XIMEA

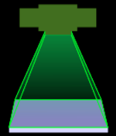
X-ray imaging

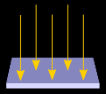
Camera and sensor technology

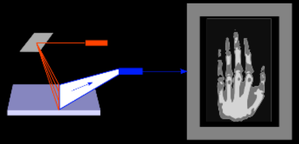
„It seemed at first a new kind of invisible light.
It was clearly something new… something unrecorded.
There is much to do…“ - Wilhelm Röntgen

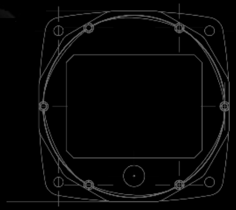
Radiography

- X-rays
  - Photons with a wavelength of ~10nm and below
  - The shorter the wavelength, the higher…
    - … the energy
      - Extreme ultraviolet (XUV): 124-10nm, ~10-124eV
      - Soft x-rays: 10-0.25nm, ~124–5,000eV
      - Hard x-rays: <0.25nm, >5keV
    - … the ability to pass through solid matter
  - X-rays allow to investigate matter structures by capturing shadow images of traversed matter when combined with imaging detectors
    - Generation 1: Film-based / x-ray film radiography
    - Generation 2: Computed radiography (CR)
    - Generation 3: Digital radiography (DR)
    - Generation 4: Computed tomography (CT)



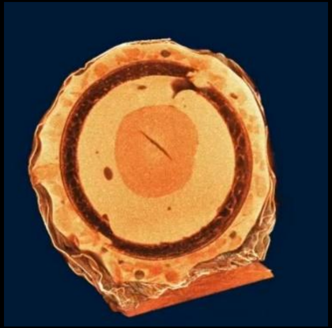


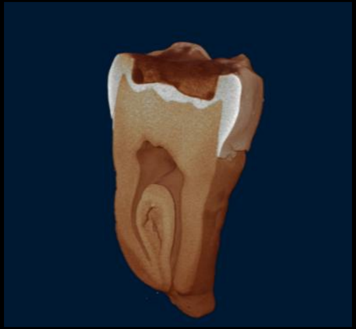


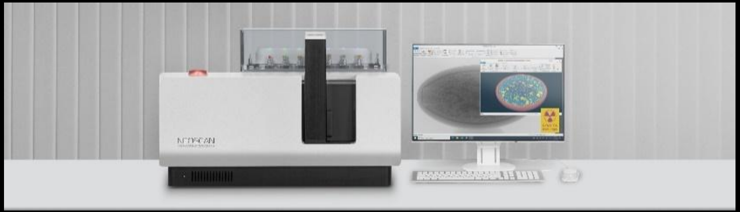


What you can do with it if you know what you're doing…

- Example images scanned with Neoscan N60 micro-CT scanner (https://neoscan.com)
  - XIMEA MJ150XR, Gpixel GSENSE5130
  - GadOx:Eu, 1:1 FOP, 21.5x12.6mm FoV

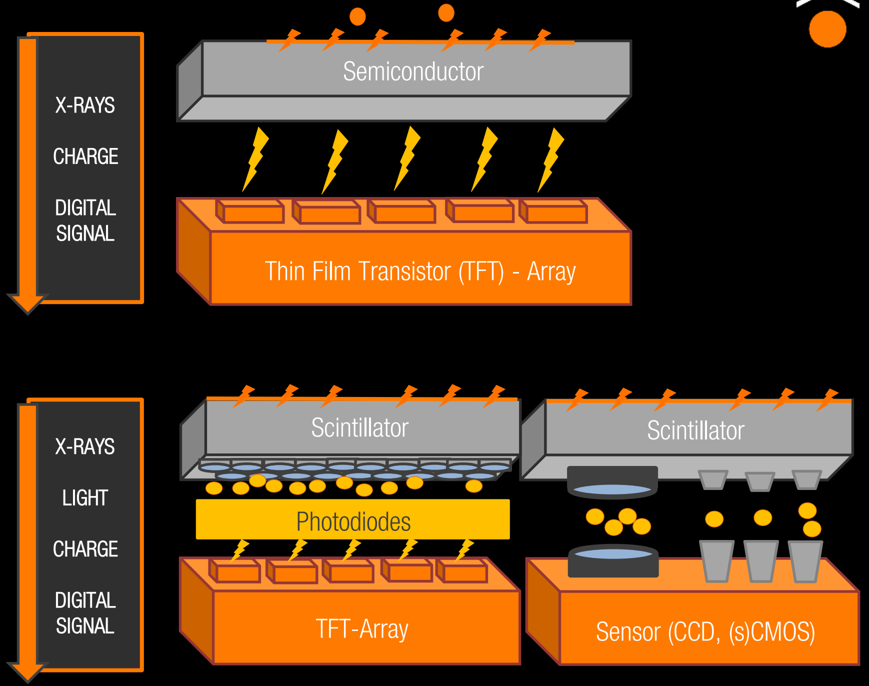




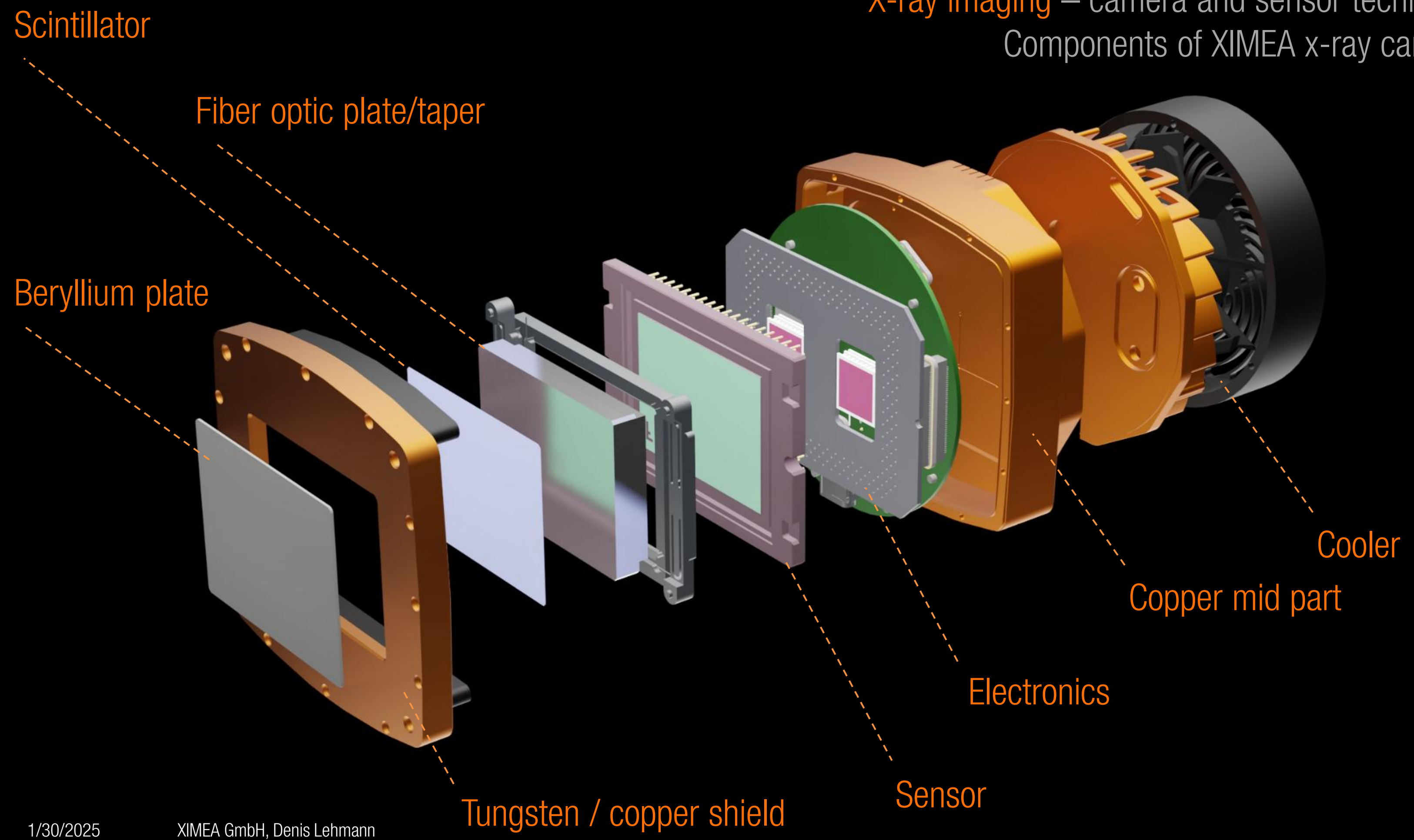


Digital radiography

- Choice of detection varies based on x-ray energy level
  - Direct detection
    - X-rays are directly converted into a proportionally sized electrical charge using a semiconductor material
    - The most used semiconductor is amorphous selenium (a-Se). The charge is usually collected with Thin Film Transistors (TFTs)
    - TFTs are better at lower energy levels (e.g., for mammography)
    - At high x-ray energy levels (30-50keV), detection becomes dominated by the Compton scattering which will blur the resulting image [2]
  - Indirect detection
    - X-rays are detected by using other materials that interact with them
    - X-rays are detected in a two-step process. First converted into visible light using a scintillator material, then converted into an electrical charge using silicon-based detectors
    - Indirect detectors support higher energy levels (e.g., for material inspection)

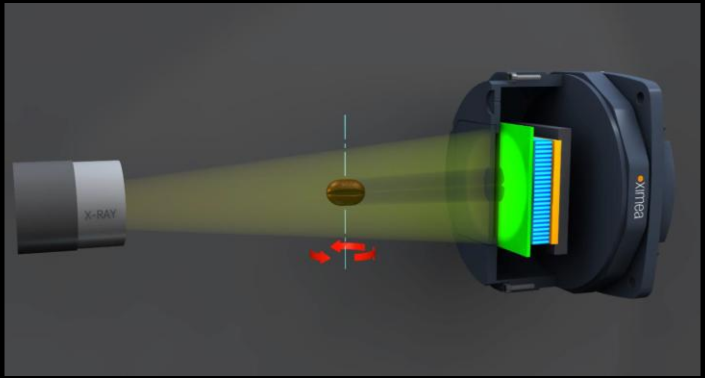


X-ray imaging – camera and sensor technology
Components of XIMEA x-ray cameras

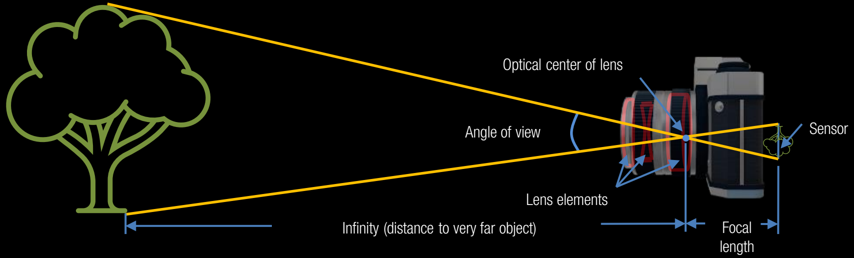


X-ray camera fundamentals

- General setup for x-ray applications
  - X-ray cameras require a radiation source
  - The sample is placed between source and camera
  - Radiation traverses the sample and hits the camera front
  - The scintillator material emits visible light if hit by radiation
  - The image is darker where matter attenuated the x-rays



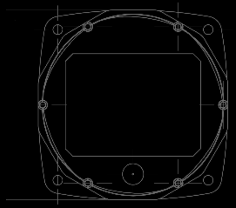
- Insofar they are different from optical setups
  - X-rays are emitted from a point source and traverse the sample without visible reflections
  - For visible light, the emitter is the reflected light of the sample surface
  - With optical cameras, samples can be larger than the camera. They can be de-magnified onto a smaller sensor surface by adjusting the focal length of the lens
  - With x-ray cameras, the sample must be equal or smaller than the scintillator screen



X-ray imaging – camera and sensor technology

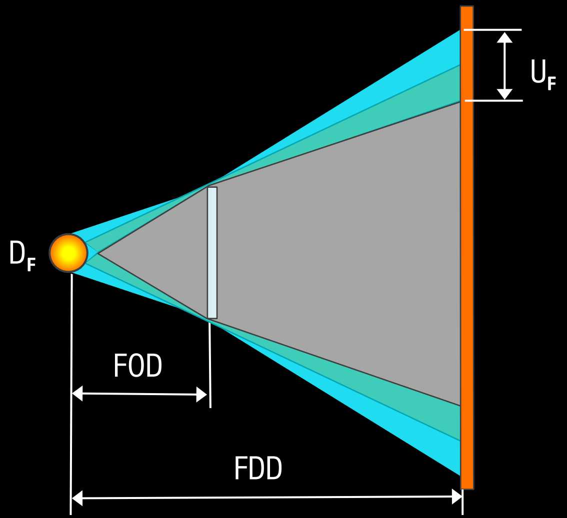
Designing x-ray cameras for x-ray applications

- The performance of x-ray cameras highly depends on the balanced combination of
  - Radiation source
  - Scintillator
    - Type
    - Thickness
    - Grain size
  - Fiber optic plate/taper
    - Type
    - Diameter
    - Thickness
    - Magnification
  - And sensor
    - Field of view, quantum efficiency, pixel size



Impacts of the radiation source

- Choice of radiation source and setup are crucial for a good overall system performance
  - There are two factors of interest
    - Focal spot size
    - Geometric magnification
  - They account for undesired image blur
    - A sample can appear larger on the sensor surface as in reality, see geometry on the right
    - This is called geometric magnification M
    - The focal spot size generates penumbras U_F, which are dependent on the magnification M
  - I.e., the closer the sample to the screen, the lower M, the lower U_F, the better the image
  - Also, the lower the spot size D_F, the better the image



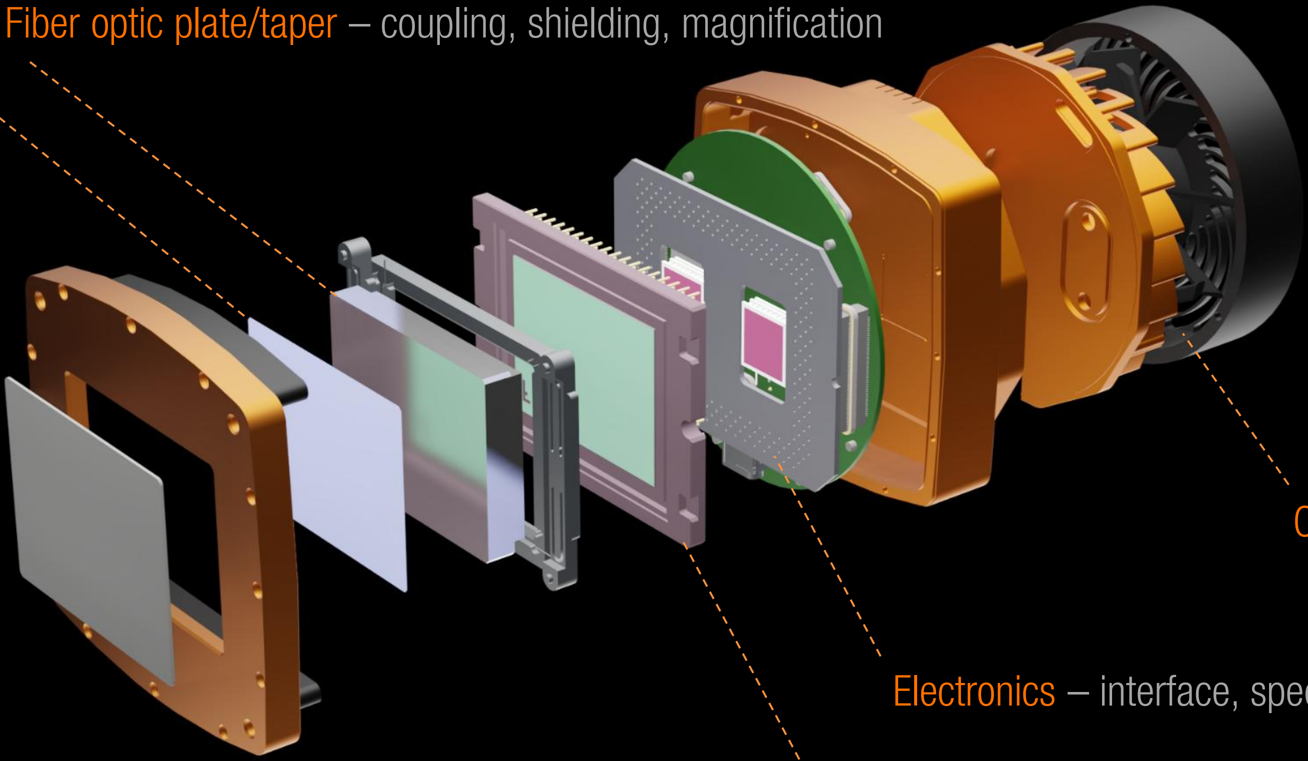
$$U_F = D_F * (M - 1),$$

$$M = \frac{FDD}{FOD}$$

X-ray imaging – camera and sensor technology
Customization options

Scintillator – type, thickness, conversion efficiency

Fiber optic plate/taper – coupling, shielding, magnification



Cooler – water, air

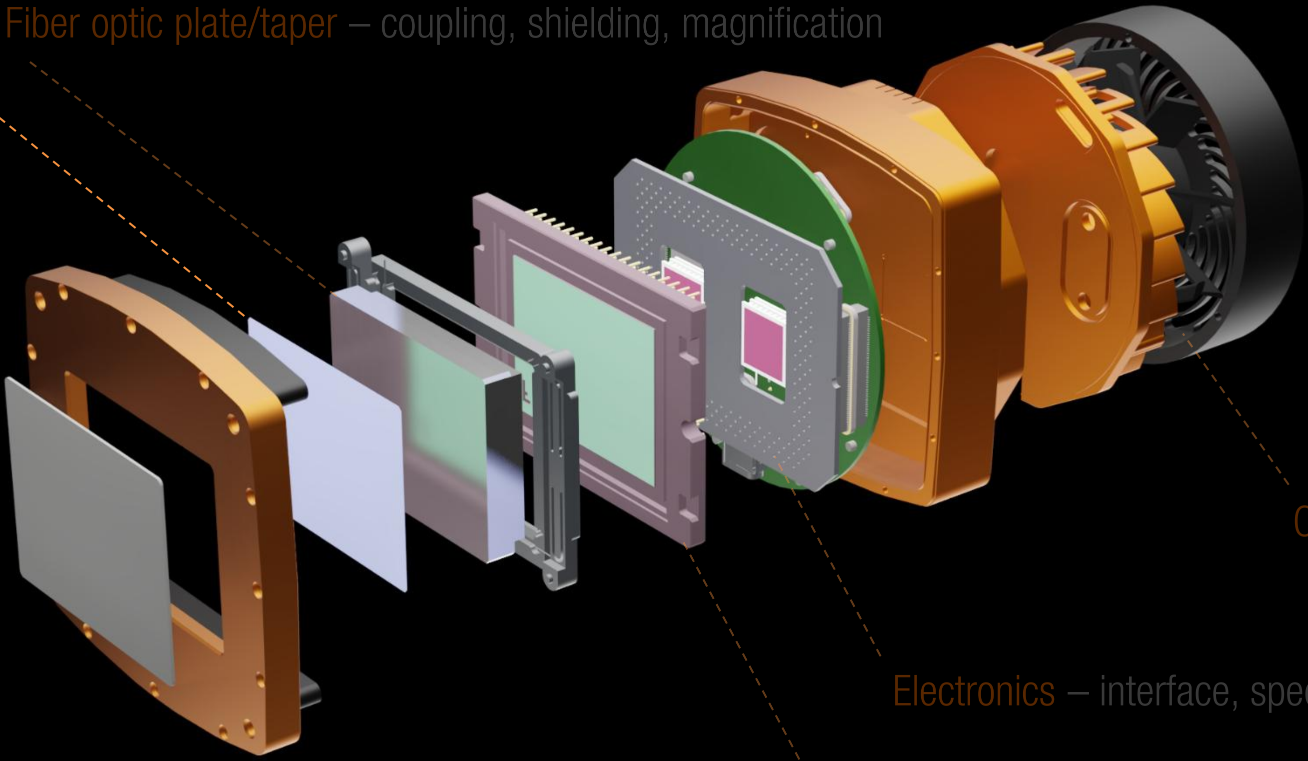
Electronics – interface, speed, connectors

Sensor – sensitivity, field of view

X-ray imaging – camera and sensor technology
Customization options

Scintillator – type, thickness, conversion efficiency

Fiber optic plate/taper – coupling, shielding, magnification



Cooler – water, air

Electronics – interface, speed, connectors

Sensor – sensitivity, field of view

Scintillator

- The scintillator determines the overall efficiency of an x-ray camera in converting x-rays into visible light by a combination of
  - Scintillator material
  - Scintillator thickness
  - Scintillator grain size
- Scintillator thickness in general determines
  - The probability that x-rays are interacting with it
  - And thus, the amount of emitted light for a given x-ray energy
- Two materials are commonly used
  - Gadolinium Oxysulfide (GadOx)
  - Cesium Iodide (CsI)

- Scintillator x-ray attenuation (%) depends on both, scintillator thickness and x-ray energy
  - CsI, 150µm, 30keV 45.8%
  - CsI, 150µm, 60keV 41.5%
  - CsI, 150µm, 80keV 22.0%
  - CsI, 150µm, 100keV 12.9%
  - CsI, 150µm, 250keV 1.70%

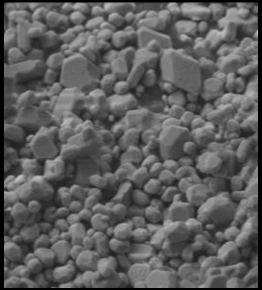
  - GadOx, 10µm, 30keV 8.91%
  - GadOx, 10µm, 60keV 7.04%
  - GadOx, 10µm, 80keV 3.41%
  - GadOx, 10µm, 100keV 1.93%
  - GadOx, 10µm, 250keV 0.23%

X-ray imaging – camera and sensor technology

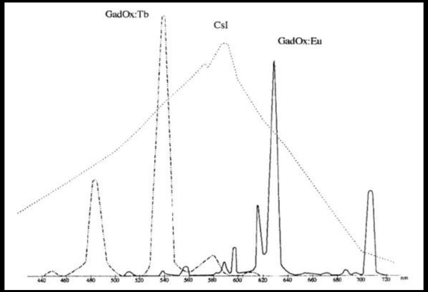
Scintillator cont.

- Gadolinium Oxysulfide (GadOx)
  - Good light output
    (60 photons/keV per incident x-ray photon for GadOx:Tb) [7]
  - Powder structure
  - Comparably cheap
  - Sharp peaks at specific wavelengths
  - Can be doped with Terbium (Gadox:Tb), Praseodymium (Gadox:Pr) or Europium (Gadox:Eu) to e.g., vary wavelength responses

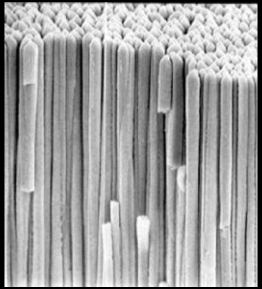
- Cesium Iodide (CsI)
  - Excellent light output
    (65 photons/keV per incident x-ray photon, CsI:Tl) [7].
    One of the brightest scintillator materials known [4]
  - Crystalline structure, grown in columns
  - Wavelength response is evenly distributed across the whole spectrum with its peak where most sensors are most sensitive
  - Can be doped with Sodium (CsI:Na) or Thallium (CsI:Tl)
  - CsI is slightly hygroscopic (binds water)



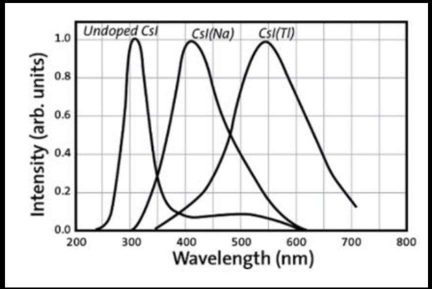
GadOx:Tb powder [5]



GadOx vs CsI wavelength emission



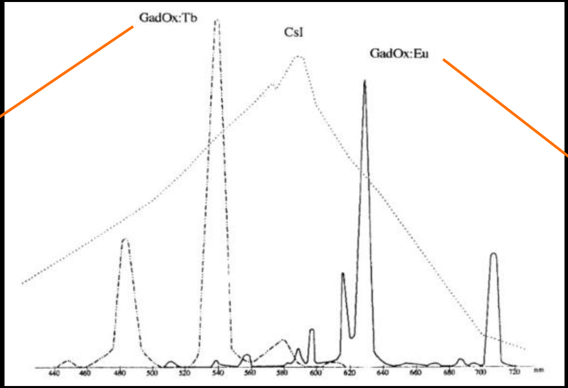
CsI:Tl crystals [3]



Undoped, Sodium, and Thallium doped CsI

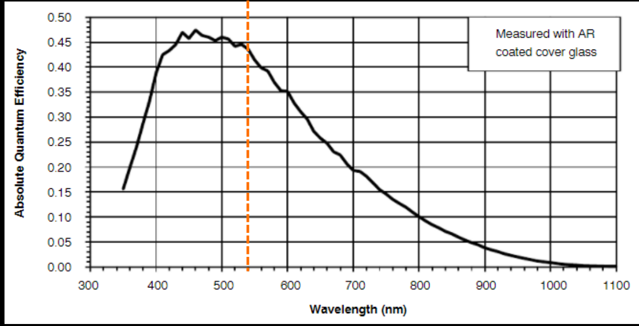
Scintillator cont.

The choice of scintillator material must match sensor properties

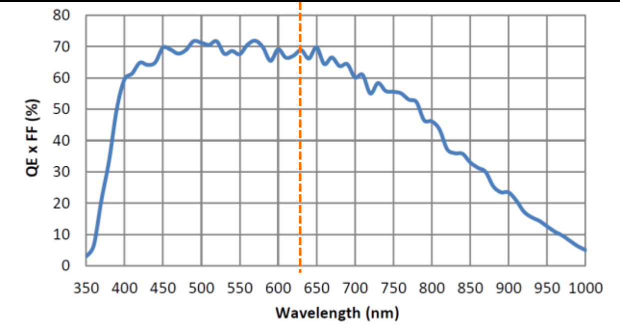


GadOx:Tb peak

GadOx:Eu peak



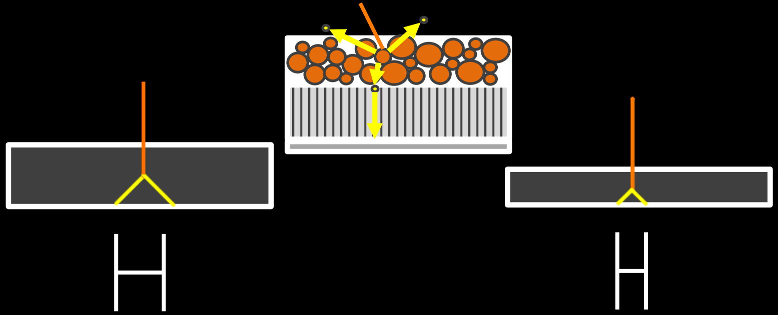
KAI-16000 CCD QE curve



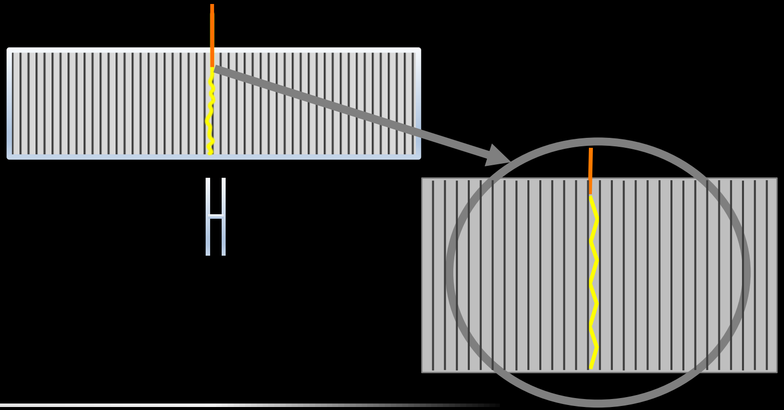
GSENSE5130 CMOS QE curve

Scintillator cont.

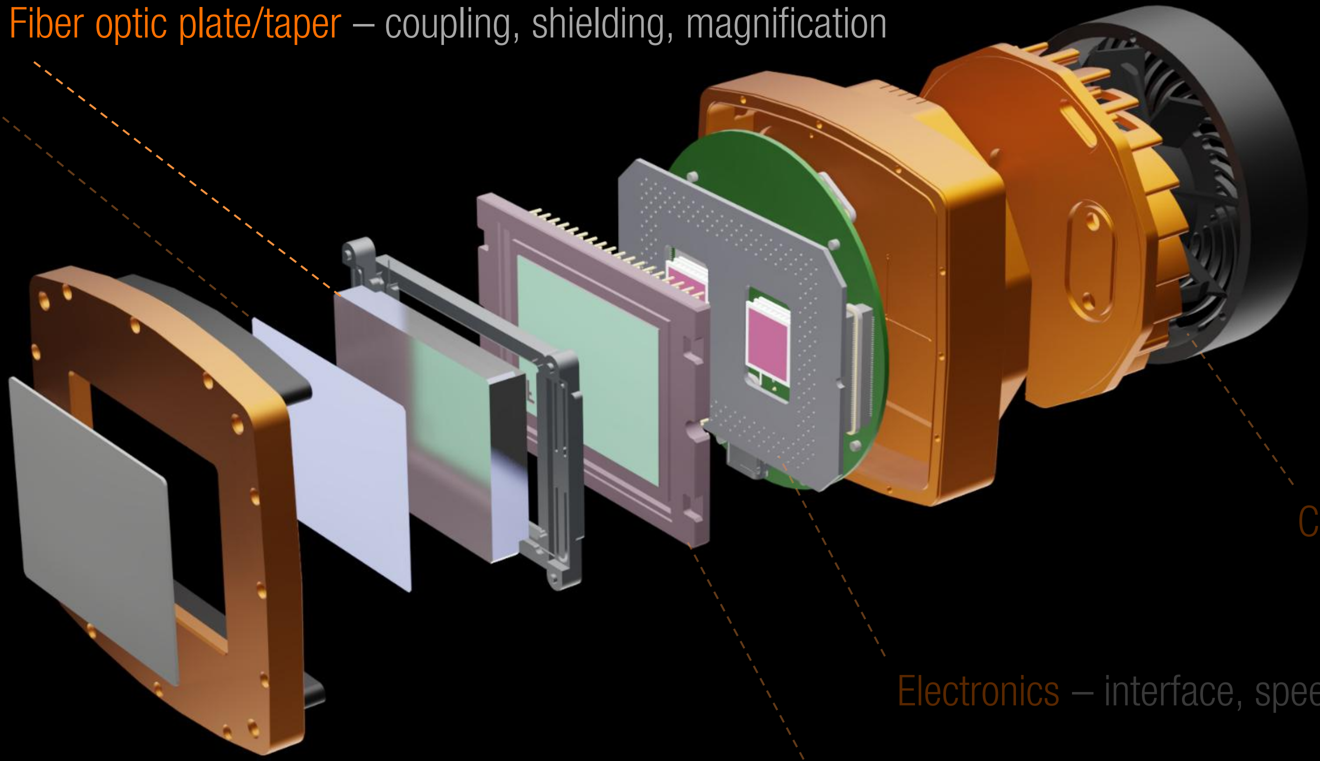
- Gadolinium Oxysulfide (GadOx)
  - Increased light scattering because of its powder structure. Such scintillators emit and scatter light into arbitrary directions
  - Thus, layer should be thin (10-40µm) and grain size should be small (2.5-8µm). Grain size distribution needs to match fiber optics diameter
  - Thicker screens yield poorer spatial resolution because of the increased scattering from the powder structure
  - GadOx is usually better for lower energy applications. High energy photons may pass through thin layers without creating a signal



- Cesium Iodide (CsI)
  - Light scattering is reduced because of its column grown crystalline structure. Light is “channeled” to the fiber optics
  - CsI allows for thicker scintillator layers (150µm and more). This can provide better results compared to GadOx, especially for higher energy applications
  - The spatial resolution for a given thickness of CsI is higher compared to GadOx because of its crystalline structure

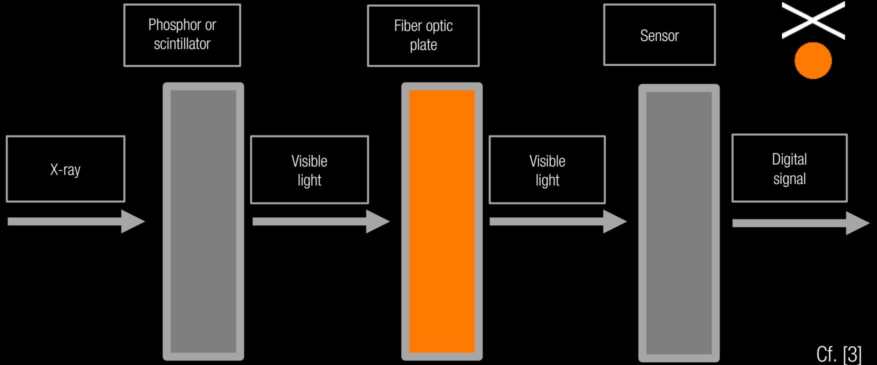


X-ray imaging – camera and sensor technology
Customization options

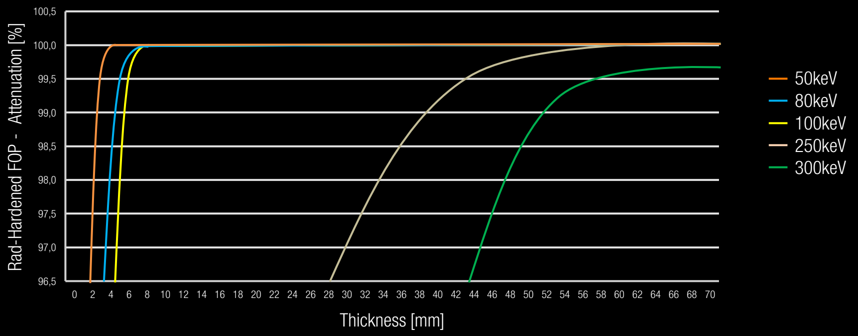


Fiber optic plate

- The main reasons for fiber optic plates are
  - Efficient light transfer, preventing scattering
  - Shielding of sensor and electronics from x-ray energy
- Shielding requirements depend on energy levels
  - Scintillator materials only absorb a fraction of the x-rays
  - High energy x-rays which are not absorbed will damage the sensor and camera electronics
  - The higher the x-ray energy, the more shielding is needed
  - Fiber optic plates transmit visible light while adding additional shielding against harmful x-rays
  - X-ray attenuation depends on the thickness of the fiber optic plate

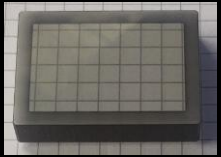


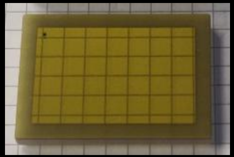
Cf. [3]



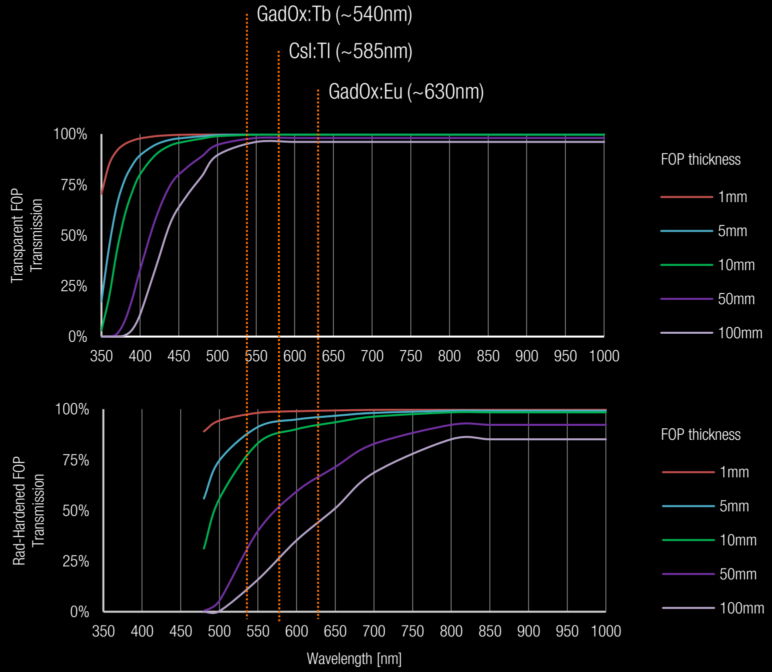
X-ray imaging – camera and sensor technology

Fiber optic plate cont.

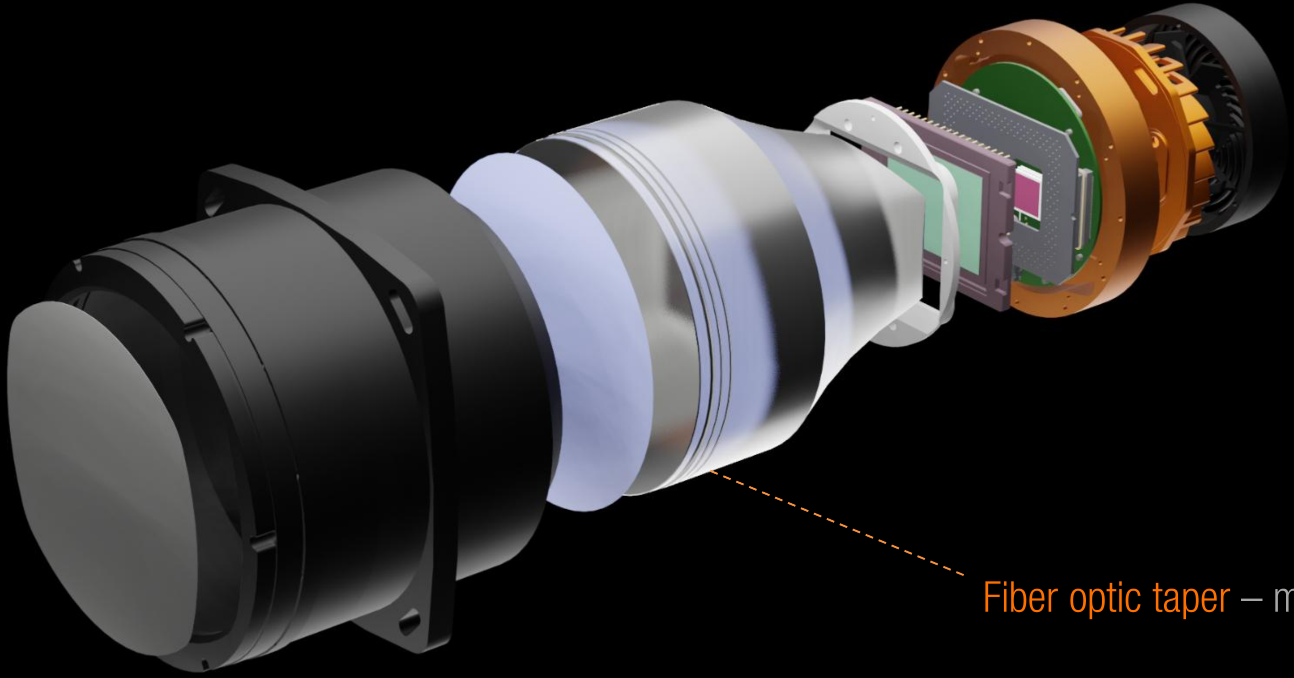




- We use two types of fiber optic plates
  - Transparent FOPs
    - Transmission is > 95% for all wavelengths emitted by any of our scintillators for any thickness 65mm and below
    - GadOx:Tb (540nm), CsI:Tl (585nm), GadOx:EU (630nm)
    - Becomes opaque over time when it is hit with x-rays because of the browning effect
  - Radiation hardened FOPs
    - Protects from browning effect
    - The smaller the wavelength, the lower the transmission
    - GadOx:Eu is preferred for applications with high energy levels
  - FOPs contain millions of individual optical fibers
    - They prevent scattering by “directing” photons to the right pixel of the sensor surface while the FOP thickness can be increased
    - Their diameter should match (>=) the sensor pixel size

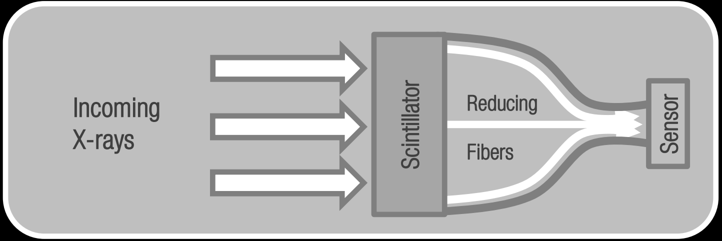


We also provide cameras that allow magnification by using fiber optic tapers



Fiber optic taper

- Fiber optic tapers are fiber optic plates where the input size is larger than the output size
  - De-magnification can reach x3 or higher
  - Allows using smaller (and cheaper) sensors for larger samples
  - Tradeoff: the greater the de-magnification, the lower the light transmission (*). I.e., only a smaller portion of the emitted light will reach the sensor
  - We use slightly larger scintillator thickness to generate more light and to match the larger fiber size on the large side of the fiber optic taper. This reduces the spatial resolution because of the increased scintillator thickness
  - I.e., detection efficiency is always better when using larger silicon sensors that do not need fiber optic de-magnification for a given application
  - However, larger silicon sensors are usually more expensive than fiber optic tapers. It's often a question of budget



(*) Explanation: The Numerical Aperture (NA) becomes smaller with increased de-magnification. NA is a measure of the maximum incidence angle at which light rays will be transmitted down the taper. The effective NA of a taper is calculated as:

$$NA_{eff} = NA_{max} * \frac{D_{min}}{D_{max}}$$

D_{min} = smallest diameter

D_{max} = largest diameter

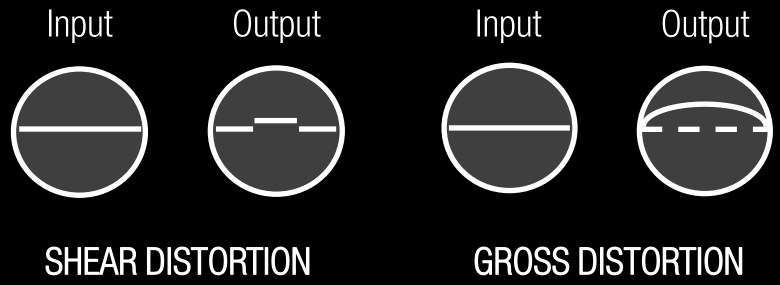
NA = numerical aperture

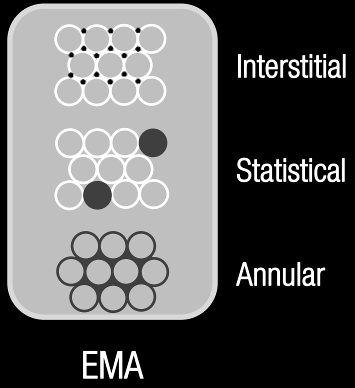
i.e., light arriving the taper at steeper angles is no longer transmitted

i.e., less light is transmitted, cf. [6]

Fiber optic taper cont.

- Primary disadvantages of fiber optics
  - Inherent presence of distortions and blemishes
    - Spot blemishes (burned or broken (dark) fibers)
    - Line blemishes (pattern of multiple broken (dark) fibers)
    - Image distortions
      - Shear: Miss-placement of a fiber
      - Gross: A straight line is imaged as a continuous curve
    - Can be corrected with software acquisition and processing techniques, e.g., flat-field or distortion-correction algorithms
  - When light enters a fiber at an angle steeper than the total internal refection angle, it will leak into the cladding
    - Loss of light, cross-talk
    - Stray-light absorbers are added, referred to as EMA (extra-mural absorption) to maintain high contrast

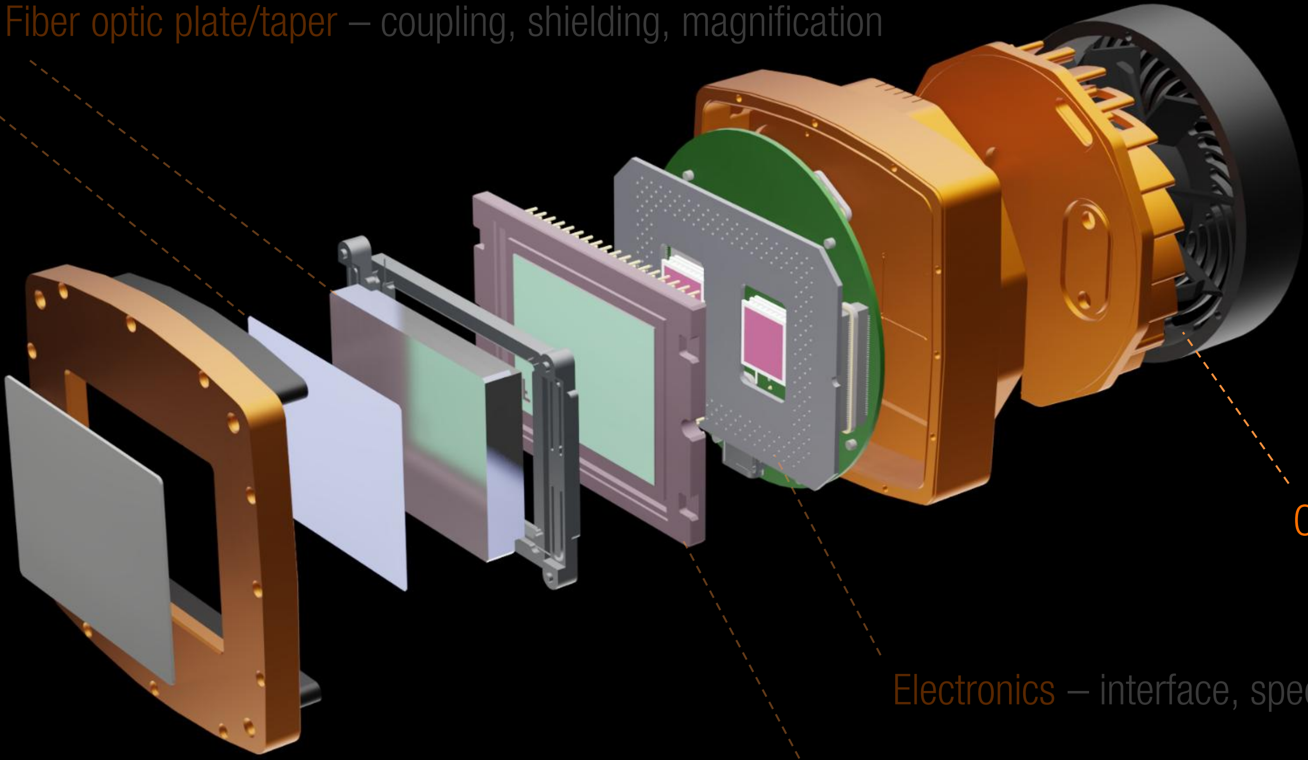




X-ray imaging – camera and sensor technology
Customization options

Scintillator – type, thickness, conversion efficiency

Fiber optic plate/taper – coupling, shielding, magnification



Cooler – water, air

Electronics – interface, speed, connectors

Sensor – sensitivity, field of view

X-ray imaging – camera and sensor technology

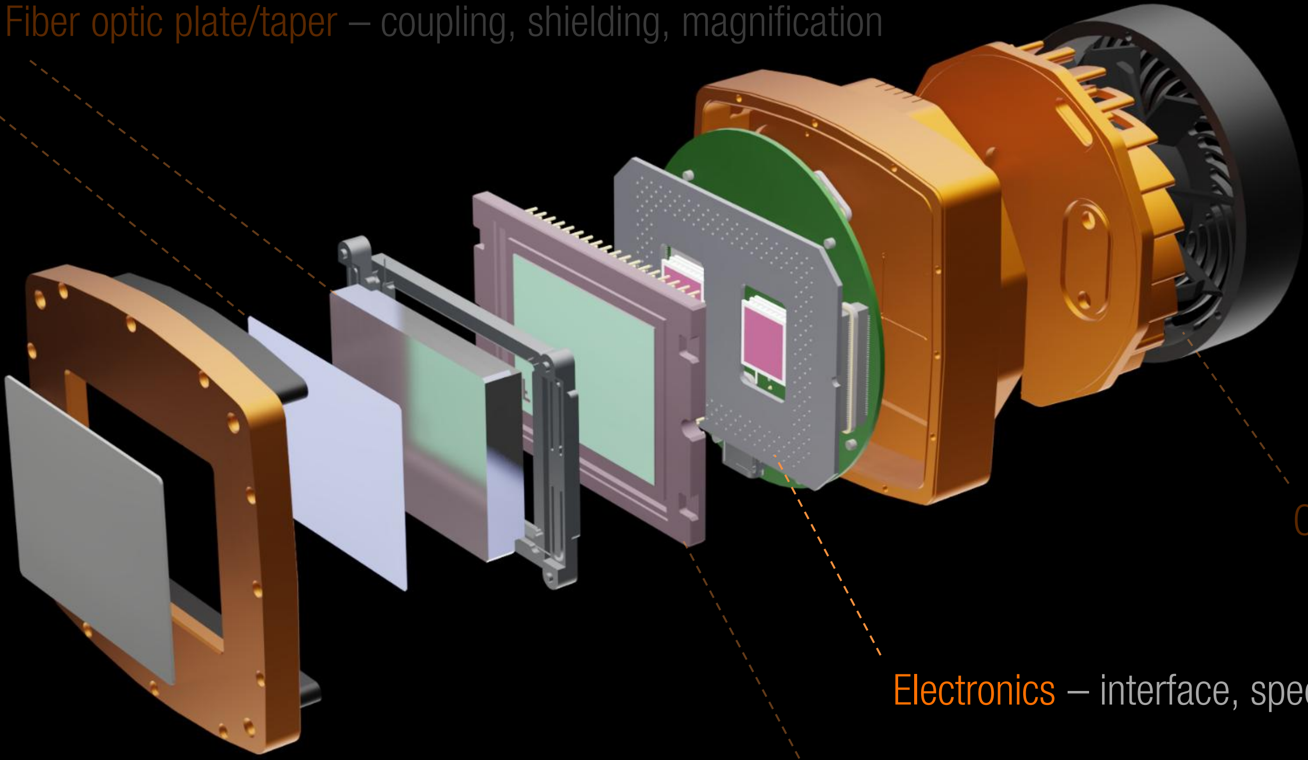
Cooler

- We support various cooling options
  - Air cooling (passive)
  - Air cooling (active)
  - Liquid cooling
- Sensors (in some models) can be cooled down
  - -10°C with active air cooling
  - -30°C with water cooling
  - Decreasing dark current
- Sensor temperature can be set via API
  - Set your desired temperature
  - Camera will reach and stabilize it, with up to -+0.1°C precision

X-ray imaging – camera and sensor technology
Customization options

Scintillator – type, thickness, conversion efficiency

Fiber optic plate/taper – coupling, shielding, magnification



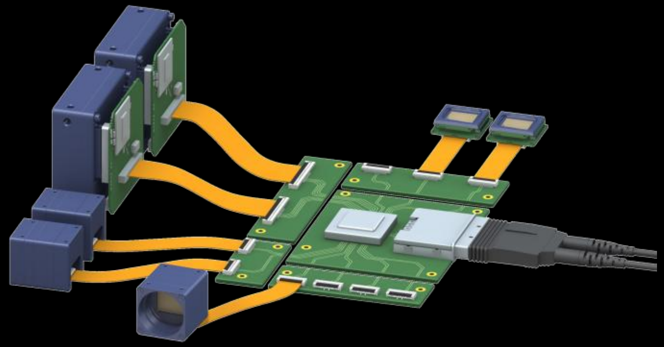
Cooler – water, air

Electronics – interface, speed, connectors

Sensor – sensitivity, field of view

Interface

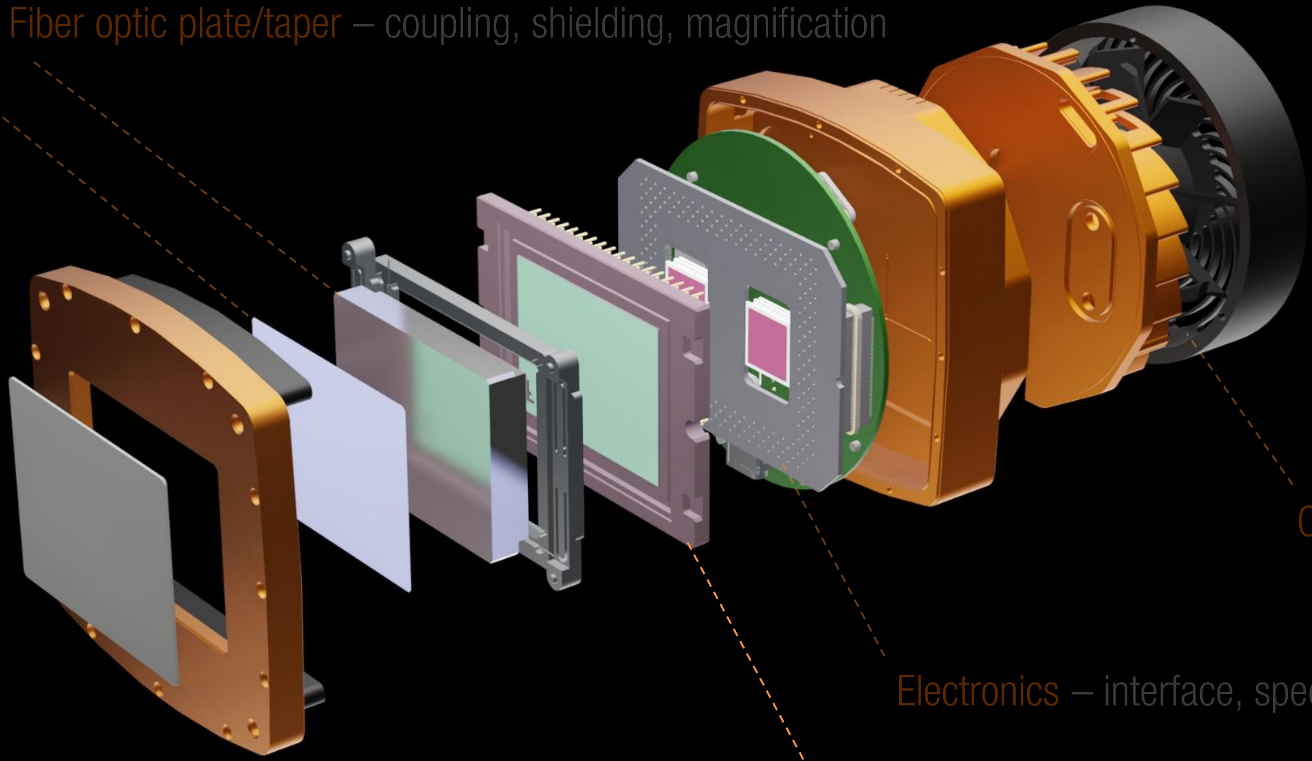
- We provide
  - USB
    - Industry standard cables
    - Good relation for bandwidth and price
  - PCI Express
    - Highest bandwidth up to 64Gbps
    - Long cable lengths (80-100 of meters)
    - Near to zero latency, e.g., data to RAM or GPU
    - Can be used with nearly all computers available today
- In various connector options
  - For USB: Micro-B, Type-C, Flat-Ribbon
  - For PCIe: MTP, FireFly, iPass, Flat-Ribbon
- With different cable orientations
  - Perpendicular to the board
  - Straight to the board
- And with options for easy multiplexing and synchronization



X-ray imaging – camera and sensor technology
Customization options

Scintillator – type, thickness, conversion efficiency

Fiber optic plate/taper – coupling, shielding, magnification



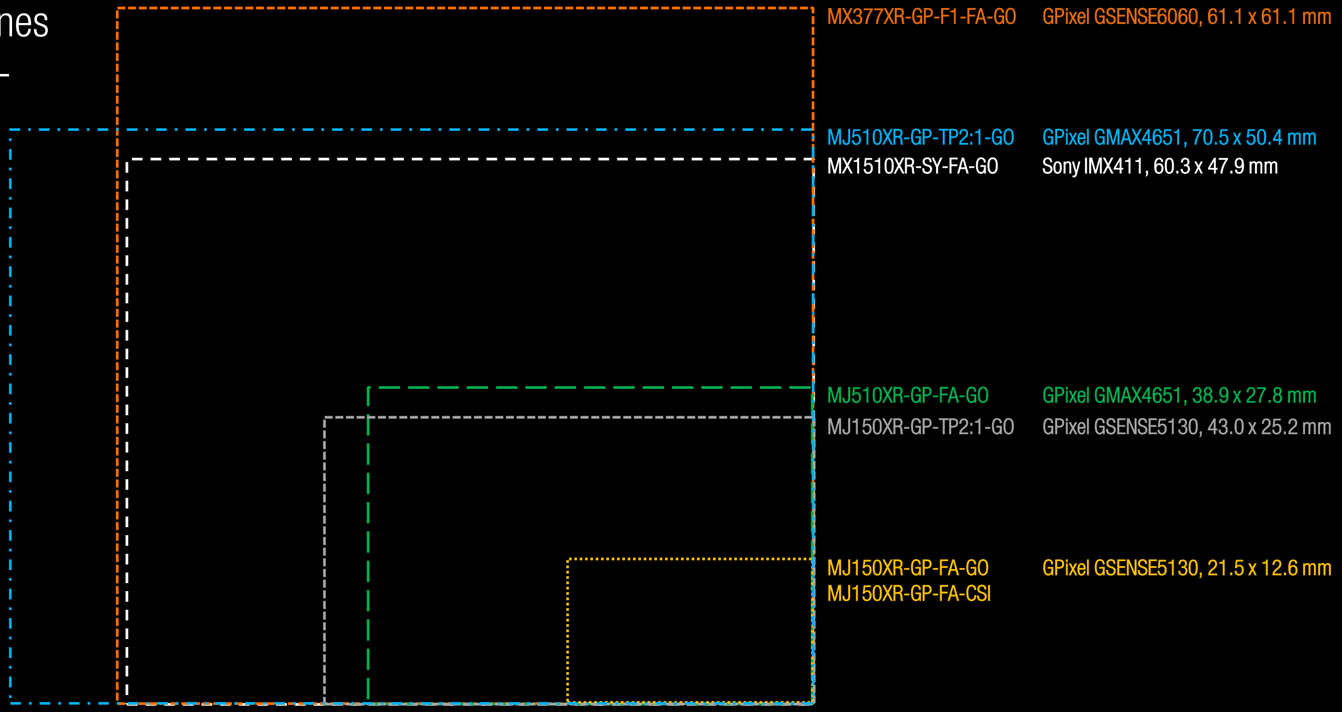
Cooler – water, air

Electronics – interface, speed, connectors

Sensor – sensitivity, field of view

Sensor / taper de-magnification

The sensor size determines the overall FoV in your x-ray application



XIMEA x-ray camera models

Model	Energy [keV]	Sensor	ADC [bits]	Pixel size [µm]	FWC [ke-]	Scintillator	FOP	Readout noise [e-]	DR [dB]	Binning	Resolution	Interface	Speed [FPS]	FoV [mm]
MH110XC-KK-FA	~7-100	OnSemi KAI-11002, CCD, Global	14	9	60	GadOx:Tb, 22µm, ø8µm	B7D59-6, 10mm, ø6µm	10	70	1x, 2x, 4x, 8x	4008x2672 11 Mpix	Firewire	2	37.3x25.7
MH110XC-KK-FA-CSI	~7-100	OnSemi KAI-11002, CCD, Global	14	9	60	CsI:Tl, 150µm	B7D59-6, 10mm, ø6µm	10	70	1x, 2x, 4x, 8x	4008x2672 11 Mpix	Firewire	2	36.0x24.0
MH160XC-KK-FA	~7-100	OnSemi KAI-16000, CCD, Global	14	7.4	30	GadOx:Tb, 22µm, ø8µm	B7D59-6, 10mm, ø6µm	10	70	1x, 2x, 4x, 8x	4872x3248 16 Mpix	Firewire	1.5	36.0x24.0
MJ150XR-GP-FA-GO	~7-100	GPixel GSENSE5130, sCMOS, Global/Rolling	2x12	4.25	17	GadOx:Eu, 10µm, ø2.5µm	BYD61-4, 8mm, ø4µm	1.5	82	1x	5056x2968 15 Mpix	USB3.1	17	21.5x12.6
MJ150XR-GP-FA-CSI	~7-100	GPixel GSENSE5130, sCMOS, Global/Rolling	2x12	4.25	17	CsI:Tl, 150µm	BYD61-4, 8mm, ø4µm	1.5	82	1x	5056x2968 15 Mpix	USB3.1	17	21.5x12.6
MJ150XR-GP-TP2:1-GO	~7-150	GPixel GSENSE5130, sCMOS, Global/Rolling	2x12	8.5	17	GadOx:Eu, 22µm, ø2.5µm	BLI58-6, +BYD61-6, 2mm	1.5	82	1x	5056x2968 15 Mpix	USB3.1	17	43.0x25.2
MX510XR-GP-FA-GO	~7-100	GPixel GMAX4651, CMOS, Global	12	4.6	24	GadOx:Eu, 10µm, ø2.5µm	BYD61-4, 8mm, ø4µm	1.6	84	1x	8464x6058 51 Mpix	TB3/ PCIe G3x4	30	38.8x27.8
MX510XR-GP-TP2:1-GO	~7-150	GPixel GMAX4651, CMOS, Global	12	8.5	24	GadOx:Eu, 22µm, ø2.5µm	BLS59-6, 92.2mm + BYD61-6, 3mm	1.6	84	1x	8464x6058 51 Mpix	TB3/ PCIe G3x4	30	70.5x50.4
MX377XR-GP-F1-FA-GO	~7-100	GPixel GSENSE6060, sCMOS, Rolling	2x14	10	110	GadOx:Eu, 22µm, ø2.5µm	BYD61-6, 12mm, ø6µm	3	90	1x	6144x6144 37.7 Mpix	PCIe G3x4	46	61.1x61.1
MX1510XR-SY-FA-GO	~7-100	Sony IMX411, CMOS, Rolling	16	3.76	50	GadOx:Eu, 10µm, ø2.5µm	BYD61-4, 10mm, ø4µm	3	78	1x, 2x	14192x10640 151 Mpix	PCIe G3x4	6	60.3x47.9

Contacts

ximea

International sales

XIMEA GmbH
Am Mittelhafen 16
D-48155 Muenster
Germany

Phone: +49 (251) 202408-0
Fax: +49 (251) 202408-99

Technology campus

XIMEA s.r.o.
Lesna 52
90033 Marianka
Slovakia

Phone: +421 (2) 205 104 26

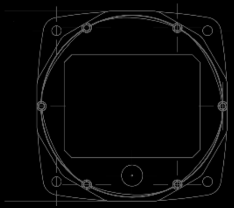
North and South Americas sales

XIMEA Corp.
12600 W Colfax Ave., Suite A-130
Lakewood, CO 80215
USA

Phone: +1 (303) 389-9838

Web: www.ximea.com
Mail: info@ximea.com

THANK YOU FIN



Sources

1. Saint-Gobain. CsI(Tl), CsI(Na) Cesium Iodide Scintillation Material. https://www.crystals.saint-gobain.com/products/csitl-cesium-iodide-thallium.
2. Hamamatsu. X-ray detectors. Chapter 09. https://www.hamamatsu.com/resources/pdf/ssd/e09_handbook_xray_detectors.pdf.
3. Nikl, Martin. Scintillation detectors for X-rays. Institute of Physics Publishing. 2006.
4. Saint-Gobain. CsI(Tl) Thallium activated Cesium Iodide. https://www.crystals.saint-gobain.com/products/csitl-cesium-iodide-thallium.
5. Trtik, Pavel; Lehmann, Eberhard H. Isotopically-enriched gadolinium-157 oxysulfide scintillator screens for the High-resolution neutron imaging. Nuclear Instruments and Methods in Physics Research. 2015.
6. Roper Scientific, Inc. Fiberoptic Tapers in High- Resolution Scientific Imaging. What you need to know when selecting a fiberoptically coupled CCD camera. https://nstx.pppl.gov/nstxhome/DragNDrop/Operations/Diagnostics_&_Support_Sys/DivertorSPRED/fiberoptics.pdf. 2000.
7. Banhart, John. Advanced Tomographix Methods in Materials Research and Engineering. Oxford University Press. 2008.
8. Ovechkina, Gaysinski, Mille, Brecher, Lempicki, Nagarkar. Multiple doping of CsI:Tl crystals and its effect on afterglow. Radiat Meas. 2007. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2170897/.