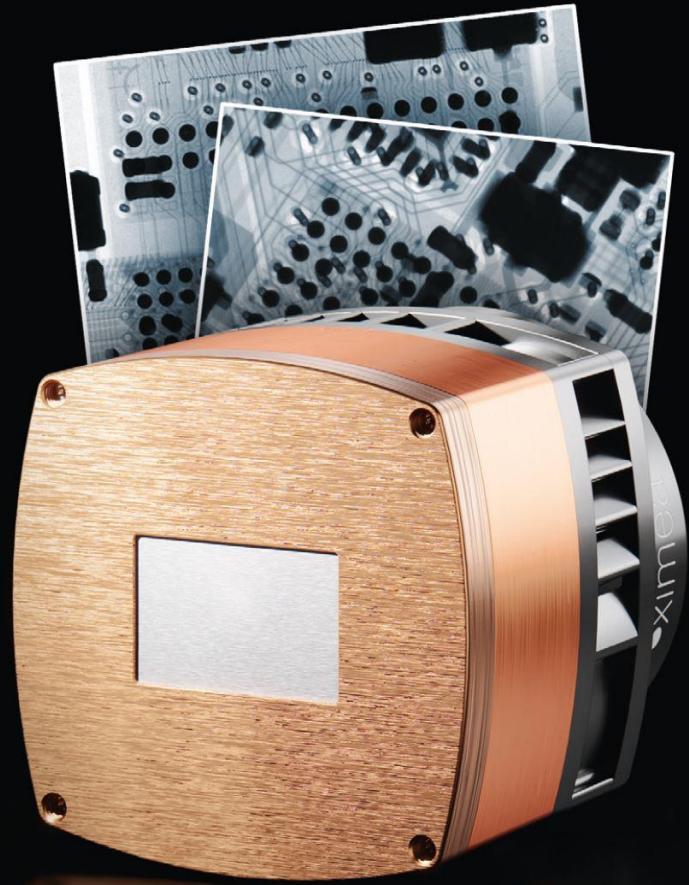


# XIMEA

X-ray imaging

Camera and sensor technology



•ximea

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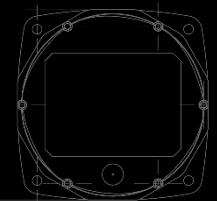
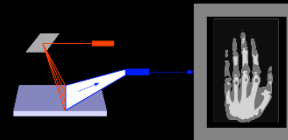
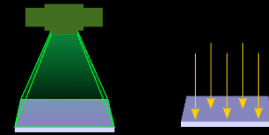
**„It seemed at first a new kind of invisible light.  
It was clearly something new... something unrecorded.  
There is much to do...” - **Wilhelm Röntgen****

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## Radiography

- X-rays

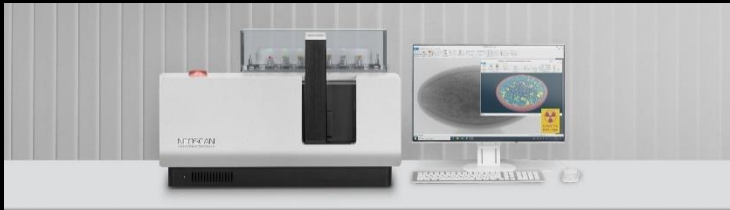
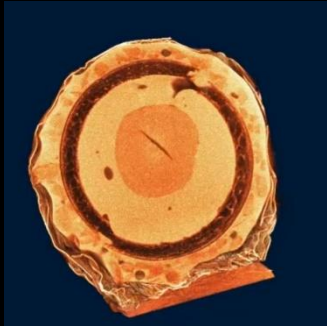
- Photons with a wavelength of  $\sim 10\text{nm}$  and below
- The shorter the wavelength, the higher...
  - ... the energy
    - Extreme ultraviolet (XUV):  $124\text{-}10\text{nm}$ ,  $\sim 10\text{-}124\text{eV}$
    - Soft x-rays:  $10\text{-}0.25\text{nm}$ ,  $\sim 124\text{-}5,000\text{eV}$
    - Hard x-rays:  $<0.25\text{nm}$ ,  $>5\text{keV}$
  - ... 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)



## X-ray imaging – camera and sensor technology

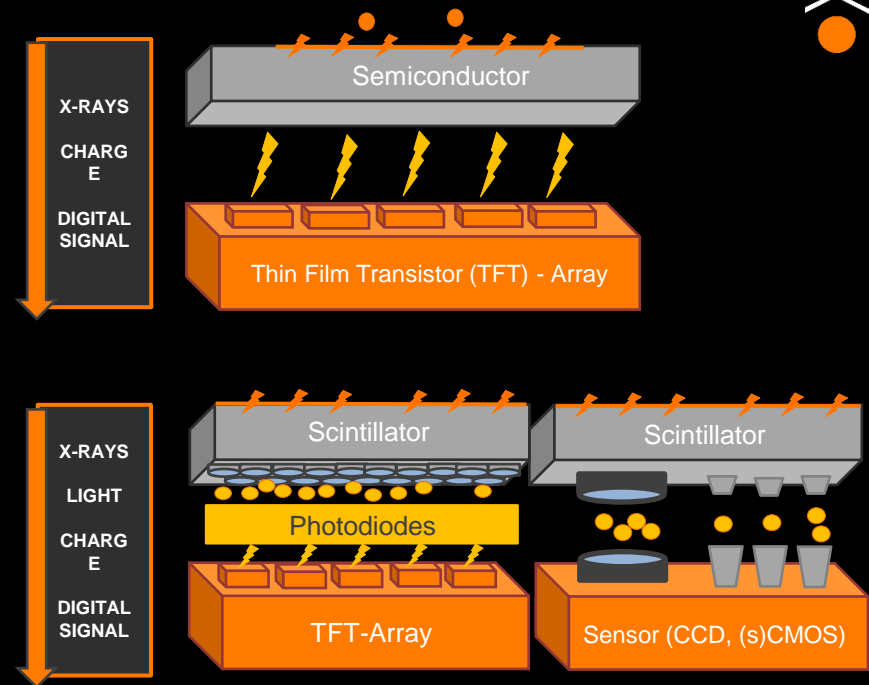
# What you can do with it if you know what you're doing...

- 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)



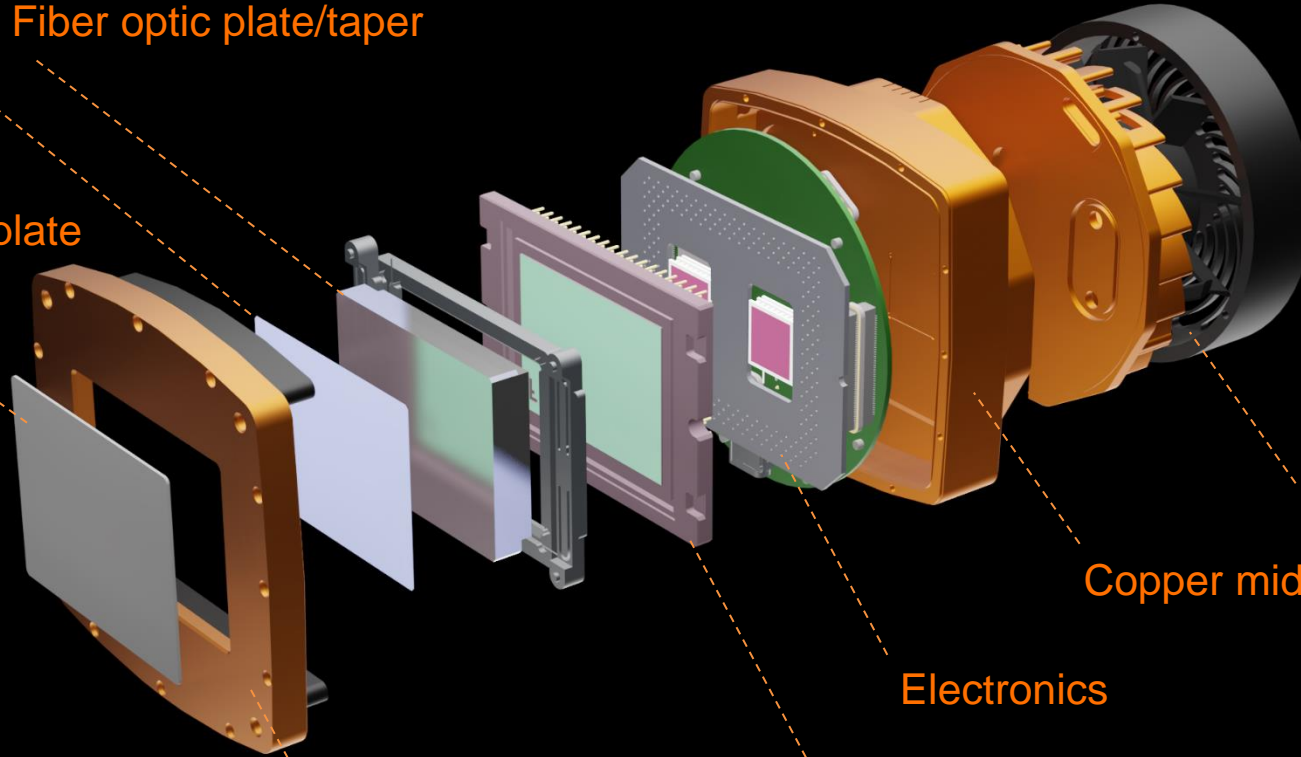
X-ray imaging – camera and sensor technology  
Components of XIMEA x-ray cameras



Scintillator

Fiber optic plate/taper

Beryllium plate



Tungsten / copper shield

Sensor

Electronics

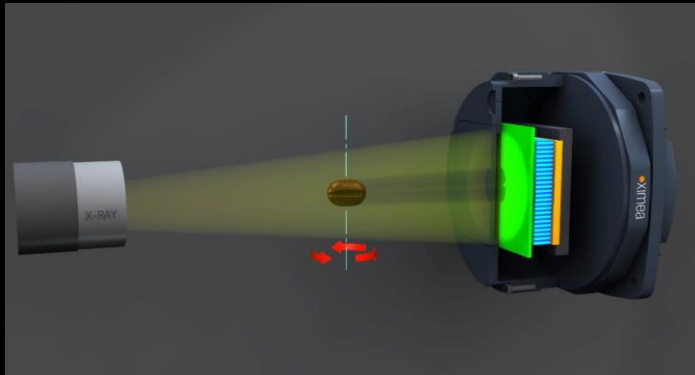
Copper mid part

Cooler

## X-ray camera fundamentals

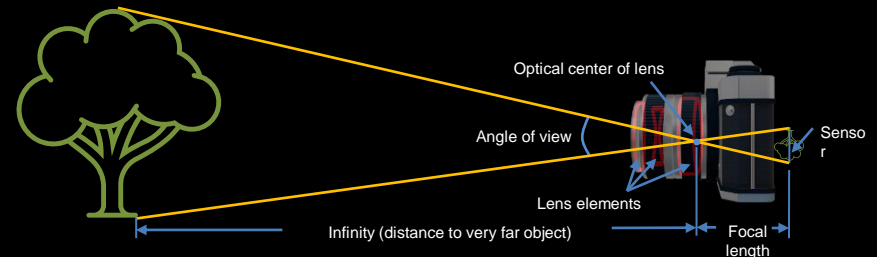
- General setup for x-ray applications

- 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



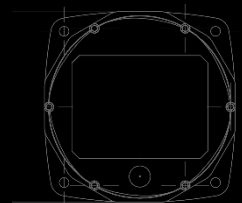
- Insofar they are different from optical setups

- 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



# Designing x-ray cameras for x-ray applications

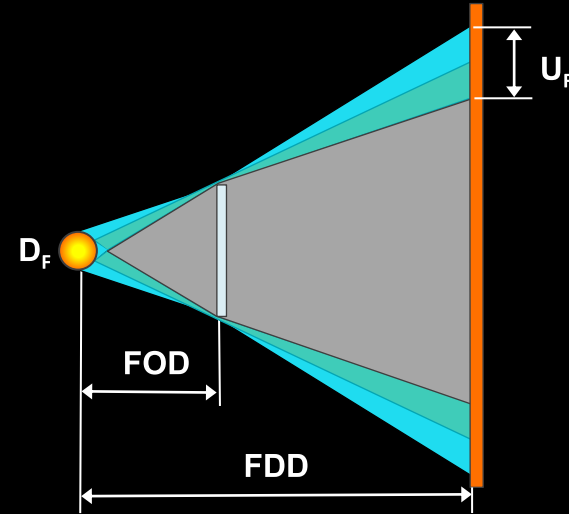
- The performance of x-ray cameras highly depends on the **balanced combination** of
  - Radiation source
  - Scintillator
    - Type
    - Thickness
    - Grain size
  - Fiber optic plate/taper
    - Type
    - Diameter
    - Thickness
    - Magnification
  - And sensor
    - Field of view, quantum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



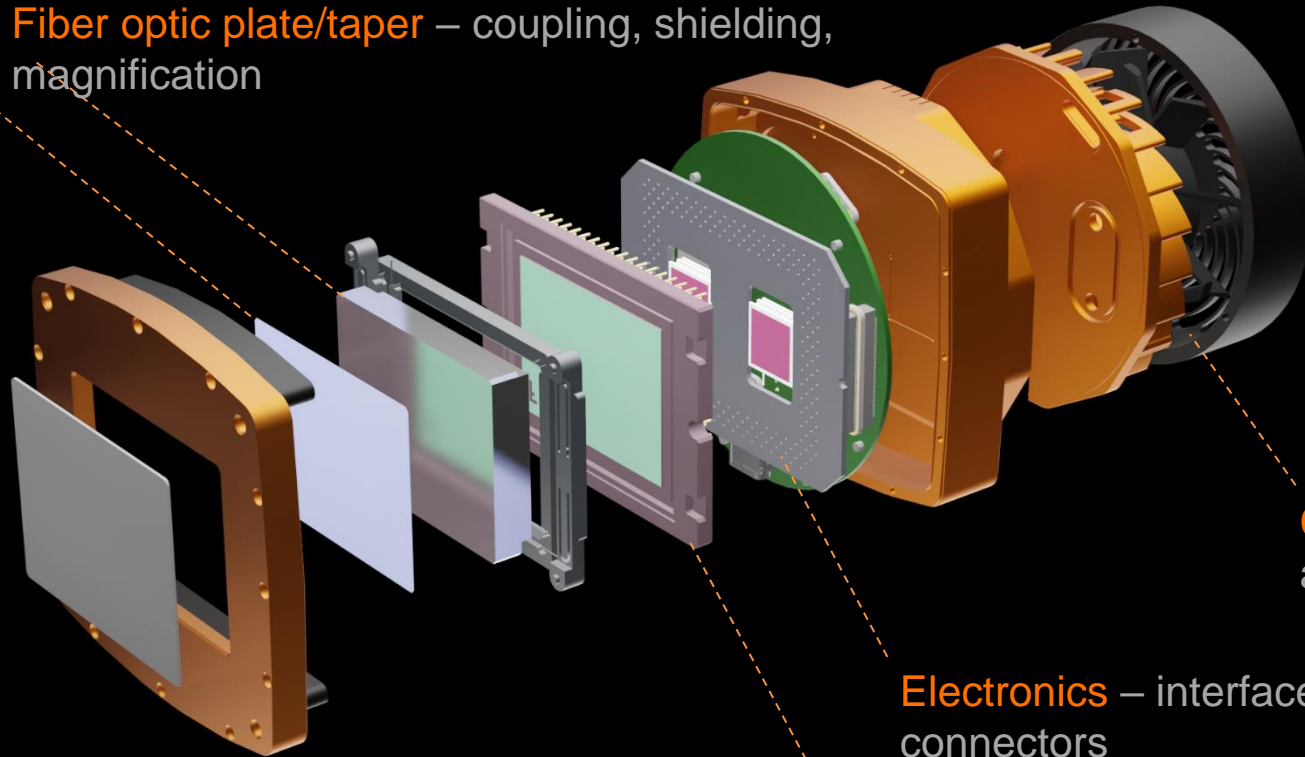
$$U_F = D_F * (M - 1),$$

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

**Scintillator** – type, thickness, conversion efficiency

**Fiber optic plate/taper** – coupling, shielding, magnification

**X-ray imaging** – camera and sensor technology  
Customization options



**Cooler** – water, air

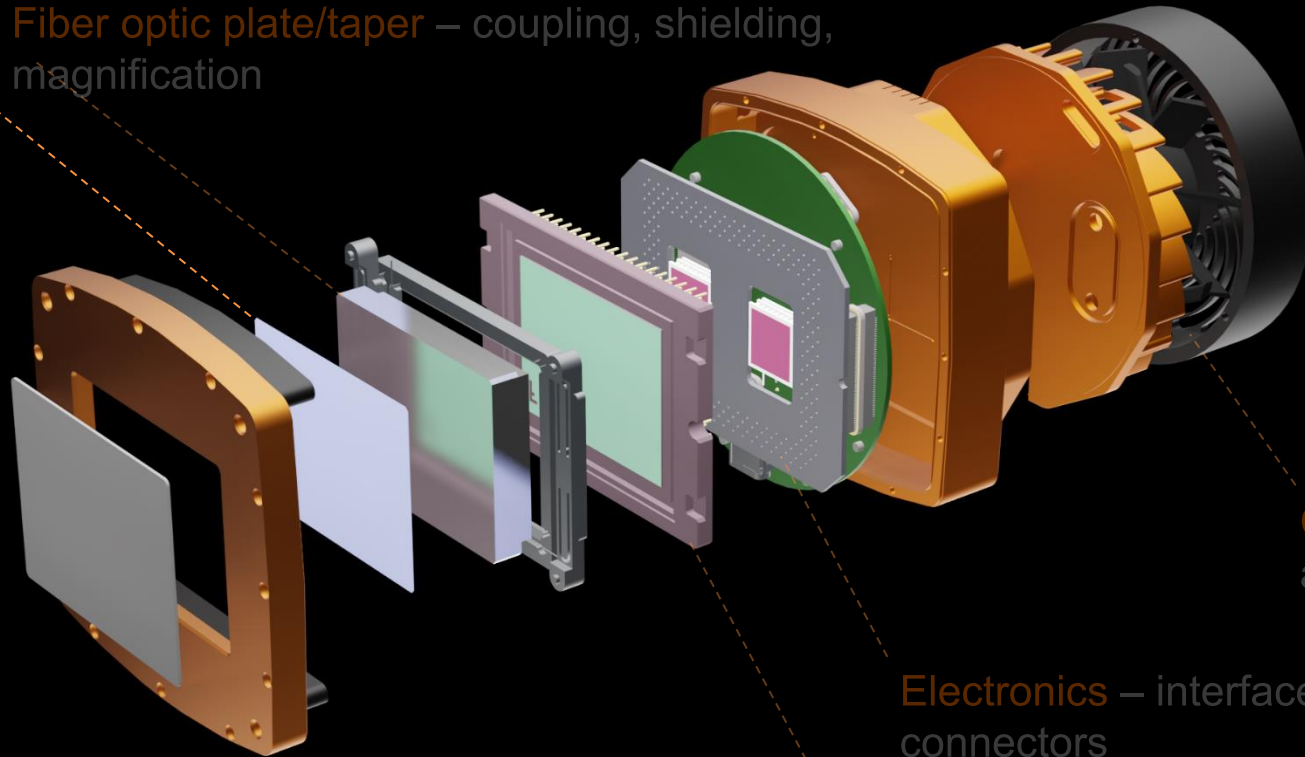
**Electronics** – interface, speed, connectors

**Sensor** – sensitivity, field of view

**Scintillator** – type, thickness, conversion efficiency

**Fiber optic plate/taper** – coupling, shielding, magnification

**X-ray imaging** – camera and sensor technology  
Customization options



**Cooler** – water, air

**Electronics** – interface, speed, connectors

**Sensor** – sensitivity, field of view

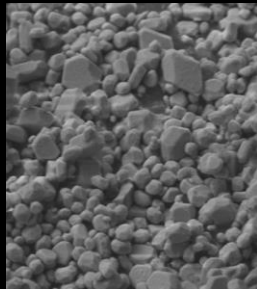
# Scintillator

- 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, 150 $\mu$ m, 30keV 45.8%
  - CsI, 150 $\mu$ m, 60keV 41.5%
  - CsI, 150 $\mu$ m, 80keV 22.0%
  - CsI, 150 $\mu$ m, 100keV 12.9%
  - CsI, 150 $\mu$ m, 250keV 1.70%
  - GadOx, 10 $\mu$ m, 30keV 8.91%
  - GadOx, 10 $\mu$ m, 60keV 7.04%
  - GadOx, 10 $\mu$ m, 80keV 3.41%
  - GadOx, 10 $\mu$ m, 100keV 1.93%
  - GadOx, 10 $\mu$ m, 250keV 0.23%

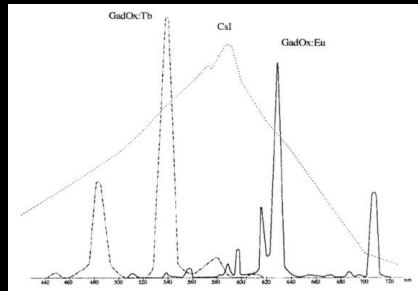
## Scintillator cont.

- 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



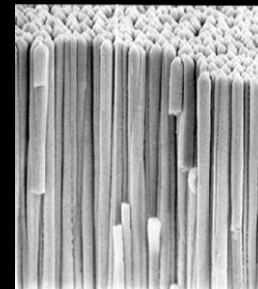
GadOx:Tb powder [5]



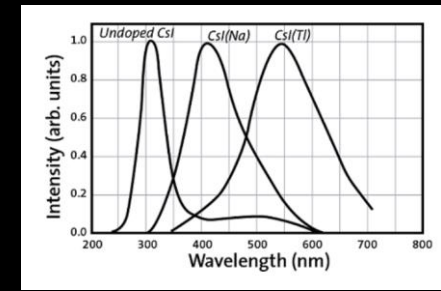
GadOx vs CsI wavelength emission

- 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)



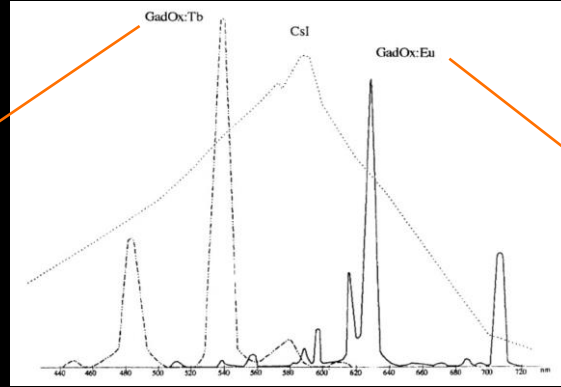
CsI:Tl crystals [3]



Undoped, Sodium, and Thallium doped CsI

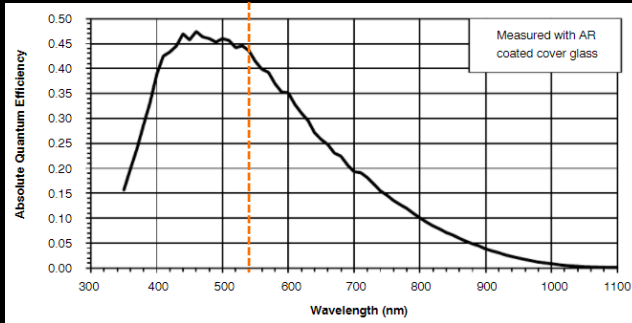
# Scintillator cont.

The **choice of scintillator material** must match sensor properties

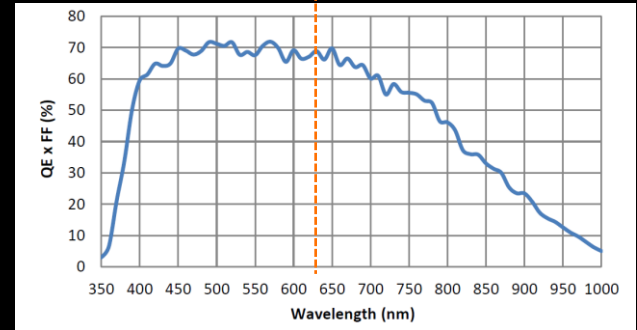


GadOx:Tb peak

GadOx:Eu peak



KAI-16000 CCD QE curve

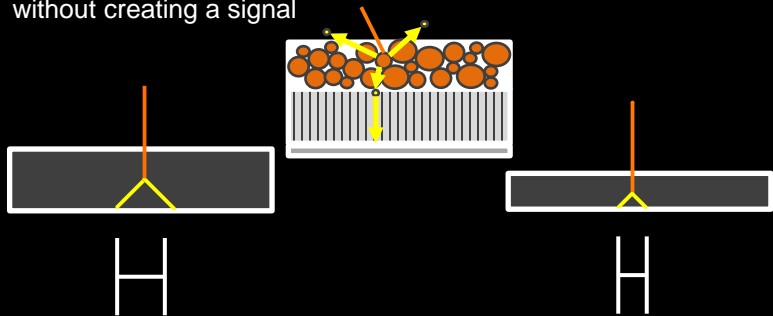


GSENSE5130 CMOS QE curve

# Scintillator cont.

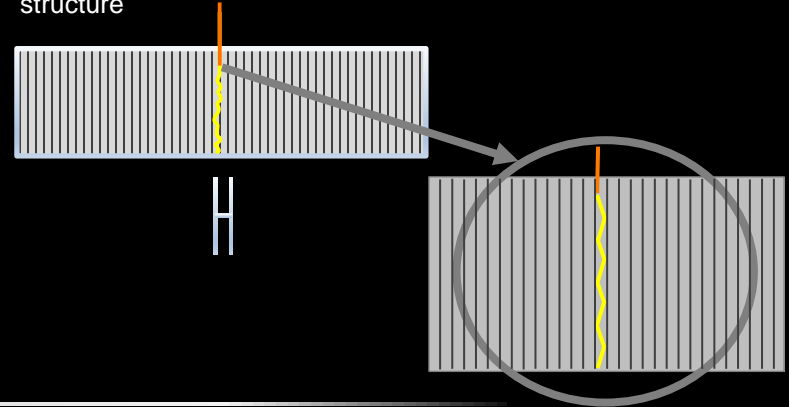
- Gadolinium Oxysulfide (GadOx)

- Increased light scattering because of its powder structure. Such scintillators emit and scatter light into arbitrary directions
- Thus, layer should be thin (10-40 $\mu\text{m}$ ) and grain size should be small (2.5-8 $\mu\text{m}$ ). 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)

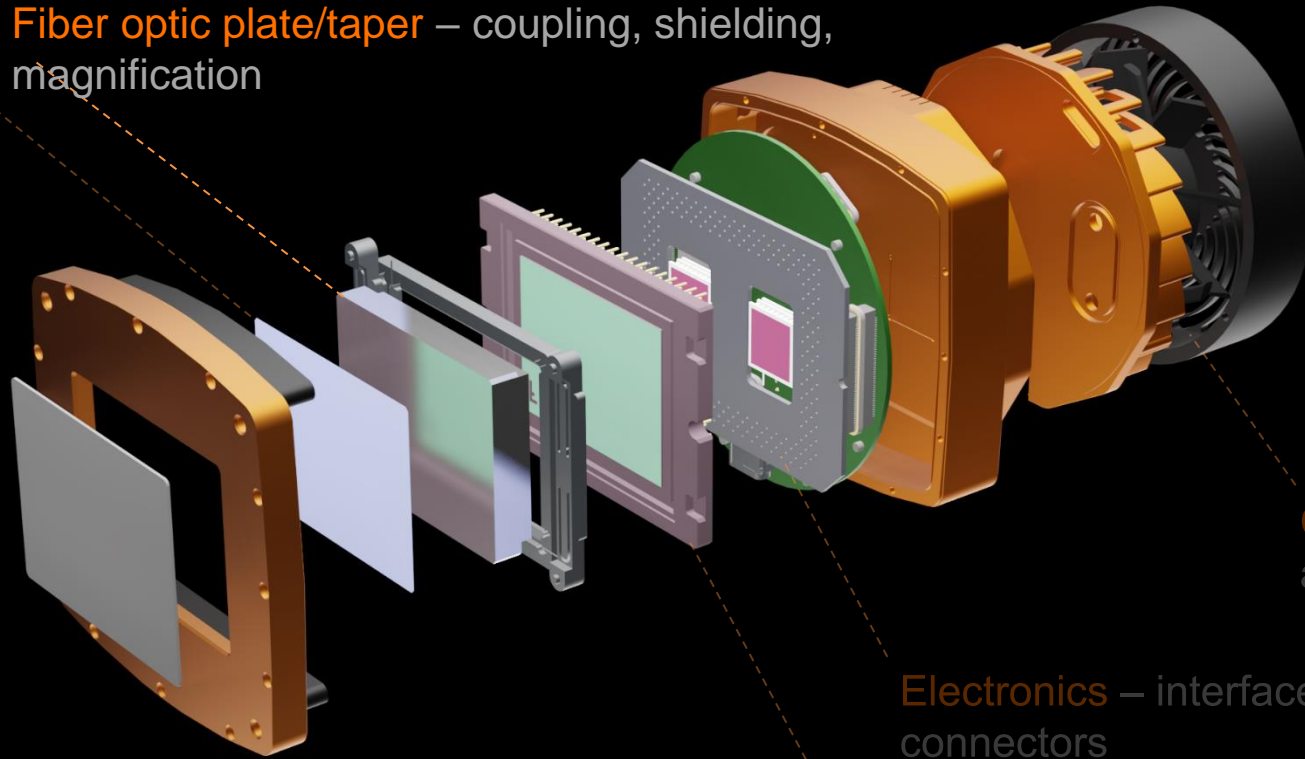
- Light scattering is reduced because of its column grown crystalline structure. Light is “channeled” to the fiber optics
- CsI allows for thicker scintillator layers (150 $\mu\text{m}$  and more). This can provide better results compared to GadOx, especially for higher energy applications
- The spatial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



Scintillator – type, thickness, conversion efficiency

Fiber optic plate/taper – coupling, shielding, magnification

X-ray imaging – camera and sensor technology  
Customization options



Cooler – water, air

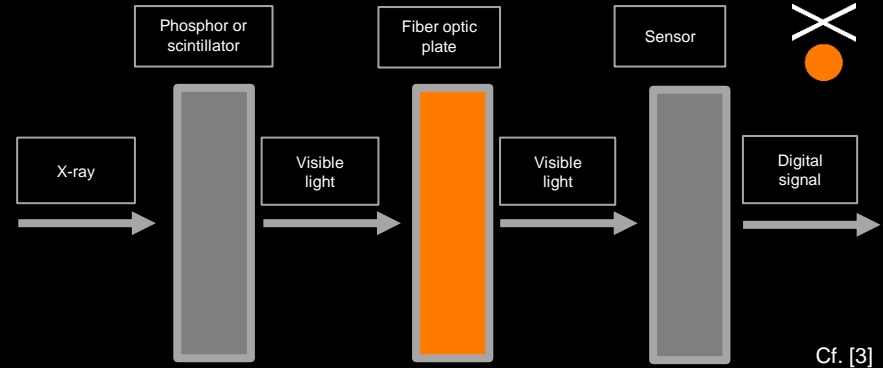
Electronics – interface, speed, connectors

Sensor – sensitivity, field of view

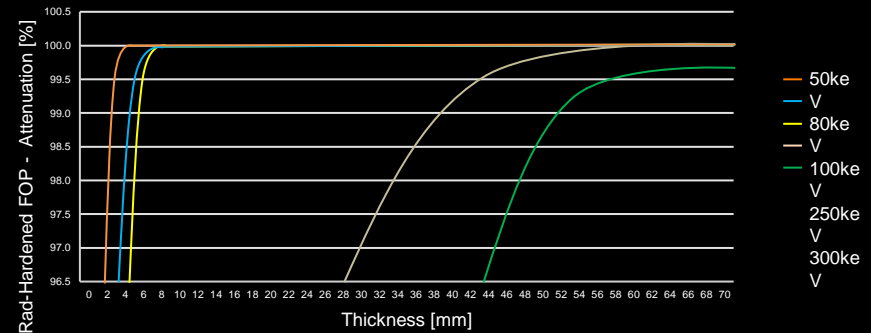


## Fiber optic plate

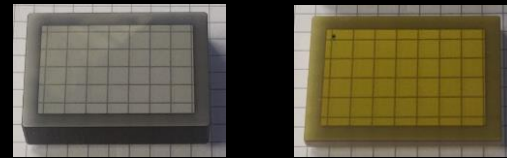
- The main reasons for fiber optic plates are
  - Efficient light transfer, preventing scattering
  - Shielding of sensor and electronics from x-ray energy
- Shielding requirements depend on energy levels
  - Scintillator materials only absorb a fraction of the x-rays
  - High energy x-rays which are 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



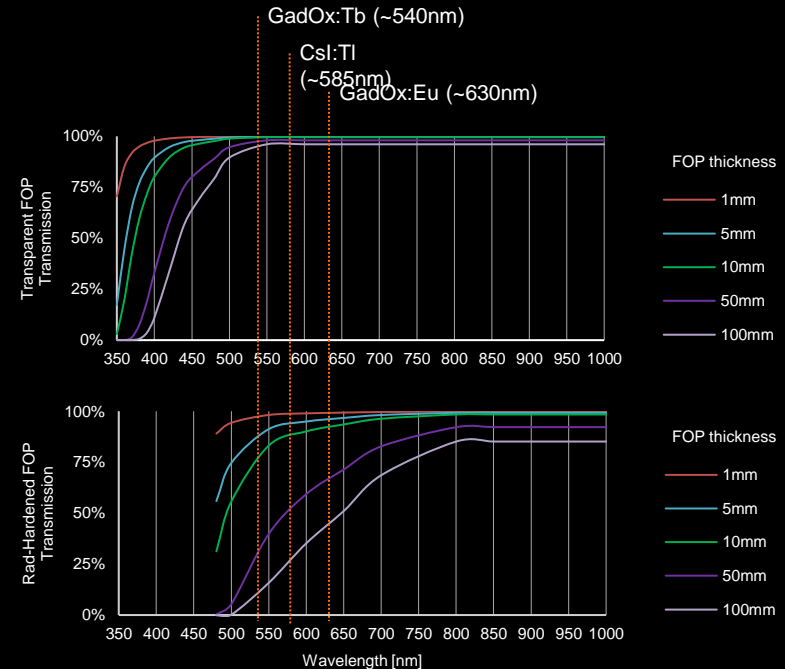
Cf. [3]



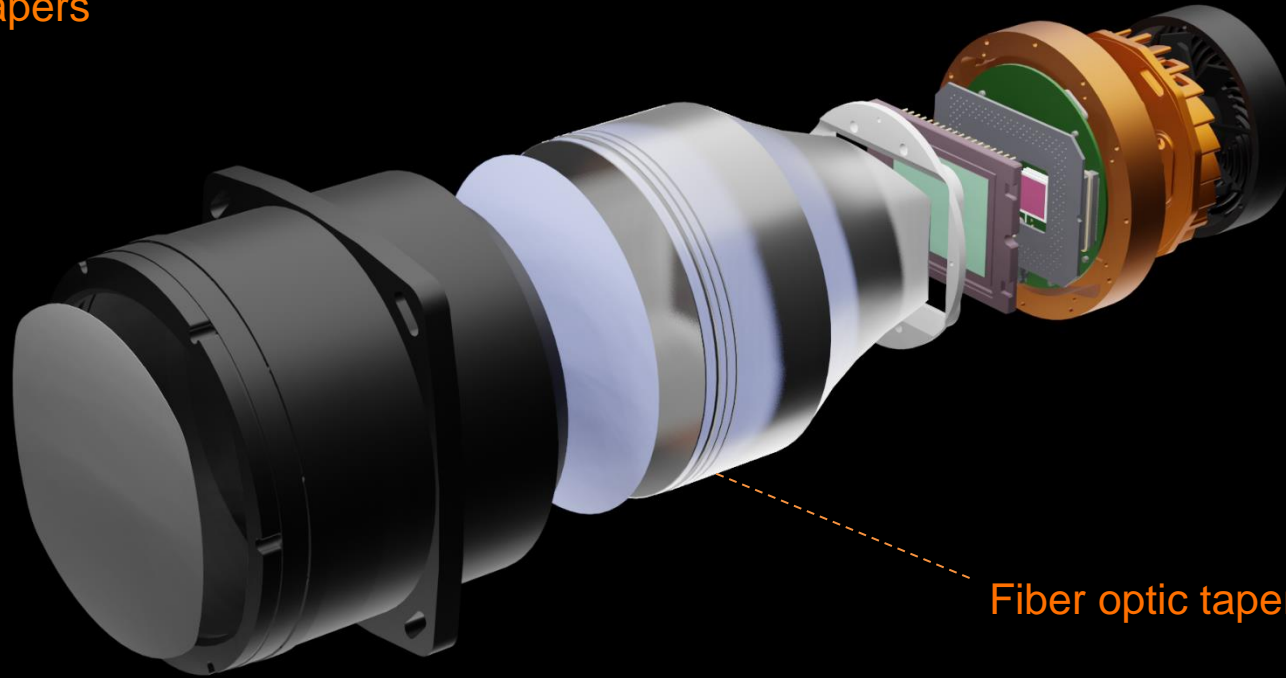
## Fiber optic plate cont.



- 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 ( $\geq$ ) the sensor pixel size



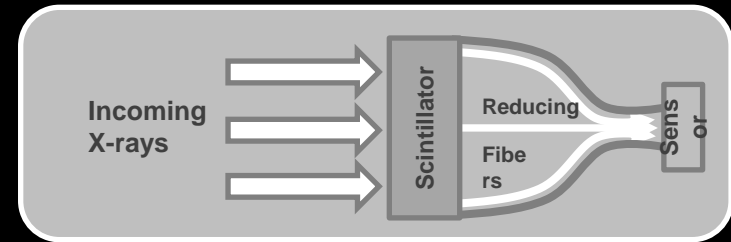
We also provide cameras that allow magnification by using fiber optic tapers



Fiber optic taper – magnification

## 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

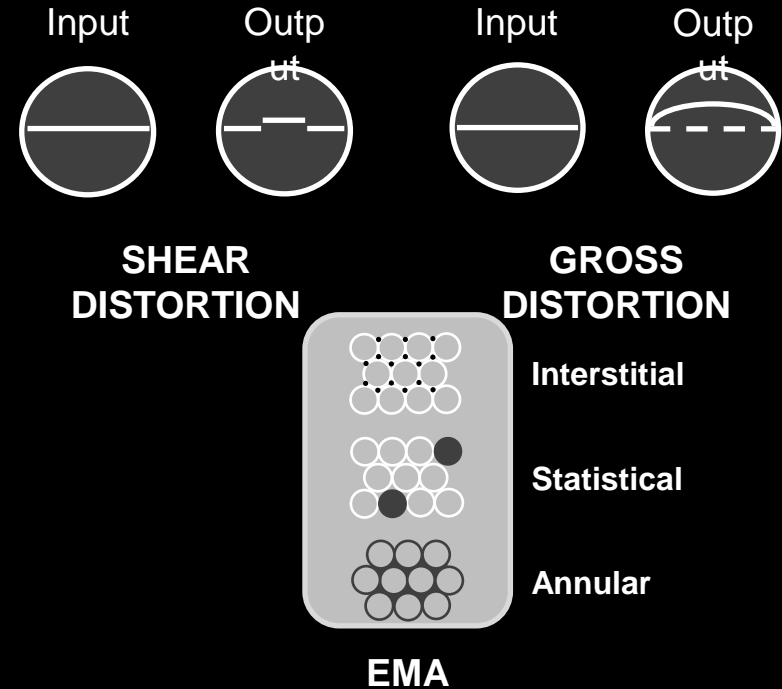
NA = numerical aperture

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.

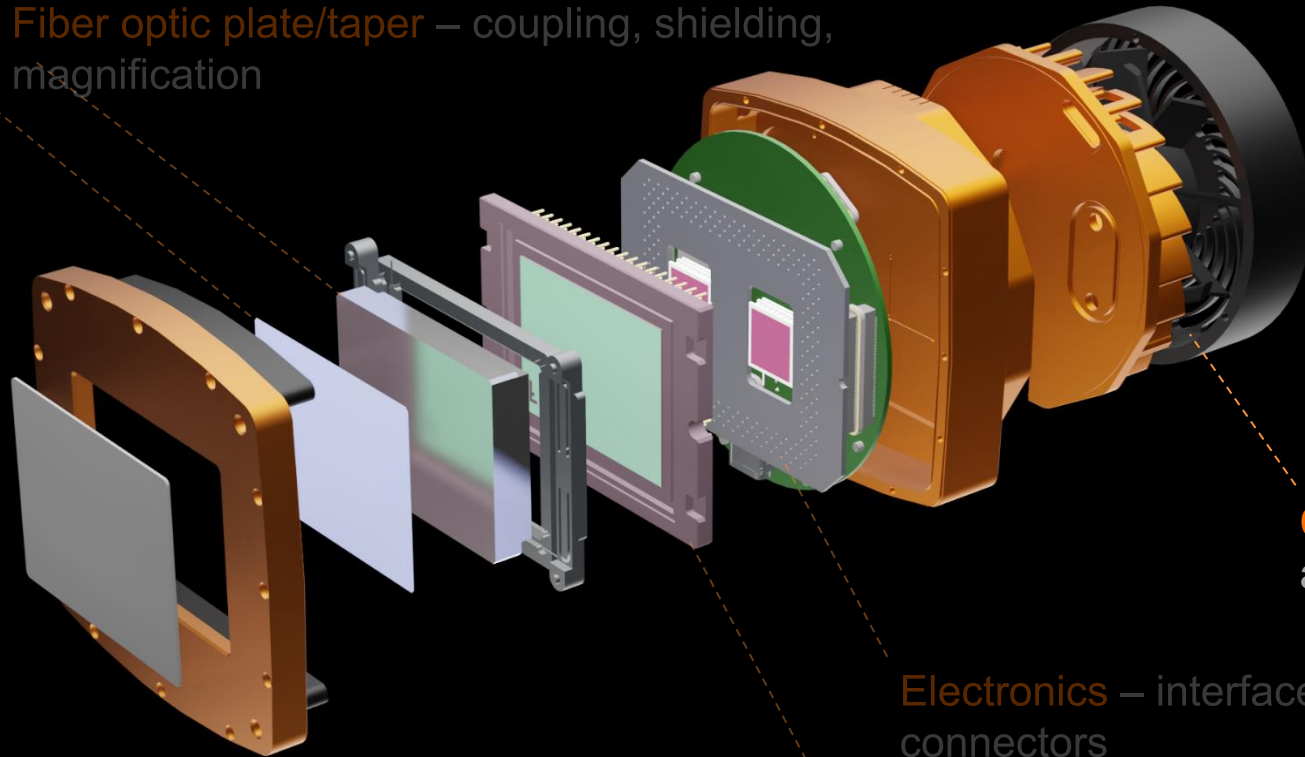
- Primary disadvantages of fiber optics
  - Inherent presence of distortions and blemishes
    - Spot blemishes (burned or broken (dark) fibers)
    - Line blemishes (pattern of multiple broken (dark) fibers)
    - Image distortions
      - Shear: Miss-placement of a fiber
      - Gross: A straight line 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 refraction 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



**Scintillator** – type, thickness, conversion efficiency

**Fiber optic plate/taper** – coupling, shielding, magnification

**X-ray imaging** – camera and sensor technology  
Customization options



**Cooler** – water, air

**Electronics** – interface, speed, connectors

**Sensor** – sensitivity, field of view

# Cooler

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



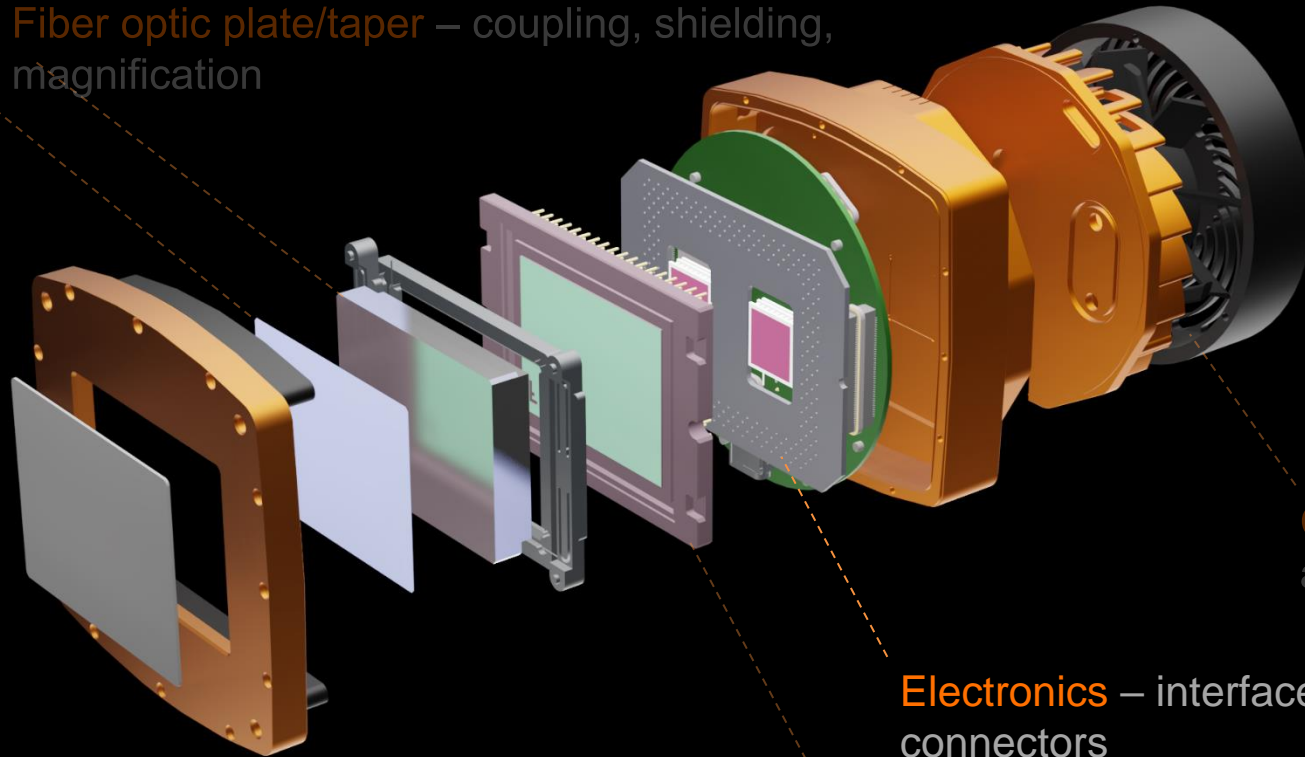
Active air cooling

Liquid cooling

**Scintillator** – type, thickness, conversion efficiency

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Customization options



**Cooler** – water, air

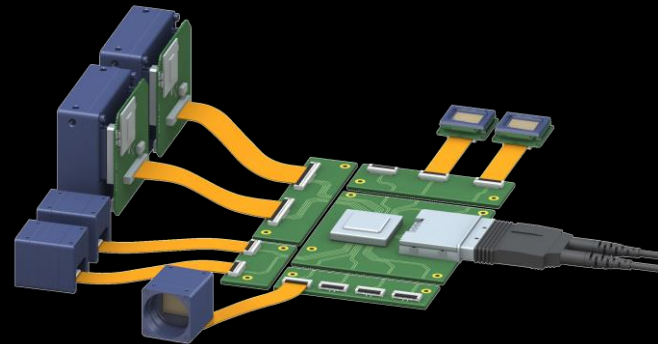
**Electronics** – interface, speed, connectors

**Sensor** – sensitivity, field of view



## Interface

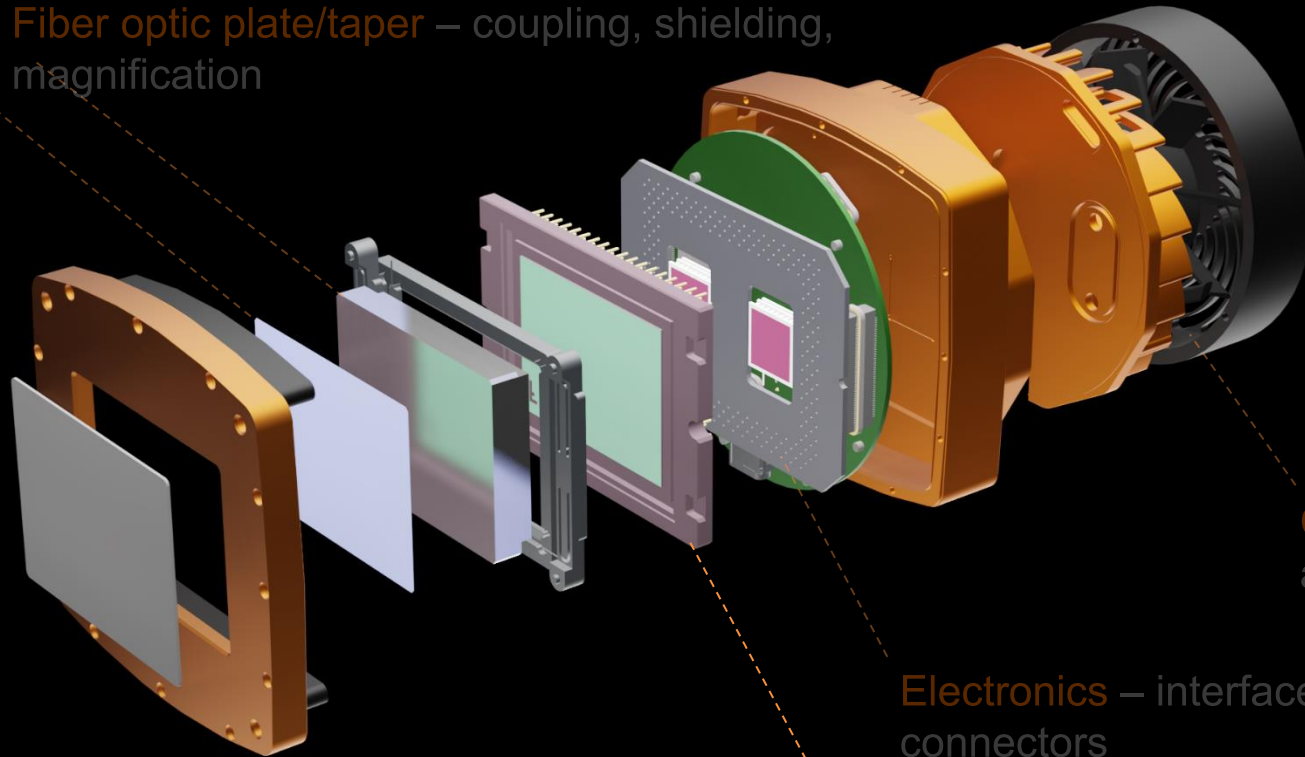
- We provide
  - USB
    - Industry standard cables
    - Good relation for bandwidth and price
  - PCI Express
    - Highest bandwidth up to 64Gbps
    - Long cable lengths (80-100 of meters)
    - Near to zero latency, e.g., data to RAM or GPU
    - Can be used with nearly all computers available today
- 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



**Scintillator** – type, thickness, conversion efficiency

**Fiber optic plate/taper** – coupling, shielding, magnification

**X-ray imaging** – camera and sensor technology  
Customization options



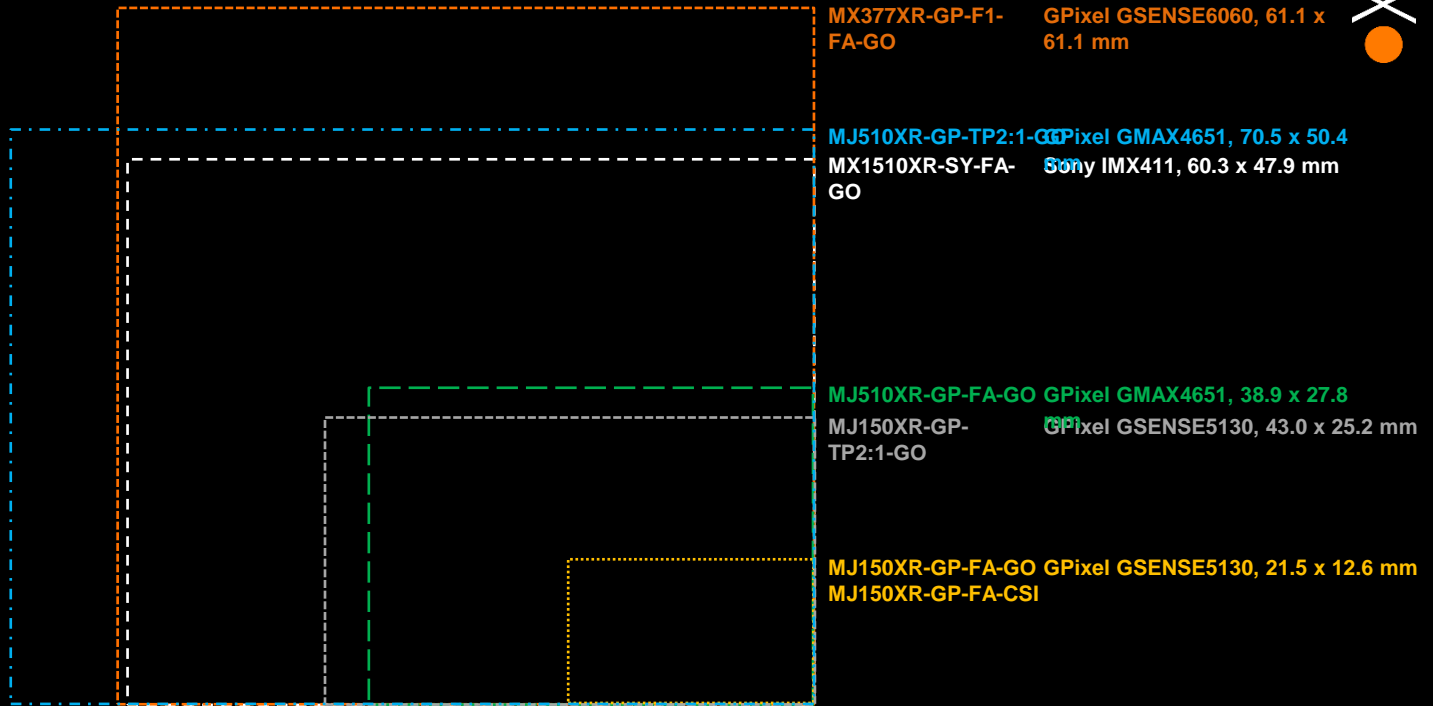
**Cooler** – water, air

**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 [ $\mu\text{m}$ ]	FWC [ke <sup>-</sup> ]	Scintillator	FOP	Readout noise [e <sup>-</sup> ]	DR [dB]	Binning	Resolution	Interface	Speed [FPS]	FoV [mm]
MH110XC-KK-FA	~7-100	OnSemi KAI-11002, CCD, Global	14	9	60	GadOx:Tb, 22 $\mu\text{m}$ , $\varnothing$ 8 $\mu\text{m}$	B7D59-6, 10mm, $\varnothing$ 6 $\mu\text{m}$	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, 150 $\mu\text{m}$	B7D59-6, 10mm, $\varnothing$ 6 $\mu\text{m}$	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, 22 $\mu\text{m}$ , $\varnothing$ 8 $\mu\text{m}$	B7D59-6, 10mm, $\varnothing$ 6 $\mu\text{m}$	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, 10 $\mu\text{m}$ , $\varnothing$ 2.5 $\mu\text{m}$	BYD61-4, 8mm, $\varnothing$ 4 $\mu\text{m}$	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, 150 $\mu\text{m}$	BYD61-4, 8mm, $\varnothing$ 4 $\mu\text{m}$	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, 22 $\mu\text{m}$ , $\varnothing$ 2.5 $\mu\text{m}$	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, 10 $\mu\text{m}$ , $\varnothing$ 2.5 $\mu\text{m}$	BYD61-4, 8mm, $\varnothing$ 4 $\mu\text{m}$	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, 22 $\mu\text{m}$ , $\varnothing$ 2.5 $\mu\text{m}$	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, 22 $\mu\text{m}$ , $\varnothing$ 2.5 $\mu\text{m}$	BYD61-6, 12mm, $\varnothing$ 6 $\mu\text{m}$	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, 10 $\mu\text{m}$ , $\varnothing$ 2.5 $\mu\text{m}$	BYD61-4, 10mm, $\varnothing$ 4 $\mu\text{m}$	3	78	1x, 2x	14192x10640 151 Mpix	PCIe G3x4	6	60.3x47.9

# X-ray imaging – camera and sensor technology

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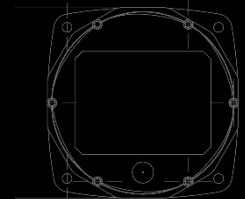
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THANK YOU

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