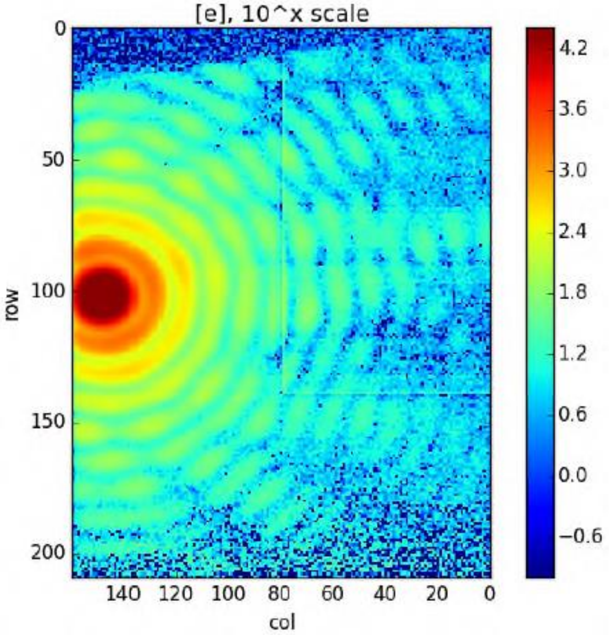
Low photons energy

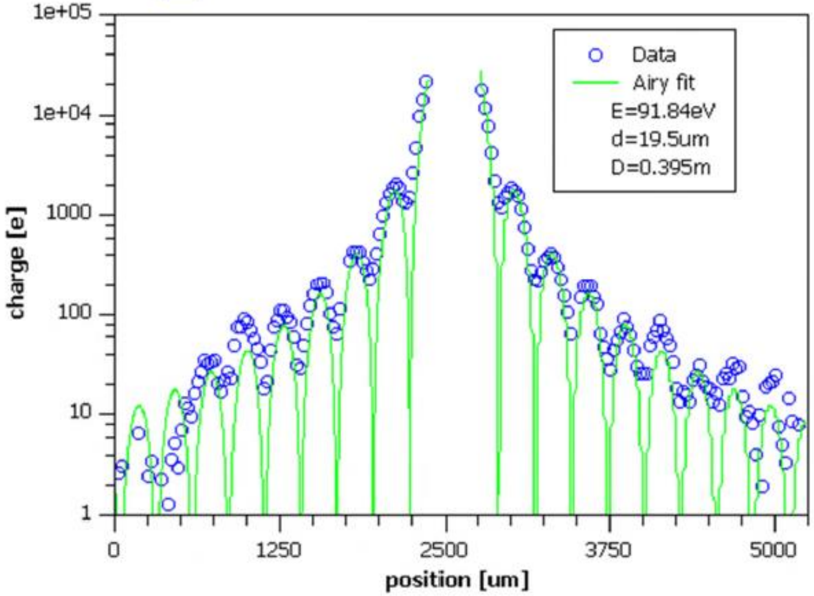




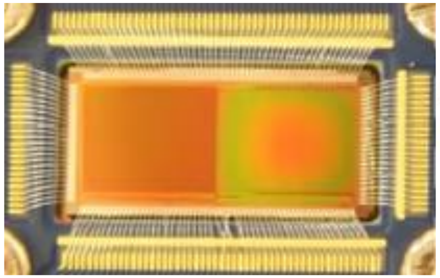
91.84eV tests at BL2 (Flash)

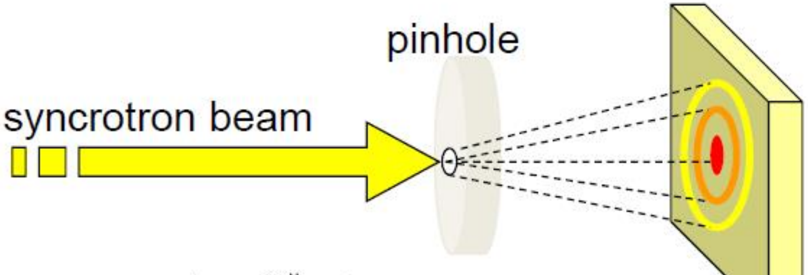
TEST sensor
- 33K pixels
- ~0.4x0.5 cm^2
- 25 µm size





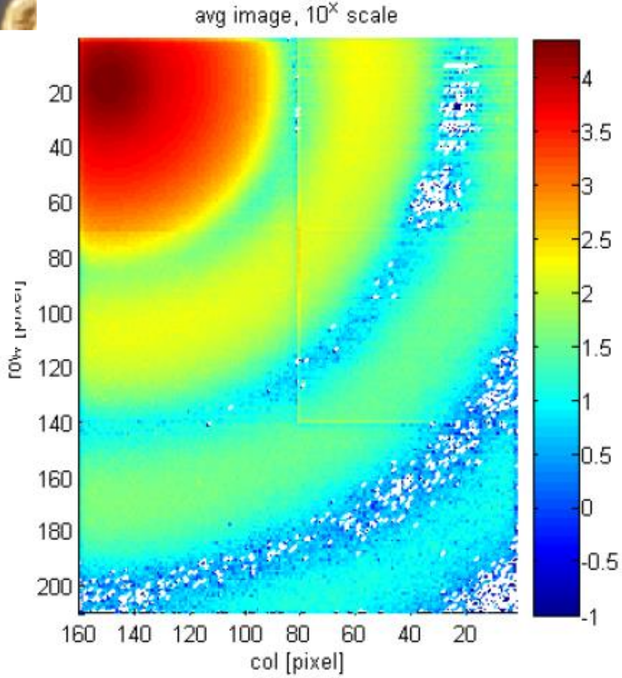
Other photons energies

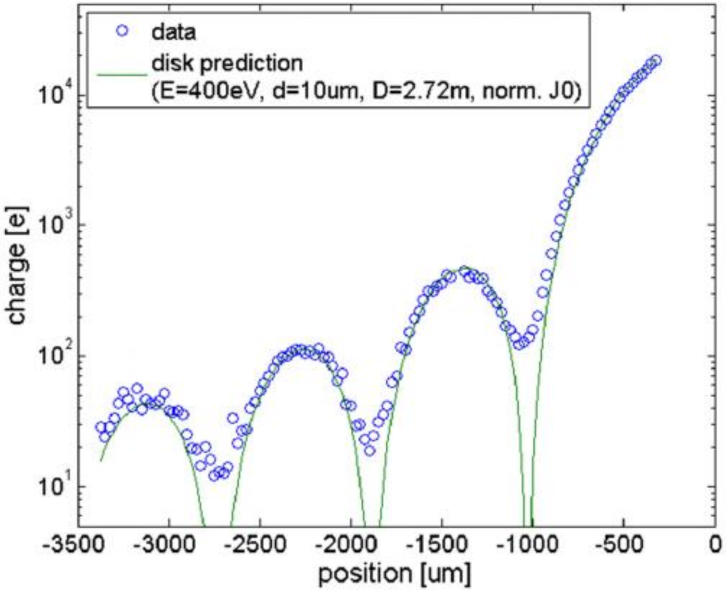




Percival
- 1-2keV tests at P04 (Petra III)
- 400eV tests at I10 (DLS)
- 100-300eV tests at Twinmic, Cipo (Elettra)

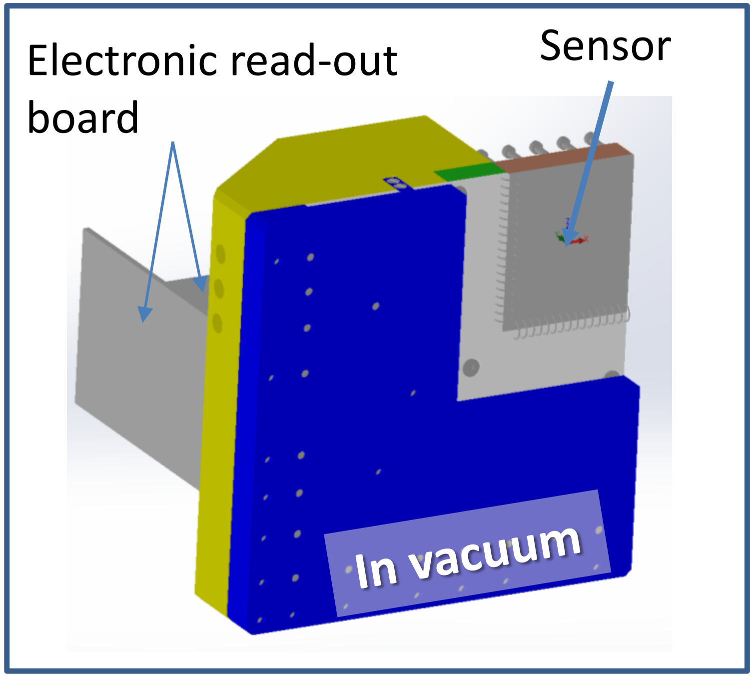
TEST sensor
- 33K pixels
- ~0.4x0.5 cm^2
- 25 µm size

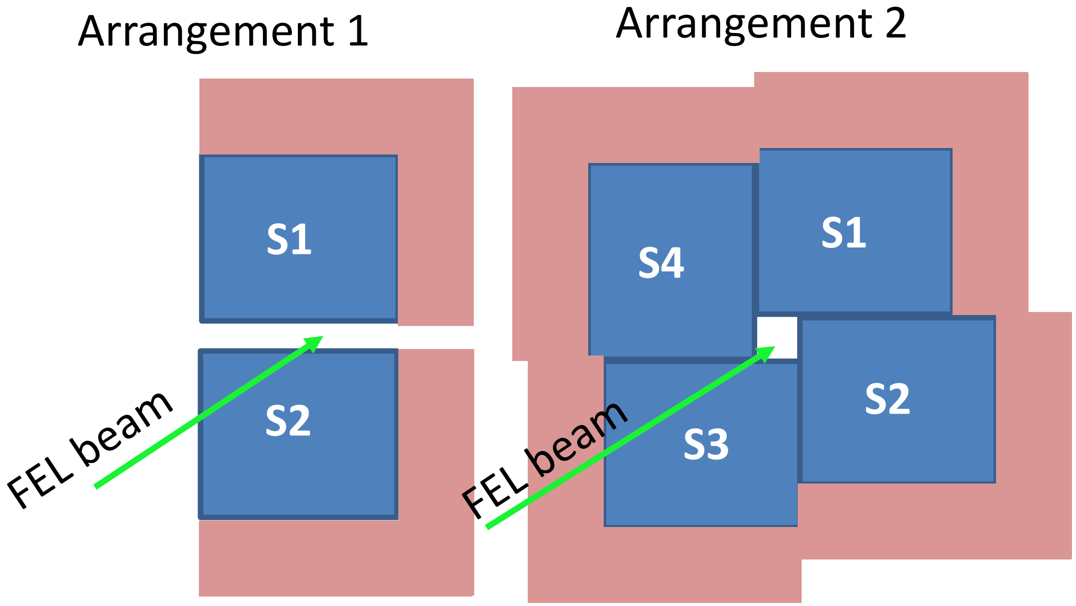




Large area scheme

Sensor Modul





To Achieve 120 fps on a 13 Mpixels sensor

- ✓ 7 ADCs (12bits + 3 bits read-out info gain and overrange) per column in parallel will operate @ 7 µs.
- ✓ 32 columns are multiplexed on one LVDS line @ 460 MHz.

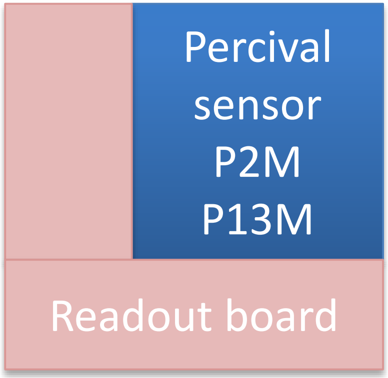
↓

In total 1 sensor has 24864 ADCs on 111 LVDS lines

↓

Data flux: 50 Gbit/s (handle by 5 Computers)

Sensor Modul



Topics

- Introduction: seeded FERMI and DiProI beamline.
- *CDI and detector requirements.*
- PERCIVAL project.
- **Research opportunities with PERCIVAL @ FERMI.**
- Conclusions..

What we could gain with Percival

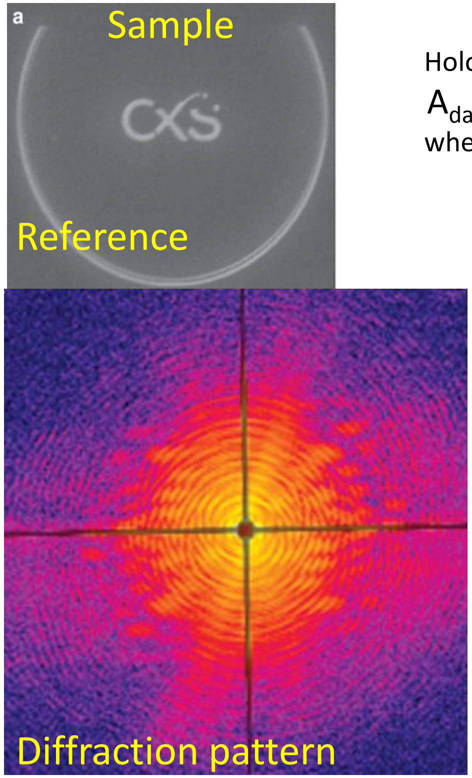
Faster and low noise readout is extrimelly nice for single-shot imaging with airbone sample

We have already proved benefit of combining CDI with Holograhy:

a) SR source, F.Capotondi et al. Optics Express, (2012).
b) FEL source, A.V. Martin et al. Nature Comm. (2014).

Seed FEL pulse has an high degree of transversal and longitudinal coherence.

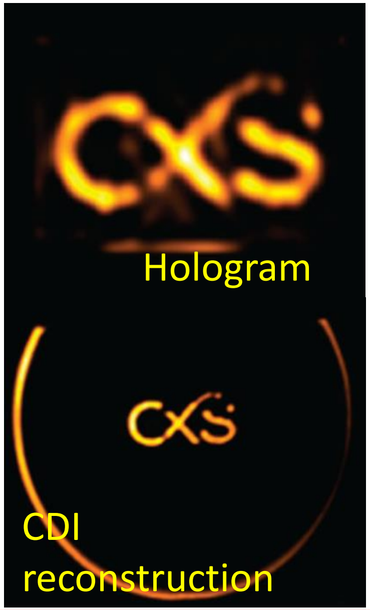
1. ***Transversal coherence is the key element in CDI.***
2. ***Longitudinal coherence is important in holography when mask is decoupled from the sample.***



Hologram obtained solving iteratively

$A_{data} - A_{ref} = C_{ref,obj}$

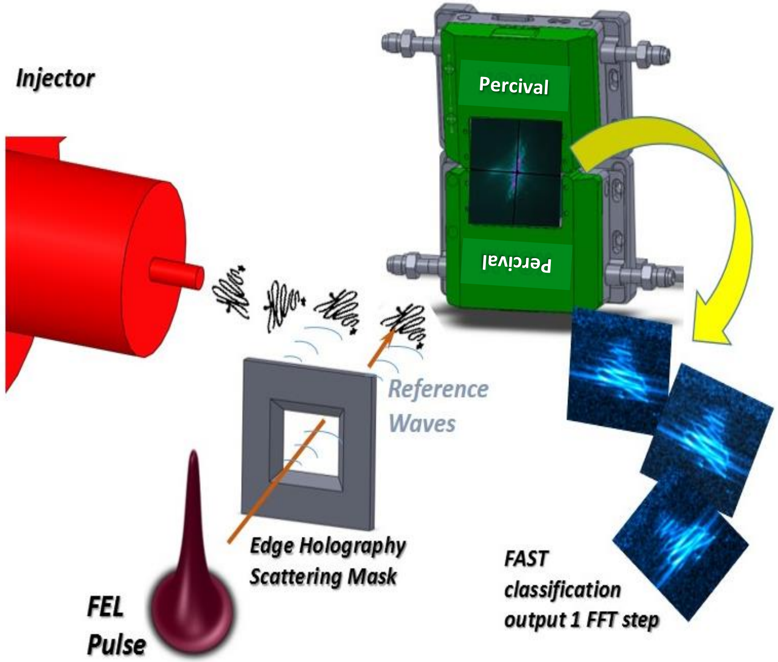
where $C_{ref,obj} = \Psi_{ref}{}^{*}\, \Psi_{obj}$



Hologram refined with RAAR phase retrivial

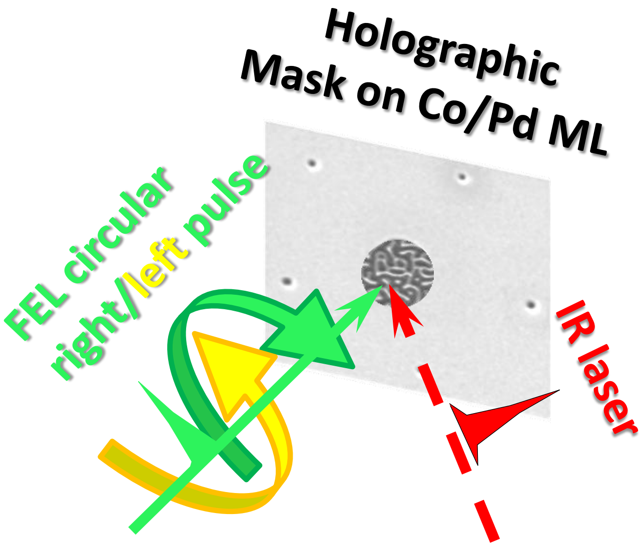
A.V. Martin. et al. “X-ray holography with customizable reference” Nature Comm. 4, 2476 (2014).

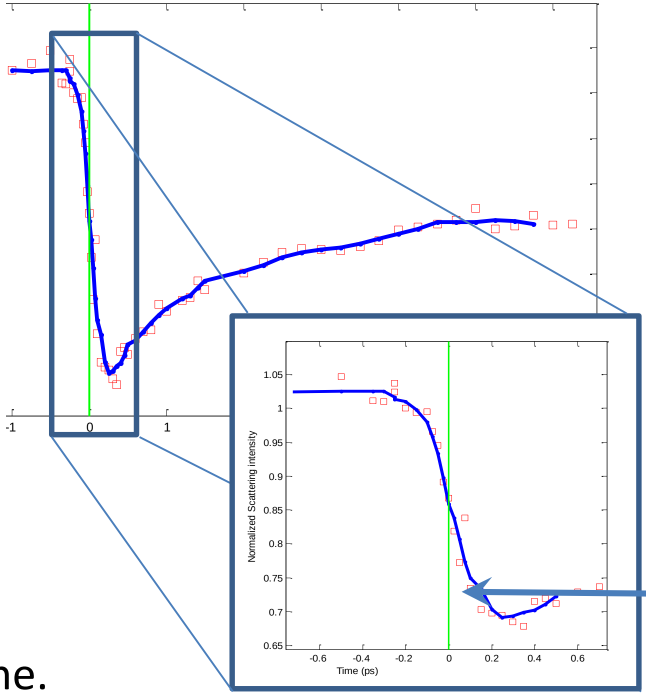
Combining Extended Reference Holography with particle injector



What we could gain with Percival

Faster and low noise readout is extrimelly nice for time resolved scattering on magnetic material





Demagnetization curve Pumping with IR laser monitoring the CCD intensity.

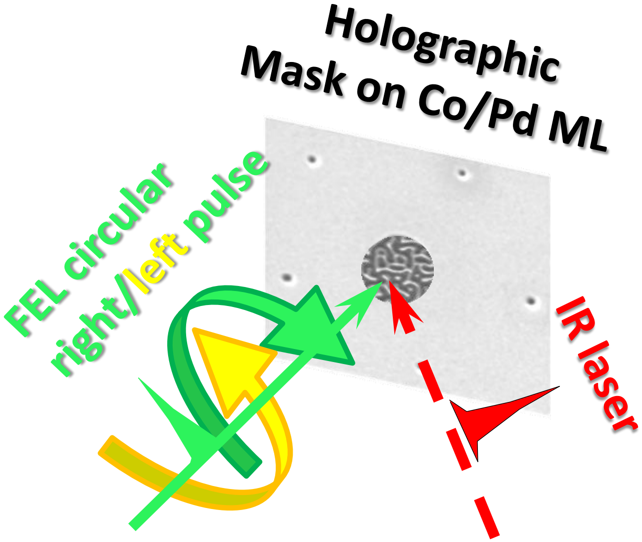
25 fs of resolution!!!

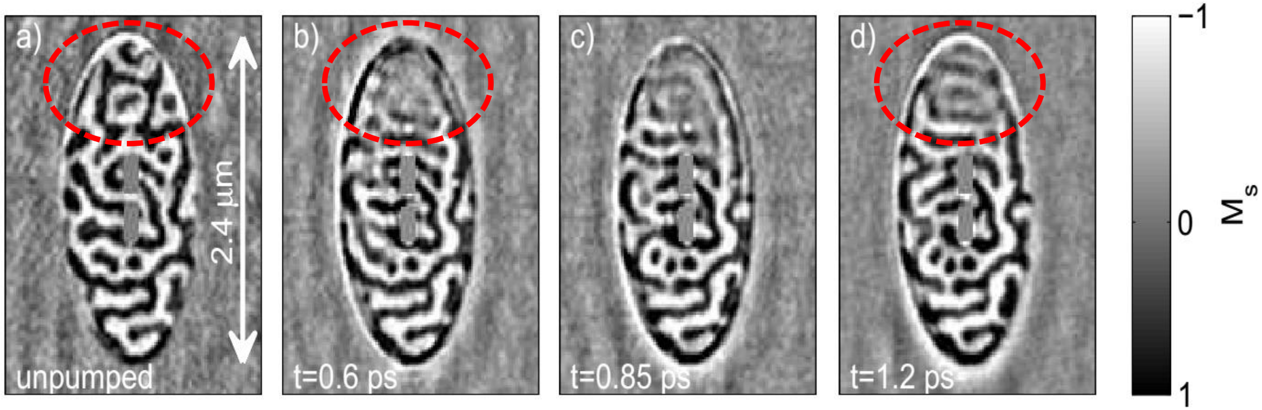
Acquired in no disctructive regime.
Acquisition time about 1h, due to the slow CCD readout.

At 50 Hz (max rap. Rate) FERMI we can do the scan in 1 min!! => More data, less sensitive to beam instability/drift on long time scale => maybe better temporal resolution.
20.8 nm (60 eV on FEL-1) out of nominal range of Percival. But other edges of magnetic interesting elements Tb, Gd have higher energy (140-150 eV), and L-edges of Tr-metals Fe-Ni-Co (700-850eV) can be reached in III harmonic with FEL-II.

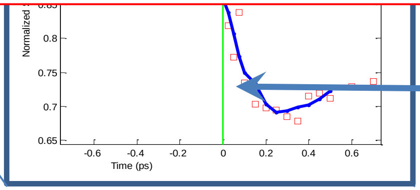
What we could gain with Percival

Faster and low noise readout is extrimelly nice for time resolved scattering on magnetic material





C. von Korff Schmising et. al., Imaging ultrafast demagnetization dynamics after a spatially localized optical excitation, Phys. Rew. Lett. (2014).



25 fs of resolution!!!

Acquired in no disctructive regime.
Acquisition time about 1h, due to the slow CCD readout.

At 50 Hz (max rap. Rate) FERMI we can do the scan in 1 min!! => More data, less sensitive to beam instability/drift on long time scale => maybe better temporal resolution.
20.8 nm (60 eV on FEL-1) out of nominal range of Percival. But other edges of magnetic interesting elements Tb, Gd have higher energy (140-150 eV), and L-edges of Tr-metals Fe-Ni-Co (700-850eV) can be reached in III harmonic with FEL-II.

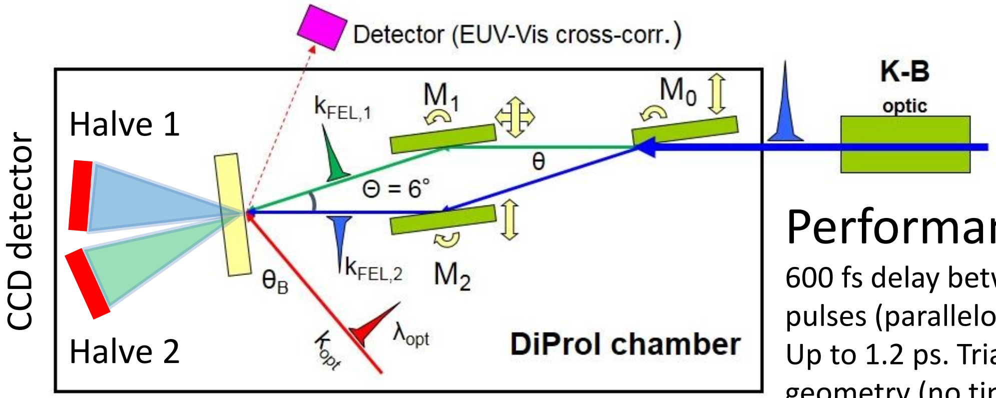
Elettra Sincrotrone Trieste

What we could gain with Percival

<u>Large area, halves and low noise readout are extrimelly nice for Stereo/Stroboscopic imaging.</u>

Compact mini-delay line

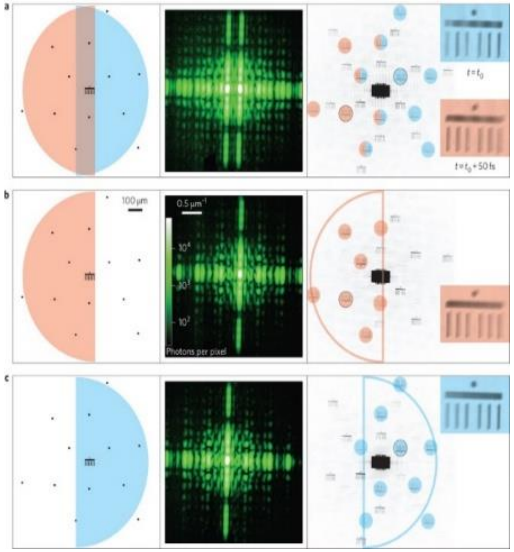
(in collaboration with F.Bencivenga C. Masciovecchio)



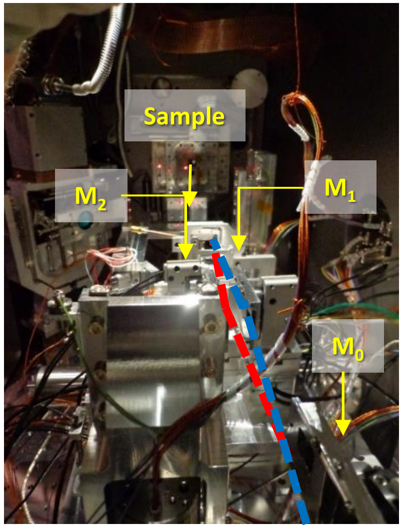
Performances:

600 fs delay between 2 FEL pulses (parallelogram geometry)
Up to 1.2 ps. Triangular geometry (no time Zero)

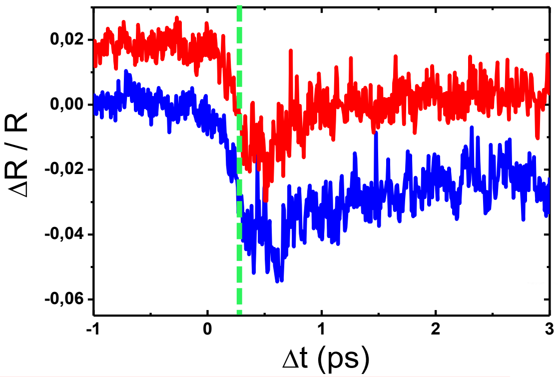
Ideal geometry for stroboscopic imaging



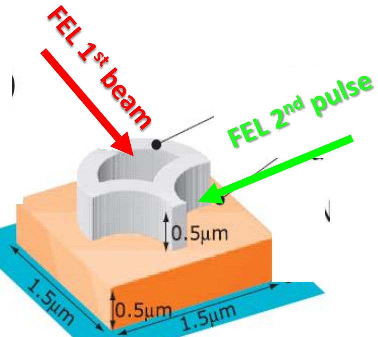
C.M. Gunther et al. Nat. Phot. 5 (2011)



Controllable delay between 2 FEL pulses



Proof of principle FWM experiment:
F.Bencivenga et. al. *Nature 520, 205 (2015).*



Collecting 2 independent diffraction patterns allows to observe the sample from different projections before explosion or delaying one arm, add time resolution.

Topics

- Introduction: seeded FERMI and DiProI beamline.
- *CDI and detector requirements.*
- PERCIVAL project.
- Research opportunities with PERCIVAL @ FERMI.
- **Conclusions.**

Conclusions

- ✓ **DiProI is a fully operative and almost user friendly multipurpose end-station dedicated to scattering experiments with FERMI-FEL**

- ✓ **PERCIVAL detector is under development:**
  1. **Pixels structure has been determined.**
  2. **Large dynamic range has been demostrated.**
  3. **Prototype chip with hardware has been test in the low energy range.**

- ✓ **Novel schemes are under consideration to extend the core capabilities of the DiProI instrument to particle injection, stroboscopic imaging and time resolved magnetic scattering using PERCIVAL detector. They open unique opportunities for novel experiments with both FERMI-FEL1 and FEL2.**

Elettra Sincrotrone Trieste

COLLABORATORS

Internal and external

Elettra Sincrotrone Trieste

DiProI: **M. Kiskinova (coordinator)**,F. Capotondi (BL scientist), E. Pedersoli (post-doc), M. Manfredda (post-doc), F.Casolari (Phd student)

FEL physic: L. Giannessi, E.Allaria, C. Spezzani, and all the FERMI COMMISSIONING TEAM

Lasers: M. Danailov, A. Demidovich, I. Nikolov (pump&probe laser)

PADReS: M. Zangrando, N. Mahne, L. Raimondi (beamlines, optics)

Others: R.H. Menk (consulting for detectors), R. Borges (software), F. Bencivenga, C. Masciovecchio, D. Fausti (collaboration for instrumentation and experiments)

CFEL SCIENCE

DESY

UH

H. Chapman

S. Bajt

A. Barty et al.

PULSE STANFORD

M. Bogan et al.

Lawrence Livermore National Laboratory

A. Nelson

M. Frank et al.

UPPSALA UNIVERSITET

J. Hajdu et al.

berlin

S. Eisebitt,

C. Von Korff

B. Pfau et al.

DESY

G.Grübel, C. Gutt, L. Müller

B. Keitel,K. Tiedtke,E. Plönjes-Palm et al.

Laser-Laboratorium Göttingen e.V.

K. Mann

T. Mey

UPMC SORBONNE UNIVERSITÉS

J. Luning,

B. Vodungbo, et al.

PERCIVAL COLLABORATION

H. Graafsma, C.B. Wunderer, A. Marras, J. Correa, P. Goettlicher, S. Lange, I. Shevyakov, S. Smoljanin, A. Delfs, H. Hirsemann, Q. Xia, M. Zimmer, S. Reza

I. Sedgwick, D. Das, N. Guerrini, B. Marsh, T. Nicholls, R. Turchetta

G. Cautero, D. Giuressi, A. Khromova, R. Menk, L. Stebel, G. Pinaroli

N. Tartoni, U. Pedersen, N. Rees, H. Yousef

H. Hyun, K. Kim, S. Rah

S. Nikzad, M.E. Hoenk, T. J. Jones, A. Jewell, A. Carver (Jet Propulsion Lab, California Institute of Technology)

PERCIVAL – Pixelated Energy Resolving CMOS Imager, Versatile and Large

THANK YOU FOR YOUR ATTENTION

www.elettra.trieste.it