ESRF – ILL 7th Summer School
Undergraduate Students

Science at synchrotrons and the ESRF

Welcome!

Francesco Sette
Director General, ESRF

ESRF
The European Synchrotron

30 years of science

EPN SCIENCE CAMPUS : A UNIQUE SITE FOR RESEARCH AND INNOVATION

A CryoEM platform

- +500 scientists in the Campus
- The most powerful research reactor and the brightest synchrotron source
- THREE INTERNATIONAL ORGANISATIONS and IBS – a French Institute for Structural Biology – working together to welcome users from all over the world

european photon & neutron science campus | ESRF The European Synchrotron | NEUTRONS FOR SOCIETY | EMBL | ibs Institut de Biologie Structurale

GIANT, A WORLD-CLASS INNOVATION CAMPUS

8 member institutions under a single banner: GIANT

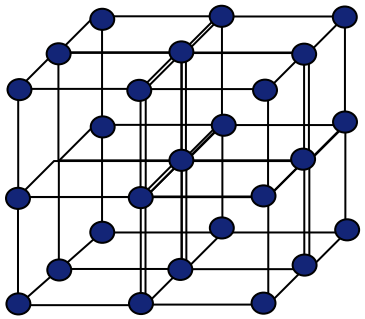
Creating synergies to foster technological breakthroughs, and to contribute answering to major challenges facing our society, such as:

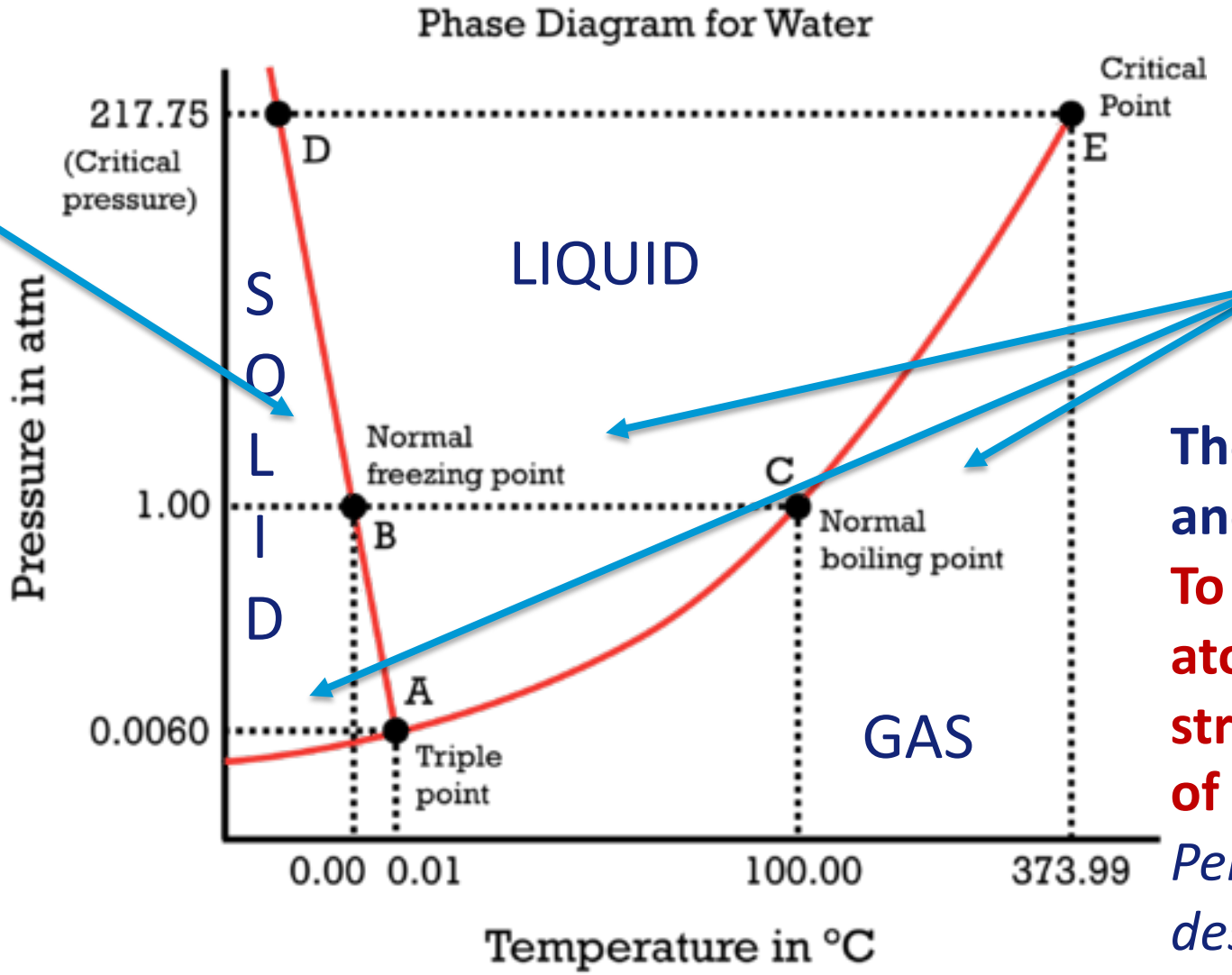
- Health
- Environment
- Energy
- Communications

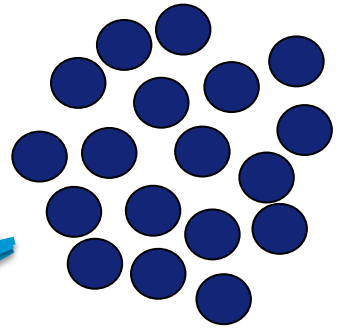
A campus organised in 7 academic and technical centers for excellence.

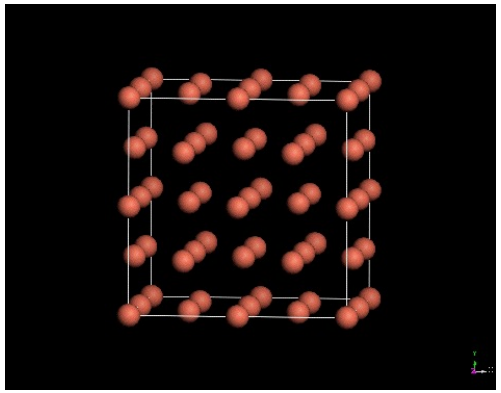
ESRF: 30 YEARS OF SCIENTIFIC EXCELLENCE AND INTERNATIONAL COLLABORATION

Atoms – Molecules – Condensed Matter

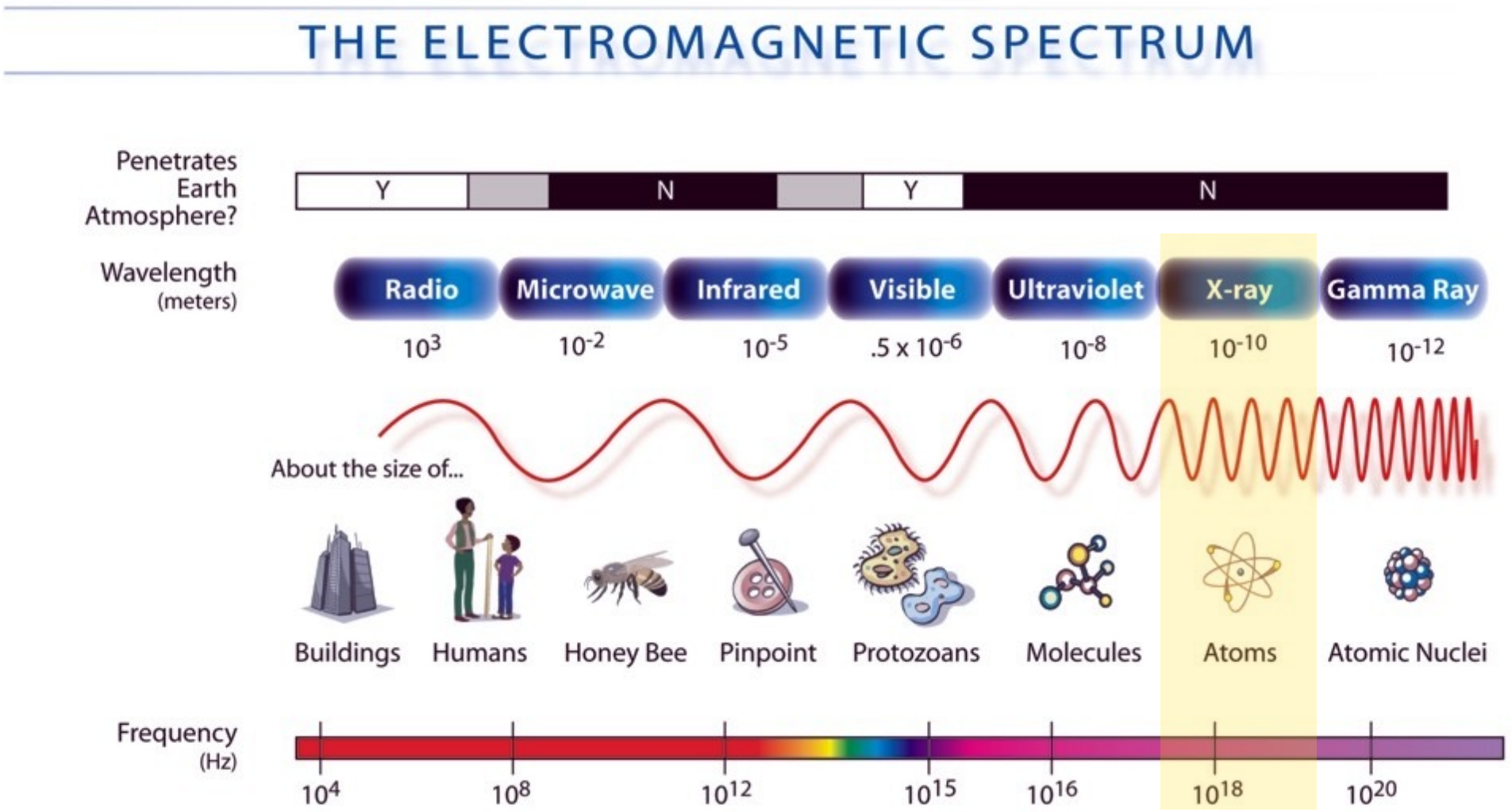








The beauty of X-rays and neutrons:
To unveil down to atomic resolution the structure and dynamics of condensed matter – *Penetration and non-destructiveness*

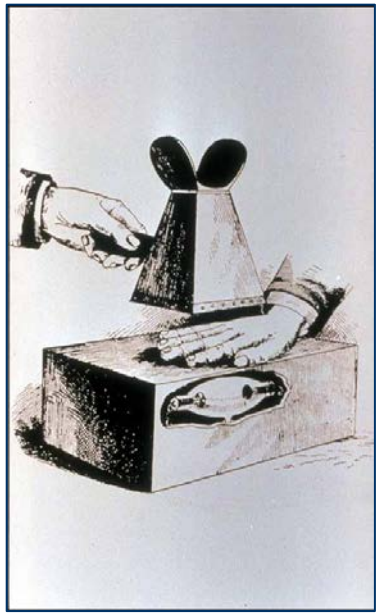

THE ELECTROMAGNETIC SPECTRUM
Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^3
10^-2
10^-5
.5 x 10^-6
10^-8
10^-10
10^-12
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency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

X-RAYS: DISCOVERY IN 1895 BY W.C RÖNTGEN

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

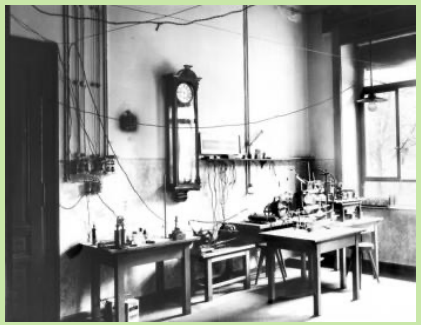
- "… A piece of sheet of aluminium, 15 mm thick, still allowed **the X-rays** (as I will call the rays, for sake of brevity) to pass …"
- "... Detection of interference phenomena has been tried without success, perhaps only because of their feeble intensity..."
- "... The refractive index ... cannot 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

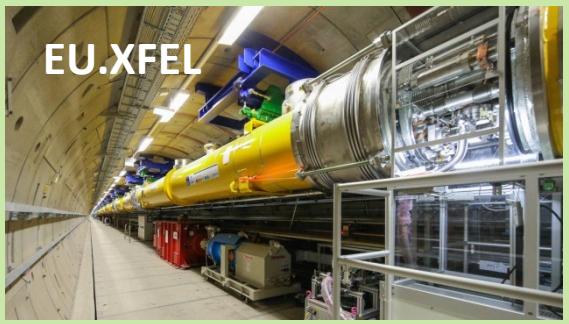
The Spectacular Success of X-ray Science

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

(COURTESY H. DOSCH)

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

1994 – The European Synchrotron Radiation Facility – 6 GeV

FIRST THIRD-GENERATION SYNCHROTRON

SYNCHROTRON FACILITIES SERVE NOWADAYS ~50 000 USERS WORLDWIDE: THE LARGEST SCIENTIFIC COMMUNITY IN THE WORLD

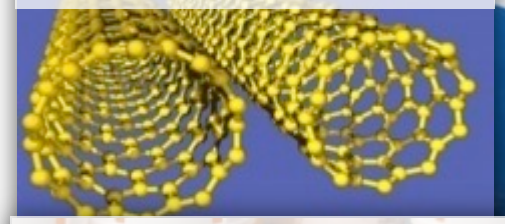
SYNCHROTRON X-RAY SCIENCE AND APPLICATIONS

Fundamental, applied and industrial research on atoms structure and dynamics

Understanding new materials, and functioning of life-related processes

- **SYNCHROTRON LIGHT SOURCES ADDRESS CRITICAL GLOBAL CHALLENGES IN AREAS SUCH AS HEALTH, ENVIRONMENT, ENERGY, FOOD SECURITY**
- **IN CONDENSED AND LIVING MATTER, SYNCHROTRON SCIENCE LINK FUNCTIONS AND PROPERTIES TO THE STRUCTURE OF ATOMS**

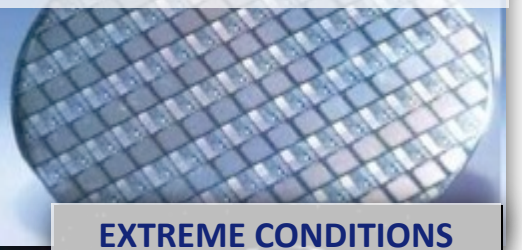
ADVANCED MATERIALS



ENERGY & ENVIRONMENT

HEALTH & FOOD

MICROELECTRONICS



CONSUMER PRODUCTS

EXTREME CONDITIONS

METALLURGY

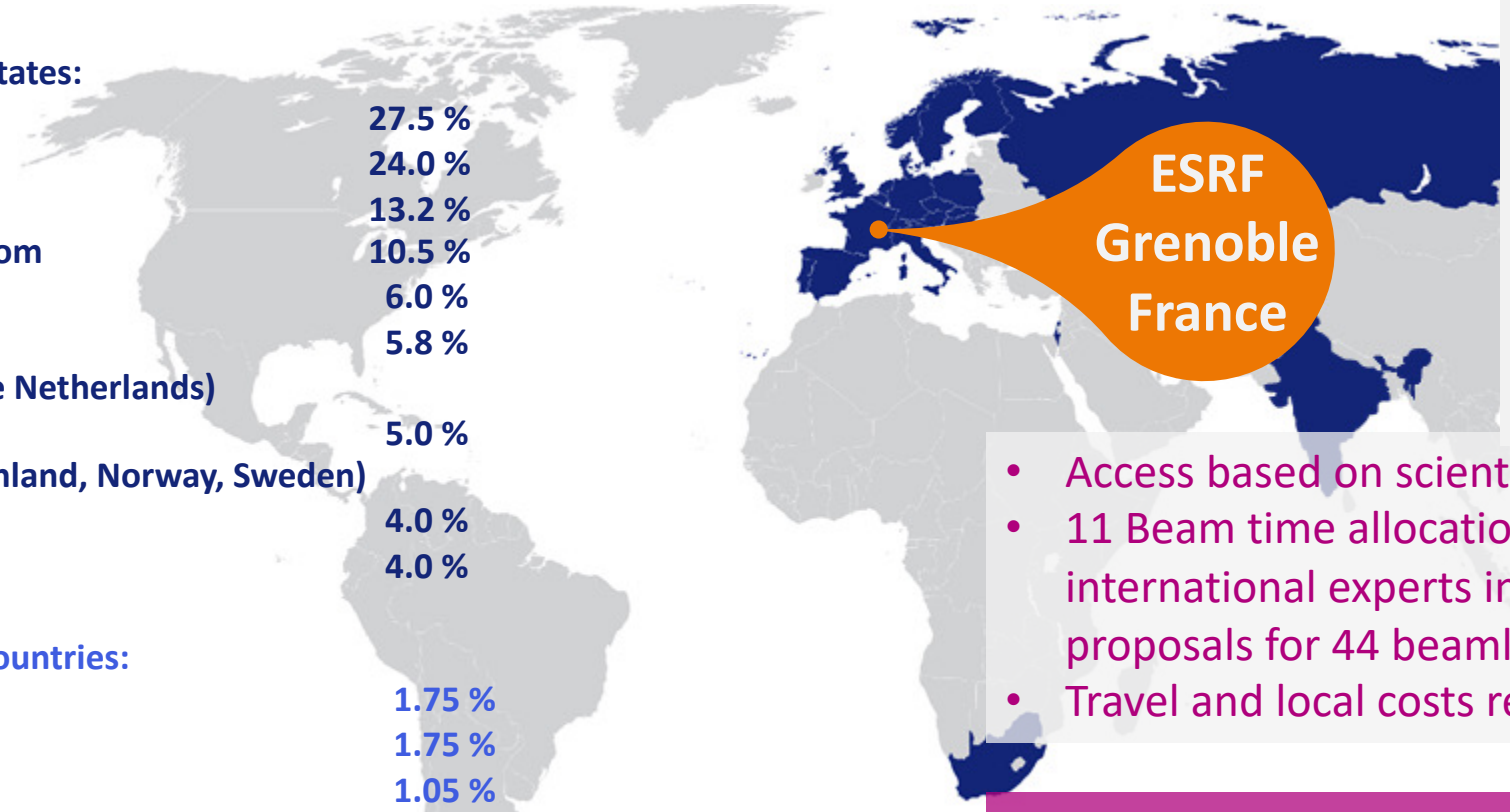
PETROCHEMICALS

CULTURAL HERITAGE

ANALYTICAL RESEARCH INFRASTRUCTURES BRING NATIONS TOGETHER THROUGH SCIENCE

ESRF: BRINGING NATIONS TOGETHER TO ATTRACT EXCELLENCE IN SCIENCE AND TECHNOLOGY

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 %
9 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 %

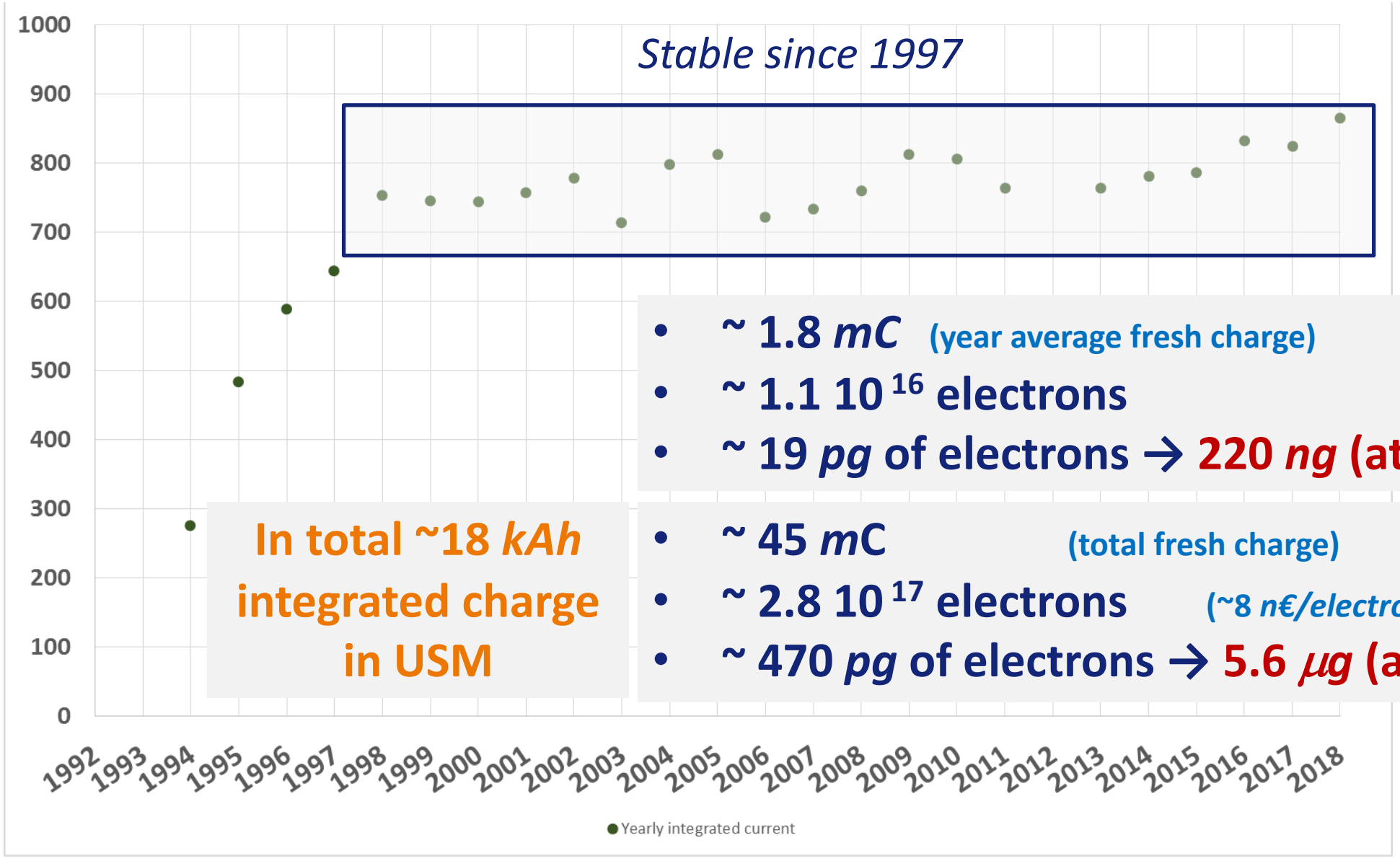
ESRF, THE FIRST THIRD GENERATION SYNCHROTRON SOURCE IN 1992, OPENS THE WAY

- 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€

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

THE FIRST THIRD GENERATION SYNCHROTRON STORAGE RING: YEARLY INTEGRATED CURRENT

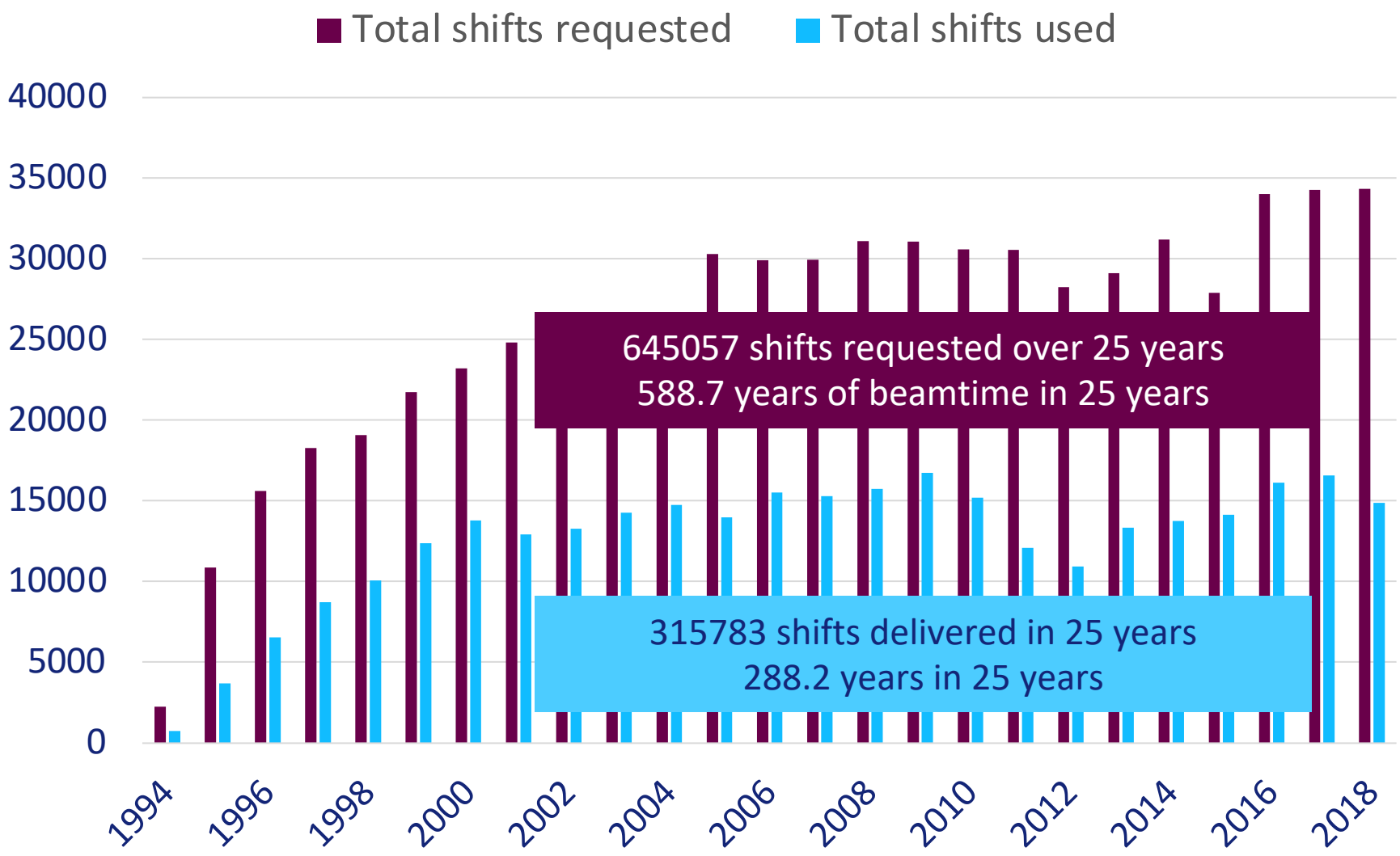


- ~ 1.8 *mC* (year average fresh charge)
- ~ 1.1 10^{16} electrons
- ~ 19 *pg* of electrons → 220 *ng* (at 6 *GeV*)

In total ~18 *kAh* integrated charge in USM

- ~ 45 *mC* (total fresh charge)
- ~ 2.8 10^{17} electrons (~8 *n€/electron*)
- ~ 470 *pg* of electrons → 5.6 *μg* (at 6 *GeV*)

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



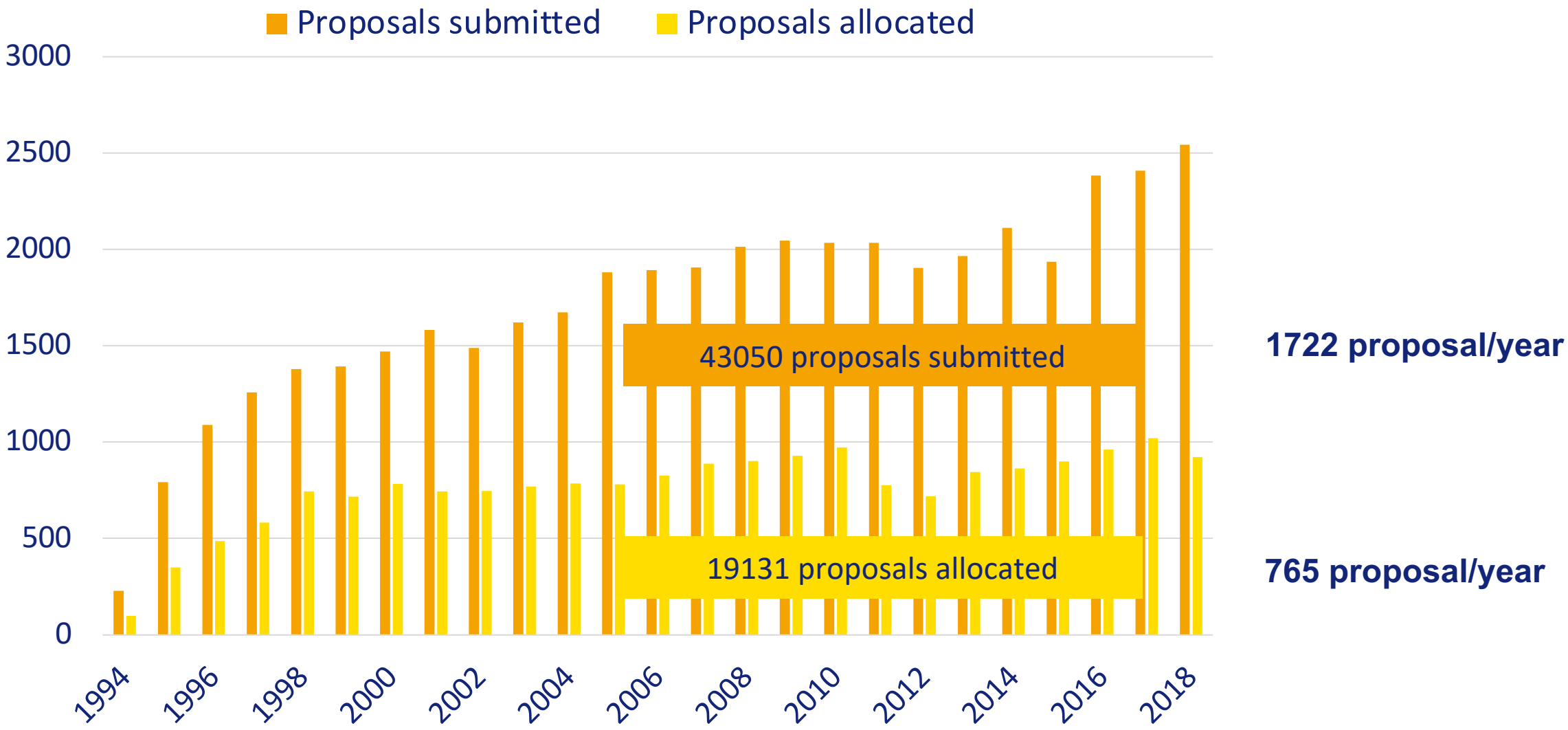
~ 600 years of requested beamtime

~ 23.5 years/year

~ 300 years of delivered beamtime

11.5 years/year

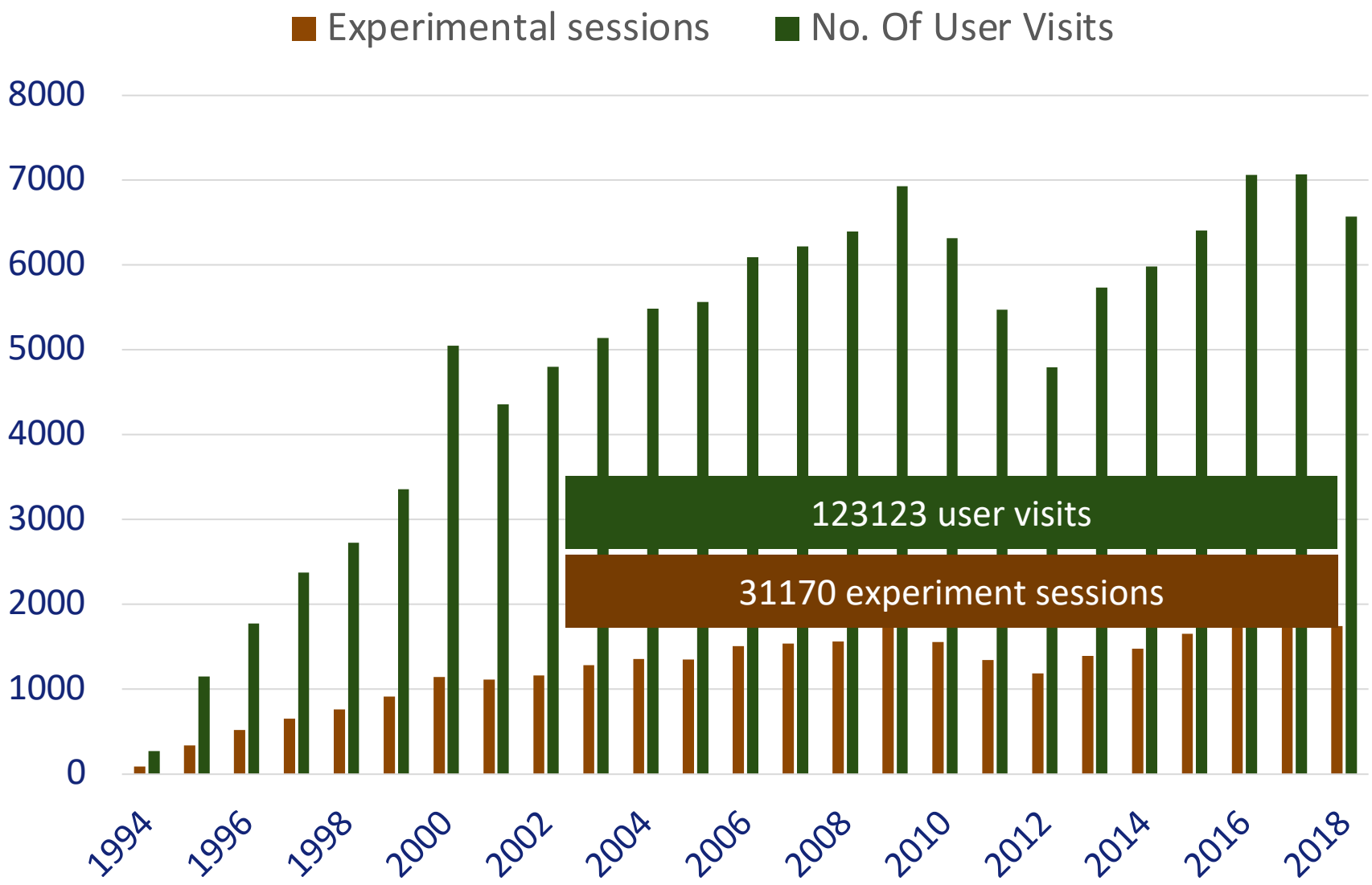
THE FIRST THIRD GENERATION SYNCHROTRON STORAGE RING: PROPOSALS 1994 - 2018



1722 proposal/year

765 proposal/year

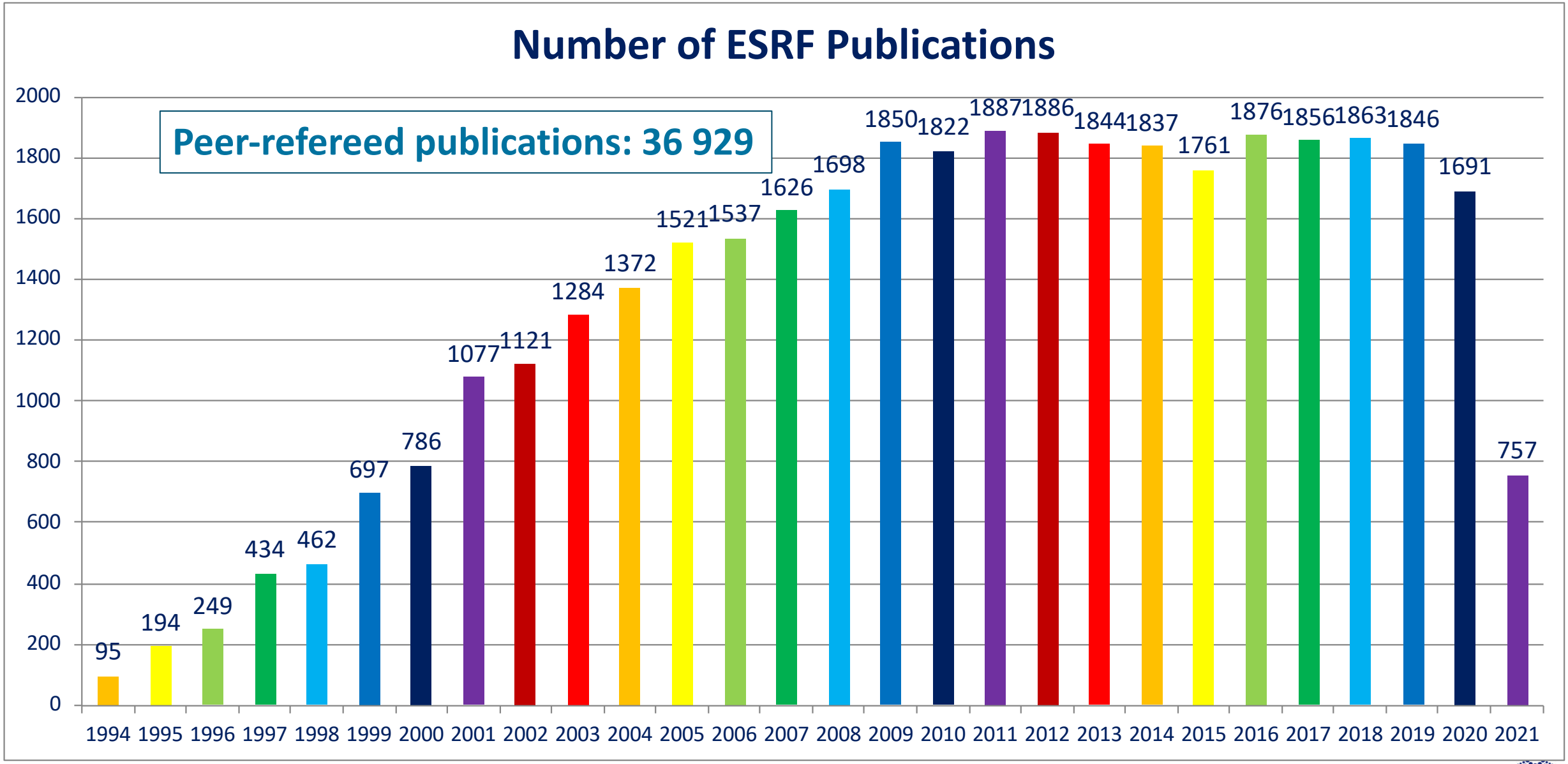
THE FIRST THIRD GENERATION SYNCHROTRON STORAGE RING: USERS VISITS 1994 - 2018



4924 user visits/year

765 exp. session/year

REFEREED PUBLICATIONS FROM WORK DONE AT THE ESRF: 1994 TO 2021 – UP TO 26-08-2021



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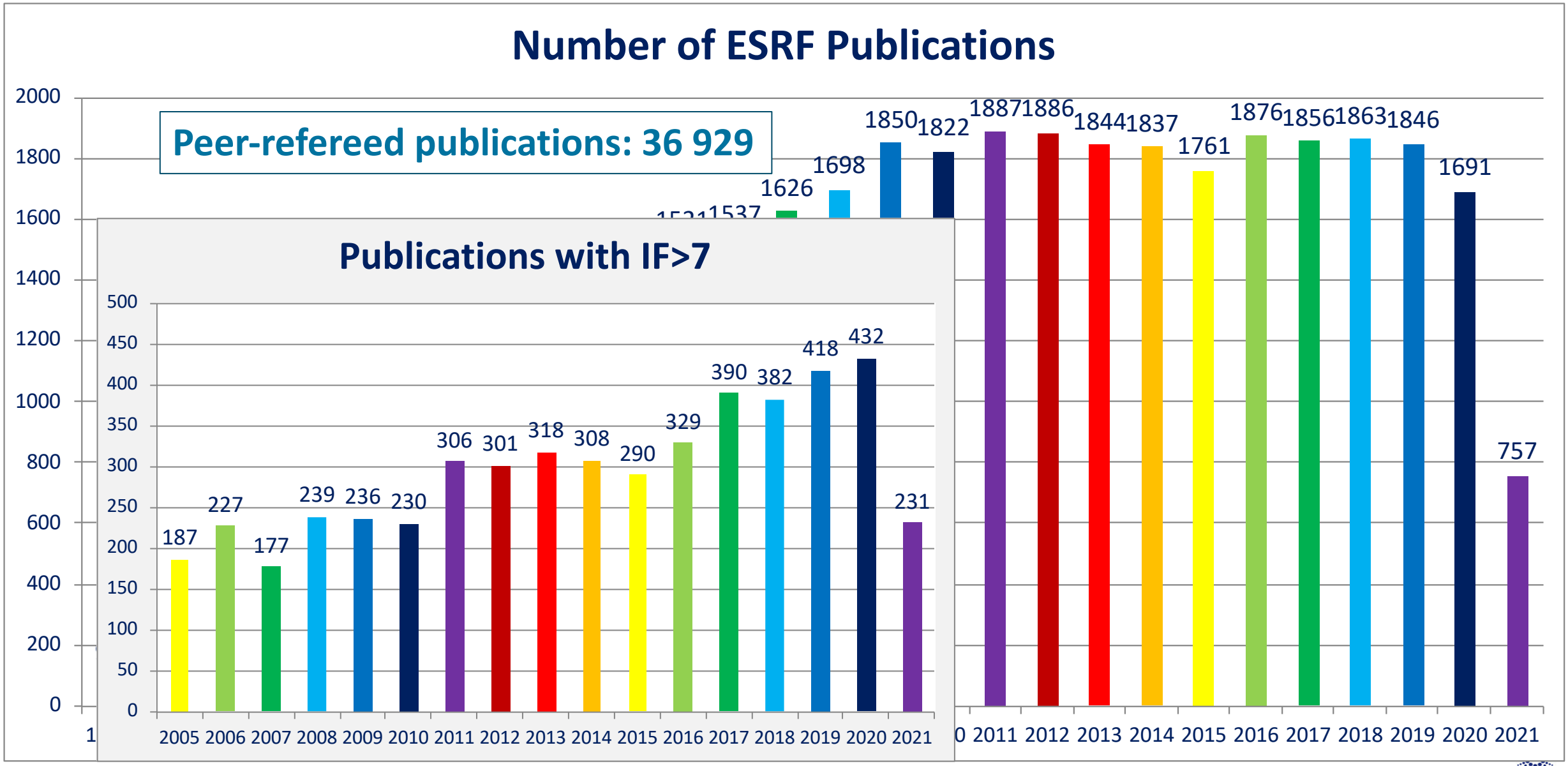
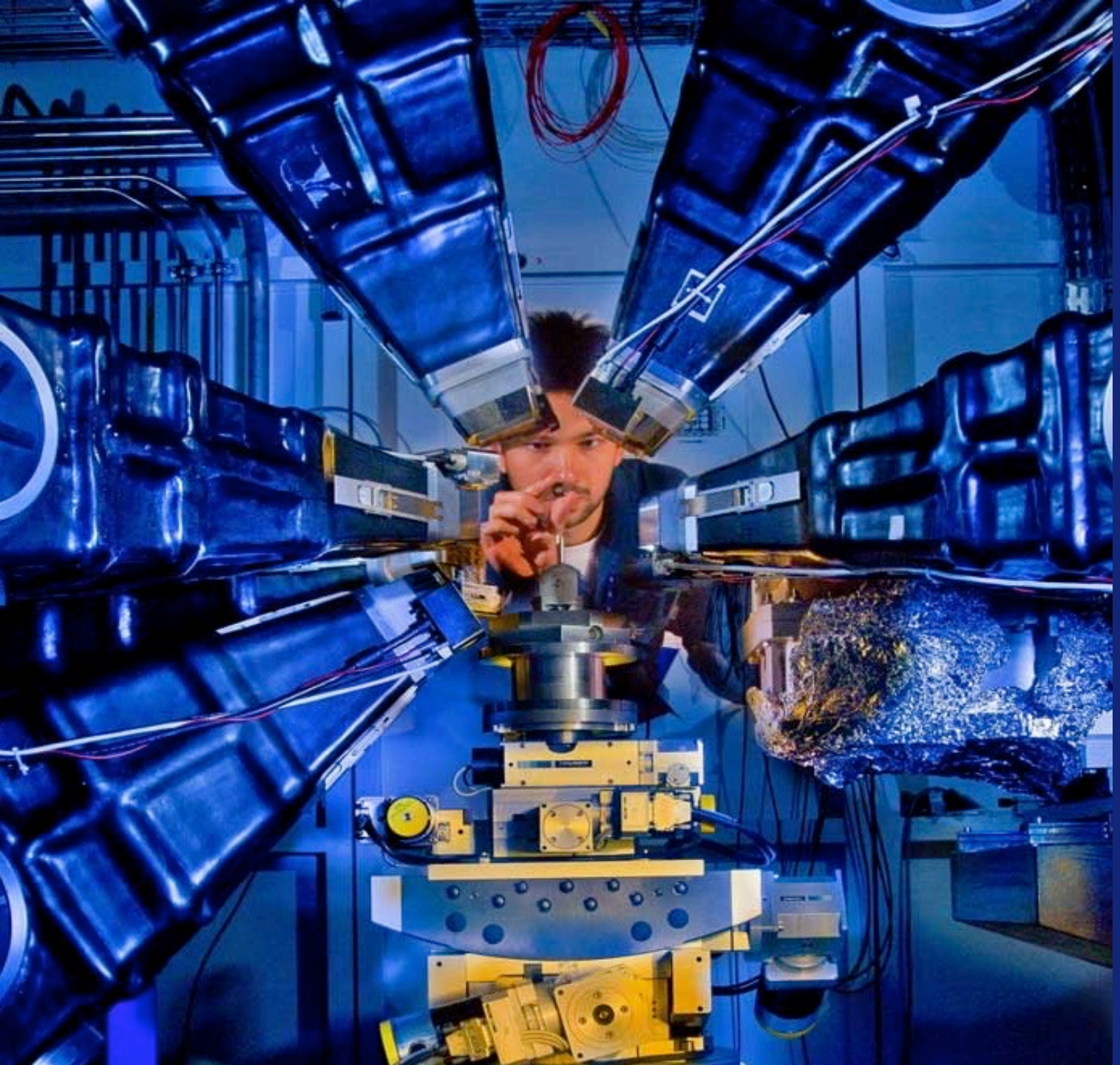
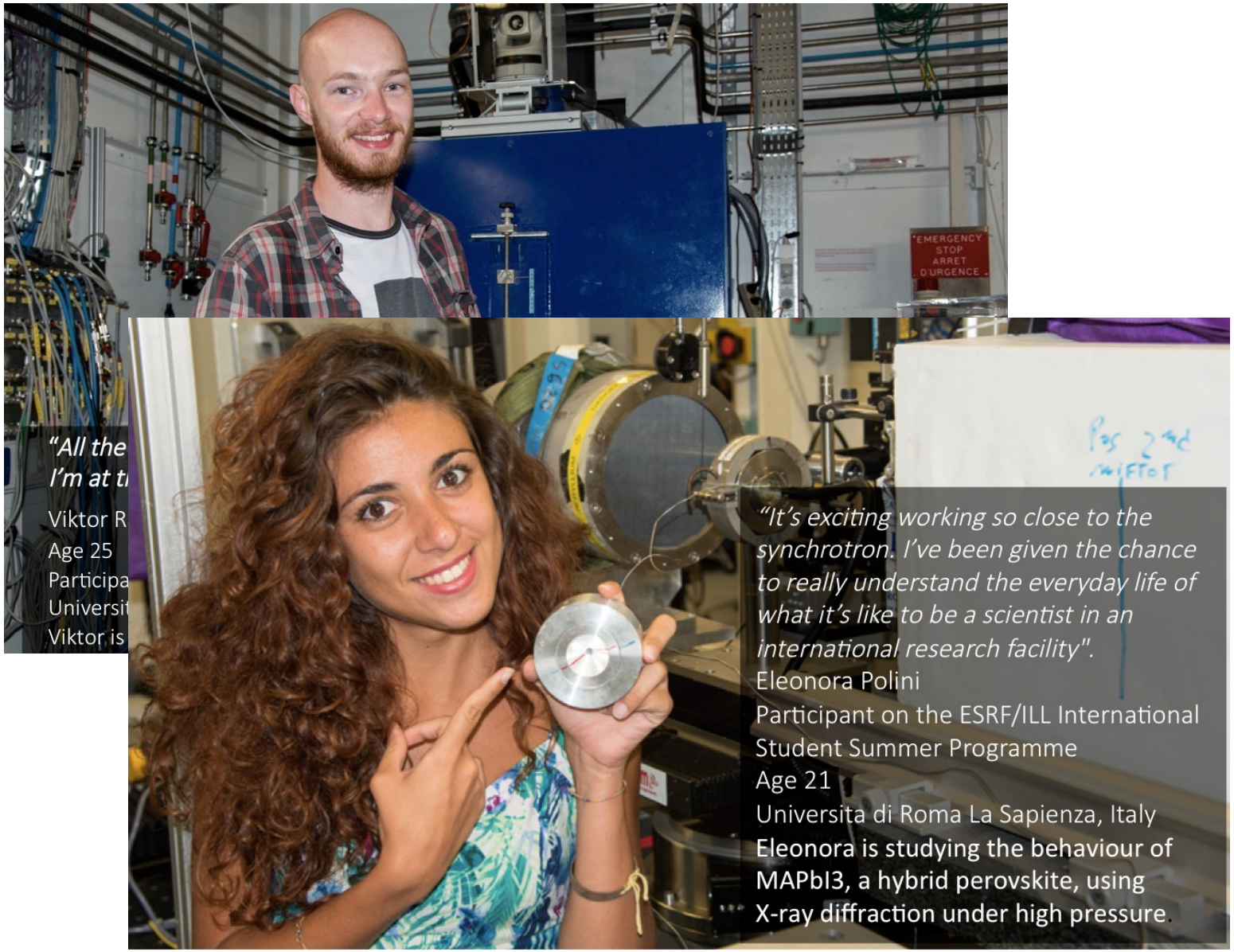




ESRF's missions

- 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

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

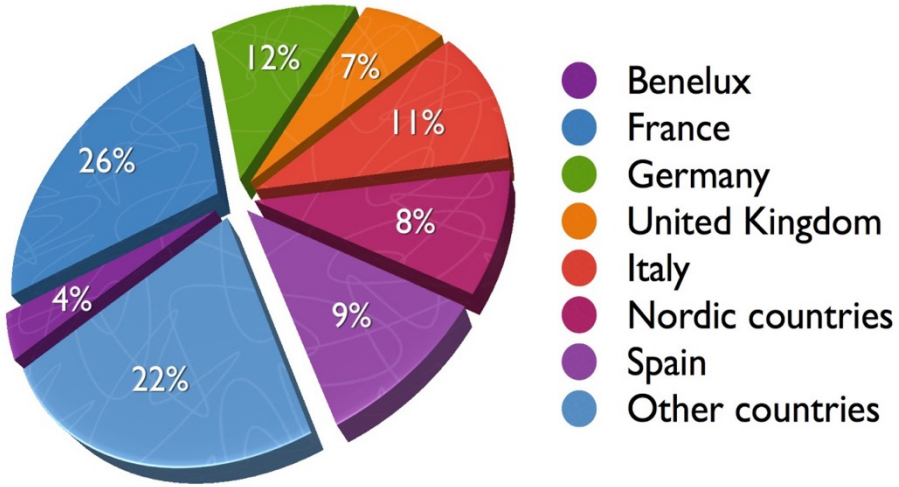
HERCULES

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

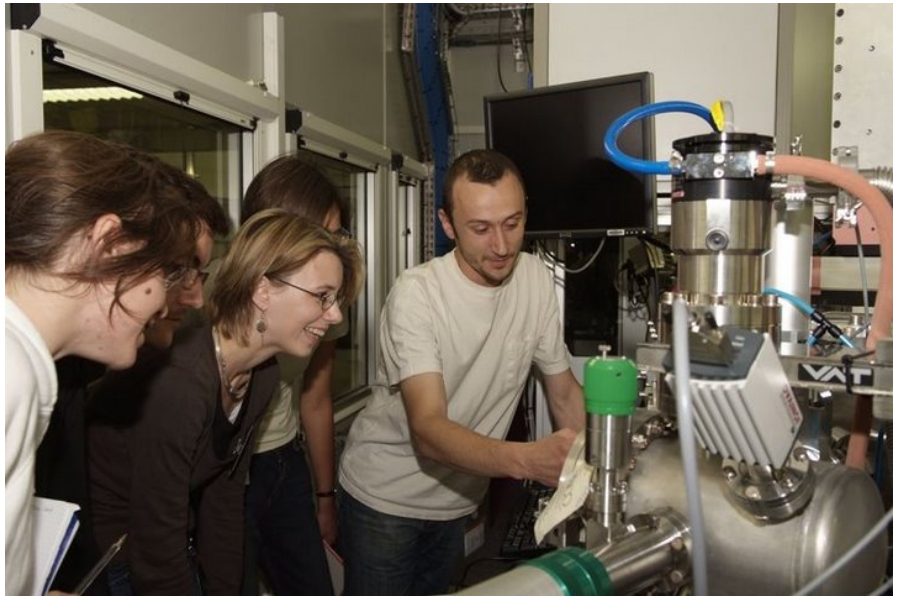
UNIVERSITÉ Grenoble Alpes

- **> 2200 participants since 1991**



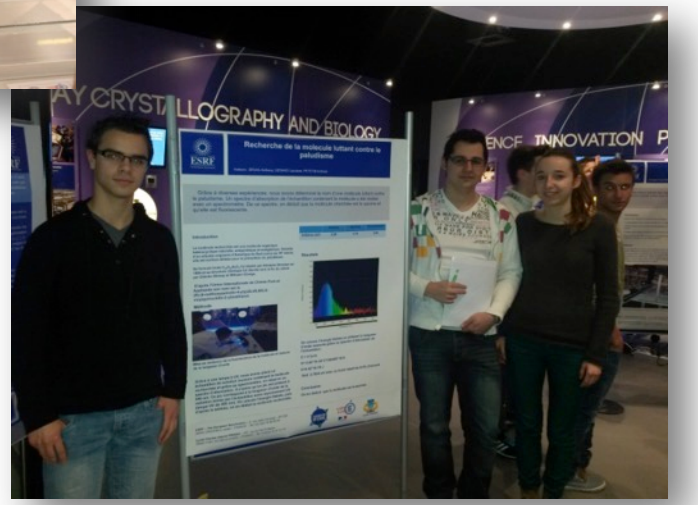
➪31 Hercules Annual Sessions (1991-2021)

➪~75 participants/session



ESRF | Institut Laue-Langevin | DESY | Elettra Sincrotrone Trieste | European XFEL | Soleil Synchrotron

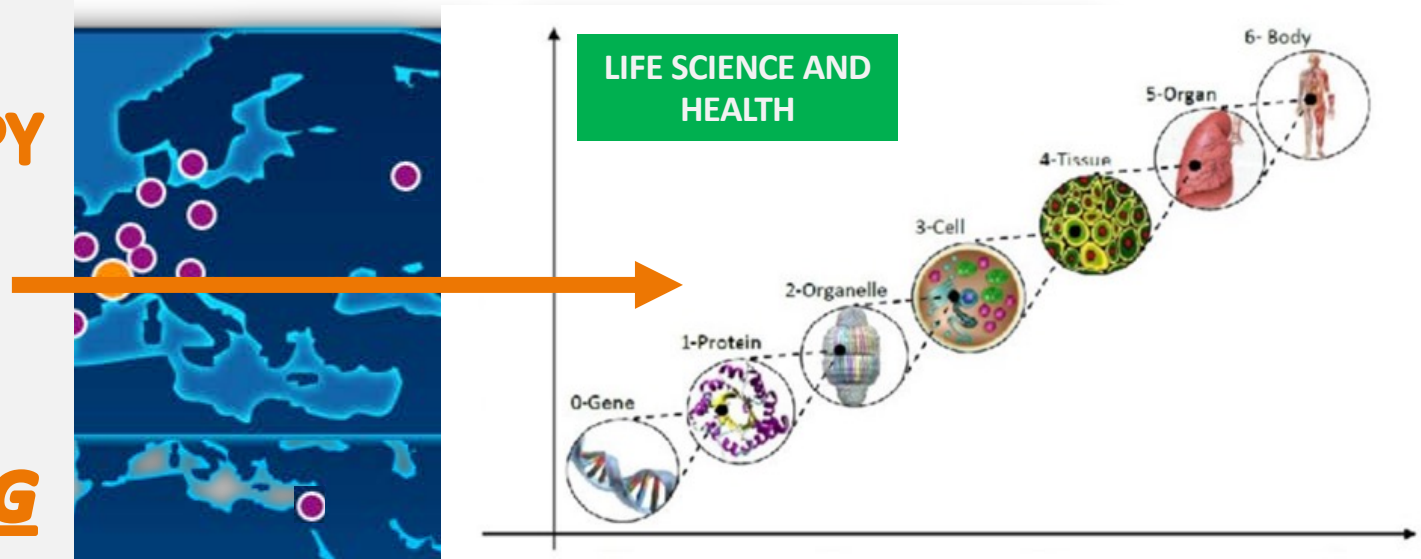
Science made by and for the youngsters

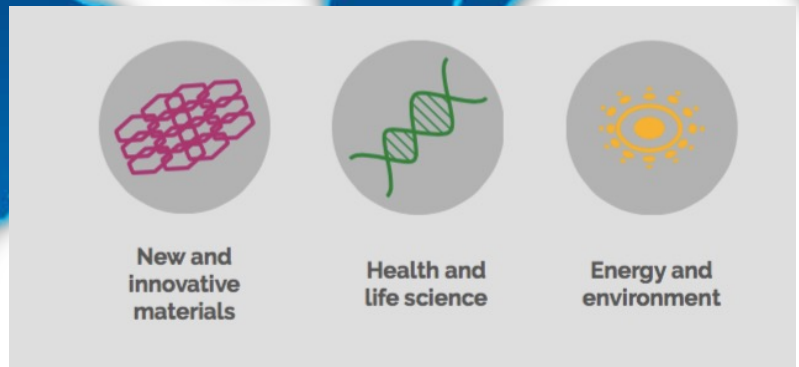


- A partnership of ESRF and Académie de Grenoble
- ~1 500 high school students every year
  - High schools with scientific and technical specializations
- A day of full scientific immersion, with scientific experiments carried out
- Schools fr*om all over*

FUTURE SYNCHROTRON X-RAY SCIENCE

TIME FOR THE NEXT STEP
X-RAY IMAGING AND MICROSCOPY
TO UNDERSTAND:
COMPLEXITY
FROM NANOMETRIC/ATOMIC
LEVEL TO THE FULL FUNCTIONING
MACROSCOPIC OBJECT





ESRF EBS: AN AMBITIOUS NEW STANDARD FOR SYNCHROTRON STORAGE RINGS

Purple Book January 2008

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

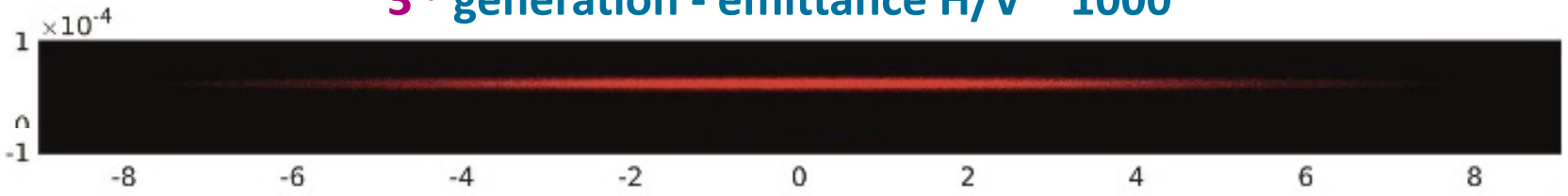
- **19 NEW BEAMLINES FOR NANOSCIENCE**
- **STUDY A NEW HIGH-BRILLIANCE–HIGH-ENERGY X-RAY STORAGE RING**

- **BEAMLINES SUCCESFULLY DELIVERED AND IN USER OPERATION SINCE 2015**
- **THE ESRF EXTREMELY BRILLIANT SOURCE PROGRAMME**

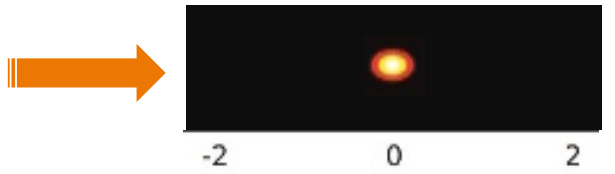
ESFRI

European Commission

3rd generation - emittance H/V ~ 1000



4th generation – emittance H/V ~ 1



D. Einfeld (1993): from the double-bend Chasman-Green achromat lattice (BNL 1975) to its multiple (*n*)-bend lattice version to drastically reduce the Horizontal Emittance

Unfortunately, however, this approach is a *no-go for 6+ GeV* (ESRF, P. Elleaume 2005), and more generally for an upgrade of existing machines

- Small Dynamical Aperture (unstable operation & poor injection efficiency)
- Focusing optics with technologically *"impossible"* field gradients

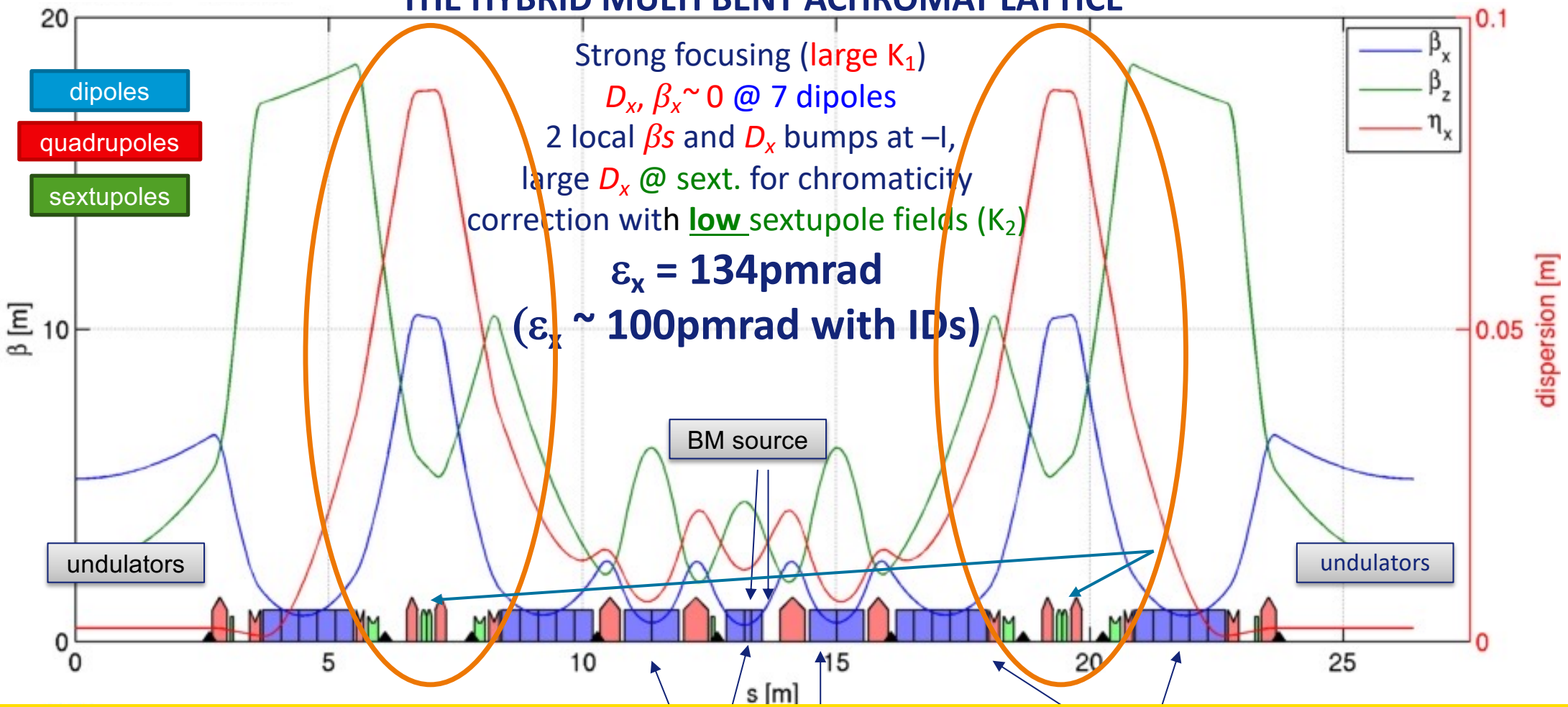
➢ Not for upgrading existing machines at the same e-energy

No real interest to upgrade existing (high) energy storage ring facilities as the science reach and case would dramatically change

PETRA-III (DBA)
NSLS-II (Green-field DBA)
MAX-IV (Green-field MBA)
SIRIUS (Green-field MBA)
DIAMOND (DDBA)
SPRING-8 → SPRING-6
ETC ..

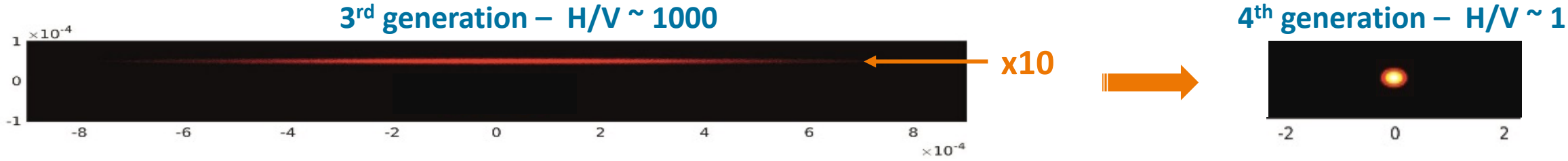
2012 – 2013: P. RAIMONDI AND ESRF COLLEAGUES INVENT AND DEVELOP THE HMBA LATTICE CONCEPT

THE HYBRID MULTI BENT ACHROMAT LATTICE



THIS DREAM BECOMES POSSIBLE THANKS TO THE INVENTION OF *THE HMBA LATTICE* BY P. RAIMONDI AND ESRF COLLEAGUES

ESRF UPGRADE PROGRAMME –THE QUEST FOR INCREASED BRILLIANCE AND COHERENCE



Synchrotron X-ray brilliance and coherence to the benefit of science

The objectives of the ESRF-EBS project:

- **Decrease the storage ring horizontal emittance – MBA CONCEPT (= a factor 100-1000 better than the 3rd SR generation)**
- Increase the source brilliance (= a factor 100)
- Increase the coherence of the beam (= a factor 40)
- Re-use the existing infrastructure (90%)
- Minimise the impact on the ESRF activity (dark-brown time)
- Reduce environmental impact – reduce electrical power consumption by ~20%

ESRF-EBS LATTICE VS. PREVIOUS ESRF-DBA LATTICE: DBA → H7BA

➢ **Previous ESRF lattice (cell)**

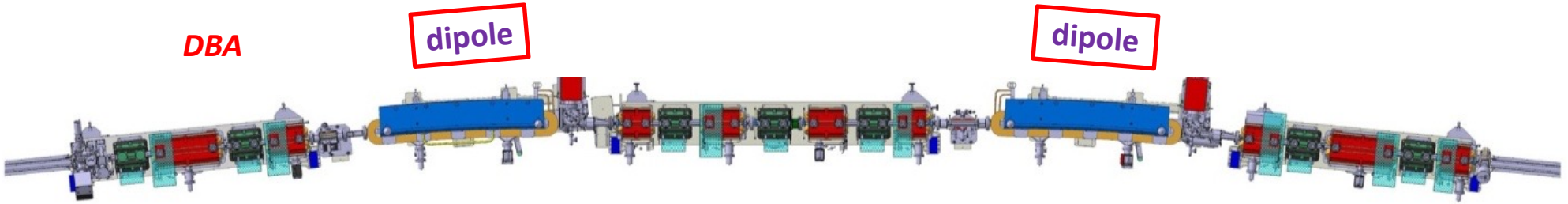
Double Bend Achromat = (2 dipoles + 15 quad. sext.) per cell
ID length = 5 m (standard) / 6m / 7m

$$\varepsilon \propto \frac{E_e^2}{\left(N_{sect} \cdot N_{dipole}\right)^3}$$

➢ **EBS lattice (cell)**

Hybrid 7 Bend Achromat = (4 dipoles-lg + 3 dipole-quad + 16 quad., 6 sext., 2 oct.)
ID length = 5 m

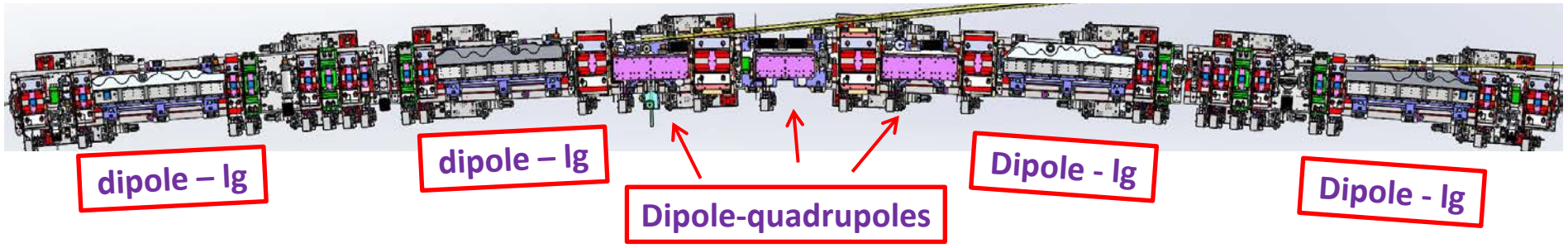
DBA



31 magnets per cell instead of 17

32 cells (arcs) with 4 girders each

EBS-H7BA



ESRF-EBS LATTICE VS. PREVIOUS ESRF-DBA LATTICE: DBA → H7BA

Emittances with EBS: H/V=10 – x100 brighter X-rays

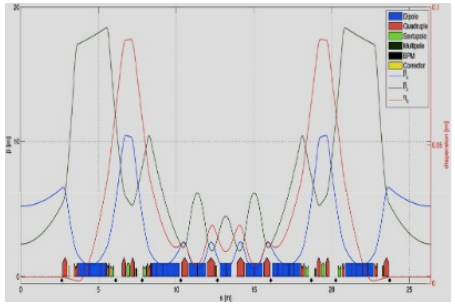
x10

	ESRF-EBS	ESRF-3rd G
Energy [GeV]	6.04	6.04
Tunes	75.21, 26.34	36.44, 13.39
Emittance x [pmrad]	134	4000
Emittance y (target) [pmrad]	2	3
Energy loss per turn [MeV]	2.6	4.9
RF voltage (acceptance) [MV]	6 (5.6%)	9 (4%)
Chromaticity	6, 4	4, 7
Circumference [m]	843.98	844.39
Energy spread [%]	0.095	0.106
Beam current [mA]	200	200
Lattice type	HMBA	DBA
Touschek lifetime [h]	~20	~80

UPGRADE OF EXISTING STORAGE RINGS TO A NEW LOW HORIZONTAL EMITTANCE LATTICE IS NO LONGER A DREAM:
ALL FACILITIES WORLWIDE IMPLEMENTING OR CONSIDERING AN *HMBA* BASED UPGRADE

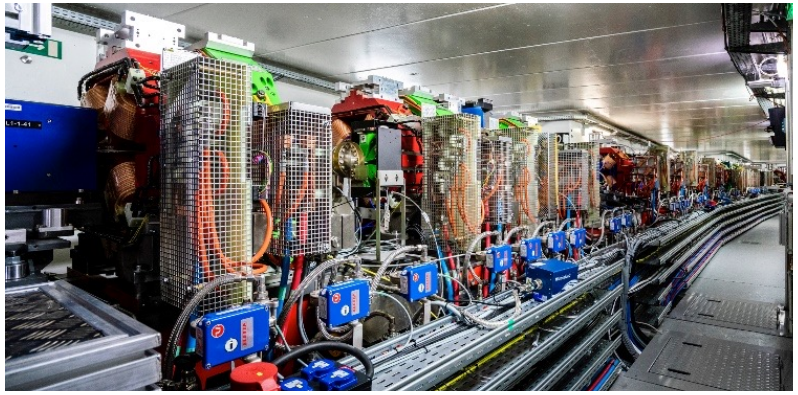
ESRF-EBS: A MACHINE DREAM BECOMES A REALITY IN 5 YEARS SINCE ITS CONCEPTION

From the idea – 2011/13

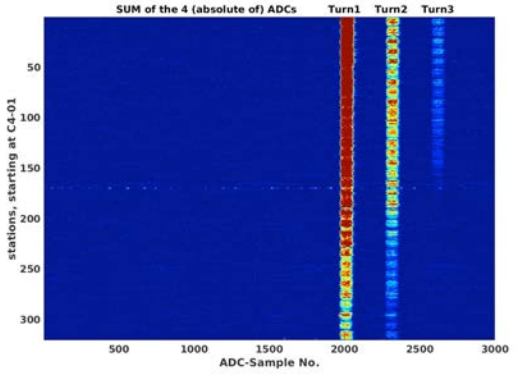


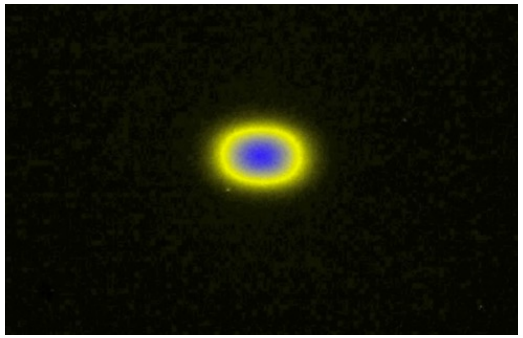
To the design – 2015/16

To the installation – 2016/19

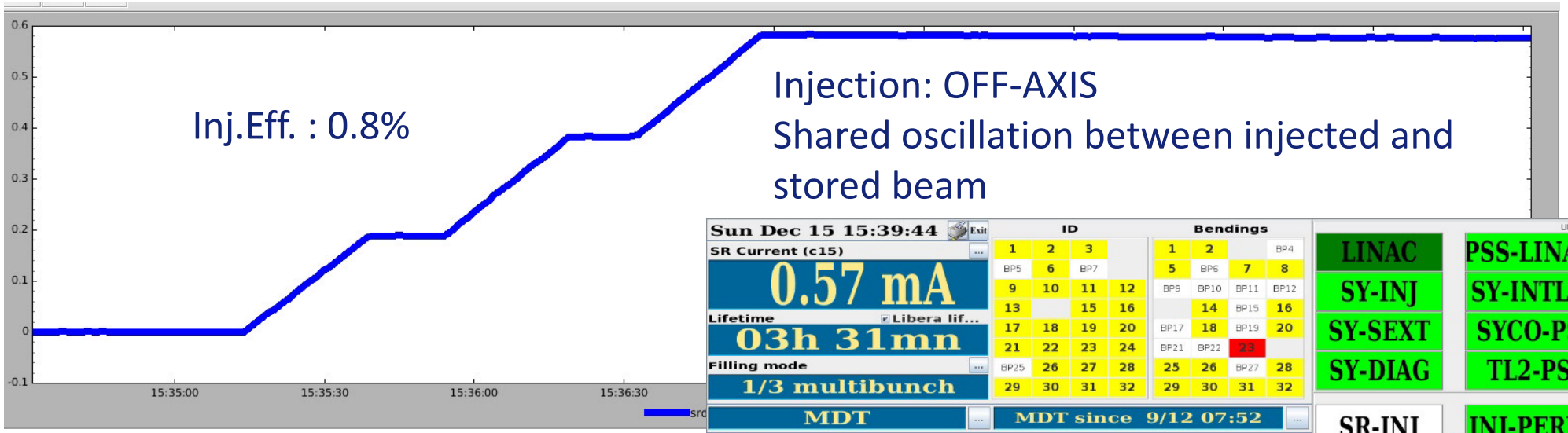


To the 1st electrons – 28-11-2019



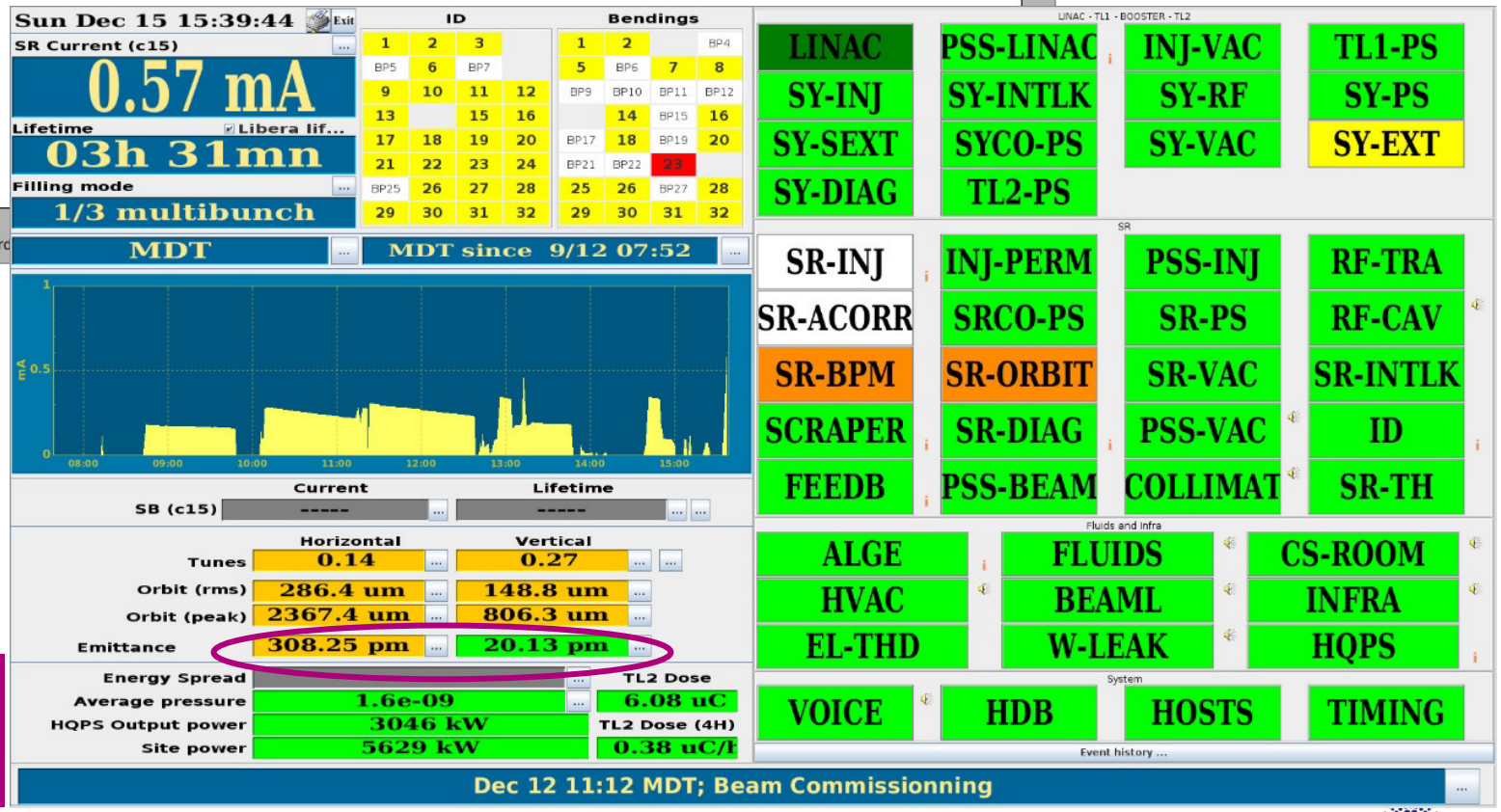


2019 DECEMBER 15TH : FIRST ACCUMULATION



Inj.Eff. : 0.8%

Injection: OFF-AXIS
Shared oscillation between injected and stored beam

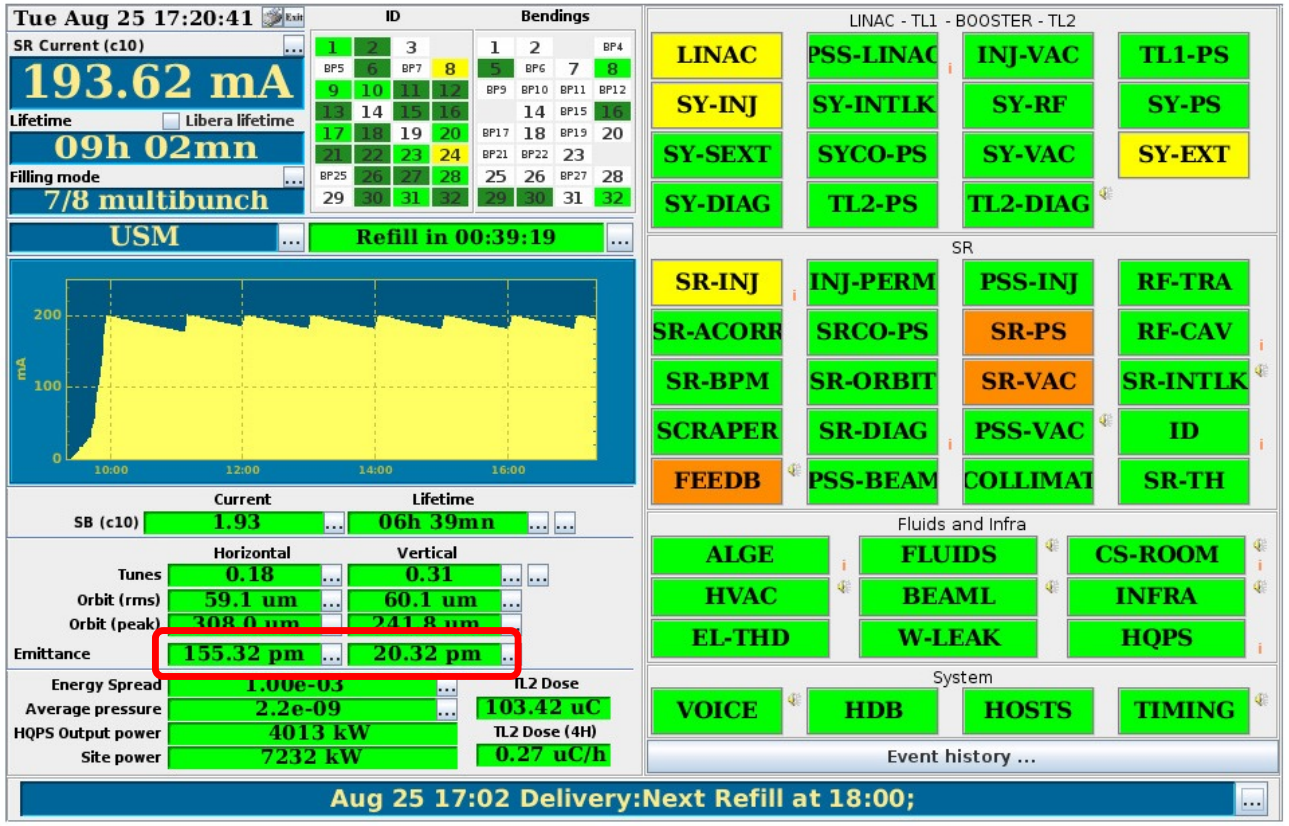


FIRST e⁻ ACCUMULATION
IN THE EBS Storage Ring
15th Dec 2019 @ 15.39

17 DECEMBER 2019 – 5 mA
EBS exceeds former SR brightness

25TH AUGUST 2020 : A TIME TO REMEMBER !

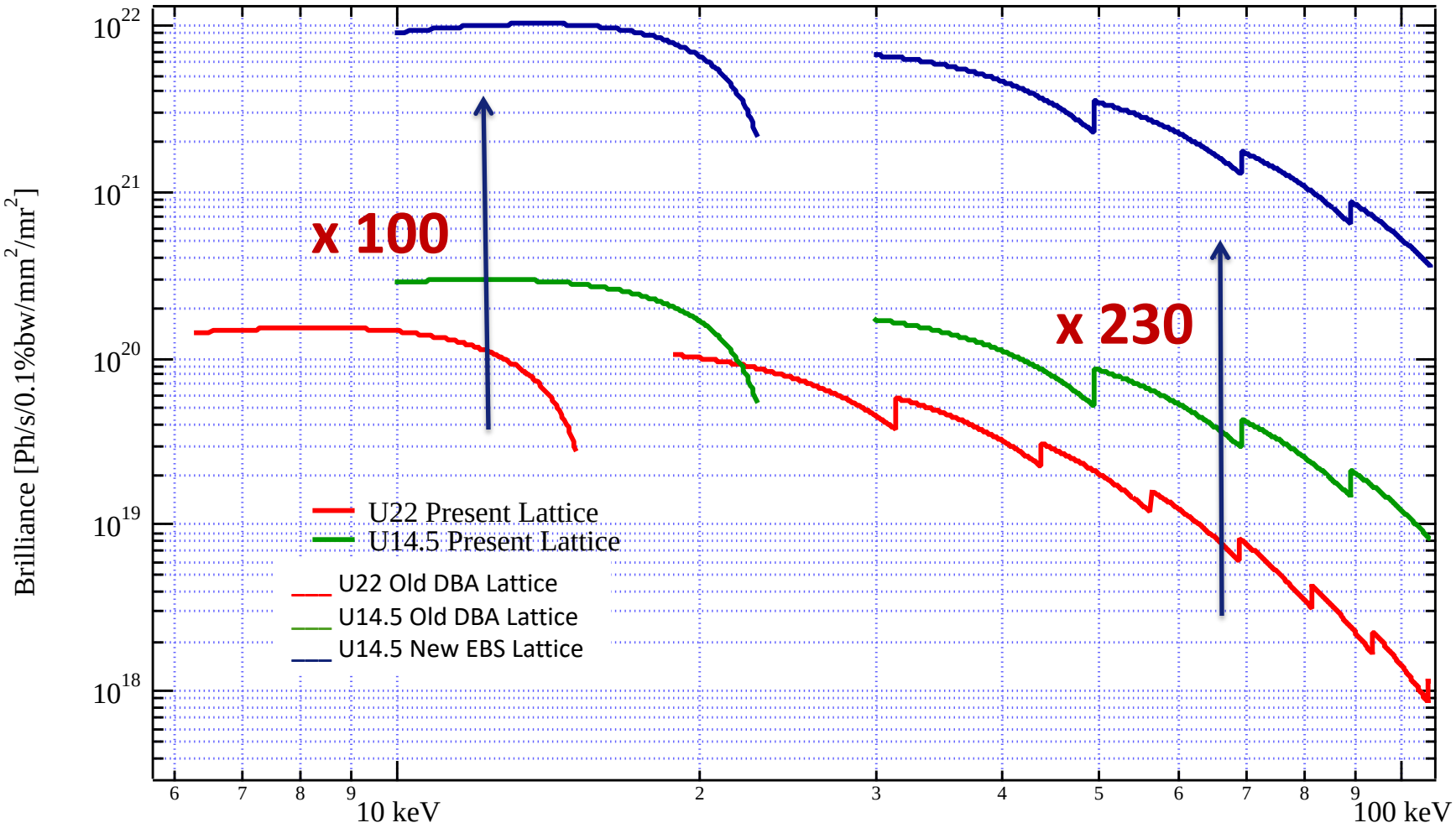
The 25th August 2020, first official USM shift starts



- 28 beamlines take beam
- 200 mA
- $\varepsilon_x = 150\ pm \cdot \mathrm{rad}$
- $\varepsilon_z = \ \ 20\ pm \cdot \mathrm{rad}$

ON TIME – WITHIN BUDGET

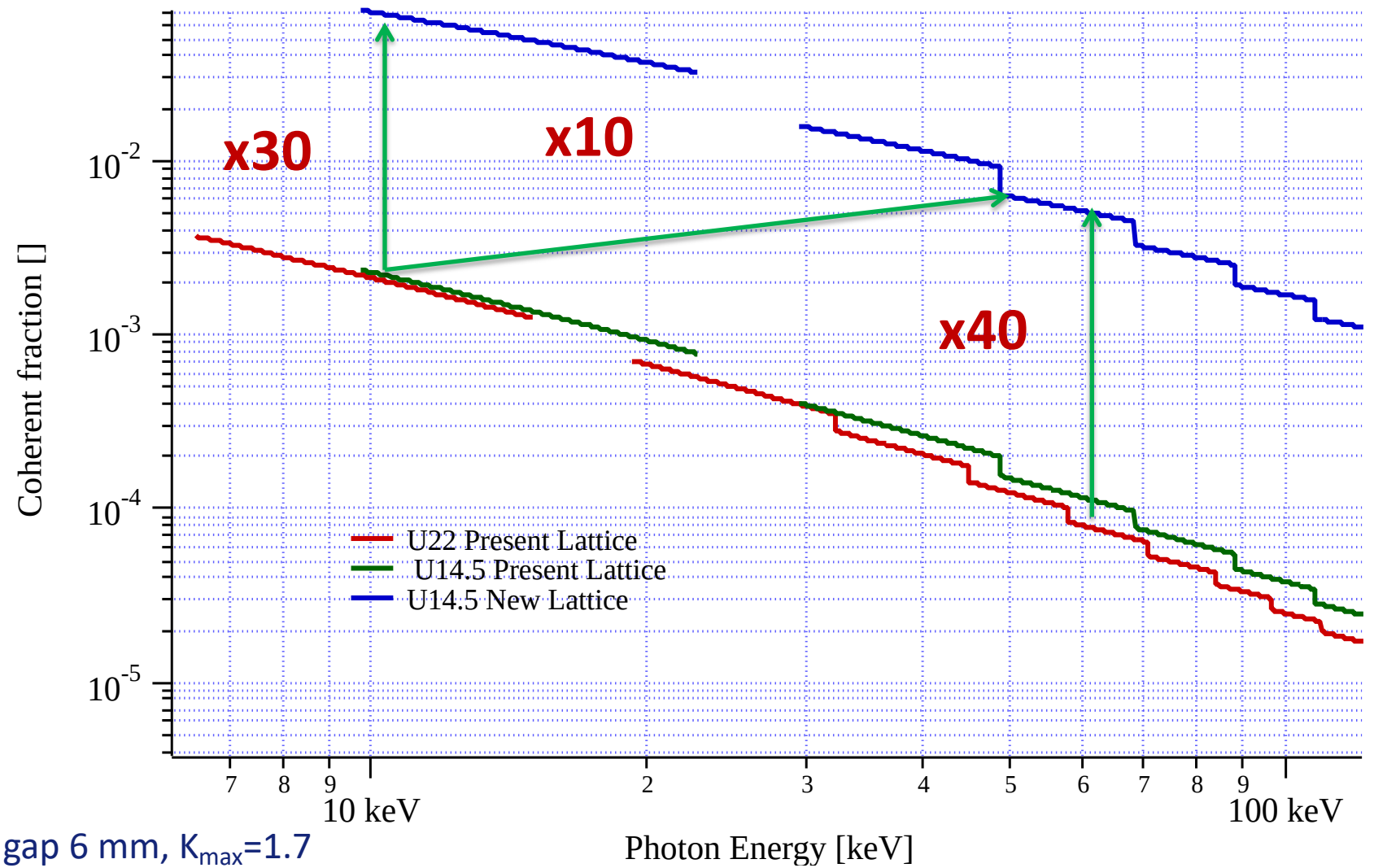
CPMUS AT SMALLER GAP: INCREASED BRILLIANCE



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

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

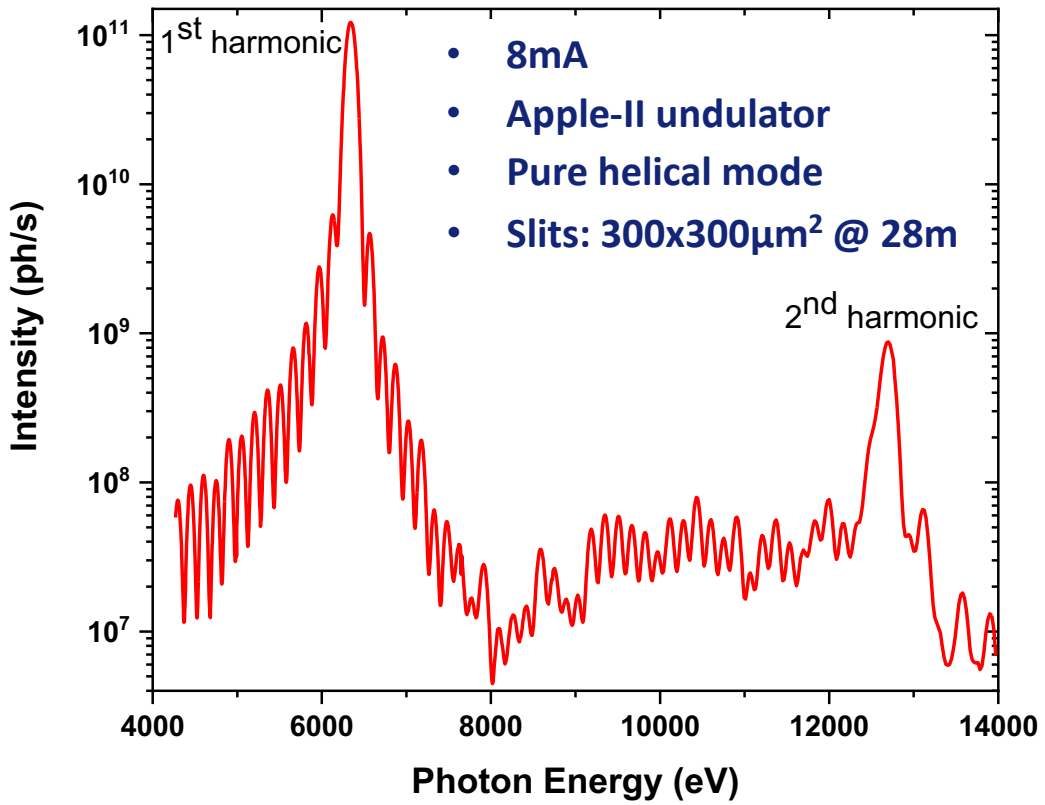
ESRF-EBS: MAIN LATTICE PARAMETERS



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

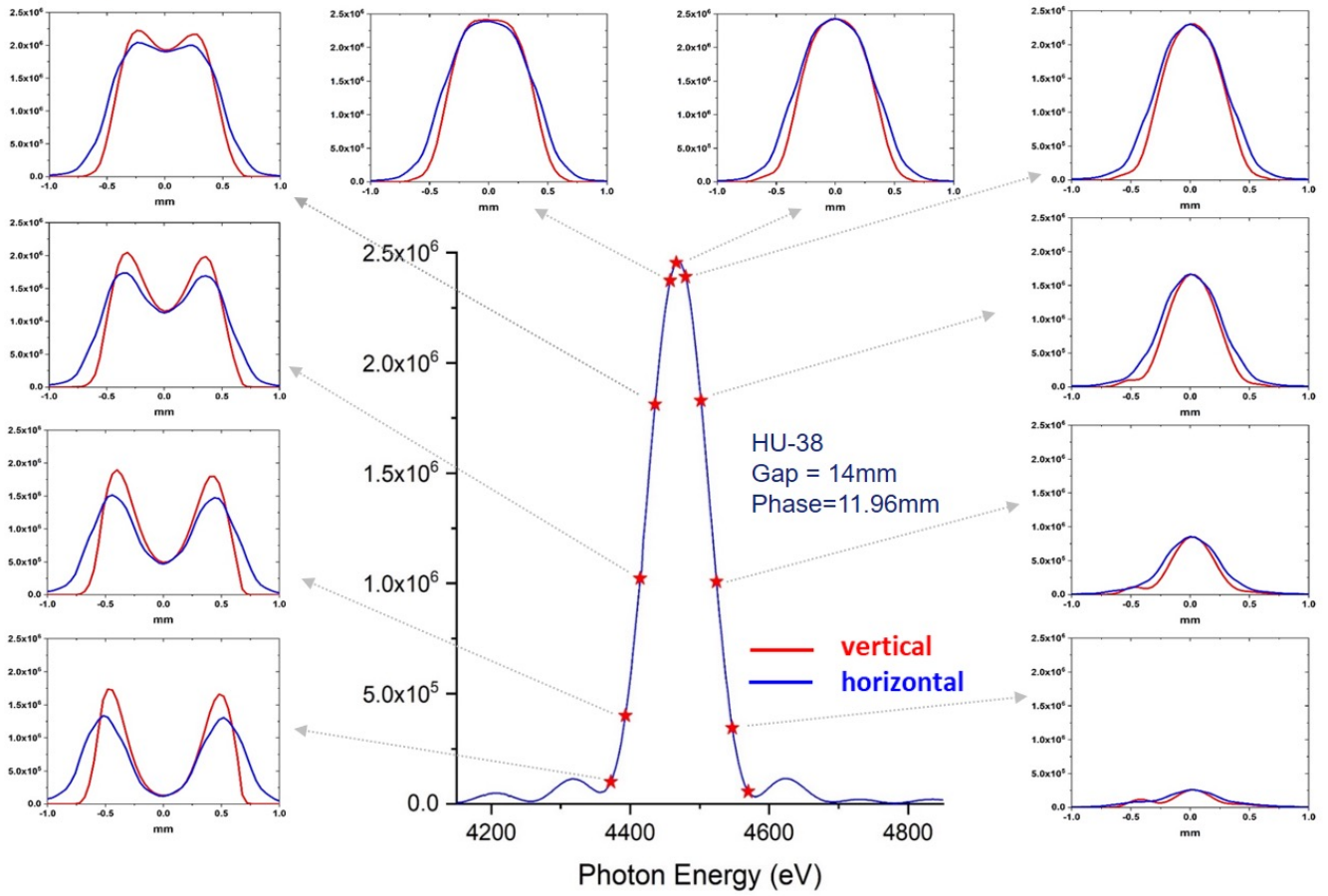
CPMU14.5 min. gap 4 mm, K_{max}=1.7

CONTROL AND FINE-TUNING OF UNDULATORS



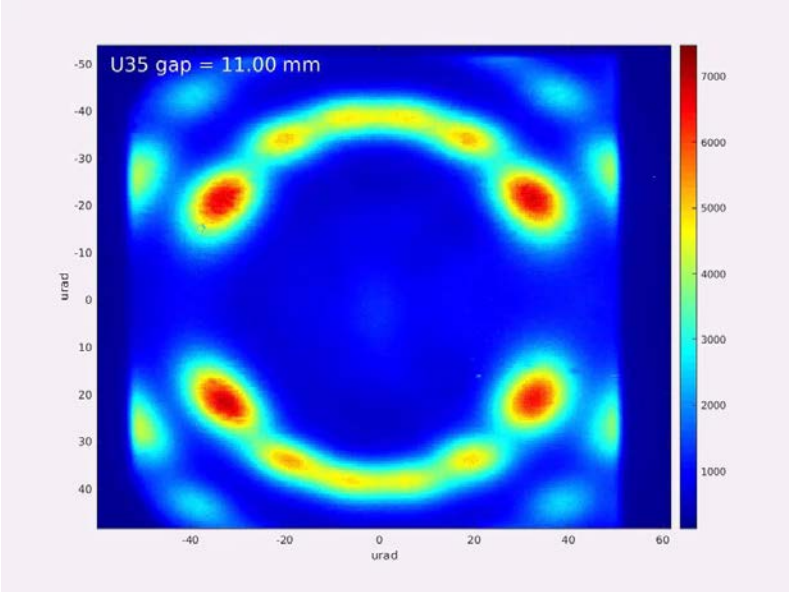
Courtesy of A. Rogalev (ID12)

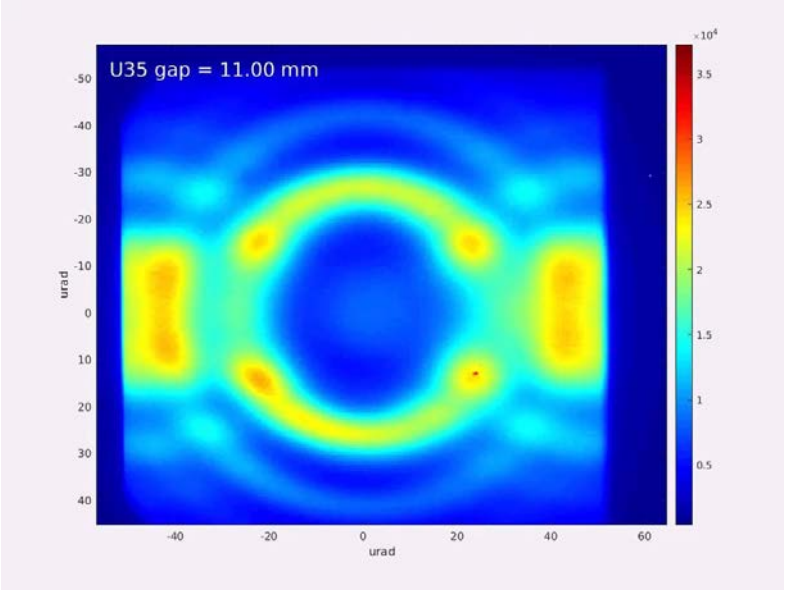
X-ray beam profiles at different photon energies of the 1st harmonic - slits 60x60μm² @ 28m

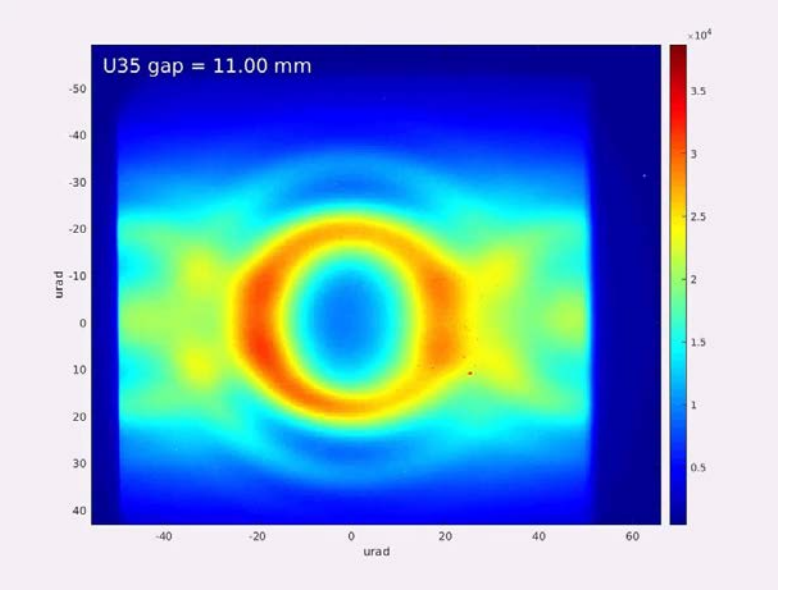


A gain of factor of 5 in flux due to smaller beam size
Second harmonic intensity is reduced by at least a factor of 10

FIRST BEAM AT ID15A







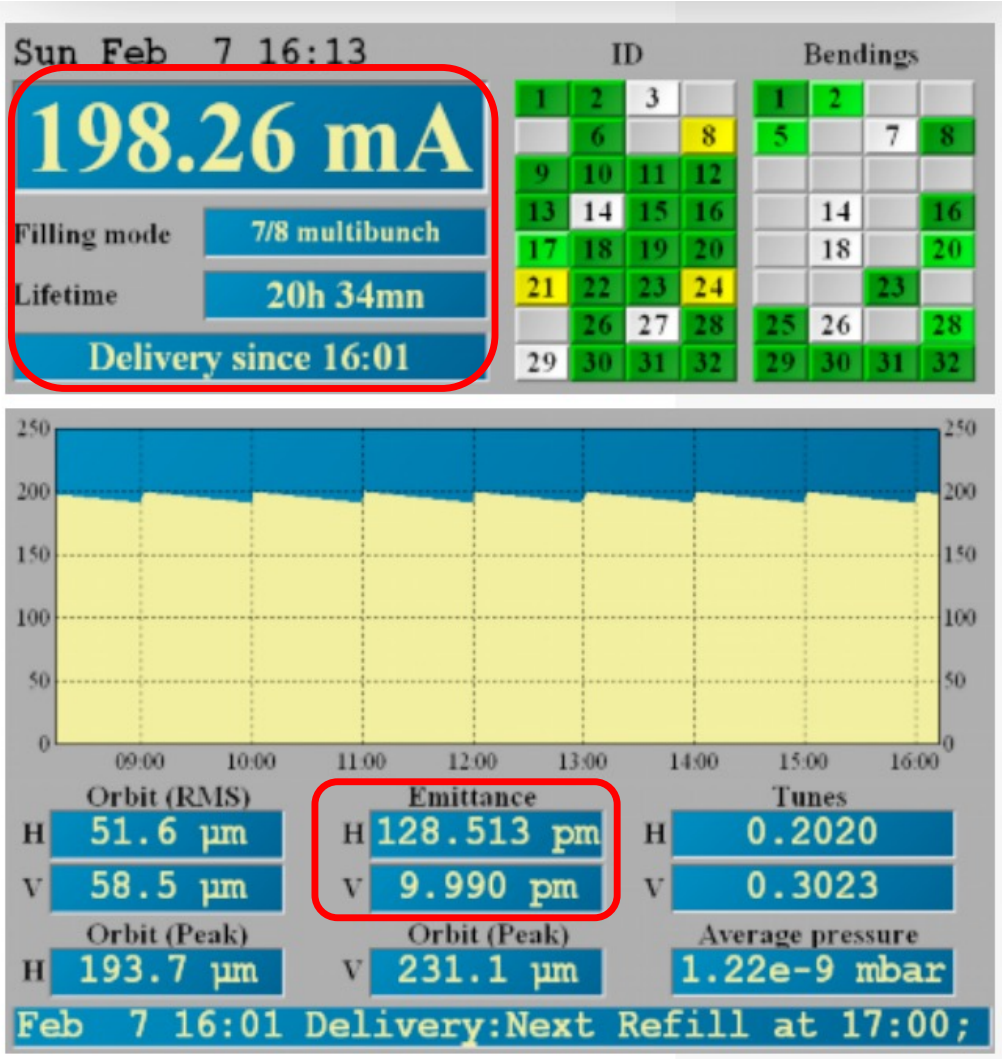
40 keV **70 keV** **100 keV**

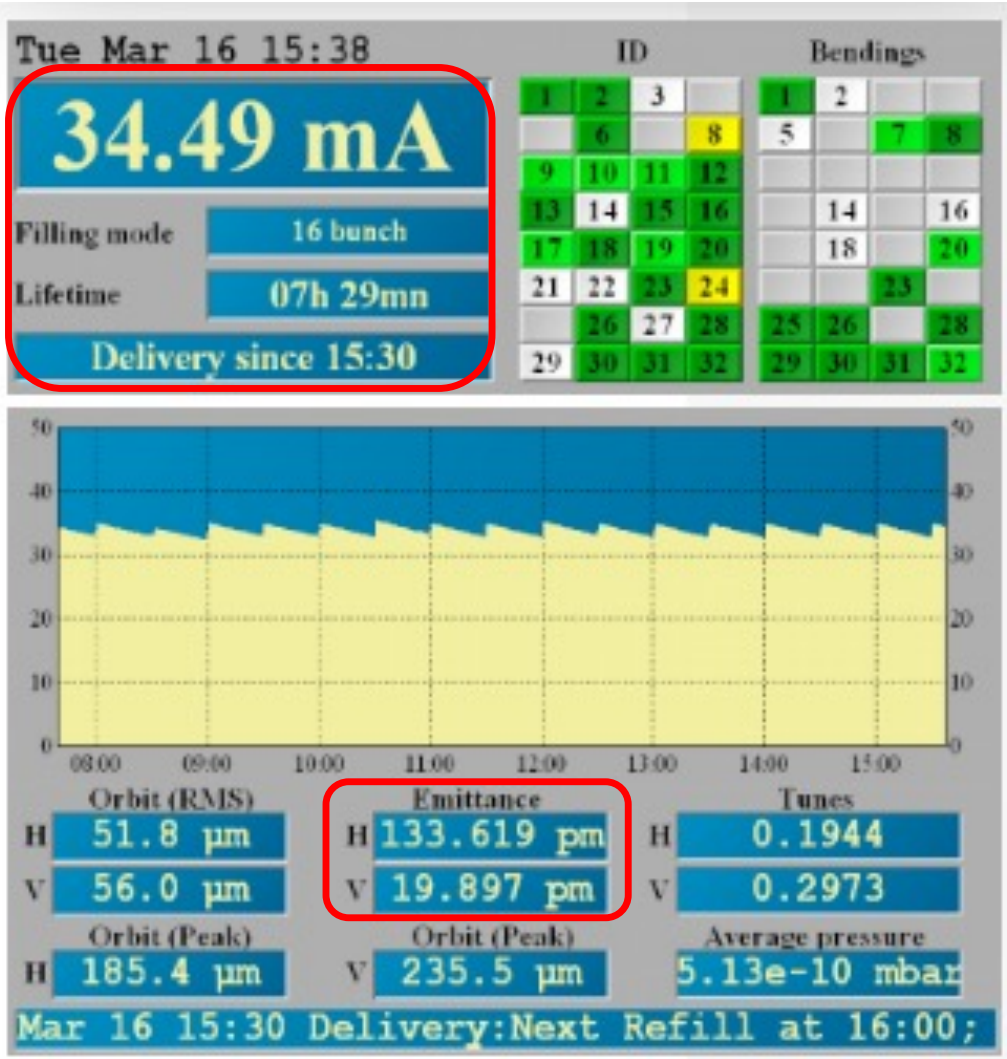
monochromatic beam from a U35 [Laue-Laue monochromator with approx. 3. 10^{-3} energy resolution]

(band width narrower than undulator harmonics)

images taken at ~65 meter with PCO-edge camera with 1:1 optics (6.7 mm pixel size)

EBS Machine – incredibly stable and operating very smoothly

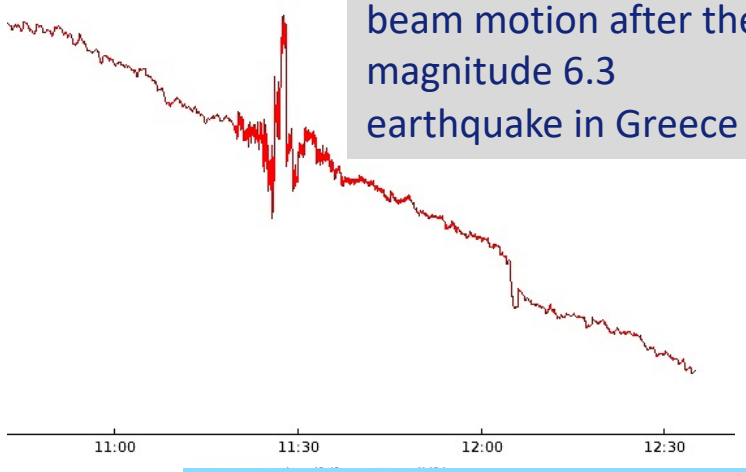




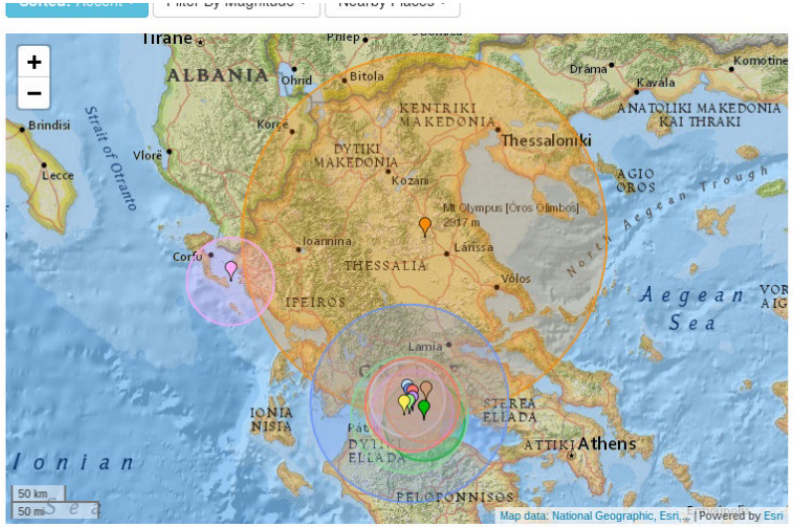
One top-up every hour (7/8+1) or every 30 minutes (16)

ID18 – Nuclear Scattering Beamline: "Bunch purity is perfect! Residual electrons in adjacent *empty* bunches is $< 10^{-10}$!!"

EBS Machine – but also very sensitive

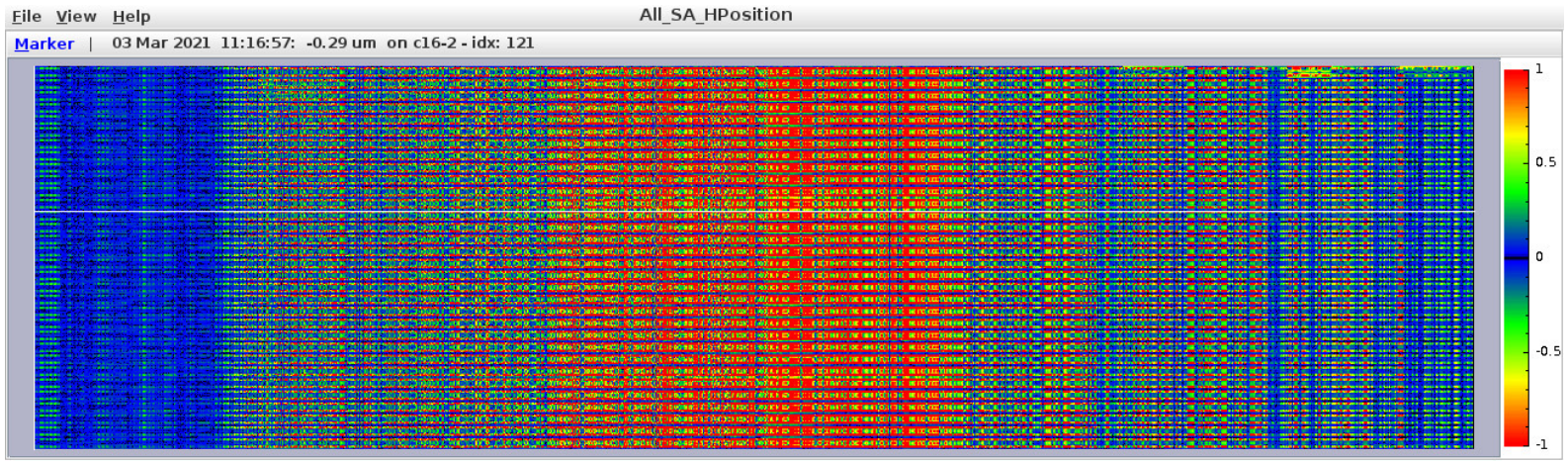


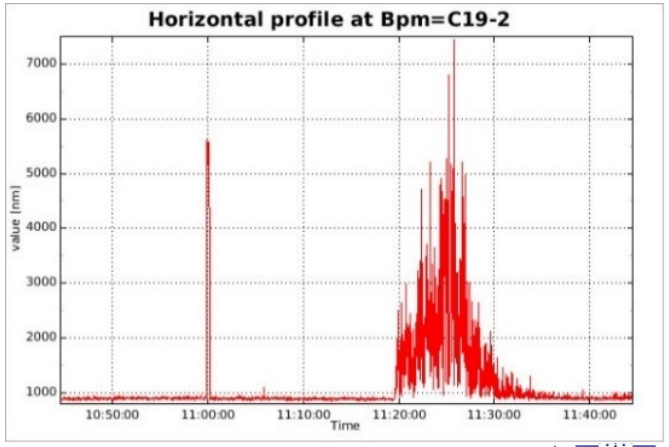
Wed. Mar. 3rd @11:30, beam motion after the magnitude 6.3 earthquake in Greece



4th March, another vibrant day:
@14:47: a M6.9 in New Zealand
@20:35: a M5.6 in Greece
@22:30: a M8.1 in New Zealand

horizontal beam disturbance along the ring (Y) over time (X)





USER STATISTICS AND ACTIVITIES FROM 25 AUGUST 2020 UNTIL 15 JUNE 2021

41/46

41 out of 46 beamlines hosted user's experiments

10 550

10 550 shifts (84 550 hours) delivered: 8657 for public users, 1518 for CRG, 375 for proprietary research

1 527

1 527 user experiments, 1149 for public users (75%), 122 for CRG (8%) and 256 for proprietary research (17%)

1 097

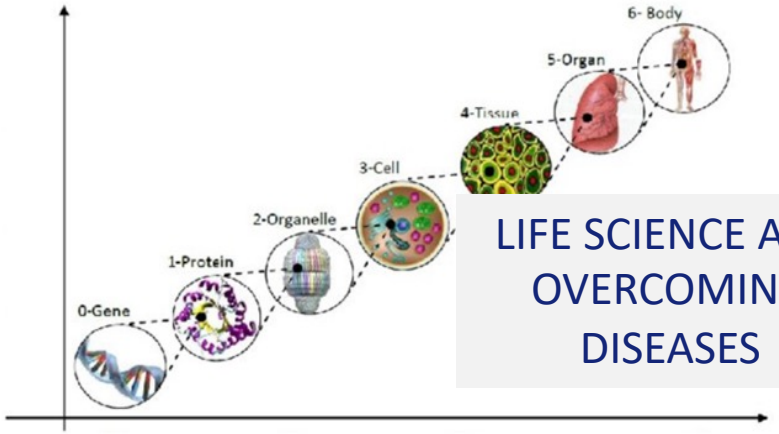
1097 fully remote (72%), 165 only one user (11%), and 265 with users (17%)

FIRST EBS SCIENCE

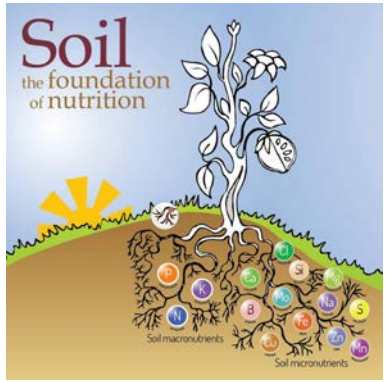
ESRF-EBS, AN EXTREMELY BRILLIANT SOURCE TO TACKLE GLOBAL CHALLENGES

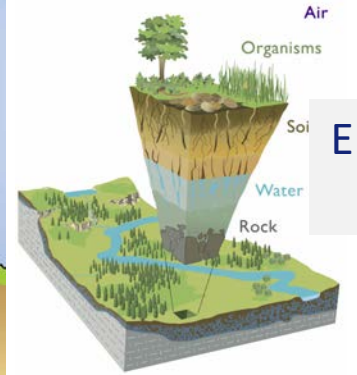
1. **Health, Health Innovation**, overcoming diseases and pandemics
2. **Material for tomorrow,** and innovative and sustainable industry
3. **Clean Energy transition**, sustainable energy storage and clean hydrogen technologies
4. **Planetary research** (terrestrial and extra-terrestrial)
5. **Environmental and climatic challenges**,
6. **Bio-based economy and food security**
7. **Humanity and world cultural heritage**

FUNDAMENTAL AND APPLIED SCIENCE WITH X-RAYS: UNDERSTANDING COMPLEXITY IN CONDENSED AND LIVING MATTER



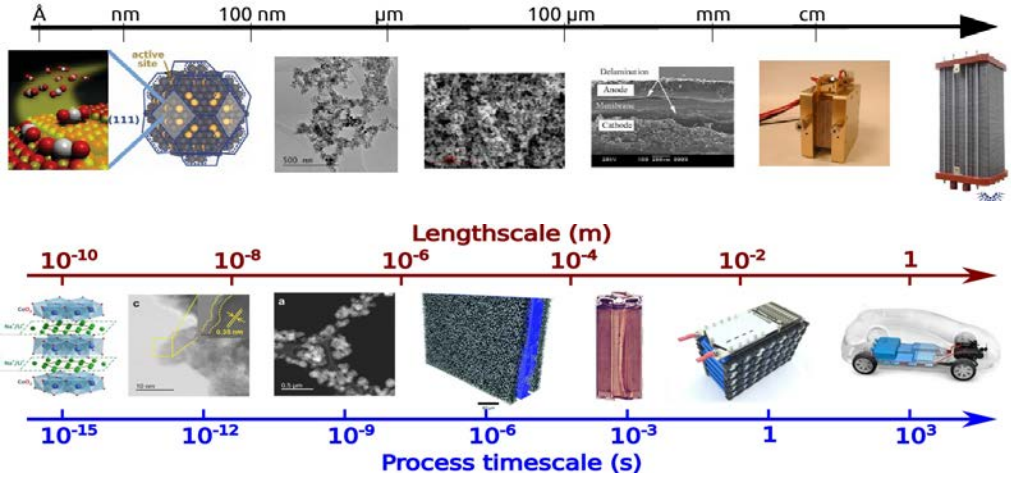
LIFE SCIENCE AND OVERCOMING DISEASES

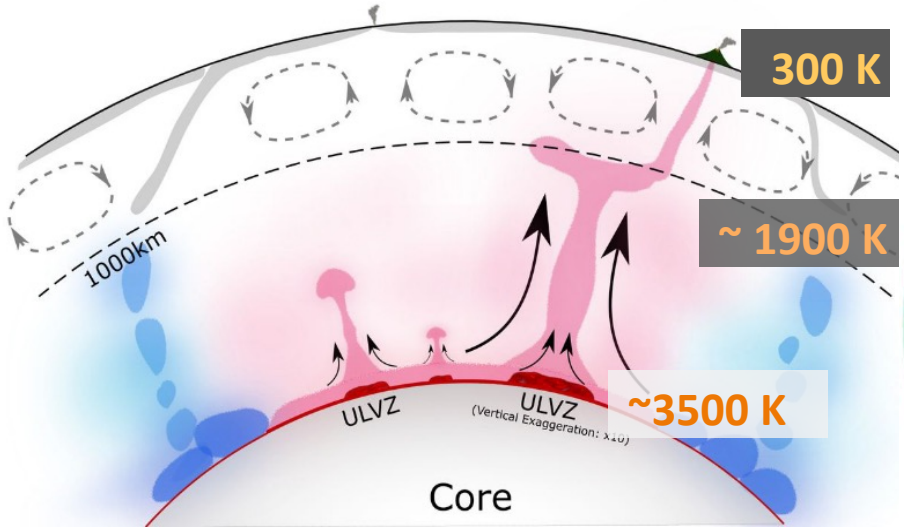




ENVIRONMENT AND SUSTAINABILITY

MATERIALS AND PROCESSING

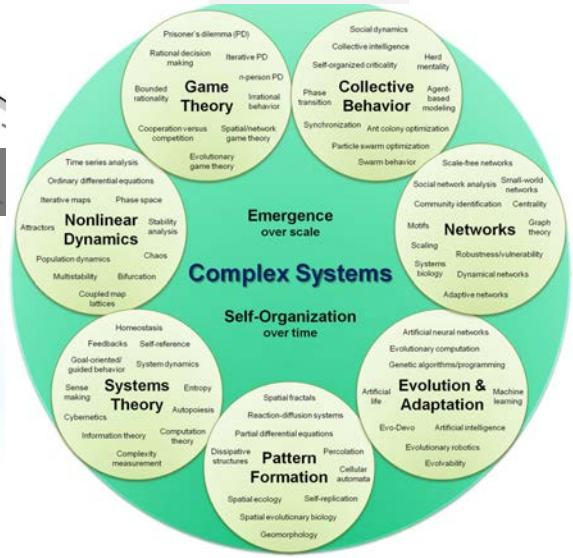




~6000 K

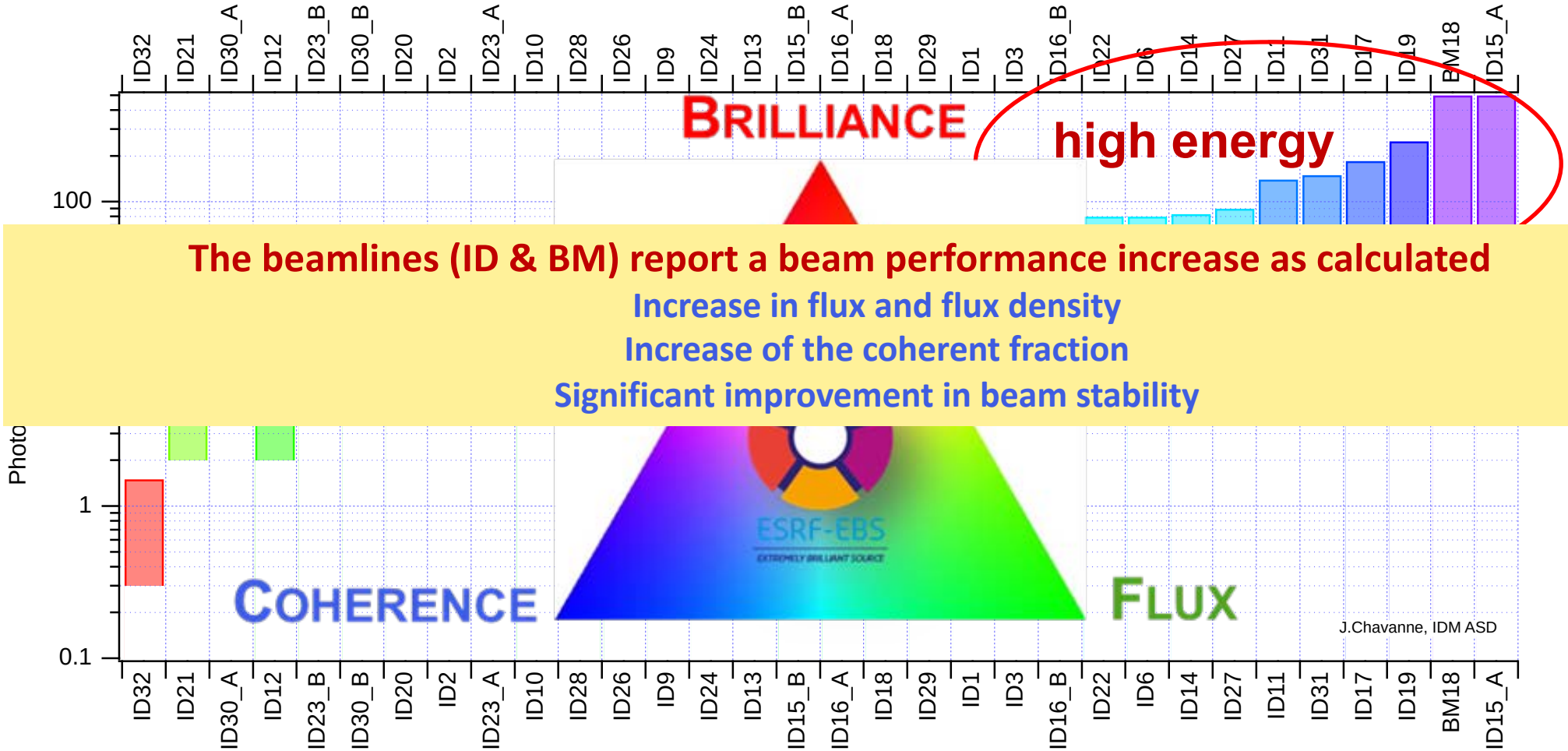
GEOSCIENCE

PHYSICS



EBS – the first 4th generation high energy SR source:

A big step forward for X-ray science



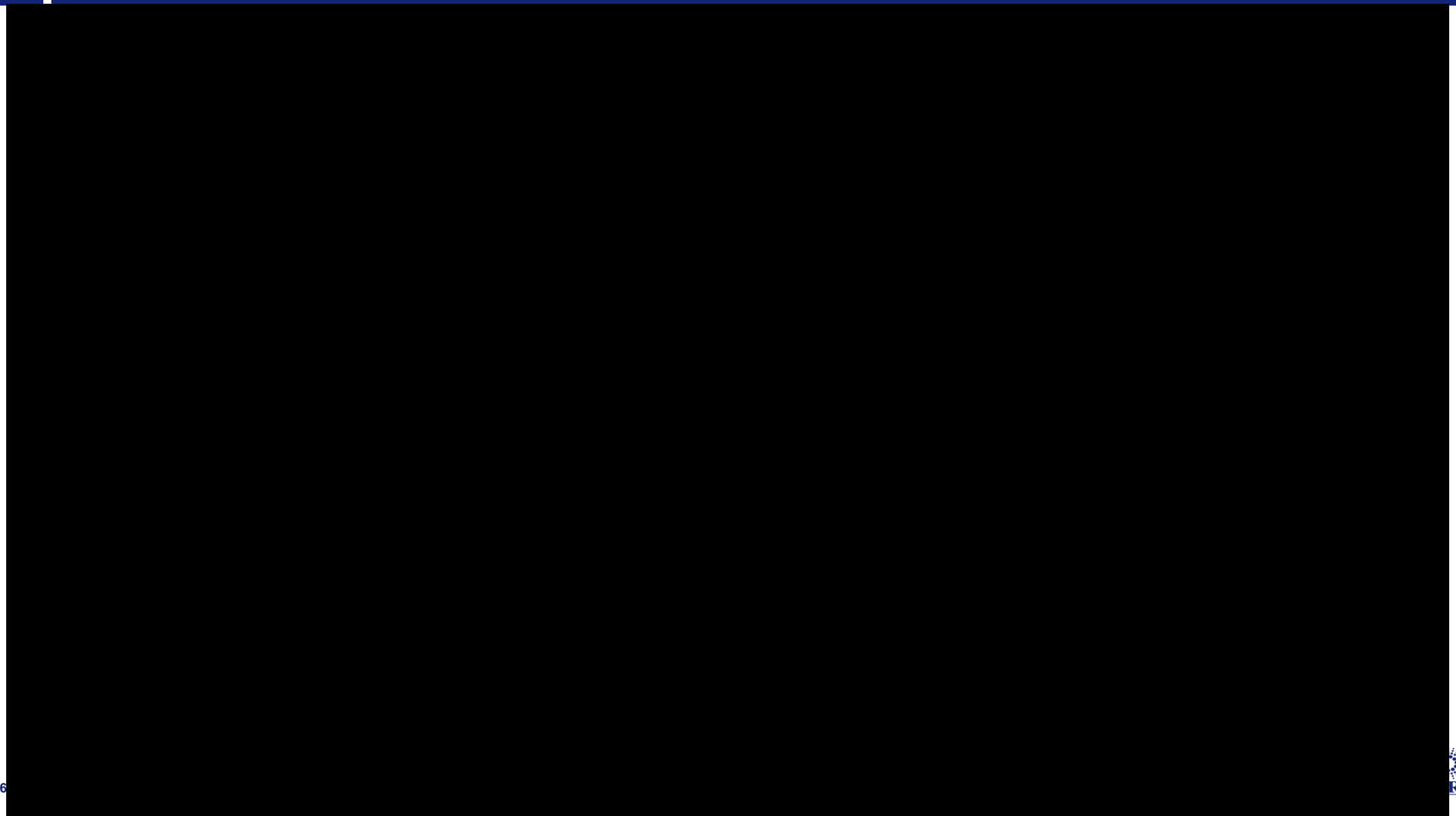
The beamlines (ID & BM) report a beam performance increase as calculated

Increase in flux and flux density

Increase of the coherent fraction

Significant improvement in beam stability

FIRST EBS SCIENCE AT THE ESRF



ESRF: KEEPING SCIENCE AND INNOVATION AT THE FOREFRONT

R&D AND CHALLENGES FOR 2021 -2025

Delivery of new state-of-the-art beamlines (health, innovation, biology, new materials, etc.)

- EBSL3-BM18 2021
- ID21 – uXAS 2021
- EBSL8-ID29 2022
- ID27 – HP 2022
- ID24 – XAS 2022
- ID14 – NRS 2024
- EBSL2-ID03 2023
- EBSL1-ID18 2024

A far looking accelerators programme

INCREASED BRIGHTNESS COHERENCE, RELIABILITY AND STABILITY

NEW GENERATION UNDULATORS, 4TH HARMONIC CAVITY, IMPROVED INJECTION CHAIN, PREVENTIVE MAINTENANCE

An IT-DATA PROGRAMMNE to fully exploit the information contained in the EBS DATA

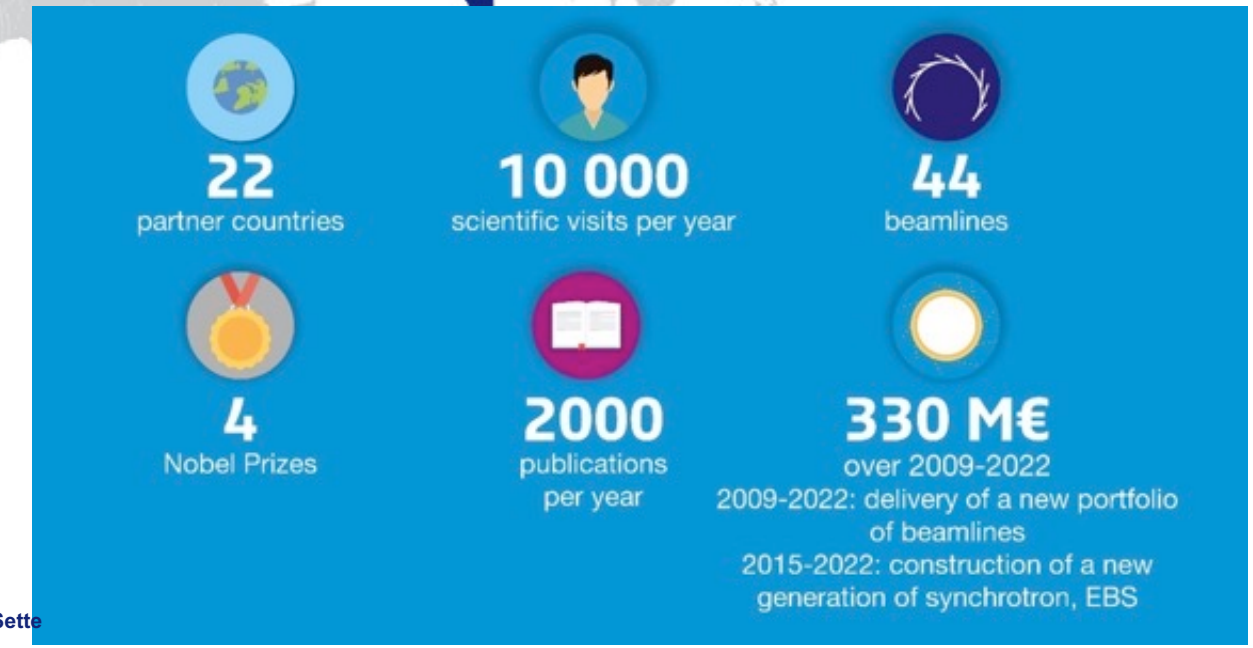
IT DIGITAL STRATEGY
and a new DATA-CENTER

ESRF: BRINGING NATIONS TOGETHER TO ATTRACT EXCELLENCE IN SCIENCE AND TECHNOLOGY

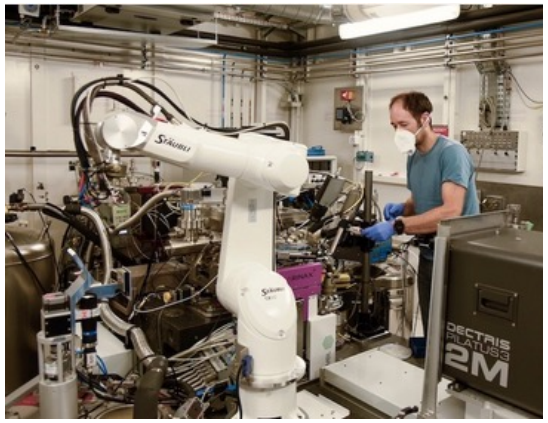
22 PARTNER COUNTRIES

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 %
9 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 %

2020: ESRF-EBS, THE FIRST OF A NEW GENERATION OF HIGH-ENERGY SYNCHROTRON SOURCES



CONCLUSIONS



EXCITING TIME FOR X-RAY SCIENCE!

→ *NEW SCIENTIFIC OPPORTUNITIES*

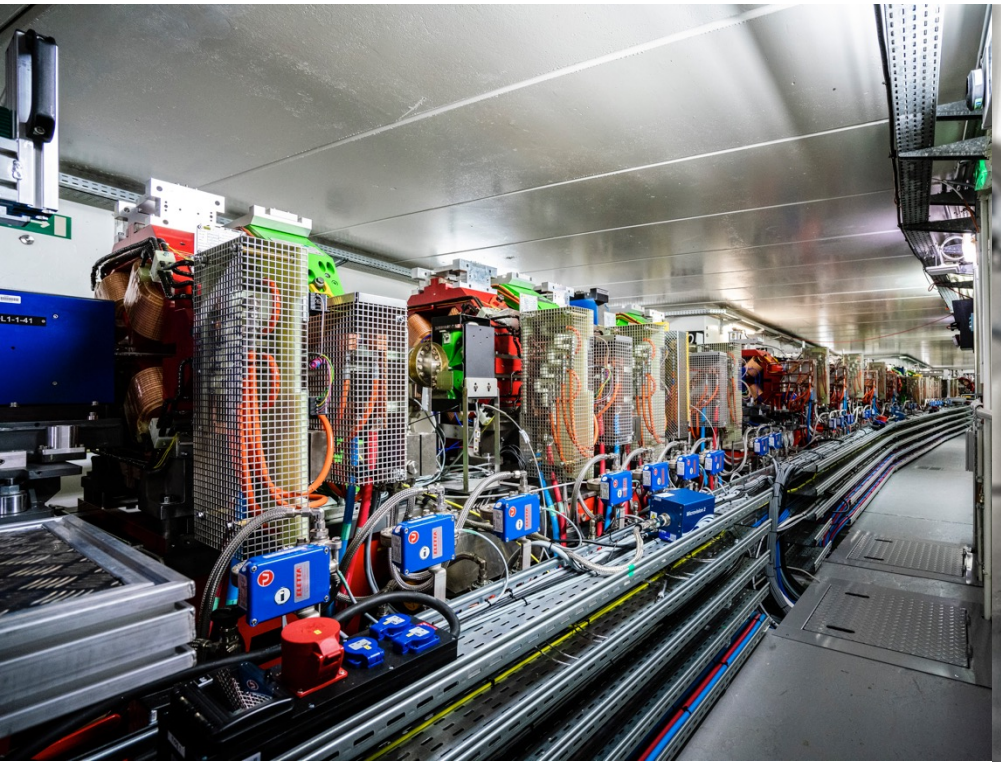
→ *TECHNOLOGICAL, INSTRUMENTATION AND IT CHALLENGES*

ESRF-ILL SUMMER SCHOOL: A GREAT OPPORTUNITY TO:

- BECOME ACTOR IN X-RAY AND NEUTRON SCIENCE, AND
- CONTRIBUTE NEW KNOWOLEDGE TO OVERCOME THE GREAT CHALLENGES FACING HUMAN SOCIETY

WELCOME!

THANKS FOR YOUR ATTENTION



Looking forward to welcoming you at the ESRF!

- Twitter @esrfsynchrotron – Instagram @esrf_synchrotron