
ESRF
The European Synchrotron

PIONEERING SYNCHROTRON SCIENCE

ESRF
The European Synchrotron

30 years of science

2019

ESRF – ILL 6th Summer School Undergraduate Students

Science at synchrotrons and the ESRF

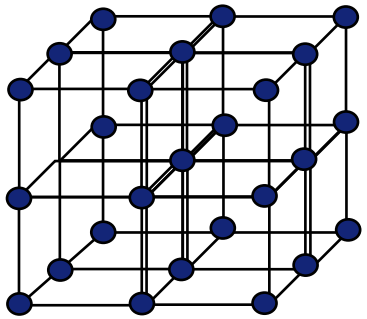
Welcome!

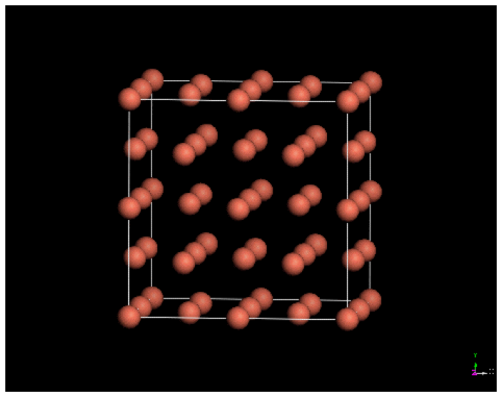
Francesco Sette

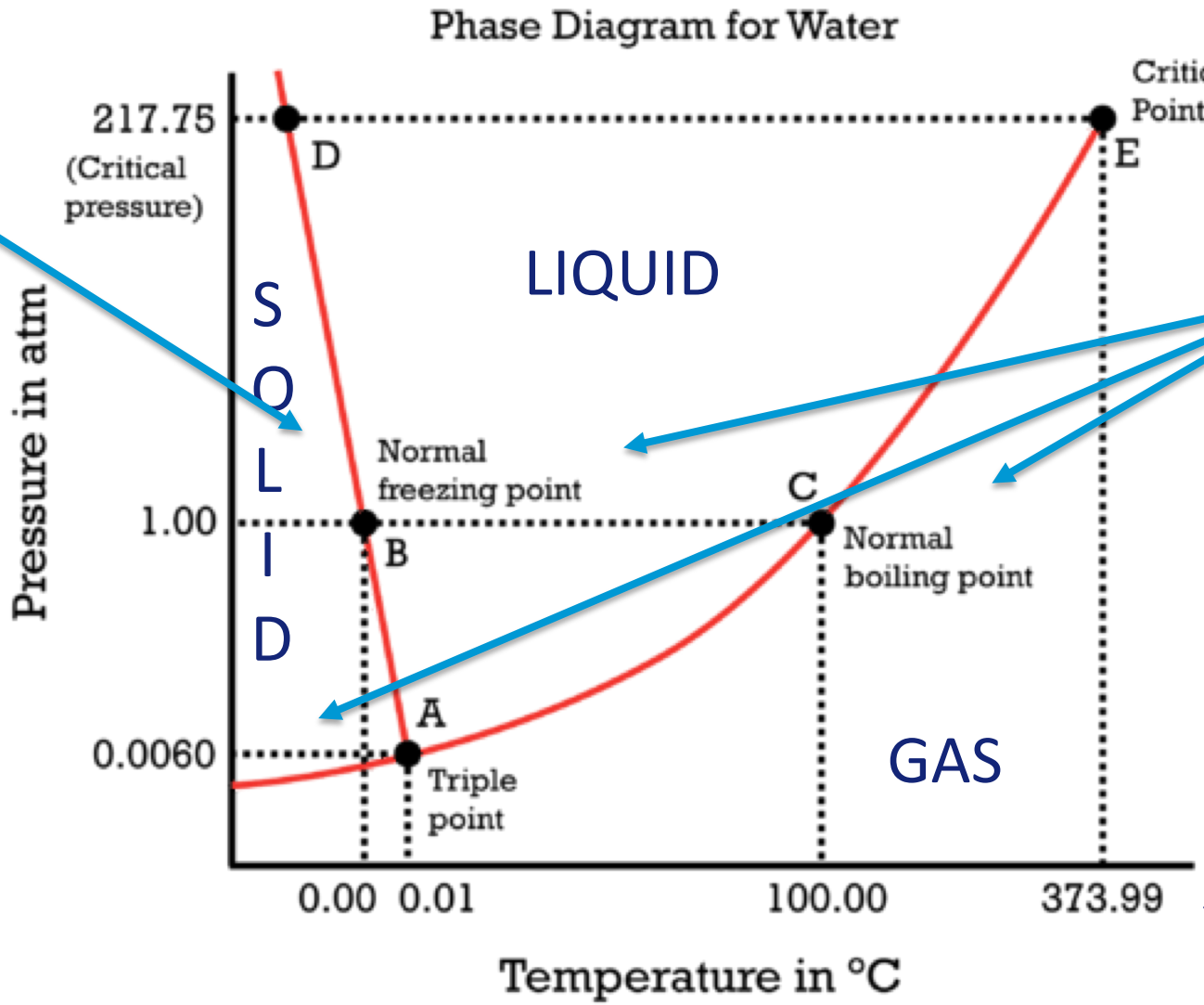
Outlook:

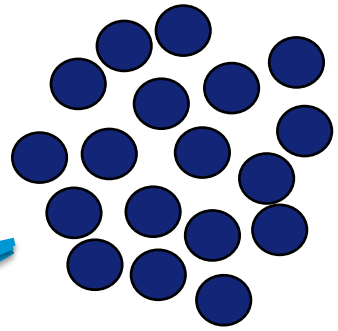
- X-ray science and the development of Synchrotron Radiation as a unique source of light
- Examples and future perspectives

Atoms – Molecules – Condensed Matter







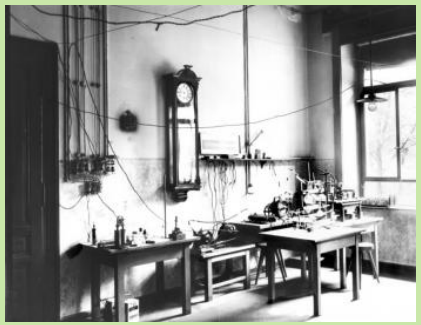


The beauty of X-rays (and neutrons):
To unveil down to atomic resolution the structure and dynamics of condensed matter – *X-rays penetration and non-destructiveness*

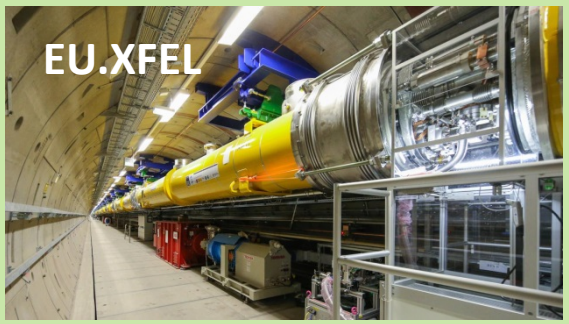
The Spectacular Success of X-ray Science

X-ray Science: Imaging, Scattering, Diffraction, Spectroscopy

1895 **2019**



W.C. Röntgen



Coherent X-ray Sources

25 Nobel prizes in Physics (14), Chemistry (12) and Medicine and Physiology (1) since the first one in 1901

Era of Crystals

1900

Structure-function-relations
Phase diagrams
Large unit cell crystals
Protein crystallography

Era of Complexity

2000

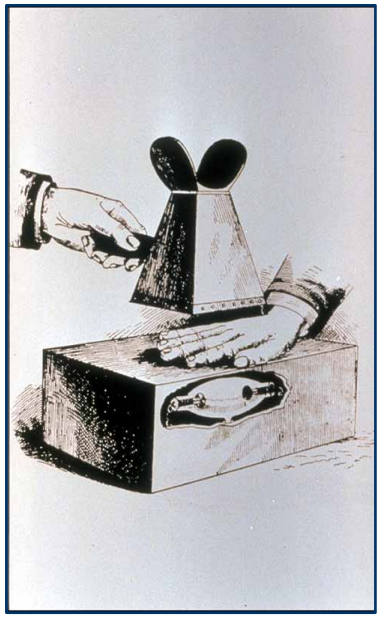
Bio- and nano-technologies
Highly correlated systems
Non-equilibrium matter

X-RAYS: DISCOVERY IN 1895 AND THE FIRST STEPS

X-rays ... some kind of unknown particles without mass and charge

Wilhelm Conrad Röntgen (1845-1923)
First Nobel Prize for Physics, 1901

The first "röntgenogram"
8 November 1895



(1895) RÖNTGEN'S EXPERIMENT

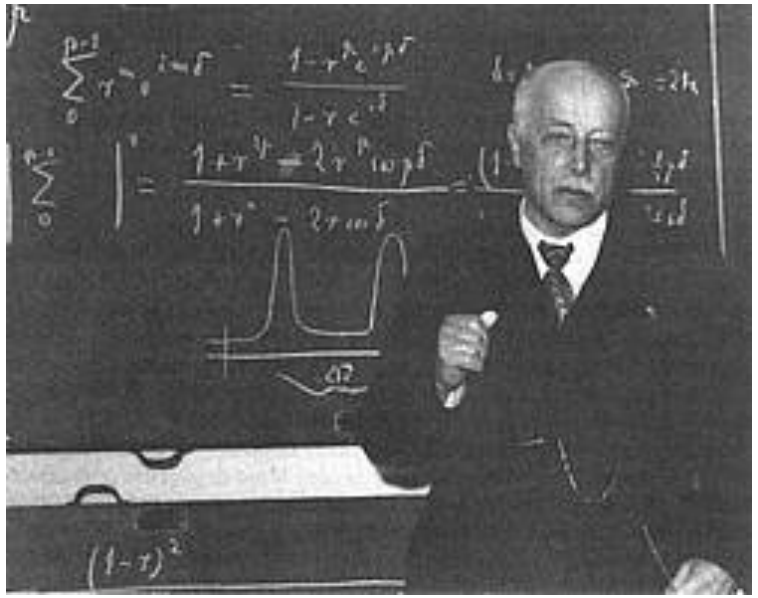
after W.C. Röntgen
Über eine neue art von Strahlen.
Phys.-Med. Ges., Würzburg, 137, (1895)
English translation in Nature 53, 274, (1896)

On a new kind of Rays

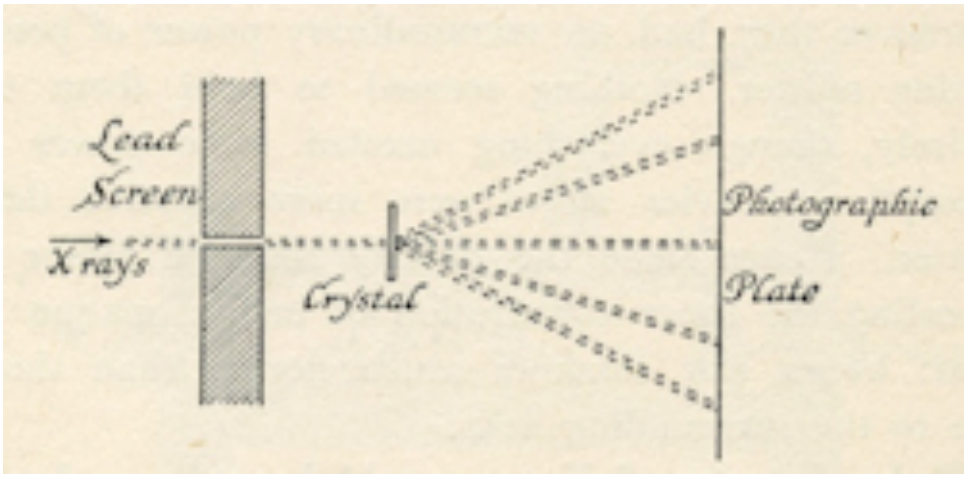
- "… A piece of sheet of aluminium, 15 mm thick, still allowed **the X-rays** (as I will call the rays, for sake of brevity) to pass …"
- "... Detection of interference phenomena has been tried without success, perhaps only because of their feeble intensity..."
- "... The refractive index ... cannot be more than 1.05 at most ... X-rays cannot be concentrated by lenses ..."
- "... Photographic plates and film are *susceptible to X-rays*, providing a valuable means of recording the effects ..."

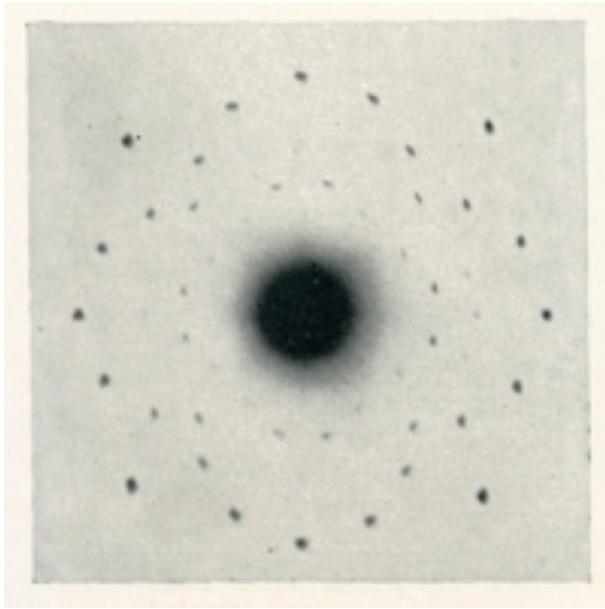
name, coherence, optics, detectors

X-rays ... some kind of waves



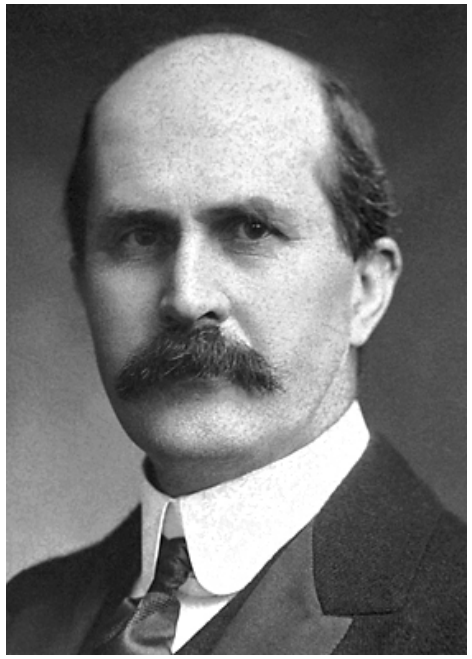
Max Von Laue (1879-1960)
Nobel Prize for Physics, 1914

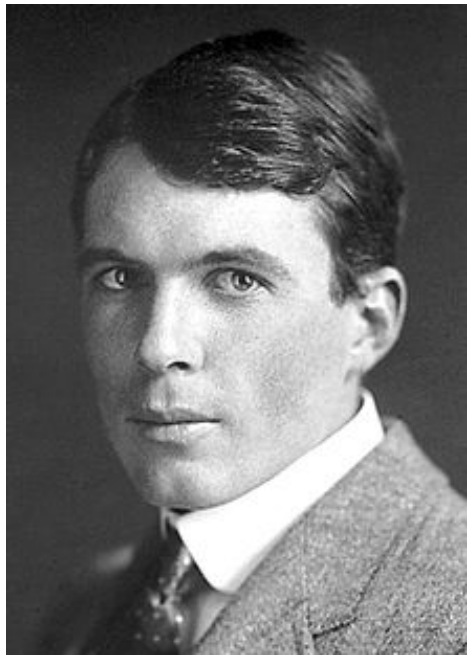


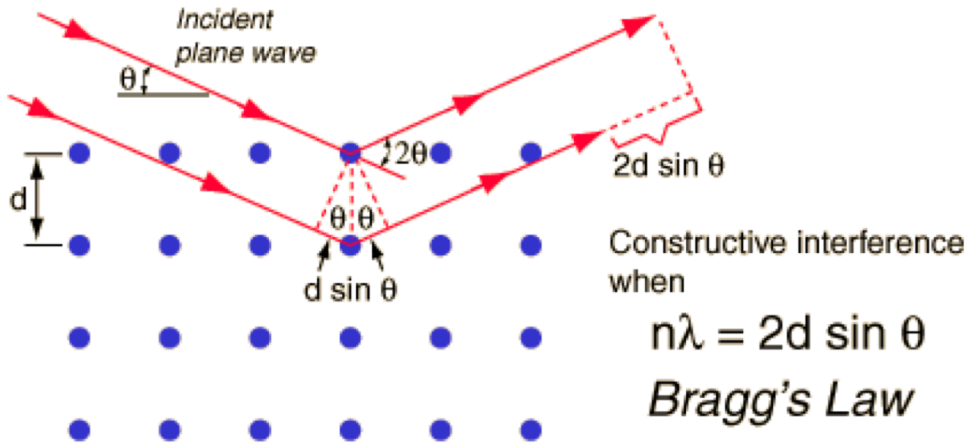


X-RAYS: DISCOVERY OF BRAGG'S LAW AND CRYSTALLOGRAPHY IN 1913

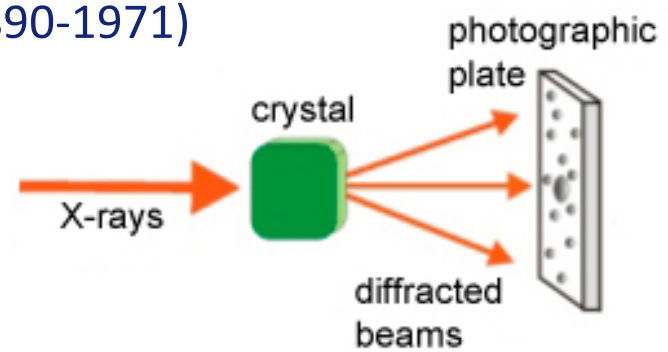
X-rays ... some kind of waves with "atomic resolution"

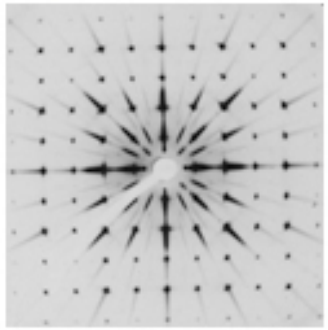




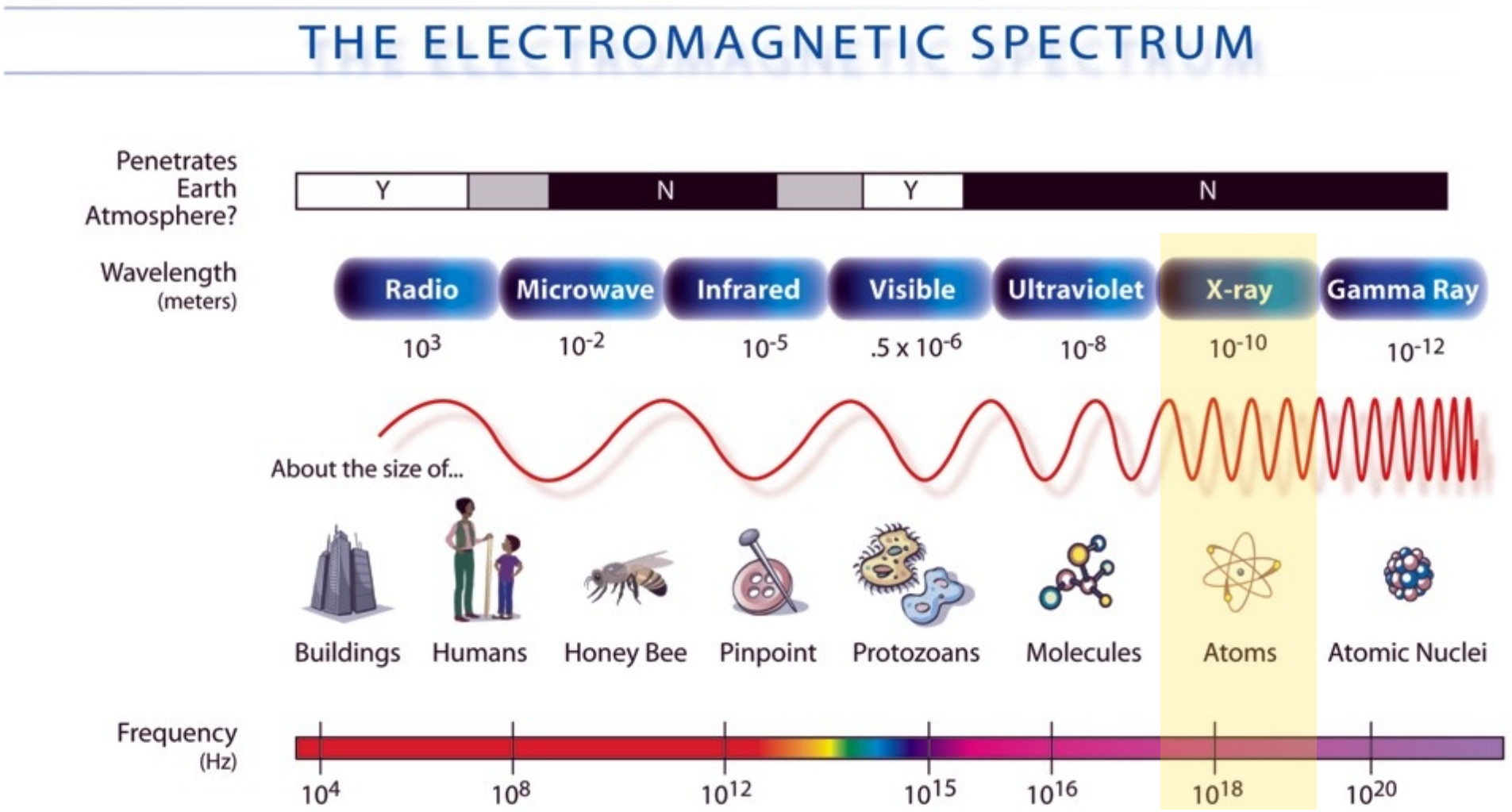


W.H. (1862-1942) and W.L. Bragg(1890-1971)
Nobel Prize for Physics, 1915

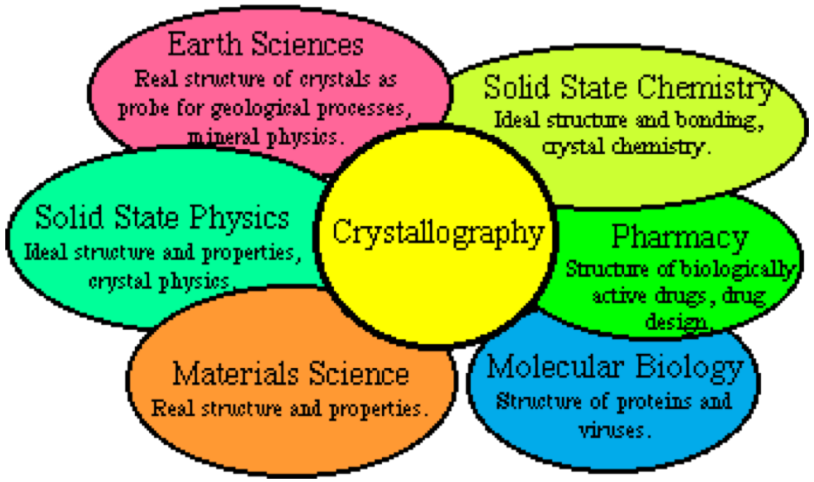


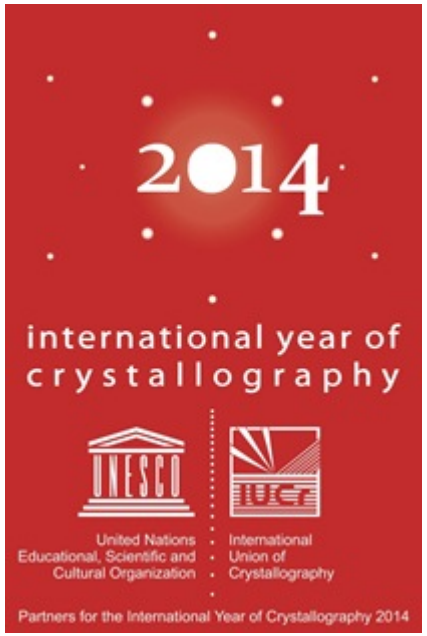


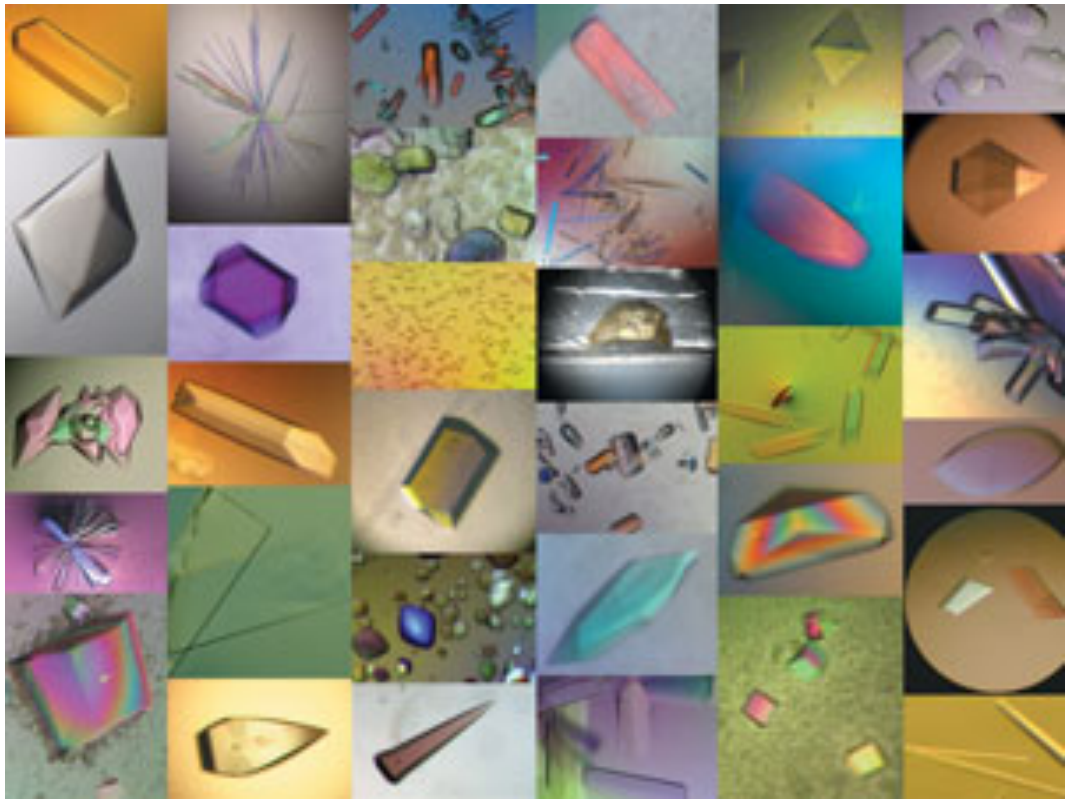
difraction pattern


THE ELECTROMAGNETIC SPECTRUM
Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^3
10^-2
10^-5
.5 x 10^-6
10^-8
10^-10
10^-12
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20

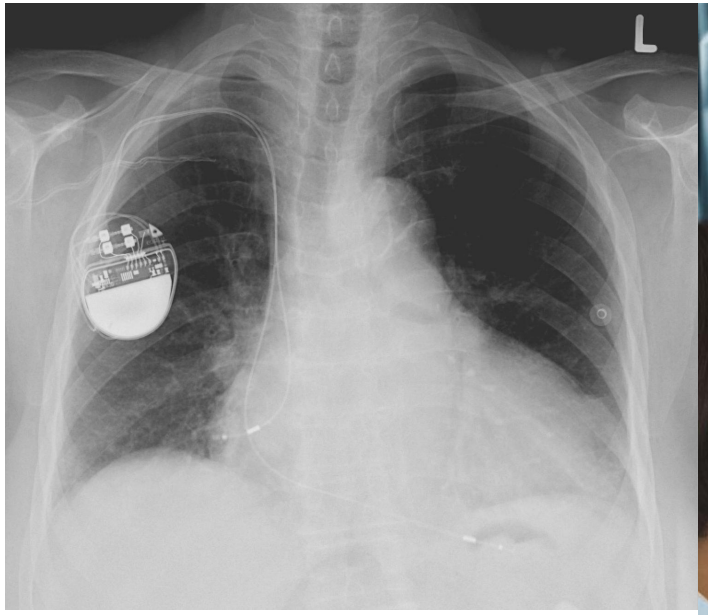
X-ray crystallography: understanding materials and living matter



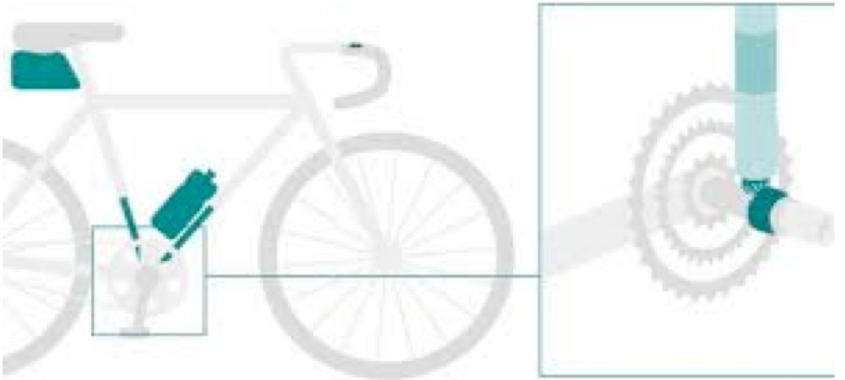


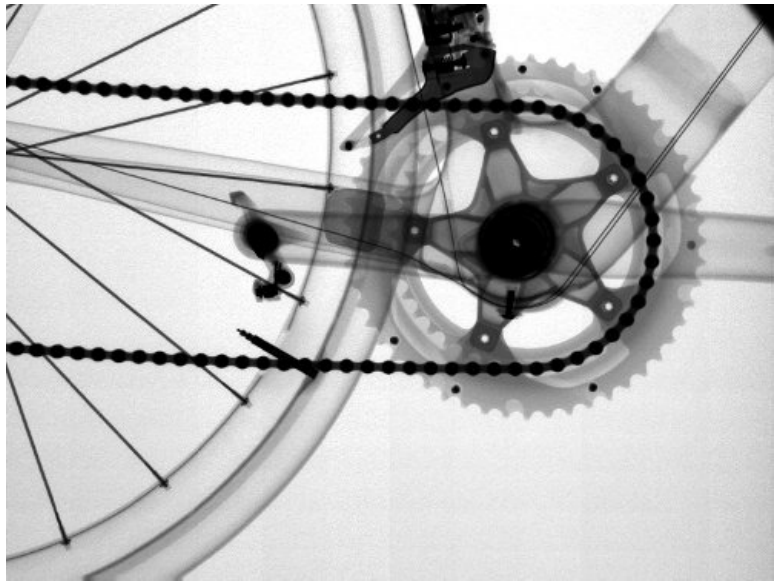


X-rays and Medical Applications

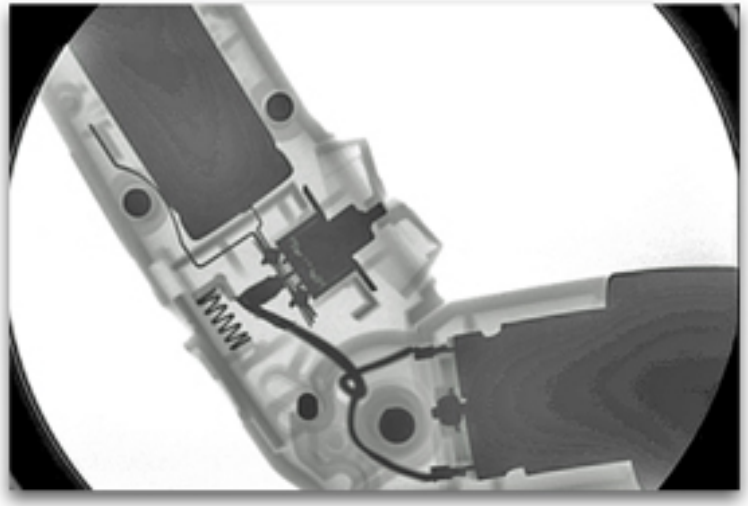


X-rays for security and against fraud

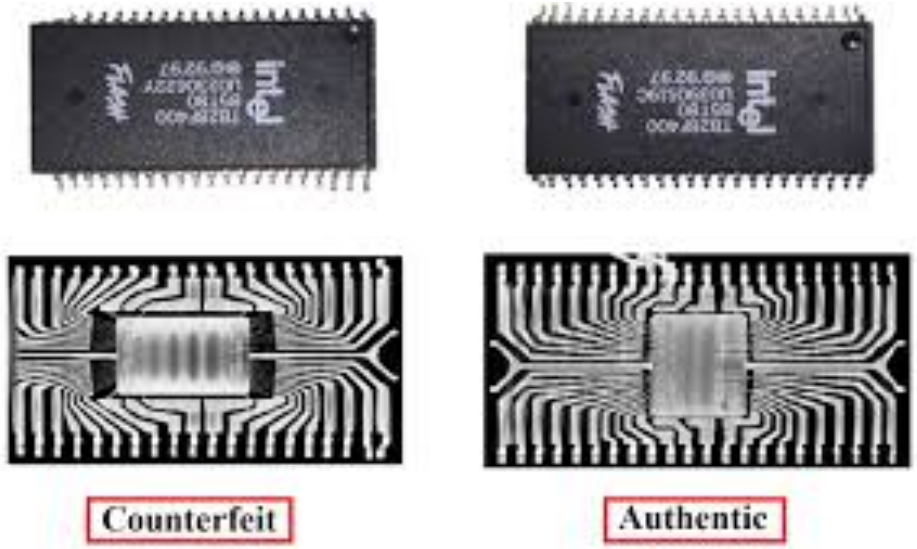




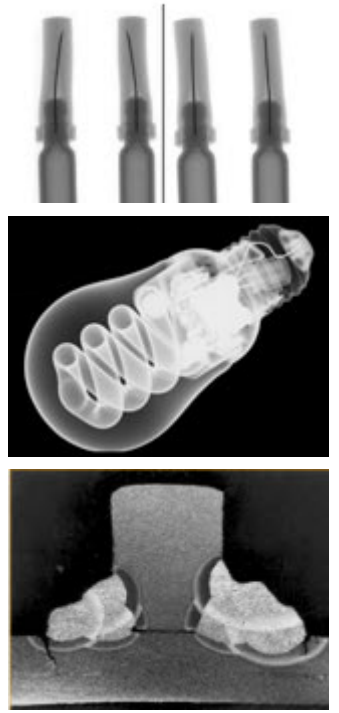
X-rays and Manufacturing Quality and Counterfeiting Control



Automotive Industry

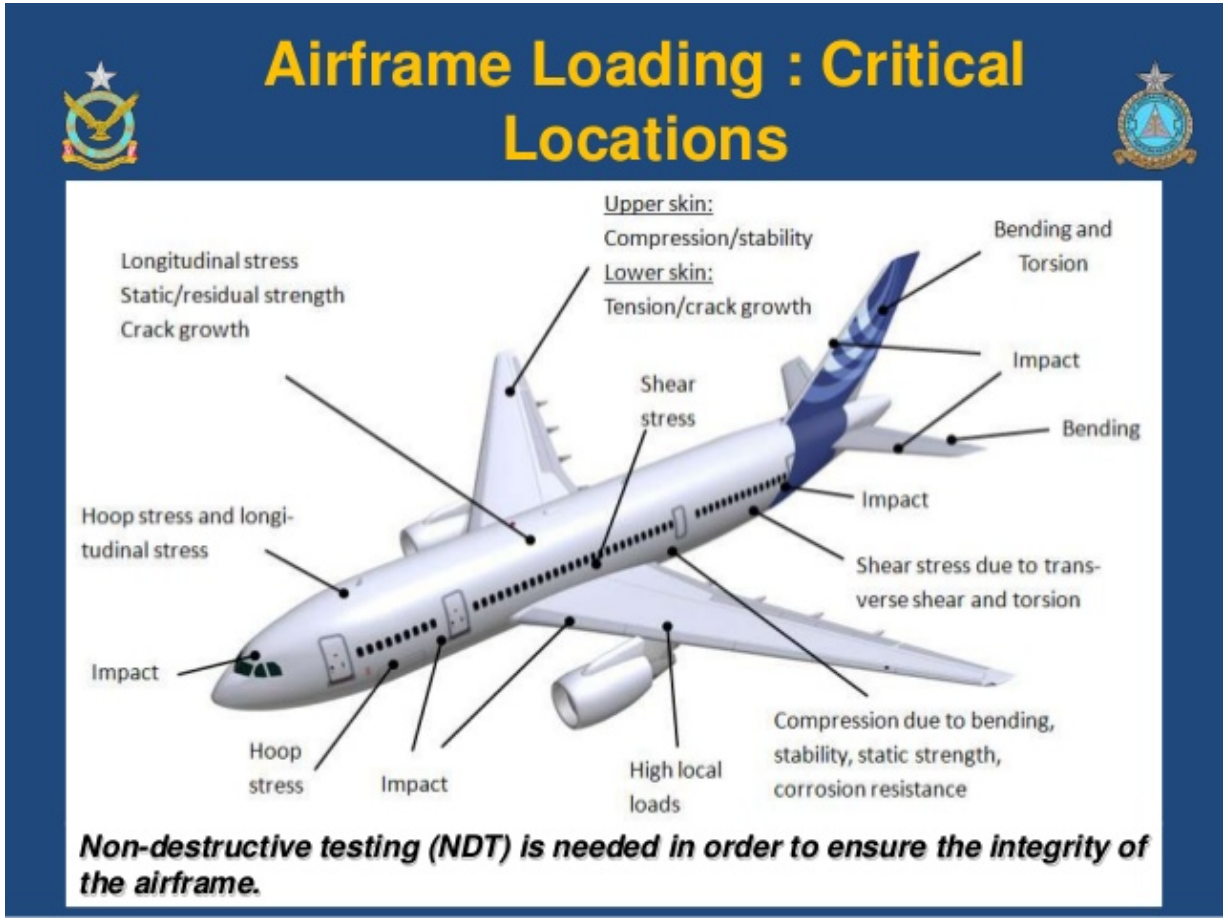


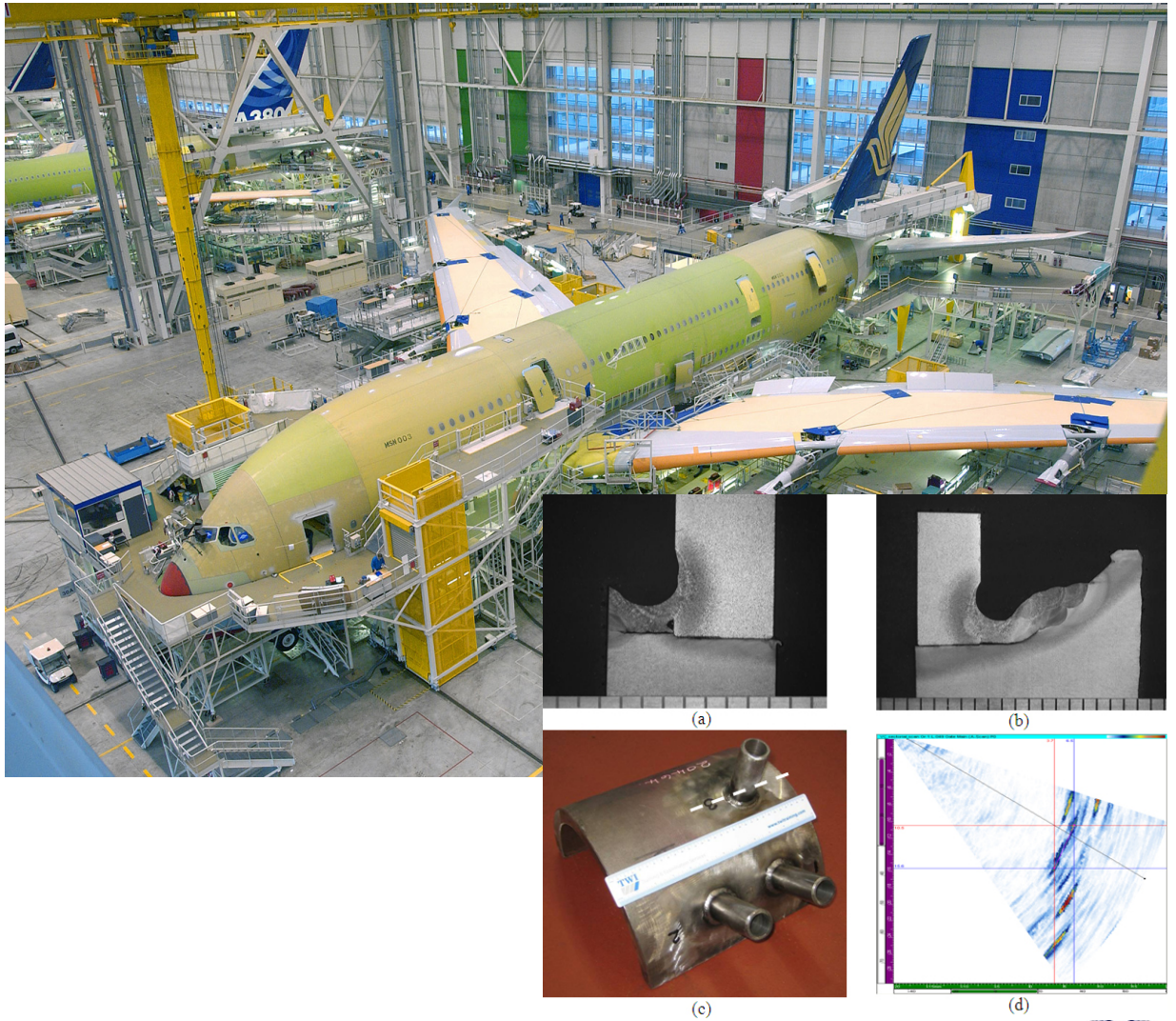
Micro-electronics Industry



Non-destructive Testing

X-rays and critical controls: Airplanes, Boats, Trains, etc.





X-rays and food control

Bruker Portable Handheld XRF Analyser

BMC Plant Biology

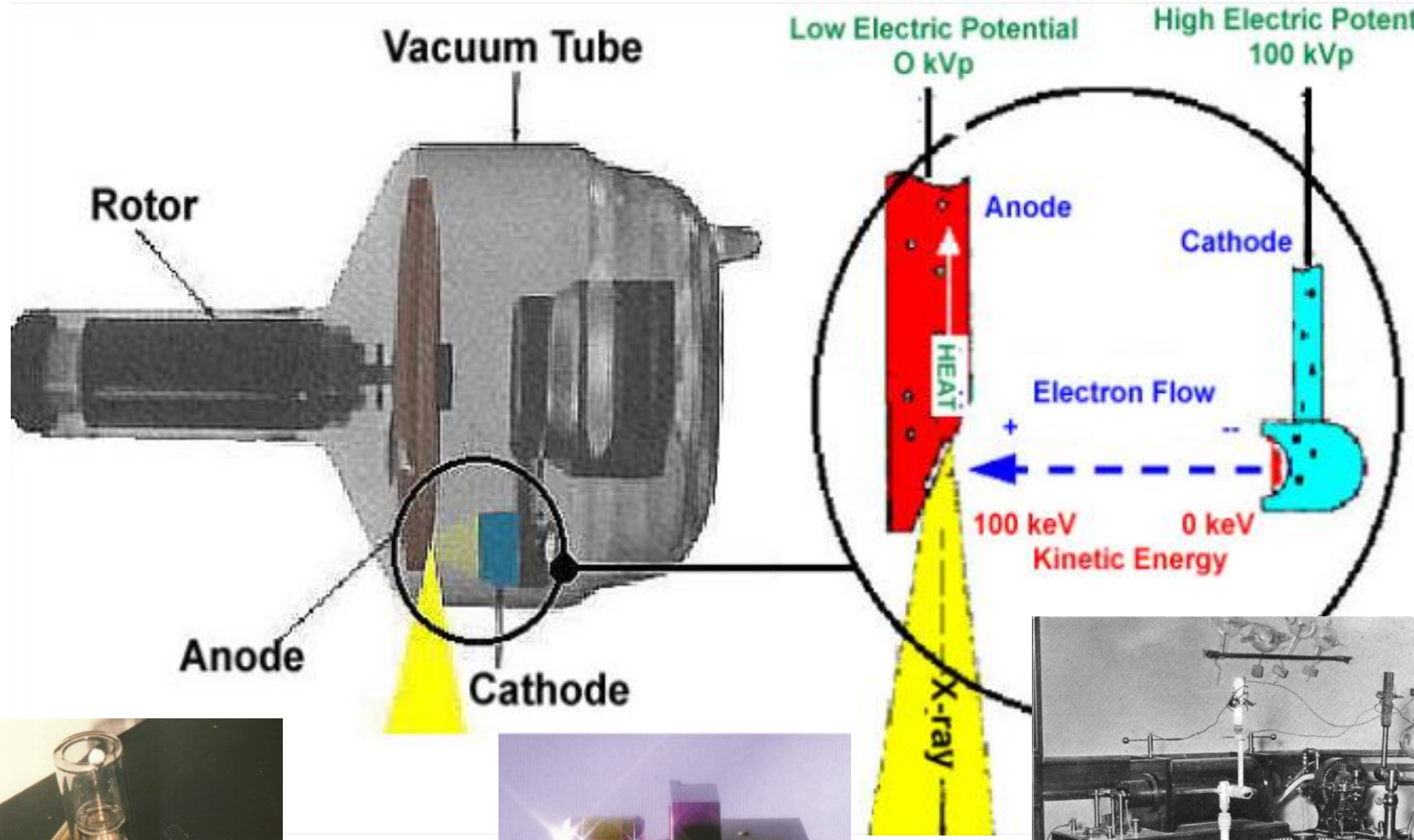
Synchrotron based phase contrast X-ray imaging combined with FTIR spectroscopy reveals structural and biomolecular differences in spikelets play a significant role in resistance to Fusarium in wheat

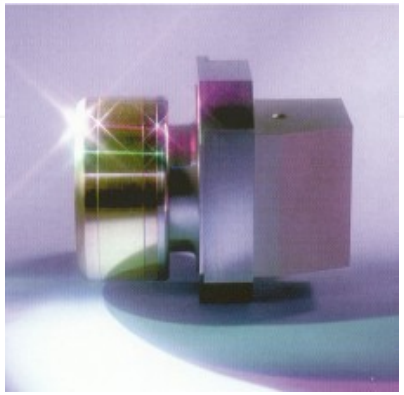
Lahlali *et al.*

BioMed Central

Lahlali *et al. BMC Plant Biology* 2015, **14**:357
http://www.biomedcentral.com/1471-2229/14/357

X-RAY SOURCE

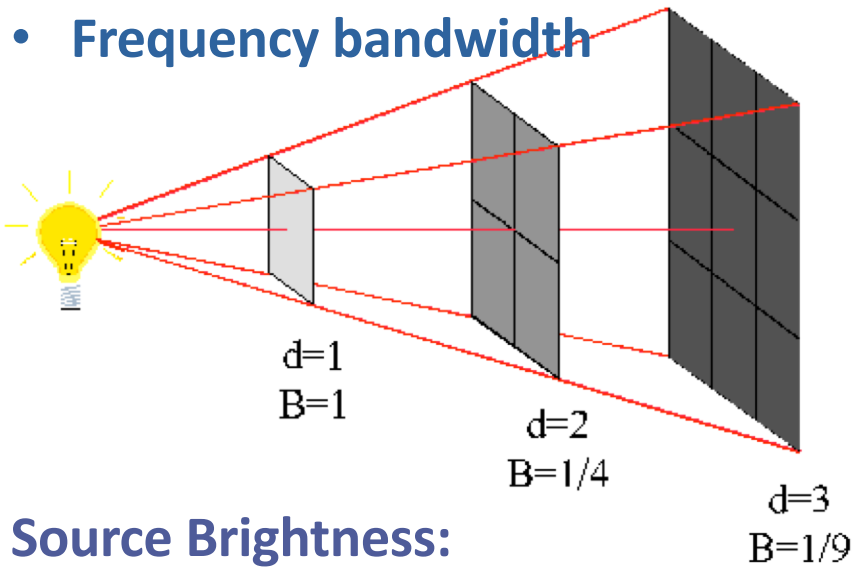

Vacuum Tube
Rotor
Anode
Cathode
Low Electric Potential
O kVp
High Electric Potential
100 kVp
Anode
Cathode
HEAT
Electron Flow
+
--
100 keV
0 keV
Kinetic Energy
X-ray



Conventional X-ray Sources

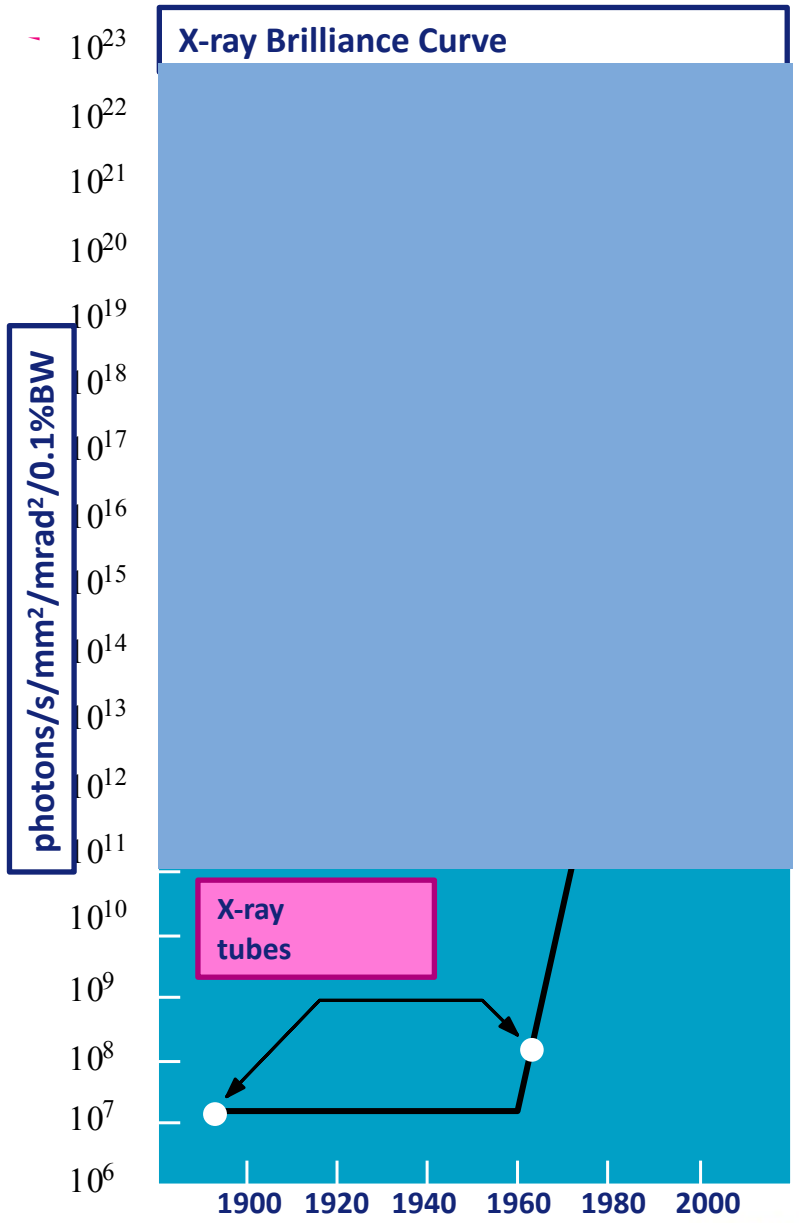
Source Brilliance:
Number of photons normalized to

- Transverse source area
- Source emission angle
- Frequency bandwidth



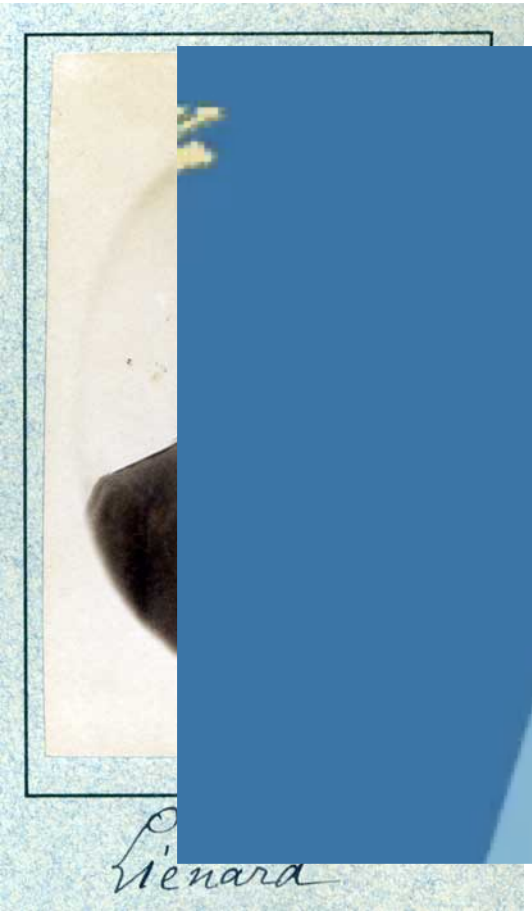
Source Brightness:
Number of photons normalized to

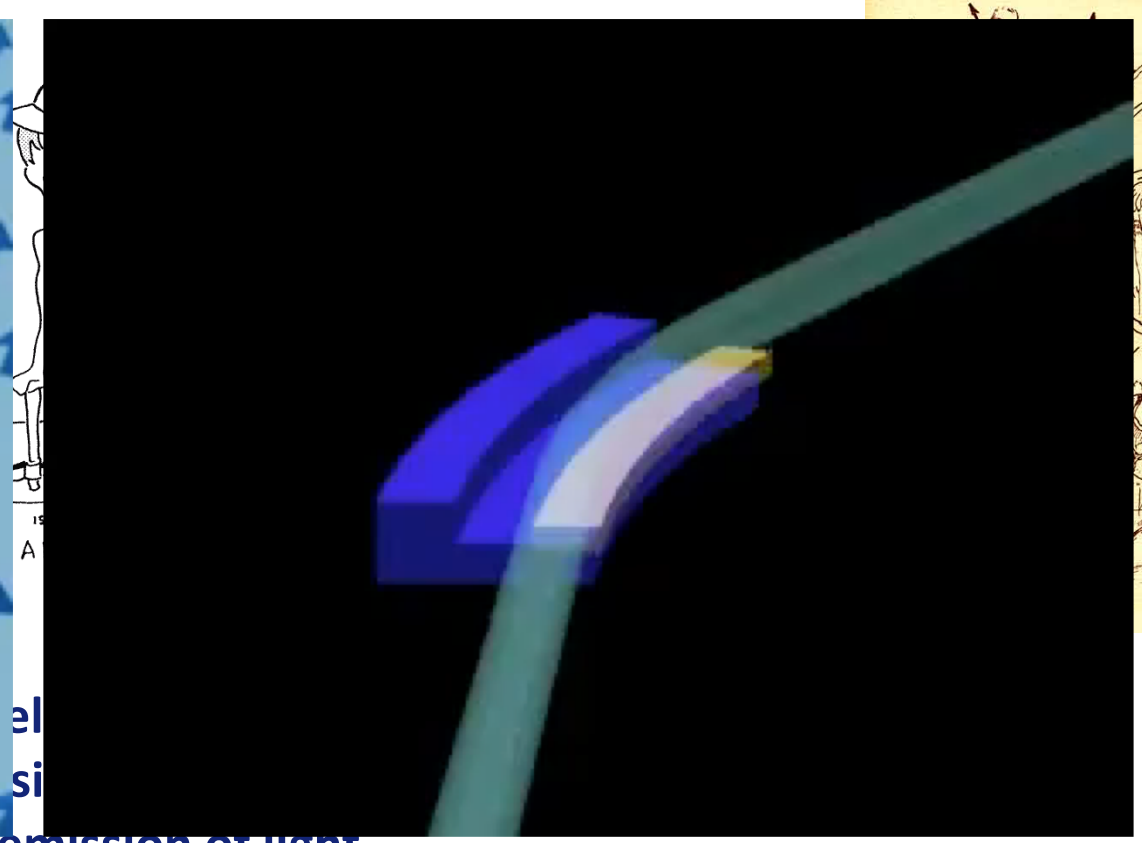
- Unit area
- Frequency bandwidth



RELATIVISTIC ELECTRONS

Alfred-Marie LIENARD (1869-1958)





el
si
by emission of light

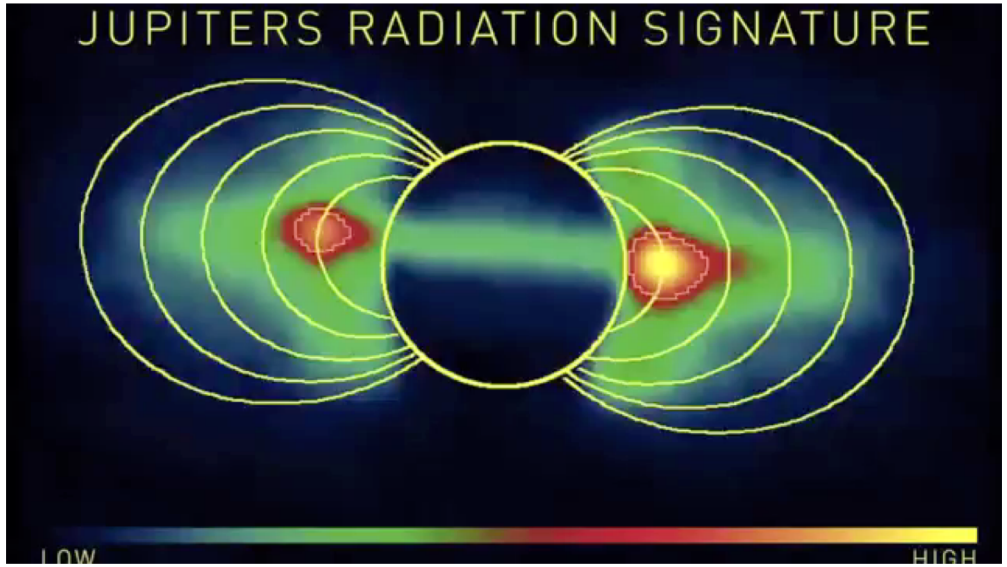
"Champ électrique et magnétique produit par une charge électrique concentrée en un point et animée d'un mouvement quelconque"
L'Éclairage Électrique, 16(27), pp. 5-14 (1898)

Synchrotron Radiation from the Sky

Crab Nebula

Gas emission (reddish) and synchrotron radiation (bluish) generated by high energy electrons in the magnetic field of a neutron star.

Jupiter's radiation belts



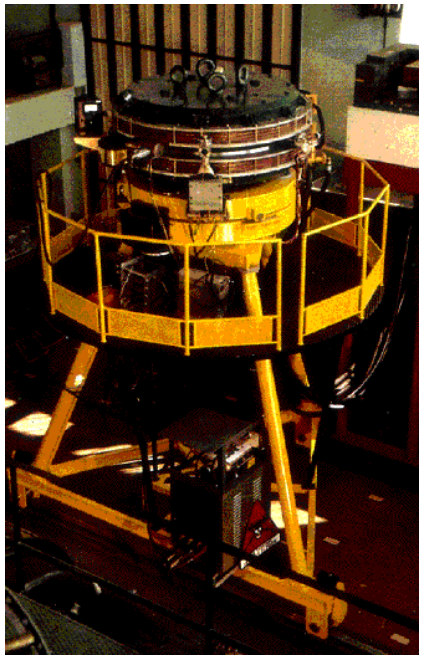
Radiation belts of Jupiter: high energy electrons in the magnetic field of the planet produce synchrotron light, which reproduces the field distribution.

First Observation of Synchrotron Radiation

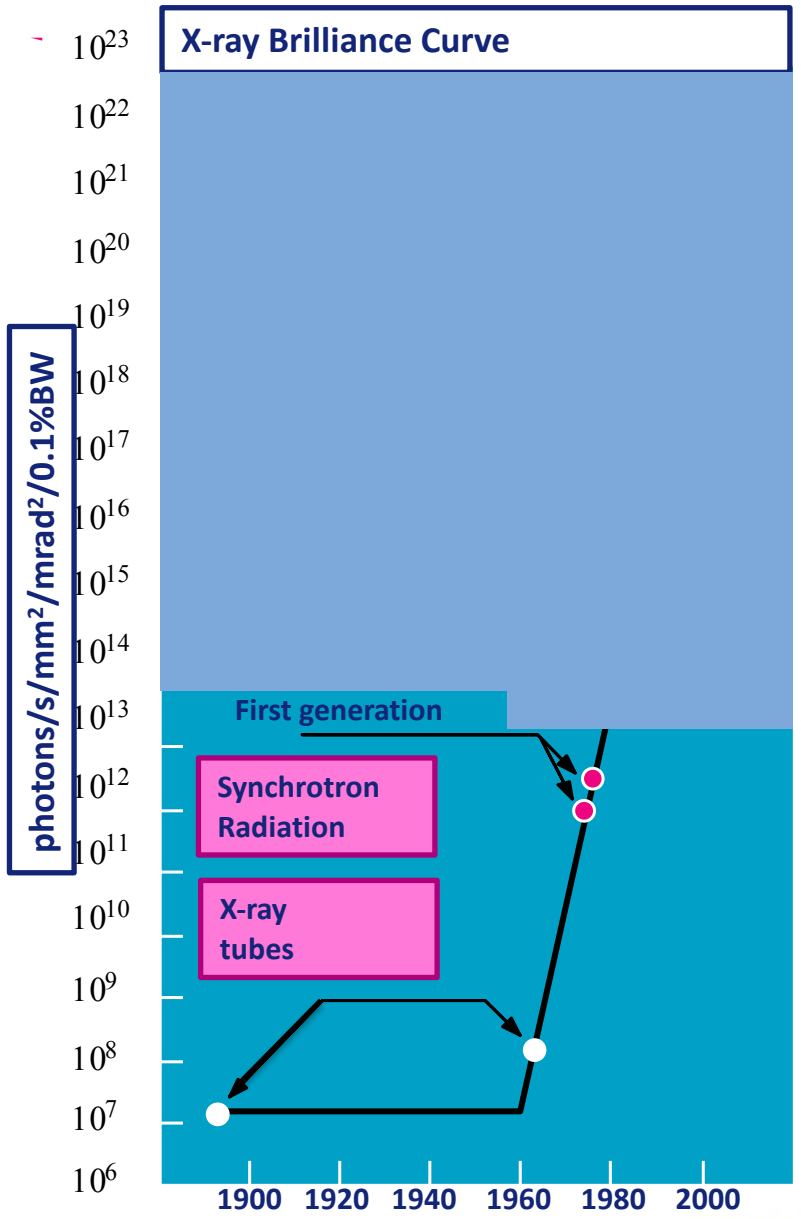
The General Electric team (Langmuir, Elder, Gurewitsch, Charlton and Pollock) looking at the vacuum chamber of the 70 MeV synchrotron (1947).

Conventional X-ray Sources and Synchrotron Radiation

Storage Ring, 1961-1964
Key Time for Synchrotron Radiation
First Generation SR Sources

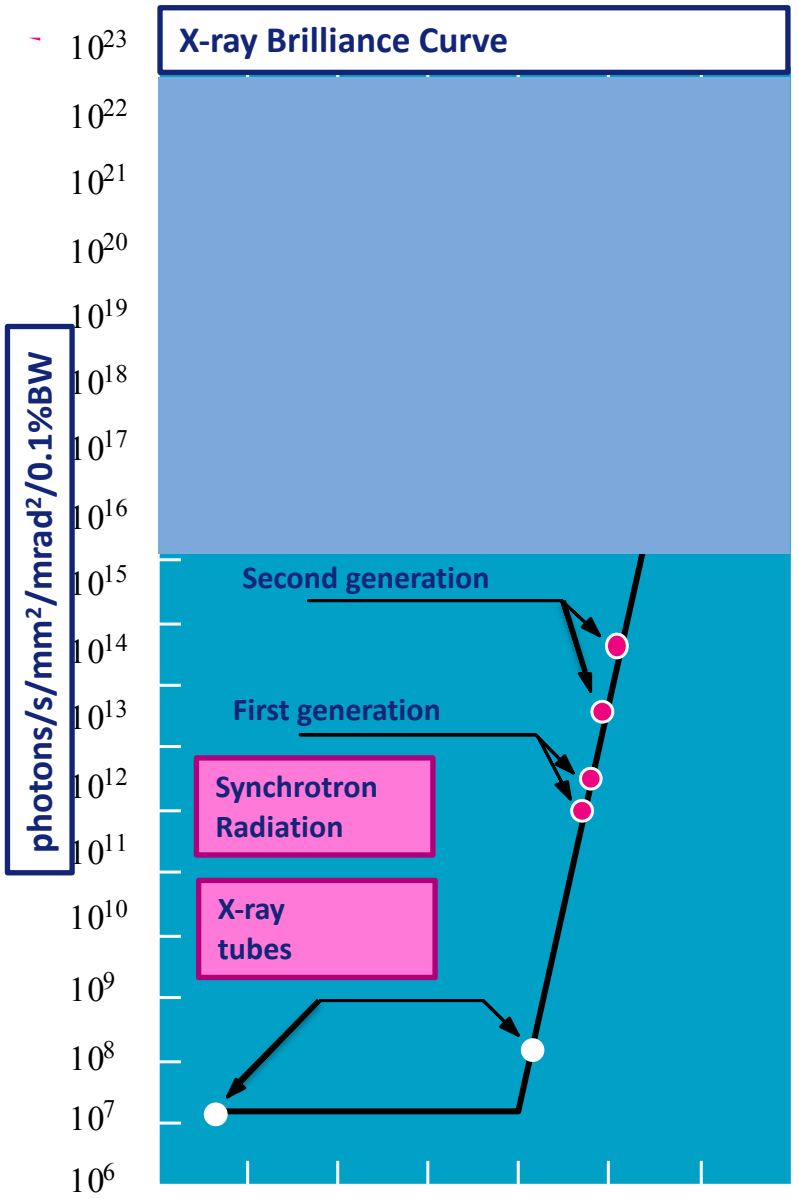


ADA in Frascati (INFN),
the first storage ring for electron and positron beams rotating in opposite Directions.
Proposed by **Bruno Touschek (1921-1978), in 1960**



Conventional X-ray Sources and Synchrotron Radiation

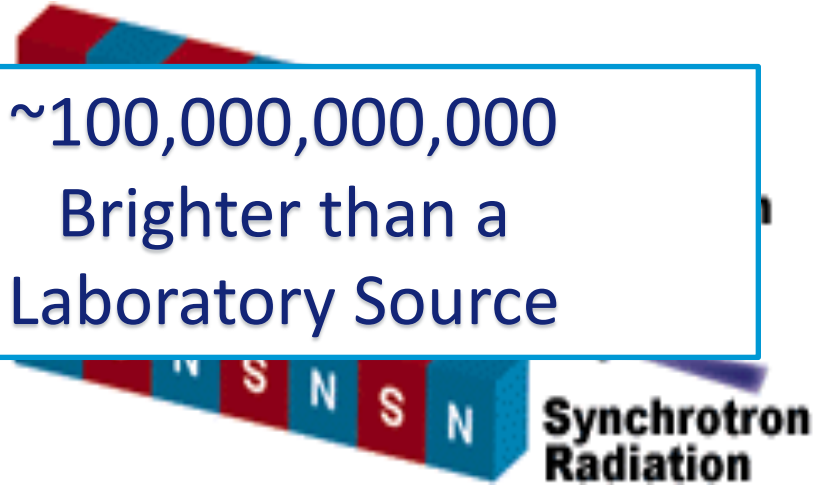
Tantalus – University of Wisconsin
The first dedicated source of Synchrotron Radiation, 1968
Second Generation SR Sources

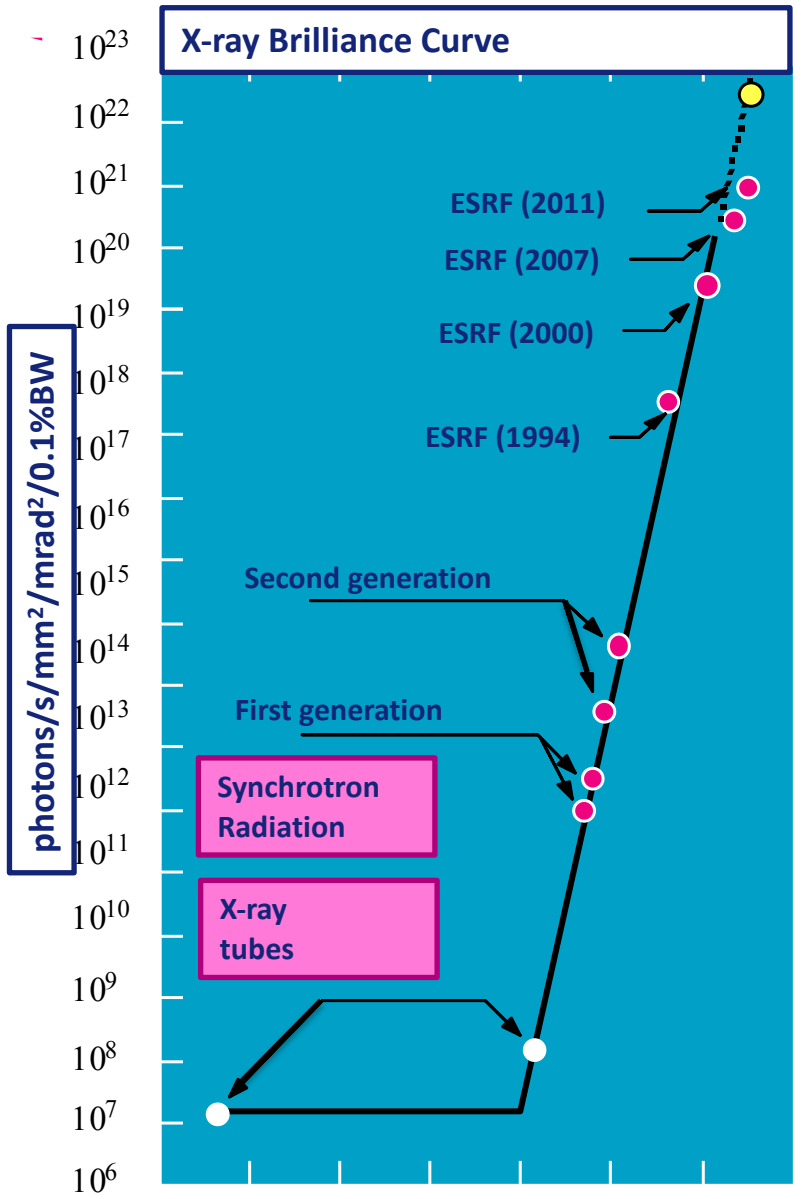


Conventional X-ray Sources and Synchrotron Radiation

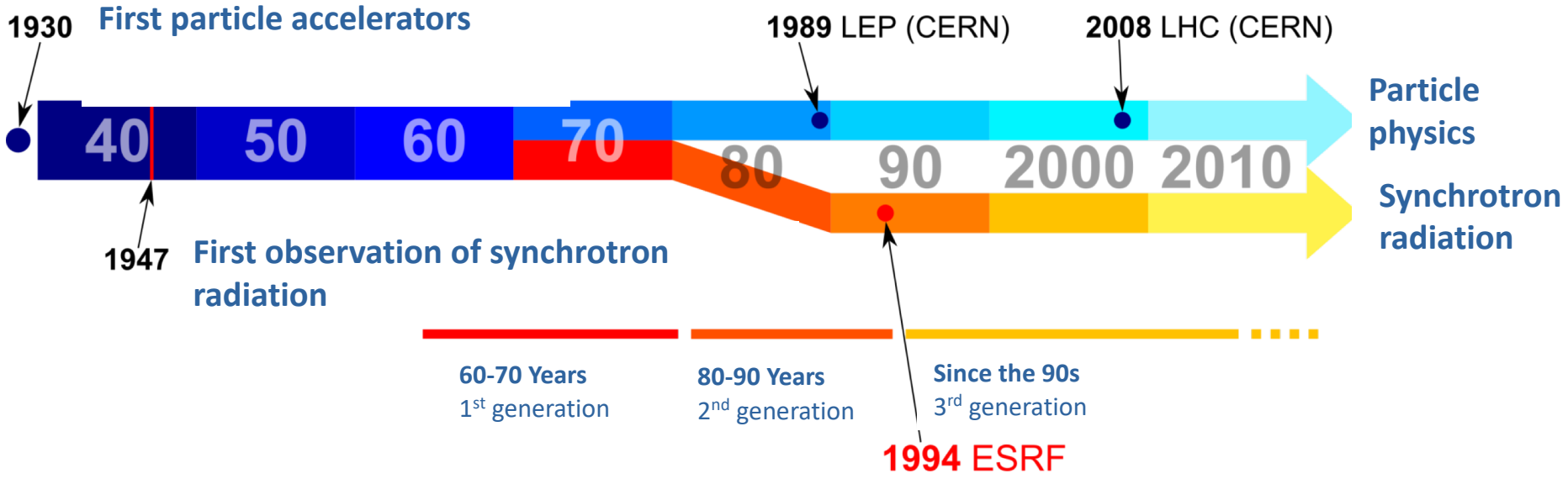
Chasman-Green Lattice
Brookhaven, 1975
The way to very low vertical emittance storage rings, and to very high brightness
Third Generation SR Sources
ESRF 1992

~100,000,000,000
Brighter than a
Laboratory Source





HISTORY OF THE SYNCHROTRON SOURCES



at General Electric (USA).

1994 - *ESRF (France)*

A QUESTION OF SCALE

- **CERN**

The Large Hadron Collider:
circumference 27 km

7 TeV protons and anti-protons on two opposite trajectories

Operation-cost/year:
700 million euros

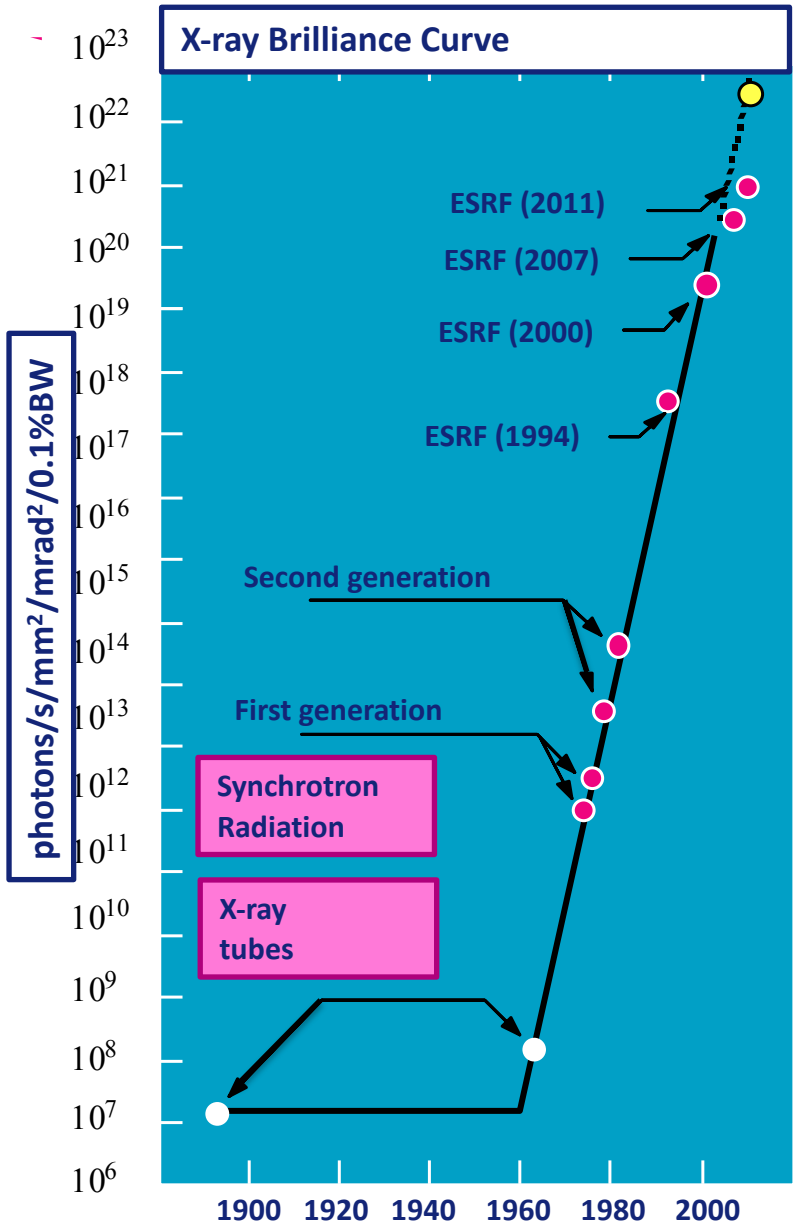
- **ESRF**

The storage ring for Synchrotron Light:
circumference 844 m

6 GeV electrons

Operation-cost/year:
80 million euros

A VERY BRILLIANT LIGHT



Remarkable properties of synchrotron light

- Brilliance
- Coherence
- Pulsed emission
  (duration of a flash: 50 ps)

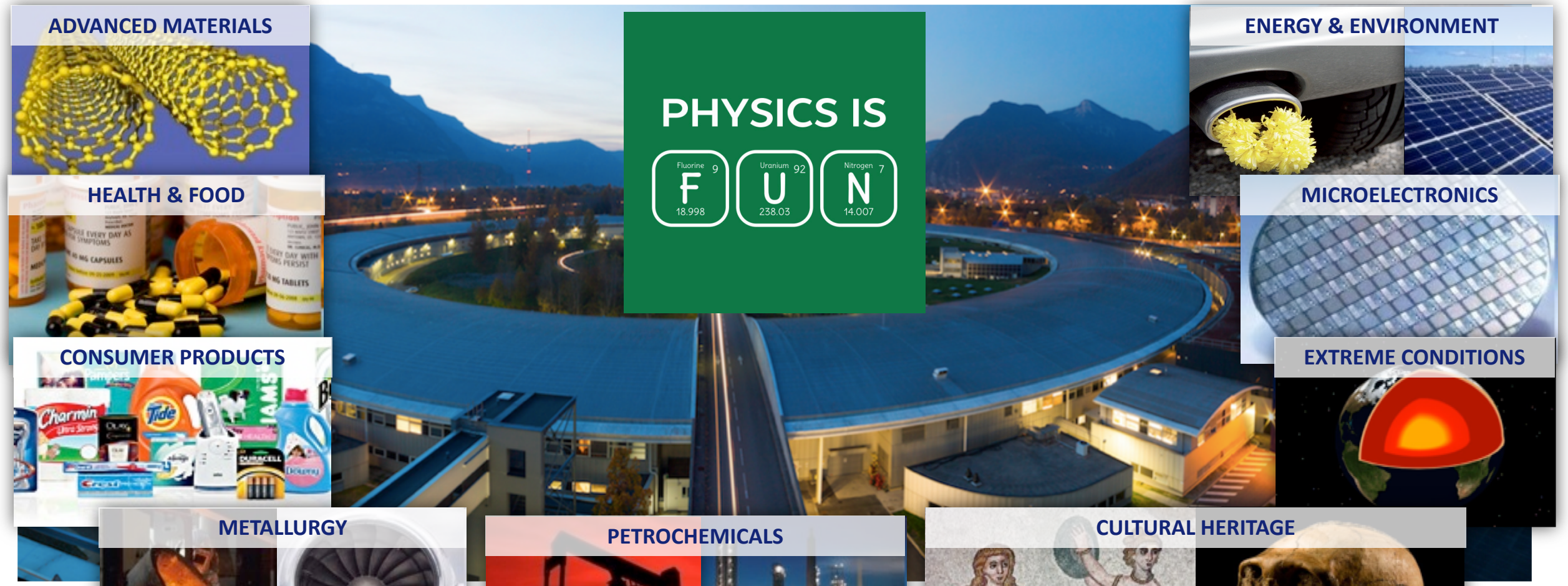
Moreover:

- Flux
- Polarisation
- Beam stability

Major synchrotrons in the world

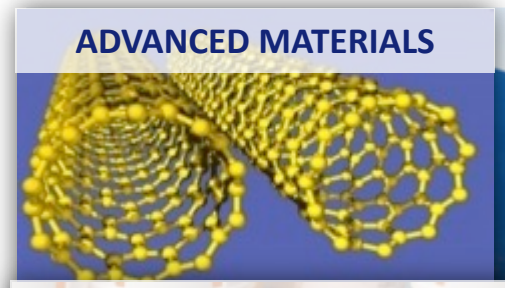
Fundamental, applied and industrial research on atoms structure and dynamics

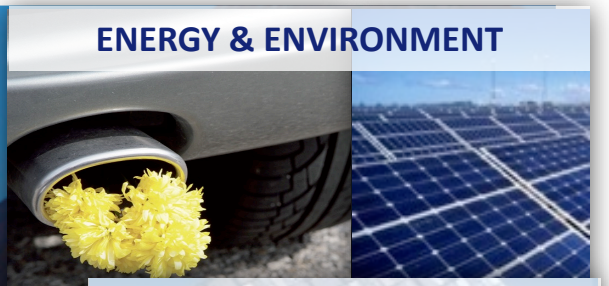
link function and atomic structure: *imagining and imaging* new materials and processes

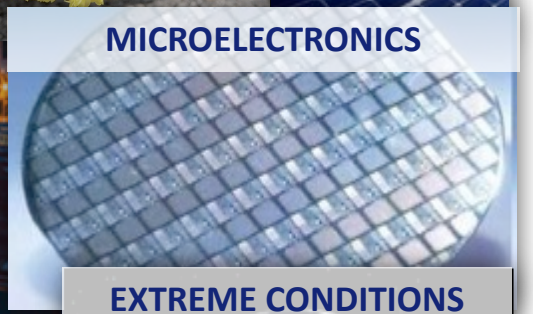


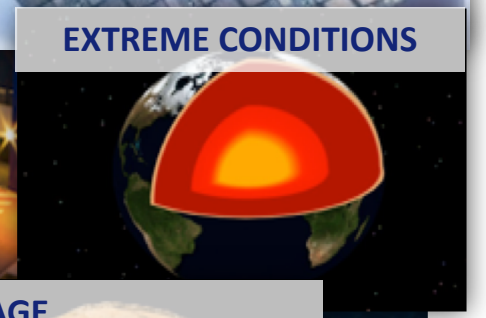
ESRF : X-RAY SCIENCE AND APPLICATIONS

Fundamental, applied and industrial research on atoms structure and dynamics link function and atomic structure: *imagining and imaging* new materials and processes









- How to evolve from TODAY'S ECONOMY to a new **SUSTAINABLE PARADIGM**?
- How to address **CRITICAL GLOBAL CHALLENGES** for a **PEACEFUL** and **SUSTAINABLE WORLD GROWTH** for the next generation? **RESOURCES ARE FINITE**
- **HEALTH, ENVIRONMENT, ENERGY, FOOD AND WATER SUPPLY: A NEW GLOBAL SOCIAL PACT BASED ON KNOWLEDGE**

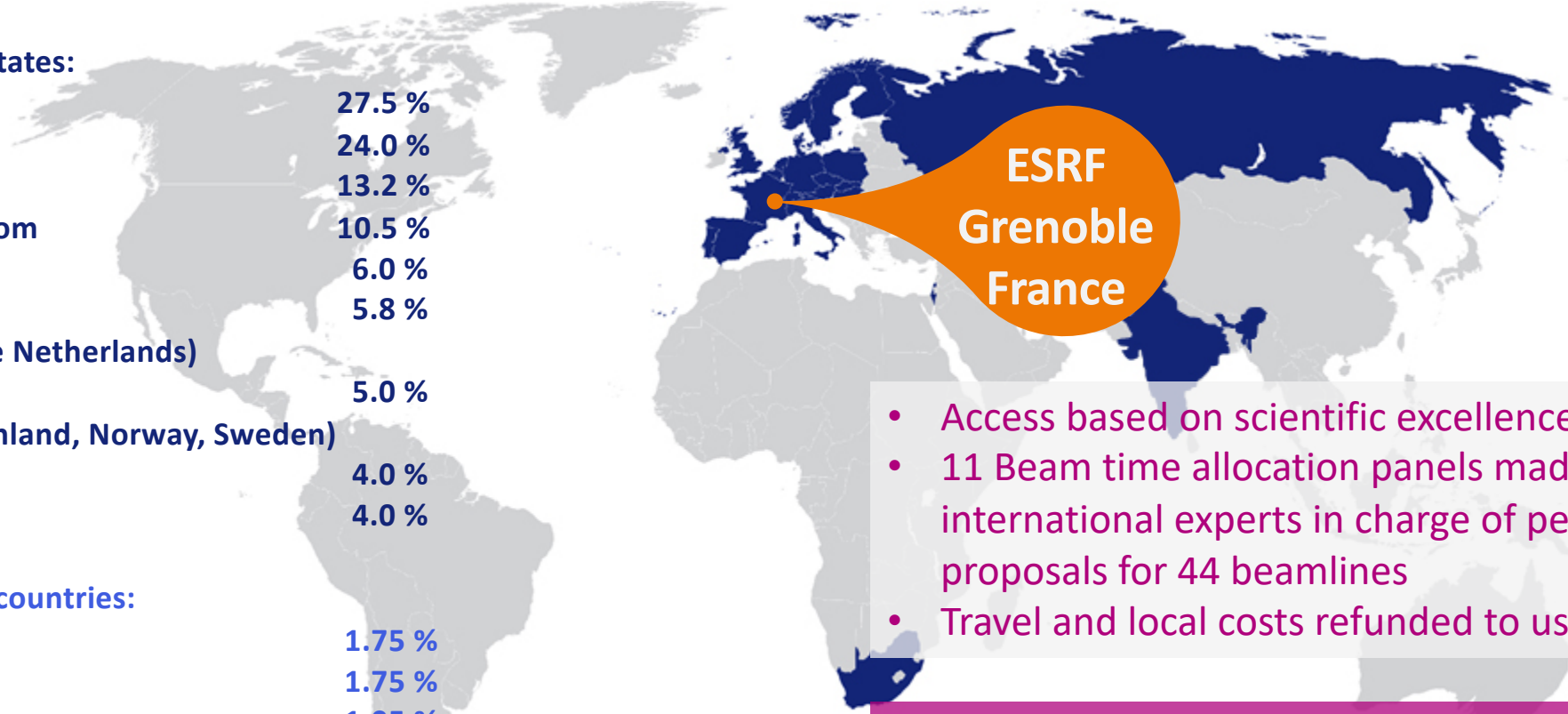
MODERN THIRD GENERATION SYNCHROTRONS WORLDWIDE: CONSTRUCTED ON THE SUCCESS OF THE **ESRF**

MANDATE OF THE ESRF: PIONEERING SYNCHROTRON SCIENCE TO THE BENEFIT OF THE PARTNER COUNTRIES

THE ESRF: BRINGING NATIONS TOGETHER THROUGH SCIENCE

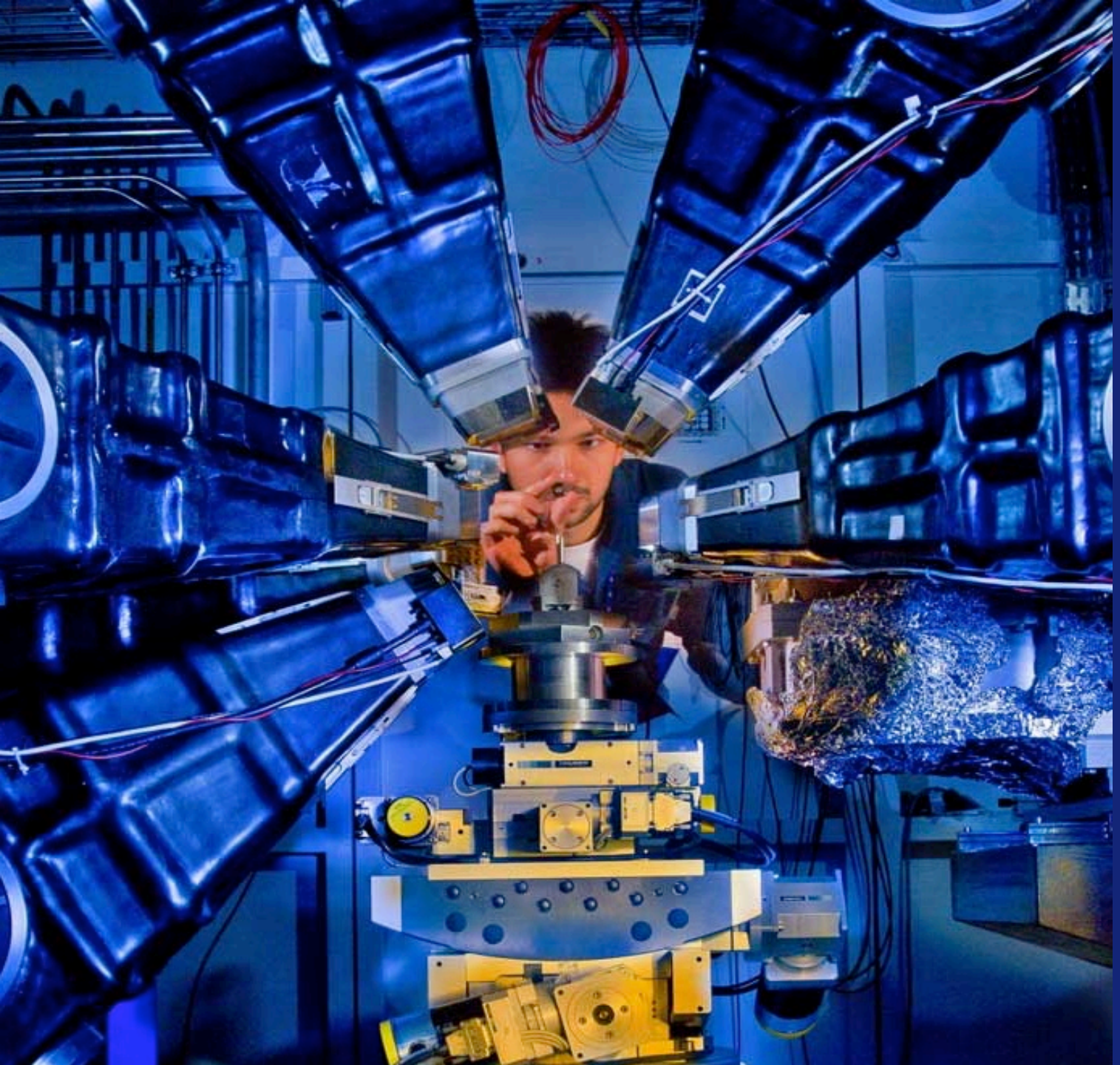
22 PARTNER COUNTRIES

13 Member states:	
France	27.5 %
Germany	24.0 %
Italy	13.2 %
United Kingdom	10.5 %
Russia	6.0 %
Benesync (Belgium, The Netherlands)	5.8 %
Nordsync (Denmark, Finland, Norway, Sweden)	5.0 %
Spain	4.0 %
Switzerland	4.0 %
10 Associate countries:	
Austria	1.75 %
Israel	1.75 %
Centralsync (Czech Republic, Hungary, Slovakia)	1.05 %
Poland	1.00 %
Portugal	1.00 %
India	0.66 %
South Africa	0.30 %



- Access based on scientific excellence
- 11 Beam time allocation panels made of international experts in charge of peer-reviewing proposals for 44 beamlines
- Travel and local costs refunded to users

- Staff: ~ 700
- Partner countries' contributions: ~ 85 M€/year
- Annual Operation Budget: ~100 M€



ESRF's missions

- Design, construct, operate and develop state-of-the-art X-ray synchrotron instruments to the benefit of the scientific communities of the Member and Associate countries
- Serve the international community for the advancement of knowledge and to address global societal challenges
- Support the use of X-rays by industry from Member and Associate countries to strengthen its competiveness in the global scale
- Train the next generation of scientists, engineers and technical staff

BRINGING NATIONS TOGETHER THROUGH SCIENCE


Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
Région RhôneAlpes
isère Conseil Général
Plus proche de vous !
VILLE DE GRENOBLE
GRENOBLE • ALPES MÉTROPOLE
GIANT
INNOVATION CAMPUS
GRENOBLE ECOLE DE MANAGEMENT
cea
NEUTRONS FOR SOCIETY
EMBL
ESRF
The European Synchrotron
Grenoble INP
cnrs
UNIVERSITÉ Grenoble Alpes
ESRF, 30 YEARS OF EUROPEAN SCIENCE AT THE HEART OF THE FRENCH ALPS, GRENOBLE, FRANCE

EPN SCIENCE CAMPUS : A UNIQUE SITE FOR RESEARCH AND INNOVATION

PSB
THE PARTNERSHIP FOR STRUCTURAL BIOLOGY

PSCM
PARTNERSHIP FOR SOFT CONDENSED MATTER

epn
european photon & neutron science campus

Collaboration
ESRF – EMBL - IBS - ILL

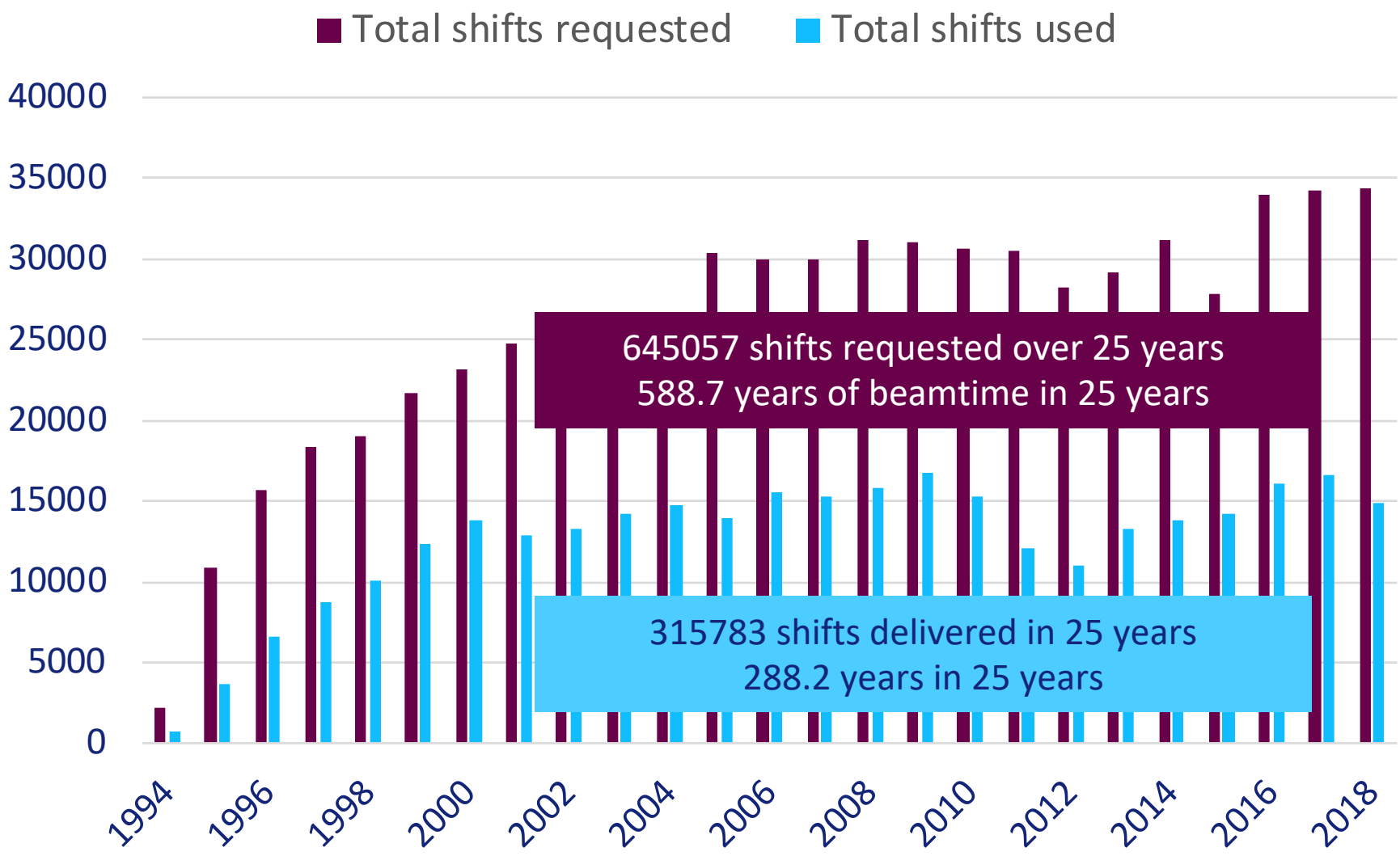
- +500 scientists in the Campus
- 3 European Organisations and the IBS – a French Institute for Structural Biology – working together to welcome users from all over the world

EMBL ibs Institut de Biologie Structurale

Most powerful research reactor and brightest synchrotron source worldwide at 400 m from each other

30 YEARS OF SCIENTIFIC EXCELLENCE TO THE BENEFIT OF THE INTERNATIONAL COMMUNITY AND SOCIETY

THE FIRST THIRD GENERATION SYNCHROTRON STORAGE RING: BEAM TIME 1994 - 2018



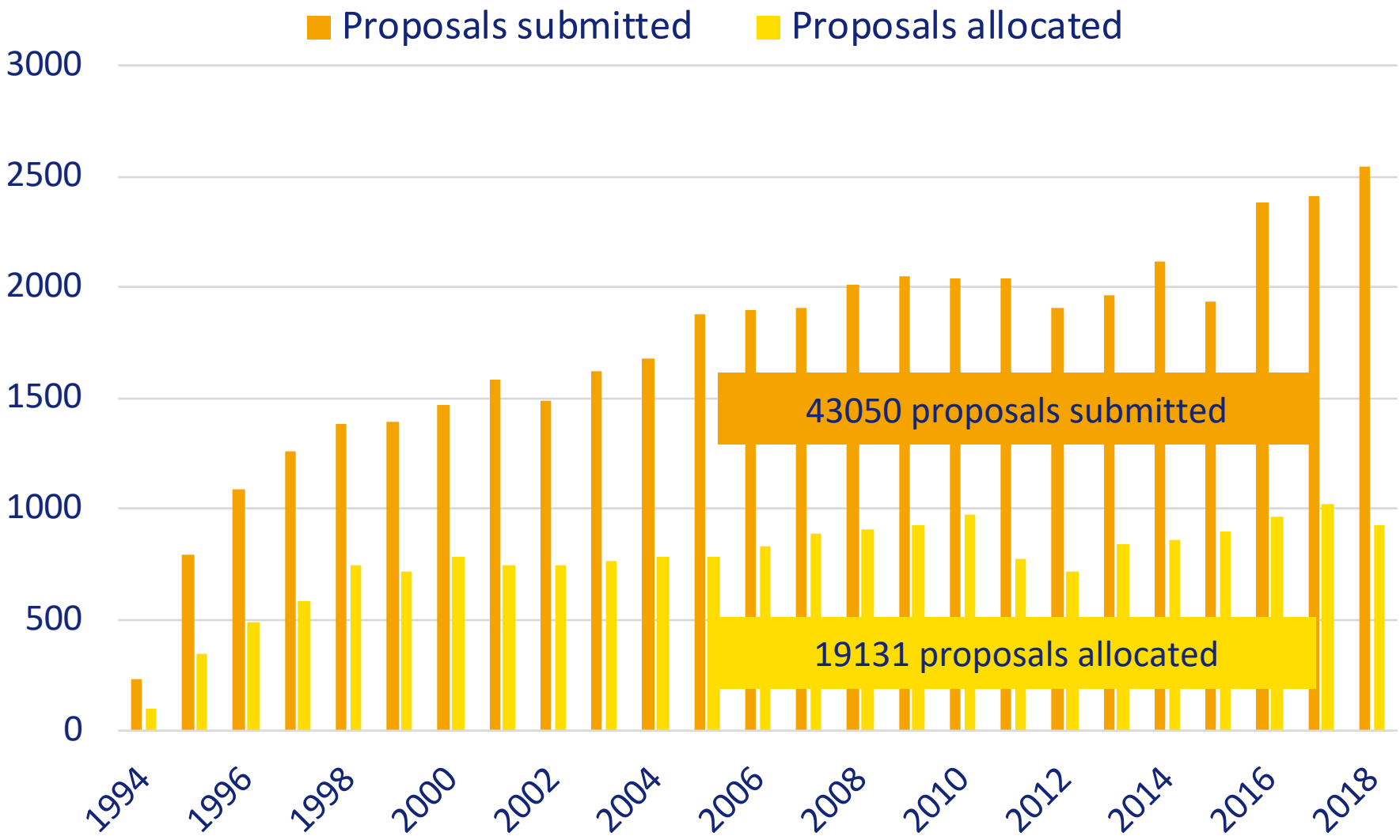
~ 600 years of requested beamtime

~ 23.5 years/year

~ 300 years of delivered beamtime

11.5 years/year

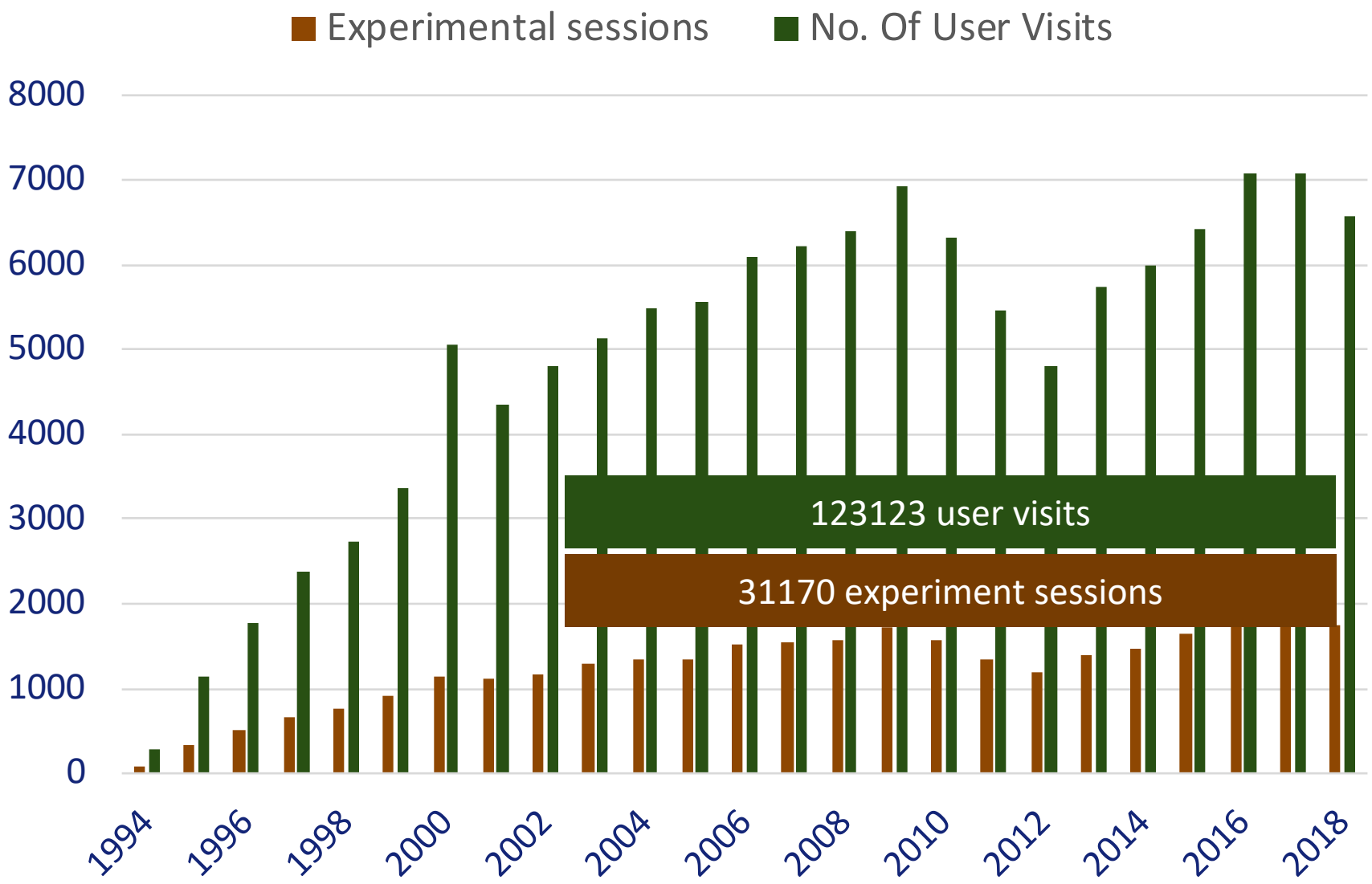
THE FIRST THIRD GENERATION SYNCHROTRON STORAGE RING: PROPOSALS 1994 - 2018



1722 proposal/year

765 proposal/year

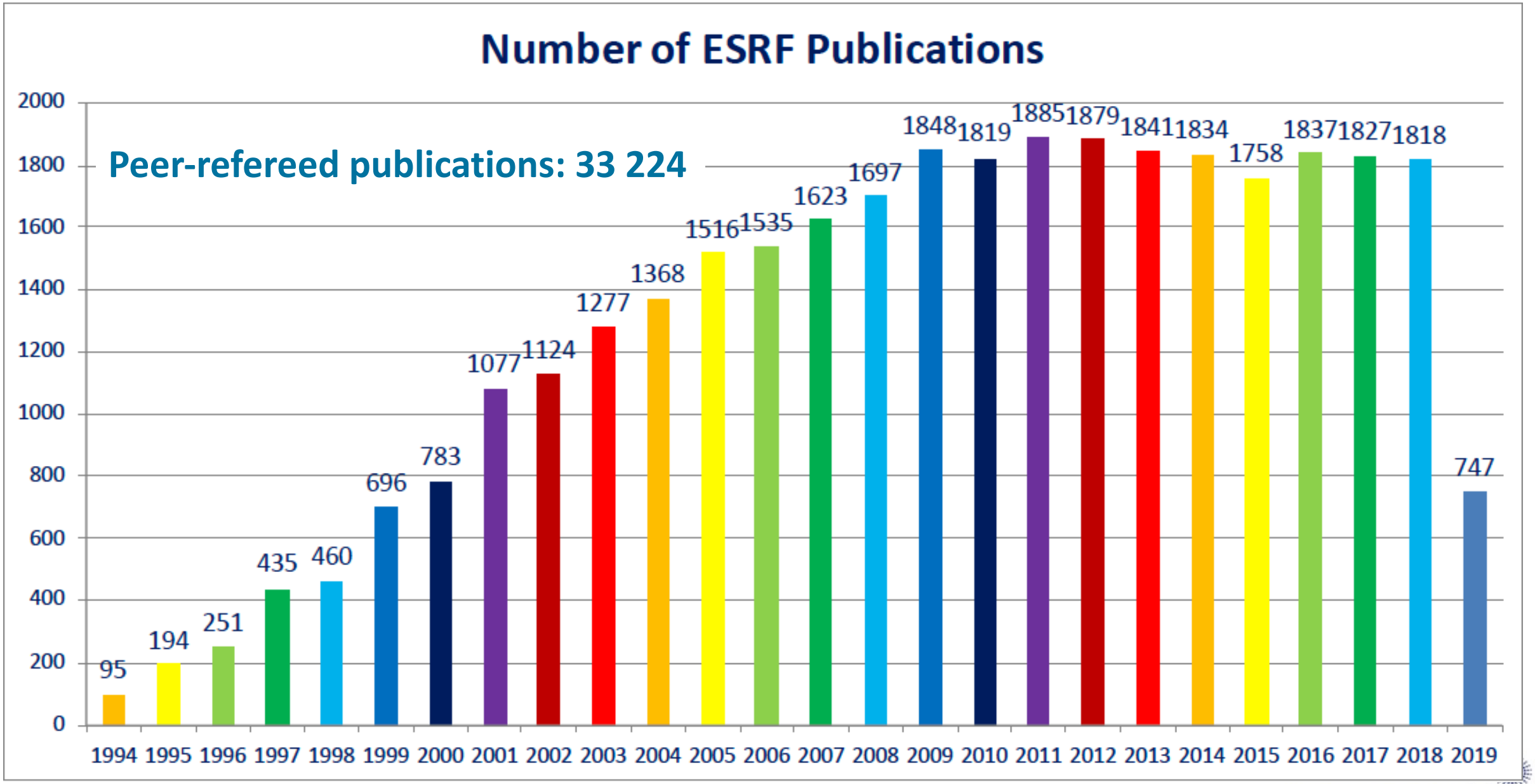
THE FIRST THIRD GENERATION SYNCHROTRON STORAGE RING: USERS VISITS 1994 - 2018



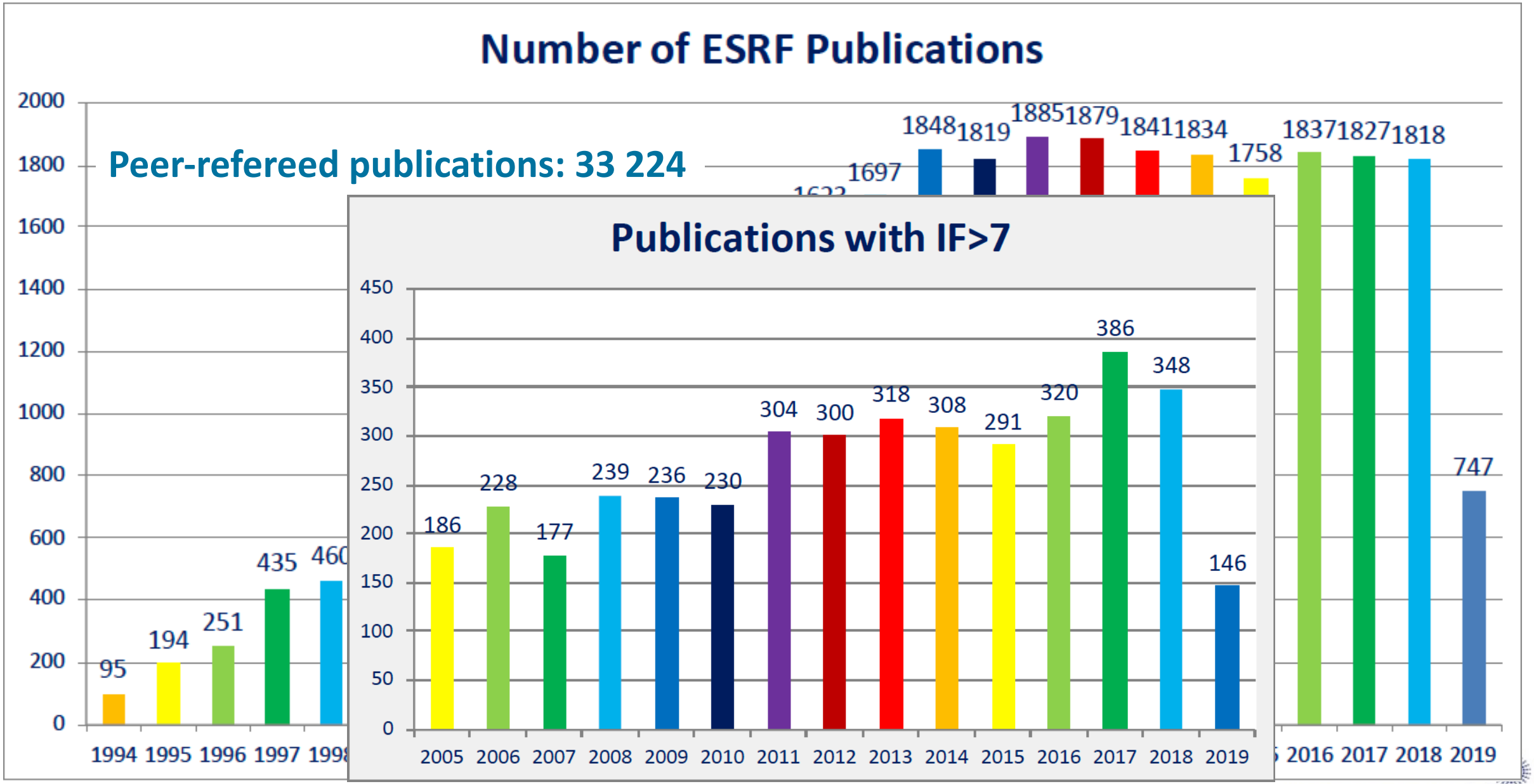
4924 user visits/year

765 exp. session/year

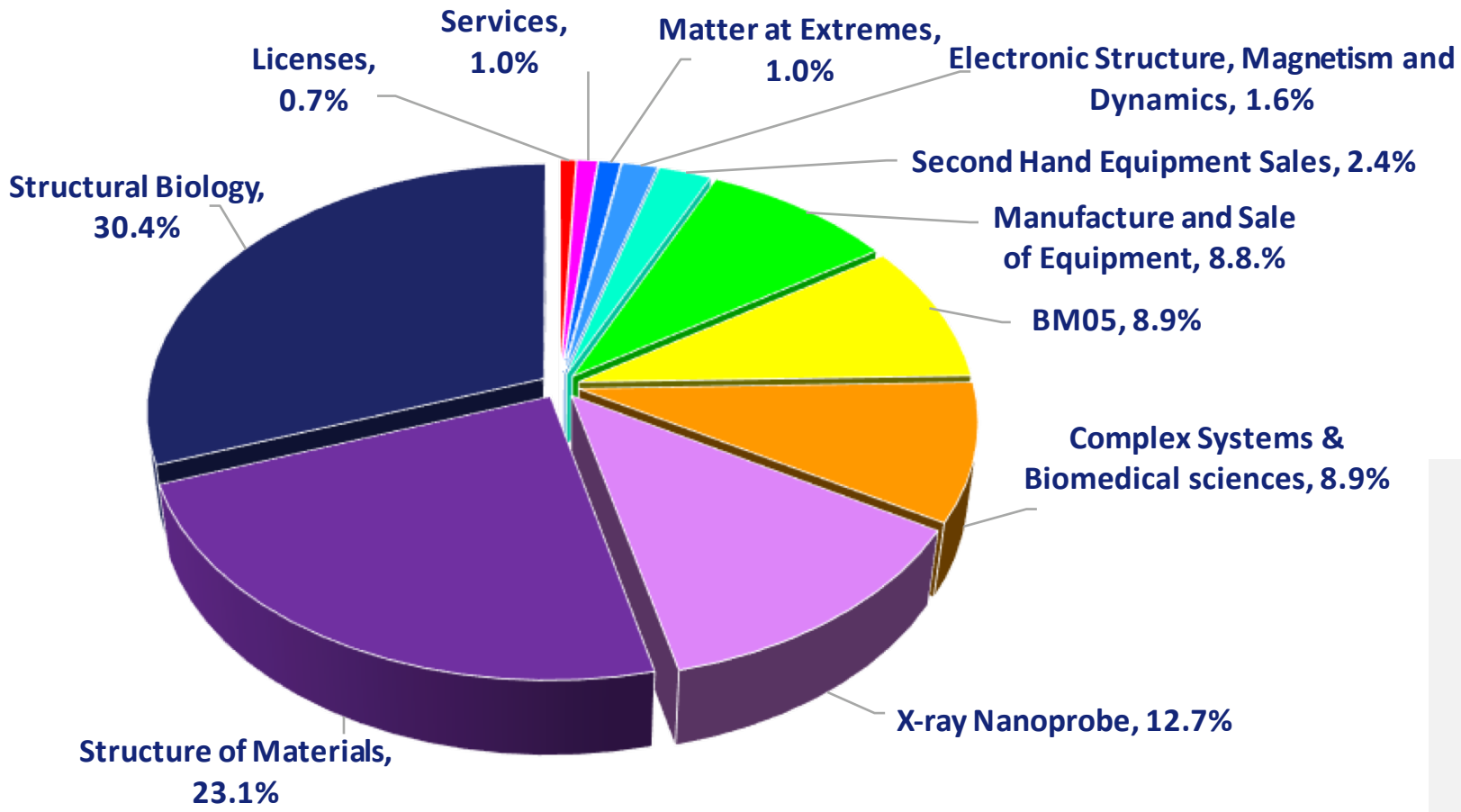
THE FIRST THIRD GENERATION SYNCHROTRON STORAGE RING: PUBLICATIONS 1994 TO 2019



THE FIRST THIRD GENERATION SYNCHROTRON STORAGE RING: PUBLICATIONS 1994 TO 2019



Commercial and Industrial activities at the ESRF
Income of 3.1 M€ in 2018 (~3% Budget Operation)



Collaborative Approach:

- Problem identification
- Experiment strategy
- Experiment
- Data analysis
- Result

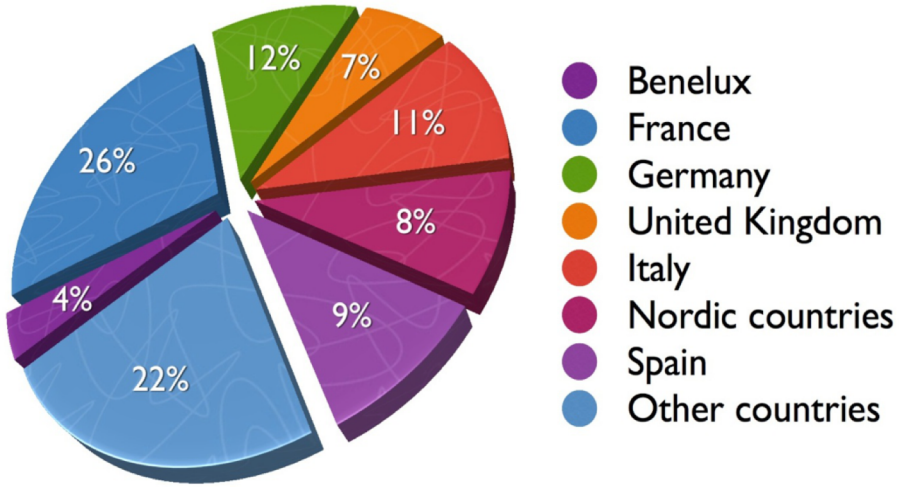
HERCULES

European School

HERCULES UNIQUENESS relies on a careful balance between **lectures** from internationally well known experts **and practical work at cutting edge experimental setups**, in neutron and synchrotron radiation large facilities

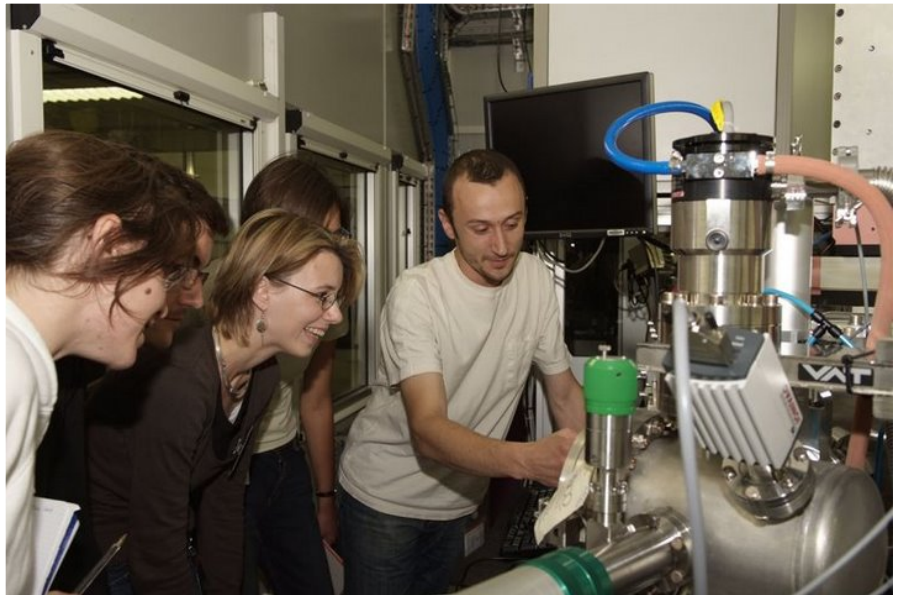
UNIVERSITÉ Grenoble Alpes

- **> 2200 participants since 1991**



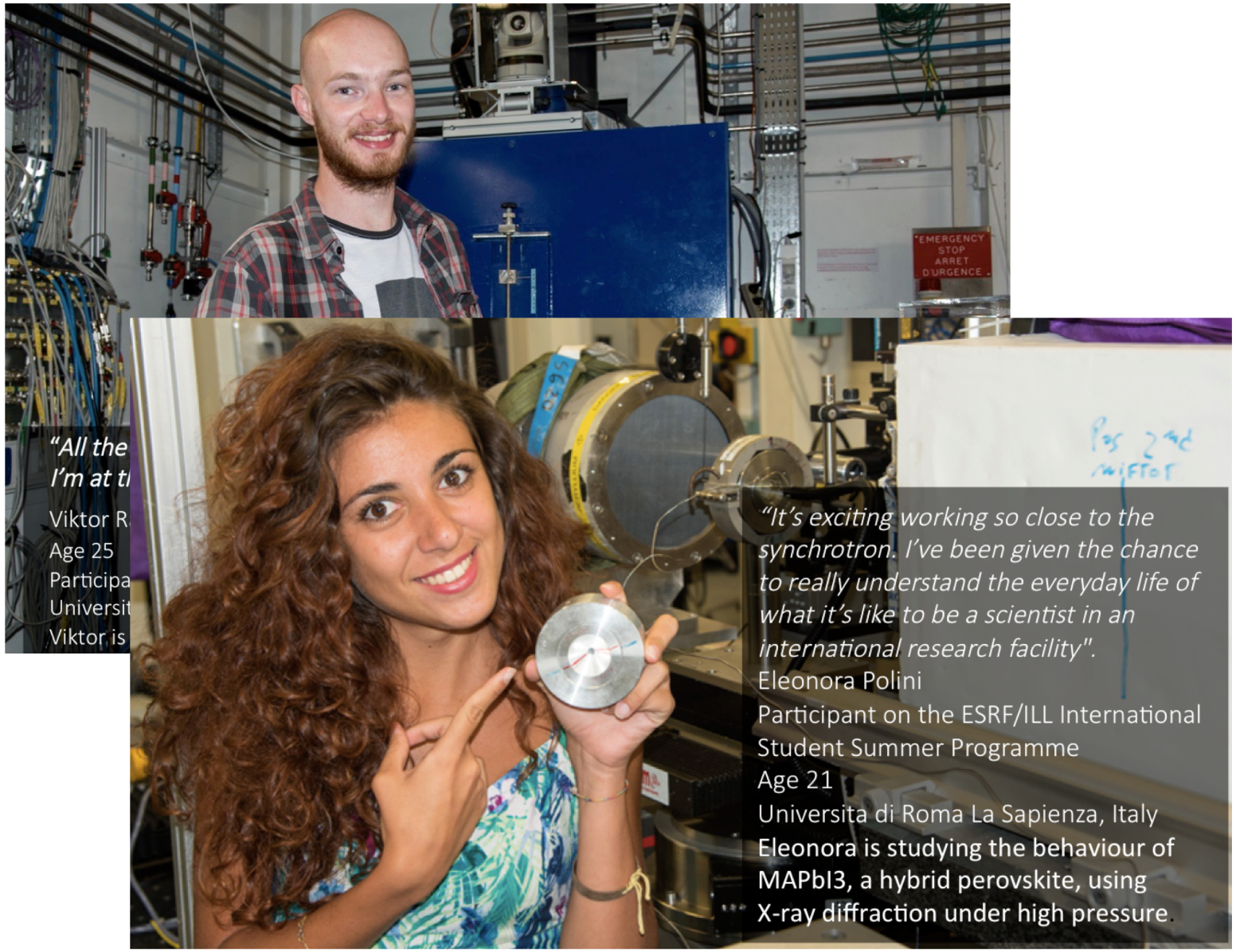
➪29 Hercules Annual Sessions (1991-2019)

➪~75 participants/session



ESRF | Institut Laue-Langevin | DESY | Elettra Sincrotrone Trieste | European XFEL | Institut Laue-Langevin | PAUL SCHERRER INSTITUT PSI | SOLEIL SYNCHROTRON

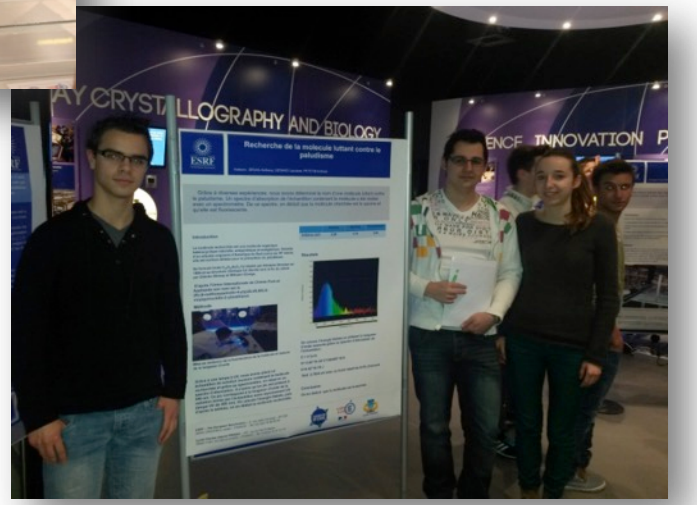
ESRF FOR THE NEXT GENERATIONS: UNDERGRADUATE STUDENT SUMMER PROGRAMME



ESRF-ILL International Undergraduate Student Summer Programme

- **Increase visibility and attractiveness of ESRF and ILL among undergraduate students**
- ~170 applications
- 20 students from 10-15 countries

Science made by and for the youngsters



SYNCHROTRON @ SCHOOL

- A partnership of ESRF and Académie de Grenoble
- ~1 500 high school students every year
  - High schools with scientific and technical specializations
- A day of full scientific immersion, with scientific experiments carried out
- Schools fr*om all over*

académie Grenoble

MINISTÈRE DE L'ÉDUCATION NATIONALE

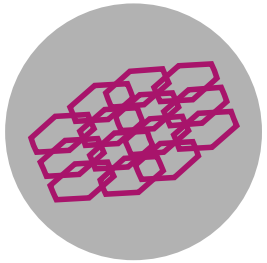
MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA RECHERCHE

X-ray science and tomorrow's challenges

Challenges and Objectives of Storage Ring and XFEL sources:

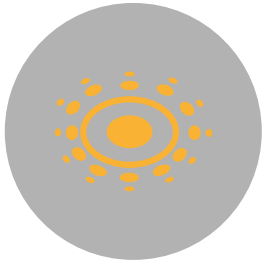
- Explore from the extremely fast:
  TIME RESOLVED SCIENCE DOWN TO THE FEMTO-SECOND
- Explore from the extremely small:
  SPACE RESOLVED SCIENCE DOWN TO THE NANO-WORLD
- New tools to investigate condensed and living matter, bridging gaps and complementing optical and electron microscopies
- News tools to address pressing technological, health and environmental challenges facing Society.

New, better science



New and innovative materials

Health & life sciences



Energy and Environment

❖ **A new paradigm for beamlines and source:** **European X-ray Free Electron Laser**
ESRF Upgrade Programme PHASE I and ESRF-EBS

ESRF X-ray science programme lines up with HORIZON EUROPE challenges

New and innovative materials | Health & life sciences | Energy and Environment

ESRF SCIENCE MISSION FOR THE COMING DECADE – ENABLING USERS SCIENCE CONTRIBUTING TO:

1. Health, health innovation, and overcoming cancer and neuro-degenerative diseases
2. Material for tomorrow, and innovative and sustainable industry
3. Clean Energy transition, sustainable energy storage and clean hydrogen technologies
4. Planetary (terrestrial and extra-terrestrial) formation
5. Environmental and climatic challenges, water supplies and earth atmosphere
6. Bio-based economy and food security
7. Humanity and world cultural heritage

EBS SCIENCE PROGRAMME STATUS AND MID-TERM REVIEW: PREPARING EBS SCIENCE

Purple Book January 2008

ESRF UPGRADE PHASE I
180 M€ (2009-2015):

- ESFRI ROADMAP 2006-2016
- ESFRI LANDMARK (2016)
- IN TIME – WITHIN BUDGET

19 NEW BEAMLINES:

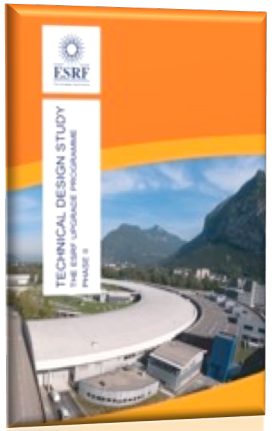
- many specialised on *nano*-science
- Proven successful and productive (2015-2018)
- Study for a new brighter storage ring X-ray source

ESFRI

European Commission

ESRF EBS: AN AMBITIOUS NEW STANDARD FOR SYNCHROTRON STORAGE RINGS

Purple Book January 2008



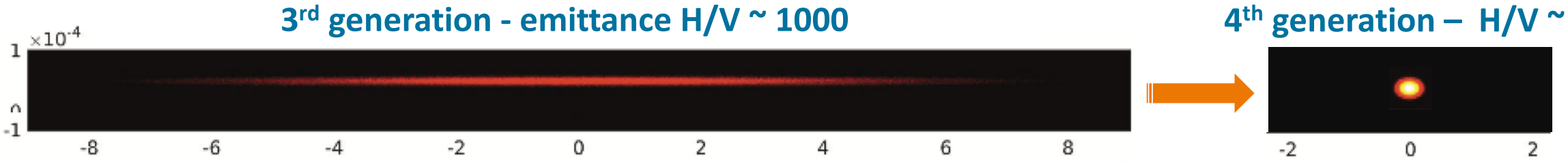
Orange Book January 2015

ESRF UPGRADE PHASE I
180 M€ (2009-2015):
ESFRI ROADMAP 2006-2016
ESFRI LANDMARK (2016)
In time – within the budget
- **19 new beamlines specialised on nano-science**
- **Study for a new brighter storage ring X-ray source**

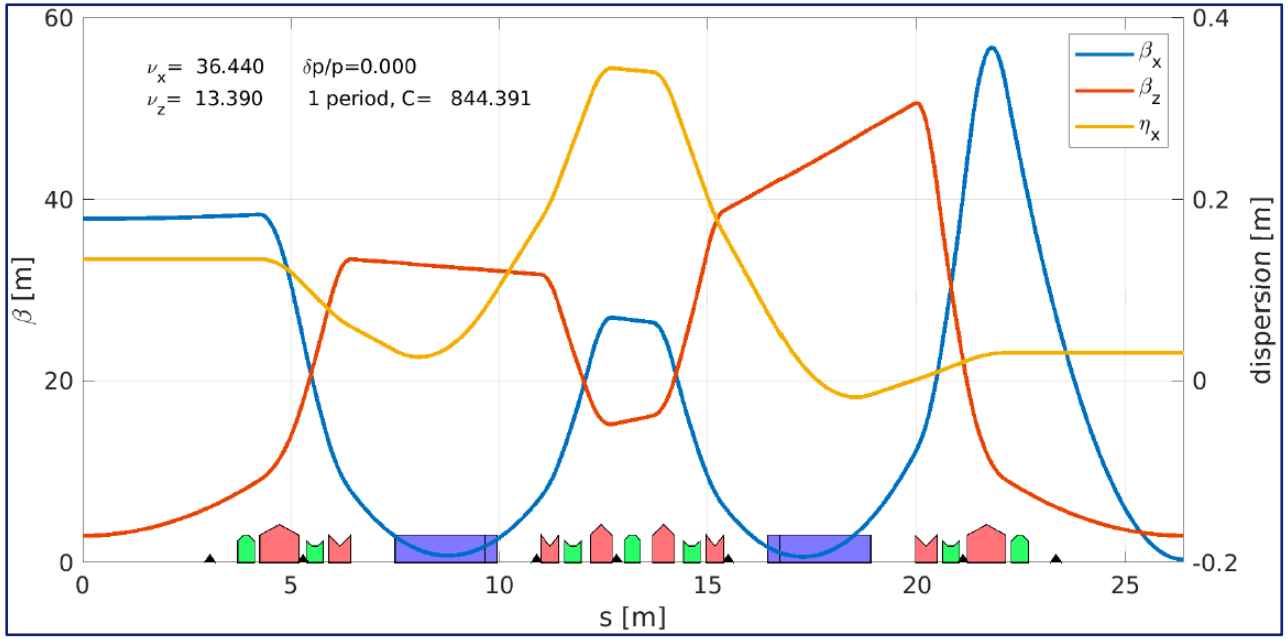
ESRF-EBS
Extremely Brilliant Source
150M€ (2015-2022)
ESFRI LANDMARK (2016):
- **The 1st high-energy fourth-generation synchrotron**
- **4 new flagship beamlines**
- **Detectors, Instrumentation and Data Management Infrastructure**

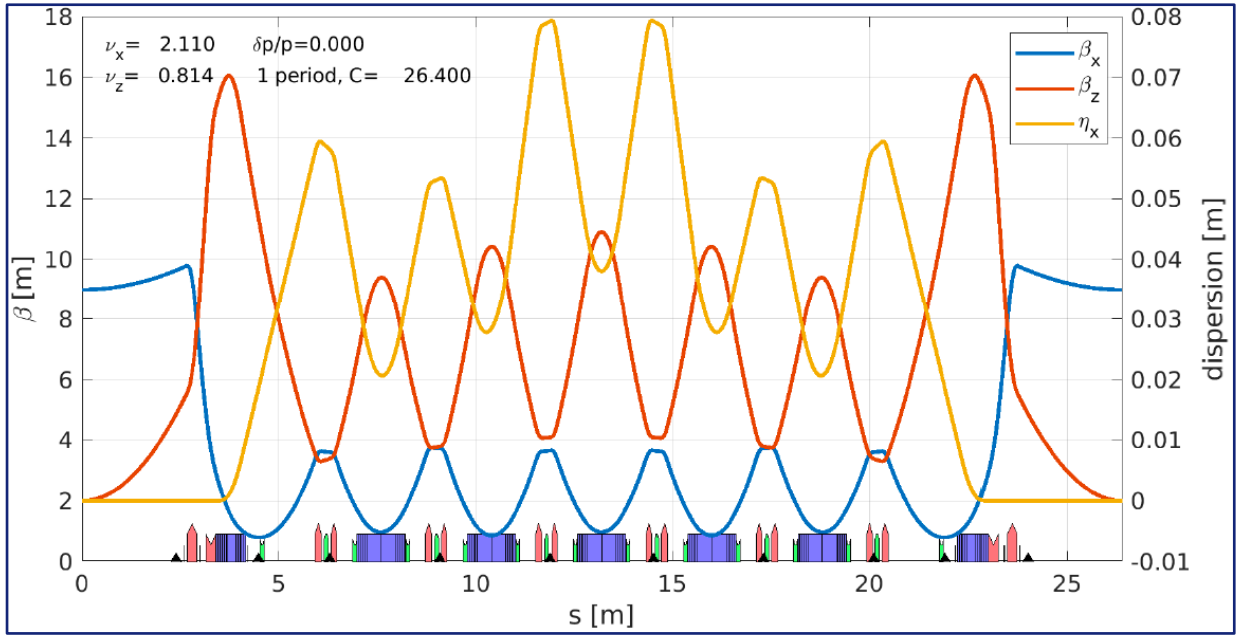
ESFRI

European Commission



D. Einfeld (1993): from the double-bend to the multiple (*n*)-bend Chasman-Green achromat lattice to drastically reduce the Horizontal Emittance

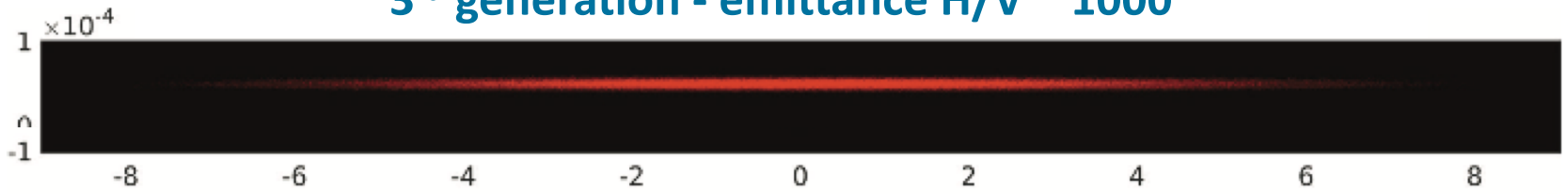




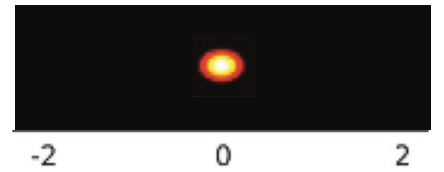
Unfortunately, however, this approach is a *no-go* for upgrading 6+ GeV rings (ESRF, P. Elleaume 2005):

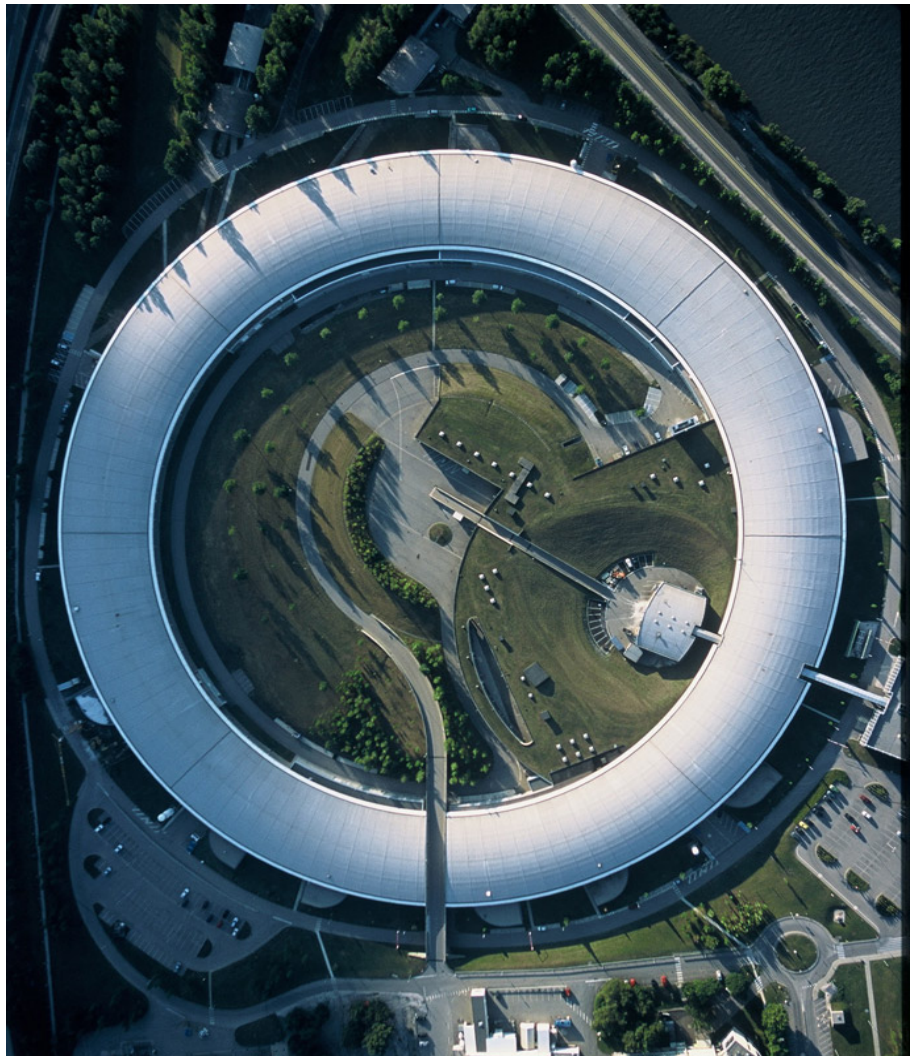
- Very small Dynamical Aperture (unstable Operation)
- Quadrupole and sextupole optics with field gradients out of technological reach
- Not for an Upgrade keeping the same electron energy and the same ring tunnel

3rd generation - emittance H/V ~ 1000



4th generation – H/V ~ 1

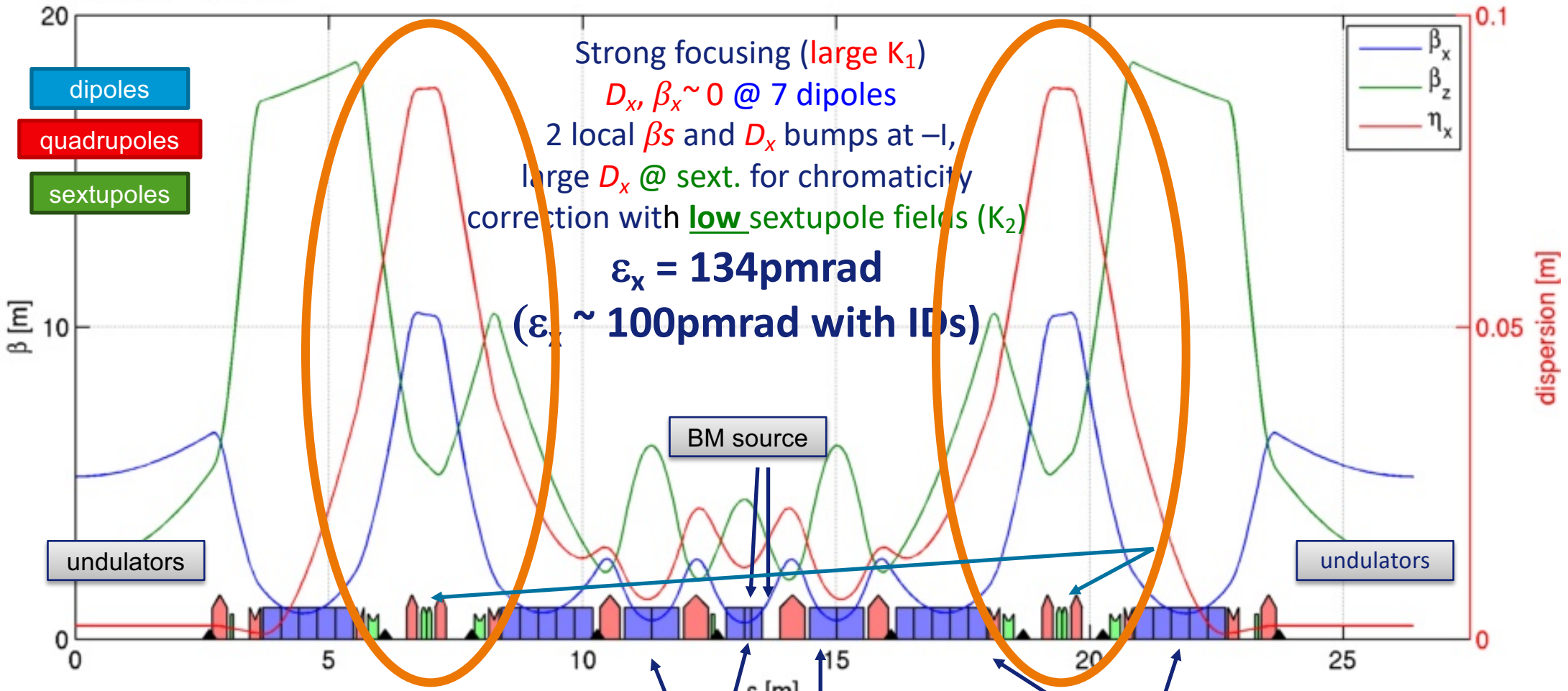




No real interest to upgrade existing high energy storage ring facilities

But …. a factor of at least $(23/4)^2 \sim 40$ of potential horizontal emittance reduction is still looking at you …

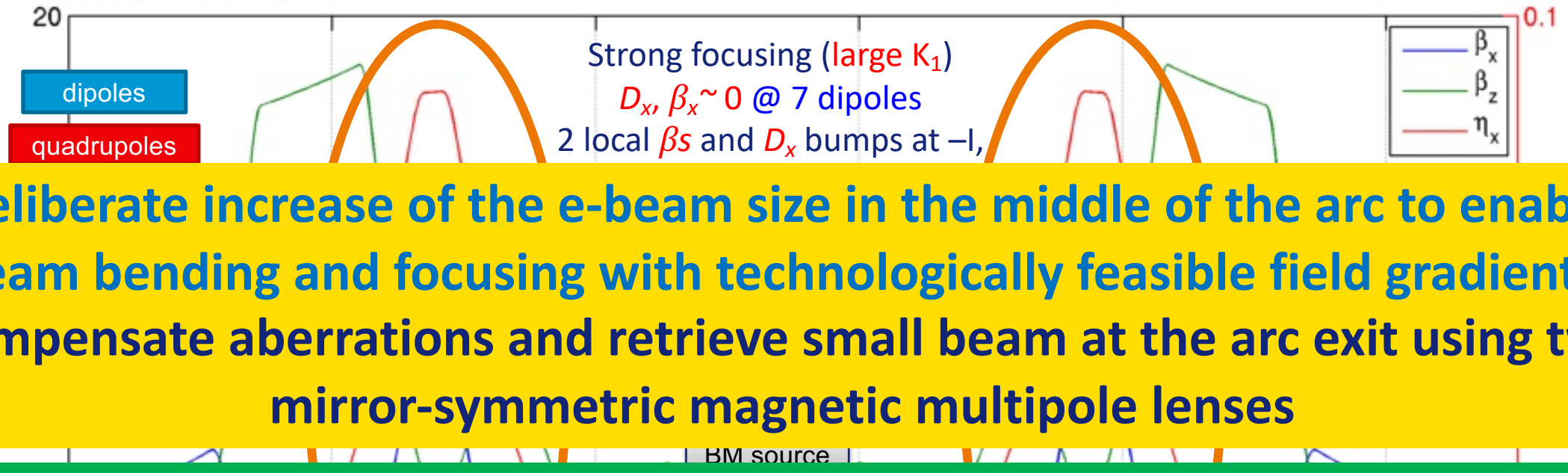
2012 – 2013: P. RAIMONDI AND ESRF COLLEAGUES INVENT AND DEVELOP THE HMBA LATTICE CONCEPT



$$E_x \propto \frac{\beta_x D_x}{\rho} \quad (@\,dipoles)$$

$$Chromaticity\ [>0] \propto -\beta_x K_1\ (@\,quads)\ + D_x K_2\ (@\,sext.)$$

2012 – 2013: P. RAIMONDI AND ESRF COLLEAGUES INVENT AND DEVELOP THE HMBA LATTICE CONCEPT



Deliberate increase of the e-beam size in the middle of the arc to enable beam bending and focusing with technologically feasible field gradients.

Compensate aberrations and retrieve small beam at the arc exit using two mirror-symmetric magnetic multipole lenses

Upgrades of existing storage rings to a new low horizontal emittance lattice is no longer a dream.

90% of the infrastructure preserved.

ESRF-HMBA is the "FUTURE" and MBA is the "PAST"

$$Chromaticity\ [>0] \propto -\beta_x K_1\ (@quads)\ + D_x K_2\ (@sext.)$$

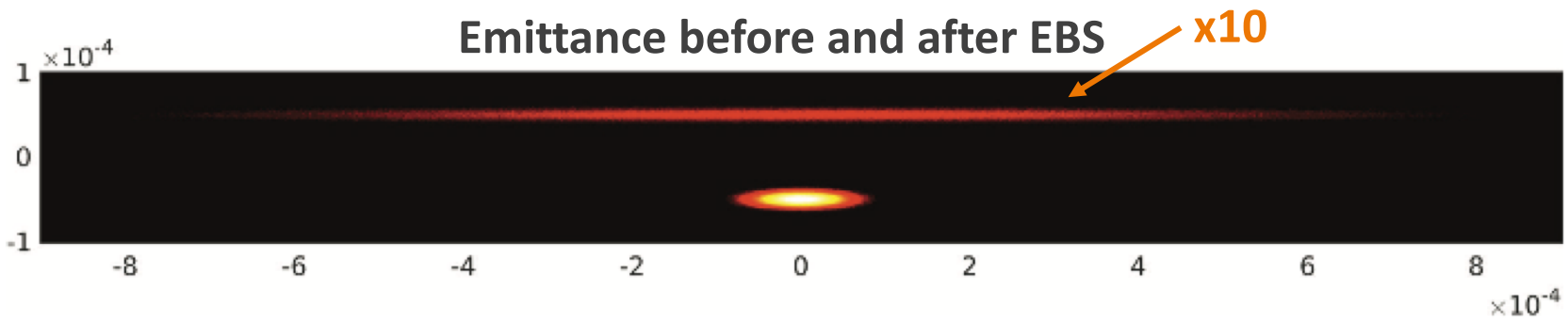
Dipoles + quadrupole gradient

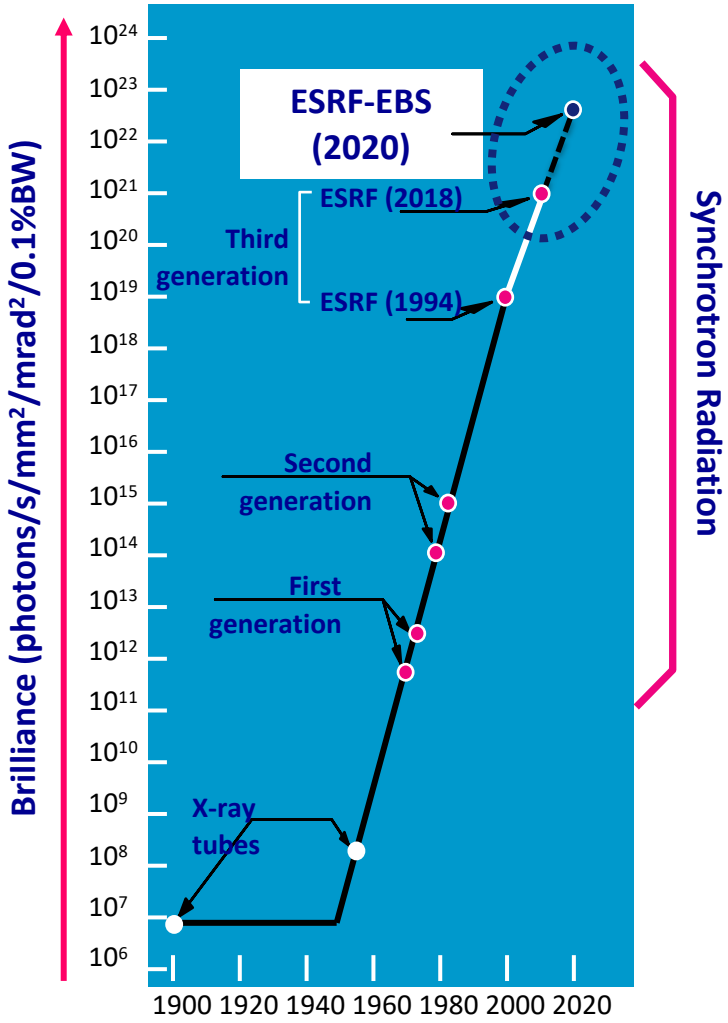
Dipoles longitudinal gradient

ESRF Extremely Brilliant Source
The 1st high-energy 4th-generation synchrotron light source

Pantaleo Raimondi wins the Gersch Budker IPAC17 Prize

For his invention of the "Hybrid Multi Bend Achromat" (HMBA) lattice, which has become the design basis of most future "fourth generation" synchrotron sources in the world





2015-2018: Design, Engineering, Prototyping, Procuring, Testing, Assembling the 129 girders of EBS

Moderate gradient Quadrupole & dipole-quadrupole magnets

Vacuum Chamber support

SS vacuum chambers

High-gradient quadrupole & sextupole magnets

Vacuum valves

Octupole magnets

Four families of 32 girders each (128)

One girder on a straight section for injection

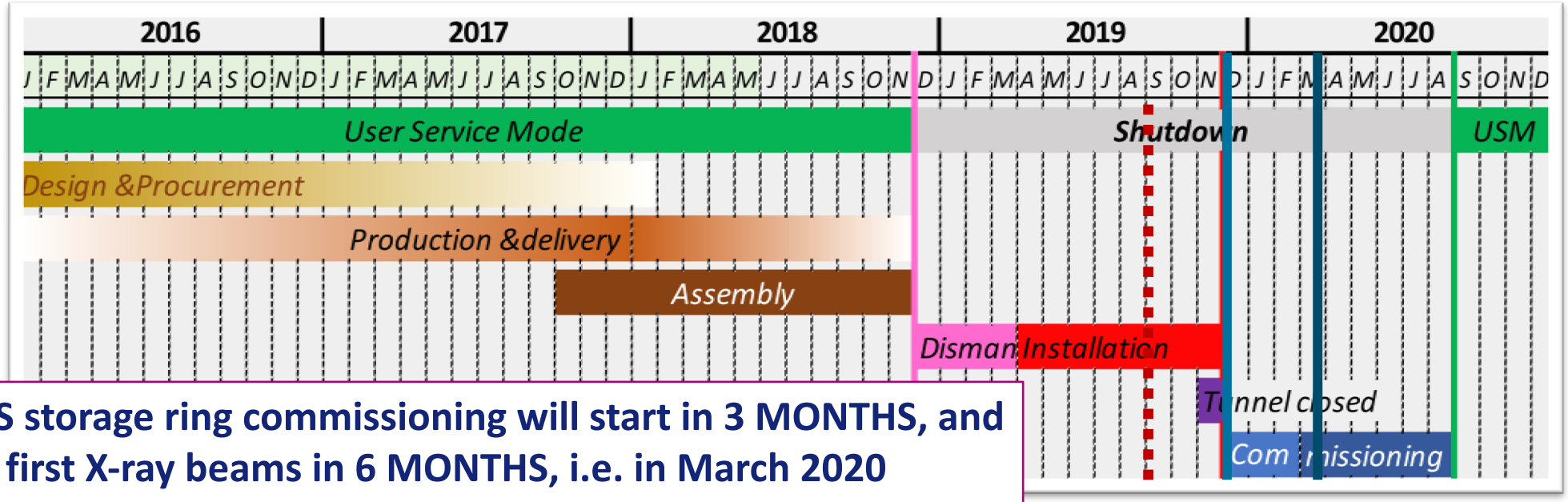
Corrector Magnet

Vacuum chambers & absorbers

Girders

EBS STORAGE RING STATUS: MASTER SCHEDULE

EBS schedule



- The EBS storage ring commissioning will start in 3 MONTHS, and deliver first X-ray beams in 6 MONTHS, i.e. in March 2020
- 28 JUNE 2019 – THE EBS SR PROGRAMME IS ON SCHEDULE

months)

10 December	2018	End of USM & start of shutdown (*20 months*)
		Dismantling *(3 months)* and installation *(8 months)*
8 November	2019	Tunnel closed
December	2019	Accelerator commissioning *(4 months)*
March	2020	Beamlines & Accelerator commissioning *(5 months)*
25 August	2020	Back to User Mode

EBS STORAGE RING: CONSTRUCTION OF THE 129 GIRDERS

2015-2018: Design, Engineering, Prototyping, Procuring, Testing, Assembling the 129 girders of EBS

Moderate gradient Quadrupole & dipole-quadrupole magnets

Vacuum Chamber support

SS vacuum chambers

High-gradient quadrupole & sextupole magnets

Vacuum valves

Octupole magnets

Four families of 32 girders each (128)

One girder on a straight section for injection

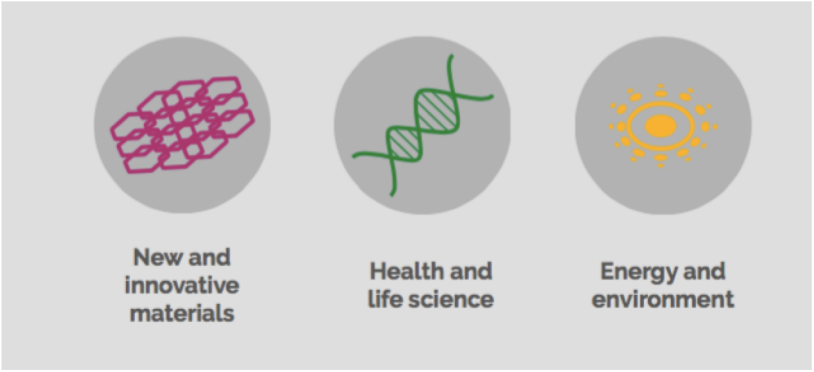
Corrector Magnet

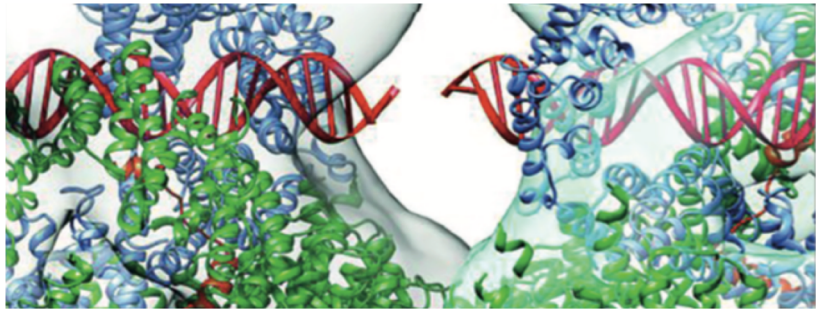
Vacuum chambers & absorbers

Girders

LAST BEAM FROM THE ORIGINAL ESRF DBA STORAGE RING: 8:00 AM ON 10 DECEMBER 2018

EBS EXPERIMENTAL PROGRAMME: THE FOUR FLAGSHIP BEAMLINES





EBS will enable scientists to discover new opportunities in X-ray science on the investigation of materials and living matter

Construction of 4 flagships beamlines:

EBSL1 – Beamline for Coherent X-rays Dynamics and Imaging Applications

EBSL2 – Beamline for Hard X-ray Diffraction Microscopy

EBSL3 – Beamline for High throughput Large Field Phase-contrast Tomography

EBSL8 – Beamline for Serial Macromolecular Crystallography

New and better science unveiling the secrets of nature

Detect new phenomena

Go to extreme conditions

Images Down to Below(?) 1 nm

Higher throughput and faster dynamics

ESRF is opening a new page in X-ray science

Address complexity in condensed and living matter:

- Functioning of fundamental molecular processes: overcoming cancer and neuro-degenerative diseases

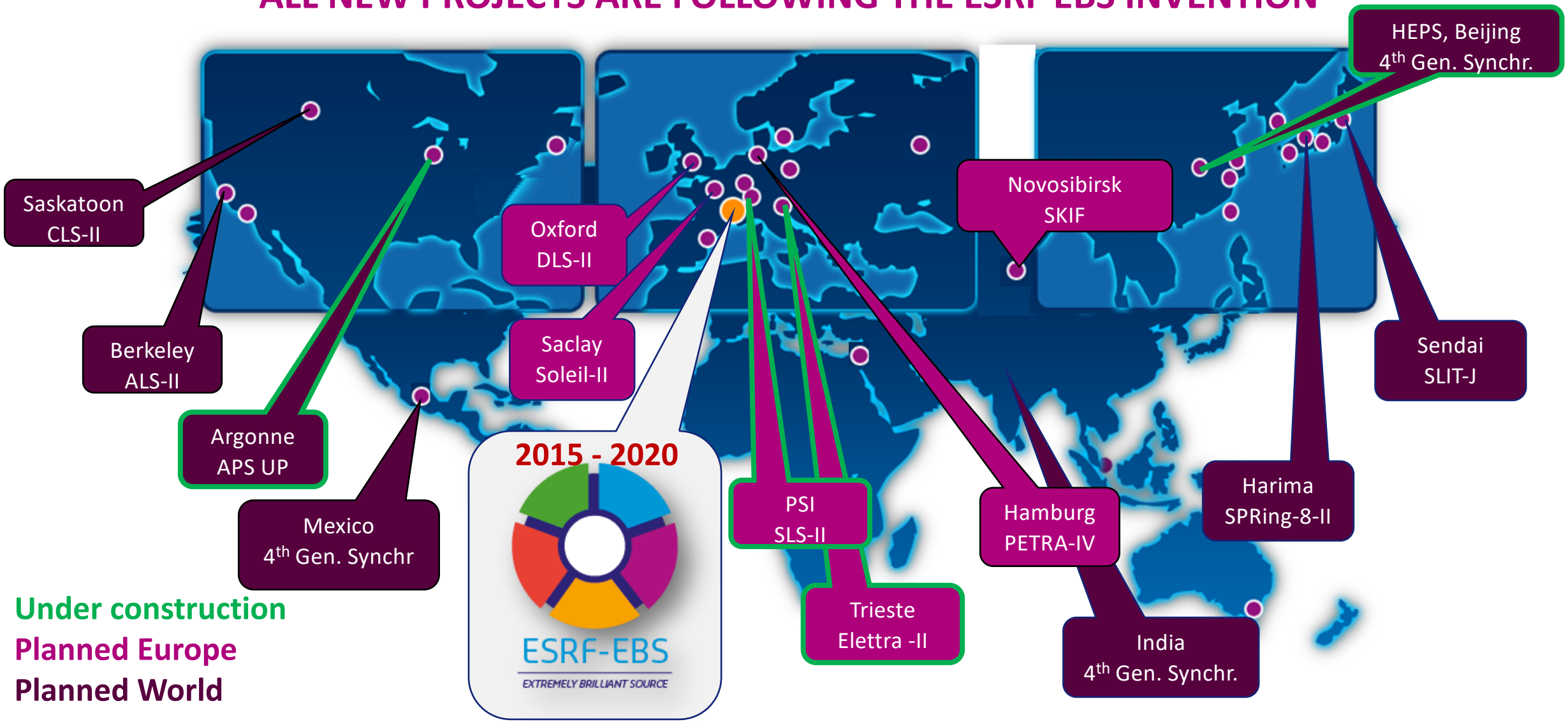
Integrated Structural Biology

- Understanding organisation, processing, use and life-cycle sustainability of materials for tomorrow: energy materials for hydrogen production and storage; bio-mineralisation processes; image formation in photonic devices; domain fluctuations in high-Tc superconductors, innovative material processing
- And much more …

Integrated Material Science

FUTURE SYNCHROTRON STORAGE RINGS IN THE WORLD

ALL NEW PROJECTS ARE FOLLOWING THE ESRF EBS INVENTION



THE EBS STORAGE RING WILL ENABLE A NEW SCIENCE REACH TO ESRF USERS

WITH A FULL BEAMLINE PORTFOLIO FROM 2020

ESRF UPGRADE PROGRAMME ☛ EBS RING AND ~40 BEAMLINES FROM 2021

~ A decade ahead of any other synchrotron facility in the world

Offering a new and revolutionary science reach to the synchrotron users

Thanks for your attention! @esrfsynchrotron