Optique Peter

OPTICAL & MECHANICAL ENGINEERING

Optically coupled X-Ray imaging systems, from microscopy to macroscopy

SFR Online conference, 13 July 2020

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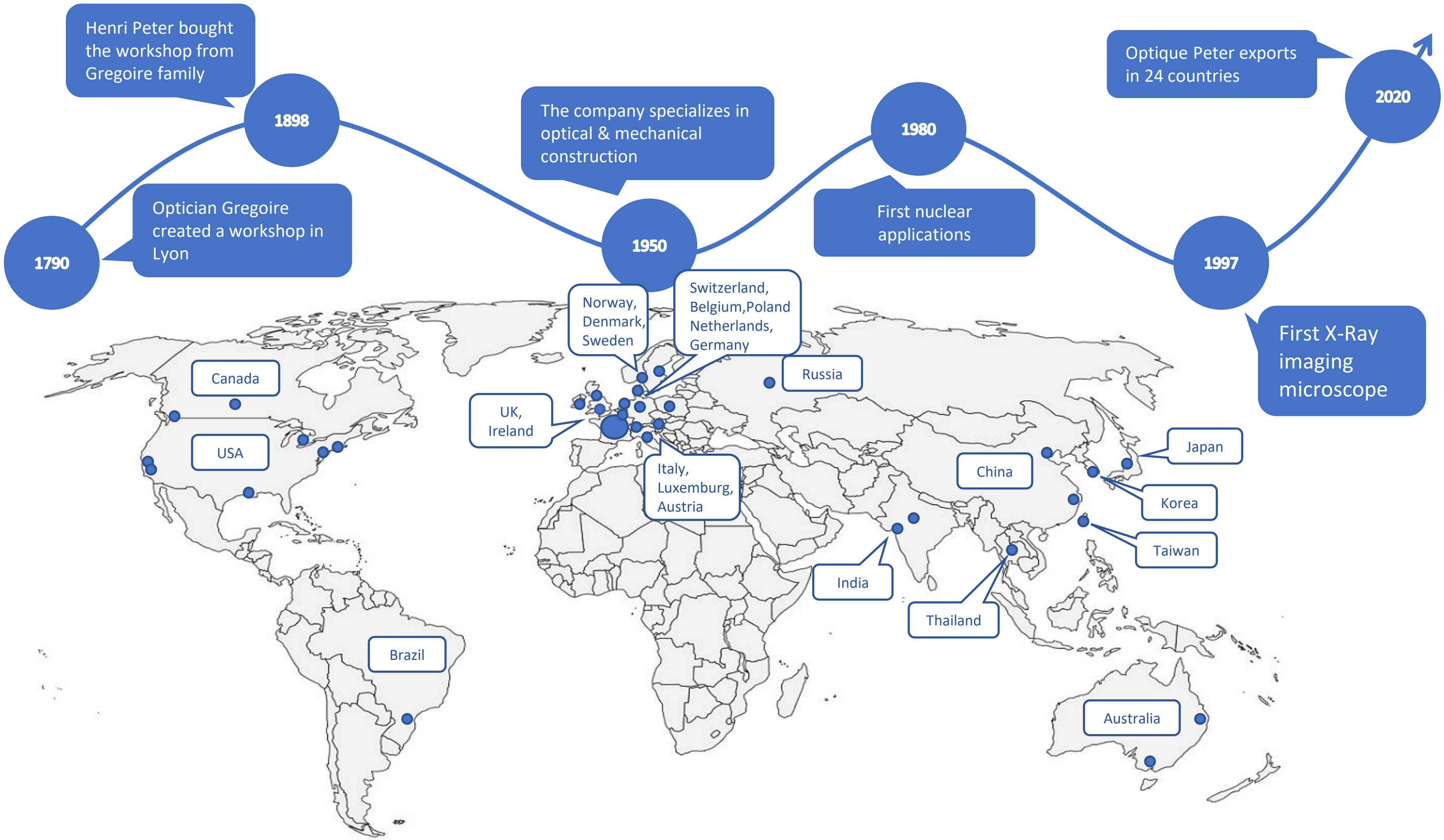
Optically coupled X-Ray imaging systems, from microscopy to macroscopy

230 years of history

Optique Peter



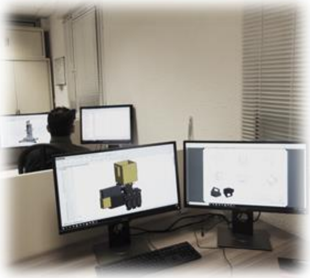
Optique Peter

Organization Structure

- Family-owned company
- Long experience in serving industries
- Small but responsive and versatile structure
- High scientific and technical skills
- Self-sufficient from

Design ⟶ Manufacturing ⟶ Integration ⟶ Installation
Maintenance
Training
Calibration

Office and workshop in Lentilly - France



Design

Manufacturing

Integration

Service

23 Years of experience in X-Ray Imaging Systems

First Monochromatic Beam
X-Ray imaging microscope
delivered to ESRF / ID22 in 1997

First White Beam
X-Ray imaging macroscope
delivered to SLS in 2002

First White Beam
X-Ray imaging microscope
developed for Scintax project
in 2008

REFERENCES FOR X-RAY & NEUTRON IMAGING APPLICATIONS

75 X-Ray imaging microscopes and macroscopes delivered to 29 research institutes and synchrotrons

ESRF
SOLEIL SYNCHROTRON
ILL NEUTRONS FOR SCIENCE
European XFEL
DESY
KIT Karlsruher Institut für Technologie
Fraunhofer
RWTH AACHEN UNIVERSITY
HZB Helmholtz Zentrum Berlin
diamond
UCL
PAUL SCHERRER INSTITUT PSI
Elettra Sincrotrone Trieste
Lawrence Livermore National Laboratory
SLAC NATIONAL ACCELERATOR LABORATORY
MIT Massachusetts Institute of Technology
BERKELEY LAB LAWRENCE BERKELEY NATIONAL LABORATORY
BROOKHAVEN NATIONAL LABORATORY
LSU
Canadian Light Source Centre canadien de rayonnement synchrotron
UBC THE UNIVERSITY OF BRITISH COLUMBIA
LNLS
Australian Synchrotron
Zhengzhou University
中国科学院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences
SSRF
Raja Ramanna Centre for Advanced Technology, Indore
Siam Photon
PAL POHANG ACCELERATOR LABORATORY

Optically coupled X-Ray imaging systems (Lens coupling)

Summary :

- Single lens vs tandem configuration

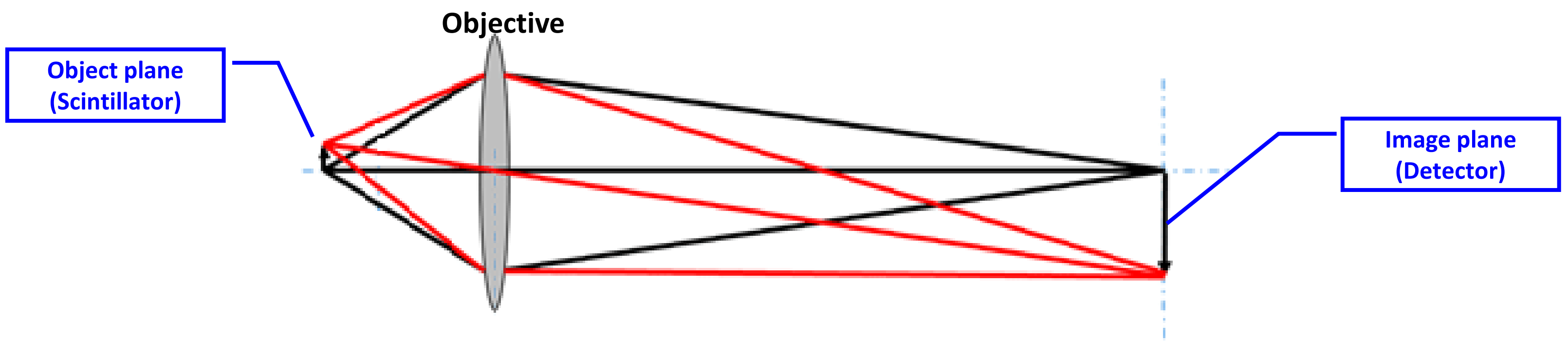
- Single lens systems
  - Standard single lenses limitations for X-Ray imaging
  - Special single lens systems
  - Tandem lens systems

- Standard lenses limitations for tandem configuration in X-Ray imaging
  - Tandem lenses microscopy systems
  - Tandem lenses macroscopy systems

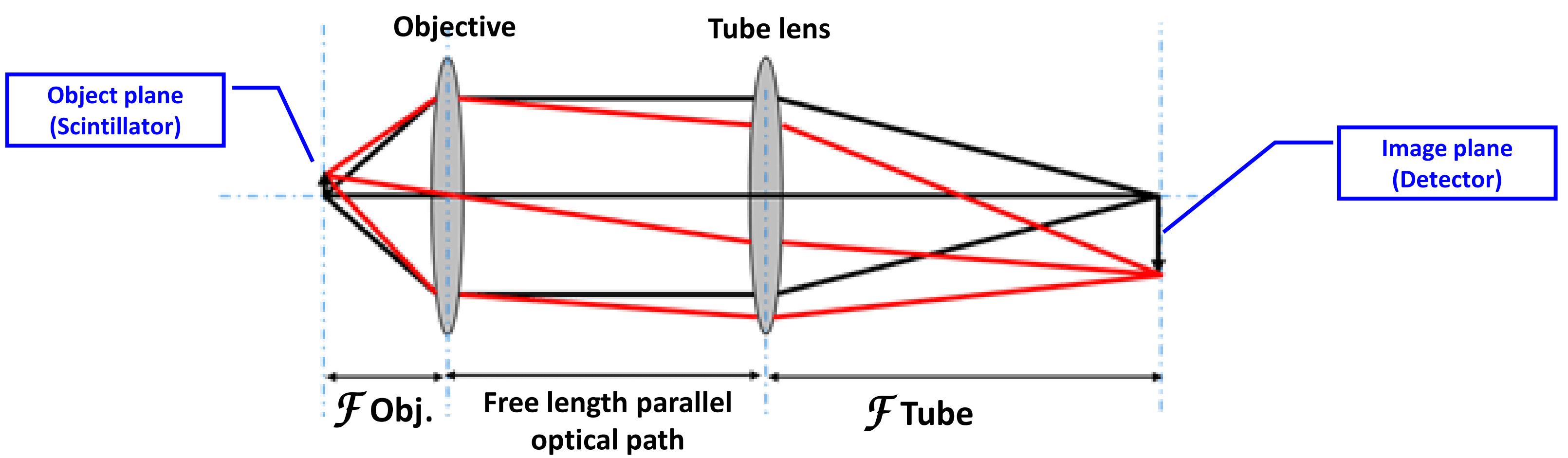
- Zoom X-Ray imaging systems
- Combined Zoom / microscope X-Ray imaging systems

Optically coupled X-Ray imaging systems
Single lens vs tandem configurations

Single lens system : finite corrected optics

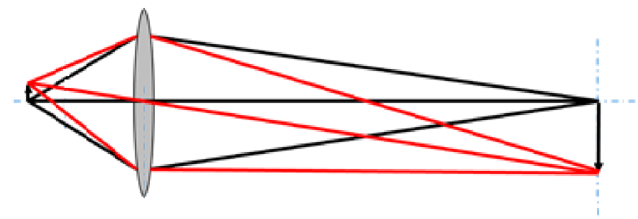


Tandem lens system : infinite corrected optics



Optically coupled X-Ray imaging systems
Single lens vs tandem configurations

Single lens system : finite corrected optics



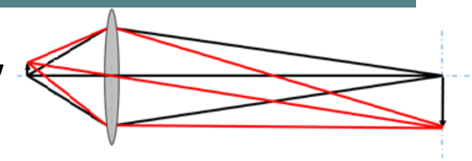
- **Advantages :**
  - **Simpler system (only one objective)**
  - **Easy design for macroscopy**
    (not used for microscopy except some mirror objectives)
  - **Available standard good quality macro objectives on the market**
  - **Cheaper solution even in case of specific optic design**

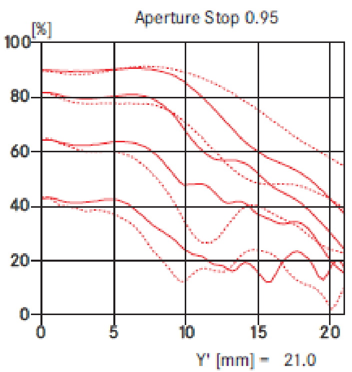
- **Drawbacks**
  - **Standard available objectives do not combine high aperture with high optical quality (resolution, distortion, vignetting)**
  - **Image magnification can slightly vary if focusing is done by moving the objective in respect of the camera/scintillator**
    (It is better to keep constant the distance between camera and objective, but then a more complex mechanical design)

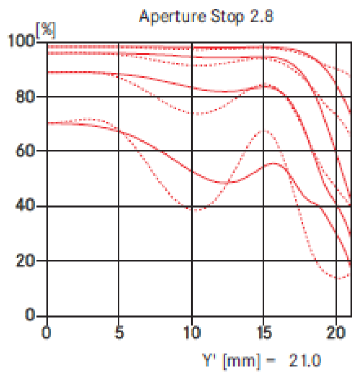
Optically coupled X-Ray imaging systems
Standard single macro high aperture lens limitation

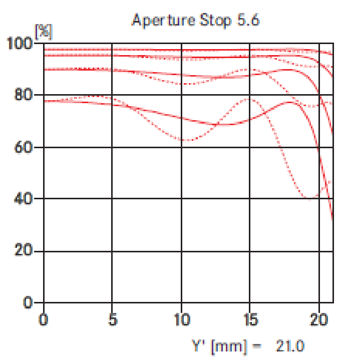
- Standard macro objectives do not combine high aperture with high optical quality (resolution, distortion, vignetting)
- Some standard objectives propose very high aperture

- Example : F50 mm f/0,95 - But :
  - Optical performance are not always adapted for macro applications with short closeup
  - Aperture Iris have to be partially closed to get good resolution









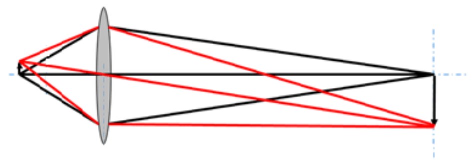
FTM limited at full aperture

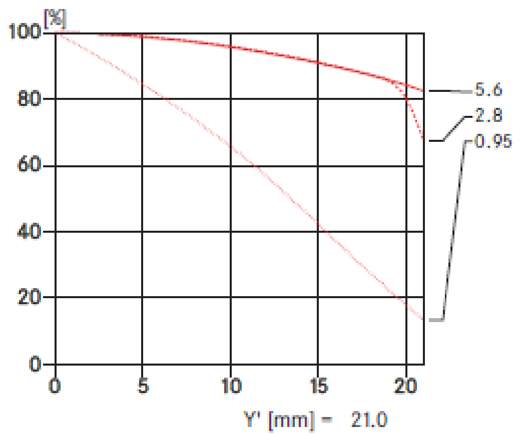
Aperture stop has to be closed to 5,6 to have a better resolution

Optically coupled X-Ray imaging systems

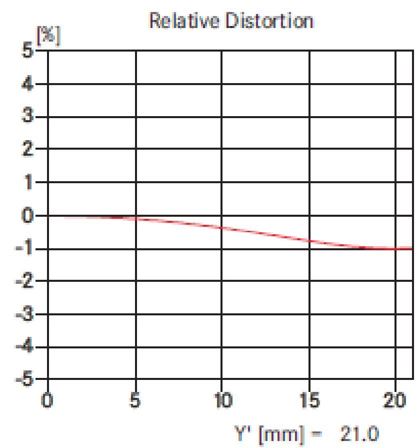
Standard single macro high aperture lens limitation

- **Vignetting and distortion**
- **Most standard high aperture objectives have an important vignetting when fully open**
- **Most high aperture objectives have a significant distortion for 3D reconstruction**



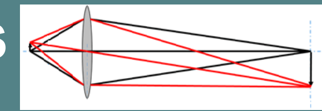


Vignetting is very important at full objective aperture
Will need a strong background correction
and generate lost of dynamic in image corners



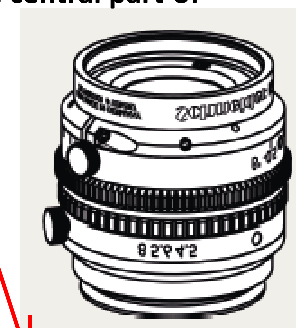
1% relative distortion is penalizing
for tomography applications

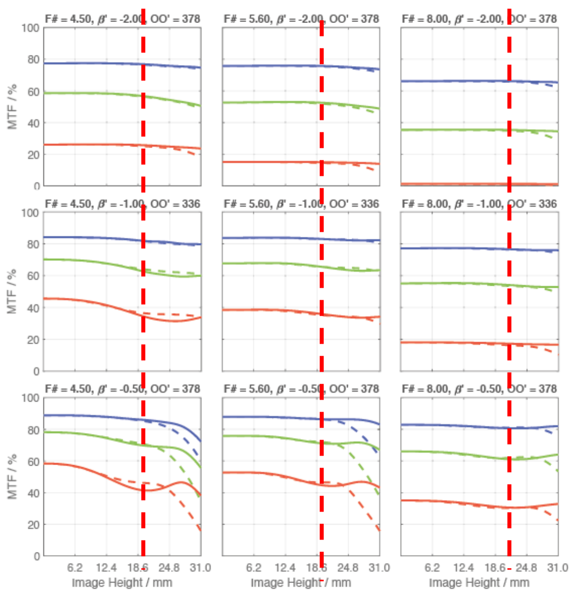
Optically coupled X-Ray imaging systems



Standard single macro high resolution lens limitation

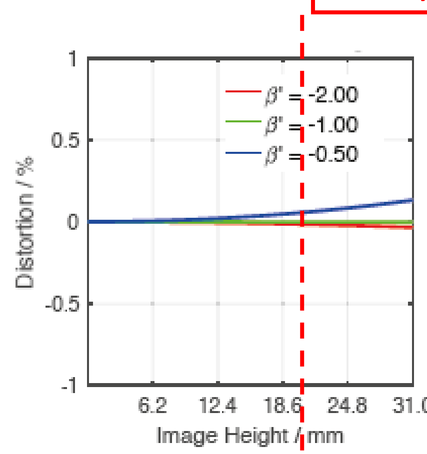
- **Standard macro objectives do not combine high aperture with high optical quality (resolution, distortion, vignetting)**
- **Some standard machine vision objectives propose very high resolution with low distortion and vignetting**
- **Those objectives have large image circle, this is interesting even if the detector is smaller, in this case the central part of the image circle is used, with better quality than the outer part of the image circle**
- **Example : F85 mm f/4.5**
  - **Very versatile objective in the range of 0,5X to 2X magnification - 62 mm image circle**
  - **Perfect but the objective aperture is limited to f/4.5 (limited for high speed imaging)**

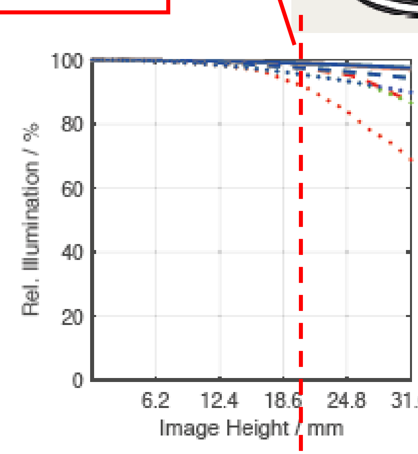




Very good FTM from 0,5x to 2x magnification

Max detector size (half diagonal) for most cameras used in synchrotrons

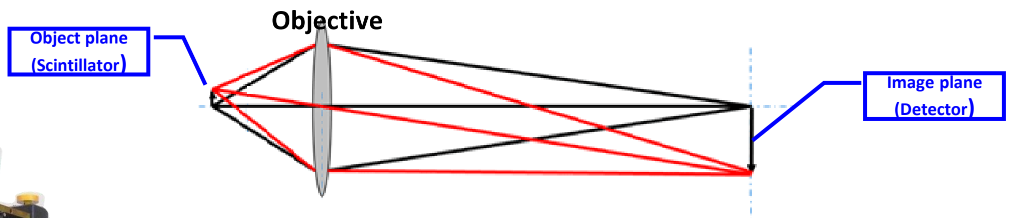




Low distortion and low vignetting for most cameras used in synchrotron

Optically coupled X-Ray imaging systems

Single lens systems for low magnification macro optics

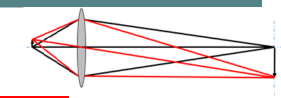


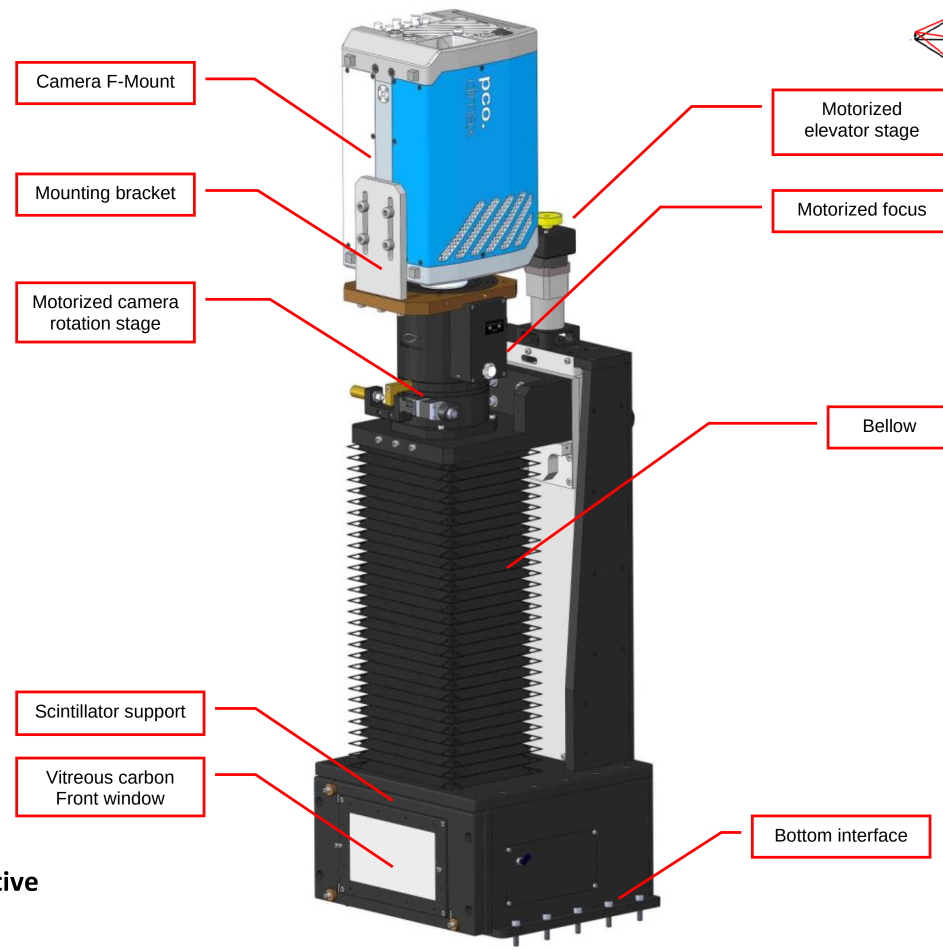
Low magnification Macroscope
0,16x to 0,25X magnification
Field of view up to 250 mm

Special X-Ray imaging objectives
4X/0,20
Image circle up to 88 mm

Special Mirror objective
10X/0,40

Optically coupled X-Ray imaging systems
Low magnification macroscope

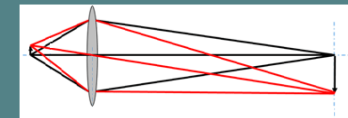




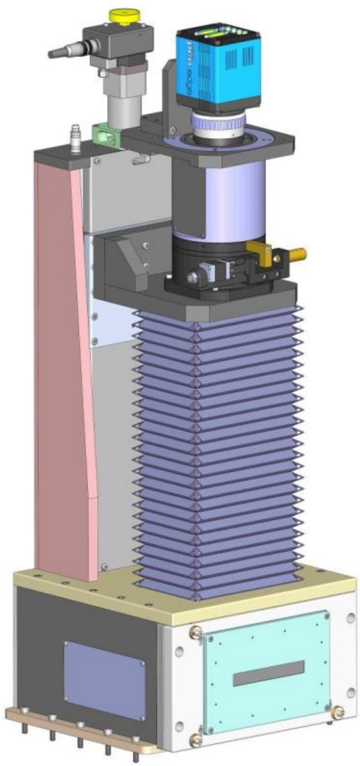
Low magnification Macroscope
F91 mm F/3,1 high resolution macro objective
0,16x to 0,25X magnification
Field of view up to 250 mm

Optically coupled X-Ray imaging systems

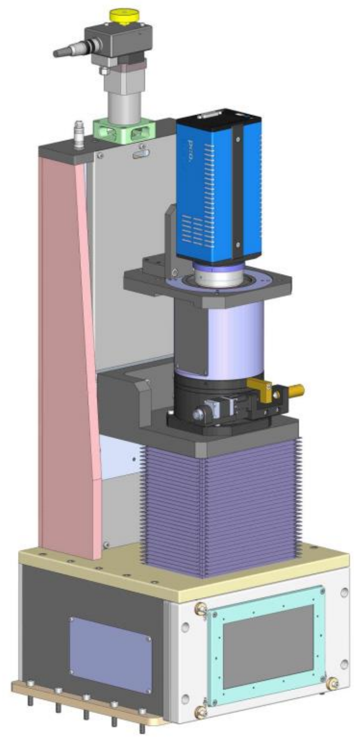
Low magnification macroscope



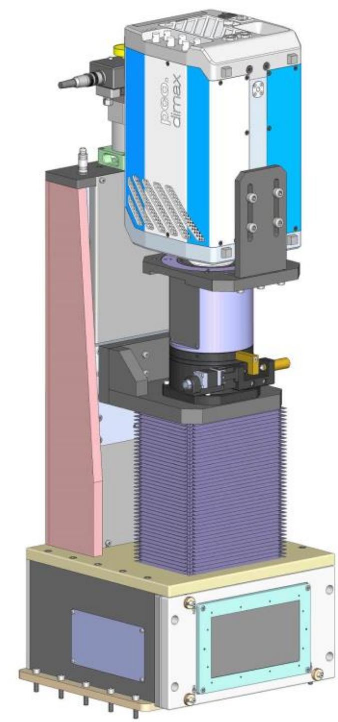
Versatile macroscope configuration : 0,14x to 0,24 x adjustable magnification



PCO Edge
100 mm with scintillator

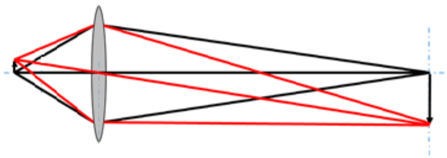


PCO 4000
150 mm with scintillator



PCO Dimax
150 mm with scintillator

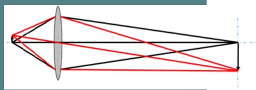
Optically coupled X-Ray imaging systems
Single lens systems for high resolution macroscopy



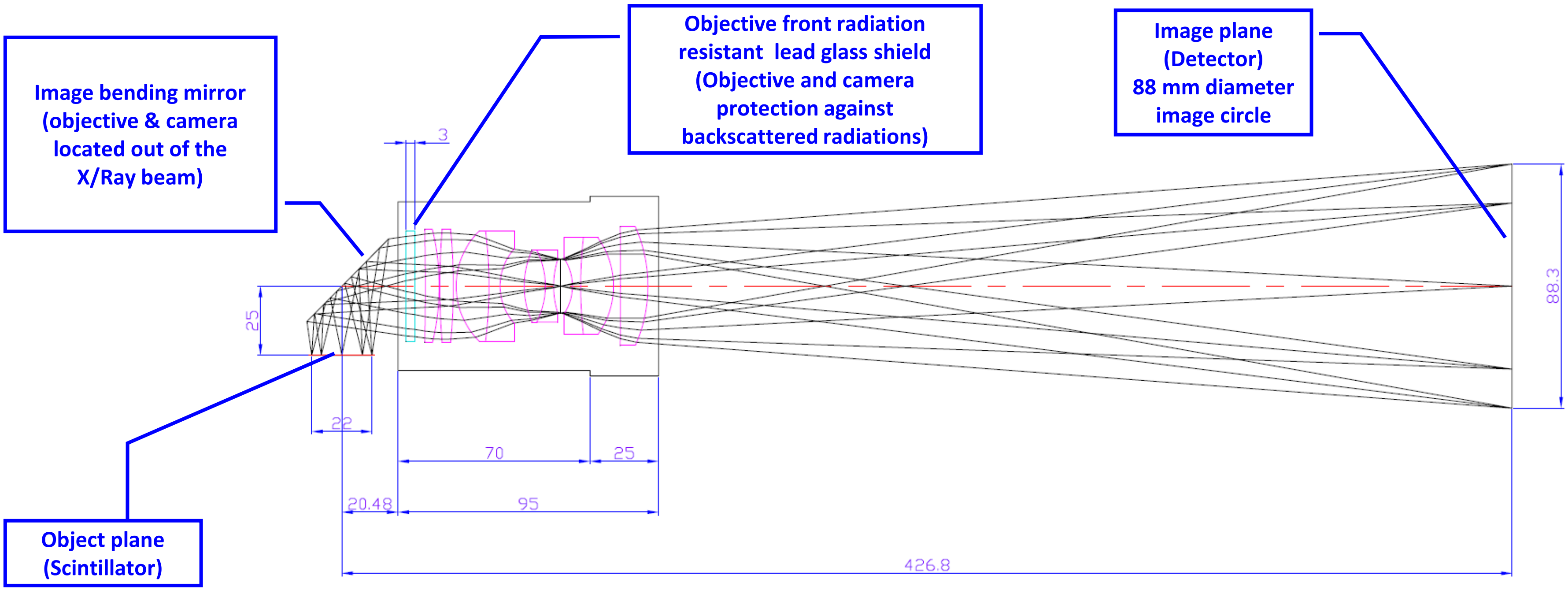
Special design for X-Ray imaging applications on very large detectors (89 mm image circle)

- High NA 4X/0.20
- 89 mm image circle :
  - 22 mm diameter object field of view
  - Image surface 12 times larger than a standard 4X objective
- High resolution close to diffraction limit
- Long working distance allowing a bending mirror between objective and scintillator

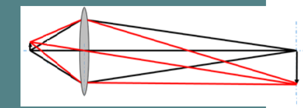
Optically coupled X-Ray imaging systems



4X/0,20 macro objective (Single lens system)



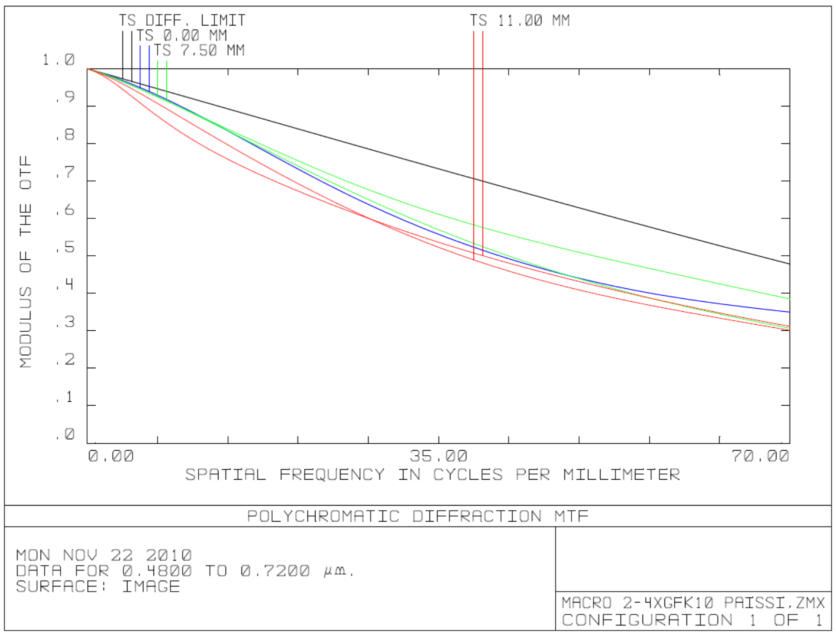
Optically coupled X-Ray imaging systems

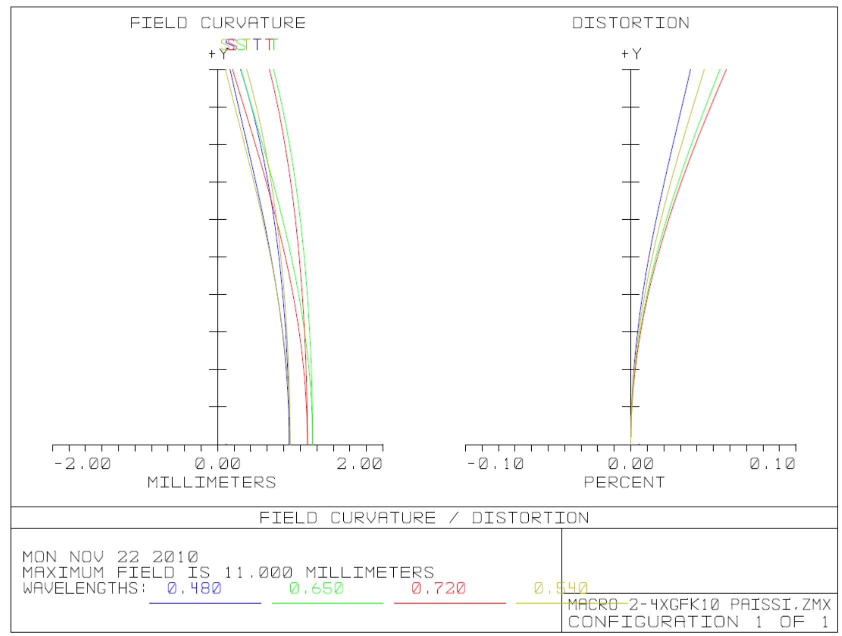


4X/0,20 macro objective (Single lens system)

Outstanding optical performances

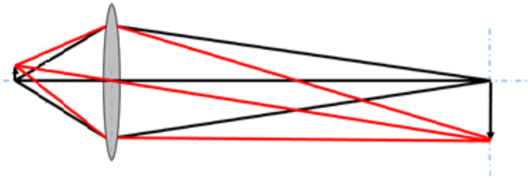
- FTM not far from diffraction limit
- Vey low distortion : allows easy 3D reconstruction for tomography





Optically coupled X-Ray imaging systems
Single lens systems for high magnification microscopy

10X/0,40 Mirror objective



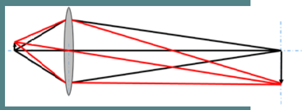
Single lens microscope systems are not common for X-Ray imaging

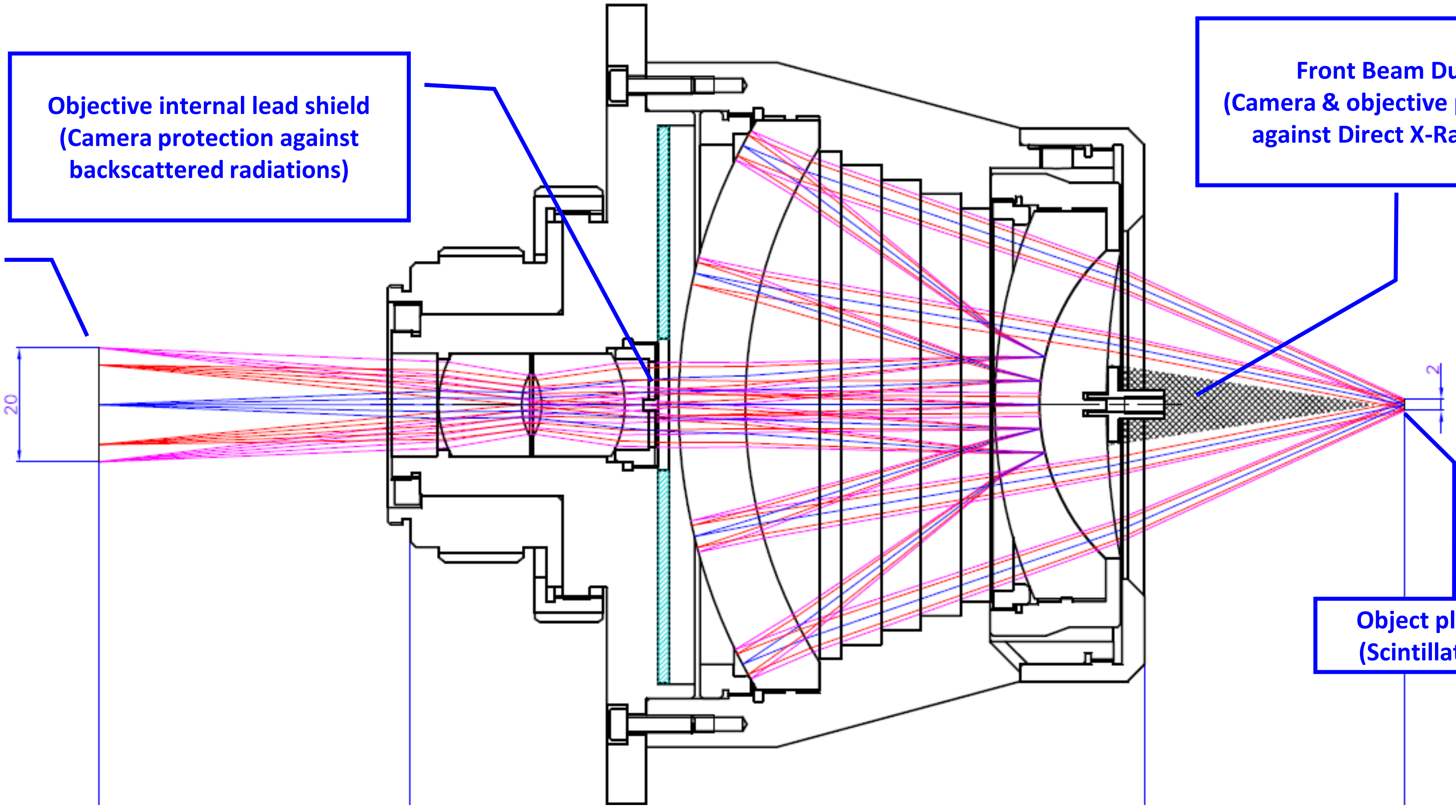
The 10X/0,40 Mirror objective has been designed for special applications

- High flux / high energies X-Ray White Beam
- In-line setup
- In-line camera protection by integrated lead shield
- Front beam stopper

Optically coupled X-Ray imaging systems

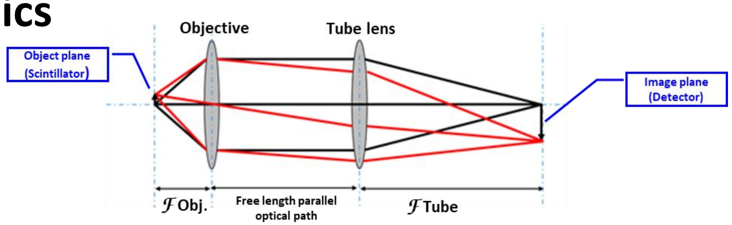
10X/0,40 mirror objective (Single lens system)





Optically coupled X-Ray imaging systems
Single lens vs tandem configurations

Tandem lens system : Infinite corrected tandem optics

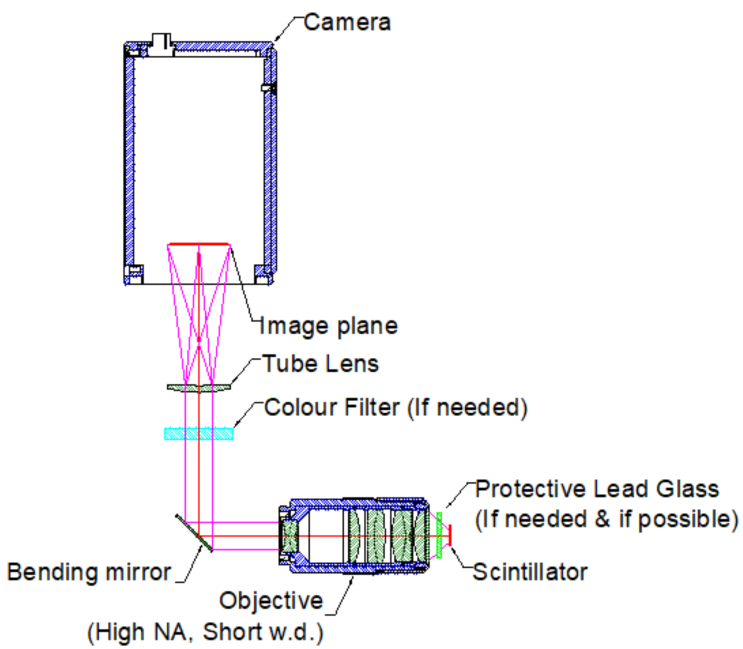


- **Advantages :**
  - **Easy design for microscopy**
    (Many components available)
  - **Available standard good quality micro objectives on the market**
  - **Focusing by moving the objective vs camera & scintillator does not affect the magnification, easy mechanical integration**
  - **Flexible deign : magnification can be adapted by mixing different focal tube lens and objectives**

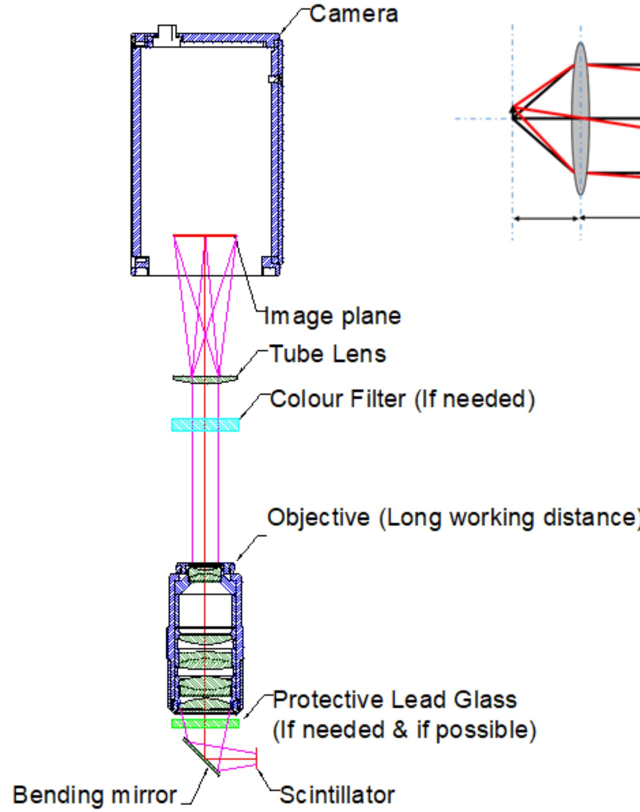
- **Drawbacks**
  - **More expensive solution (two optical components)**
  - **For white beam microscope applications :**
  - **Standard microscope objective are not radiation hardened, have to be protected (or special objectives have to be designed)**
  - **Tandem design with standard objectives not so easy considering the pupil adjustment between the two objectives, not all standard objectives are suitable for tandem applications**

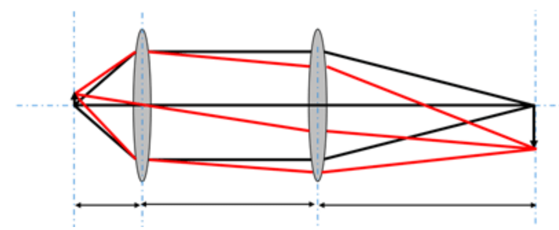
Optically coupled X-Ray imaging systems
Tandem lens configuration for microscopy

Monochromatic Beam configuration
vs
White Beam configuration



"Monochromatic" configuration
(Objective located inside beam axis)

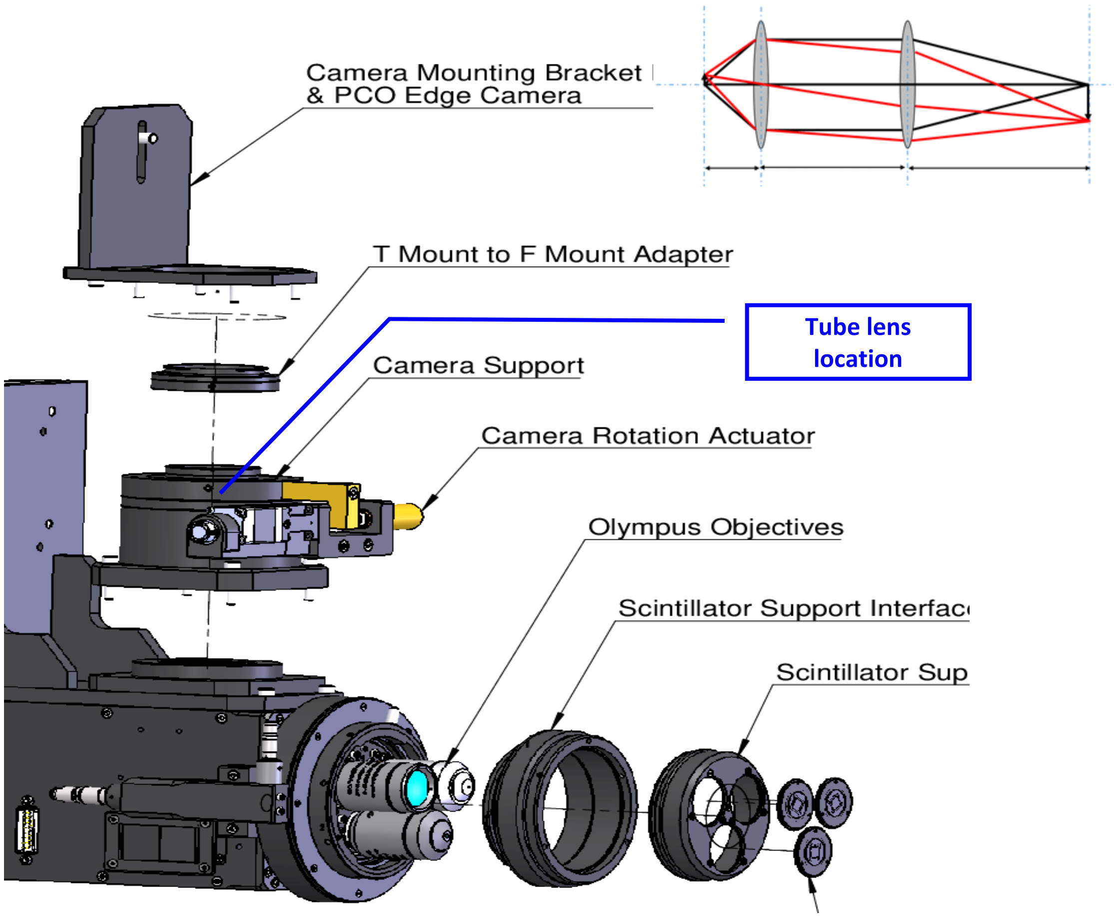




"White beam" configuration
(Objective located out of beam axis)

Optically coupled X-Ray imaging systems

Tandem lens for microscopy – Monochromatic Beam configuration



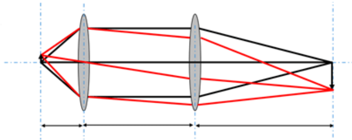
Optically coupled X-Ray imaging systems

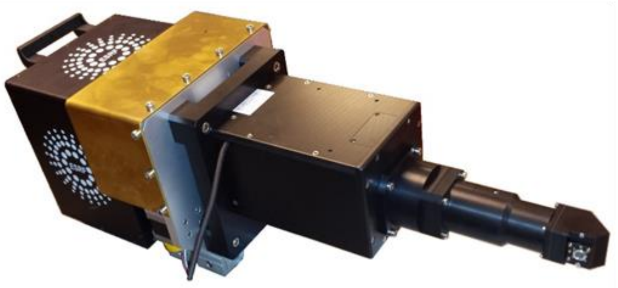
Tandem lens for microscopy – White Beam configuration


Double objectives


Triple objective

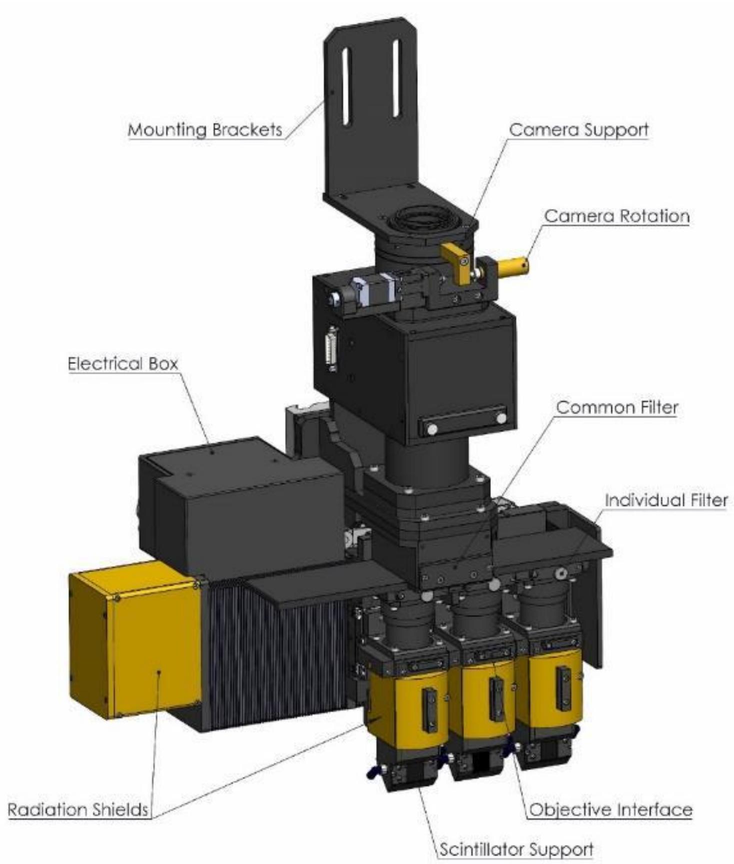

Single objective

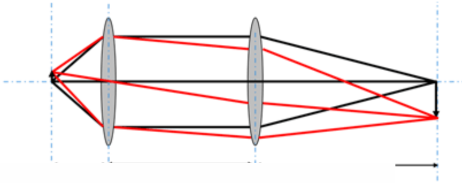


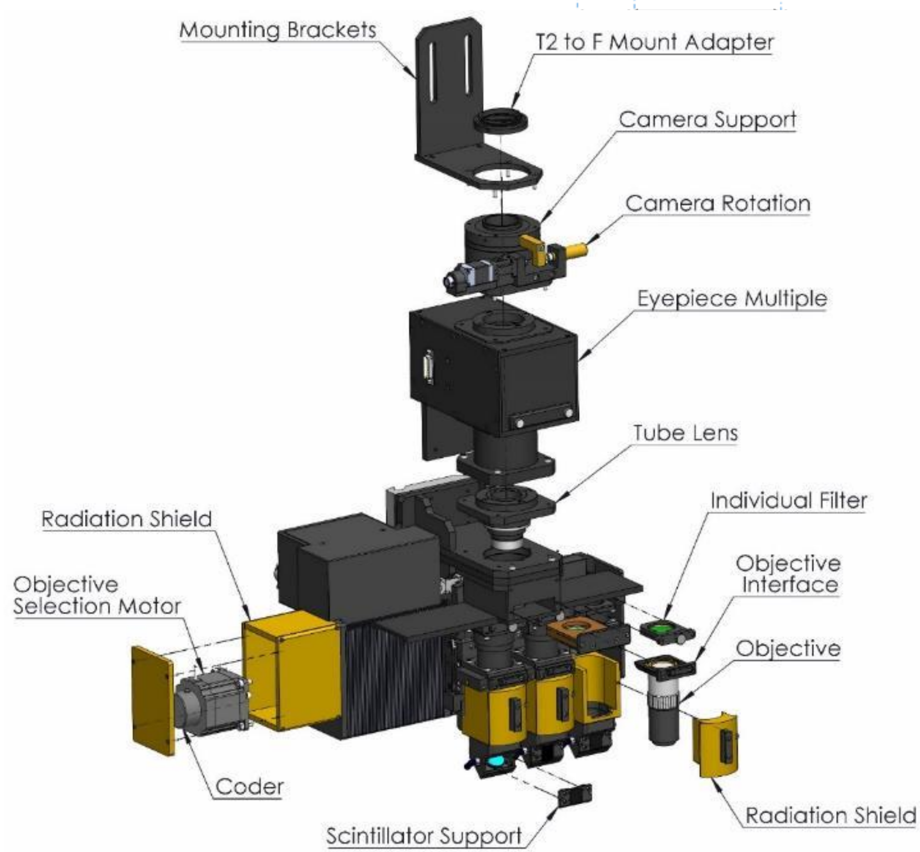

Near Field - Single objective

Optically coupled X-Ray imaging systems

Tandem lens for microscopy – White Beam configuration







Optically coupled X-Ray imaging systems

Tandem lens for microscopy – White Beam configuration

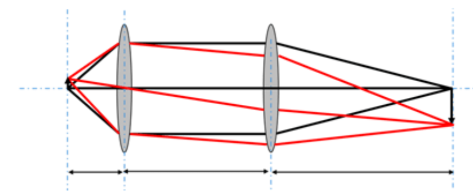
The bending mirror between the scintillator and the objective can be made of low Z material (Such as Glassy Carbon)

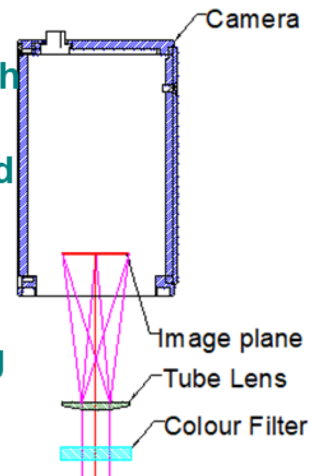
This allows the remaining X-Ray beam to be used for a second instrument located behind the microscope :

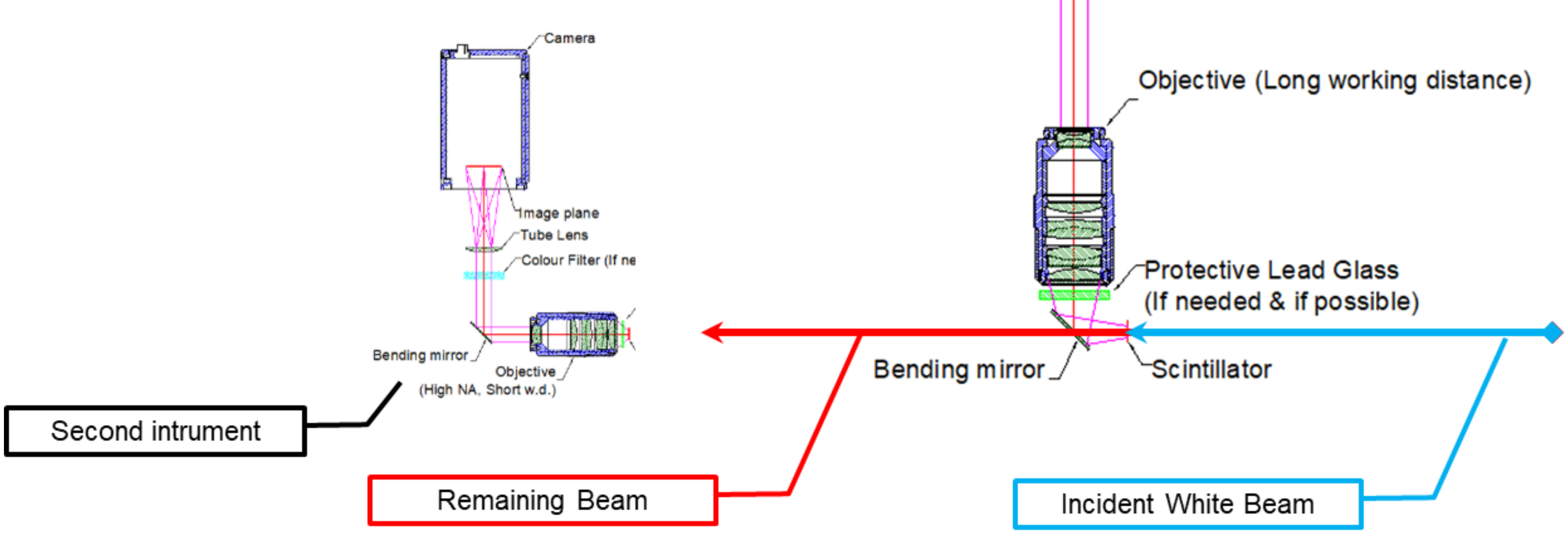
- Diffractometer

- Second microscope for phase contrast imaging

- …

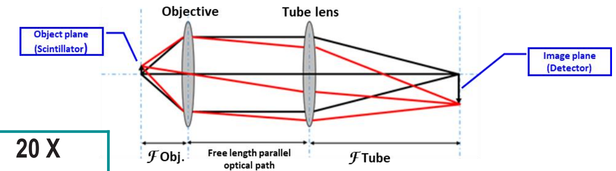






Optically coupled X-Ray imaging systems

Tandem lens for microscopy – White Beam configuration

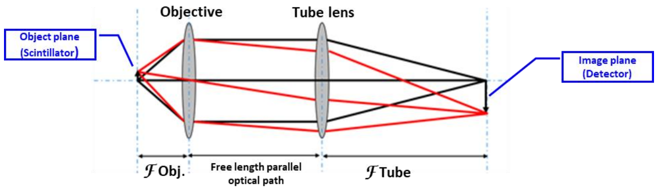


Objective	2 X	5 X	HR 5X	7,5 X	10 X	20 X
Front Shield Thickness (mm)	**4,0**	**4,0**	**3,0**	**4,5**	**4,5**	**3,0**
NA	0,055	0,14	0,21	0,21	0,28	0,42
Resolution Limit (µm) - (@ 550nm)	6,1	2,4	1,6	1,6	1,2	0,80
FROND RADIATION RESISTANT GLASS SHIELD EFFICIENCY (X-RAY ABSOPTION)						
X-Ray energy						
<= 30 KeV	100 %		100 %	100 %		100 %
40 KeV	99,8 %		99 %	99,9 %		99 %
50 KeV	98 %		94 %	98,5 %		94 %
60 KeV	91 %		83,4 %	93 %		83 %
70 KeV	81 %		71 %	84 %		71 %
80 KeV	70 %		59,8 %	74 %		60 %
88 KeV	96 %		91,4 %	97 %		91 %
100 KeV	91 %		83,4 %	93 %		83 %
120 KeV	79 %		68,8 %	83 %		69 %
150 KeV	61 %		50,5 %	65 %		50 %

Special White Beam X-Ray imaging dedicated long working distance objectives with Radiation Hardened front lens

Optically coupled X-Ray imaging systems

Tandem lens for microscopy – White Beam configuration



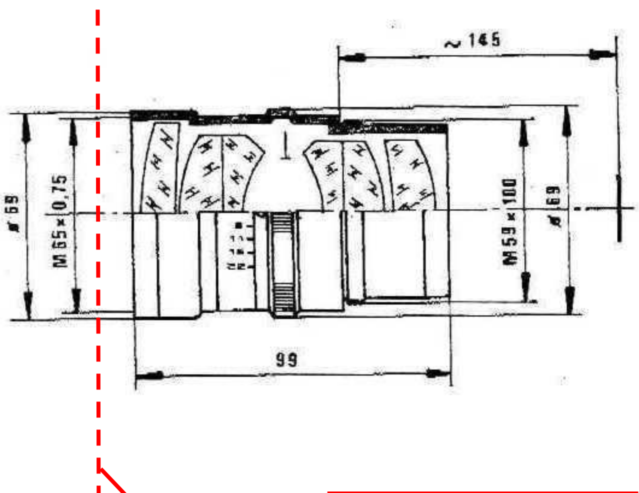
Radiation resistant objectives

(New 1X objective available September 2020)

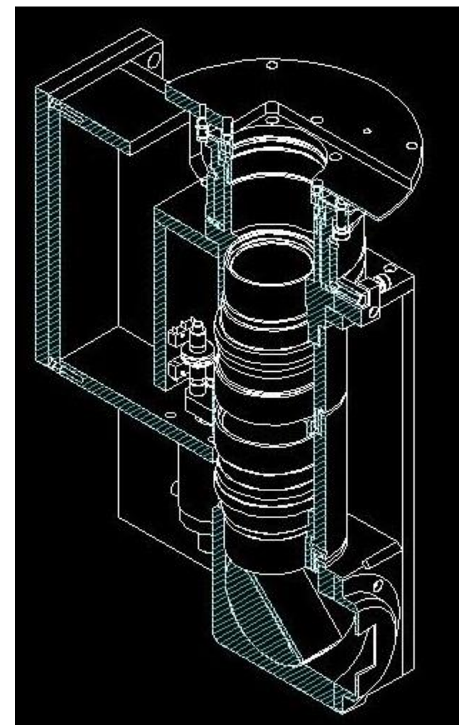
Tandem lens for macroscopy – 1X White Beam Macroscope

1X Macroscope

- Tandem lens configuration
- Two F150mm f/2,5 Lenses

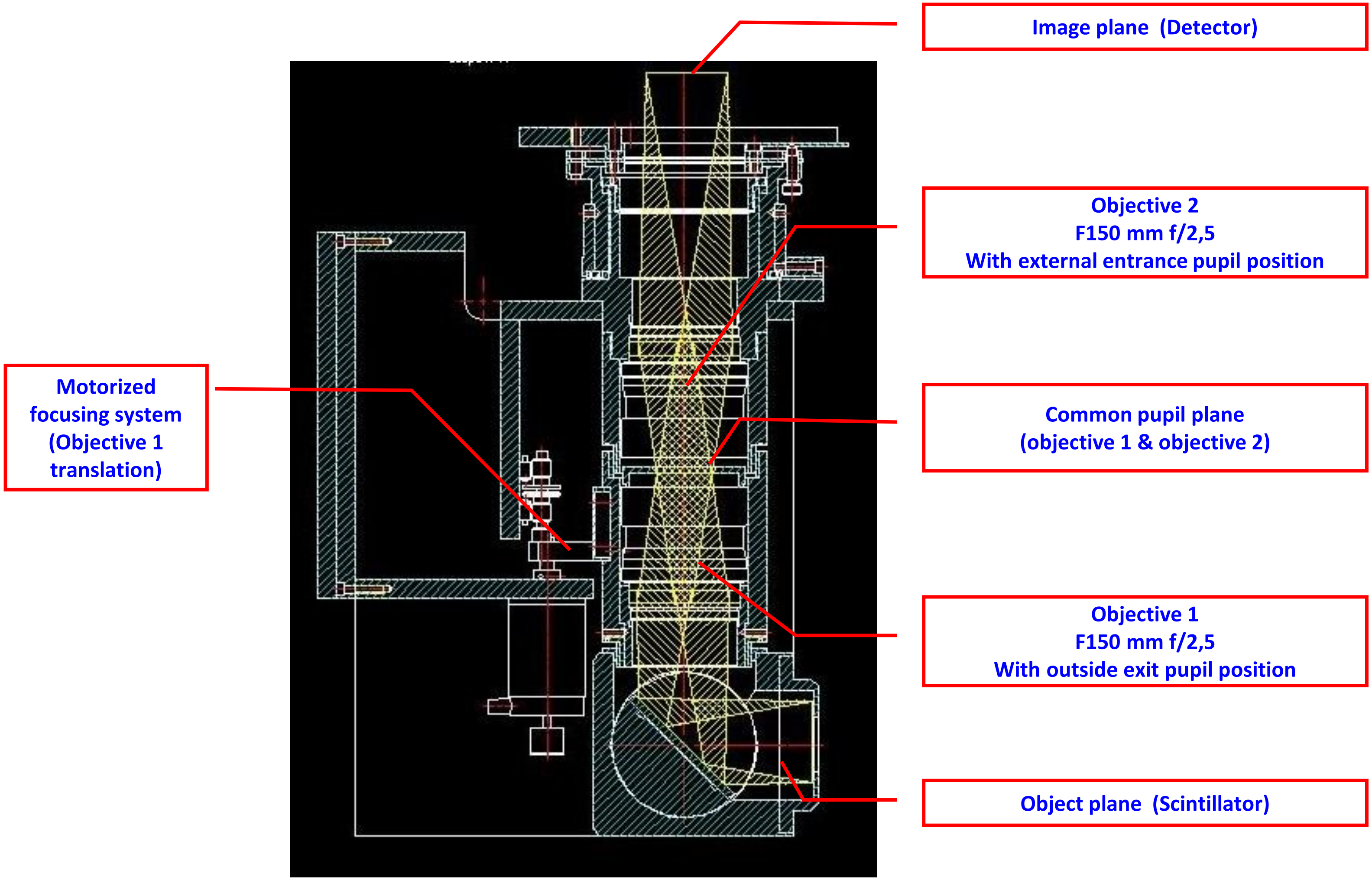


Objective entry pupil plane located in front of the objective



Optically coupled X-Ray imaging systems

Tandem lens for macroscopy – 1X White Beam Macroscope



Tandem lens for macroscopy – for versatile magnification setup

F300 mm lens dedicated to macro tandem X-Ray imaging

This lens has an exit pupil position located far from the objective

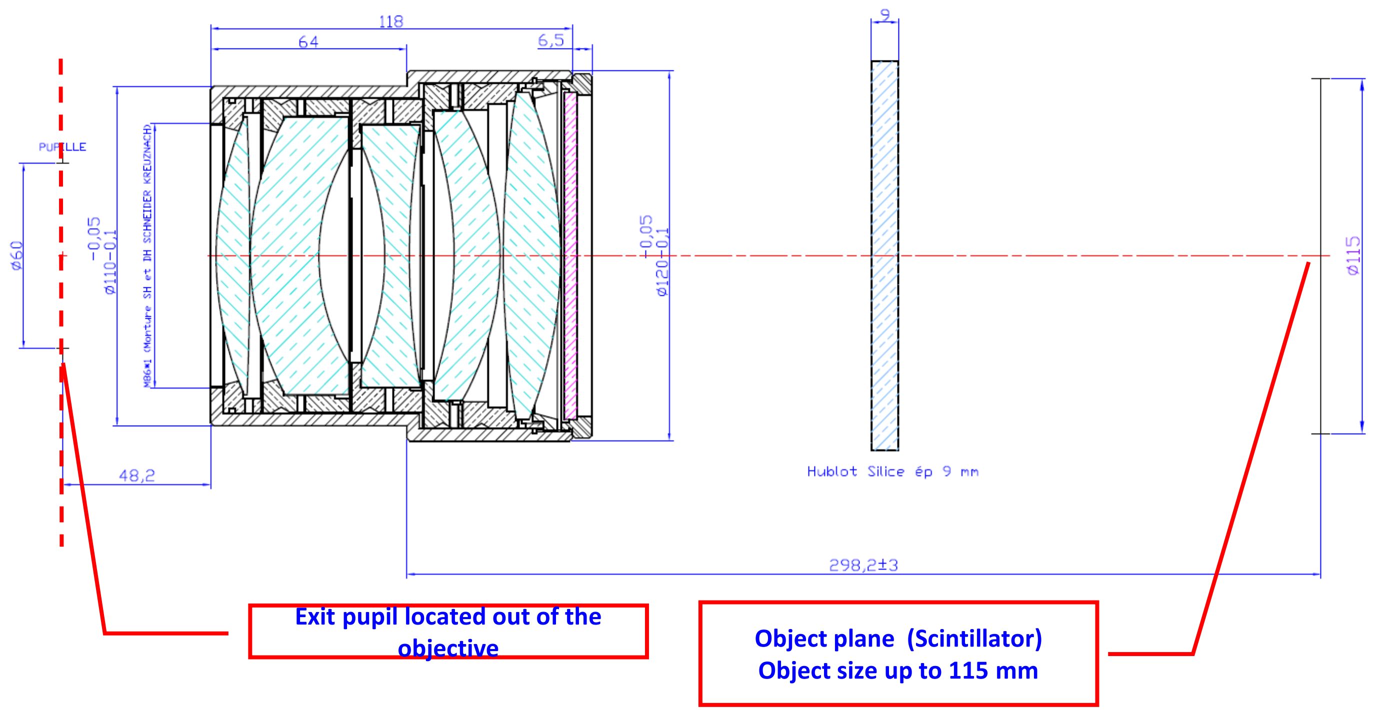
Can be combined with any standard macro lens (even with pupil inside the objective)

Tandem lens for macroscopy – for versatile magnification setup

F300 mm f/5 lens dedicated to macro tandem X-Ray imaging

This lens has an exit pupil position located far from the objective

Can be combined with any standard macro lens (even with pupil inside the objective)

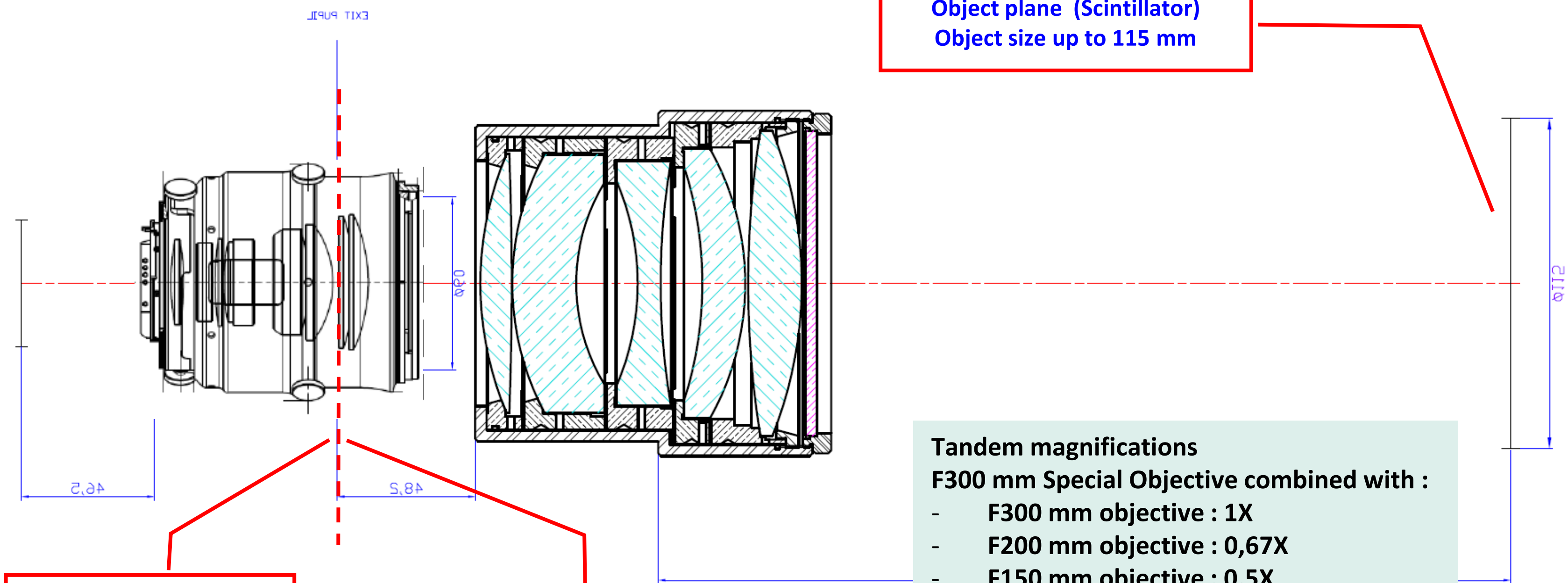


Optically coupled X-Ray imaging systems

Tandem lens for macroscopy – for versatile magnification setup

F300 mm f/5 lens combined with a standard F-Mount objective

Figured with a Zeiss F100 mm f/2 objective – total magnification = 100/300 = 0,33X



Object plane (Scintillator)
Object size up to 115 mm

Entry pupil located inside the n°2 objective (Standard F-Mount)

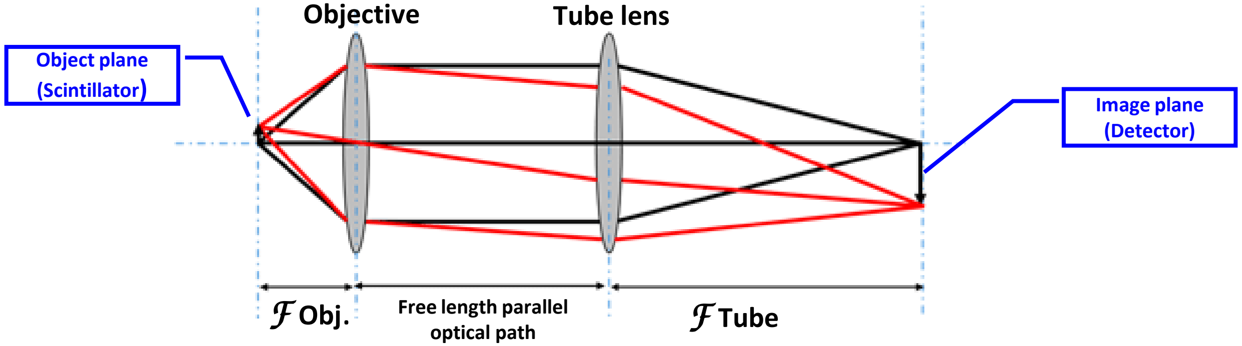
Exit pupil located out of the n°1 objective (special F300)

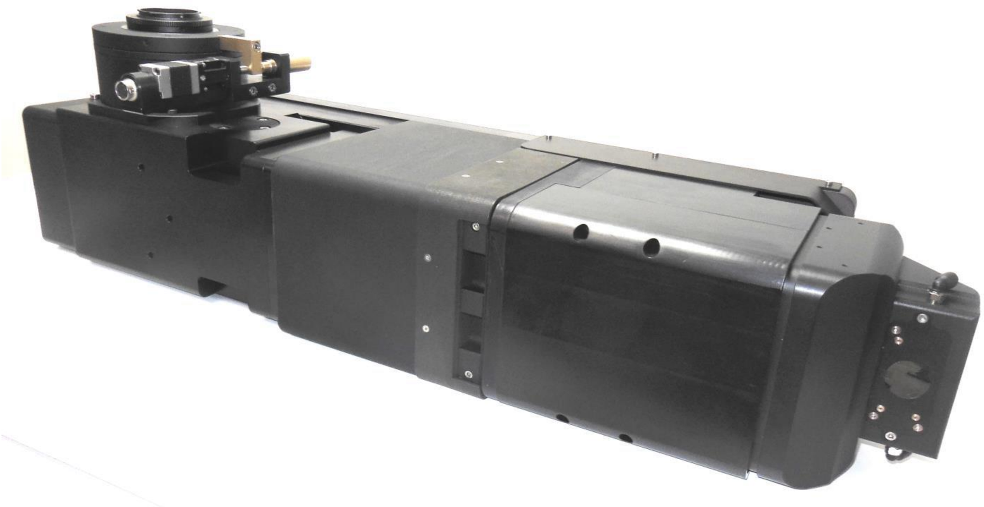
Tandem magnifications
F300 mm Special Objective combined with :

- **F300 mm objective : 1X**
- **F200 mm objective : 0,67X**
- **F150 mm objective : 0,5X**
- **F100 mm objective : 0,33X**
- **F85 mm objective : 0,28X**
- **F50 mm objective : 0,17X**

Optically coupled X-Ray imaging systems
4X/0,35 macroscope - Tandem configuration

Tandem lens system : infinite corrected optics

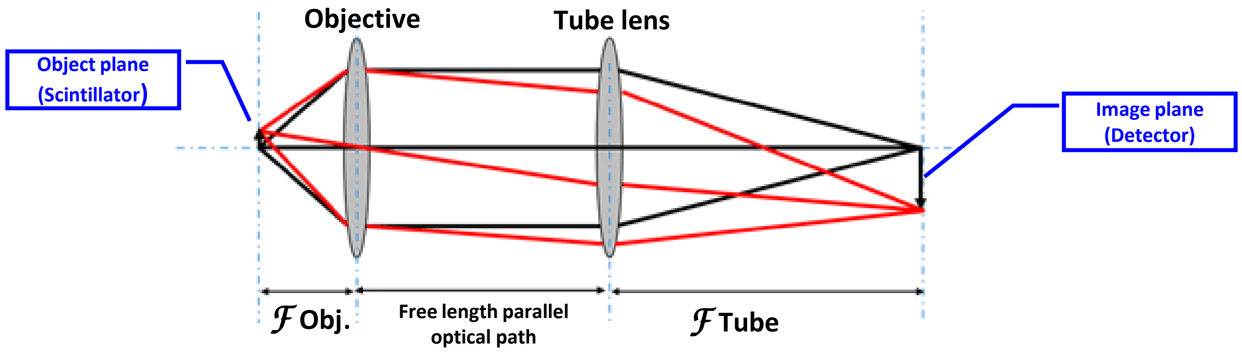




Optically coupled X-Ray imaging systems

4X/0,35 macroscope - Tandem configuration

Tandem lens system : infinite corrected optics



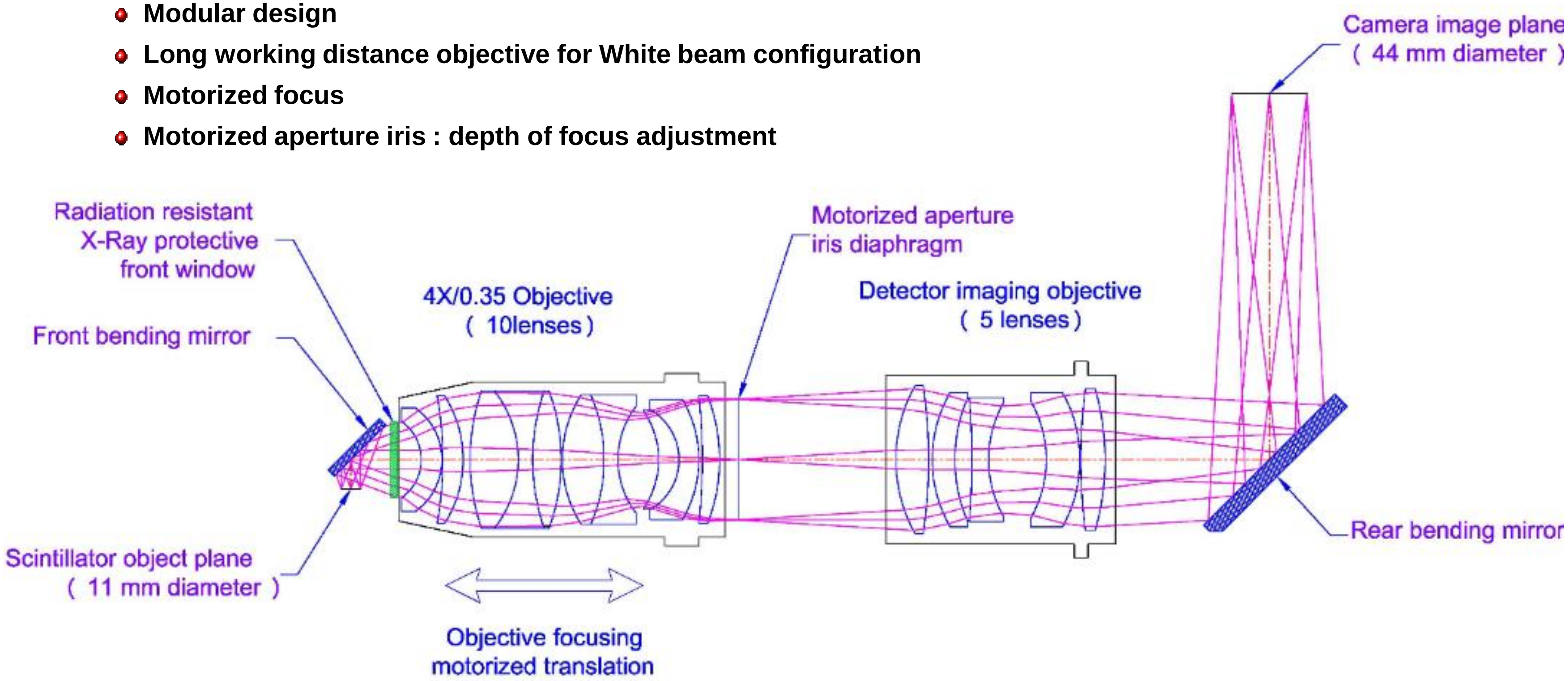
Front infinite correct objective (10 lenses)

Tube lens (5 lenses)

Optically coupled X-Ray imaging systems
4X/0,35 macroscope - Tandem configuration

Pushing the performances to the limit

- **Higher NA : 0,35**
- **Large camera format : up to 44 mm detector diagonal**
- **Modular design**
- **Long working distance objective for White beam configuration**
- **Motorized focus**
- **Motorized aperture iris : depth of focus adjustment**



Optically coupled X-Ray imaging systems

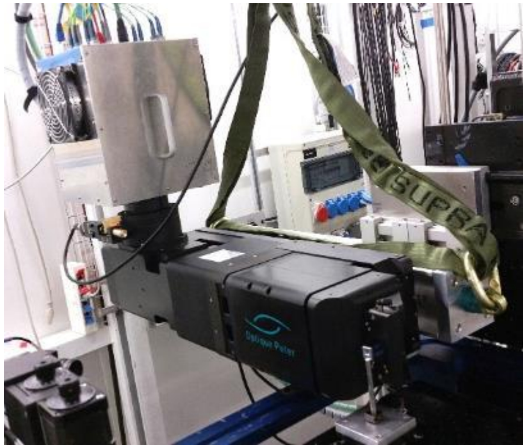
4X/0,35 macroscope - Tandem configuration

Pushing the performances to the limit

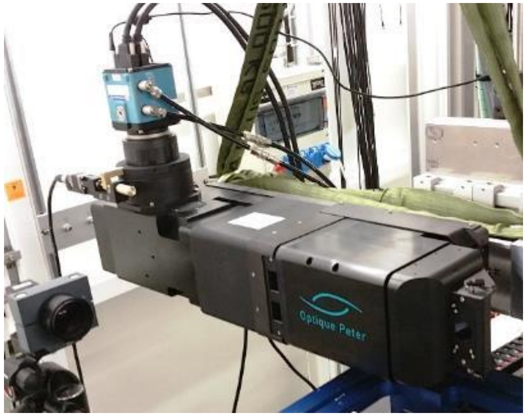
Macroscope vs microscopes	**Microscope with standard objectives**		**4X/0.35 Macroscope**
Camera format Detectord max diagonal	Medium Format up to 26 mm	Large format Up to 44 mm	Medium/Large format Up to 44 mm
Camera models	PCO Edge - PCO 2000 Andor Neo - Zyla Orca Flash4.0	PCO Dimax PSI GigaFrost PCO 4000 ESRF Frelon	Any camera
Objective NA Enlarging eyepiece	4X 0.16 none	2X 0.08 2X	4X 0.35 none
Max diagonal object field of view	6.5 mm	11 mm	11 mm
Resolution limit (µm) (@ 550 nm wavelength)	2.10	4.19	0.96
Light collection vs 4X/0.16 objective	100%	25%	478%

Optically coupled X-Ray imaging systems

4X/0,35 macroscope - Modular and flexible mounting at SLS Synchrotron



Lateral GigaFrost camera mounting



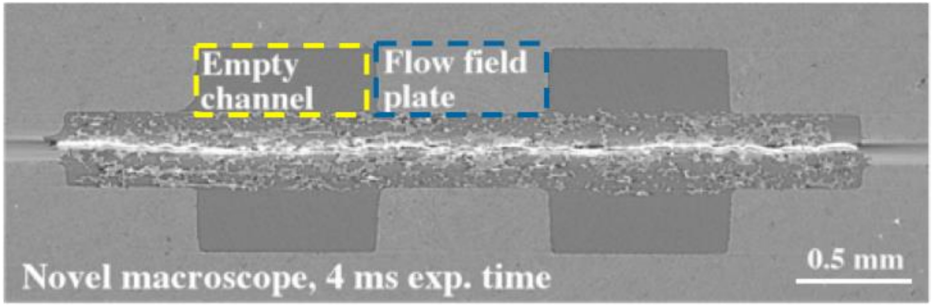
Lateral PCO Edge camera mounting

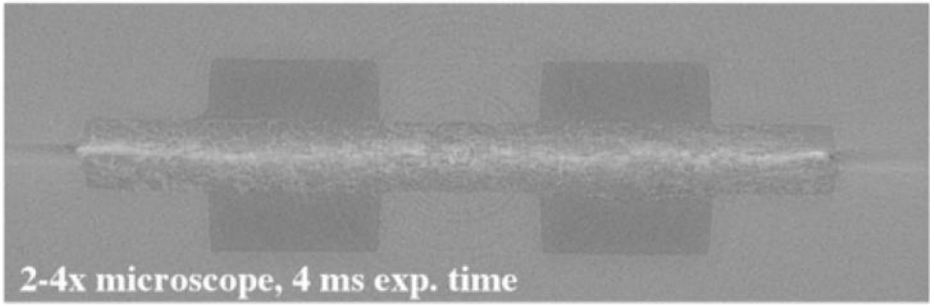
In-line GigaFrost camera mounting

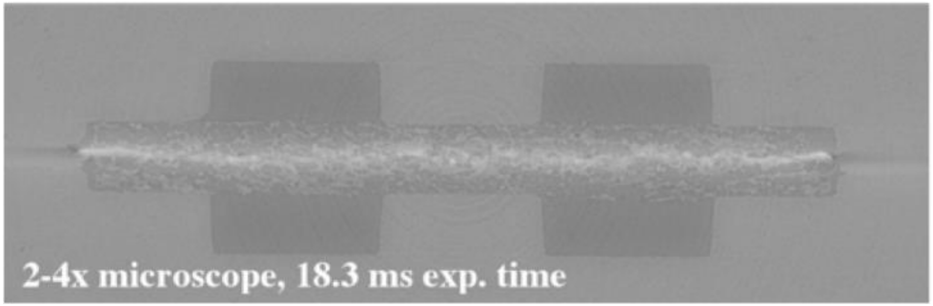
Courtesy Swiss Light Source
Dr. Federica Marone
Prof. Marco Sampanoni

Optically coupled X-Ray imaging systems

4X/0,35 macroscope – Image quality in 3D





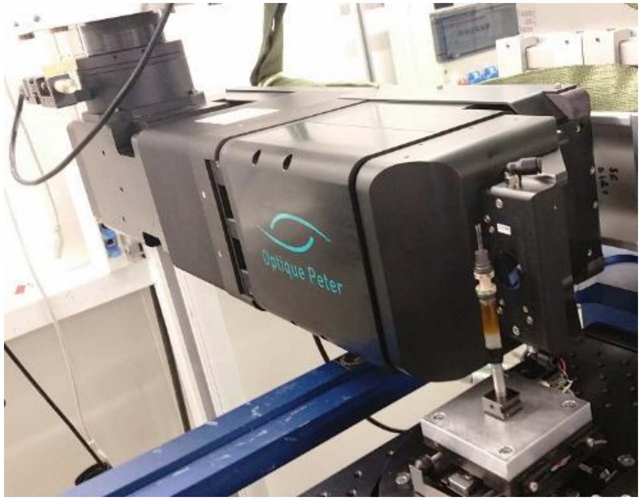


Tomographic slices of the fuel cell sample.

Top: reconstruction from novel macroscope images and 4 ms exposure time.

Middle: reconstruction from Elya Solutions microscope images and 4 ms exposure time.

Bottom: reconstruction from Elya Solutions microscope images and 18.3 ms



Courtesy Swiss Light Source

Dr. Federica Marone – Prof. Marco Sampanoni

4X/0,35 macroscope
Comparison with existing macroscope and microscope at SLS

- The exposure times for high temporal resolution experiments can be decreased by a factor of 4 and for high spatial resolution experiments by nearly a factor of 8.5 compared to the setups previously used at TOMCAT
- The spatial resolution reached in time resolved studies is up to 6 times higher than when the Elya Solutions microscope is used
- The spatial resolution is also superior, by a factor of 1.5, for high-resolution investigations
- Spatial resolution and image quality provided by the novel macroscope will enormously expand the systems that can be investigated with high temporal resolution and will make 10-20 Hz studies routinely possible

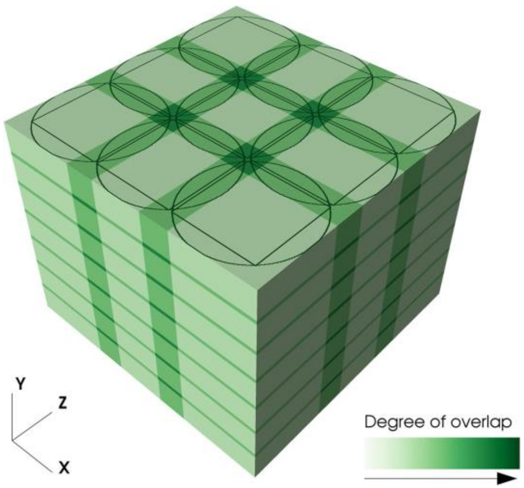
The setup 4X/0,35 macroscope with Giga FRoST High speed imaging and readout system has reached up to 1000 tomograms per second at the TOMCAT beamline X02DA of the Swiss Light Source (SLS) facility

Courtesy Swiss Light Source Dr. Federica Marone – Prof. Marco Sampanoni

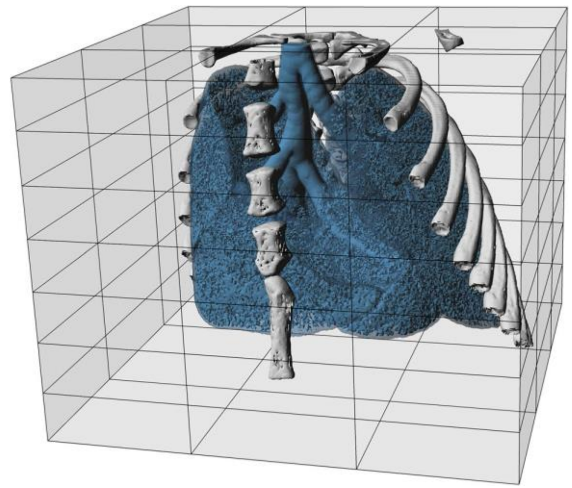
Optically coupled X-Ray imaging systems - 4X/0,35 macroscope

Micrometer-resolution X-ray tomographic full-volume reconstruction of an intact post-mortem juvenile rat lung

Borisova et al - Histochemistry and Cell Biology - https://doi.org/10.1007/s00418-020-01868-8

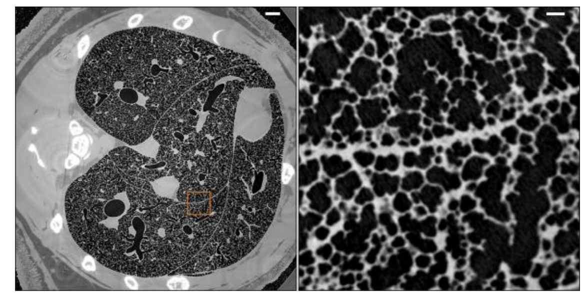


Data acquisition
3x3x7 tiles



Volume view of the full data set
9095 × 9106 × 7084 voxels
25.0 × 25.0 × 19.5 mm^3.

horizontal slice through the final stitched dataset



18.9 x 18.9 mm^2 ***1.5 x 1.5 mm^2***

Tomography carried out at the TOMCAT beamline X02DA of the Swiss Light Source (SLS) facility
- 150 µm thick LuAG:Ce scintillator
- 4X/0.35 X-Ray imaging macroscope from Optique Peter
- GigaFRoST High speed imaging and readout system

High-resolution tomographic data acquisition was completed in under 22 min, which was within the 20–30 min time limit to image soft tissue before structural degrading started to take place

Courtesy Swiss Light Source - Dr. Federica Marone – Prof. Marco Sampanoni

Optically coupled X-Ray imaging systems
New macroscope optics for Tandem configuration

New macro objectives under development for high NA / high resolution tandem macro configurations :

- **All those high resolution objectives have :**
  - **A front radiation resistant lead glass shield,**
  - **A long working distance suitable for mounting an image bending mirror between the scintillator and the objective**
  - **High resolution**
  - **No corner vignetting**
  - **Very low geometrical distortion**
  - **Exit pupil located outside the objective, allowing easy tandem setups**

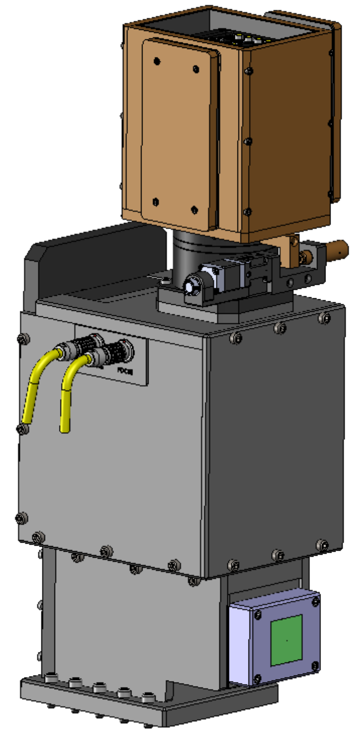
- **F100 mm 0,27 NA (f/1.8) objective – 22 mm max image circle**
- **F150 mm 0,18 NA (f/2.7) objective – 33 mm max image circle**
- **F200 mm 0,135 NA (f/3.6) objective – 44 mm mas image circle**

Tandem setup examples :

- **With camera detector diagonal up to 22 mm (PCO Edge, Andor Neo, Hamamtsu Orca Flash 4) :**
  0,5X/0.27 or 0,67X/0.27 or 1X/0.27 macroscope
- **With camera detector diagonal up to 33 mm (PCO Dimax, Andor Marana, Hamamtsu Orca Lightning) :**
  0,75X/0.18 or 0,1X/0.18 or 1.33X/0.18 macroscope
- **With camera detector diagonal up to 44 mm (PCO 4000, Andor iKon 936L) :**
  1X/0.135 or 0.33X/0.135 or 2X/0.135 macroscope

X-Ray imaging zoom macroscopes
6.3X and 16X zoom macroscopes

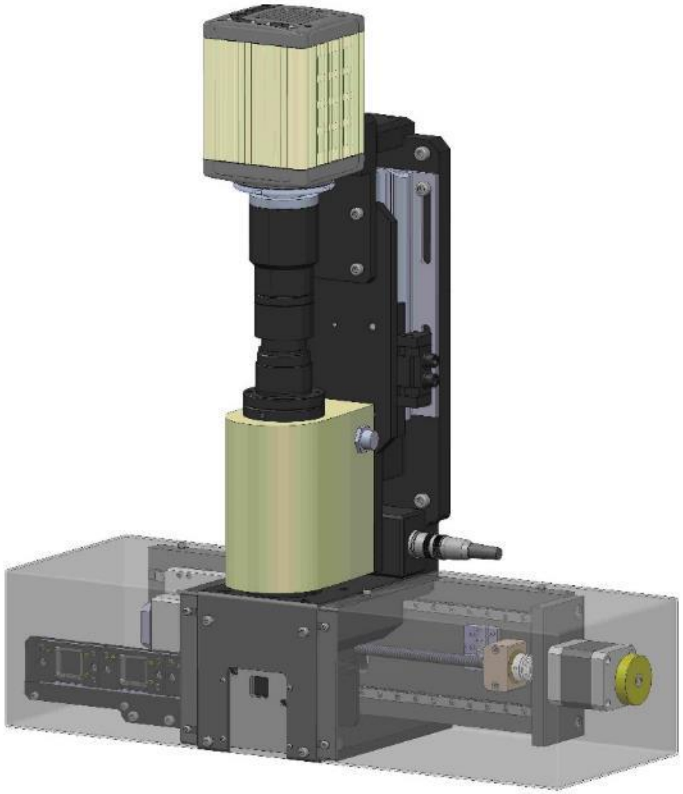

White beam Zoom macroscope - 6,3 X zoom ratio
11,7 mm to 1,8 mm H field of view (with 2X objective)
Single or quadruple motorized scintillator support

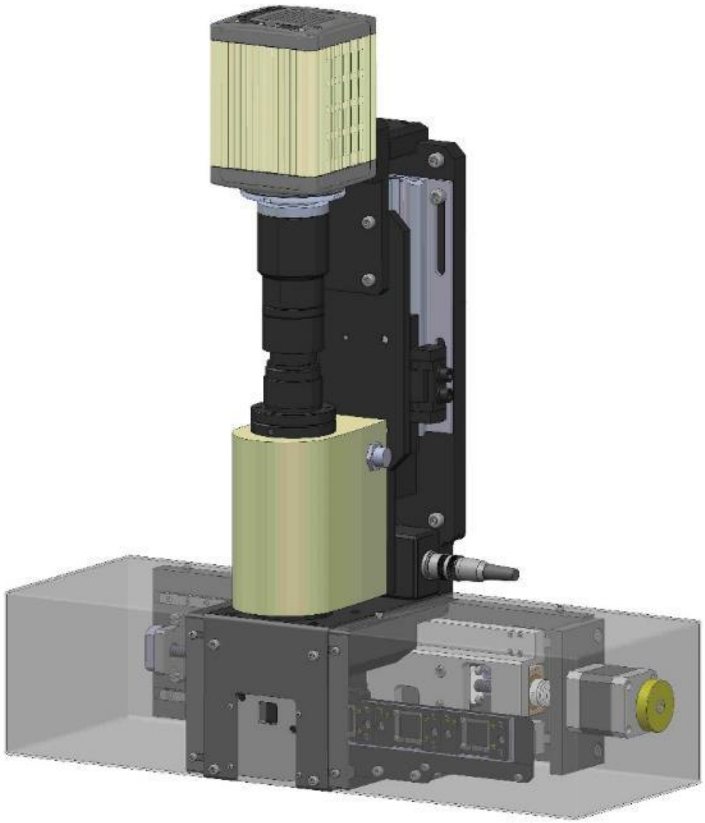


White beam Zoom macroscope - 6,3 X zoom ratio
29 mm to 4,6 mm H field of view (with 0,8 X objective)
23,3 mm to 3,7 mm H field of view (with 1 X objective)
Single or quadruple motorized scintillator support

X-Ray imaging zoom macroscopes

6X and 16X zoom macroscopes



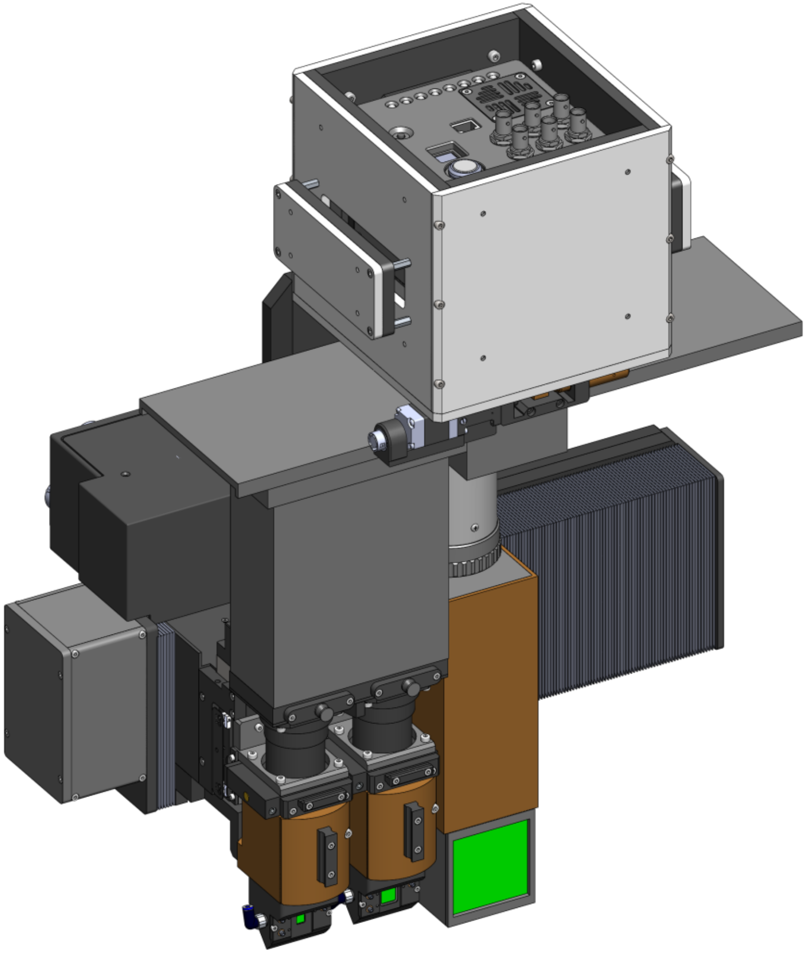


Quadruple motorized scintillator support on zoom with 2X front objective
(1,14X to 7,2X magnification)

X-Ray imaging combined zoom & microscopes
6.3X zoom macroscope and 2 microscope objectives

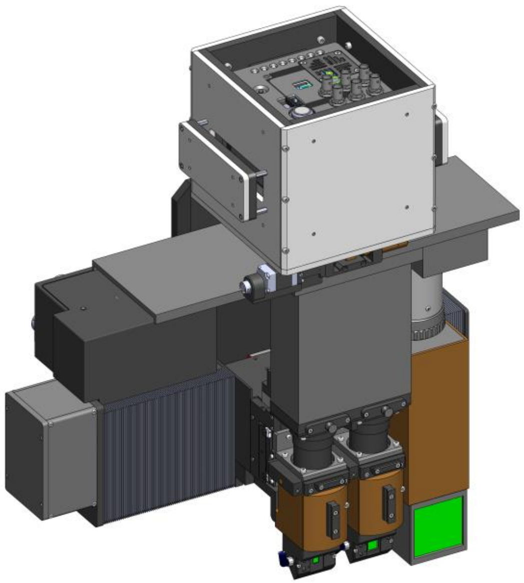
Low magnification 6,3X zoom
- 0,285X to 3,6X magnification
- Up to 50 mm H Field of view

Two microscope channels
- Objectives range from 2X to 20X

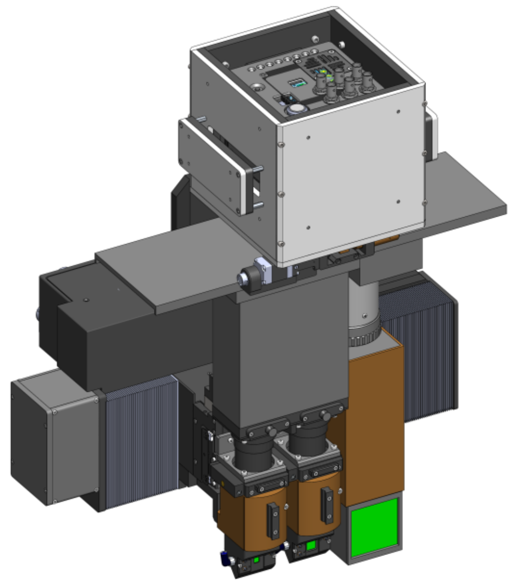


X-Ray imaging combined zoom & microscopes

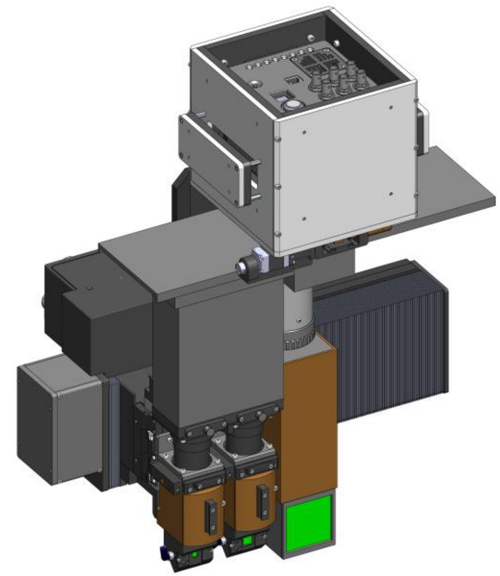
6.3X zoom macroscope and 2 microscope objectives



Microscope objective 1
(2X to 20X)



Microscope objective 2
(2X to 20X)



Zoom system
(0.285X to 1.8 X)

Motorized configuration selection

X-Ray imaging combined zoom & microscopes

6.3X zoom macroscope and 2 microscope objectives

	Microscope objectives (with F200 mm tube lens)						6x zoom (0.57X to 3.6 x)	
	2 X	5 X	5 X	7.5 X	10 X	20 X	.5 X	.5 X
Objective			**HR**				**.285 X**	**1.80 X**
							Zoom 6x	Zoom 6x
							Mini	*Maxi*
NA	0.055	0.14	0.21	0.21	0.28	0.42	0.010	0.059
Lead glass shield thickness (mm)	4	4	3	4.5	4.5	3	4	4
CMOS FASTCAM Mini UX100								
(1280x720 pixels 10x10µm - Detector diagonal= 14.686mm)								
Hor. Object field (mm)	6.40	2.56	2.56	1.71	1.28	0.64	44.91	7.11
Vert. Object field (mm)	3.60	1.44	1.44	0.96	0.72	0.36	25.26	4.00
Diag, field of view (mm)	***7.34***	***2.94***	***2.94***	***1.96***	***1.47***	***0.73***	***51.53***	***8.16***
Object H&V pixel size (µm)	5.00	2.00	2.00	1.33	1.00	0.50	35.09	5.56
Oversampling ratio(obj res/pix size)	*1.2*	*1.2*	*0.8*	*1.2*	*1.2*	*1.6*	*2.1*	*2.2*
Vignetting free detector diameter	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
+/- Depth of focus (µm) - (@550nm)	136	21	11	9.4	5.3	2.2	4504	128
							(*): Vignetting free detector	
sCMOS PCO Edge 5.5							diameter for zoom :	
(2560x2160 pixels 6.5x6.5µm - Detector diagonal= 21.772mm)							2194x1890 pixels	
Hor. Object field (mm)	8.32	3.33	3.33	2.22	1.66	0.83	50.04	7.92
Vert. Object field (mm)	7.02	2.81	2.81	1.87	1.40	0.70	43.11	6.94
Diag, field of view (mm)	***10.89***	***4.35***	***4.35***	***2.90***	***2.18***	***1.09***	***66.04***	***10.46***
Object H&V pixel size (µm)	3.25	1.30	1.30	0.87	0.65	0.33	22.81	3.61
Oversampling ratio(obj res/pix size)	*1.9*	*1.8*	*1.2*	*1.8*	*1.8*	*2.5*	*3.2*	*3.5*
Vignetting free detector diameter	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100% (*)*	*100% (*)*
+/- Depth of focus (µm) - (@550nm)	120	19	9.3	8.3	4.7	1.9	3890	111

Optique Peter
OPTICAL & MECHANICAL ENGINEERING

Optically coupled X-Ray imaging systems,
from microscopy to macroscopy

Thank you for your attention

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