
ESRF
The European Synchrotron

ESRF - ILL

3rd Summer School Undergraduate Students

Welcome!

Science at synchrotrons and the ESRF

Francesco Sette

WHAT DOES IT MAKE THE EPN SCIENCE CAMPUS SO SPECIAL?

- ESRF: the brightest synchrotron source in the world
- ILL: the most powerful research reactor in the world

PRESQU'ILE SCIENTIFIQUE

Large scale European laboratories

Academic partners

Research organisations

Local Authorities

THE GIANT ALLIANCE

GIANT Alliance

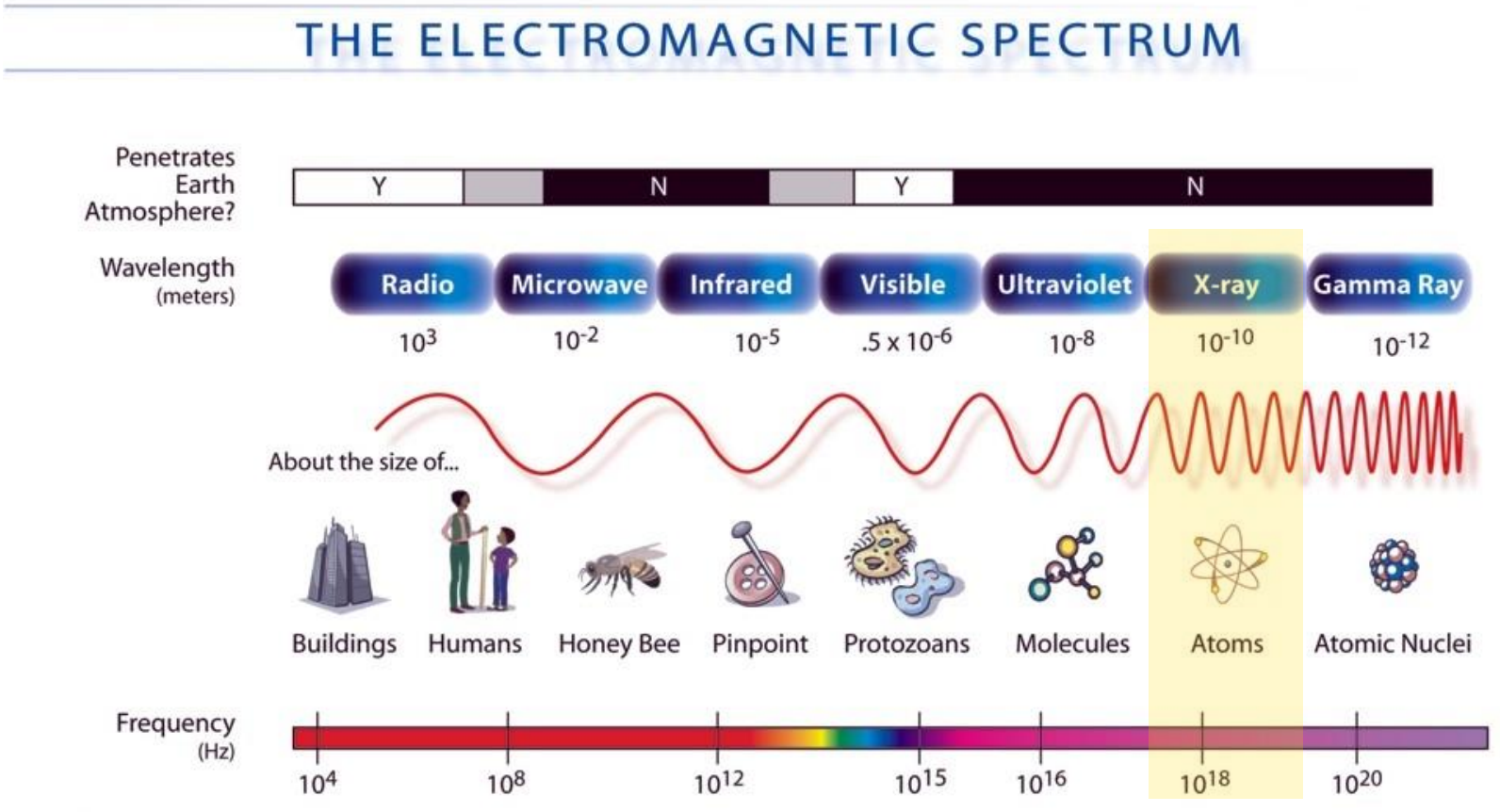
EMBL ESRF NEUTRONS FOR SCIENCE cea CNRS UNIVERSITÉ Grenoble Alpes GRENOBLE ECOLE DE MANAGEMENT

- Responding to societal challenges: health, environment and digital revolution
- Transcending barriers to create excellence
- Enhancing international visibility and attractiveness of the site
- Fostering higher education, research and interest to industry
- Boosting technological innovation
- Harmonizing urban and scientific development

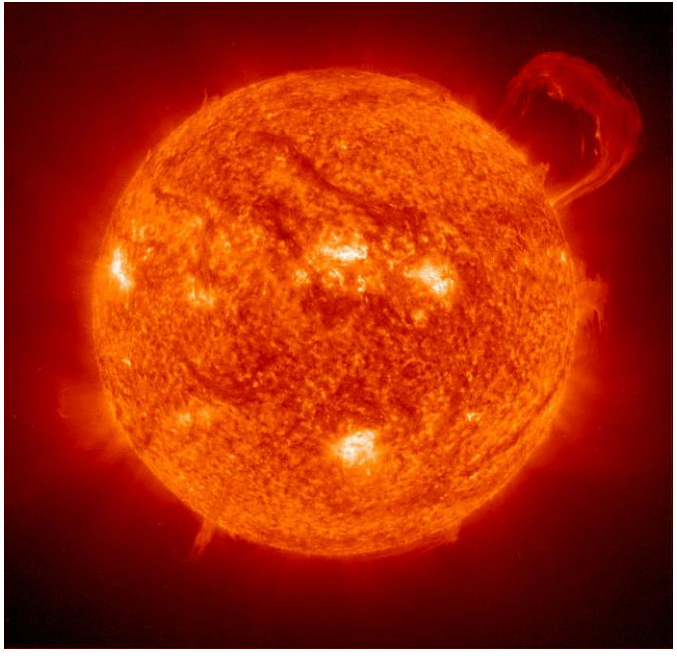
GRENOBLE AND ITS SURROUNDINGS: A BEAUTIFUL REGION

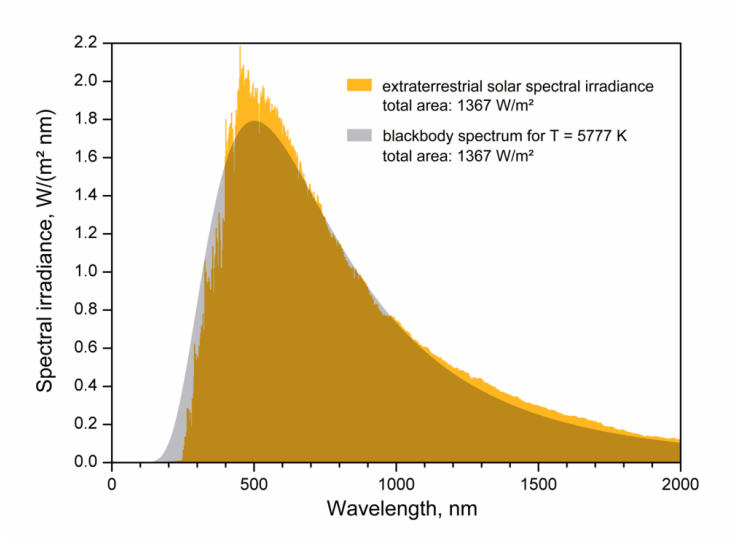
- X-ray science and the development of Synchrotron Radiation as a unique source of light
- Examples and future perspectives

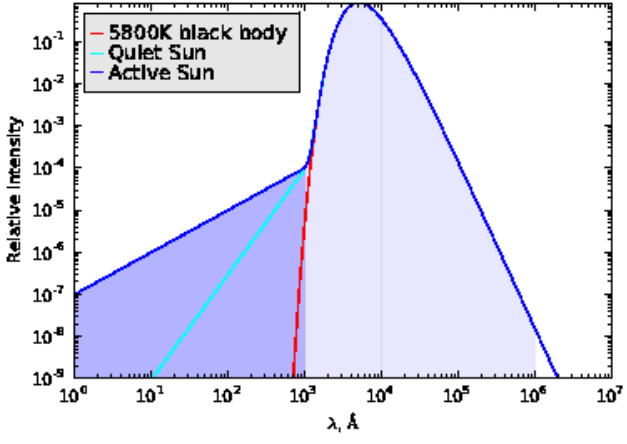
LIGHT


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

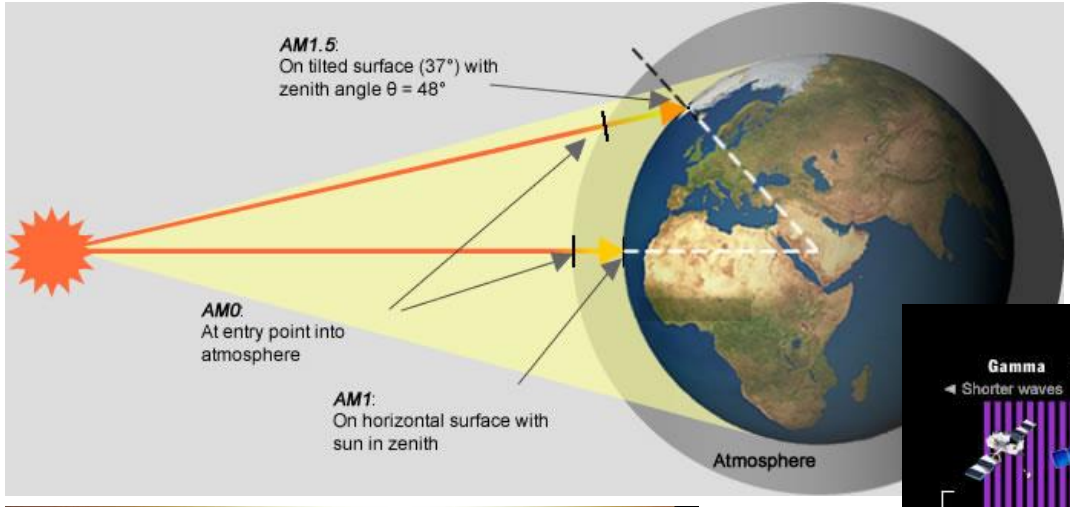
THE SUN

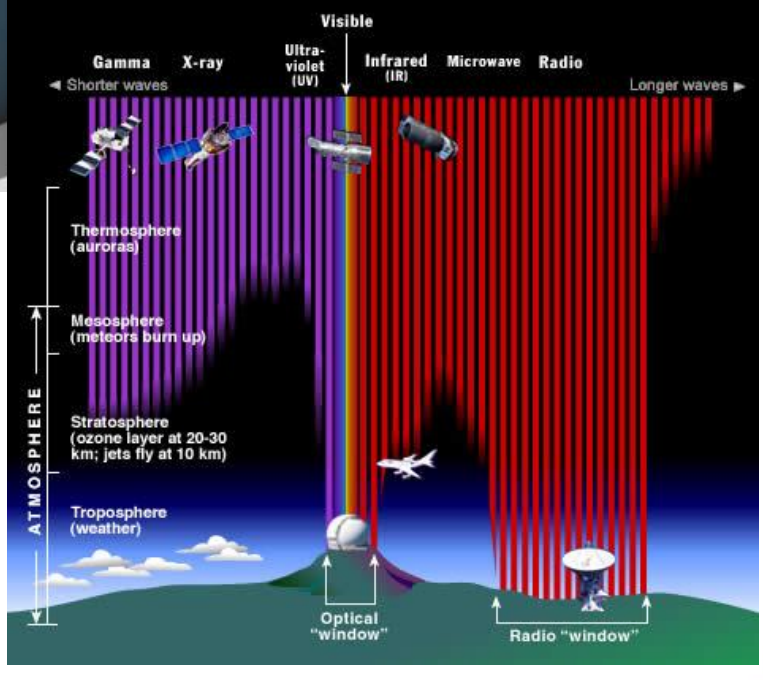



extraterrestrial solar spectral irradiance
total area: 1367 W/m²
blackbody spectrum for T = 5777 K
total area: 1367 W/m²
Spectral irradiance, W/(m² nm)
Wavelength, nm
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
0
500
1000
1500
2000


5800K black body
Quiet Sun
Active Sun
Relative Intensity
λ, Å

FILTERING SUN LIGHT





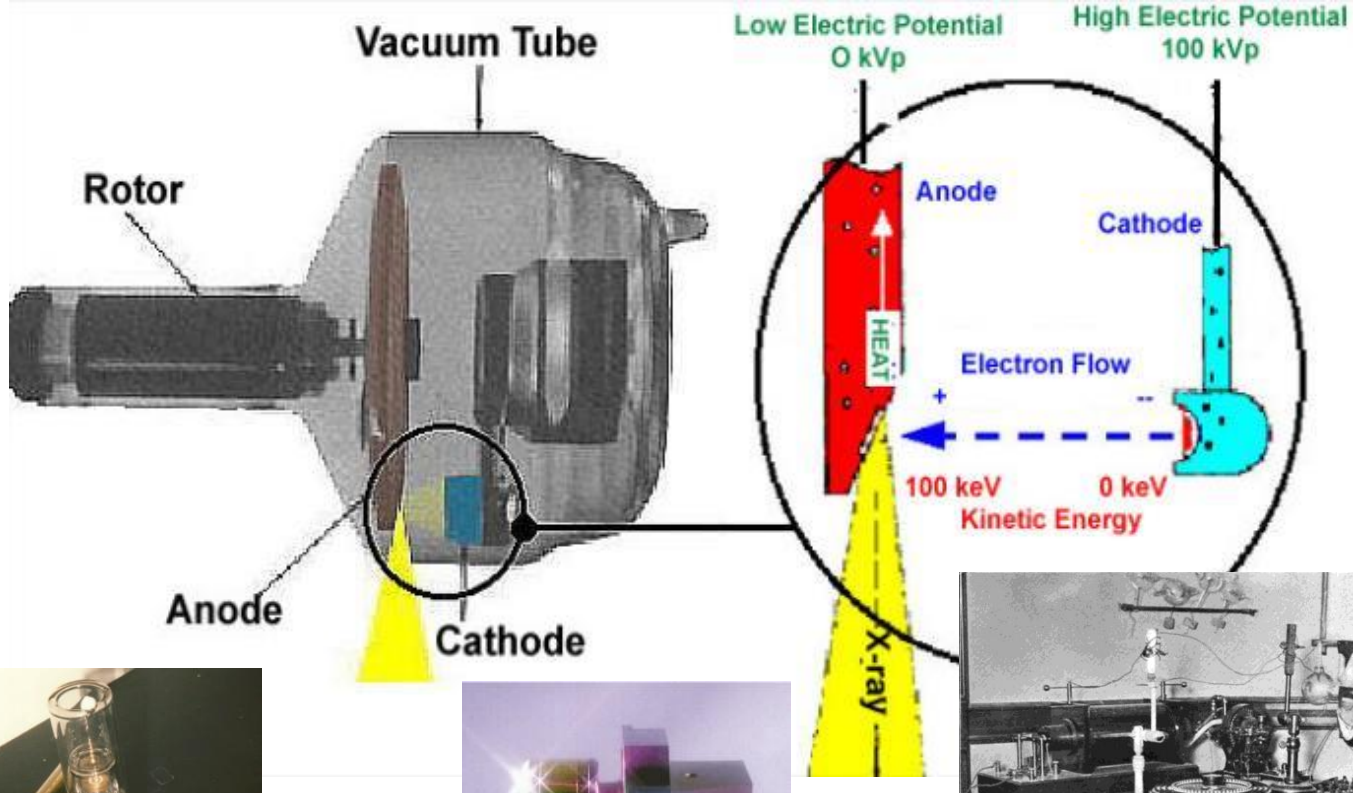
X-RAYS: DISCOVERY IN 1895 AND THE FIRST STEPS

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

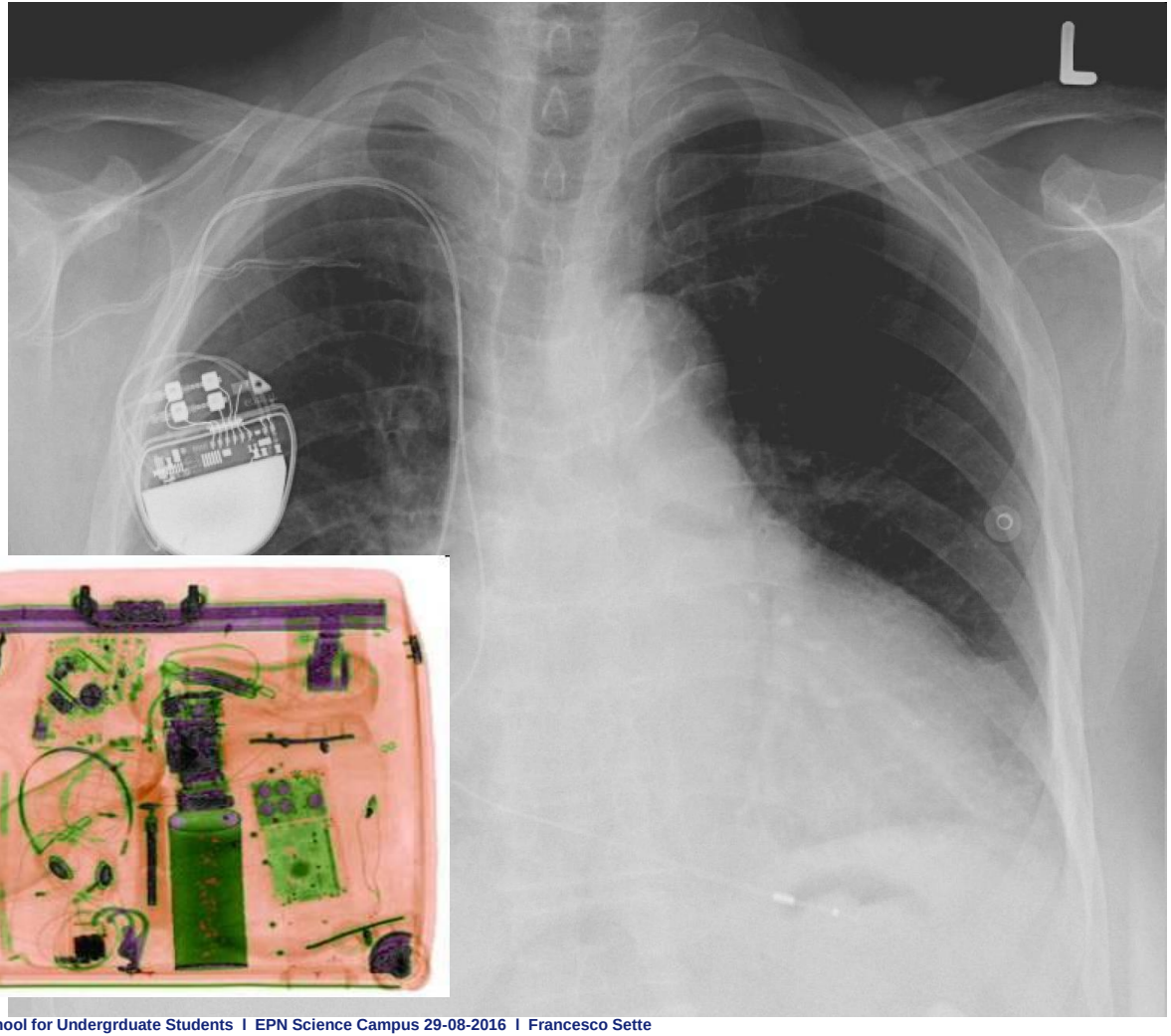
Wilhelm Conrad Röntgen (1845-1923)
First Nobel Prize for Physics, 1901

The first "röntgenogram"
8 November 1895

X-RAY SOURCE

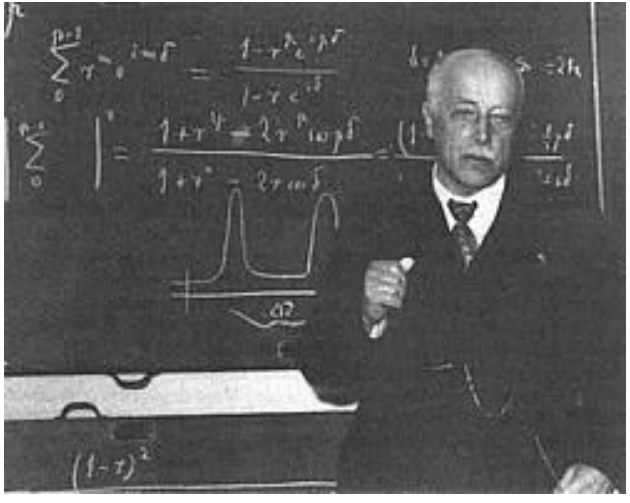

Vacuum Tube
Rotor
Anode
Cathode
Low Electric Potential
O kVp
High Electric Potential
100 kVp
Anode
Cathode
HEAT
Electron Flow
+
--
100 keV
0 keV
Kinetic Energy
X-ray

X-RAY IMAGING

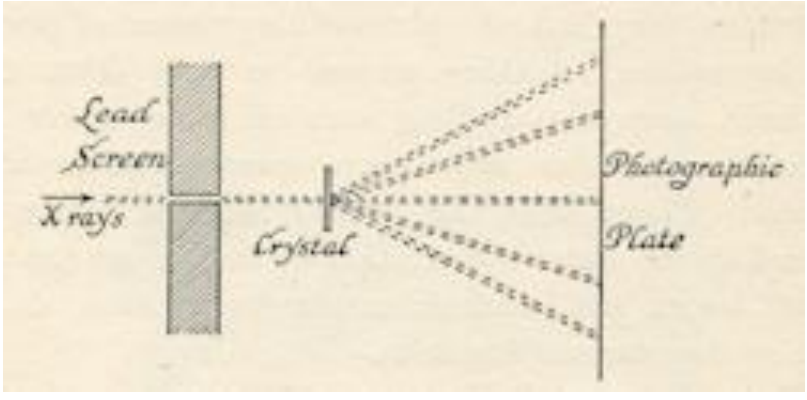


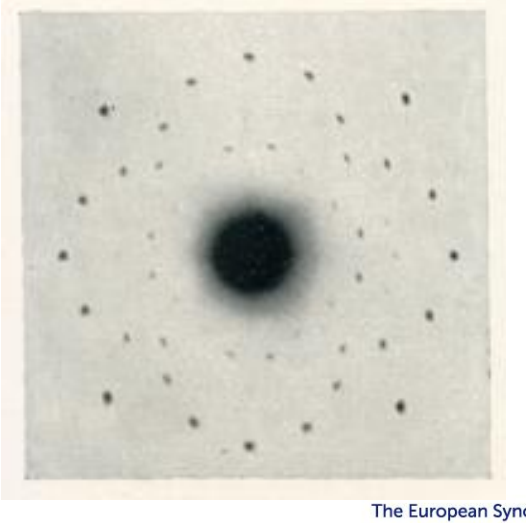
X-RAYS: DISCOVERY OF X-RAY DIFFRACTION IN 1912

X-rays ... some kind of waves



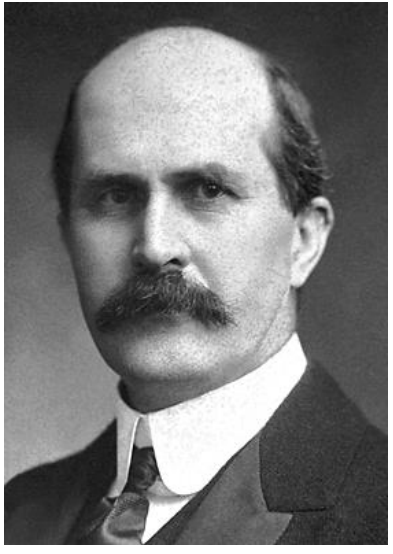
Max Von Laue (1879-1960)
Nobel Prize for Physics, 1914

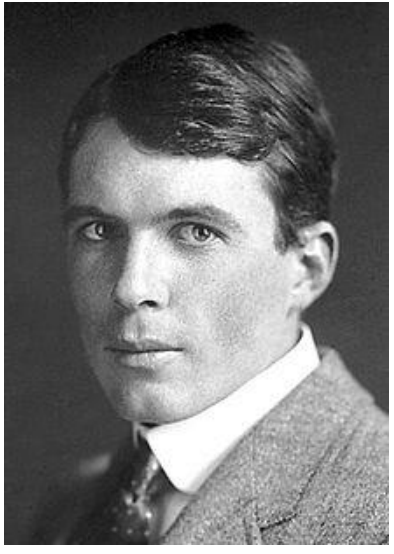


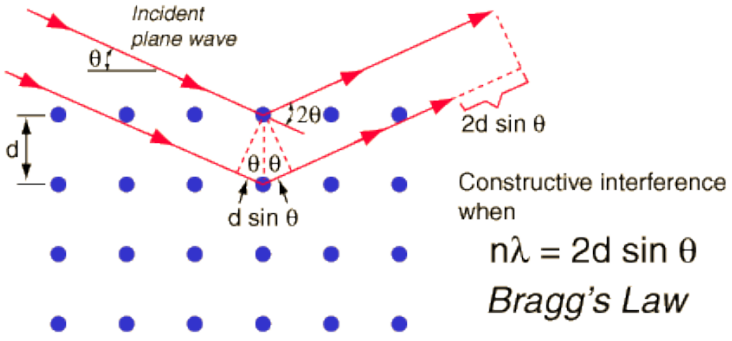


X-RAYS: DISCOVERY OF BRAGG'S LAW AND CRYSTALLOGRAPHY IN 1913

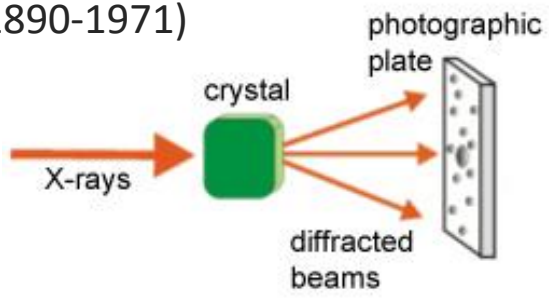
X-rays ... some kind of waves with "atomic resolution"

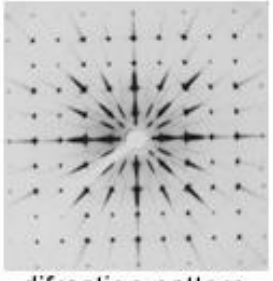




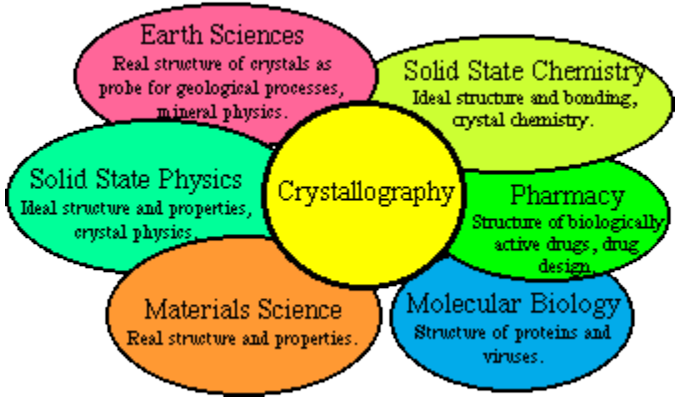


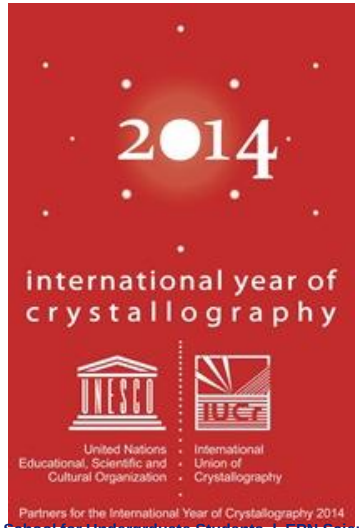
W.H. (1862-1942) and W.L. Bragg(1890-1971)
Nobel Prize for Physics, 1915



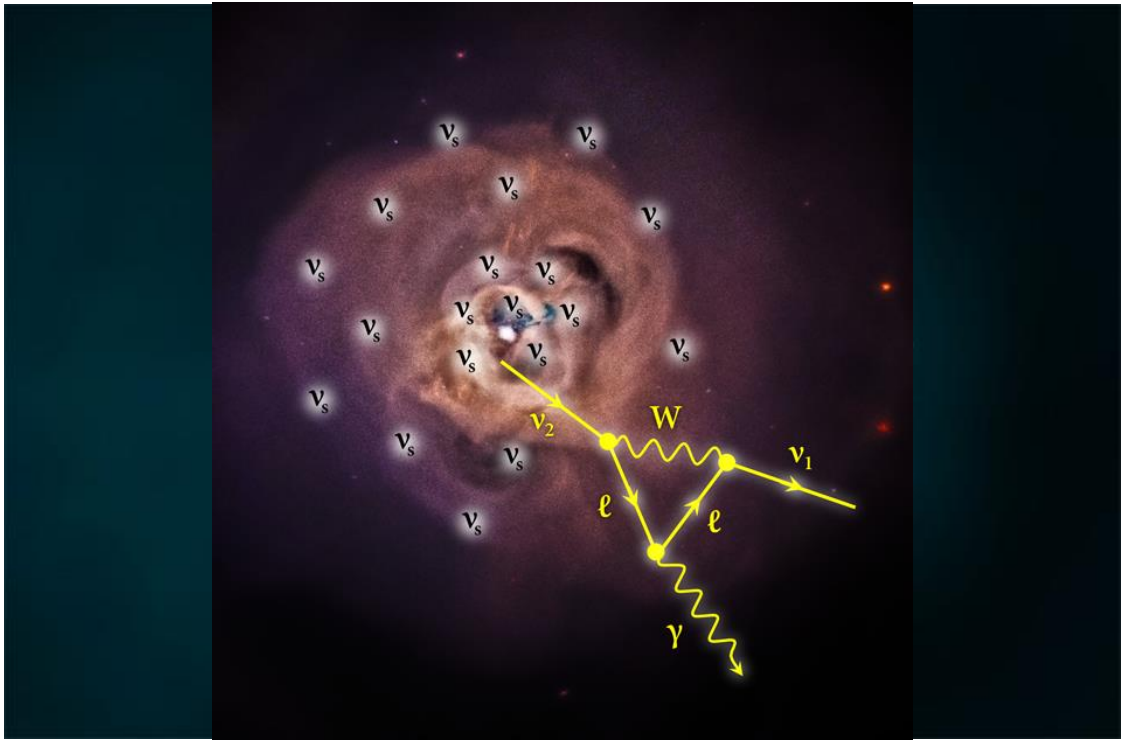


X-ray crystallography: understanding materials and living matter





Mysterious X-Ray Signal Could Reveal Dark Matter



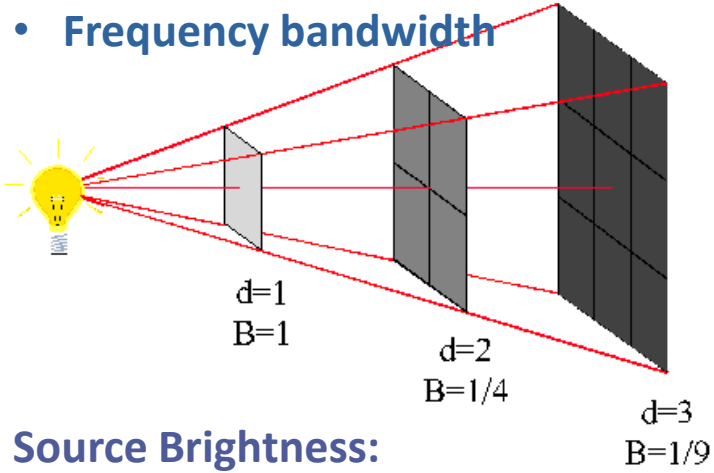
An X-ray image of the hot gas in the central region of the Perseus Cluster of galaxies, taken by the Chandra X-ray Observatory
http://arxiv.org/pdf/1402.4119v1.pdf

X-RAY SOURCES: TUBES

Conventional X-ray Sources

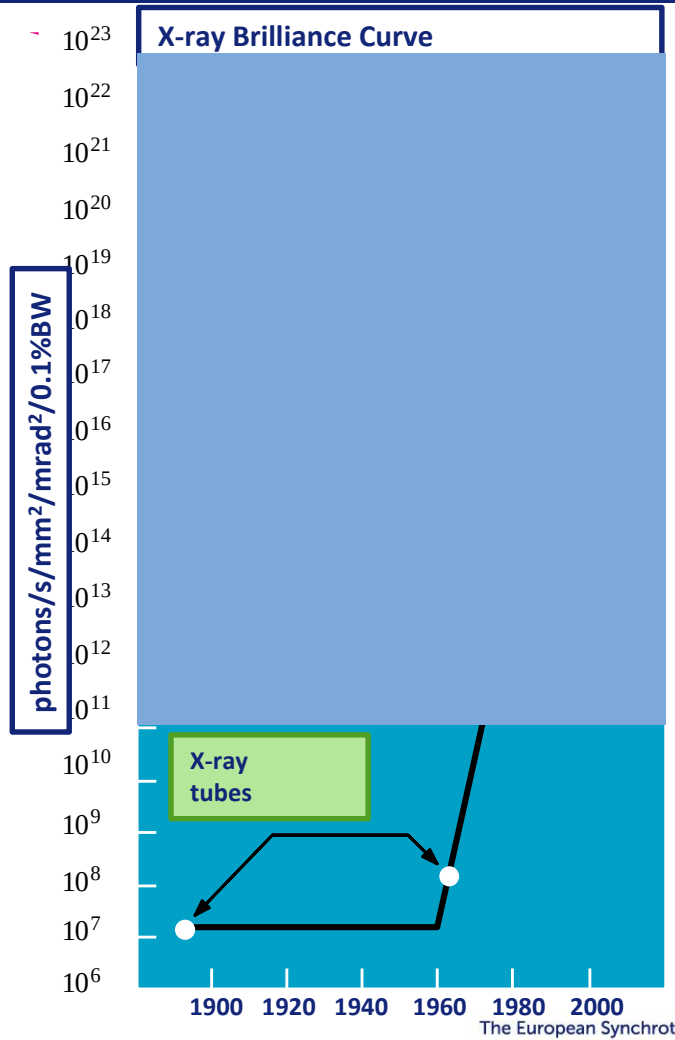
Source Brilliance:
Number of photons normalized to

- **Transverse source area**
- **Source emission angle**
- **Frequency bandwidth**



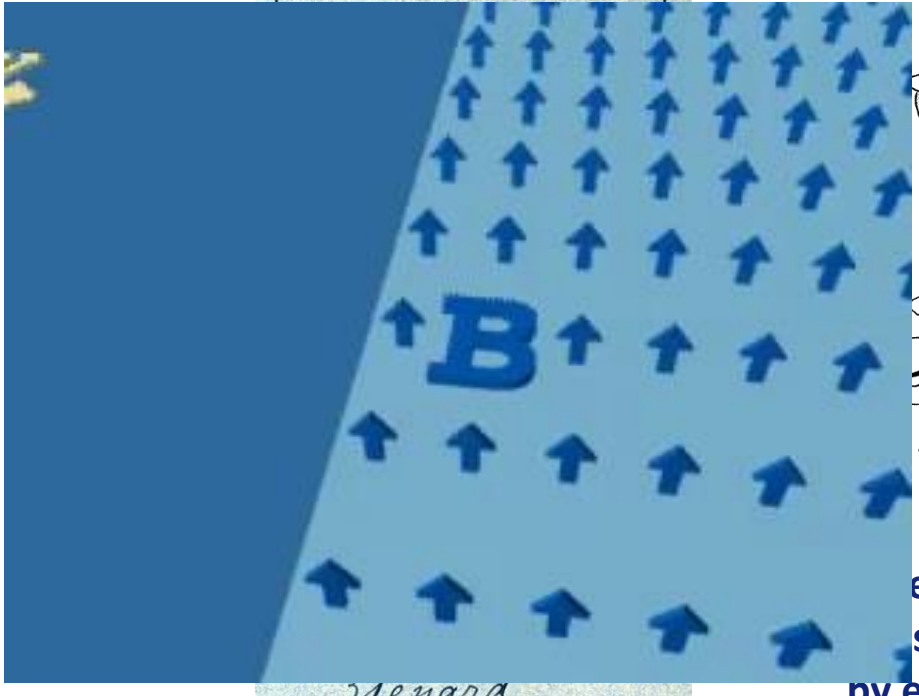
Source Brightness:
Number of photons normalized to

- **Unit area**
- **Frequency bandwidth**



RELATIVISTIC ELECTRONS

Alfred-Marie LIENARD (1869-1958)



by emission of light

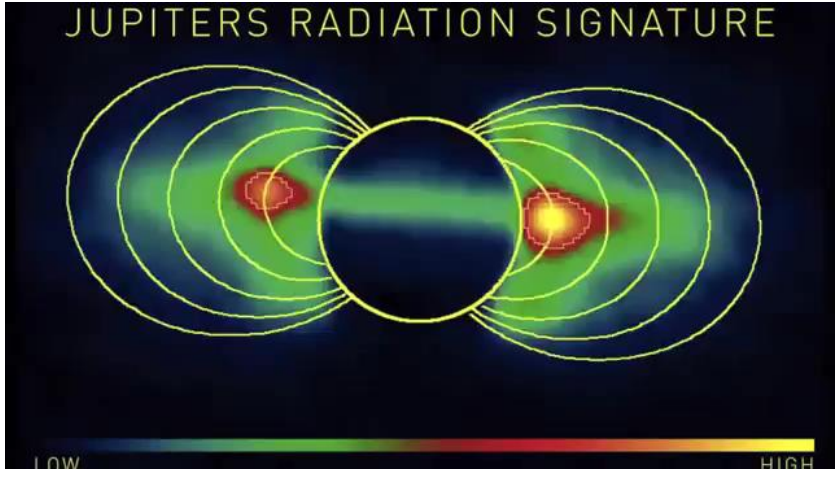
"Champ électrique et magnétique produit par une charge électrique concentrée en un point et animée d'un mouvement quelconque"
L'Éclairage Électrique, 16(27), pp. 5-14 (1898)

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.

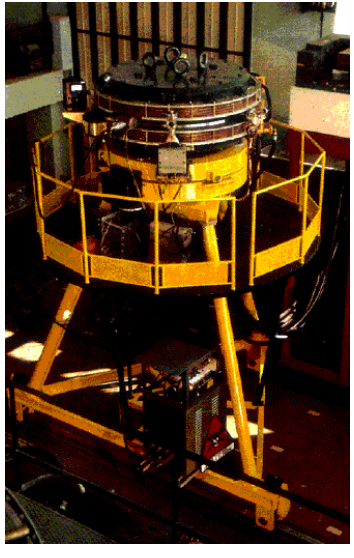
First Observation of Synchrotron Radiation

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

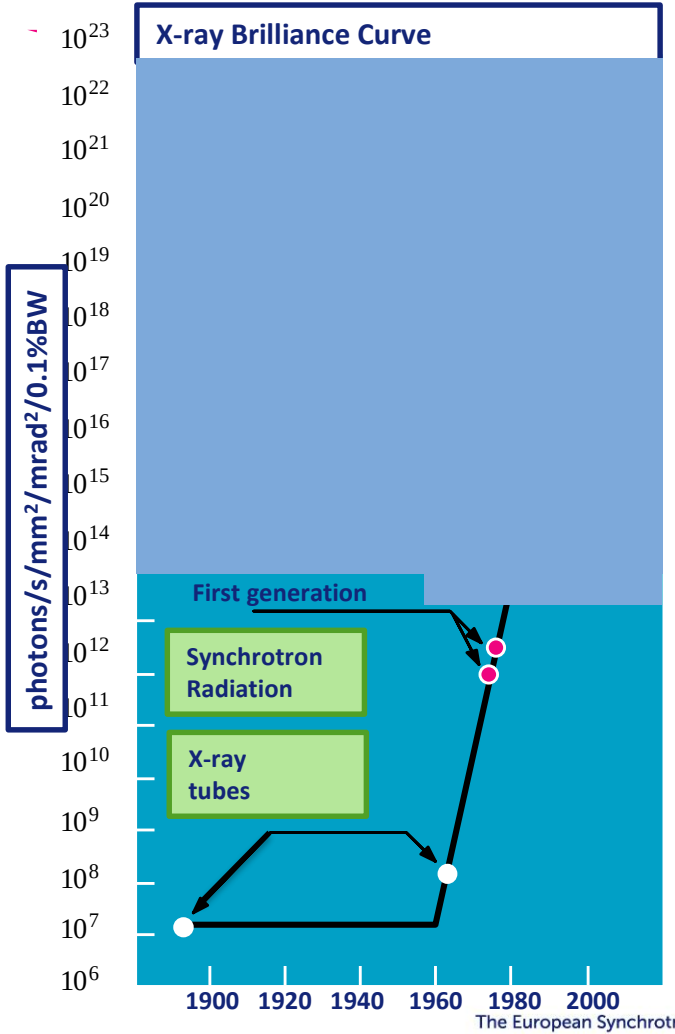
X-RAY SOURCES: TUBES AND SYNCHROTRON LIGHT

Conventional X-ray Sources and Synchrotron Radiation

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



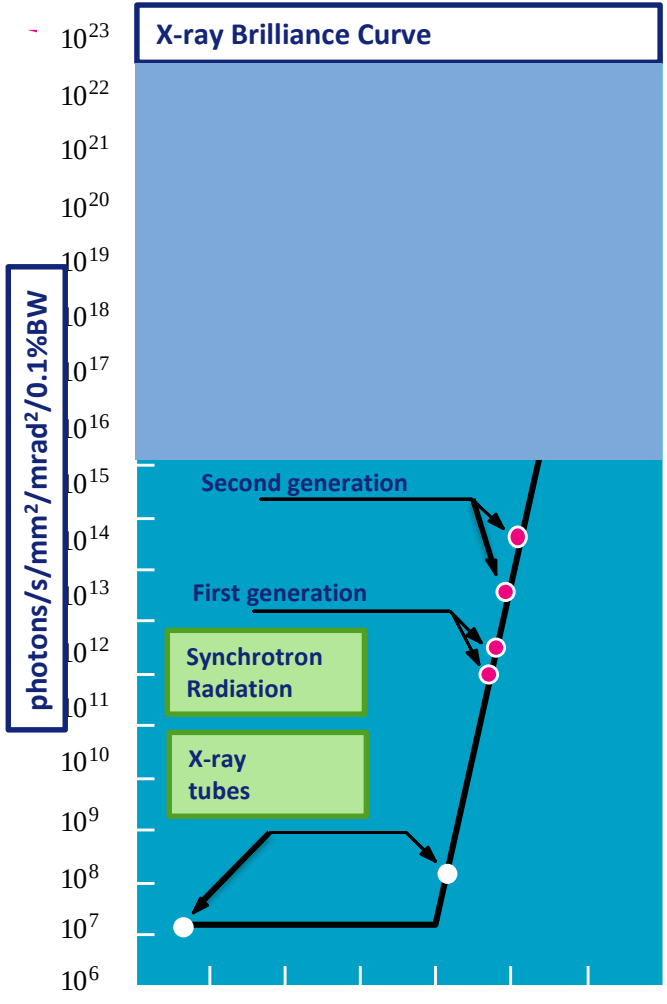
ADA in Frascati (INFN),
the first storage ring for electron and positron beams rotating in opposite Directions.
Proposed by **Bruno Touschek (1921-1978), in 1960**



X-RAY SOURCES: TUBES AND SYNCHROTRON LIGHT

Conventional X-ray Sources and Synchrotron Radiation

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

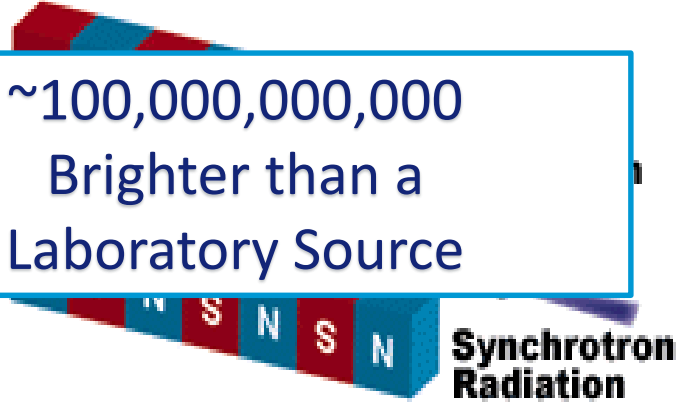


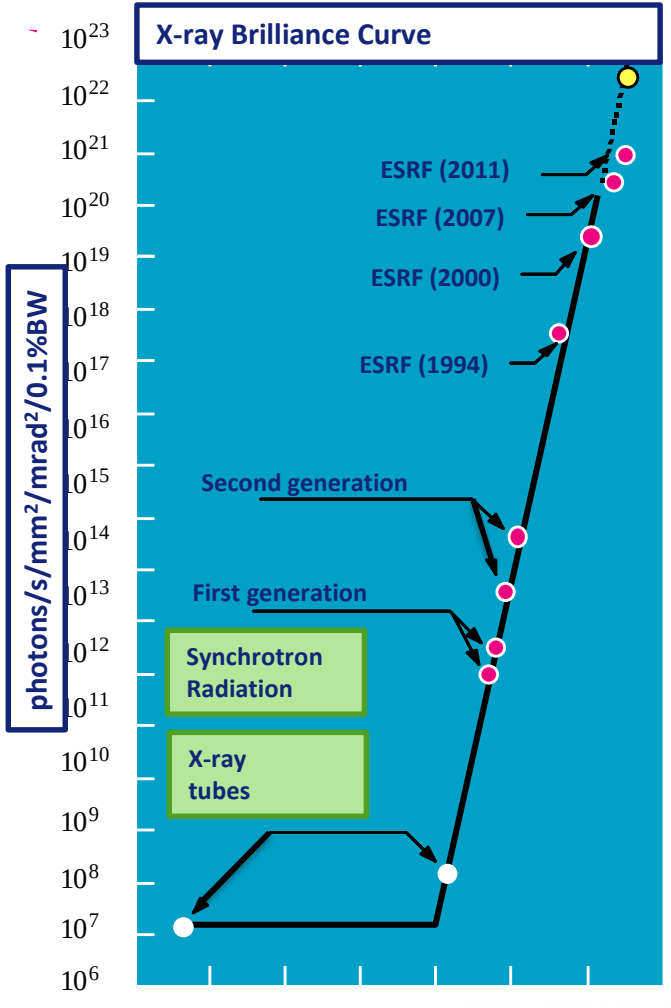
X-RAY SOURCES: TUBES AND SYNCHROTRON LIGHT

Conventional X-ray Sources and Synchrotron Radiation

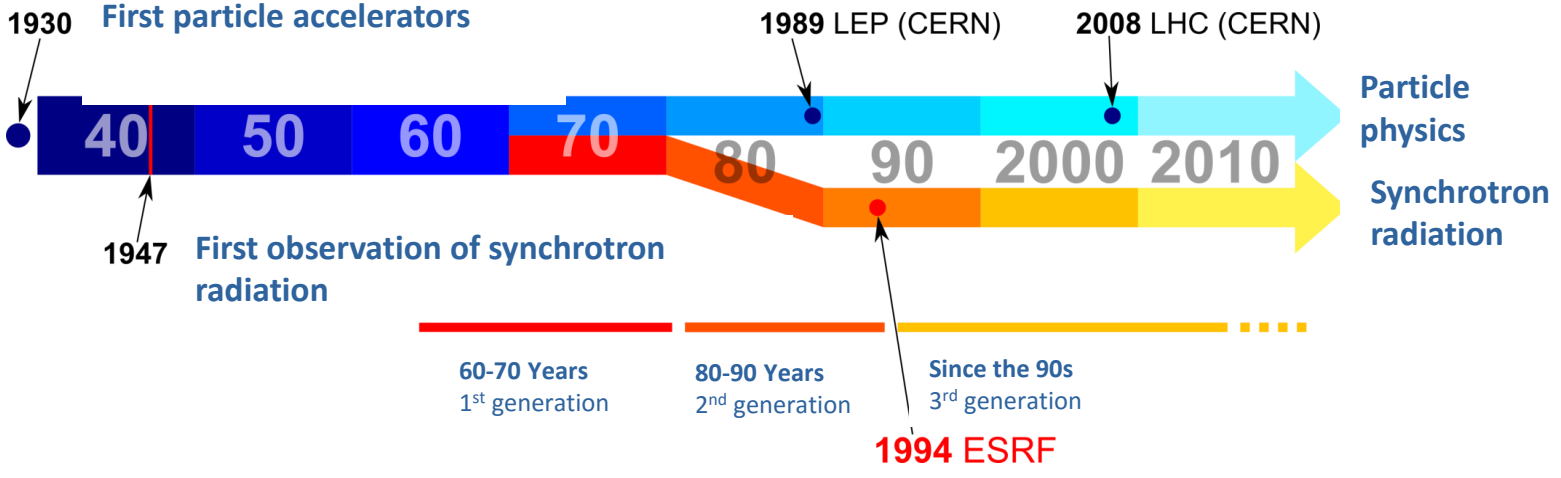
Chasman-Green Lattice
Brookhaven, 1975
The way to very low vertical emittance storage rings, and to very high brightness
Third Generation SR Sources
ESRF 1992

~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 of 27 km

13 TeV protons on two opposite trajectories

700 million euros

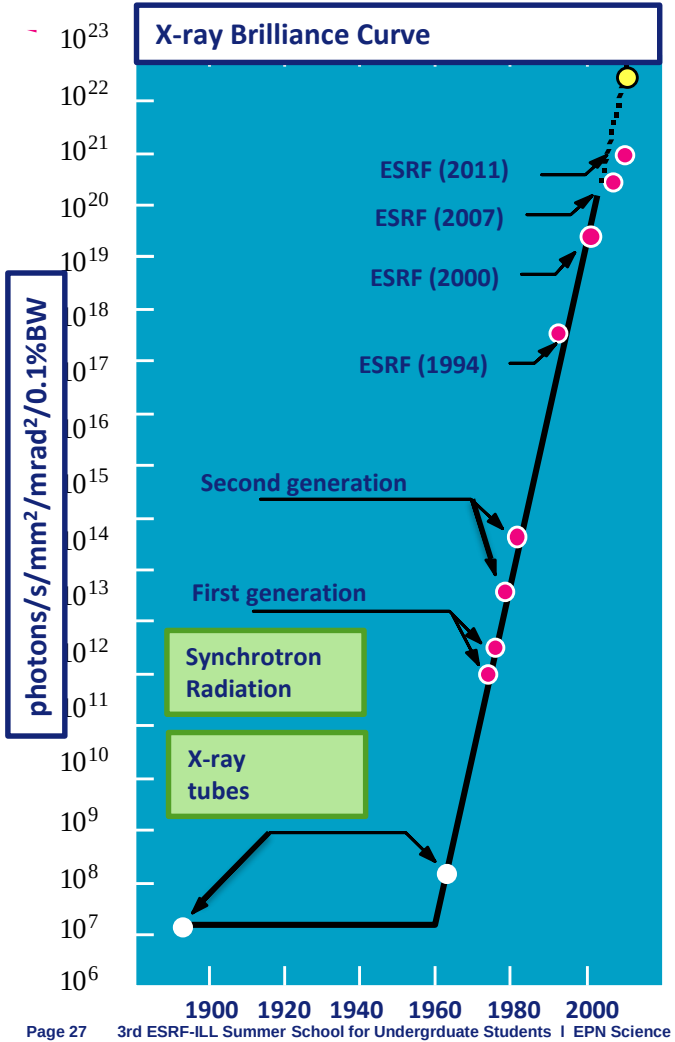
- **ESRF**

The storage ring for synchrotron light: circumference of 844 m

6 GeV electrons

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

2009 – PETRA III – 6 GeV

1996 – Advanced Photon Source - 7 GeV

1994 – European Synchrotron Radiation Facility – 6 GeV

1997 – Super Photon RING 8 GeV

X-RAY SCIENCE : DISCOVERING WHERE ATOMS ARE AND HOW THEY MOVE

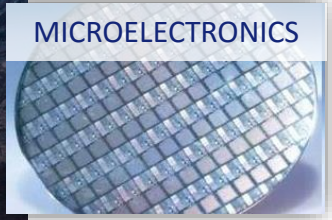
Fundamental and applied studies on materials and living matter

ADVANCED MATERIALS

ENERGY & ENVIRONMENT

HEALTH & FOOD

MICROELECTRONICS



CONSUMER PRODUCTS

EXTREME CONDITIONS

METALLURGY

PETROCHEMICALS

CULTURAL HERITAGE

X-RAY SCIENCE : ELEVEN NOBEL PRIZES IN PHYSICS, AND EIGHT IN CHEMISTRY

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

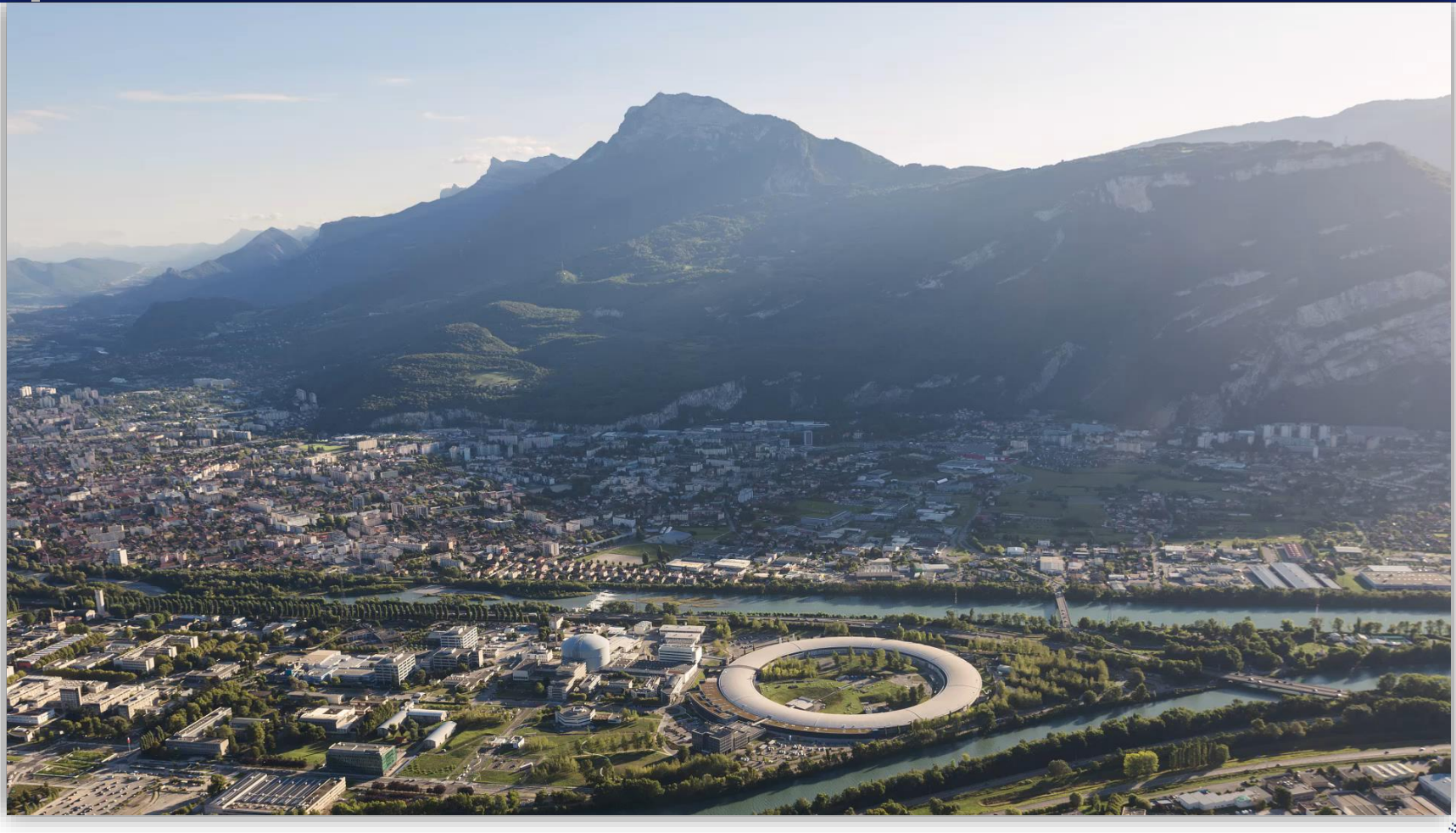
PHYSICS

1981 - Kai M. Siegbahn
"for his contribution to the development of high-resolution electron spectroscopy"
1961 - Rudolf Ludwig Mössbauer
"for his researches concerning the resonance absorption of gamma radiation and … the effect which bears his name"
1958 - Pavel Alekseyevich Cher
"for the discovery and the interp
1936 - Victor Franz Hess
"for his discovery of cosmic radia
1927 - Arthur Holly Compton
"for his discovery of the effect na
1924 - Karl Manne Georg Siegb
"for his discoveries and research
1917 - Charles Glover Barkla
"for his discovery of the characte
1915 - Sir William Henry Bragg
"for their services in the analysis
1914 - Max von Laue
"for his discovery of the diffracti
19015 - Philipp Eduard Anton v
"for his work on cathode rays"
1901 - Wilhelm Conrad Röntge
"in recognition of the extraordin

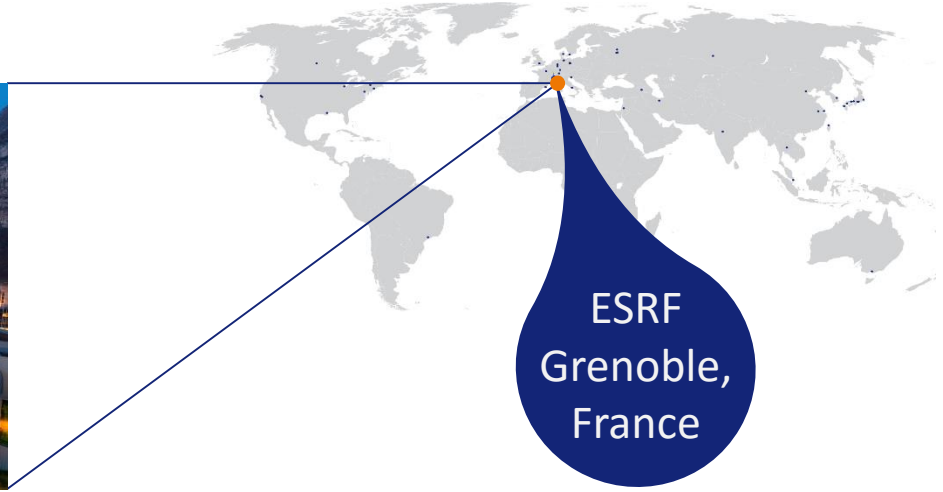
CHEMISTRY

2012 - Robert J. Lefkowitz and Brian K. Kobilka
"for studies of G-protein-coupled receptors"
2011 - Dan Shechtman
"for the discovery of quasicrystals"
2009 - Venkatraman Ramakrishnan, Thomas A. Steitz and Ada E. Yonath
"for studies of the structure and function of the ribosome"
1985 - Herbert A. Hauptman and Jerome Karle
"for their outstanding achievements in the development of direct methods for the determination of crystal structures"
1972 - Christian B. Anfinsen
"for his work on ribonuclease, especially concerning the connection between the amino acid sequence and the biologically active conformation"
1972 - Stanford Moore and William H. Stein
"for their contribution to the understanding of the connection between chemical structure and catalytic activity of the active centre of the ribonuclease molecule"
1964 - Dorothy Crowfoot Hodgkin
"for her determinations by X-ray techniques of the structures of important biochemical substances"
1962 - Max Ferdinand Perutz and John Cowdery Kendrew
"for their studies of the structures of globular proteins"

HOW DOES THE ESRF WORK?



ESRF: A LANDMARK FOR SCIENCE



A world landmark for Science

- First in scientific output: 2000 publications/year, with ~30/year on Nature and Science Magazines
- Leader in number of users: 6 500 user visits/year, more than 10 000 users in the last three years
- 4 Nobel Prizes granted to laureates using ESRF
- Very high reliability and quality service to users
- Strong synergies with national synchrotrons

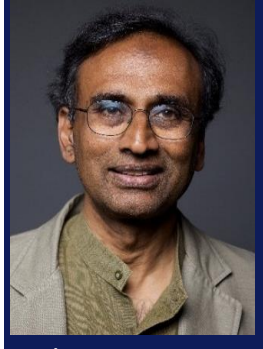
ESRF today: the world's most performing and brilliant « third-generation » light source

2009 AND 2012 NOBEL PRIZES IN CHEMISTRY

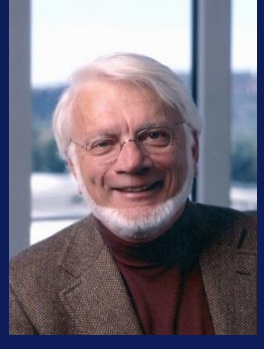
RIBOSOME

The molecular machines responsible for protein synthesis in living cells - roughly one third of the molecules in a typical bacterial cell

The Nobel Prize in Chemistry 2009



Venkatraman Ramakrishnan
MRC Laboratory of Molecular, Cambridge UK



Thomas A. Steitz
Yale University, New Haven, CT, USA

Ada E. Yonath
Weizmann Institute of Science, Rehovot, Israel

V. Ramakrishnan, T. A. Steitz, A.E. Yonath
Determined the first structures of ribosomal subunits

G-PROTEIN COUPLED RECEPTORS

800 different proteins controlling body functions and drug transit across membrane

The Nobel Prize in Chemistry 2012

Robert J. Lefkowitz
Howard Hughes Medical Institute, Duke University Medical Center, Durham, NC, USA

Brian K. Kobilka
Stanford University School of Medicine, Stanford, CA, USA

Robert J. Lefkowitz and Brian K. Kobilka
Studied the functioning and determined the structures of G-protein-coupled receptors

AN INTERNATIONAL COLLABORATION FUNDED ON AN INTERGOVERNMENTAL CONVENTION

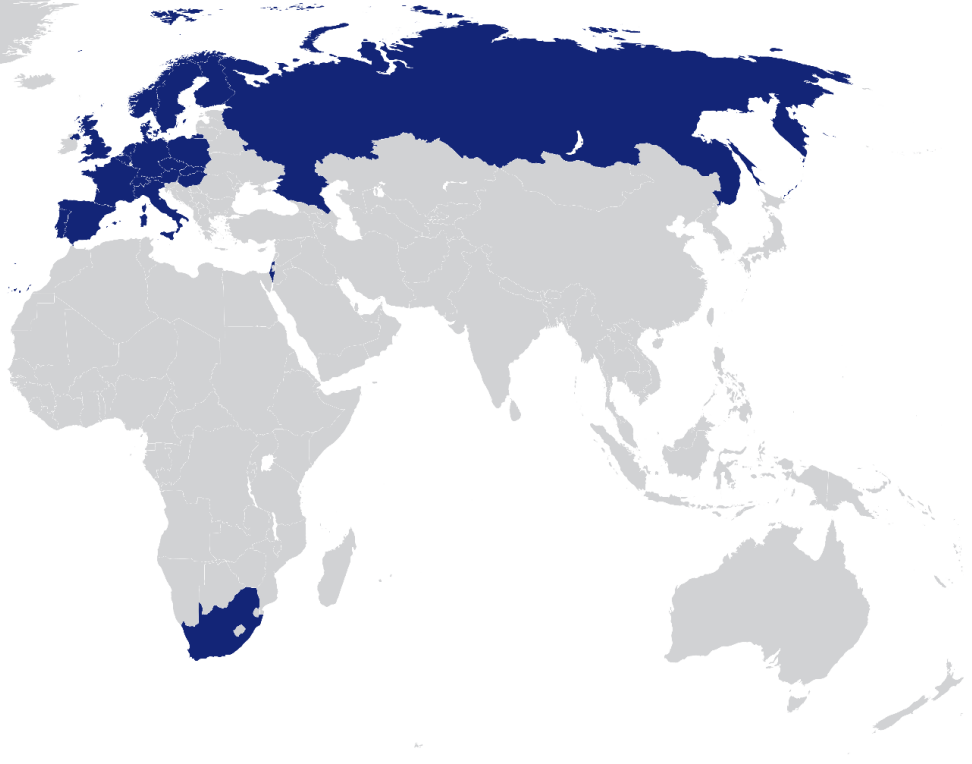
21 PARTNER COUNTRIES

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 %

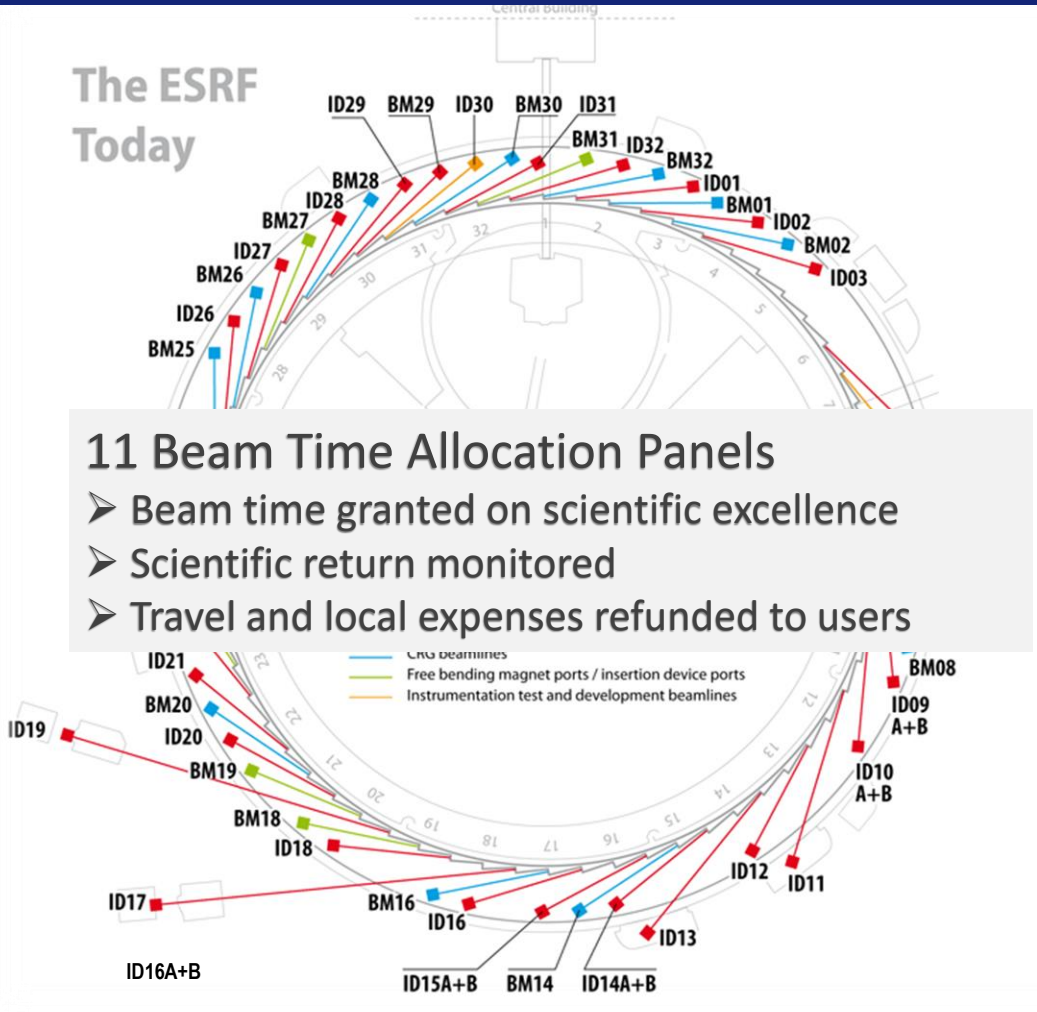
8 Associate countries:

Israel	1.5 %
Austria	1.3 %
Centralsync (Czech Republic, Hungary, Slovakia)	1.05%
Poland	1.0 %
Portugal	1.0 %
South Africa	0.3 %



ESRF TODAY - THE EXPERIMENTAL PROGRAMME

- Research in all areas of condensed matter, materials, and living matter



ESRF operates 43 beamlines:
- **30 PUBLIC**
- **13 CRG**

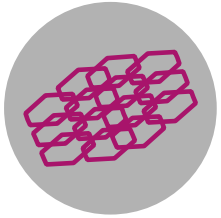
(Teams from Member States)

X-ray science and tomorrow's challenges

Challenges and Objectives of Storage Ring and XFEL sources:

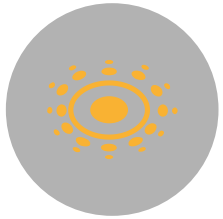
- Explore from the extremely fast:
  FEMTO-SECOND SCALE
- Explore from the extremely small:
  NANO-WORLD
- New tools to investigate condensed and living matter, bridging gaps and complementing optical and electron microscopies
- News tools to answer the pressing technological, economic, health and environmental challenges facing Society.

New, better science



New and innovative materials

Health & life sciences



Energy and Environment

➢ A new paradigm for beamlines and source: **ESRF Upgrade Programme and ESRF-EBS**

ESRF UPGRADE PROGRAMME: AN AMBITIOUS PROGRAMME TO PREPARE THE FUTURE

Purple Book January 2008

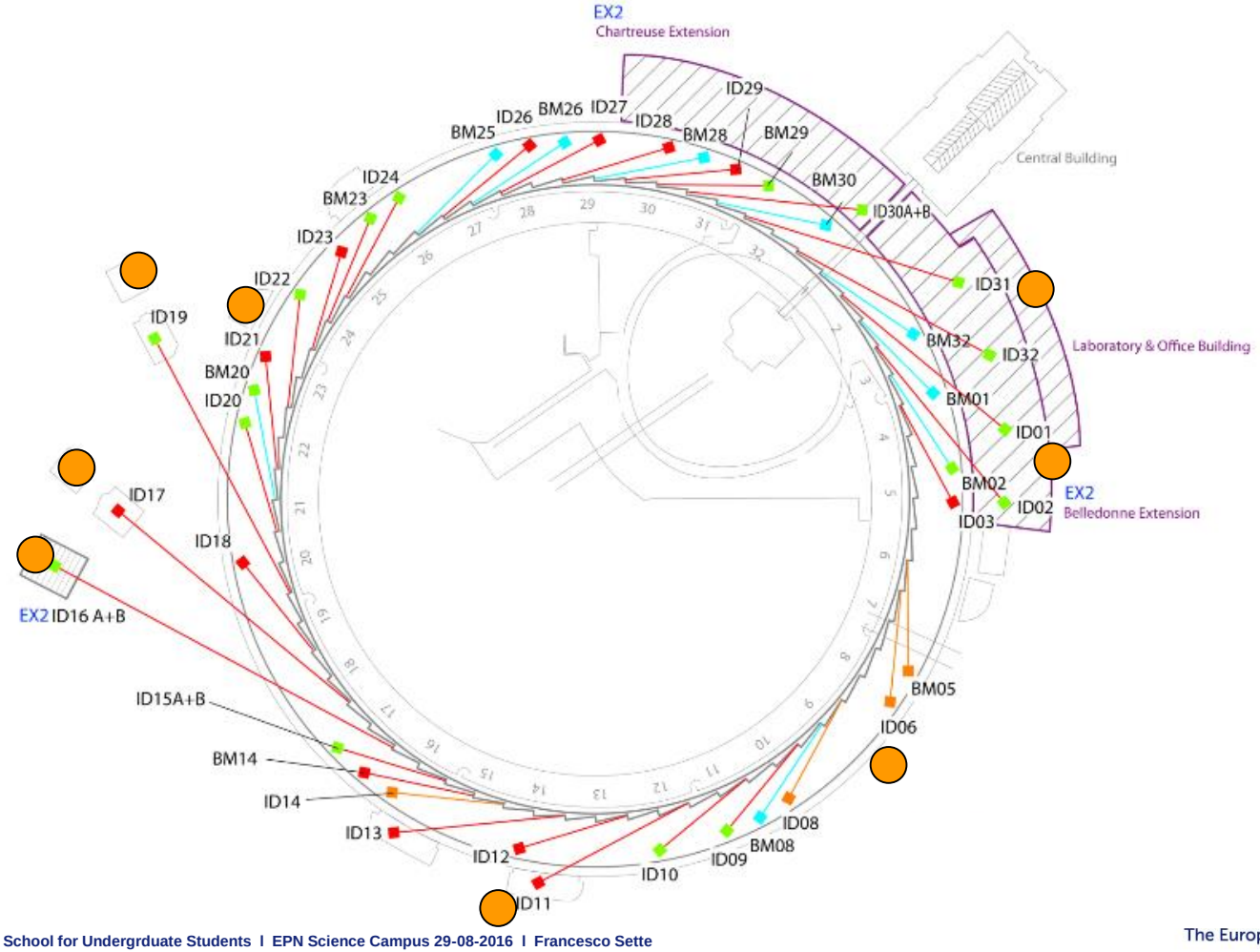
ESRF UPGRADE PHASE I
180 M€ (2009-2015):
ESFRI ROADMAP 2006-2016
IN TIME – WITHIN BUDGET

- 19 new beamlines, many specialised on *nano*-beam science
- Upgrade and renewal of facilities and support laboratories

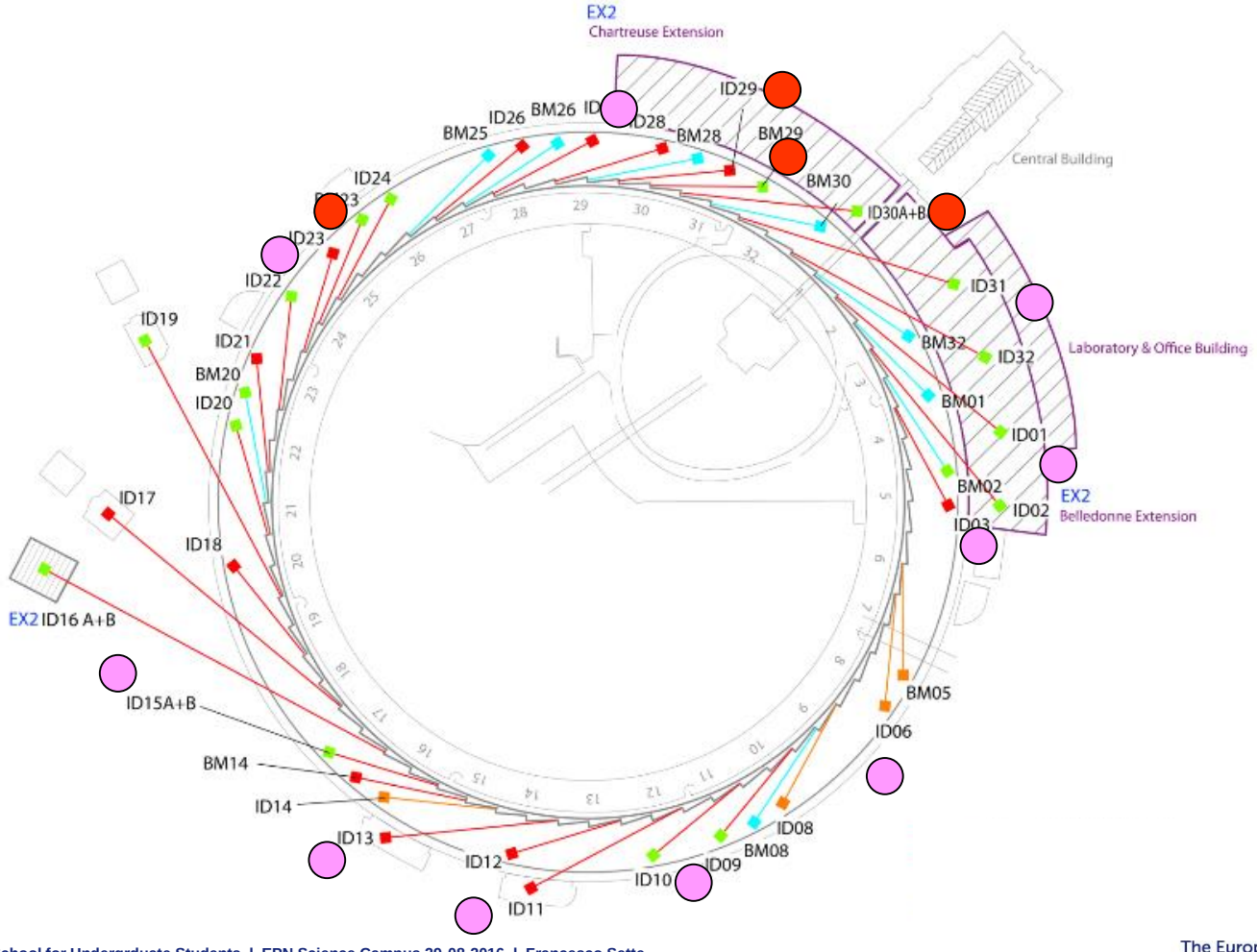
ESFRI

European Commission

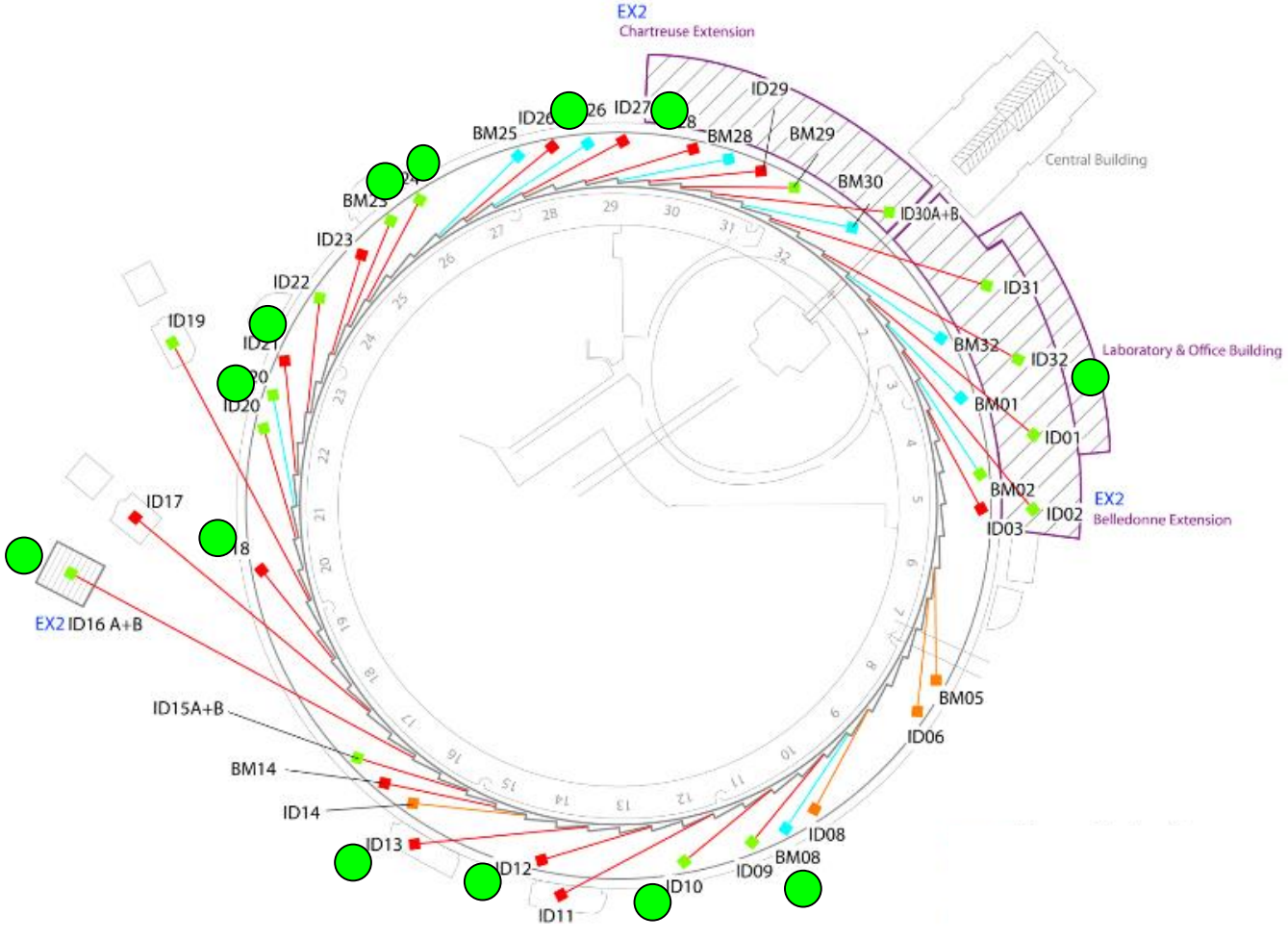
ESRF UPGRADE PROGRAMME PHASE I – A NEW BEAMLINE PORTFOLIO: IMAGING



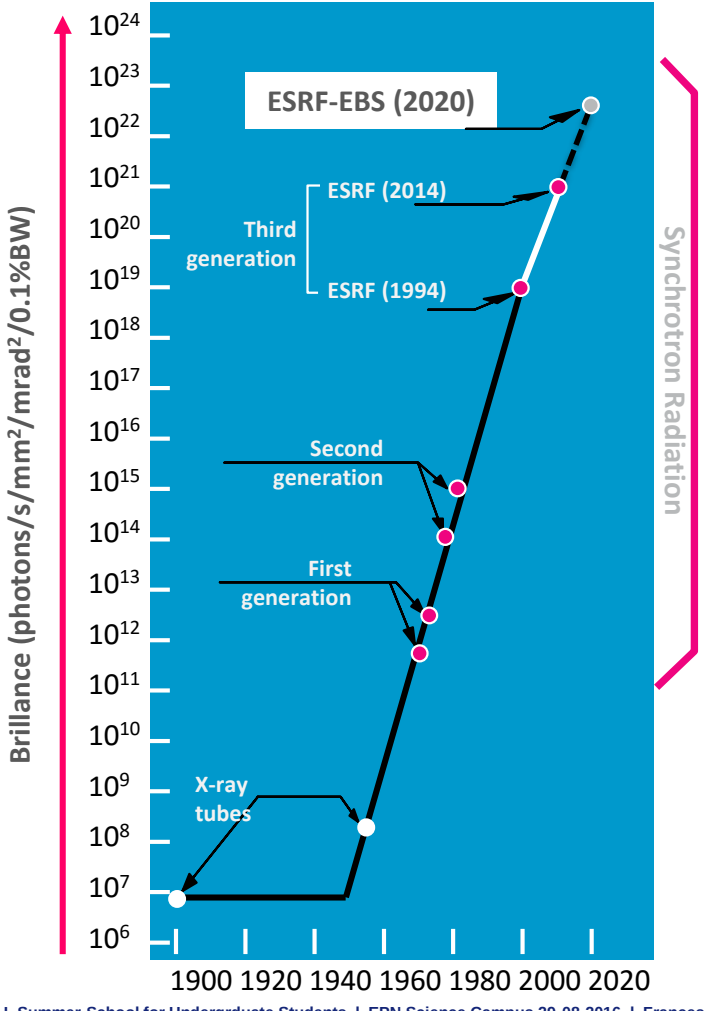
ESRF UPGRADE PROGRAMME PHASE I – A NEW BEAMLINE PORTFOLIO: DIFFRACTION



ESRF UPGRADE PROGRAMME PHASE I – A NEW BEAMLINE PORTFOLIO: SPECTROSCOPY



ESRF UPGRADE PROGRAMME



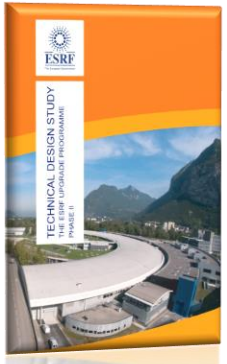
ESRF Upgrade Programme PHASE I –

STUDIES FOR A NEW STORAGE RING

- IS IT POSSIBLE TO QUALITATIVELY UPGRADE THE EXISTING STORAGE RING?
- GOOD SOLUTIONS EXIST FOR MEDIUM ENERGY RINGS, BUT WHAT ABOUT HIGH ENERGY (6-8 GEV) RINGS?

ESRF UPGRADE PROGRAMME: AN AMBITIOUS PROGRAMME TO PREPARE THE FUTURE

Purple Book January 2008



Orange Book January 2015

ESRF UPGRADE PHASE I
180 M€ (2009-2015):
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- 19 new beamlines, many specialised on *nano*-beam science
- Upgrade and renewal of facilities and support laboratories

ESRF-EBS
Extremely Brilliant Source
150 M€ (2015-2022)
ESFRI LANDMARK (2016)

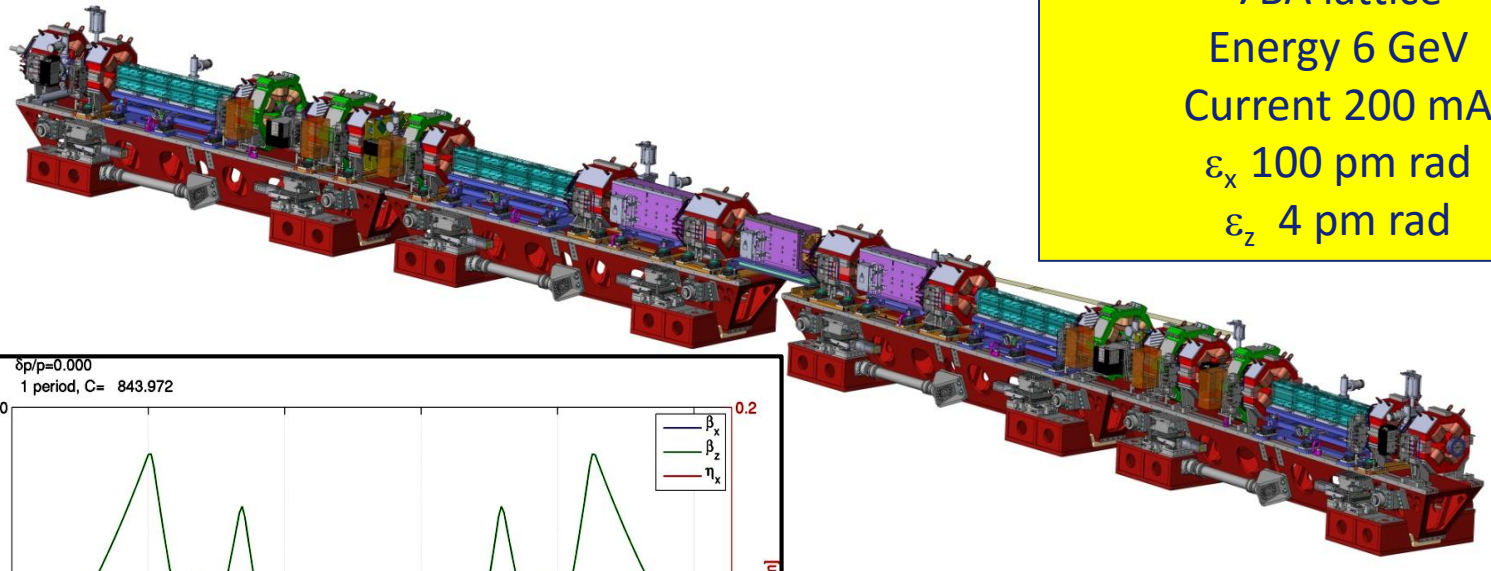
revolutionary design for a new generation of synchrotron source storage rings

ESFRI

European Commission

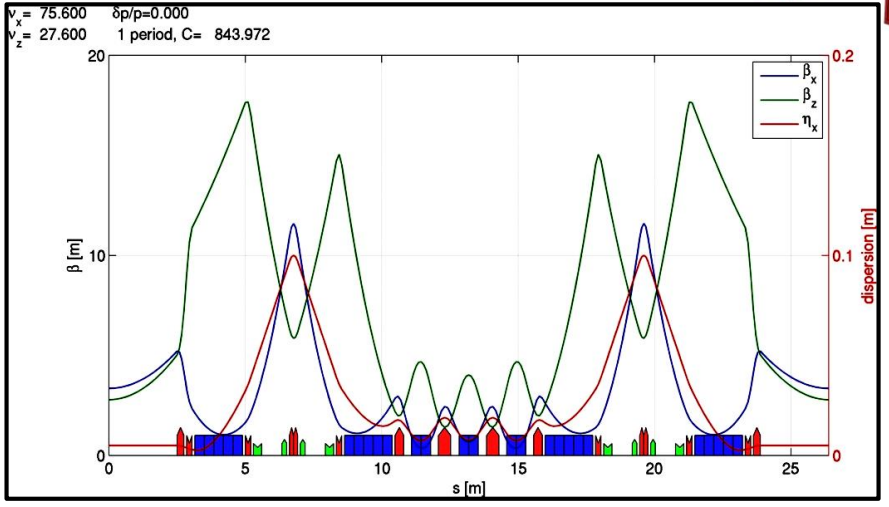
The European Synchrotron | ESRF

NEW ESRF LATTICE: 7BA – SEVEN BENDS ACHROMAT LATTICE (RAIMONDI LATTICE)



Key Paramaters

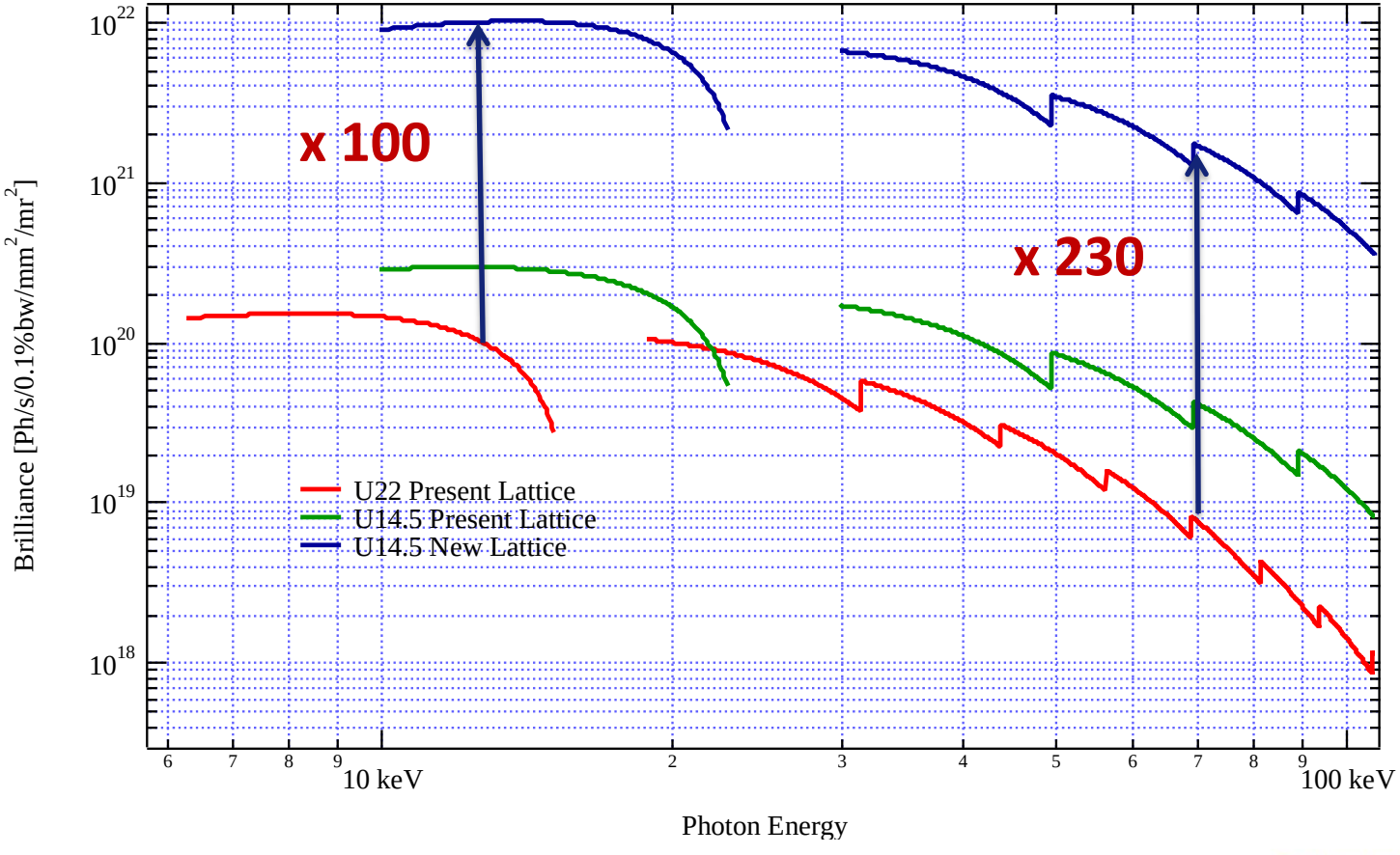
7BA lattice
Energy 6 GeV
Current 200 mA
ε_x 100 pm rad
ε_z 4 pm rad



2 M IVUS & CPMUS

IVUN22 min. gap 6 mm, K_{max}=1.7

CPMU14.5 min. gap 4 mm, K_{max}=1.7



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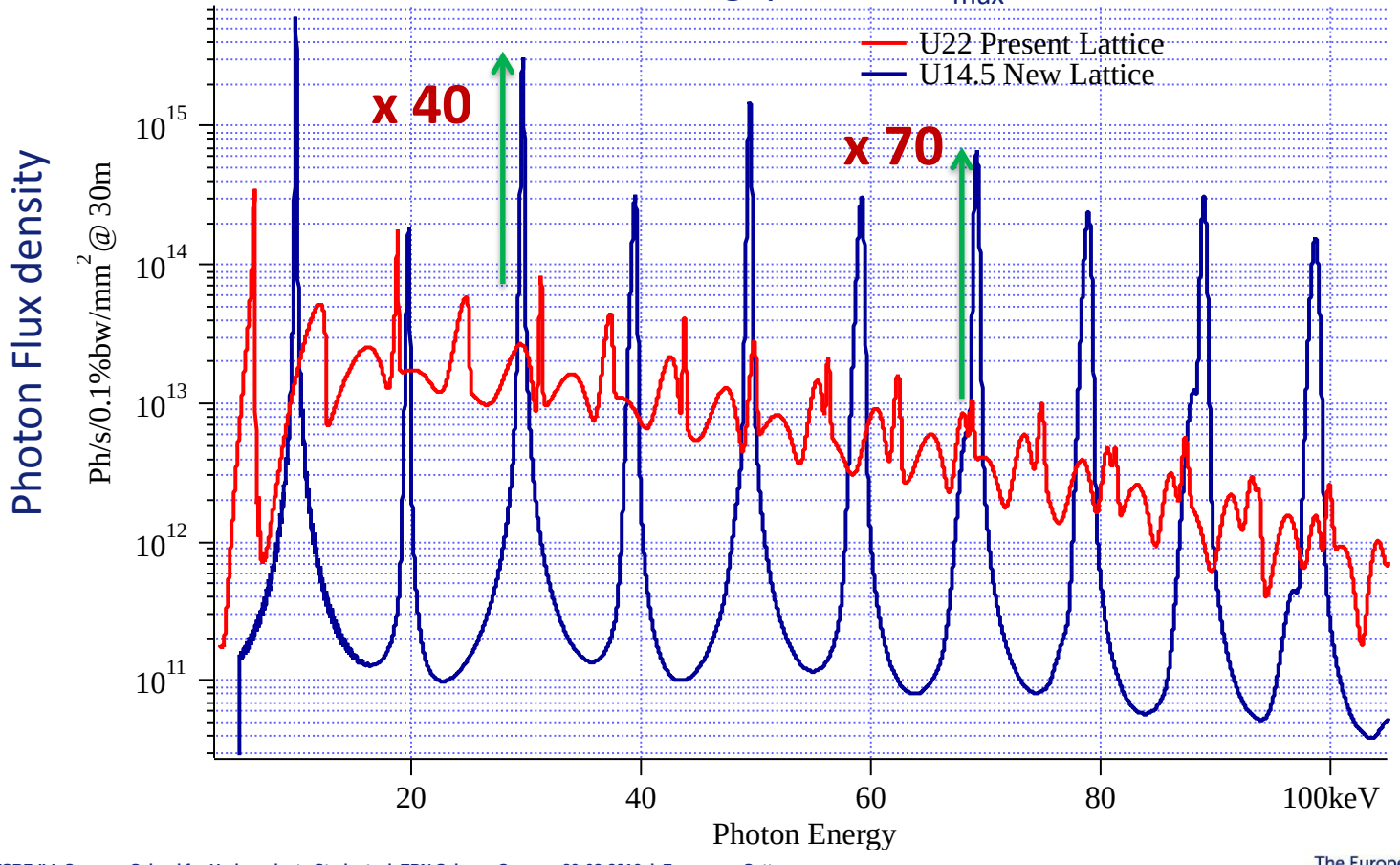
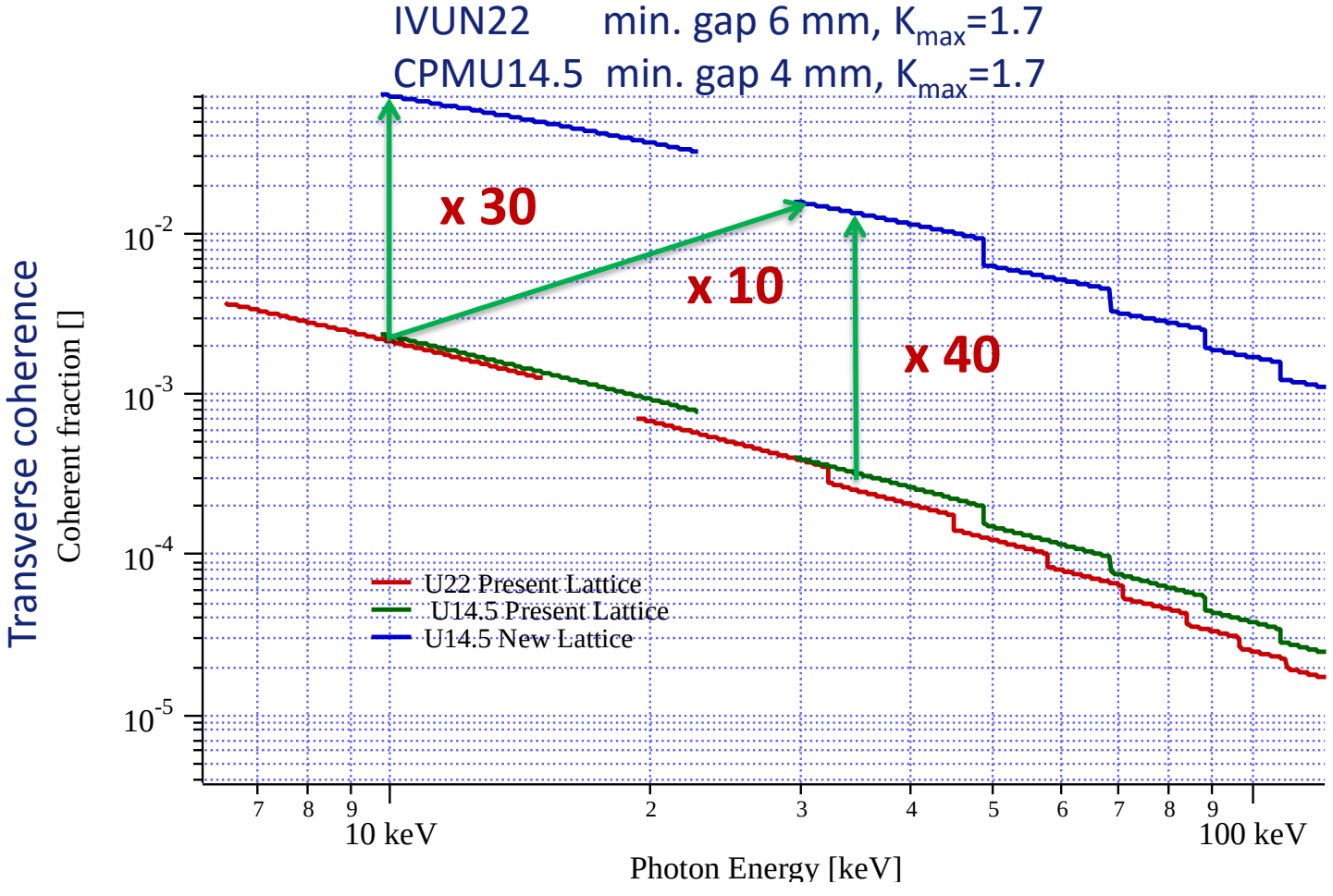
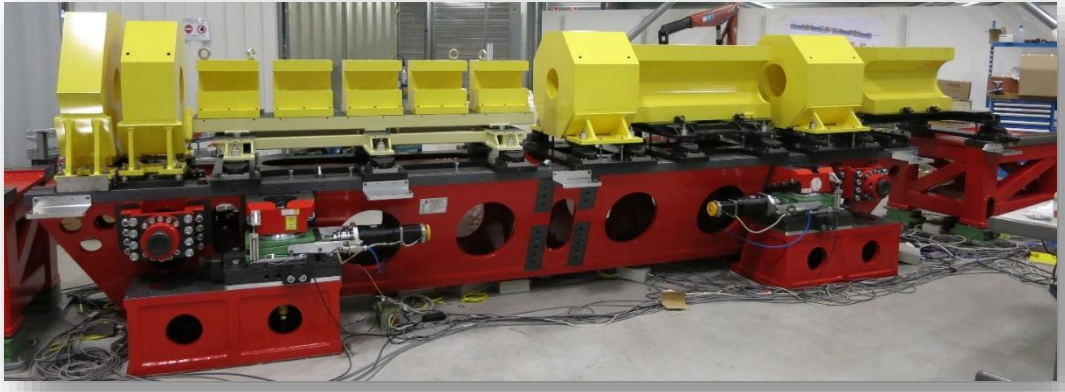


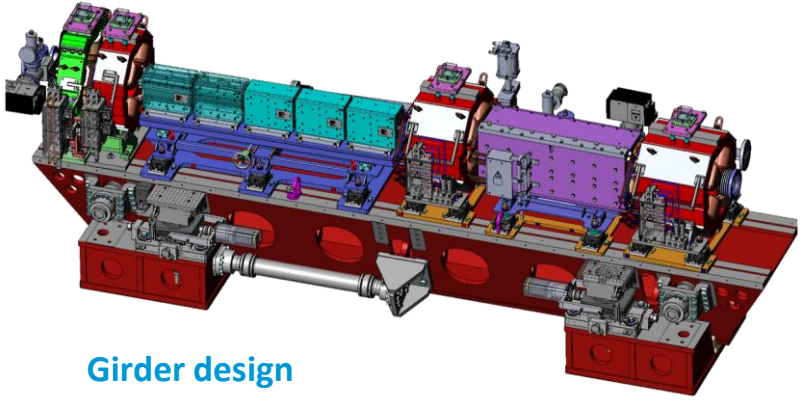
2 M IVUS & CPMUS



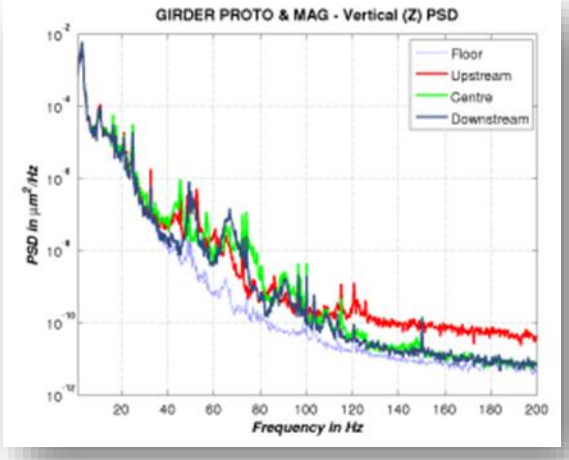
Girder prototype tests: 128 girders construction started



Girder prototype with dummy magnets for mechanical tests



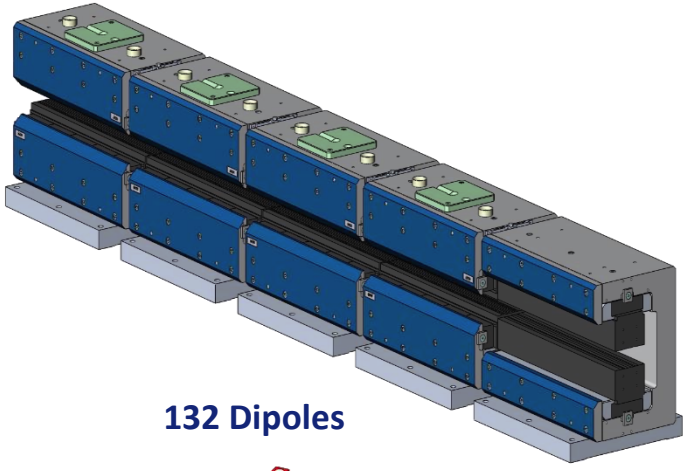
Girder design



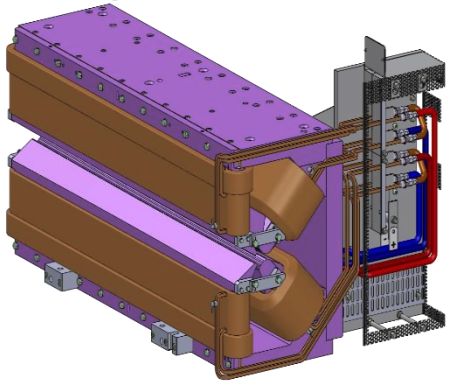
First vibrational mode at 40 Hz

Virtually no amplification of natural ground motion

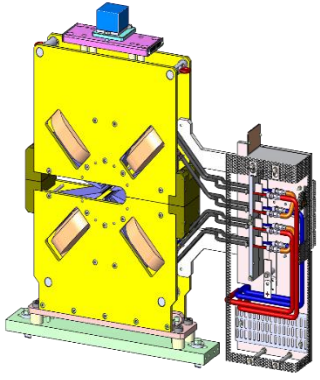
Magnets: more than 1 000 magnets construction started



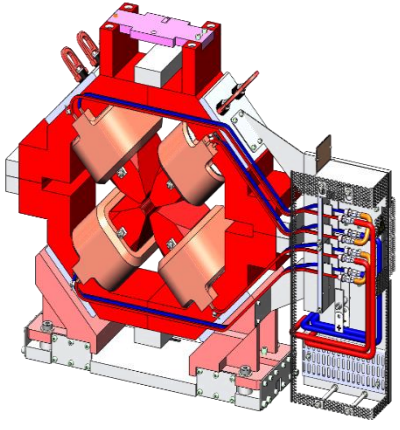
132 Dipoles



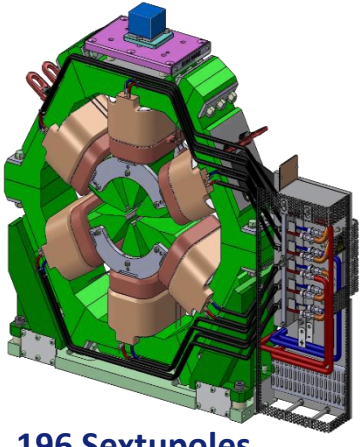
98 Dipole-quadrupoles



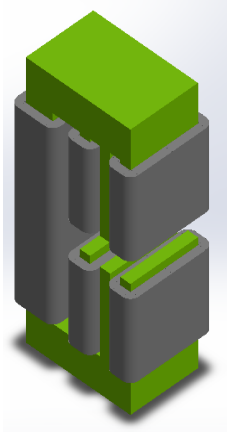
66 Octupoles



526 Quadrupoles

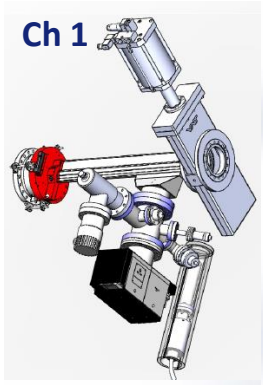


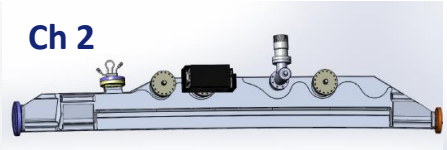
196 Sextupoles

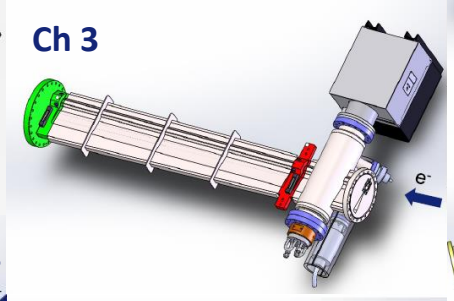


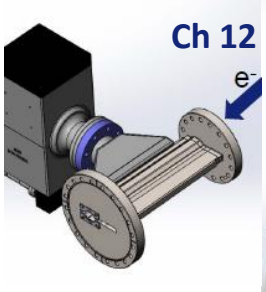
98 Correctors

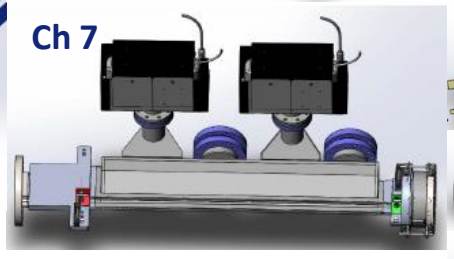
Vacuum chambers: more than 450 chambers construction started

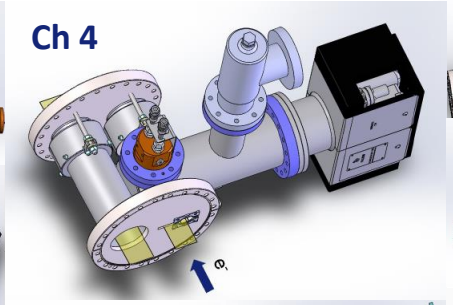


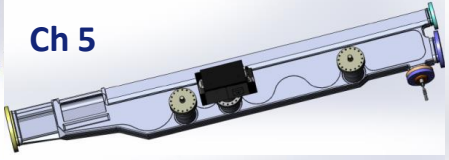


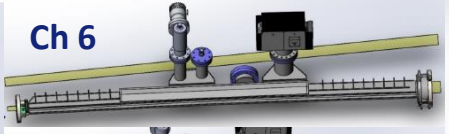


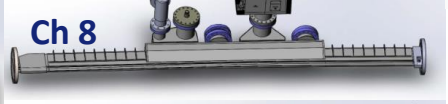


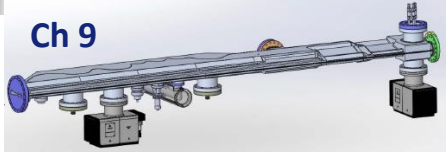


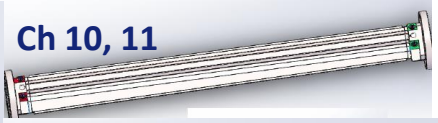


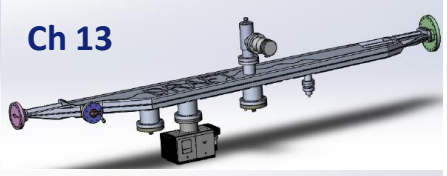


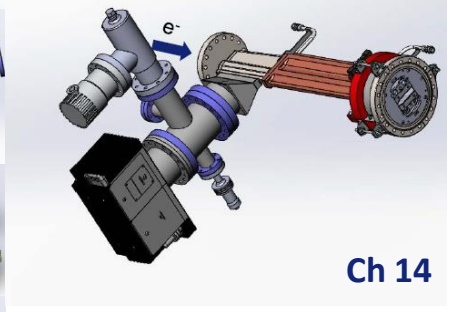












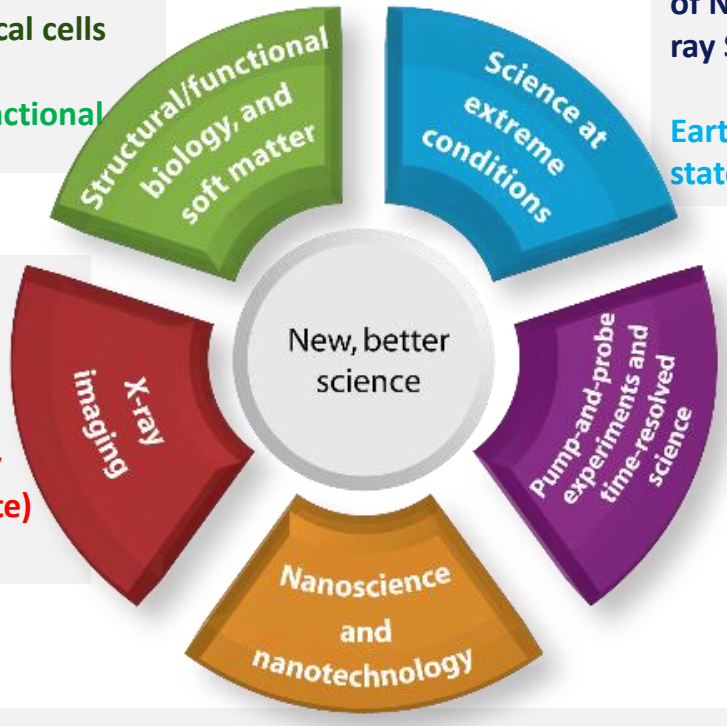
ESRF UPGRADE PROGRAMME: SCIENCE CASE

Revolutionizing life sciences at the ESRF: from serial crystallography to molecular machines in functional biological cells

Structure and Dynamics of Functional Biological Units

Revealing the hidden treasures of Nature with a diffraction-limited X-ray Source

Earth & Planetary Science, Novel states of matter



Time-resolved bio-response of organisms to exogenous materials

Bio-regeneration, Evolutionary Biology
Materia **mposite)**

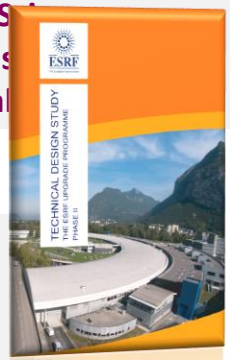
Diffraction-limited sources: opportunities for in-situ studies

Energy S
Catalysis
Materia

Purple Book January 2008

5D diffraction imaging of electronic devices and nanostructures

Nanotechnology, Information technology, Quantum computing



Orange Book January 2015

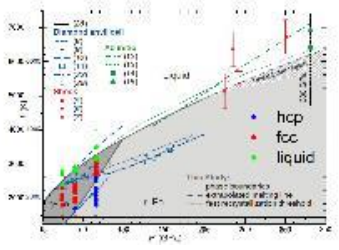
The European Synchrotron | ESRF

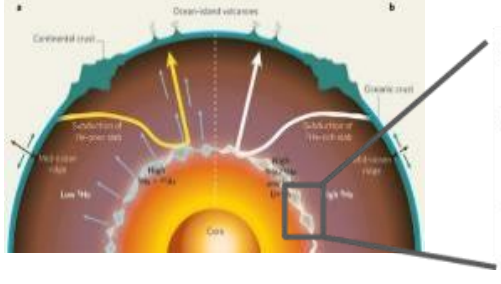
MATTER AT EXTREME CONDITIONS

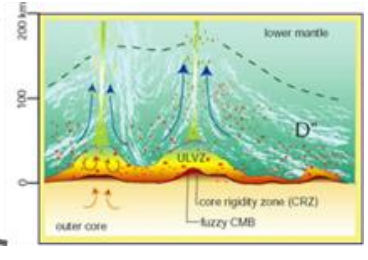
Opportunities

- Probing structural complexity and its relation to, e.g. superconductivity and quantum phenomena
- Imaging materials complexity in the TPa regime at the nanoscale
- Understanding the structure and dynamics of Earth's and Exo-planets deep interiors

Phase diagram





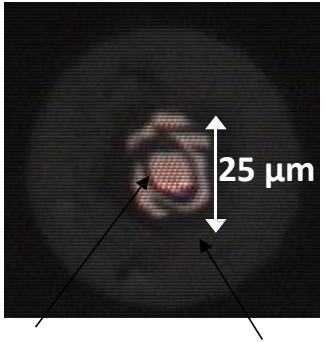


Creating thermodynamic conditions that exist only in a very small volume and/or for a very short time

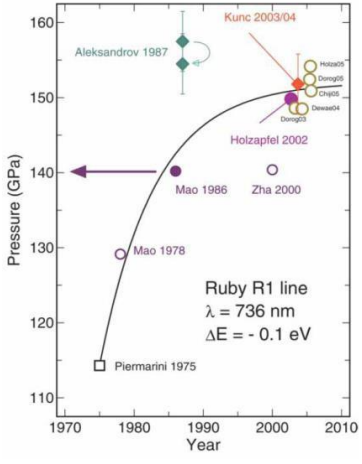
Limitations	Solution
beam size	brightness
time resolution	brightness
data analysis	IT and software

A STRONG COMMUNITY EFFORT AT ESRF

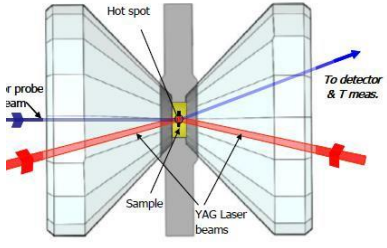
Samples + Metrology + ESRF



H2 single crystal He



Many techniques have been used.
Some dedicated beamlines.
XRD, XAS, IXS, NSR, XRI



Accuracy of the P-T measurements
Ruby scale
Diamond or c_BN scale
Pyrometry

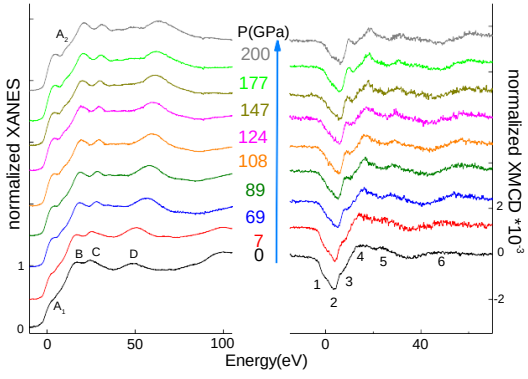
= interesting physics.

Study of material properties at Mbars pressures accurately as at ambient pressure:

MAJOR ACHIEVEMENT OF THE HP FIELD

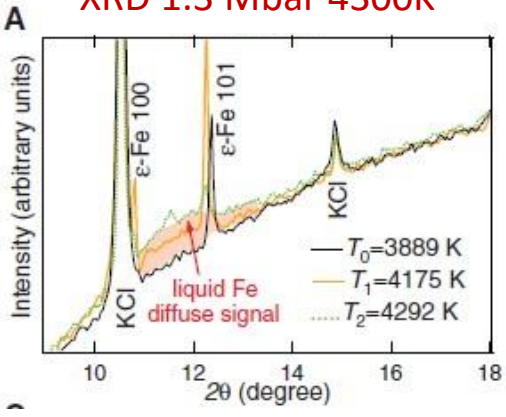
SOME RECENT HIGHLIGHTS

XMCD 2 Mbar



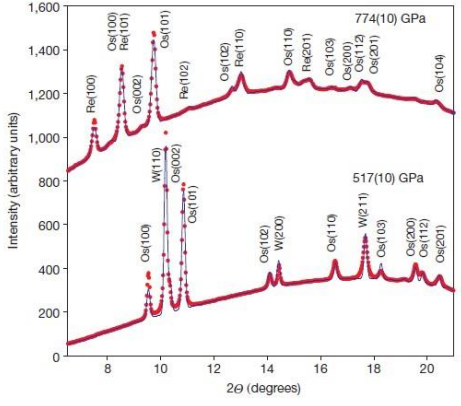
Torchio PRL 2011

XRD 1.3 Mbar 4300K



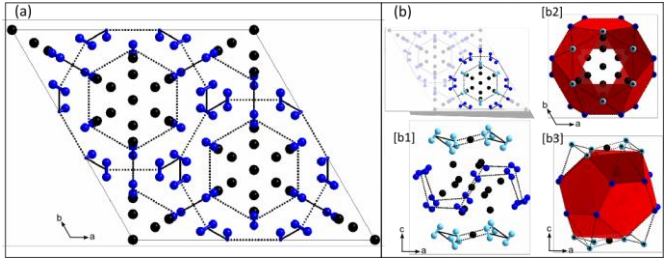
Anzellini Science 2013

XRD 7 Mbar



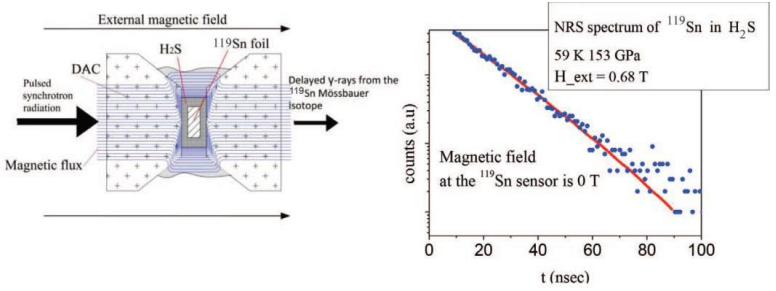
Dubrovinsky Nature 2015

Single-crystal XRD



Spaulding, Nature Comm. 2014

NRS

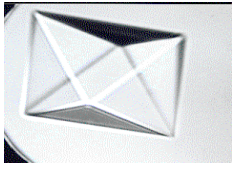


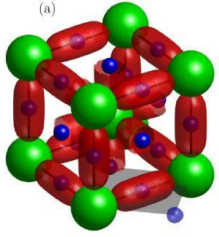
Troyan, Science 2016

PUSH THE FRONTIERS

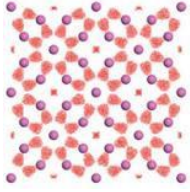
- **Go more extreme. TPa & eV** **WDM**

H20@1GPa → **H30@ TPa**



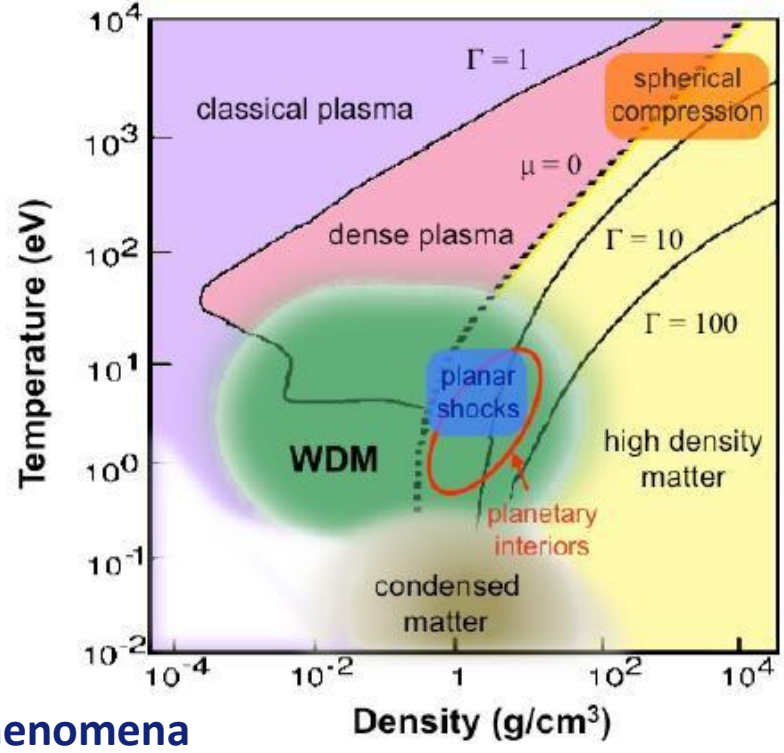


Tc>200K



Novel materials

Al@ 4 TPa: an electride (Pickard&Needs 2010)

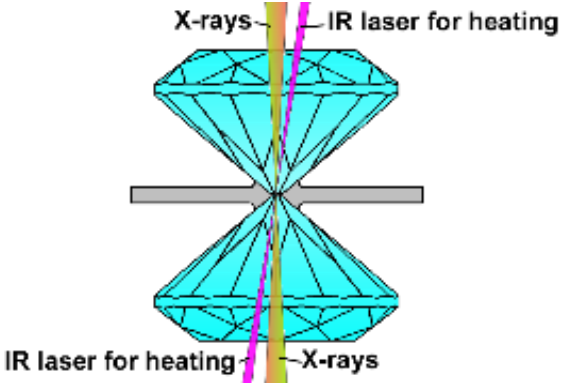


- **Explore the time scale of high pressure phenomena**

- Mechanism and nucleation of phase transitions.
- Yield strength (dynamics of dislocations).
- Nanostructuration; amorphisation; metastable phases.

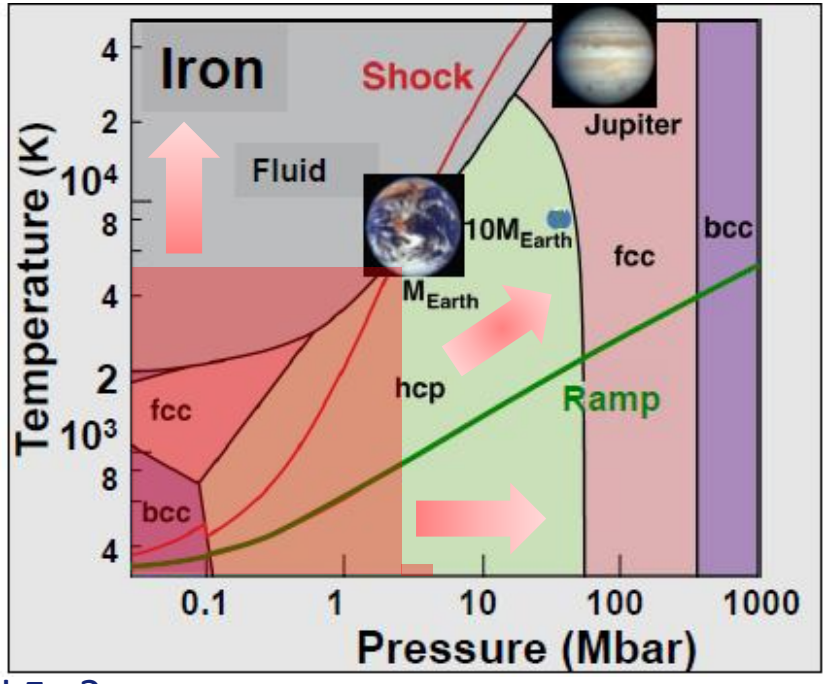
Go TPa & ns

GOING BEYOND THE LIMIT OF STATIC COMPRESSION



Static compression with LH–DAC covers Earth's core conditions

~ 360 GPa, 5500 K



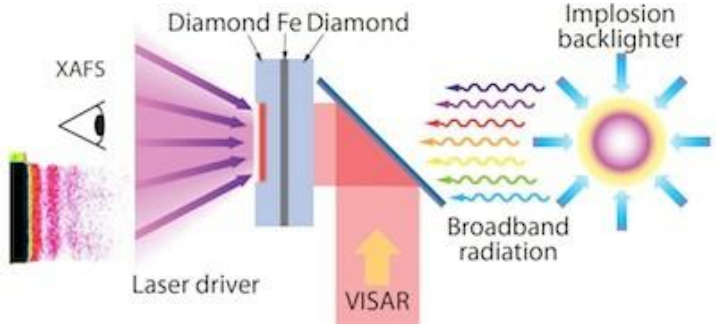
1. What is the stability limit of hcp phase in solid Fe ?
2. What is the local structure in the liquid ?
3. What is the nature of ion-ion correlations in the WDM regime ?

Can we create and probe WDM at the synchrotron, with data quality as "at ambient"?

DYNAMIC COMPRESSION WITH LASERS

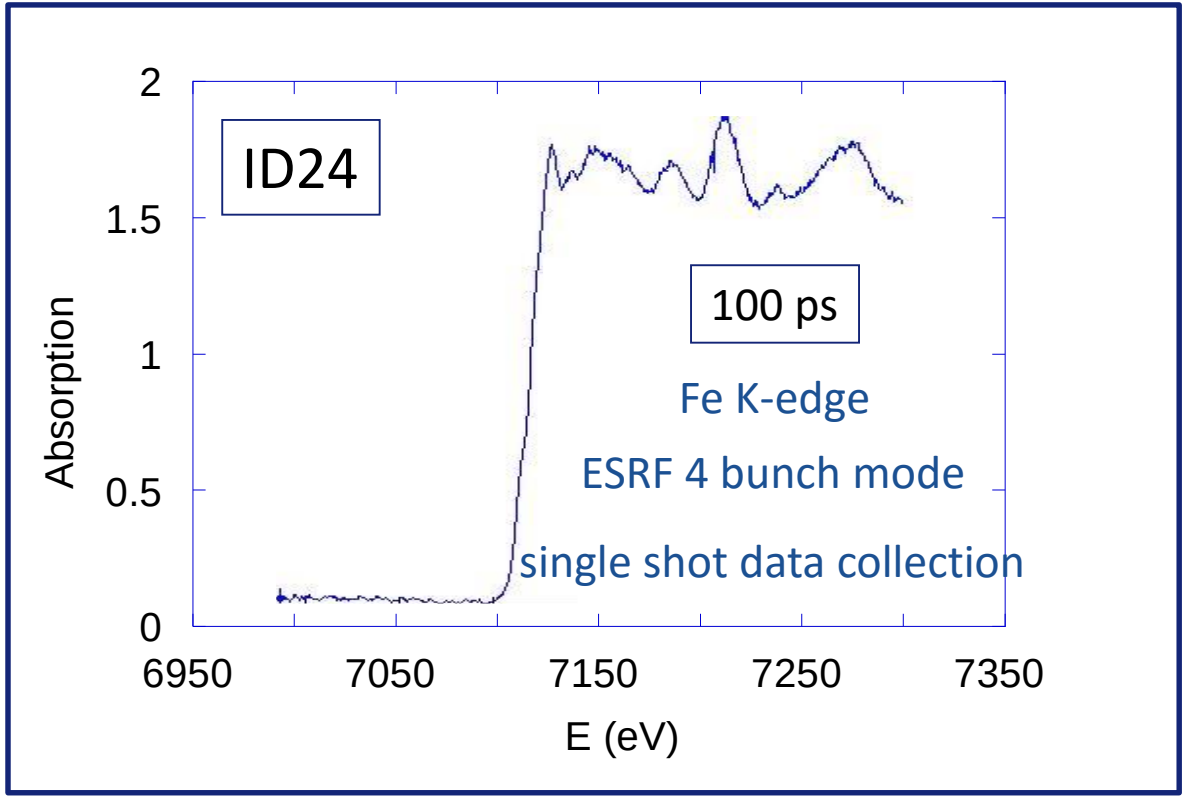
From macroscopic properties to atomic structure → X-ray diagnostics

High power laser facility + X-ray backlighter



- X-ray scattering, XRD, XAS, XES
- Phase transitions, new structures, WDM electronic and structure changes, etc…
- Test approximations used in theories

DETECTION LIMITS FOR SINGLE SHOT STUDIES: ED-XAS



data quality corresponds to 50 spectra before

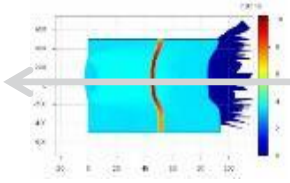
Ge XH microstrip (STFC)

SINGLE SHOT EXAFS ON DYNAMICALLY COMPRESSED FE

ID24

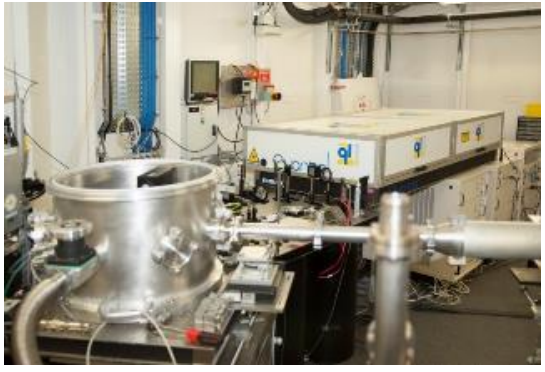
Institute of Shock Physics

Science & Technology Facilities Council

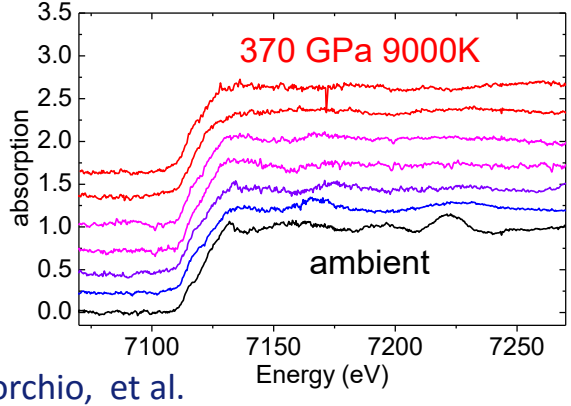


X-rays 0.1 ns

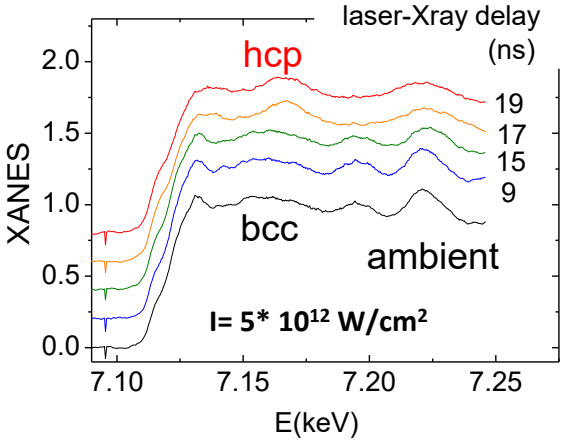
LASER ns



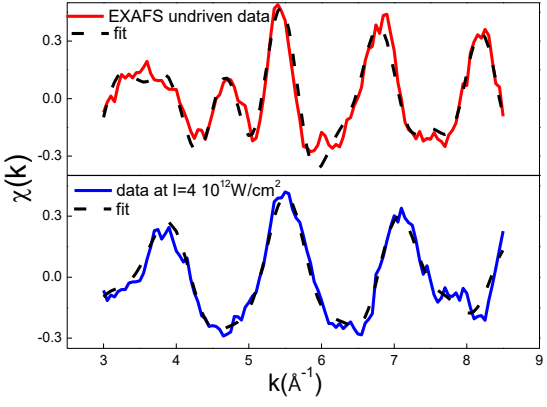
I(W/cm²)	P(GPa)	T(K)
1 10^{13}	160	2800
2 10^{13}	270	7000
3 10^{13}	320	8000
5 10^{13}	370	10000



Single bunch XANES



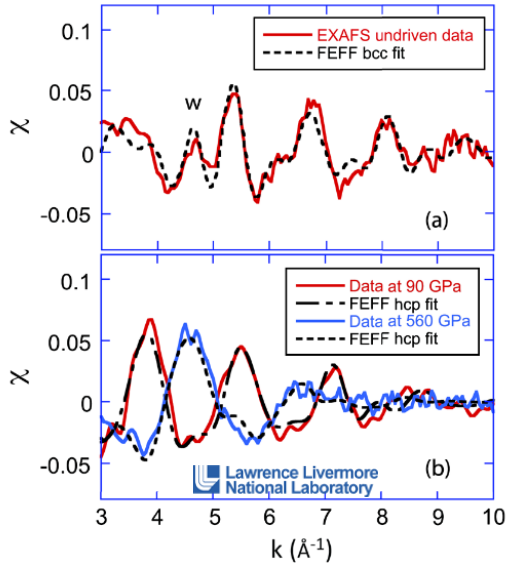
Single bunch EXAFS



F. Occelli, O. Mathon, A. Sollier, R. Torchio, et al.

XAS STUDIES ON LASER SHOCKED FE

High Power Laser Facility
OMEGA
single shot

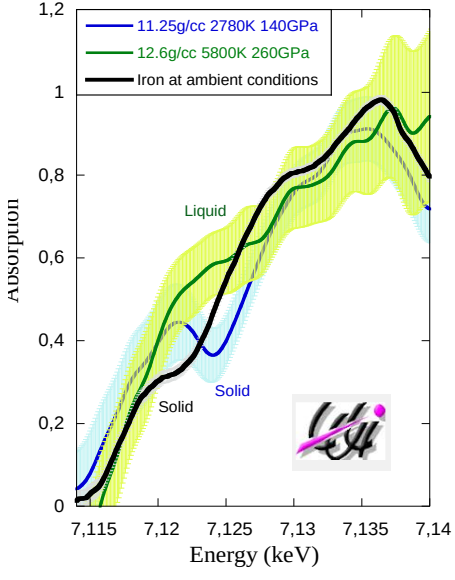


Only EXAFS region

Max 10 shots/day

Max 2 days/year

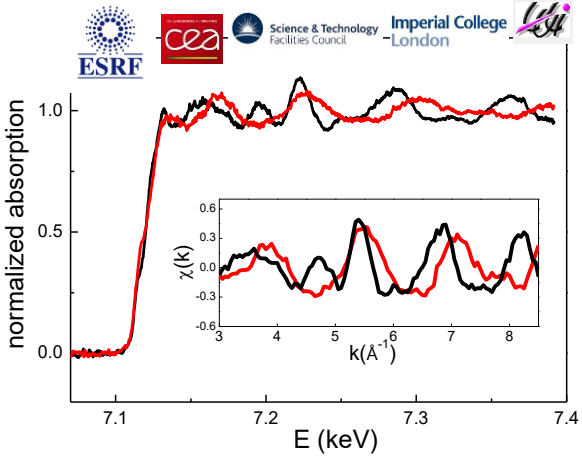
X-ray Free Electron Laser
LCLS
average over many shots



Only edge region

No. shots limited only by laser frequency

Synchrotron
ESRF
single shot



XANES and EXAFS

No. shots limited only by laser frequency

Thank you for your attention,
and my best wishes for a great stay in the EPN Science Campus!