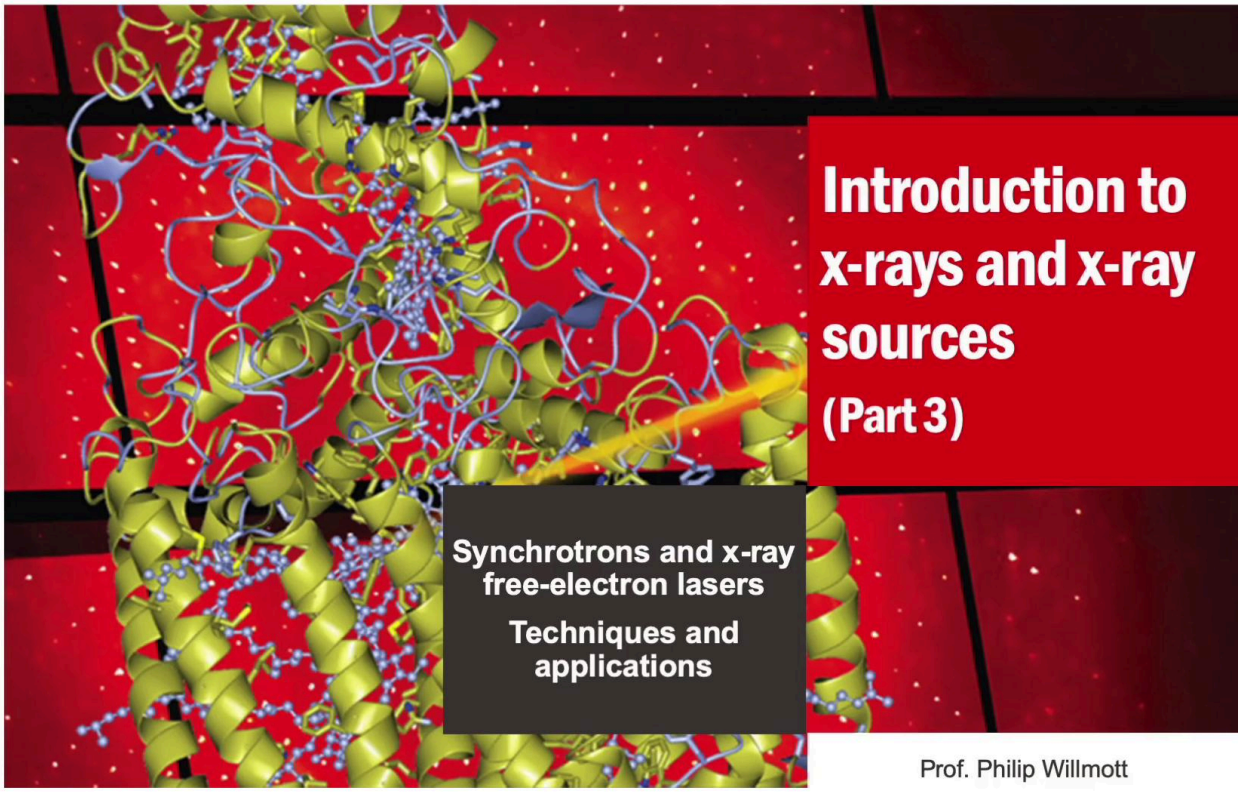
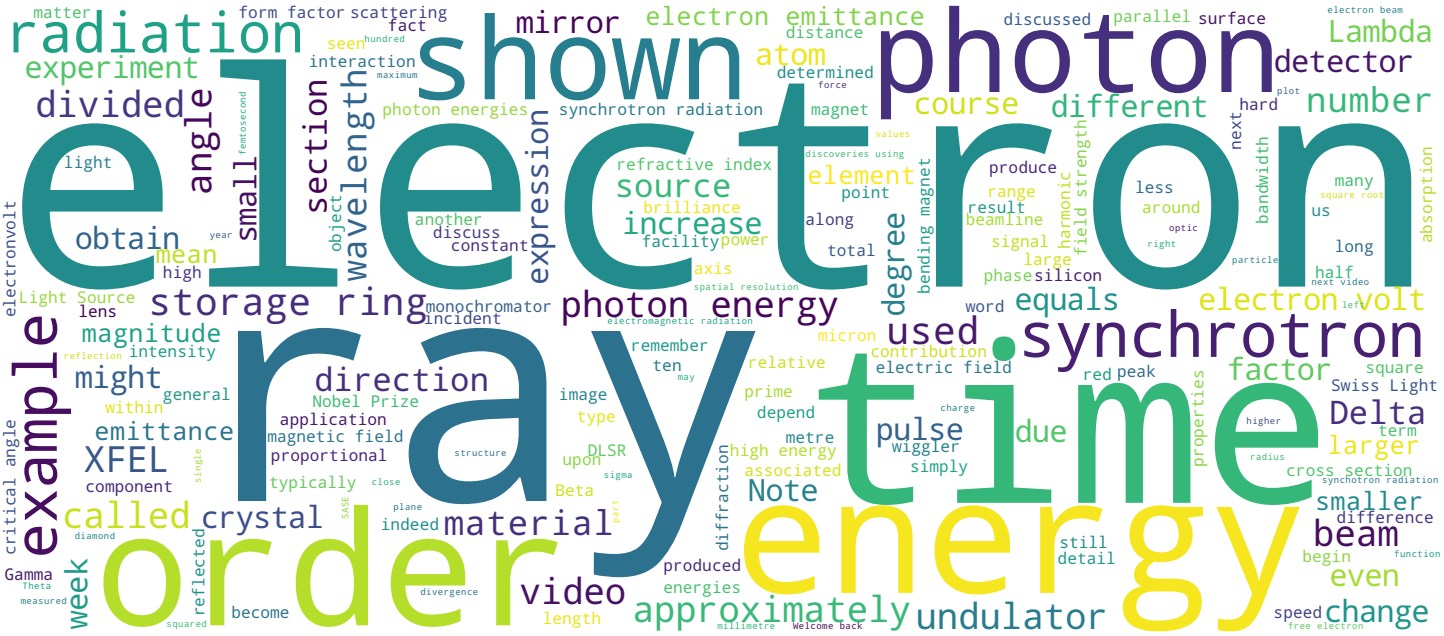


École polytechnique fédérale de Lausanne

Prof. Philip Willmott



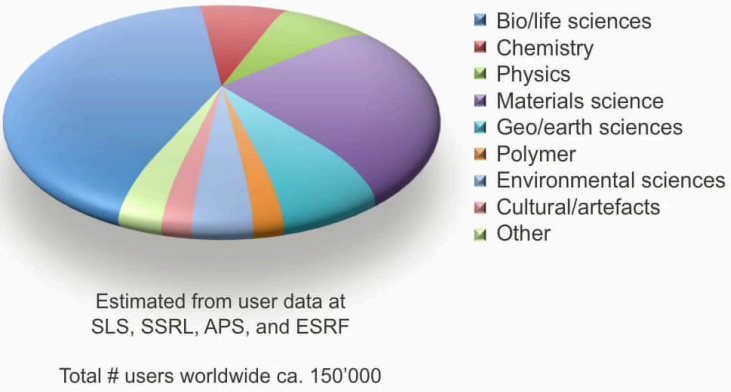
In this video we will see who might use synchotrons as part of their arsenal of research tools, and where they might best achieve their scientific goals. This is followed by a brief history of seminal scientific breakthroughs using X-rays that resulted in Nobel Prizes, and some teaser highlights of recent scientific discoveries using EXFELs and synchrotrons.

Notes

Summary

0m 05s

Uses and users of synchrotron light



Estimated from user data at
SLS, SSRL, APS, and ESRF

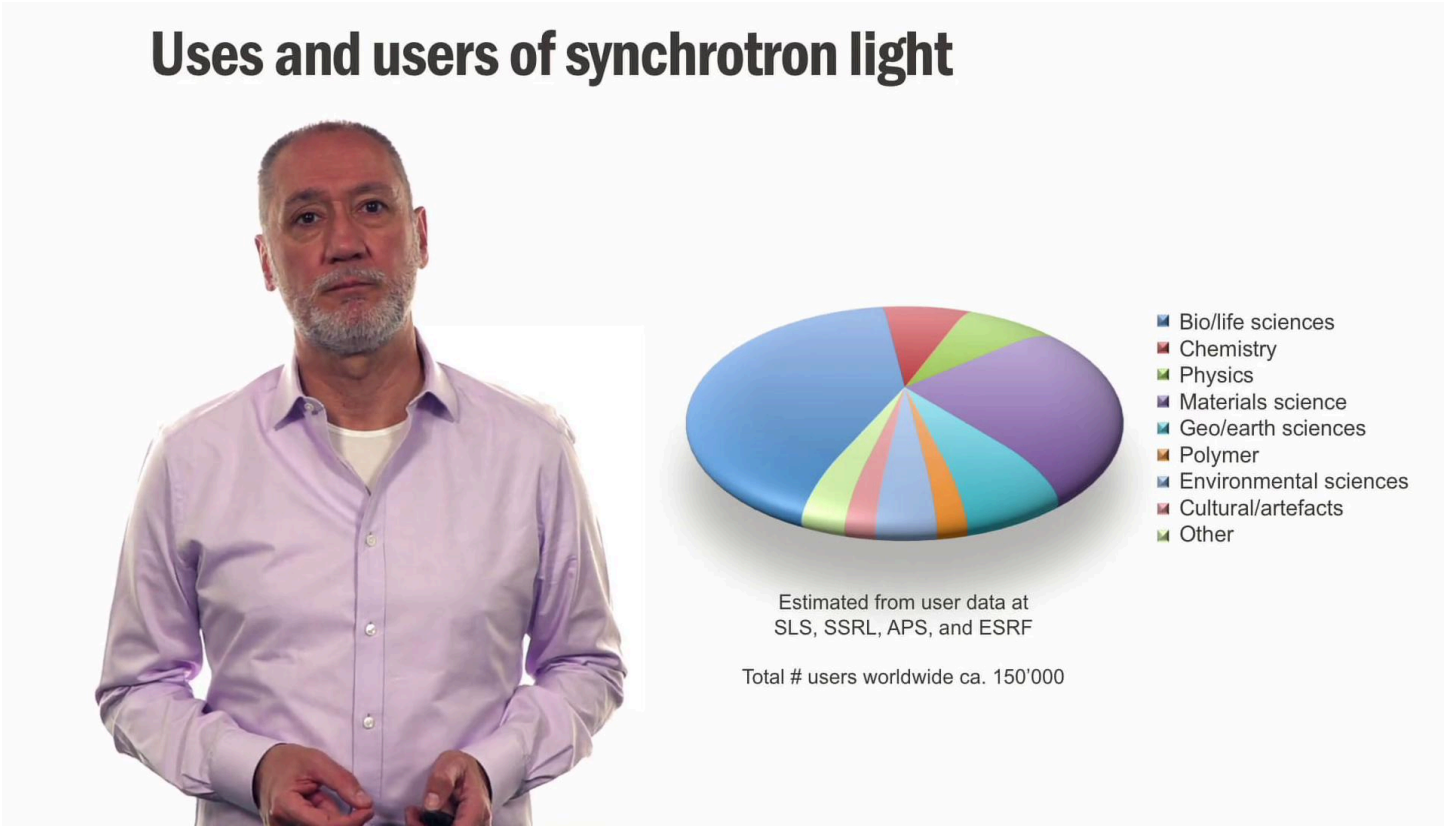
Total # users worldwide ca. 150'000

The first generation of synchrotron users was sometimes referred to as parasitic, reflecting perhaps the perception of the primary users of these facilities towards these interlopers, as the synchrotrons were primarily designed for high-energy or nuclear physics experiments. These parasitic users were overwhelmingly physicists, with a small fraction of adventurous physical chemists. As synchrotron facilities have developed, and being constructed to explicitly generate intense beams of X-rays, they have over the years attracted an ever-broader spectrum of disciplines from the natural sciences, engineering, and medicine. This widespread range of applications of X-rays represents perhaps the principal example of multidisciplinary research. Nowadays, although physicists and chemists continue to profit handsomely from synchotron's research, many other fields, most notably in the life sciences, enjoy the manyfold insights that synchotron radiation can offer. The pie chart shown here was collated from data over four years from 2013 to 2016 at the Swiss Light Source, the Stanford Synchotron Radiation Facility, the Advanced Photon Source, and European Synchrotron Radiation Facility.

Notes

Summary

0m 30s



It is my belief that this diversity of applications would be further expanded if (A) the power of synchotron science were more effectively disseminated to the wider community, and (B) those contemplating using synchotron light were not so intimidated by the perceived complexity of this powerful tool. One of the primary aims of this course is to tackle both of these obstacles.

Notes

Summary

1m 51s

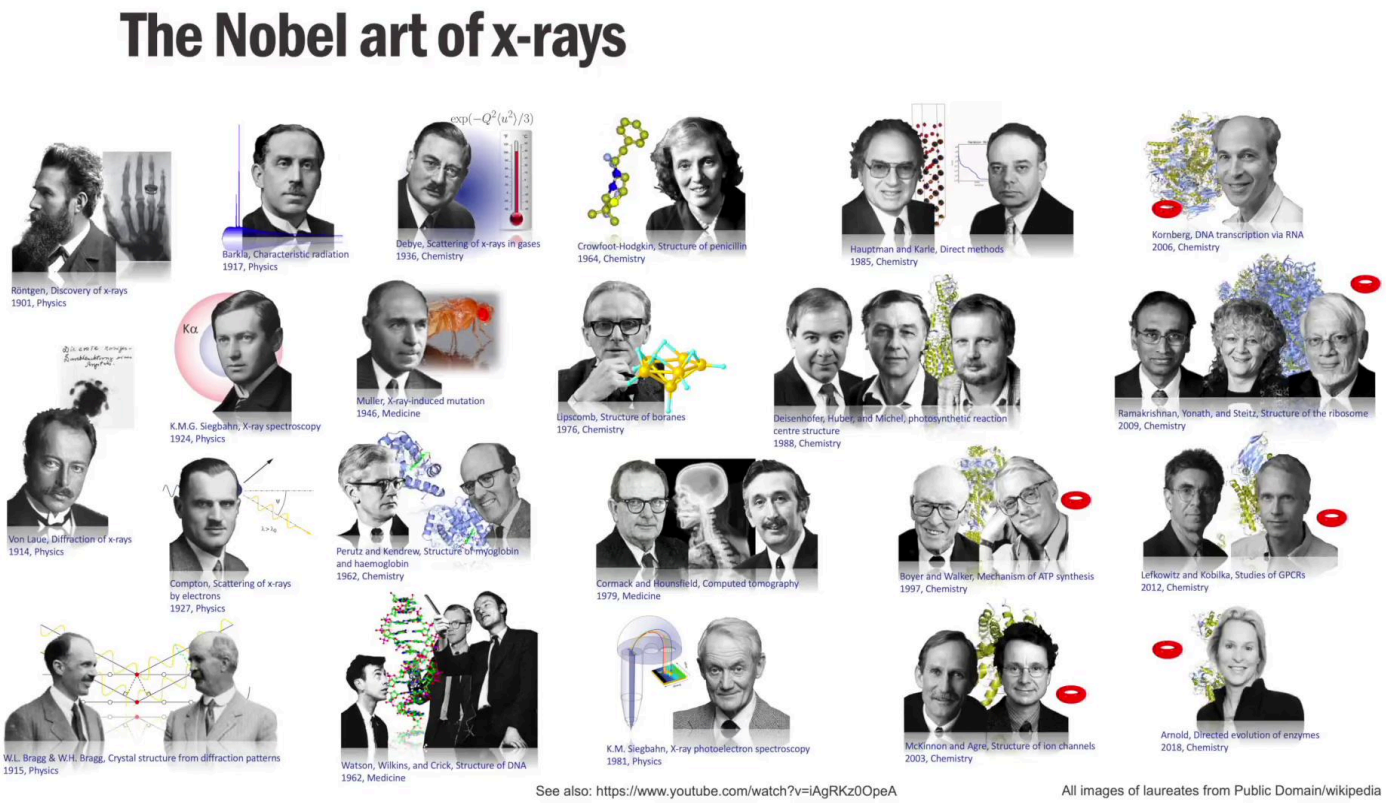
Synchrotrons and XFELs around the world

There are some 50 synchrotron and EXFEL facilities worldwide, either in operation or under construction. The location of prominent examples are shown on this world map. Synchotrons in gold, EXFELs in red. Any one facility will have a range of expertise and scientific specialities, though no one facility will cover all possibilities. The types of experiments carried out at any one facility will, to a large extent, be dictated by the energy of the electrons in that synchrotron storage ring. Low-energy storage rings tend to concentrate on soft X-ray experiments, while high-energy storage rings serve experiments that use so-called hard X-rays.

Notes

Summary

2m 16s



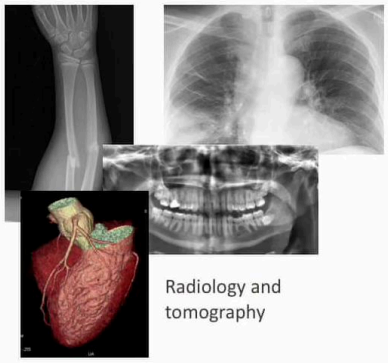
The impact of X-rays and synchrotron light on society is reflected in the number of Nobel Prizes that had been awarded in this field. Shown here are the 22 recipients of Nobel Prizes awarded in the field of X-ray research since the first Nobel Prize in Physics was rewarded to Wilhelm Röntgen for his discovery of X-rays. There is a plethora of information here and I'll leave it to you to discover these tour de force at your own leisure. You can also look at the link provided at the bottom. Note that the six most recent prizes, labelled with red rings and dating from 1997 onwards, all use synchotron radiation to obtain their X-ray data.

Notes

Summary

3m 06s

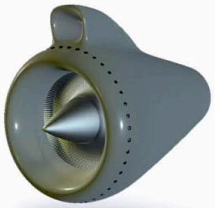
X-rays in modern society



Radiology and tomography

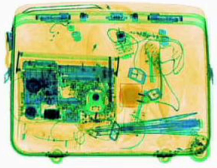
Radiation therapy

Cultural heritage

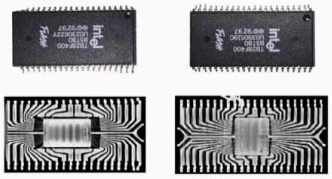


Aeronautics industry

Drug discovery



Border security



Tackling industrial counterfeiting

X-rays also play an everyday role in modern society. Very few of us have not been X-rayed at the dentist or in a hospital. Approximately 100 million CT scans were performed in the US alone in 2019. That's one scan for every three to four people. X-rays are not just used in medicine to identify broken bones or cardiovascular conditions, but are also employed actively in a therapeutic role in radiation therapy. Moreover, they are used, not least synchatrons, to identify and determine the atomic structure of compounds that are effective in combating disease in the extremely important activity of drug discovery. X-rays are used in industry for quality assurance in the aeronautical and automotive industries, and in tackling industrial counterfeiting, for example, in the semiconductor industry. We have all had our hand baggage checked at airports. Perhaps, however, fewer of us realise that X-rays are used extensively in cultural heritage in order, for example, to uncover the provenance of prehistoric artefacts and the materials and processes that were used in their construction, to determine causes for the failure in preservation techniques used to salvage historically significant warships, to identify works of art that may have been painted over, and even to identify the colour of feathers of avian dinosaurs from their fossil remains.

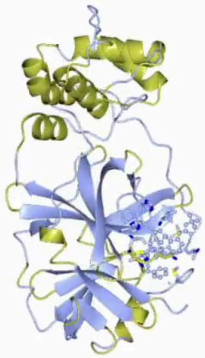
Notes

Summary

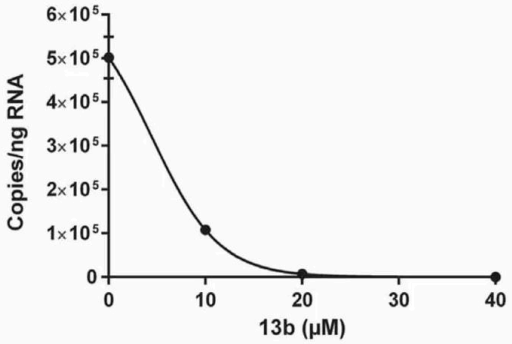
3m 50s

Recent highlights of synchrotron science

COVID-19 protease
w/o 13b α-ketoamide inhibitor



COVID-19 protease
with 13b α-ketoamide inhibitor



Crystal structure of SARS-CoV-2 main protease – a basis for design of improved inhibitors
Protein crystallography
Beamline BL14.2 of BESSY

Zhang *et al.*, Science 368: 409-412 (2020). doi:10. 1126/science.abb3405
See also: https://www.youtube.com/watch?v=KOchIPVUE_E

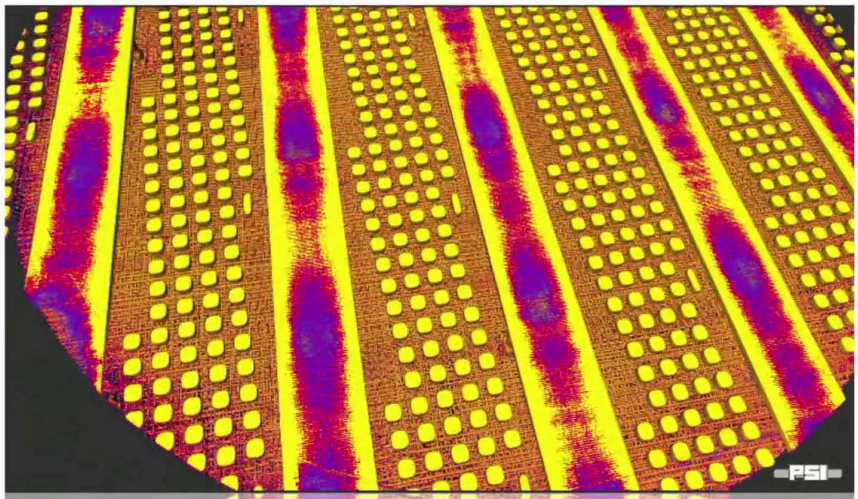
We now look at some recent highlights of synchrotron-based X-ray science, beginning with research on potential drugs to inhibit the spread of the COVID-19 coronavirus within the lungs of a human body. The researchers in this example, who used hard X-ray synchotron light at the BESSY facility in Berlin, targeted the main protease of the virus, as it is an essential enzyme for processing the polyproteins that are translated from the viral RNA. Inhibiting the biochemical activity of this protease was shown to be highly effective, even for 10 or 20 micromolar concentrations. Note that this research was published within a month of lockdown in Germany in early 2020, exemplifying the crucial role played by synchotron science in modern society.

Notes

Summary

5m 28s

Recent highlights of synchrotron science



3D architecture of semiconductor chip with 19 nm resolution
Ptychographic laminography
cSAXS beamline, Swiss Light Source

Holler *et al.*, Nature Electronics 2: 464-470 (2019). doi:10.1038/s41928-019-0309-z
See also: https://www.youtube.com/watch?v=uWHxggc-O94

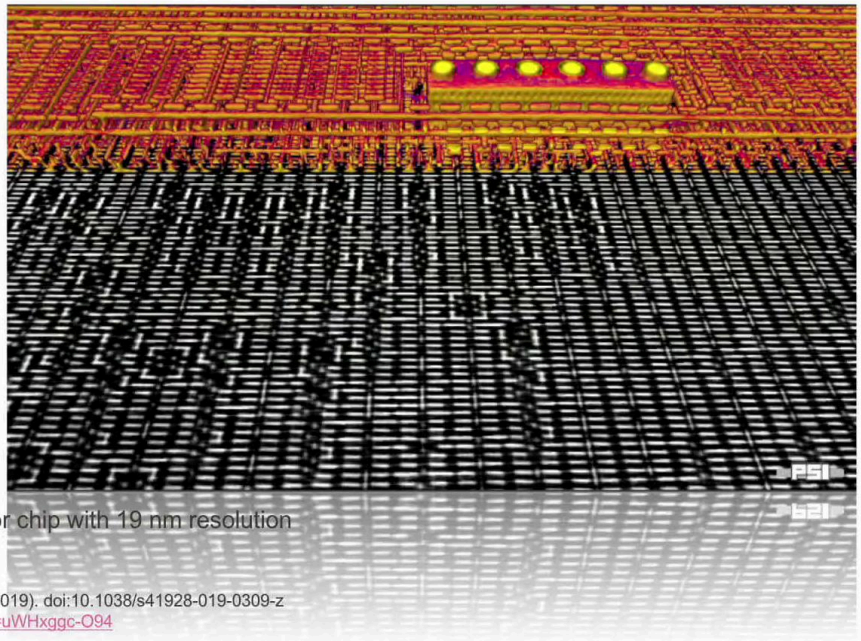
Our next example uses an X-ray imaging technique called ptychographic X-ray laminography, which is a bit of a mouthful, so we often call it PyXL.

Notes

Summary

6m 26s

Recent highlights of synchrotron science



3D architecture of semiconductor chip with 19 nm resolution
Ptychographic laminography
cSAXS beamline, Swiss Light Source

Holler *et al.*, Nature Electronics 2: 464-470 (2019). doi:10.1038/s41928-019-0309-z
See also: https://www.youtube.com/watch?v=uWHxggc-O94

This variant of so-called lensless imaging is used for flat objects for which one dimension is much smaller than the other two, such as in leaves, or here, a semiconductor chip. Using PyXL, researchers at the Swiss Light Source were able to non-destructively image the 3D architecture of a modern integrated circuit chip down to a resolution below 20 nanometers, and over hundreds of thousands of cubic microns of the chip.

Notes

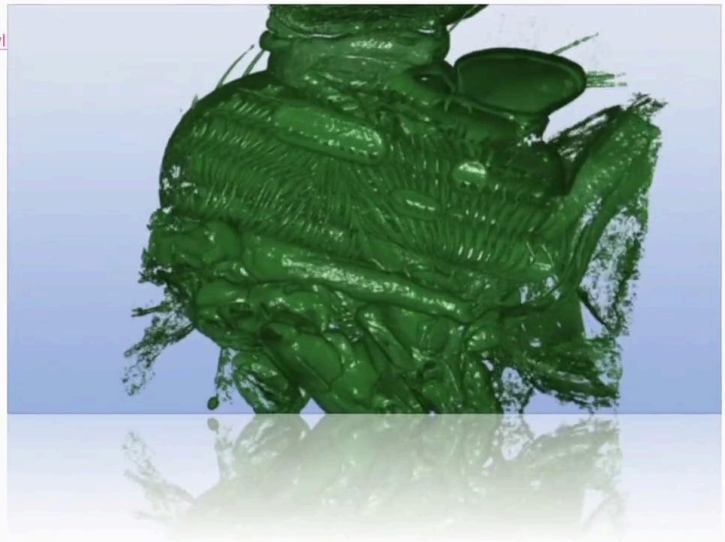
Summary

6m 41s

Recent highlights of synchrotron science

Flight muscles of a blowfly in vivo studies
Phase-contrast x-ray computed tomography (XTM)
TOMCAT beamline, Swiss Light Source

Walker *et al.*, PLoS Biol **12**: e1001823 (2014).
doi:10.1371/journal.pbio.1001823
See also: https://www.youtube.com/watch?v=yl



In a second imaging study from the Swiss Light Source, the flight muscles of live blowflies during the beating of their wings were visualised with micron spatial resolution, and an effective frame rate of 2,500 Hz.

Notes

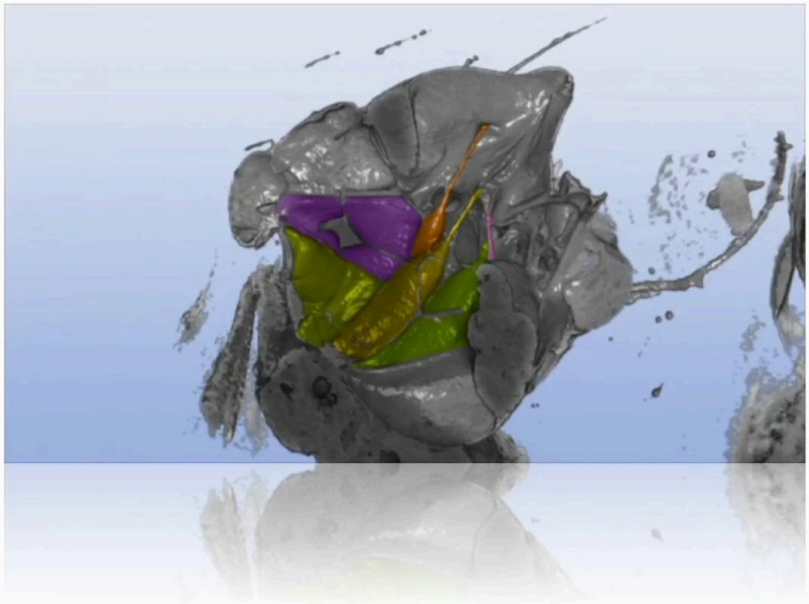
Summary

7m 07s

Recent highlights of synchrotron science

Flight muscles of a blowfly in vivo studies
Phase-contrast x-ray computed tomography (XTM)
TOMCAT beamline, Swiss Light Source

Walker *et al.*, PLoS Biol **12**: e1001823 (2014).
doi:10.1371/journal.pbio.1001823
See also: https://www.youtube.com/watch?v=yIKl_JMrYuE



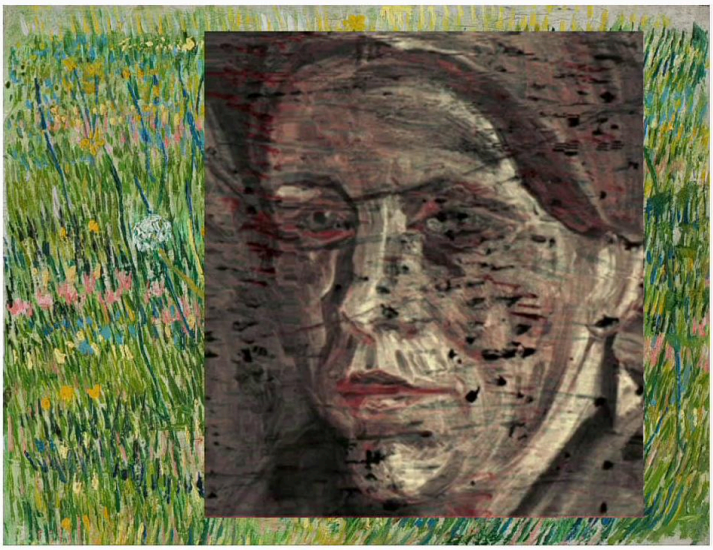
The fly was seen to control each wing beat, using numerous tiny steering muscles, some as thin as a human hair.

Notes

Summary

7m 22s

Recent highlights of synchrotron science



Hidden painting by van Gogh
Scanning x-ray fluorescence (XRF)
DORIS beamline L, HASYLAB

"Patch of Grass", van Gogh, 1887

Dik *et al.*, Anal. Chem. 80: 6436 (2008). doi: 10.1021/ac800965g
See also: https://www.youtube.com/watch?v=d0sial4qin4

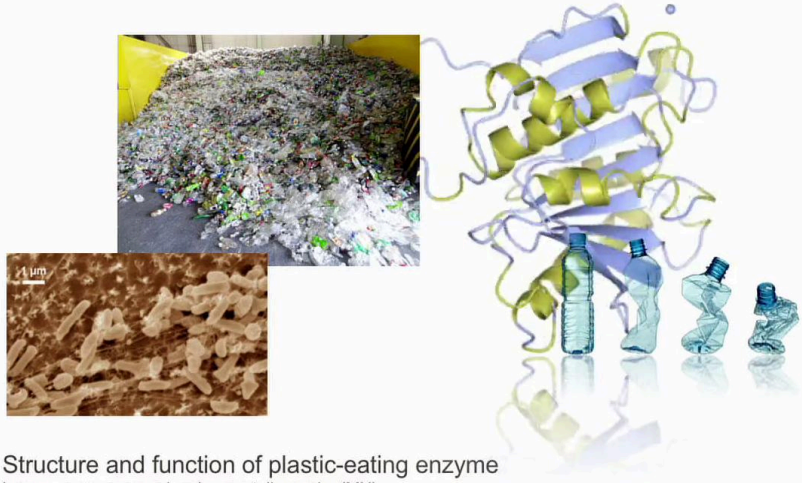
This next example beautifully illustrates the use of X-rays in cultural heritage. Most of Vincent van Gogh's paintings are from the last two to three years of his life, and there is a lack of examples from his earlier oeuvre, which, due to poverty, he often painted over. Shown here is the hidden portrait of a peasant woman's head under a later painting, Patch of Grass, revealed using scanning X-ray spectroscopy.

Notes

Summary

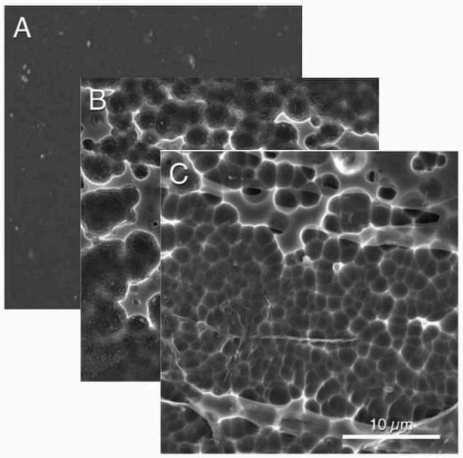
7m 31s

EPFL Recent highlights of synchrotron science



Structure and function of plastic-eating enzyme
Low-energy macromolecular crystallography (MX)
I23 beamline, Diamond Light Source

"PETase"



Austin *et al.*, Proc. Nat. Acad. Sci. USA 115: E4350 (2018). doi: 10.1073/pnas.1718804115
See also: https://youtu.be/rtZs-MPFcHo

The deleterious impact of waste and microplastics on the environment is well-documented, and one of the most pernicious problems in our environment today. One of the most detrimental and ubiquitous plastics is polyethylene terephthalate, or PET, which until the discovery of a bacterium that catalyses the hydrolysis of PET in 2016, seen not to decompose at all. The enzyme produced by the bacterium responsible for PET decomposition, which was named Petase, was determined by synchotron-based crystallography, from which a mutant version was developed in 2018. This decomposes PET at a significantly higher rate still than the native Petase. This is potentially a very important step in bio-based plastics recycling.

Notes

Summary

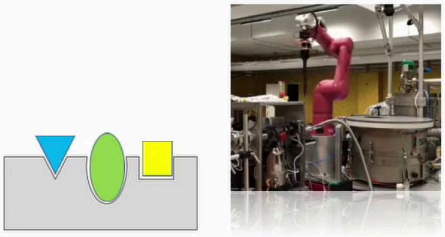
8m 00s

Recent highlights of synchrotron science

Battery failure processes revealed
Nanotomography and X-ray Absorption Spectroscopy (XAS)

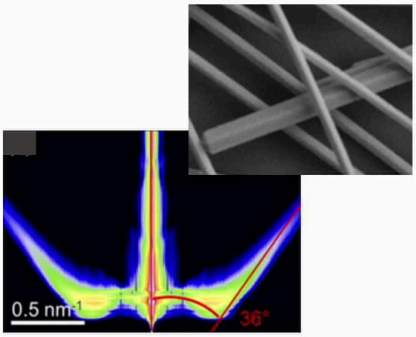
ESRF and SSRL, SLAC

Yang *et al.*, Advanced Energy Materials 9: 1900674 (2019).
doi: 10.1002/aenm.201900674



Rapid fragment screening for new pharma products
Macromolecular crystallography (MX)
X06SA beamline, Swiss Light Source

Huang *et al.*, Nature Comms. Biology 1: 124 (2018).
doi: 10.1038/s42003-018-0123-6



Fabrication and behavior of 3D-printed transparent conductors
GISAXS
P03 beamline, PETRA III, DESY

Glier *et al.*, Scientific Reports 9: 6465 (2019).
doi: 10.1038/s41598-019-42841-3

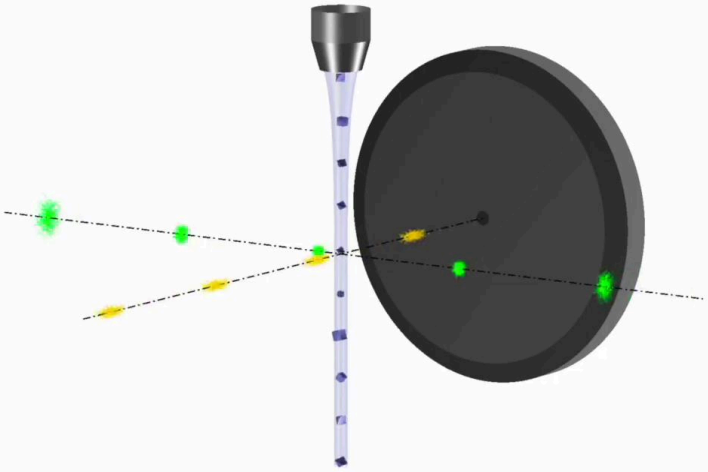
Other exciting discoveries using synchrotron radiation include an optimised catalytic process to remove NOx compounds in exhaust fumes, the identification of toxic compounds that build up in lymph nodes as a result of tattooing, the understanding and possible solutions to the unexpected decomposition of the Vasa warship on display in Stockholm, the processes responsible for battery ageing and failure, high-turnover screening of potential compounds for novel pharmaceutical products, and the fabrication and behaviour of 3D printed transparent conductors used for displays.

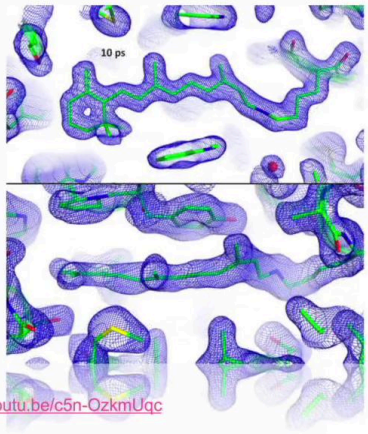
Notes

Summary

8m 56s

Recent highlights of XFEL science





How life senses light
Molecular movies of retinal in rhodopsin
Serial femtosecond crystallography (SFX)
CXI beamline, Linear Coherent Light Source

Nogly *et al.*, Science 361: 145 (2018). doi: 10.1126/science.aat0094

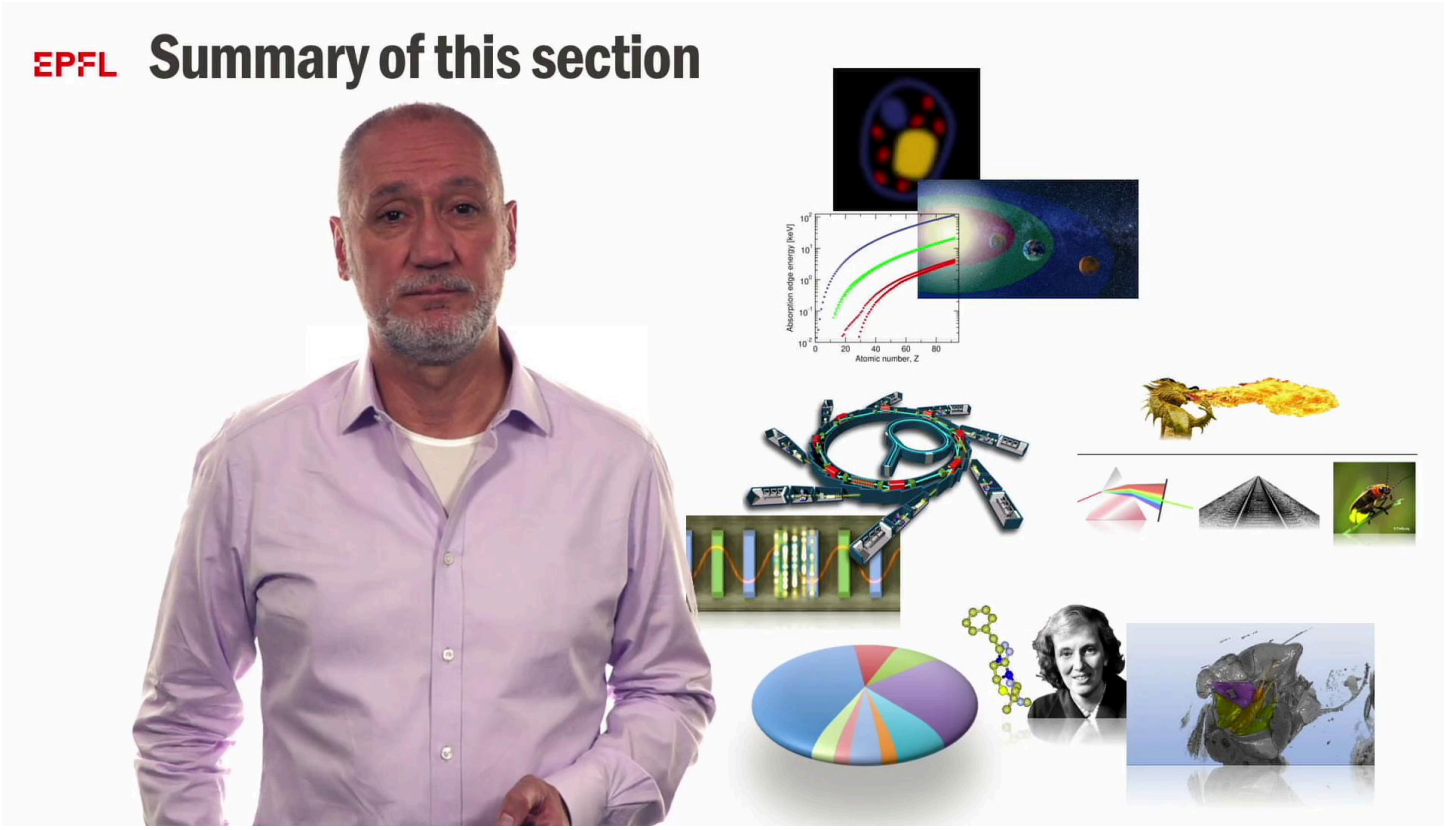
See also: https://youtu.be/c5n-OzkmUqc

EXFEL science is still very much in its infancy, but already time-resolved studies in the peak of second regime are revealing how life senses light, among many other exciting insights.

Notes

Summary

9m 43s



To summarise the three videos of this first section, we first discussed the properties of X-rays, which make them so useful as a scientific tool, including their short wavelength, which permits high spatial resolution imaging, their relative but not too extreme transparency, and the fact that they can probe specific electrons and thus also bond types, allowing the investigation of many physical chemical properties. The general architecture of synchatrons and XFELs was then introduced, plus the figure of merit known as brightness or brilliance. In the last part, we looked at who might be tempted to use synchrotrons and/or XFEL radiation in their research programme, and reviewed both some of the most historically significant discoveries using X-rays, and some recent highlights from the world of synchrotrons and XFELs. In the second section of this week, we will discuss basic concepts behind electromagnetic radiation in general, and X-rays in particular, including the different types of interaction and how strong these are.

Notes

Summary

9m 58s