Evolution of Photon Sources

Caterina Biscari

ALBA Synchrotron

Crab Nebula (www.en.wikipedia.org/wiki/Pulsar)
Electromagnetic radiation

Produced by accelerated e-beams
The first synchrotron light

This 300 MeV electron synchroton at the General Electric Co. at Schenectady, built in the late 1940s. The photograph shows a beam of synchrotron radiation emerging.

E. Wilson, Accelerator theory, 7-12-2011
Producing the synchrotron light

electrons accelerated to almost velocity of light and introduced in a magnetic field are bent and emit photons covering a wide range of wavelengths depending on e- energy + magnetic field strength
Interaction of light with matter

Photons and electrons produced by the interaction carry information on matter structure and composition.

"The usefulness of synchrotron light is limited only by our imagination"
Sir Gustav Nossal

Figure 2.1 The interaction of x-rays with matter. Surface (and interface) regions of a solid or liquid material are characterized by physical properties and structures that may differ significantly from those of the bulk structure. The x-rays may be elastically or inelastically scattered, or absorbed, in which case electrons or lower-energy photons can be emitted. If none of the above occur, the photon is transmitted through the sample.

From ‘An Introduction to Synchrotron Radiation’ Philip Willmott
Brightness

$$B(\lambda) \propto \frac{F(\lambda)}{\left(\epsilon_{x,e^-} \otimes \epsilon_r(\lambda)\right) \left(\epsilon_{y,e^-} \otimes \epsilon_r(\lambda)\right)}$$

Photon flux [photons/s/0.1% bw]

$A_s = $ Cross section of electron beam

Emittance (size and divergence)

The brilliance represents the number of photons per second emitted in a given bandwidth that can be refocused by a perfect optics on the unit area at the sample.
Storage ring spectral brilliance (brightness)

1st Generation
parasitic operation in colliders, bending magnets

2nd Generation
dedicated sources from bending magnets, high flux

3rd Generation
DBA, TBA lattices with straight sections for wigglers and undulators, high brilliance

4th Generation
emittance reduction with MBA lattices, high performance IDs, high coherent flux

From Liu Lin, LNLS, IPAC17
The latest generations of storage rings

\[ \epsilon_0 \propto \frac{\gamma^2}{N_B^3} \]

Adapted from R. Bartolini
Achieving low emittance with MBA

Emittance depends on optics at places where radiation is emitted (dipoles).

Double bend achromat - DBA

Multiple bend achromat – MBA
many small dipoles to keep horizontal focus in each dipole

From Liu Lin, LNLS, IPAC17
**From 3\textsuperscript{rd} generation of beginning of century to USR**

**ALBA**
2011 1\textsuperscript{st} beam
3 GeV
C = 269 m
$\varepsilon = 4.6 \text{ nm}$

Increase C x 3
Lower $\varepsilon$ x 3

**NSLS II**
2014 1\textsuperscript{st} beam
3 GeV
C = 792 m
$\varepsilon = 1.5 \text{ nm}$

**MAX IV**
2015 1\textsuperscript{st} beam
3 GeV
C = 528 m
$\varepsilon = 0.3 \text{ nm}$

MBA*
Increase C x 2
Lower $\varepsilon$ x 10

*MBA: Multi Bend Achromats

(Photos approximately in scale)
The evolution of light source technologies in a single lab

**MAX I**
- Energy: 0.55 GeV
- Length: 32 m
- Year: 1986

**MAX II**
- Energy: 1.5 GeV
- Length: 96 m
- Year: 1997

**MAX III**
- Energy: 0.7 GeV
- Length: 36 m
- Year: 2008
MAX IV
3.0 GeV
1.5 GeV
2017
\( \varepsilon = 300 \text{pm} \)
MAX IV
3.0 GeV
1.5 GeV
2017
ε = 300pm
The evolution to DLSR or USR (Diffraction Limited or Ultimate Storage Rings)

Even in the limit of zero beam emittance the phase space of the radiation emission from an undulator is itself finite due to diffraction effects at the source. For single-mode photon emission, the corresponding diffraction-limited ‘emittance’ of the photon beam is given by

$$\varepsilon_{\text{photon}} \leq \frac{\lambda}{4\pi} = 0.159\lambda = 98.66[\text{pm rad}] / E_\gamma[\text{keV}]$$

A light source is referred as ‘diffraction limited’ when the e beam emittance is less than that of the radiated photon beam at the desired X-ray wavelength.
Storage rings going brighter by
Making very low emittances:

ESRF: brighter beams by 2020

Other facilities planning upgrades
Tunability, polarization

\[ K = \frac{e}{2\pi m_o c} B_o \lambda_u \]

Tuning ID magnetic field and orientation, and playing with beamline optical elements large range of photon energy and polarization are available.
Evolution of Photon Sources

1. Linear accelerator
The electrons are generated and subjected to an initial acceleration.

2. Booster synchrotron
The electrons accelerate and cross open in the booster, until reaching speeds close to the speed of light.

3. Storage ring
The electrons are stored in the outer ring, guided by magnetic fields.

4. Synchrotron light
On crossing through the magnets, the electrons emit energy in the form of synchrotron light, which is sent to the beamlines.

5. Selection of wavelength
The synchrotron light contains numerous wavelengths, and a monochromator is used to select the most suitable one for each experiment.

6. Detector
The sample to be analyzed is illuminated, and a detector captures the interaction of the sample with the light.

7. Data analysis
The data are stored and analyzed.
Life science, among others...

- Protein characterization
- Imaging of biological structures at cell dimensions
- Single-cell analysis, tissue analysis and bacterial identification
- Study of human and animal tissues and their reaction to drugs
- Drug development
- Food science
- Cosmetics
- Study of effects of nanomedicine in tissues
Material science, among others...

- Magnetic properties of material (see figure of skyrmions)
- Development of new catalysts
- Characterization of material for energy transfer and storing
- Soil analysis
- Chemical properties of new materials
- Mineralogical research
- Geochemistry of organic matter and minerals in geological samples
- Analysis of thin films
- Engineering material properties
- Communication technology materials
- Cultural heritage material characterization
Nobel Prices for research using SL

1997 - Chemistry to Boyer and Walker
2003 - Chemistry to Agre and MacKinnon
2006 – Chemistry to Kornberg
2009 - Chemistry to Ramakrishnan, Steitz and Yonath
2012 - Chemistry to Lefkowitz adnd Kobilka
2013 – Medicine to Rothman, Schekman and Südhof
2013 – Chemistry to Karplus, Levii and Warshel

Dr. Peter Doherty, Nobel prize of Medicine: “Synchrotron light is presently fundamental for 80% of research and development of drugs”
ALBA Synchrotron

National public institution with 50% national + 50% regional funding (MINECO and GenCat Ministry of Research University and Industry)

National and international (21%) staff
National and international (35%) users
National and international collaborations
Participation to projects plus services providing extra 7-8% of income and 10% of staff
ALBA history

- **2003** Project approval
- **2006** Construction start

**Design**

**2012**
- Operation start
- Phase I: 7BLs

**Construction & commissioning**

**2014**
- Phase II construction start
- Expansion
- Operation consolidation

**2016**
- 8th BL in operation
- Phase III construction start

**2017/2020**
- Phase III evolution

**Users**

- 2011: 0
- 2012: 300
- 2013: 450
- 2014: 500
- 2015: 550
- 2016: 600
- 2017: 760
ALBA : 269 m circumference
3 GeV electrons producing synchrotron light
Competitive and free access
Public results

Academic

Joint academic and industrial

Industrial

Direct access covering operational costs
Private results
Scientific production

Yearly number of publications based on beamtime

Integrated total number of publication


200 150 100 50 0

1000 750 500 250 0
Technology Transfer

Other scientific infrastructures, national and international

Production

Innovative Designs

Industries

Evolution of Photon Sources
SESAME Members
Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, Palestinian Authority and Turkey

SYNCHROTRON-LIGHT FOR EXPERIMENTAL SCIENCE AND APPLICATIONS IN THE MIDDLE EAST -
Developed under the auspices of UNESCO

In commissioning

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Evolution of Photon Sources
IPM association

IPM (Institute for Research in Fundamental Sciences of Teheran, under which the ILSF has been created) is associated to ALBA as the first international partner, starting 1\textsuperscript{st} January 2017 with access to 1\% of beamtime, to be shared among all beamlines.

- 2009 – Project proposal
- 2010 Feasibility study project approved by government
- 2011 – Preliminary CDR – Site selection
- 2015 – Accelerator design approved (MAC)
- 2016 – Basic design start
- Technical staff: 48 in 2015, over 90 in 2016
- Developments in RF Power (SSA), magnetic measurements, magnet prototyping, BPM development

Staff training at ALBA

May 2017 – Student on impedance simulations (5 months)
- In progress for 2017
  - PhD student on BL design
  - Young researcher for beam dynamics (4 months)
  - Young researcher for Controls and Diagnostics (2 weeks)
  - Young researcher on Magnetic Measurements (2 weeks)
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2017: ~ 50 Synchrotrons in the world, serving a community of >50000 users

- In Operation
- In Commissioning
- In Construction

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Evolution of Photon Sources
ICALEPS 2017 – 09-10-17
Goals
Secure EU leadership for decades
Develop coherent Roadmap of all SR and FEL facilities in the EU

1) Strong & diverse user community
2) Best practice
3) Push & disseminate technology and innovation
4) Integration & sustainability
5) Enable excellent science
6) Next generation light sources
7) Open science

LEAPS Charter
LEAPS Strategy Document (Nov 2017)
Input to EC FP 9 2020-2026
FELs are long (km)
Undulators used to produce coherent radiation

Lasers illuminating cathodes
and producing very bright electron beams
Synchrotrons versus FELs

- Multi instrument/user facility (tens of BLs)
- High rep rate
- High stability
- Time structure defined by rf (hundreds of MHz)
- Pulse length in the psec range

- Single instrument/user facility (1/2 BLs)
- Rep rate depending on linac technology
- Time structure defined by rf
- Pulse length in the fsec range
- Brightness increased by coherent emission

Illustration of the Australian Synchrotron
Beating radiation damage: Diffraction before Destruction

Synchrotron

XFEL

Credits: www.slac.stanford.edu
Beating radiation damage: Diffraction before Destruction

Synchrotron

XFEL

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Synchrotron

XFEL

Credits: www.slac.stanford.edu
Diffraction before destruction

Possibilities of shooting at high frequencies and recording fast dynamic processes

LCLS
A Seeded Amplifier FEL

interaction with "seed" laser pulse leads to energy modulation

phase slip in undulator converts energy modulation to density modulation

particles within each microbunch radiate coherently
FERMI at Elettra (Italy)

Figure 3. Single-shot FEL spectrum at 32 nm obtained in SASE (on the left) and in HGHG (on the right) mode at FERMI. While the horizontal axis is dispersed in wavelength, the vertical axis represents the vertical distribution of the FEL intensity at the spectrometer CCD. The energy per pulse provided in SASE mode by using the optical klystron technique is about 100 micro-joules and the bandwidth is $3.3 \times 10^{-3}$. 
FUTURE
Brighter photon beams:
Smaller electron beam sizes
Higher currents
Coherence, short pulses, high intensity

Credit: P. Uvaal and A. Nyberg.
The frontier is moving ahead of us
Three examples of state of the art research with synchrotron and XFEL beams

1.- Transmission X ray microscope : cryo tomography and spectromicroscopy

2.- 3D reconstruction with Ptychography

3.- Ultra fast chemical reaction viewed with fs time resolution

Salvador Ferrer, Alba light source
X ray microscopy. Basic concepts

Resolving power of a microscope proportional to $\lambda$. Visible light $\lambda \sim 500$ nm
X rays: $\lambda \sim 2$ nm - 0.1 nm

Visible light microscopes are based on the refraction of visible light by lenses

Refractive index $n \sim 1.5$; $\sin\theta_i = n \sin\theta_f$; $\theta_i = 30^\circ$, $\theta_f = 19^\circ$

Which is the refractive index of X rays in materials?

$n (X ray) = 0.9995$ : very close to one
Fresnel Zone Plates: these are the lenses for X ray microscopy

- $\Delta r = 25$ nm
- $D = 63$ µm
- $N = 618$ zones
- $f = 650$ µm
- $NA = 0.05$

@ $\lambda = 2.4$ nm

Alternate transparent and opaque zones.
Key optical components for X ray microscopy.
Soft X rays ($\lambda = 2.5$ nm, $hv = 500$ eV) go through the sample (10 µm thick) and produce absorption contrast. Sample at low T to reduce X ray beam damage. Tomography: Acquire images at different angle (-70° to 70 ° steps of 0.1 °) : 3D reconstruction
Ultrastructural alterations of host cell during HCV infection

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DOI: 10.1021/acsnano.6b01374
Alteration of the mitochondria-ER contacts in HCV replicating cells

Control cell

HCV infected cell

HCV replicating cell

increasing mitochondria alterations
X ray absorption spectroscopy:
Absorption of X rays occurs at well defined energies characteristic of the absorbing atoms

X rays of variable energy

Fine structure: oscillations which depend on the distances from the absorbing atoms to its neighbors. (EXAFS)
A vacuole-like compartment concentrates a disordered calcium phase in a key coccolithophorid alga

Sanja Sviben, Assaf Gal, Matthew A. Hood, Luca Bertinetti, Yael Politi, Mathieu Bennet, Praveen Krishnamoorthy, Andreas Schertel, Richard Wirth, Andrea Sorrentino, Eva Pereiro, Damien Faivre2 & Andre´ Scheffel1

DOI: 10.1038/ncomms11228

Coccoliths are calcitic particles produced inside the cells of unicellular marine algae known as coccolithophores. They are abundant components of sea-floor carbonates, and the stoichiometry of calcium to other elements in fossil coccoliths is widely used to infer past environmental conditions. Here we study cryo-preserved cells using state-of-the-art nanoscale imaging and spectroscopy. We identify a compartment, distinct from the coccolith-producing compartment, filled with high concentrations of a disordered form of calcium. Our findings provide insights into calcium accumulation in this important calcifying organism.
a: top 2D slices of a coccolith (arrow head) and a Ca rich body (red arrow)  
bottom : 3D segmentation of the Ca rich body
b: X-ray images recorded at an energy below the Ca L2,3-edge (342 eV), at the edge energy (353.2 eV) and the grey value difference between both images
c: Averaged XANES spectra of the Ca L2,3-edge; the inset shows the exact locations in one of these cells
nucleus
chloroplast
coccolith in statu nascendi

Ca-rich bodies
Advantages of the method:

1. Few hundreds images is enough for 3D reconstruction. Acquisition time ~ 20-30 min.
2. Simple reconstruction algorithms

Limitations: resolution 20-30 nm limited by Zone Plate manufacturing. Not easy to improve

Future perspectives: Phase contrast imaging to enhance contrast of similarly absorbing samples
High-resolution non-destructive three dimensional imaging of integrated circuits

Mirko Holler, Manuel Guizar-Sicairos, Esther H. R. Tsai, Roberto Dinapoli, Elisabeth Müller, Oliver Bunk, Jörg Raabe & Gabriel Aeppli

doi:10.1038/nature21698 (March 2017)

It is impossible to image entire microelectronic ships non destructively since features are 3D and too small. This implies a lack of direct feedback between design and manufacturing processes and hampers quality control.

X ray ptychography, a high resolution coherent diffractive imaging technique can create 3D images of integrated circuits with resolution down to 15 nm. The experiments represent a major advance in chip inspection and reverse engineering over the traditional destructive electron microscopy and ion milling techniques.
Coherent diffraction imaging: speckles due to interferences

Ptychography: collect speckle patterns at different points of the sample with at least x2 oversampling

Ptychography at a collection of angles: tomographic Ptychography
Technique: ptychographic X-ray computed tomography (PXCT)

The speckle pattern originated from the diffraction of a coherent beam by the sample irregularities or density fluctuations is measured as a function of rotation and translation angle of the sample. The set of patterns is converted to a direct space 3D image with a resolution determined by the noise level of the patterns.

- a: cylindrical sample
- b: 6 keV beam
- 3: Fresnel ZP
- 6,7 interferometers
- 9: piezo scanner
- 10: sample
- c: diffraction pattern from a ASIC chip (1/235000)
- d: reconstructed 2D projection and scanning positions
- e: diffraction pattern from a ASIC chip
Results: ASIC chip (of PSI pixel detector)

Fraction of the chip selected: set-reset memory latch

a) ▼ : manufacturing fault in Ti layer
   ▲ : waviness of the AlTi layer

b) Axial section across the second lowest layer, which contains the transistor gates; the grey scale (top right) represents electron density (in e⁻ Å⁻³). The corresponding layer from the design file is shown as the partial overlay in yellow
22 nm technology Intel processor

- **c:** Axial slice: parallel to the plane of the chip
- **d:** Coronal slice orthogonal to c along line in c. Pitch of contacts 90 nm
- **e:** Sagittal slice orthogonal to c and d
- **f:** Sagittal slice along red arrow in d (plane of the gates)

Scale: 500 nm
Technical details:

Incoming beam 20 µm (H slit), \( \nu = 6 \text{ keV}, \frac{E}{\Delta E} = 10^4 \), field of view 16x12 µm². Beam at sample position: 4 µm

Present limitations

1.- Cylindrical samples for having constant transmission
2.- Thin (~ 10 µm) samples
3.- long time required (Intel chip: 66 s/projection x 1200 projections = 22 hours; 235000 images)

Future perspectives

1.- flat samples. Use laminography. Extended (mm²) scanning areas
2.- Increase photon energy
3.- increase of coherent flux in 4th generation facilities: \( \epsilon_x : x 1/10 \rightarrow x100 \) Coherent Flux
4.- better adapted optics: \( \frac{E}{\Delta E} = 10^3 \) and more efficient focusing: \( \rightarrow \sim x100 \)
5.- Faster detectors and continuous sample scans

Possibility of practical usage of this non destructive method for inspection of integrated circuits with 10 nm resolution.
Metalloprotein entatic control of ligand-metal bonds quantified by ultrafast x-ray spectroscopy

The protein cytochrome c (cyt c) plays a key role in e- transport and adoptosis switching function by modulating a Fe-S bond. This bond was investigated by provoking its rupture with a laser pulse and reformation with XFEL pulses. The bond strength was determined and understood.

Fe oscillates between III and II oxidation states
The loss of FeIII-S bond plays a role in aptosis.
Examples of SR & FEL research

Laser fluence optimized for maximum population of excited states

Liquid jet diam. 100 µm

Energy dispersive spectrometer

Laser Pump: 50 fs, 520 nm, 20 mJ/cm²

XAS: Si111 monochromator (1 eV res.)

XES: spectrometer

Fe 1s absorption

Fe 3d emission

3p

cyt c solution

Laser fluence optimized for maximum population of excited states
Absorption allows to determine the atomic environment of the Fe since Energy shifts of the spectra indicate change in oxidation state

The energy shift ← is due to change between 6 coordination to 5 coor.

The excited state has FeII-N bonds elongated and the loss of Fe-S bond
Emission spectroscopy senses the spin state (number of unpaired 3d e-)

Quintet ($S_{Fe}=2$)

Singlet ($S_{Fe}=0$)

The loss of the Fe-S bond is associated to a change from 0 to 4 unpaired e-

Low Spin, $S = 0$

High Spin, $S = 2$

The evolution of the spins state for different delays allows to determine their characteristics times

And its thermodynamics:

\[ \Delta H = 6.5 \pm 1.2 \text{ kcal/mol} \]

\[ \Delta S = 16 \pm 3.2 \text{ cal/(mol*K)} \]
Limitation:

By nature the pulses of the spontaneous emission FELS are chaotic (shot noise ampl.):

Longitudinal coherence properties

Temporal (top) and spectral (bottom) distributions of a single radiation pulse

$I/I_0$ normalization of XAS signals is not simple

**Advantage:** extremely high number of photons per pulse $10^{12} - 10^{13}$ photons /s

EXFEL, SASE1 at $\lambda = 1$ Å

thanks for your attention