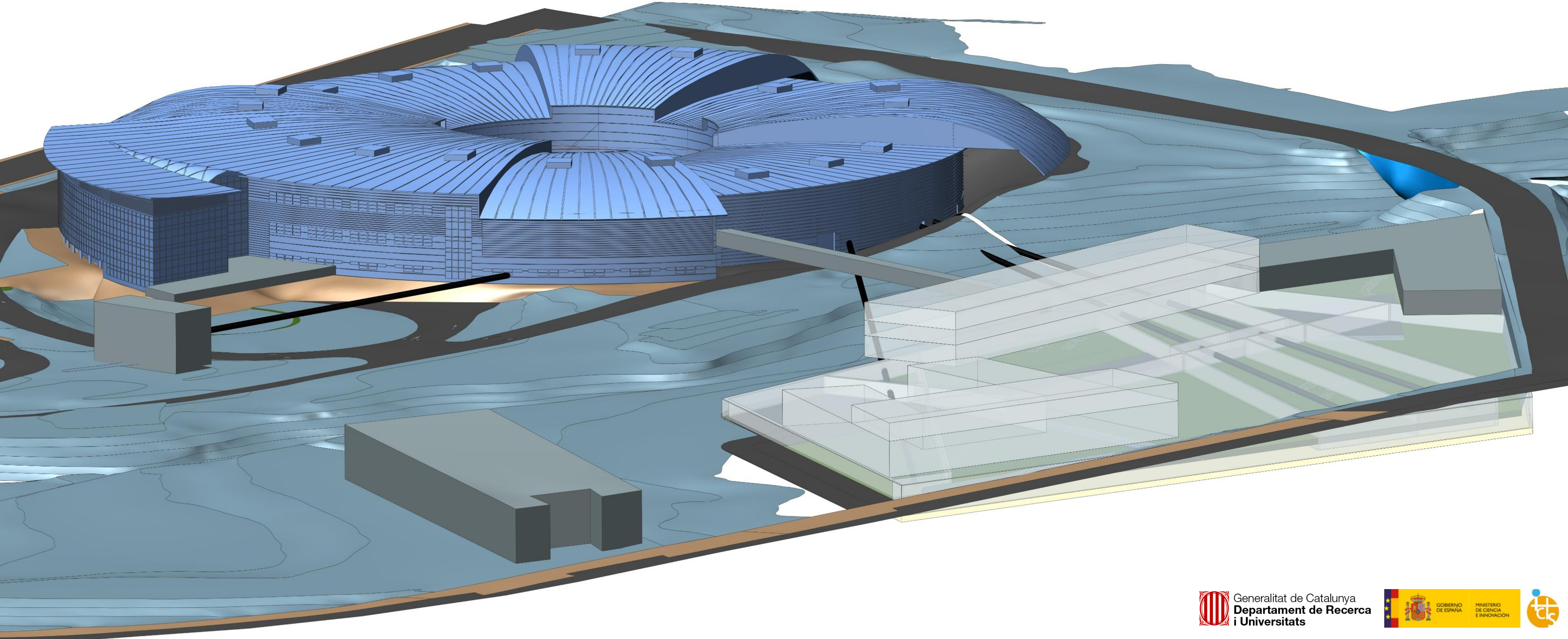
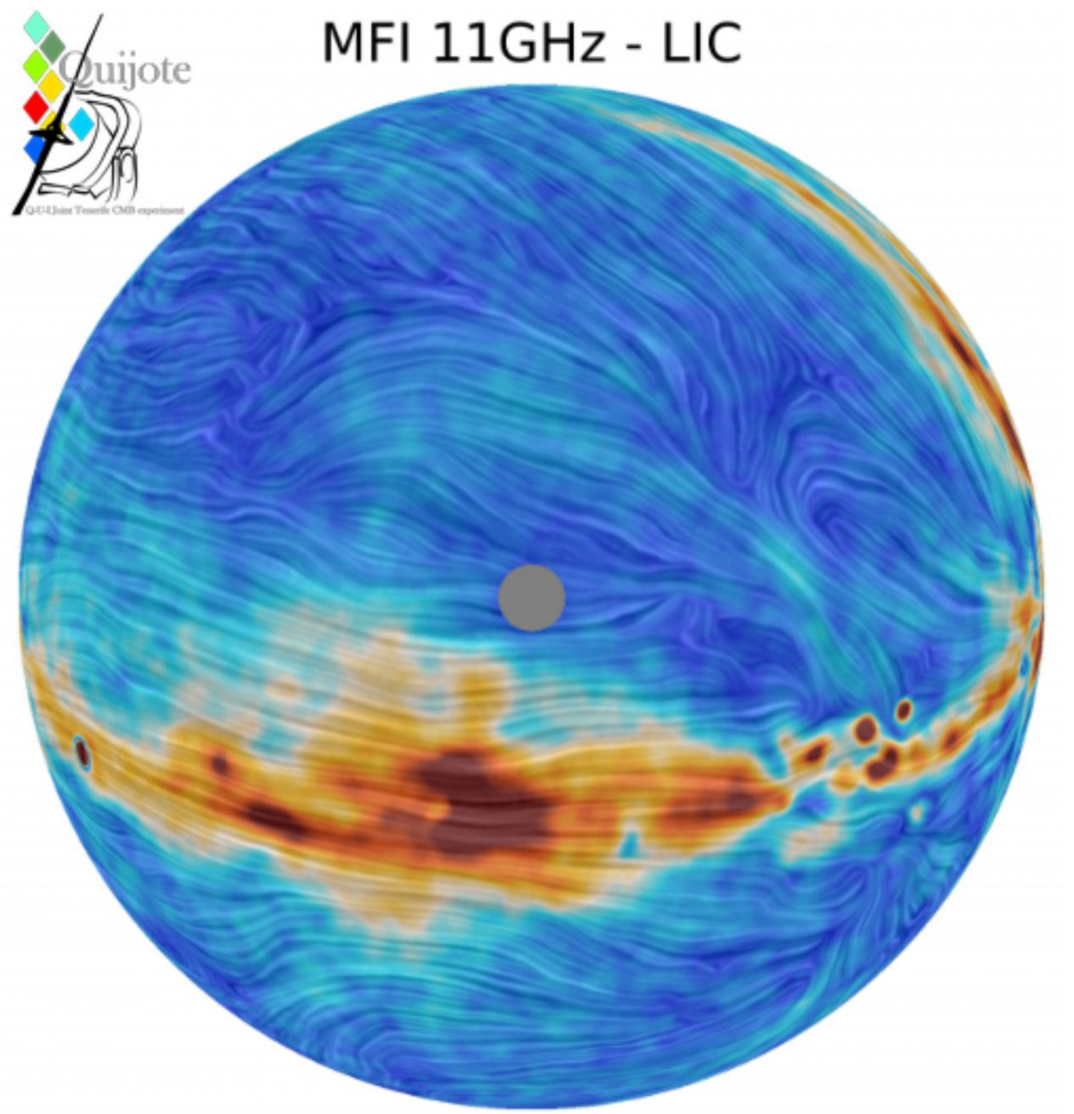
Introduction to ALBA Synchrotron

Caterina Biscari

1 October 2023



Generalitat de Catalunya
Departament de Recerca i Universitats



Esta figura muestra la estimación del campo magnético galáctico en el hemisferio norte (en realidad el ángulo de la polarización arctan(-U/Q) a 11 GHz rotado 90° como estimación del campo magnético proyectado en el plano del cielo). El círculo gris corresponde está centrado en el polo norte (en la figura que abre esta pieza la banda gris está en el plano galáctico y la gran región gris de la derecha corresponde al hemisferio sur no observable desde Tenerife).

Synchrotron light sources in the world

ALBA is near Barcelona, 70 km from here

ALBA Synchrotron Radiation Facility

National public institution with 50% national + 50% regional funding (Ministerio de Ciencia e Innovación) and GenCat (Department de Recerca i Universitats)

National and international (28%) staff

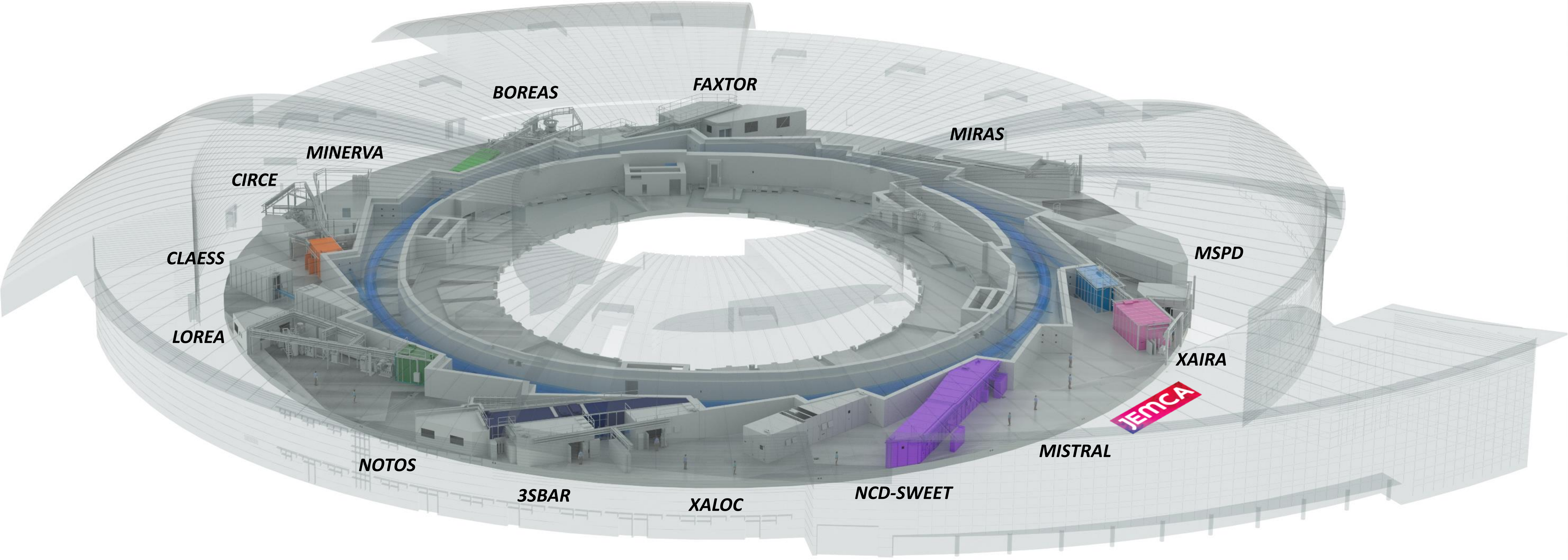
National and international (40%) users

National and international collaborations

CELLS, the public consortium in charge of building and running the facility, was founded in 2003

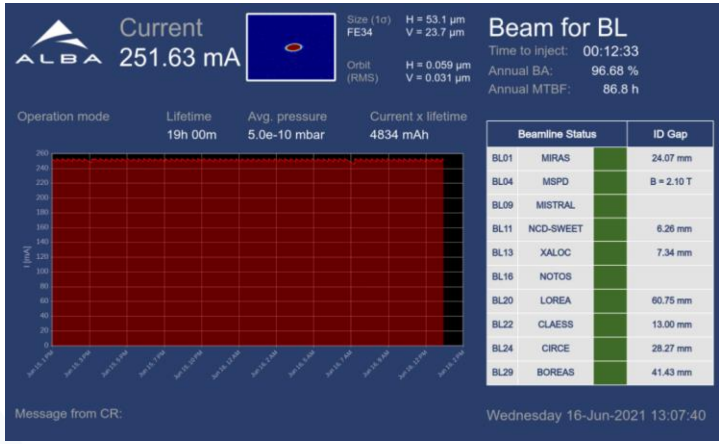
Generalitat de Catalunya
Departament de Recerca i Universitats

Synchrotron Light Source: ALBA



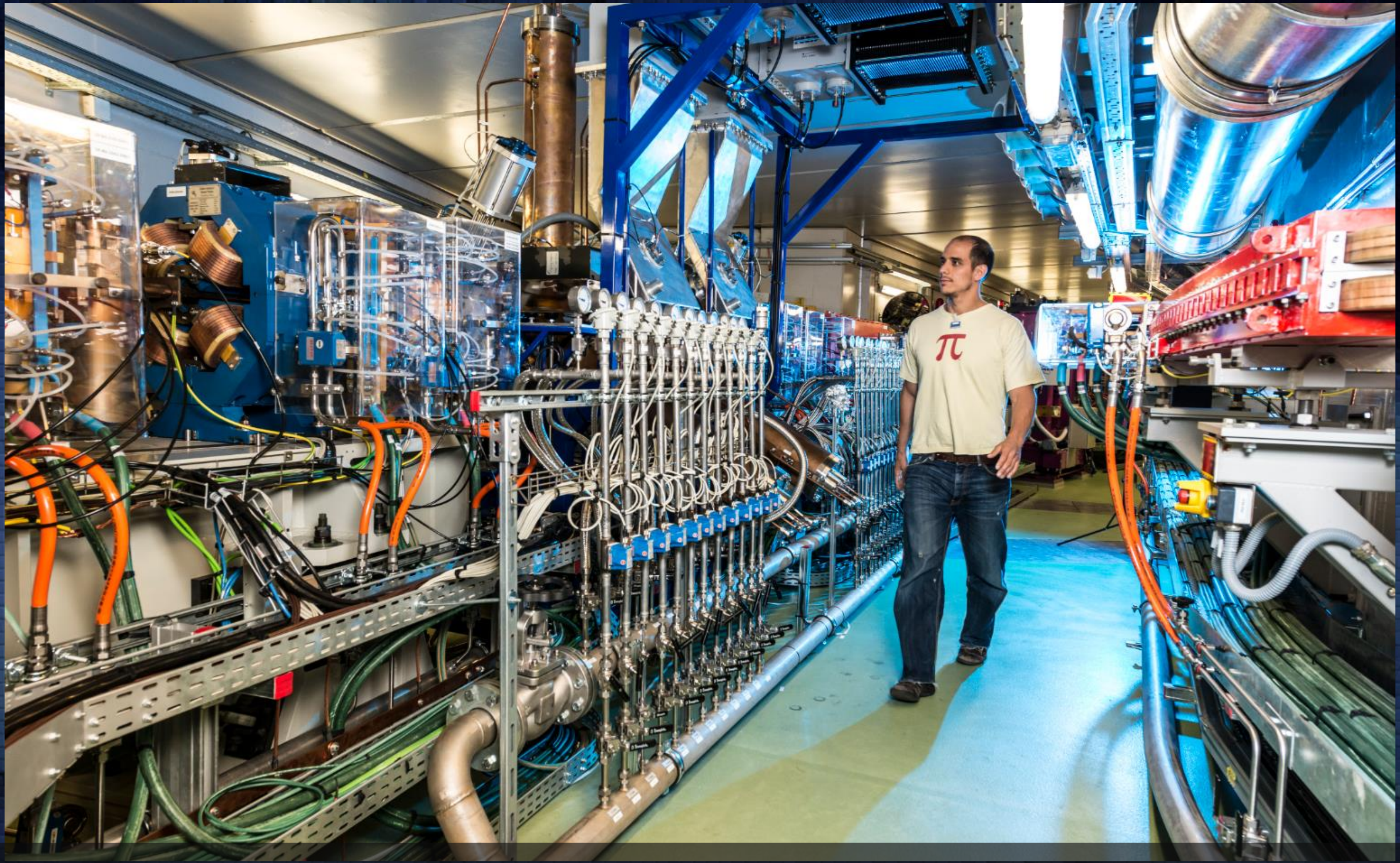
The ALBA complex of accelerators

- **LINAC**: 100 MeV
- **BOOSTER**: 100 MeV-3 GeV, 260 m circumference, emittance = 10 nm·rad, sharing the same tunnel with the storage ring
- **STORAGE RING**: 3 GeV, 268.8 m circumference, emittance = 4.5 nm·rad



ALBA operates at 250 mA in top-up mode

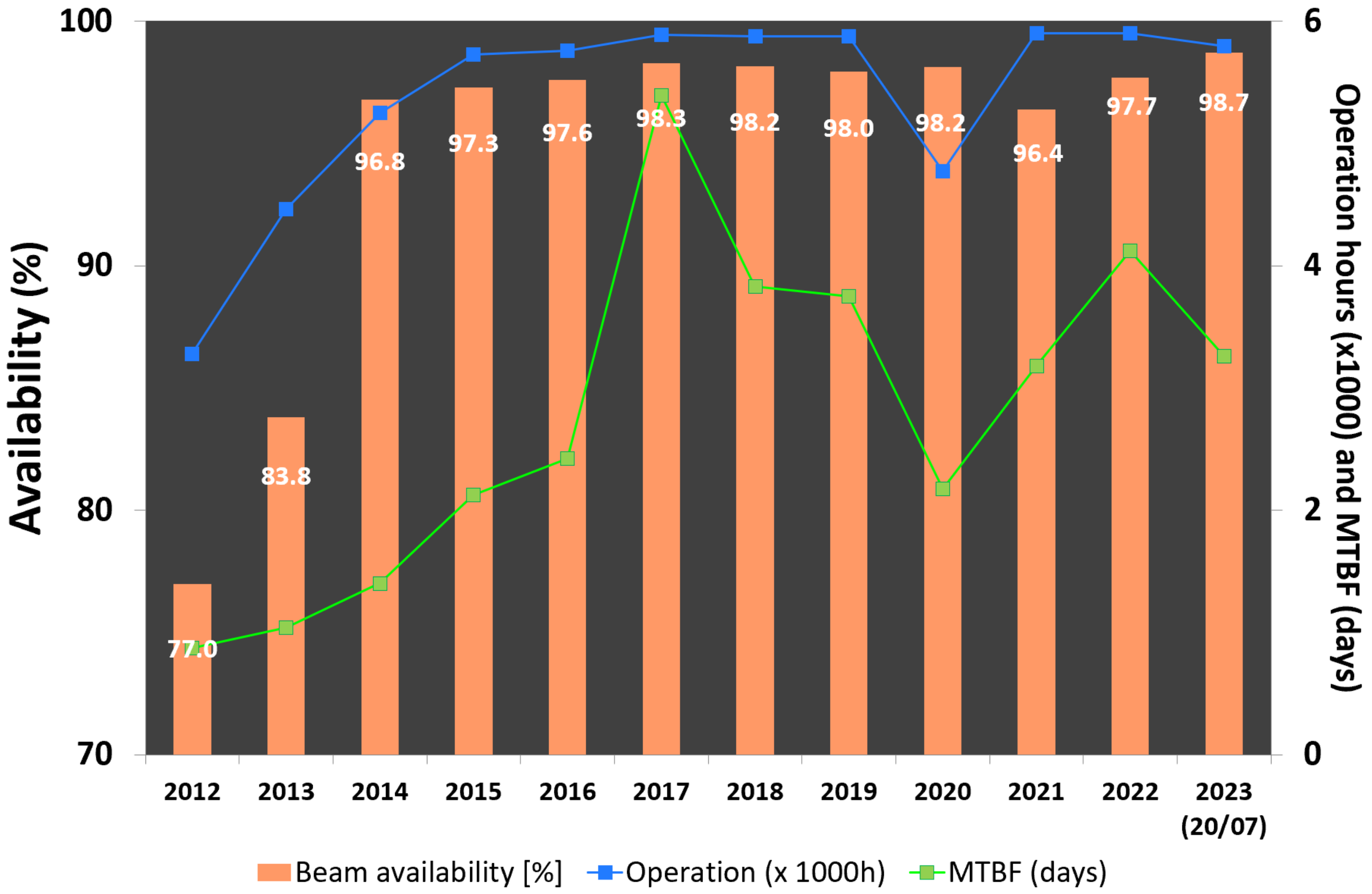
ALBA accelerator



ALBA storage ring – 3rd generation light source
3 GeV electrons - 270 m circumference

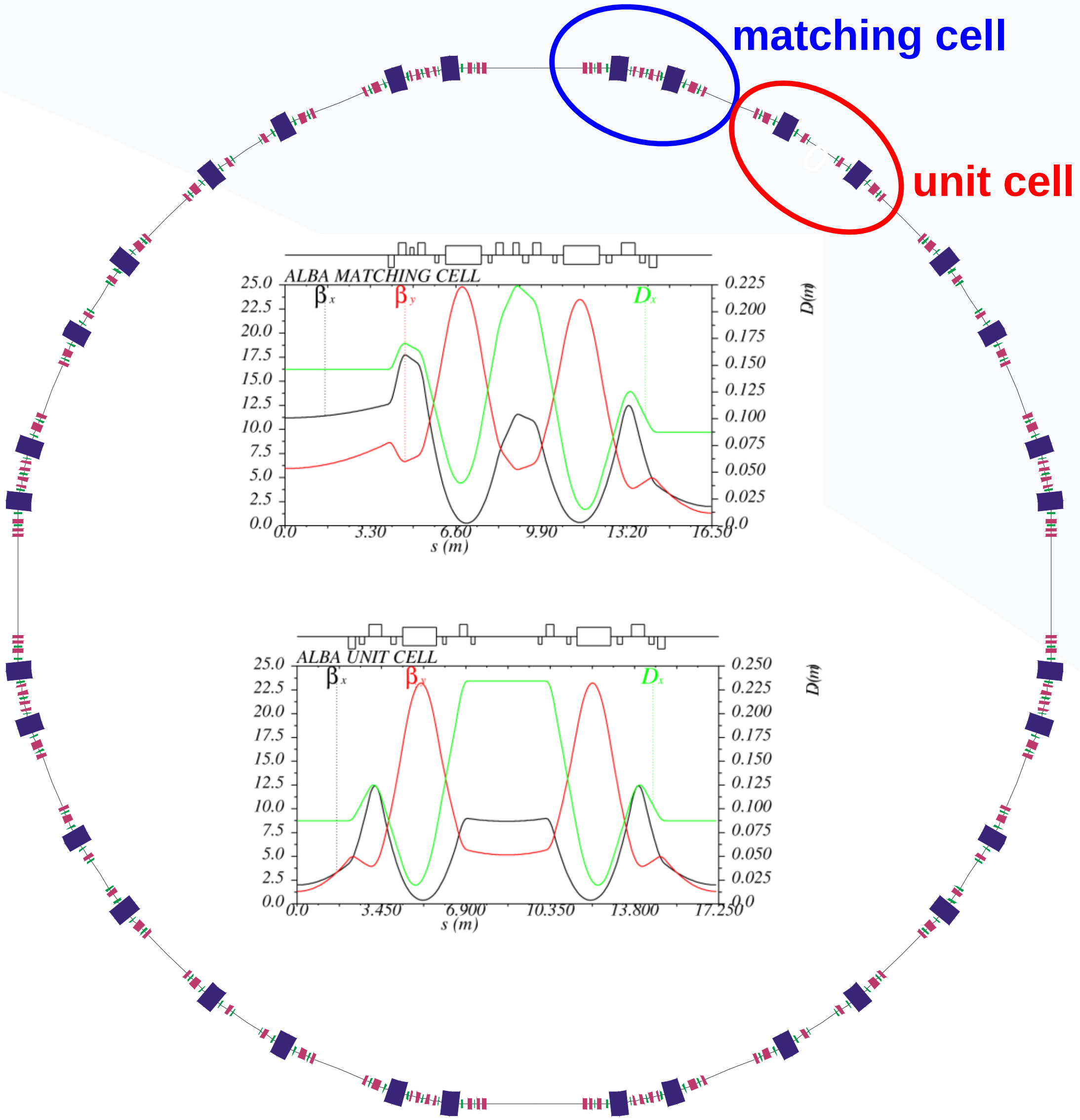
In operation since 2012

ALBA is delivering 5800 hour/year with a beam for users availability of ~98%

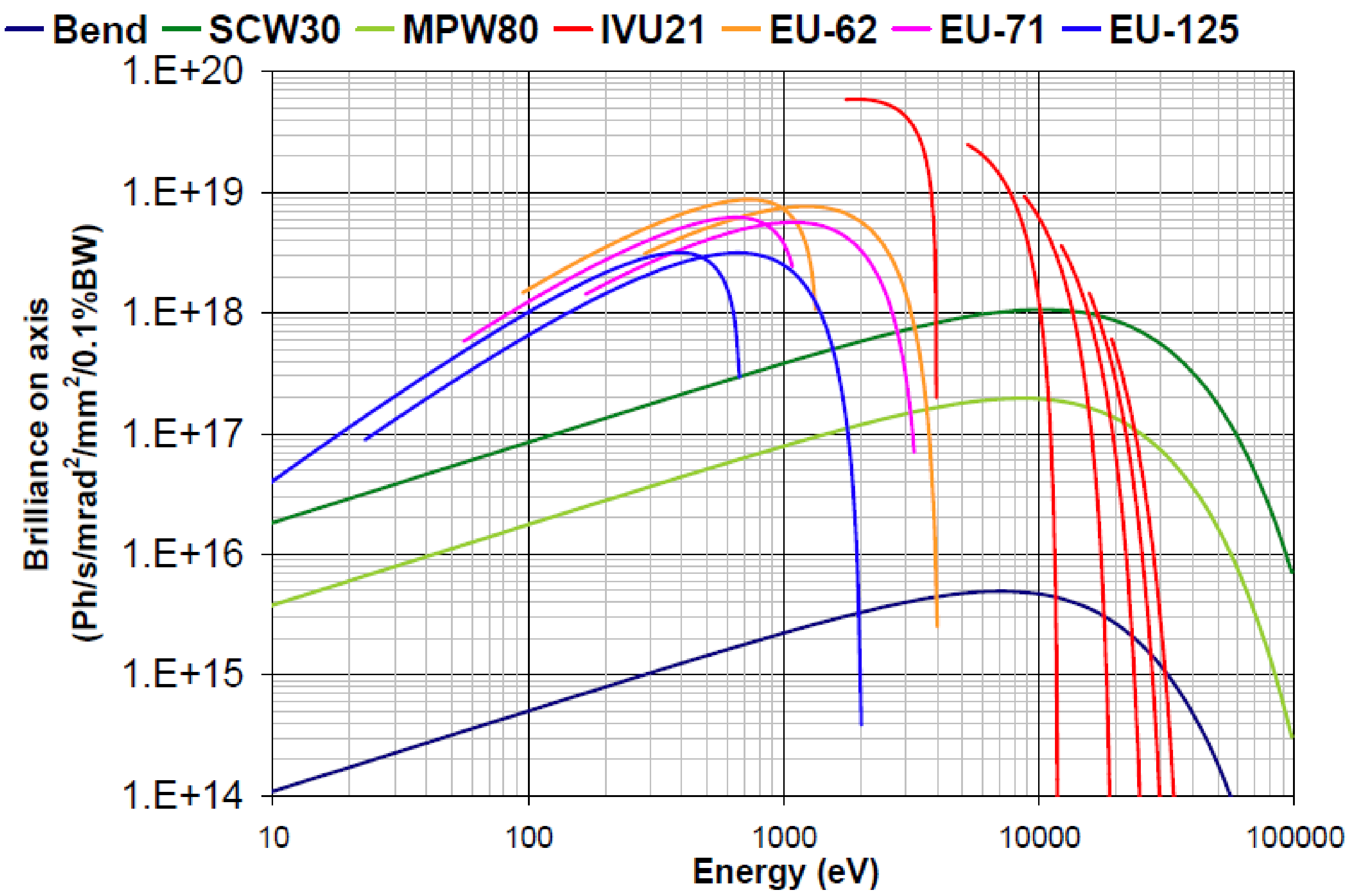


The ALBA storage ring lattice

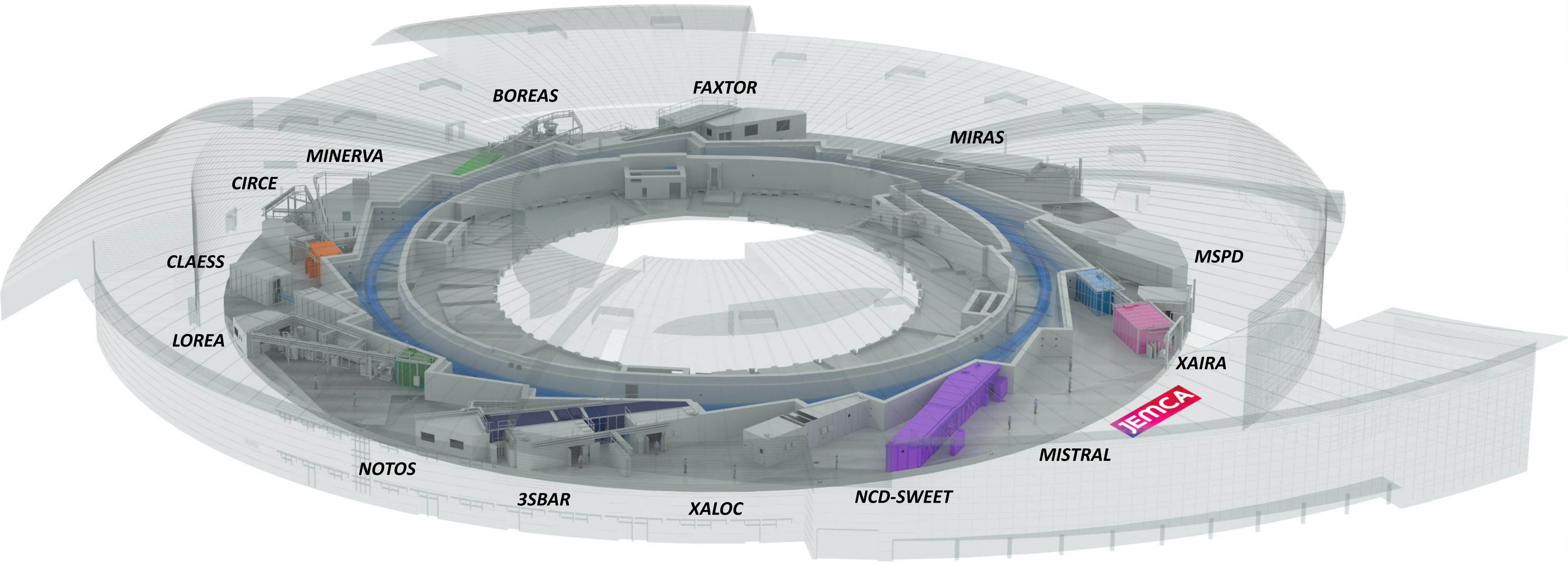
ALBA storage ring parameters	
Energy	3 GeV
Circumference	269 m
Emittance	**4.5 nm·rad**
Number of cells	8 unit + 8 match
N. of straights	4 long / 12 medium / 8 short
Straigh lengths	7.8 / 4.2 / 2.3 m
Straight ratio	36%



ALBA photon spectra



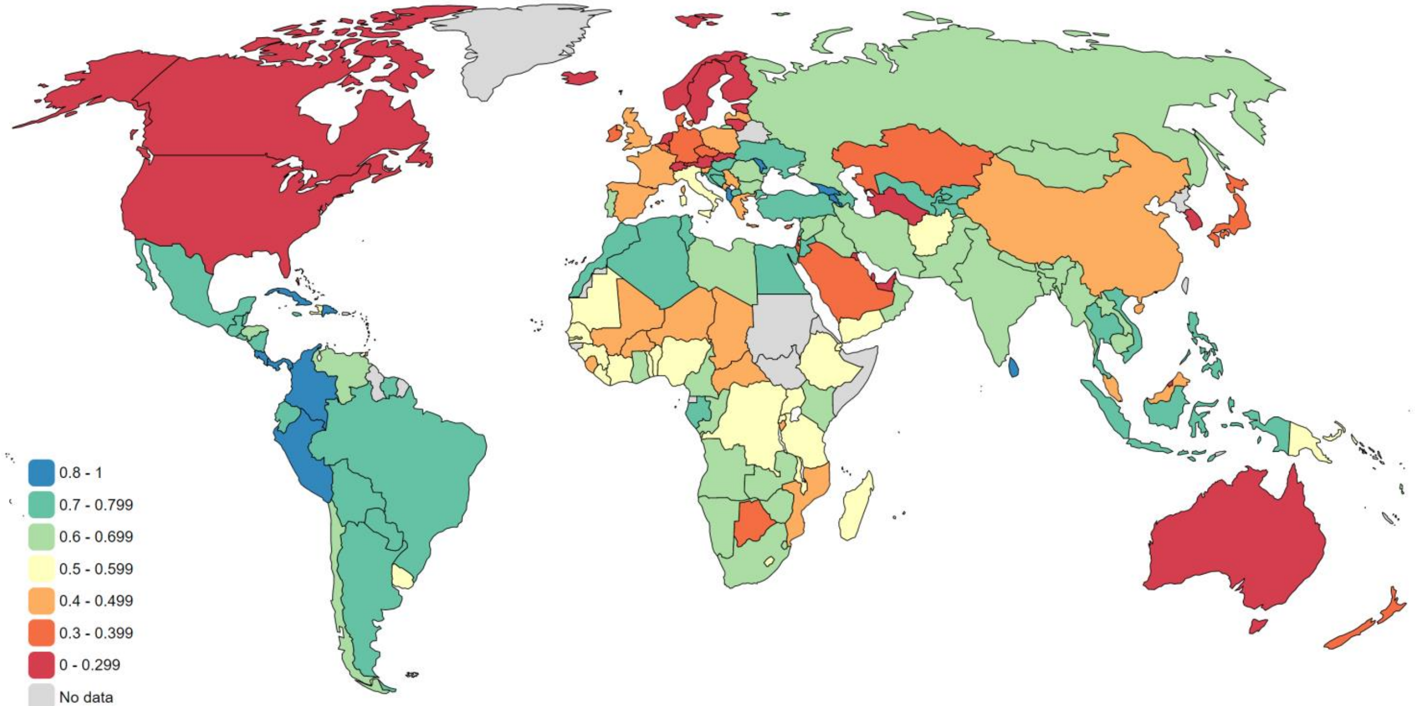
What synchrotron light sources provide to society?

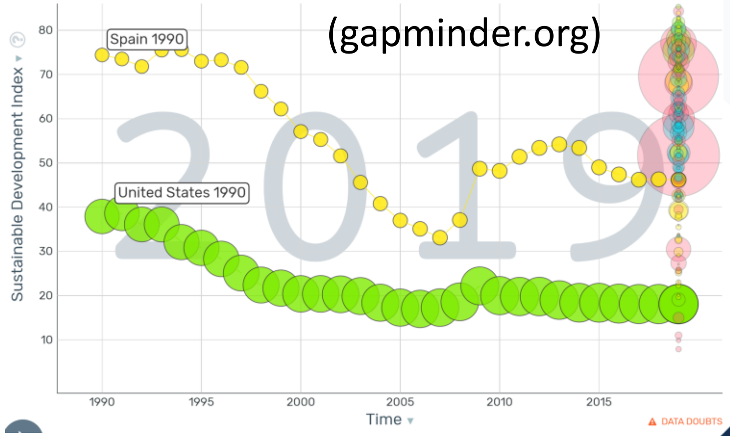


Sustainable Development Index

https://www.sustainabledevelopmentindex.org/

The Sustainable Development Index (SDI) **measures the ecological efficiency of human development, recognizing that development must be achieved within planetary boundaries**. It was created to update the Human Development Index (HDI) for the ecological realities of the Anthropocene.





SDI gets higher if

Increase: life expectancy, education and income

Decrease: consumption-based CO_2 emissions and material footprint

ALBA acting on SDi

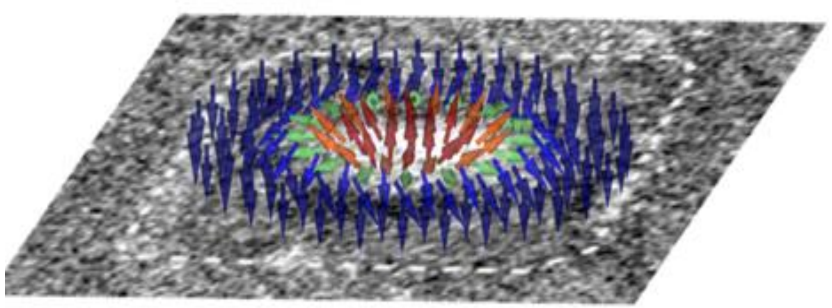
Increase: life expectancy, education and income

Health: development of drugs and vaccines,
Understanding disease mechanisms, developing bio materials, bio preparedness, food
Studying environment, contamination

Knowledge, training
cultural and historical heritage preservation

Decrease: consumption-based CO2 emissions and material footprint

Contributing to carbon neutrality and to lowering energy consumption



Nature Nanotechnology (2016) O. Bulle ….L. Aballe, M. Foester, …G. Gaudin , ALBA

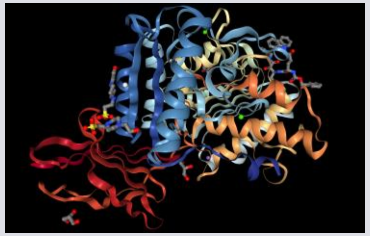
Energy materials (production, storage, transport)
Non contaminant materials
Batteries
Catalisis
Green H production
Complex materials
Quantum materials
Microelectronics based in spintronics
…

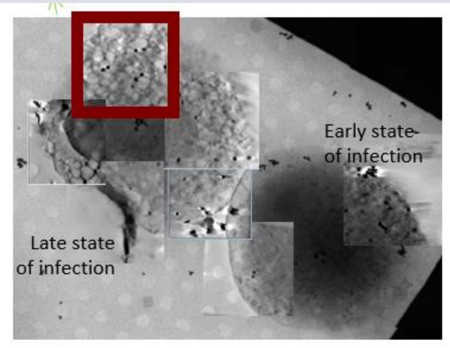
ALBA Synchrotron Research Infrastructure

Four Scientific Sections

Life Science

From the protein, to cell, to tissues

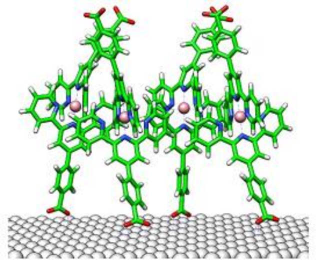




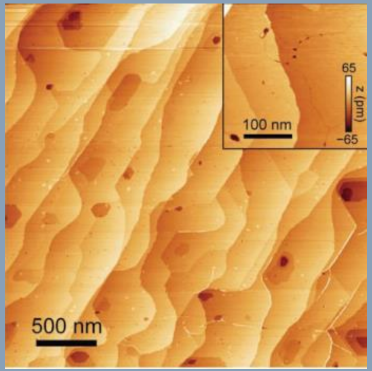
Cell infected by covid-19

Electronic and Magnetic Structure of Matter

Advanced materials

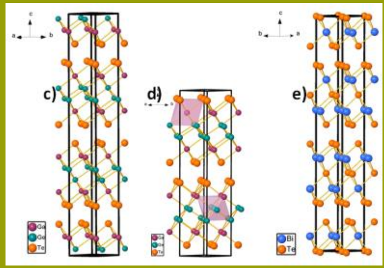


DOI: 10.1002/adfm.20230035

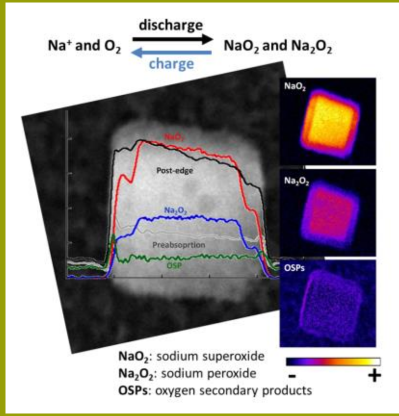


Chemistry and Material Science

Energy material, catalysts, environment



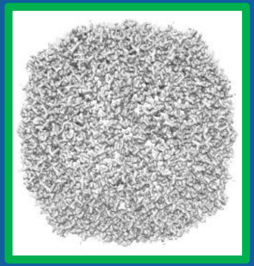
doi.org/10.1016/j.mtadv.2023.100403

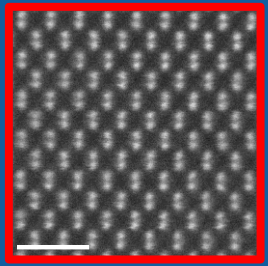


Battery developments

Interdisciplinary and Multimodal Section

Includes contribution to JEMCA and Data science





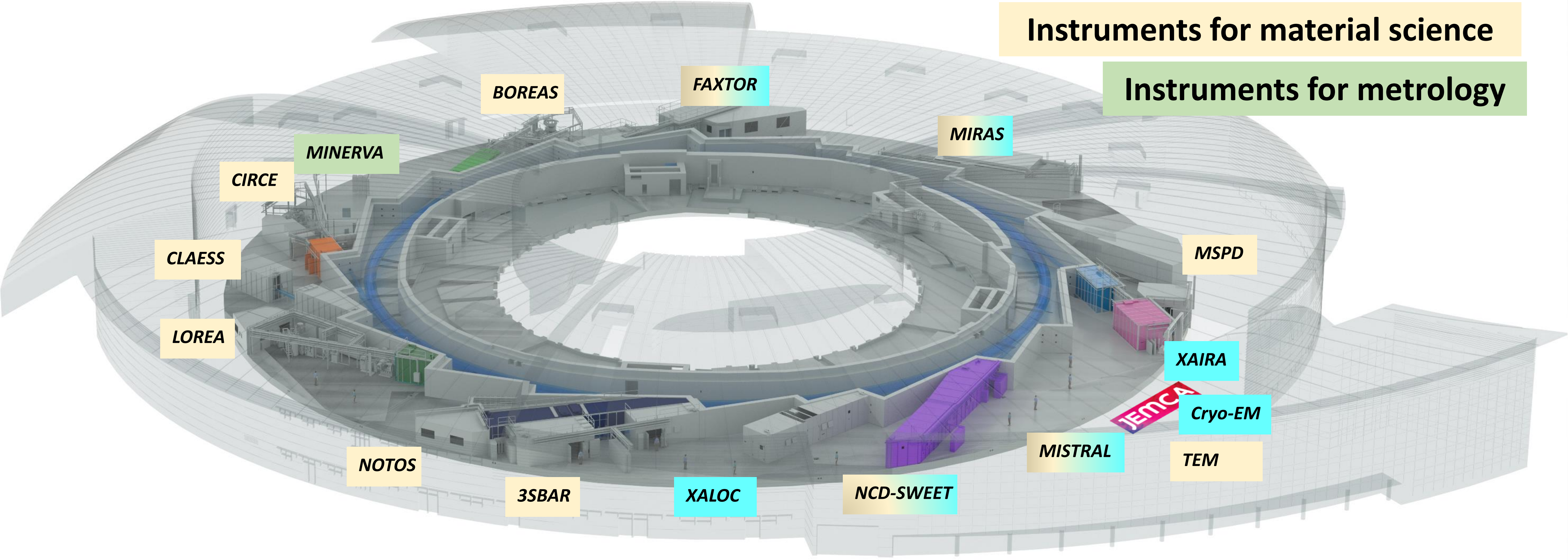
Nanomaterials for data storage

BEAMLINES at ALBA: Available today

Instruments for life science

Instruments for material science

Instruments for metrology



Joint Electron Microscope Center at ALBA (JEMCA)

50% Funded through Catalan ERDF and 50% co-funded by different partners

Life science - 200 kV Glacios cryo-TEM

Cryo-EM receiving users

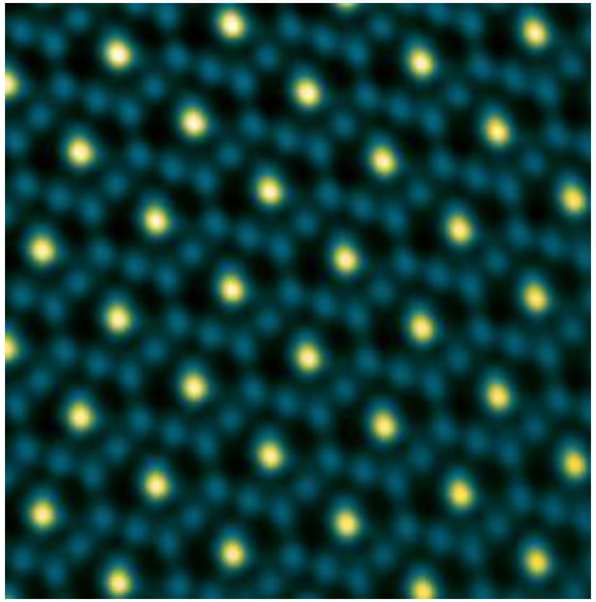
Overbooking Factor >2

Material Science - 60-300 keV Spectra (S)TEM

TEM just finished commissioning

First users now

IS*21* family transposase

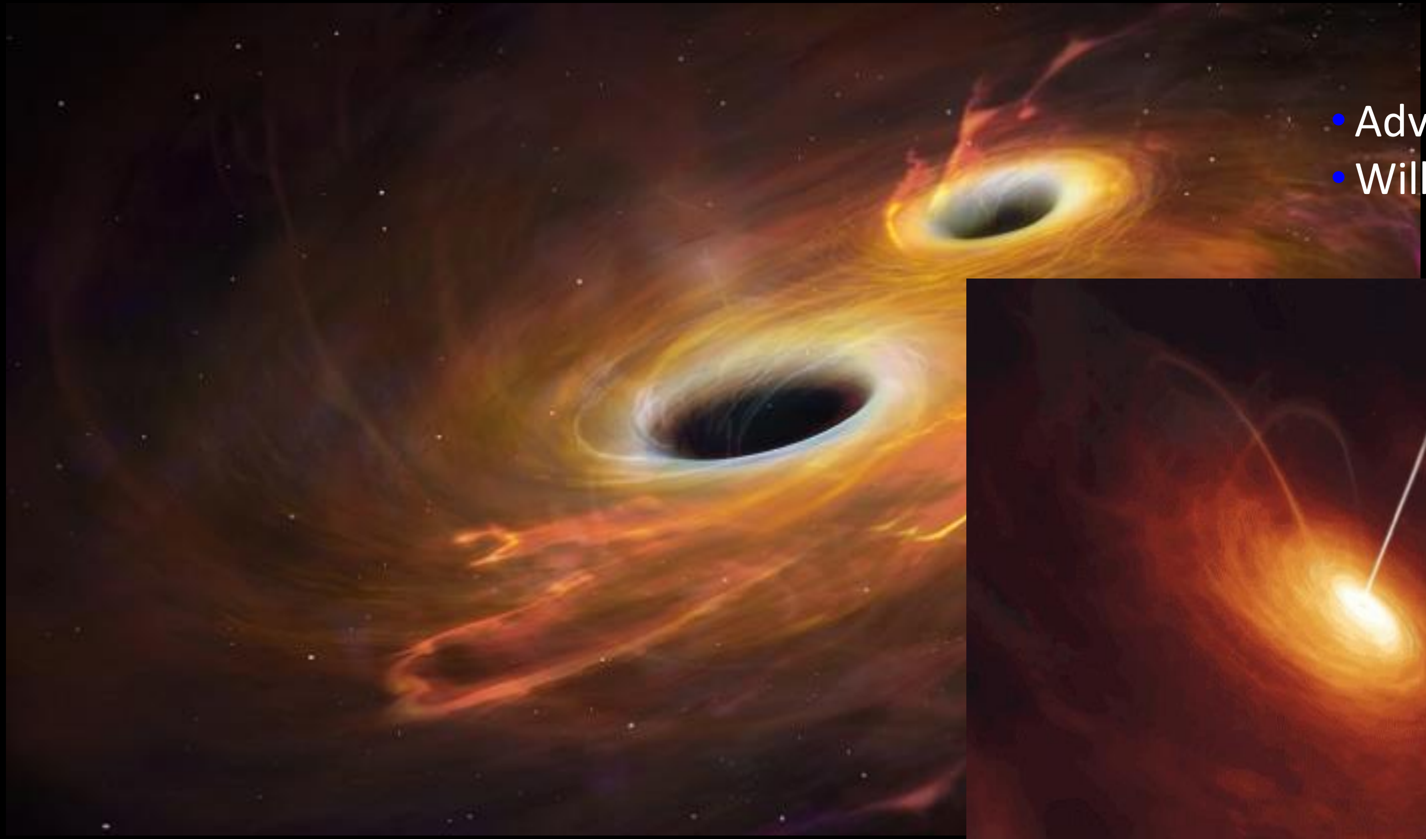


Journal of the American Chemical Society, 2023. DOI: 10.1021/jacs.3c06288

Atomic resolution aberration corrected HAADF STEM images of one of the catalyst nanoparticles and a zoom out of the Co_2FeO_4 cubic spinel structure

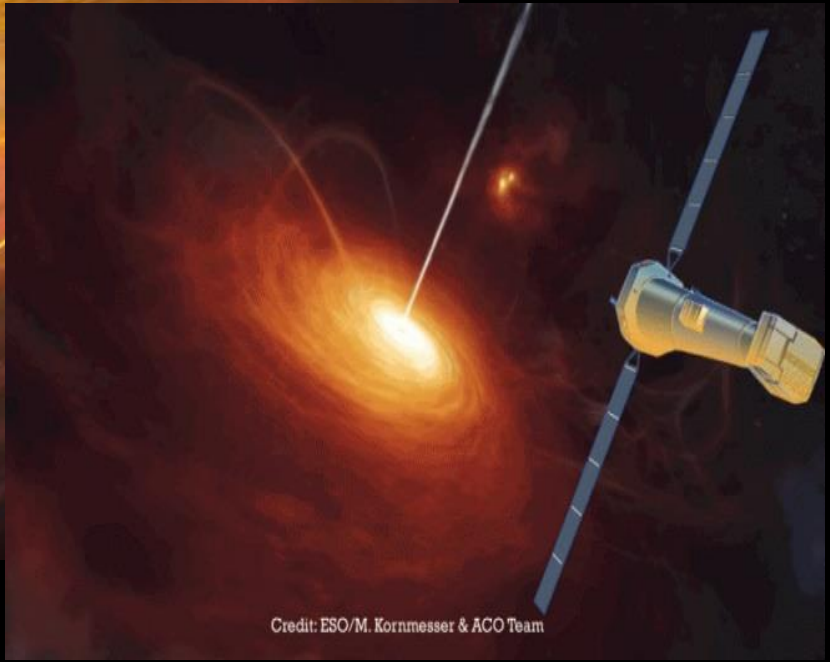
We participate in exploring the universe: ALBA - European Space Agency collaboration

In commissioning. Starting operation now



ATHENA Mission (2036)

- Advanced Telescope for High-ENergy Astrophysics
- Will study the high energy universe, including black holes



MINERVA: BL to test hundreds of mirrors to be mounted in ATHENA satellite

USERS

Direct access covering operational costs
Results can be confidential

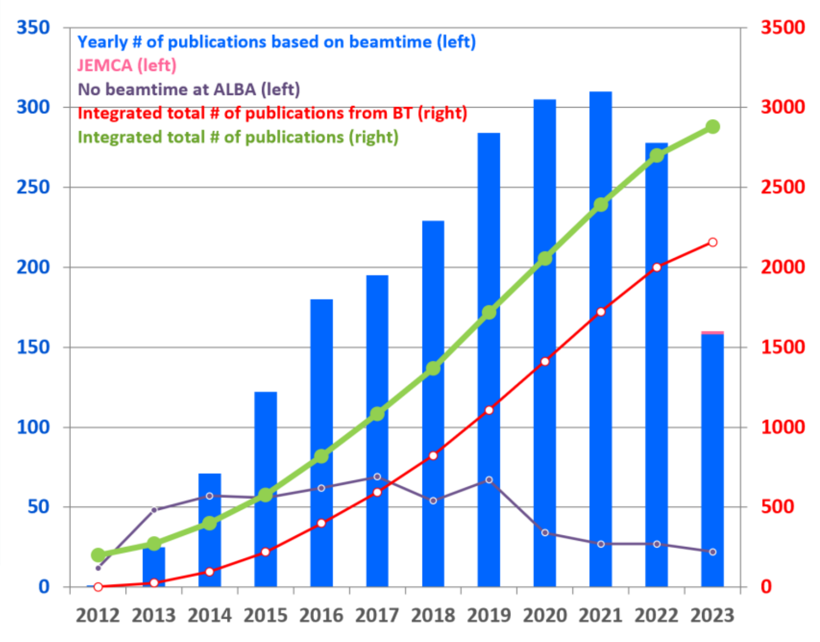
Private

Academic

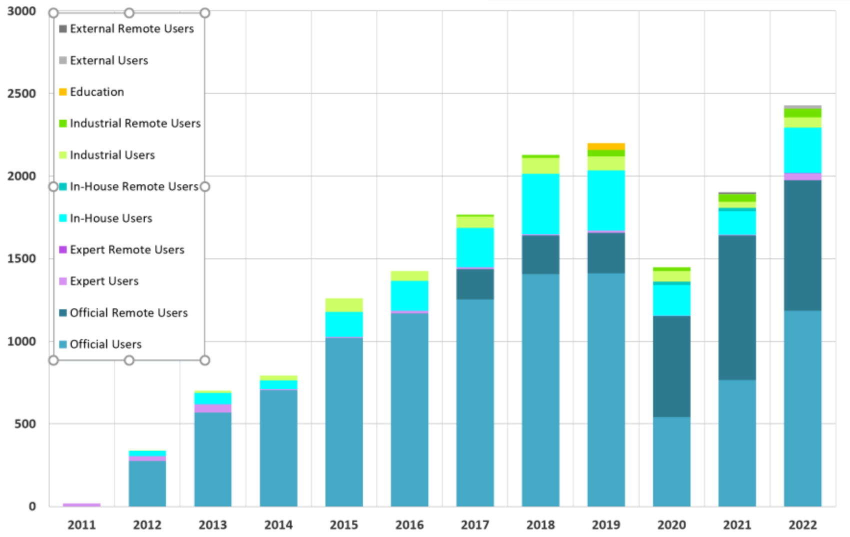
Competitive and free access
Public results

Joint academic and industrial

2 calls per year
Average overbooking factor ~2

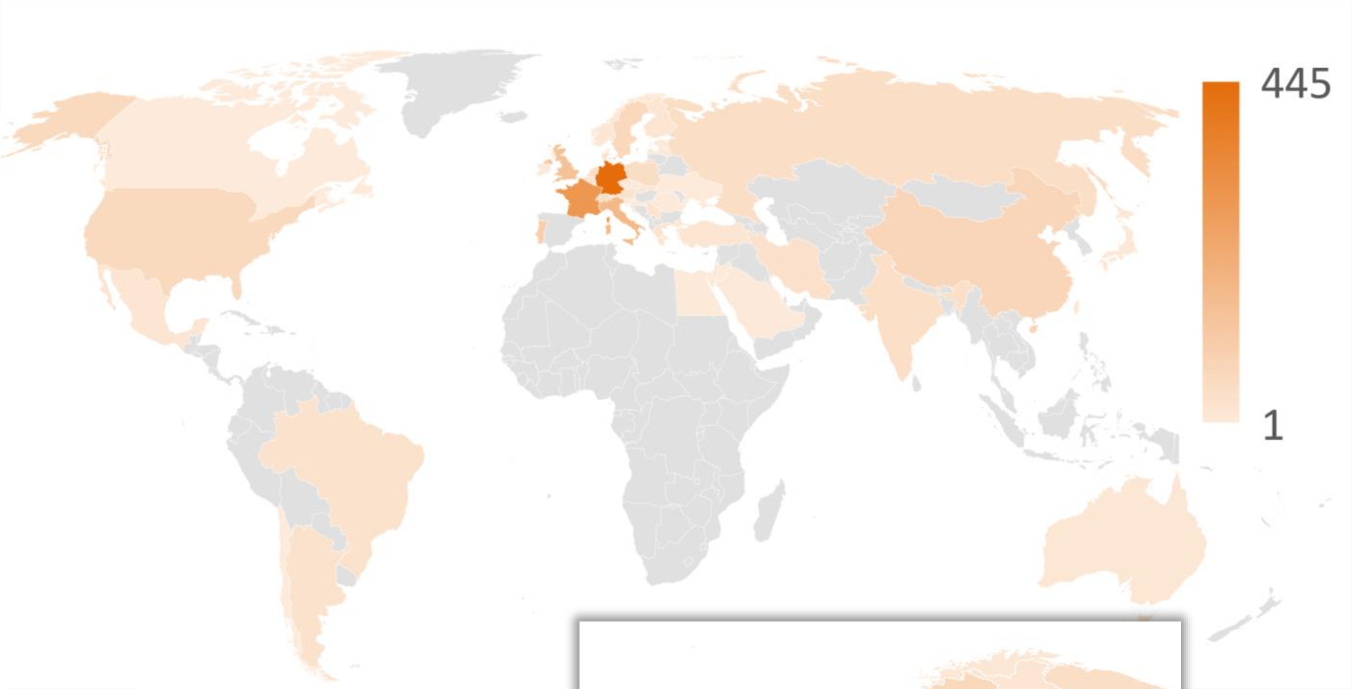


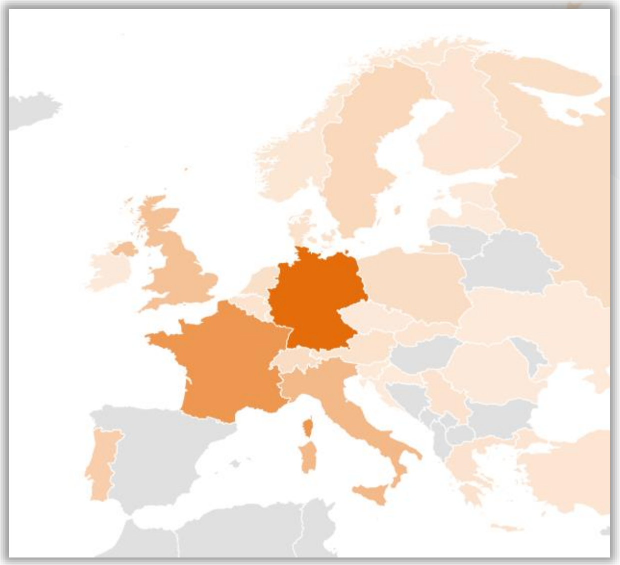
Publications
and User visits



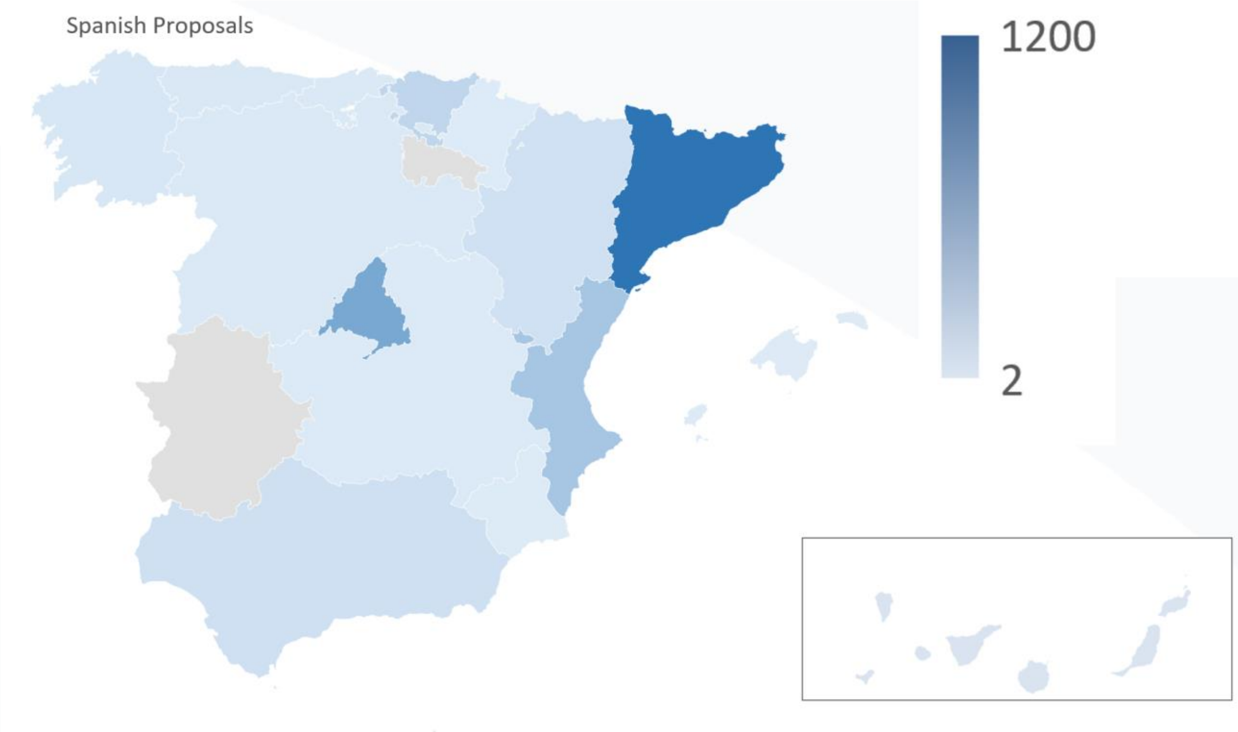
Academic Users

International proposals
(871 granted over 1972)

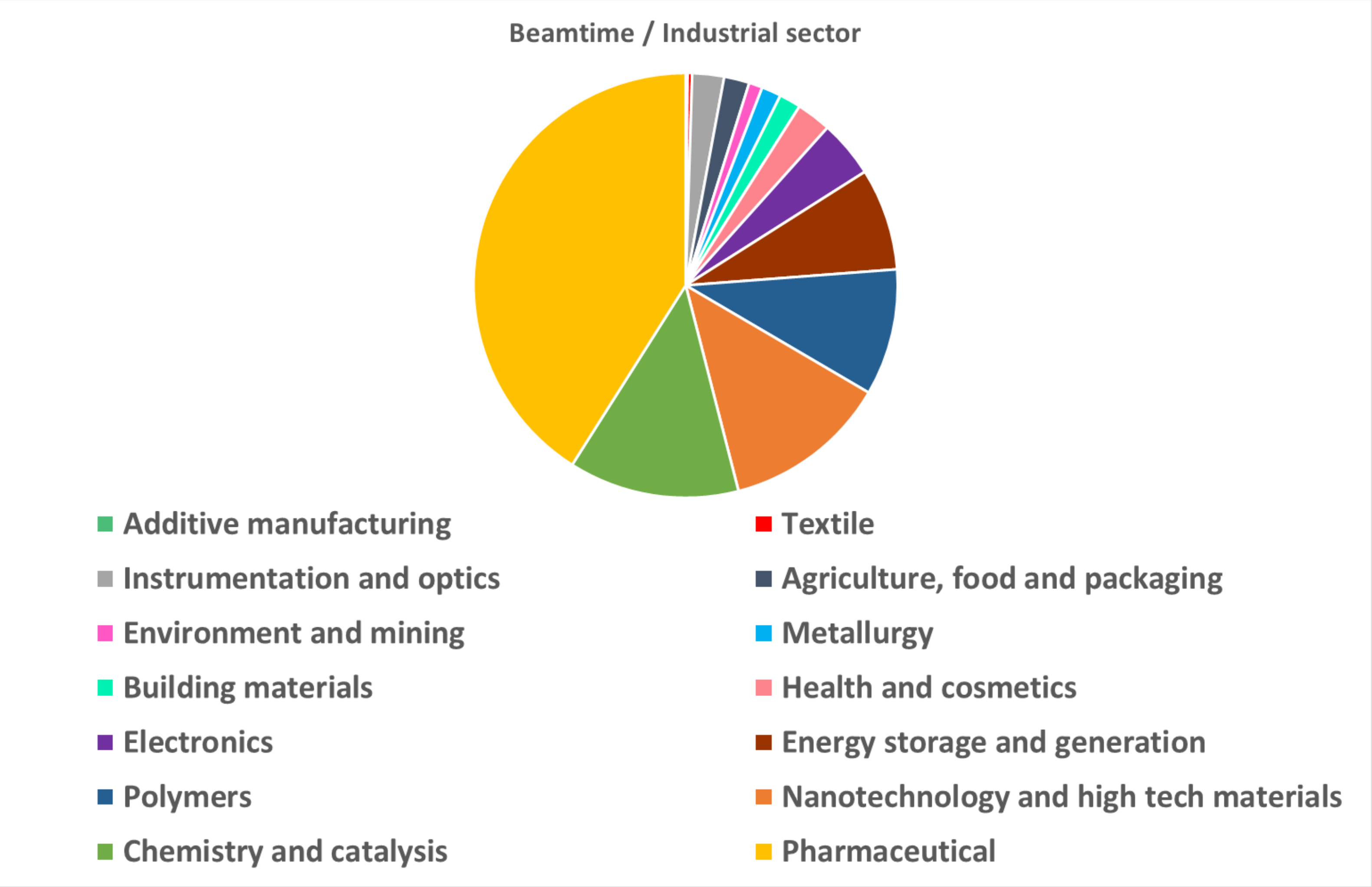




Spanish proposals
(1598 granted over 2876)



Industrial users – advancing in the innovation
More than 75 companies, 55% from Spain, 1/3 SME,
More than 500 experiments



Examples:

Improved optics for nanoelectronics manufacturing, Battery with higher energy capacity, Battery recycling, Greener concrete, Robust adhesives, Efficient products for agriculture Nanotechnology for food packaging, Drug discovery, development and validation, New polymers for biomedical applications, Biochemical Efficacy of cosmetic

Industrial services and examples

- *One-time services*
- *Long contract services (including or not personnel)*
- *Partnerships with other facilities/platforms to provide a complete service*

BASF IMPROVING THE PRODUCTION OF BATTERIES FOR ELECTRIC VEHICLES

New methodology to produce nickel-rich cathode materials used in Li batteries optimizing the production process. Increasing throughput by a factor of 3, and the efficiency of future cathode active materials production for battery electric vehicles

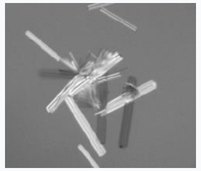
ENANTIA uses ALBA's X-rays to detect crystalline impurities in drug products

CRYSFORMA (ICIQ) characterizes polymorphs for the pharmaceutical industry at the ALBA Synchrotron

TOYOTA and CSIC proved viability of calcium-based batteries

The Spanish Research Council (CSIC) in collaboration with TOYOTA Motor Europe (TME) demonstrates the viability of Calcium rechargeable batteries using ALBA techniques.

HELIX BioStructrures performs first post-lockdown COVID-19 measurements at ALBA



HELIX BIOSTRUCTURES — CLARITY. INTEGRITY. PROFESSIONALISM.

Long term contract between HENKEL and ALBA

ALBA
key numbers

+ 2400 yearly user visits

+450 yearly experiments

+ 3700 national and + 3500 international users

+2850 publications

<IF>$_{2022}$ = 10

+2500 public experiments

+500 industrial experiments

+900 Proteins in PDB

+240 staff

Networking at International level

LEAPS is the largest consortium of analytical facilities world-wide and further expanding its service to an interdisciplinary European user community

19 facilities - **16** institutions - **10** countries

> **300** operating End Stations

➢ **1.000.000** h beamtime /year

Excellence-driven access free of charge

> **5.000** publications/year

> **15** spin off companies

> **35.000** users from all EU & beyond

researchers from all research area

Evolution of Synchrotron Radiation Sources

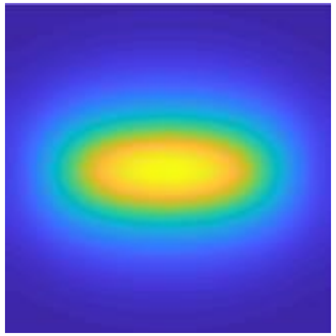
Increase in Brilliance

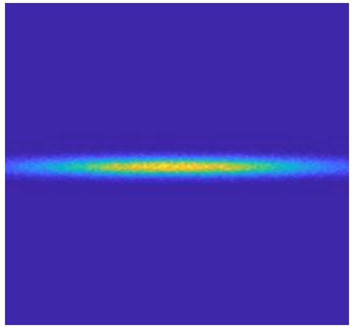
Increase in Resolution Power

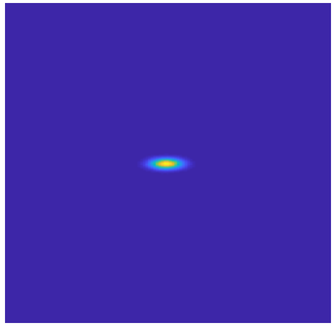
Increase in Coherence

Increase in Data management capacity

Representation of photon beam on sample →



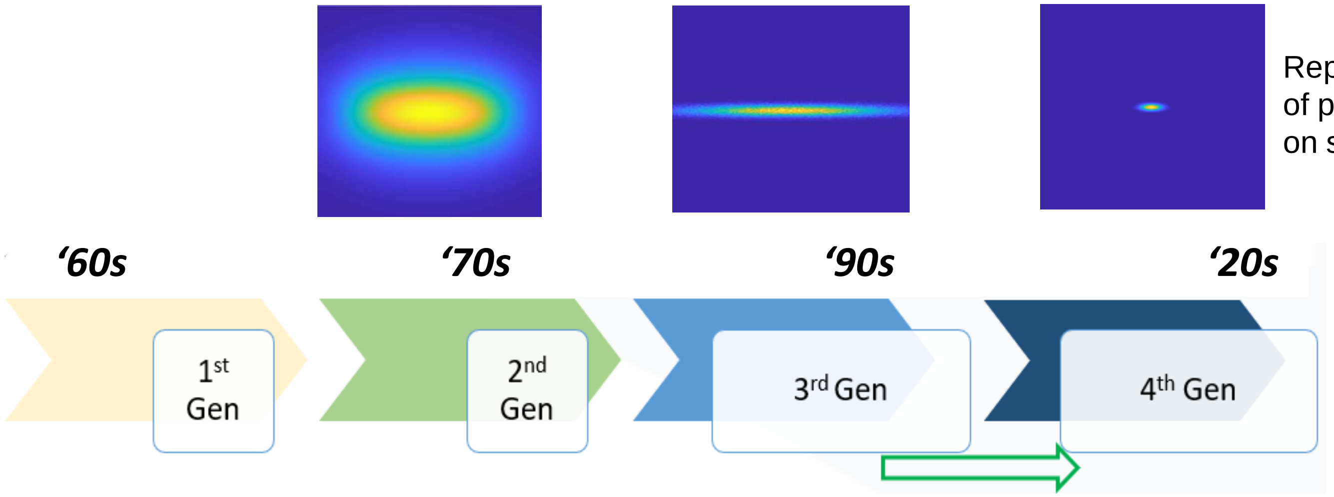




1960 | **1970** | **1990** | **2020**

1st Gen | 2nd Gen | 3rd Gen | 4th Gen

Birth of a new generation of synchrotron light sources



Representation of photon beam on sample

The implementation of the Diffraction Limited Storage Ring concept with MBA lattices (4th generation light sources) has been spearheaded by a couple of brand-new facilities: **MAX IV** in Sweden (2016) and **Sirius** in Brazil (2020).

Afterwards, many existing 3rd generation light sources followed suit or are planning to do so.

And in particular, **EBS** (ESRF) has introduced the Hybrid-MBA lattice (P. Raimondi) and **SLS-II** (PSI) has contributed with the anti-bend cell (A. Streun), that further enhance the emittance reduction.

ESRF-EBS is in operation since 2021, SLS has just shutdown to start the installation of the new storage ring

Motivation for light sources upgrades

Why electron beam emittance is so important for a synchrotron light source?
What is the limit to minimise the beam emittance?

- The smaller the electron beam emittance, the higher the photon source brilliance and coherence:
  - ✓ **Faster experiments**
  - ✓ **Higher resolution (either spatial, in time or in energy)**
  - ✓ **And more performances...**

- Emittance $\varepsilon_{e,x} = \sigma_x \sigma_{x'}$ is related with the **brilliance and coherent fraction of the generated photon beam:**

$$brilliance = \frac{flux}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \qquad F = \frac{\lambda/(2\pi)^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \qquad flux = \frac{N_{ph}}{\Delta T \Delta\,\omega/\omega}$$

$$\Sigma = \sqrt{\sigma_e^2 + \sigma_{ph}^2} \qquad \Sigma' = \sqrt{\sigma'^2_e + \sigma'^2_{ph}} \qquad \epsilon_{e^-} < \epsilon_{ph} = \frac{\lambda}{4\pi}$$

- **Σ**’s are the convolution of electron beam and intrinsic photon size and divergence:

- Brilliance and coherent fraction are **maximised** for small electron emittances until the **diffraction limit** is reached:

~100 pm·rad for diffraction limit at 1 nm (1.24 keV)
~10 pm·rad for difraction limit at 1 Å (12.4 keV)

The MBA cell concept

How the **emittance** of a storage ring can be reduced to the diffraction limit?

Basically one has to split the bending action among as many dipoles as possible→ Multi-Bend Achromat concept (MBA) introduced in the 1990's

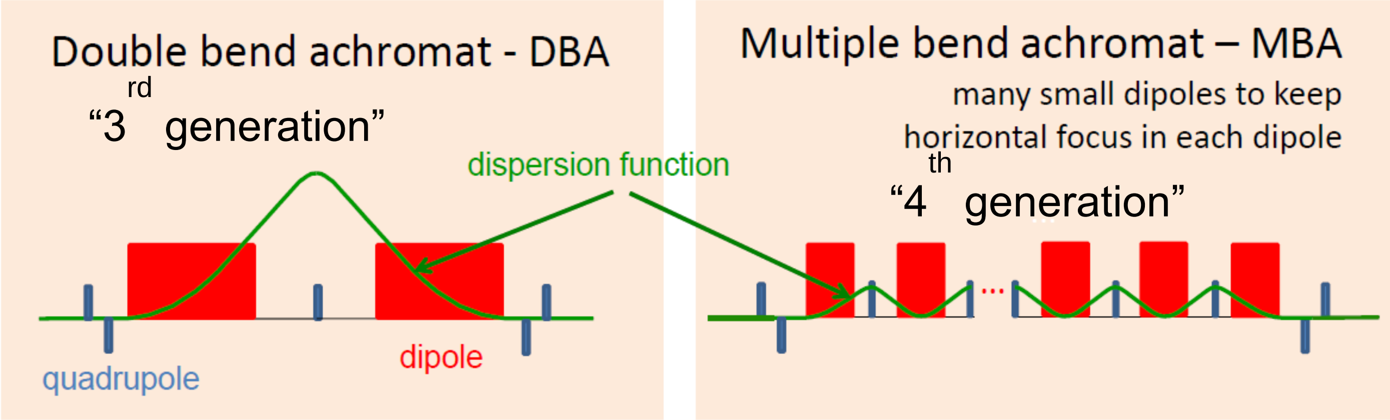
Design of a Diffraction Limited Light Source (DIFL)

D. Einfeld, J. Schaper, Fachhochschule Ostfriesland, Constantiaplatz 4, D-26723 Emden
M. Plesko, Institute Jozef Stefan, Jamova 39, P.O.B. 100, SLO-61111 Ljubljana

Proceedings PAC 1995

Equilibrium emittance scaling law: $\varepsilon_x \approx F\frac{C_q\gamma^2}{J_x}\theta^3 \propto \gamma^2\theta^3 \propto \frac{1}{N_d^3}$

C_q: constant
J_x: Robinson partition number
$\mathcal{F}$: lattice scale factor
γ: Lorentz factor
θ: deflection angle per bending
N_d: number of bendings

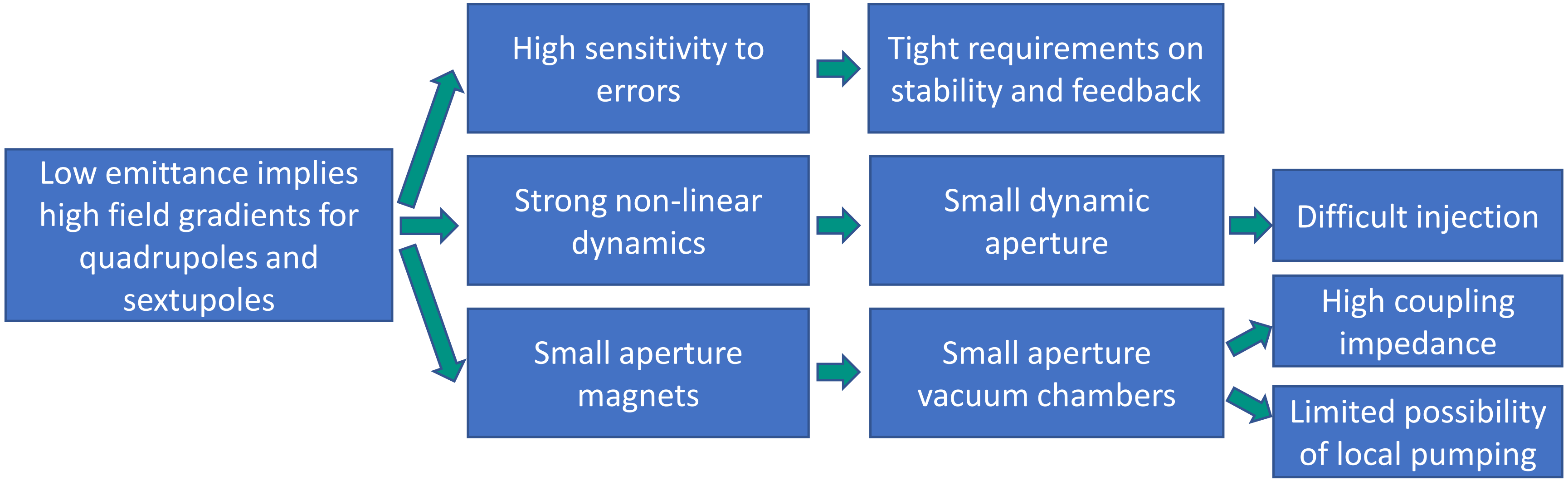


Liu Lin "Towards Diffraction Limited Storage Ring Based Light Sources", IPAC17, Copenhagen (2017)

And eventually, high quadrupole and sextupole gradients are also needed...

Why the MBA concept took so long to be implemented?

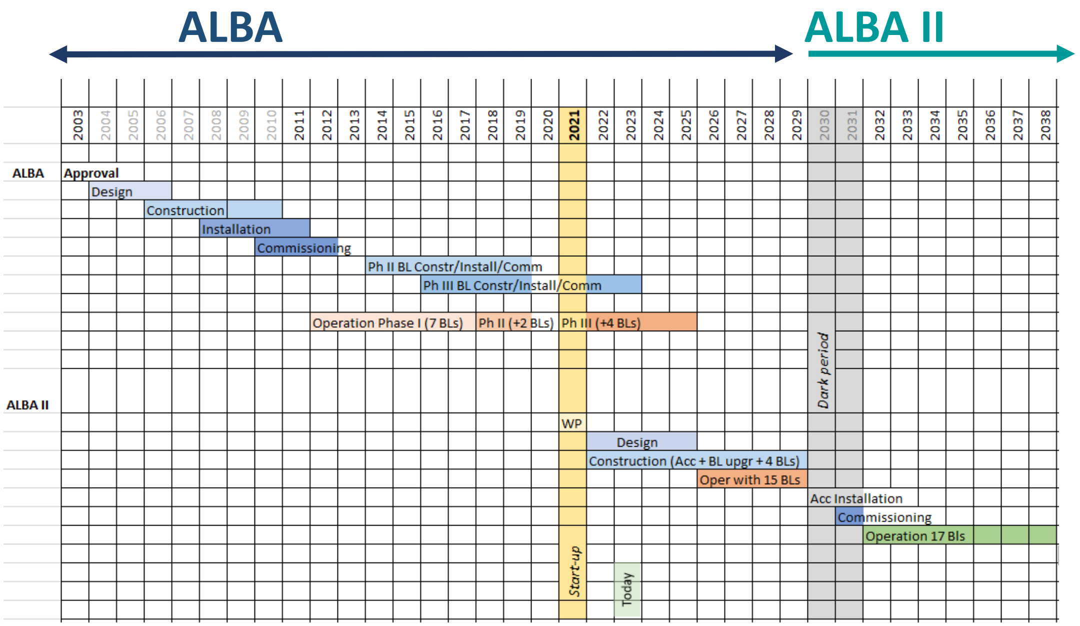
The MBA idea to design diffraction limited light sources is from th ‘90s, but many technological challenges had to be solved to bring it to reality...



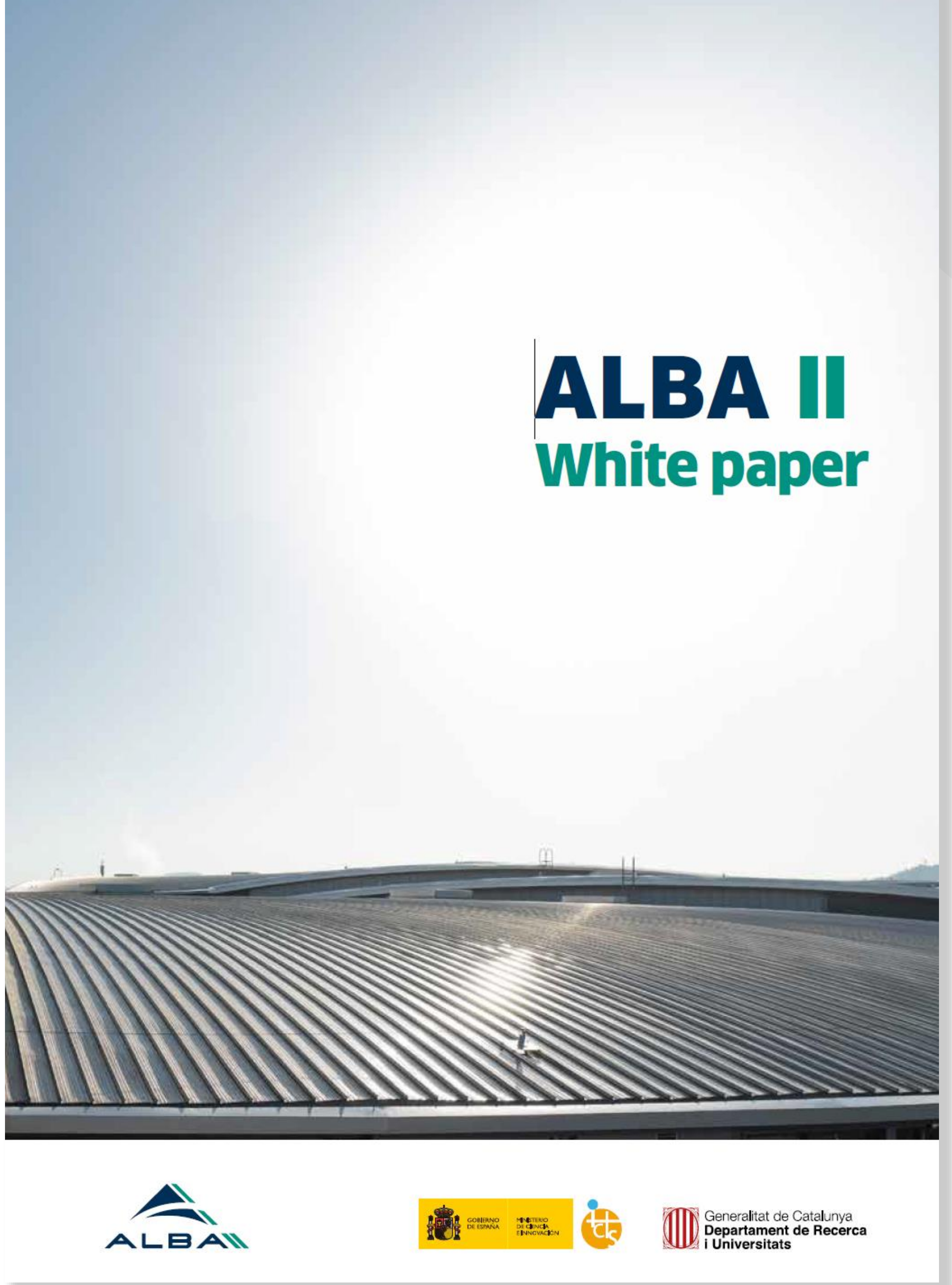
It was not until mid 2000s that, thanks to the experience gained with 3rd generation facilities and to the availability of NEG-coated vacuum chambers for distributed pumping, the first designs of facilities taking profit of the MBA cell were developed (MAX IV design report issued on 2008)

ALBA II Project

- Renovation of storage ring providing a brighter photon beam
- **New beamlines**
- **Upgrade of existing beamlines**
- **Upgrade of data infrastructure and services**



https://www.cells.es/en/science-at-alba/alba-ii-upgrade/alba-ii-whitepaper.pdf

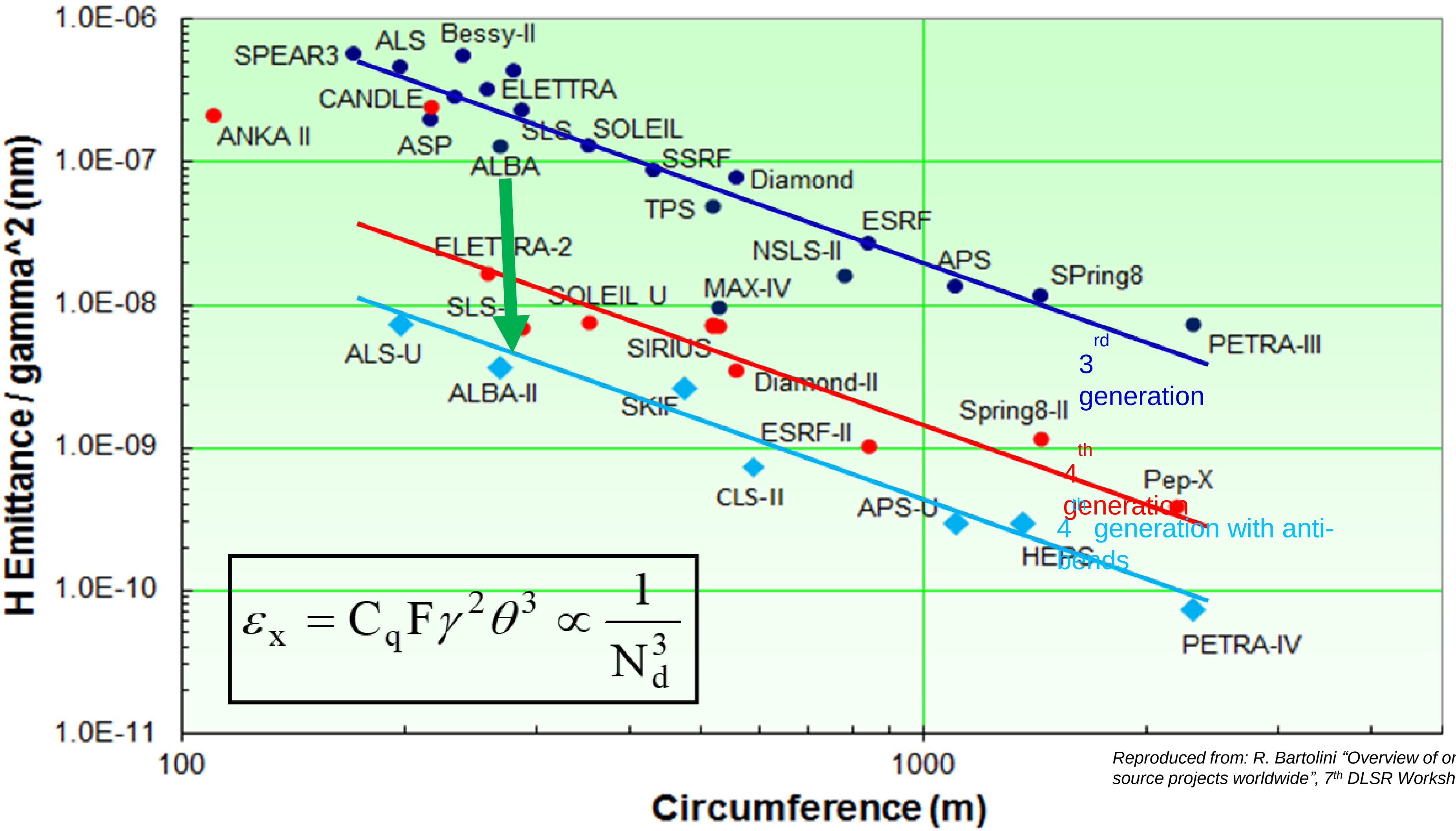


ALBA-II design

- Re-use existing tunnel: storage ring with **same circumference 268.8 m**
- Keep **beam energy at 3 GeV**
- Re-use existing injector with $\varepsilon_x^{booster}$ = 10 nm·rad
- Re-use infrastructures as much as possible
- Existing insertion device beamlines: **preserve 16 cells and beamlines positions**
- Bending beamlines can and must be relocated
- **Straight sections at least 4 m long**
- Straight sections $\beta_x^* \approx \beta_y^* \approx$ 1-2 m
- **Reduce the emittance by at least a factor 1/10**

The emittance from ALBA to ALBA-II

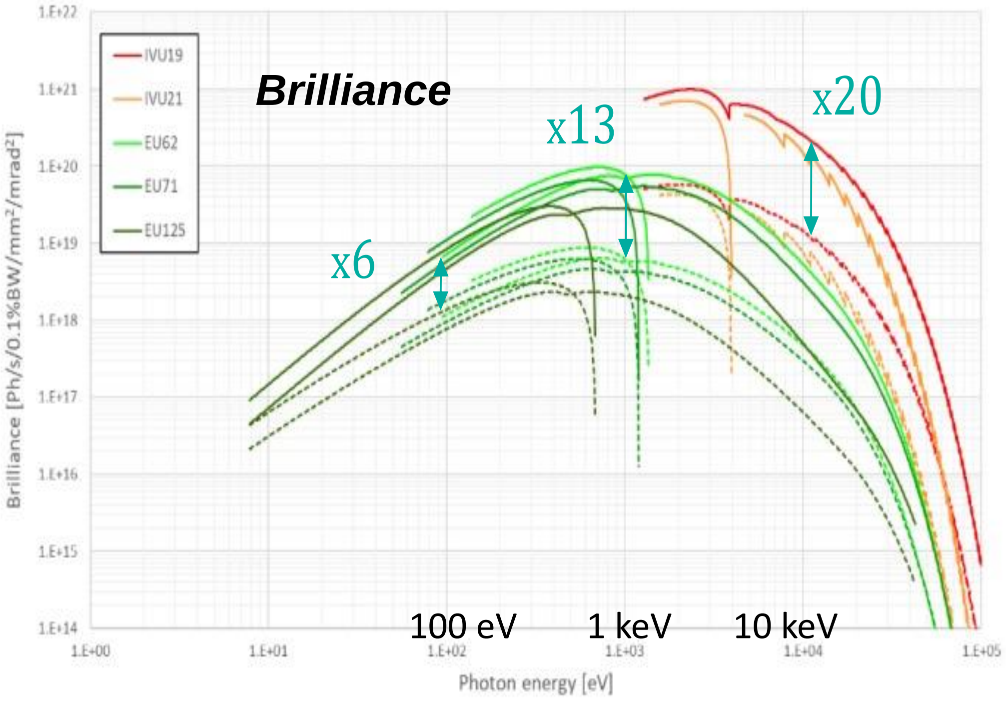
ALBA-II will reduce the **emittance** by a factor 1/20: **from 4.5 nm·rad to 220 pm·rad**

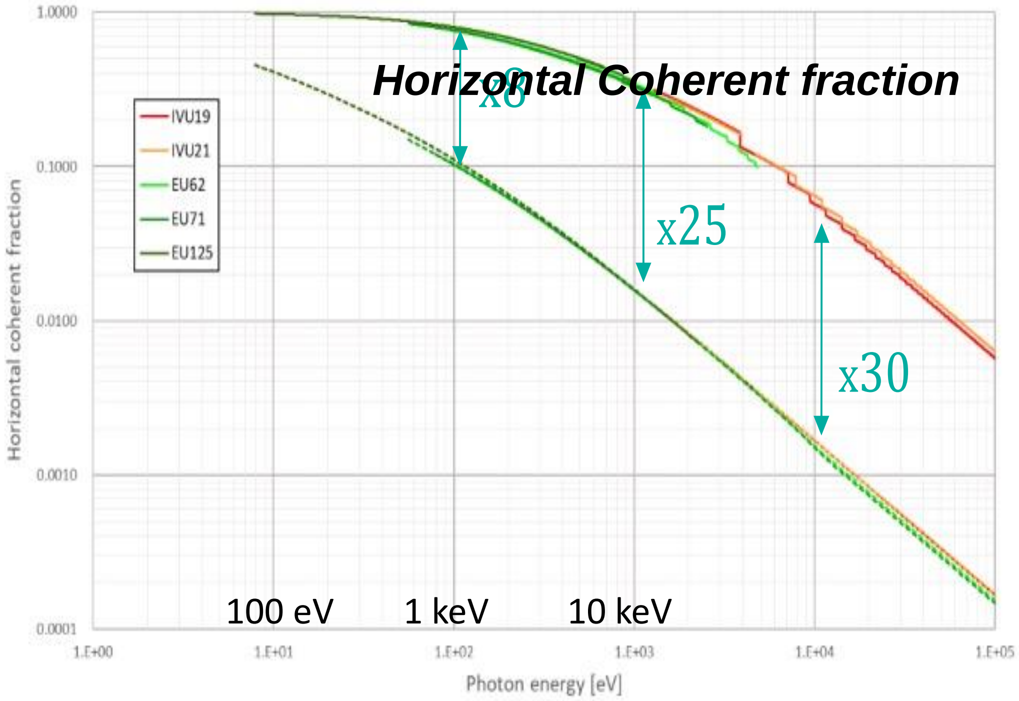


Reproduced from: R. Bartolini "Overview of ongoing 4th generation light source projects worldwide", 7th DLSR Workshop (2021)

IDs performances from ALBA to ALBA-II

Brilliance and coherent fraction will increase by more than a factor 10, especially for hard X-rays beamlines





vs. Photon Energy

A lightweight tracking code running in GPUs

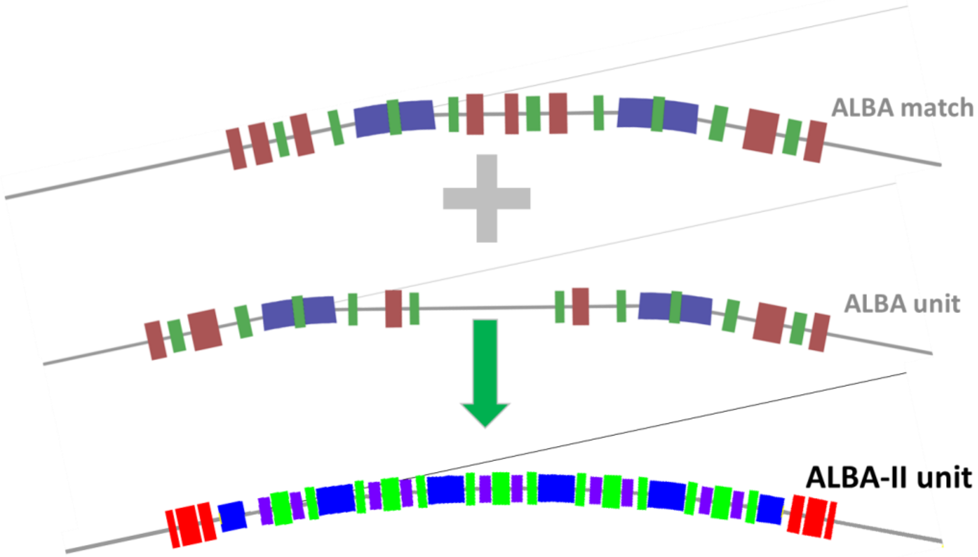
M. Carlà *"UFO, a GPU code tailored toward MBA lattice optimiszation"*, IPAC22

A particle **accelerator code running on GPUs was fully developed at ALBA** to speed up the evaluation of lots of lattices (millions...) for the optimisation of linear and non-linear optics of ALBA-II:

- Run on GPUs
- Use 32 bits variables instead of 64 (whenever possible)
- Simplify pass-methods (whenever possible)

The 6BA baseline lattice for ALBA-II

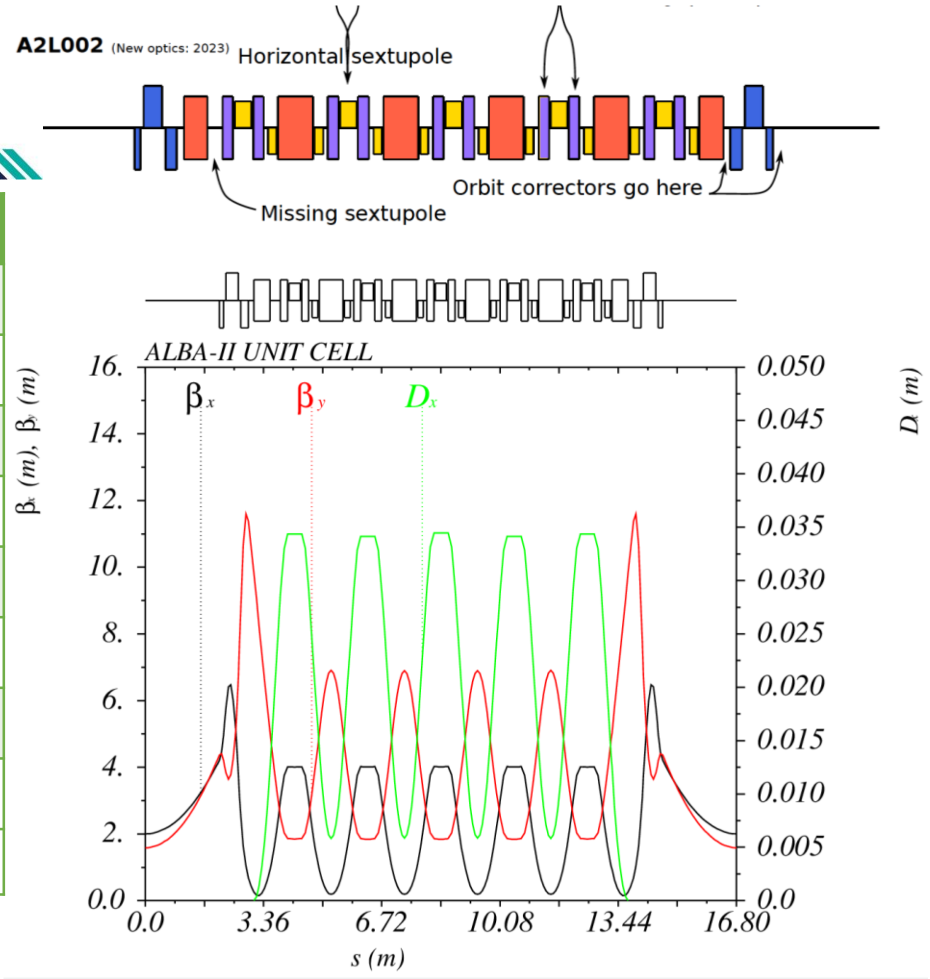
The search for the best MBA for the ALBA upgrade started in 2019 and after many studies and tests the **ALBA-II baseline lattice based on a Six Bend Achromat (6BA) cell with anti-bends** and **distributed sextupoles** has an emittance **ε_x= 220 pm·rad**



6 gradient bends 1.2 T and 15 T/m (w/o longitudinal gradient)
10 gradient anti-bends 70 T/m
6 matching quads < 100 T/m
14 sextupoles < 5000 T/m^2

Main parameters of the ALBA-II lattice

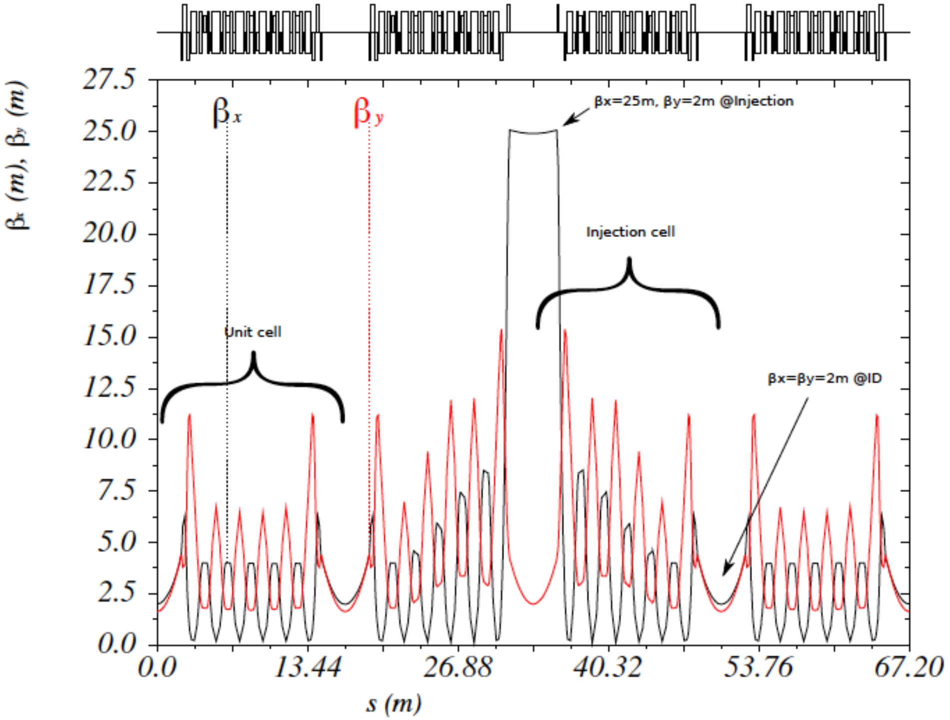
	ALBA		ALBA II
Energy	***3 GeV***		**3 GeV**
Circumference	*268.8 m*		268.8 m
Symmetry	*4-fold*		16-fold
Lattice	*8+8 DBA cells*		16 6BA cells
Emittance	***4.5 nm·rad***	÷20	**220 pm·rad**
Nº of cells	*8+8*		16
# of straights	*4 / 12 /8*		16
Straight length	*7.8 / 4.0 / 2.3m*		4.0 m
Straight ratio	*36%*		25%

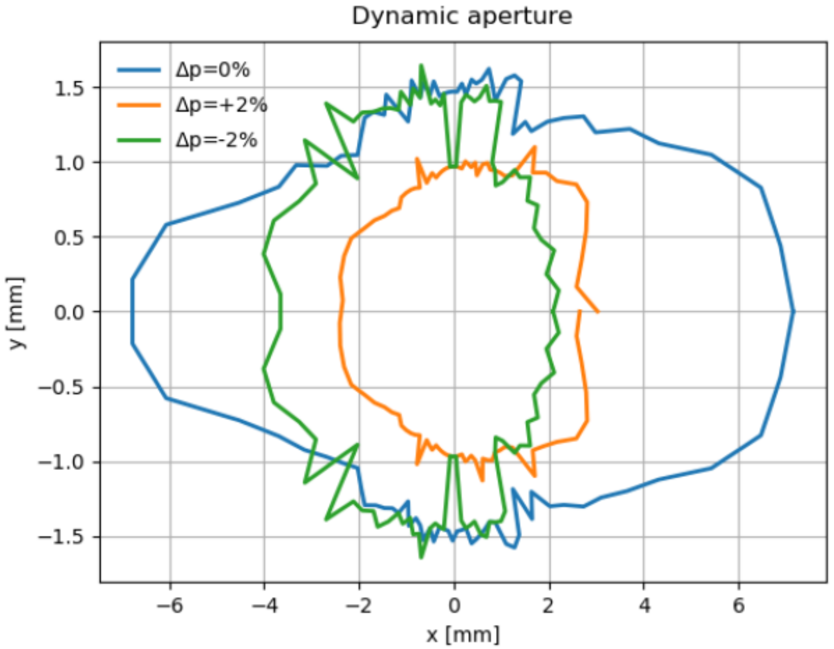


Benedetti et al. *"A distributed sextupoles lattice for the ALBA low emittance upgrade"*, IPAC21

Non-linear dynamics and injection cell

- 14 families of sextupoles for the unit cell (5 SH + 9 SV)
- plus up to 14 + 14 individual sextupoles in the two cells modified for the injection
- Dynamic aperture and energy acceptance are optimised using recipes that include genetic algorithms (NSGA2...)

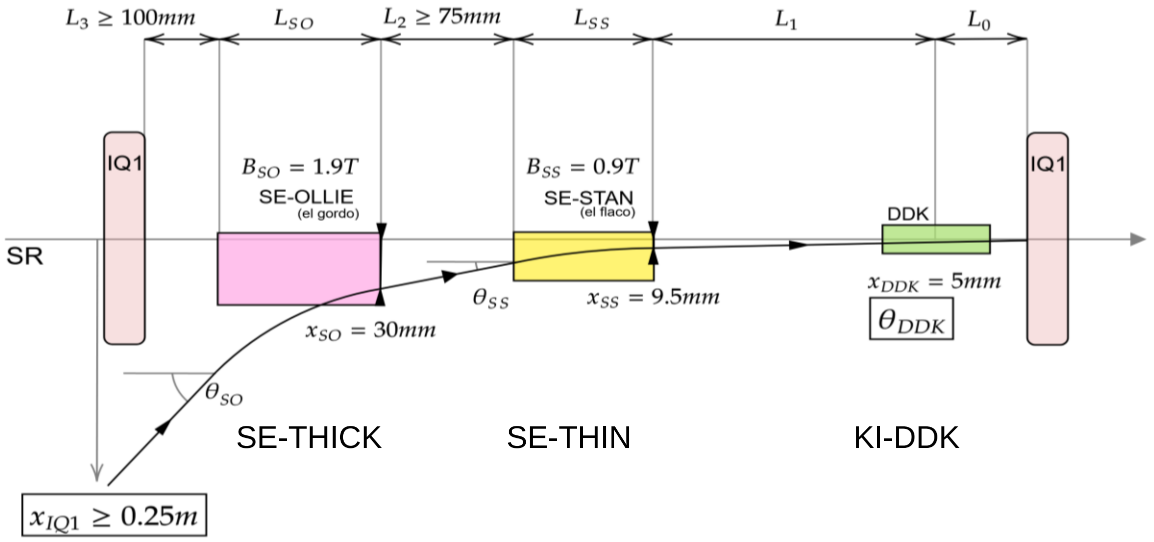




- **Dynamic aperture optimised to ±7 mm**, allowing off-axis injection
- **Lifetime** is 5.5 hours with 100% coupling and w/o 3rd harmonic cavity.
- To further increase lifetime, a 3rd harmonic RF cavity will be installed.

Injection into the ALBA-II storage ring

For ALBA-II we decided from the beginning to adopt only well known and tested injection schemes.
The ALBA-II lattice is very tight, all the injection elements have to fit in a **4 metres long straight section**.



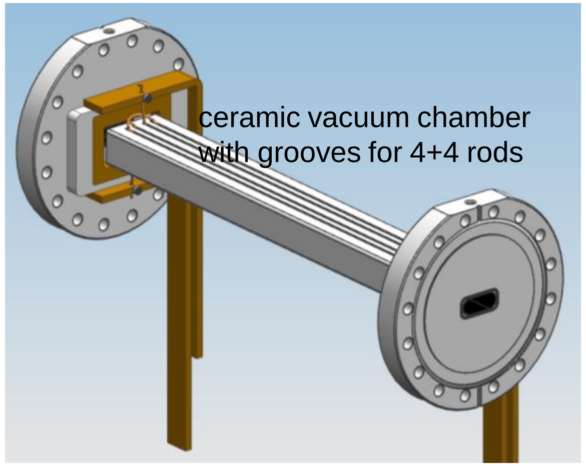
The beam from the booster is **injected off-axis** through a thick and a thick septum and a **multipole pulsed kicker** conceived and designed at ALBA (DDK) reduces its large oscillations within the dynamic aperture.

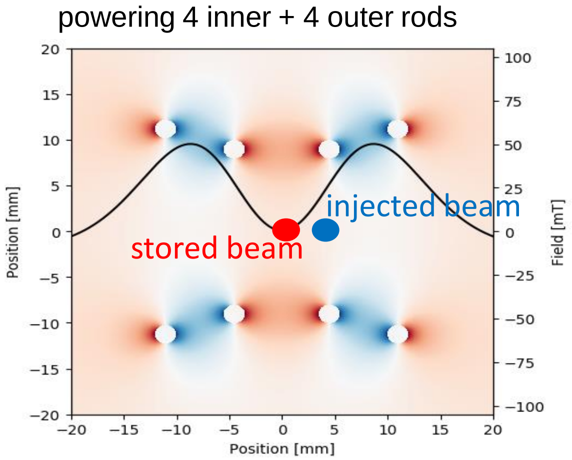
The requirement for the ALBA-II off-axis injection scheme is at least ±6 mm of horizontal dynamic aperture

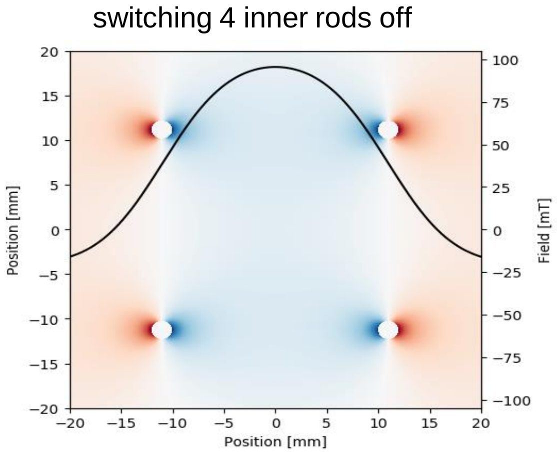
The ALBA-II Double Dipole Kicker

Pulsed multipole kickers were introduced at KEK in Japan in the 2000's and furher developed at BESSY-II.
After 2020, the MAX-IV, Sirius and Soleil synchrotrons designed their own design and installed it for off-axis injection.

ALBA is now developing a novel design with a special geometry of the coils:



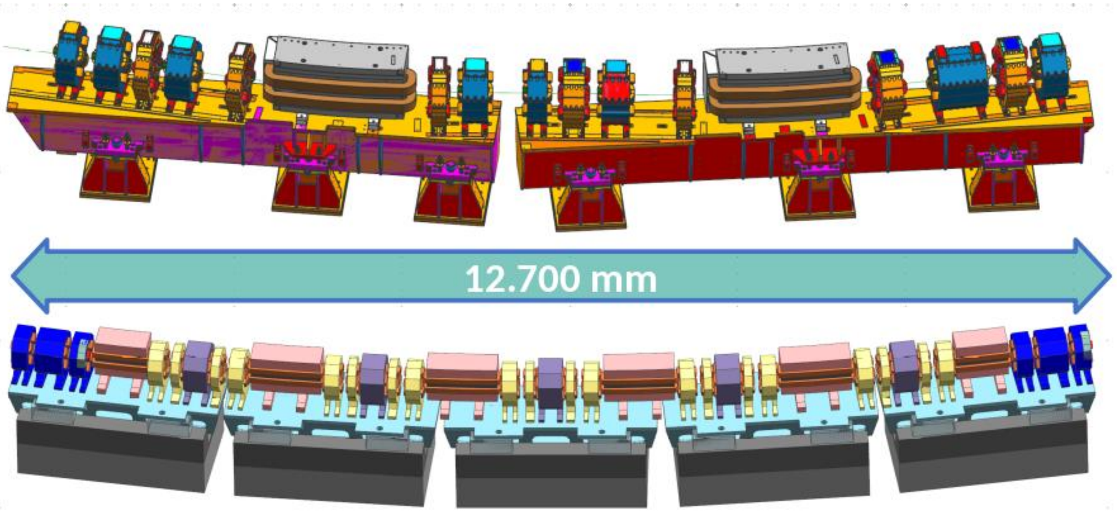




- Powering all 4+4 rods, a **multipole field is produced for off-axis injection**.
- Switching off either the inner or outer rods, a dipole field is produced.
- **A dipole is needed for on-axis injection during the ALBA-II commissioning.**
- The ALBA-II straight sections have very little room and **combining two kickers in one** is very useful.

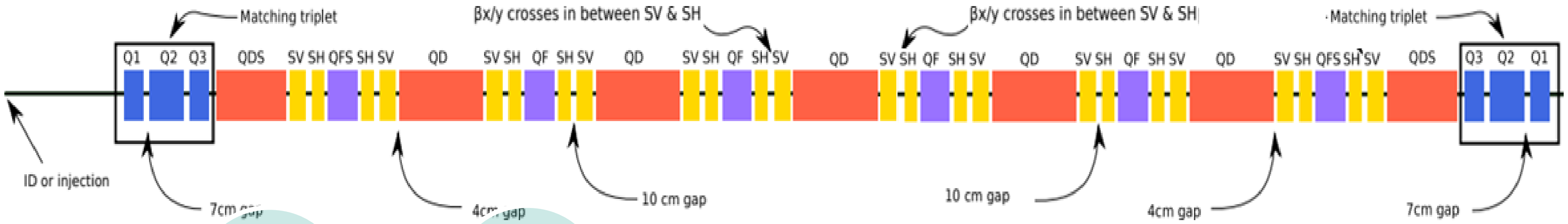
Magnets from ALBA to ALBA-II

arc architecture



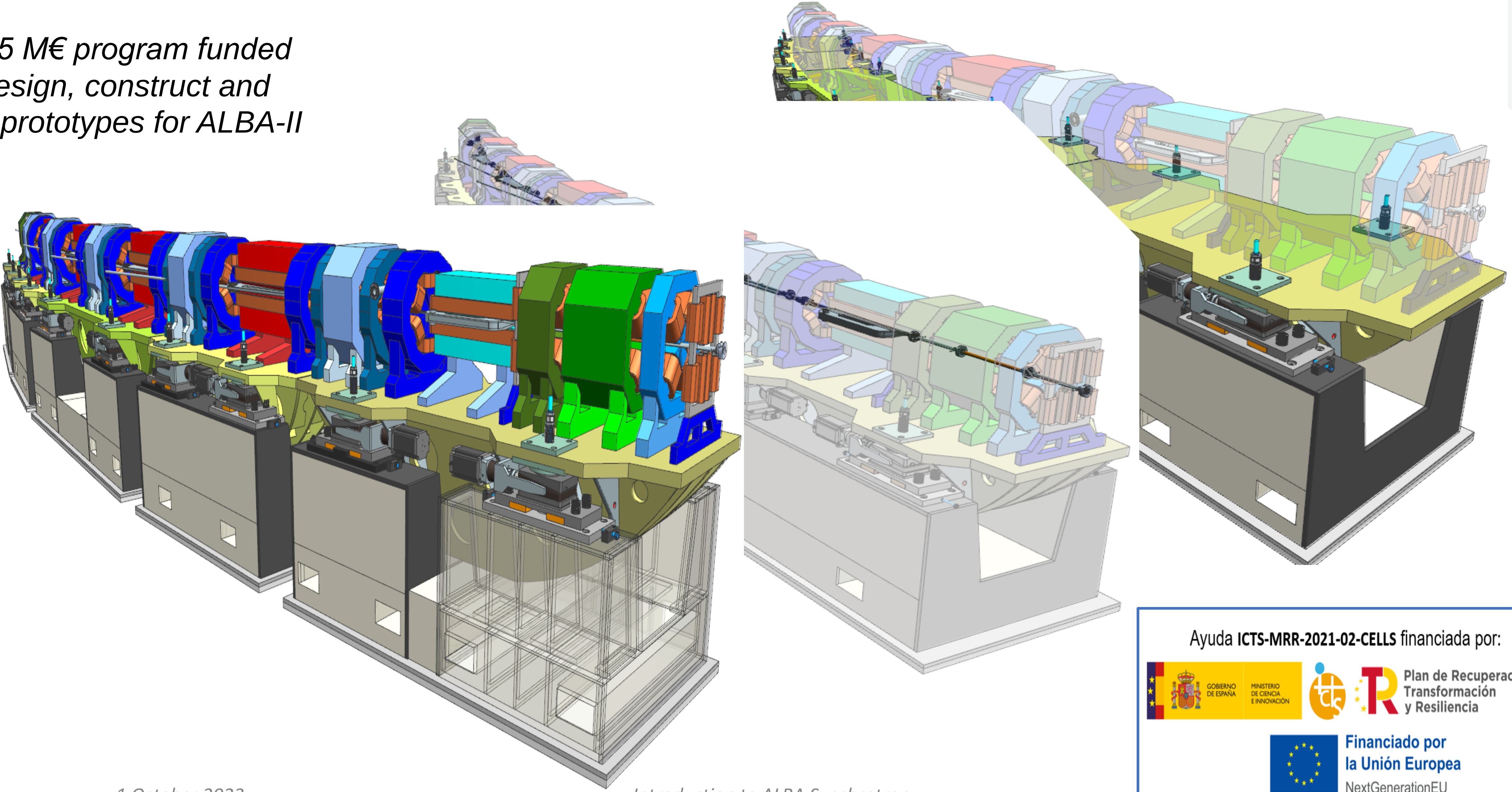
ALBA
Total magnet equivalent length: 6.18 m
Compactness: 6.18/12.7 = **49%**

ALBA-II
Total magnet equivalent length: 10.13 m
Compactness: 10.13/12.7 = ***80%***



Prototyping the ALBAII arc

A 7.5 M€ program funded to design, construct and test prototypes for ALBA-II



Ayuda **ICTS-MRR-2021-02-CELLS** financiada por:

GOBIERNO DE ESPAÑA — MINISTERIO DE CIENCIA E INNOVACIÓN

Plan de Recuperación, Transformación y Resiliencia

Financiado por la Unión Europea
NextGenerationEU

ALBA-II RF system

- Main RF high power components re-used from ALBA
- Upgrade from IOT transmitters to Solid State Power Amplifiers

ALBA EU-HOM NC cavity

Parameter	Value	Unit
Frequency	500	MHz
Number of cavities	6	-
Voltage	2.4	MV
RF acceptance	7	%
Energy loss/ turn	1.028	MeV
Transmitter power (at 300 mA)	90	kW
Synchrotron frequency*	2.25	kHz
Bunch length (σ)*	7	ps

*w/o harmonic cavity

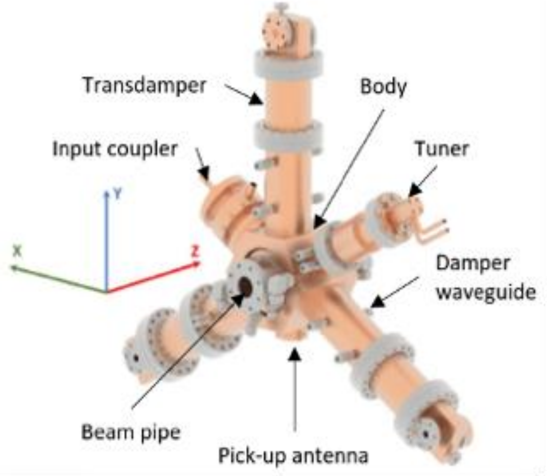
Short bunches lead to high Touschek effect and short beam lifetime, a system of 3rd harmonic cavities has been already designed and tested and will be installed in ALBA-II.

RF 3rd harmonic active cavity

The **prototype design** was co-funded by ALBA and the CERN through the collaboration agreement KE2715/BE/CLIC for the Development of CLIC Damping Ring Technologies (2015-2018).

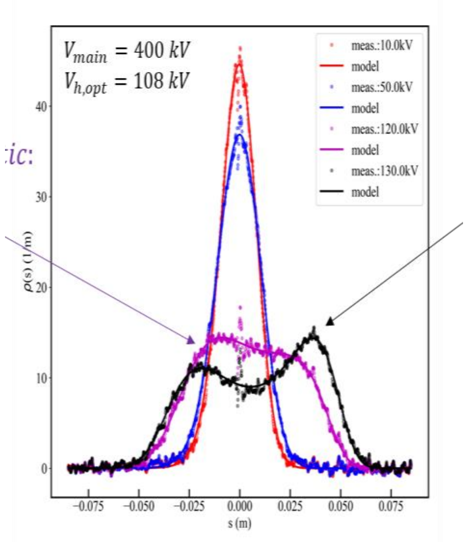
The **prototype construction** was co-funded by ALBA and the European Regional Development Fund (ERDF) within the Framework of the Smart Growth Operative Programme 2014-2020.

The **prototype tests** were co-funded by ALBA, HZB and DESY through the collaboration agreement RCN-CIN202100124 (2020-2023).



SSPA

DLLRF



Single bunch profile for different harmonic voltages

Bunch lengthening with the ALBA 3rd harmonic active prototype system was successfully tested with beam in BESSY-II storage ring in 2023.

In ALBA-II, three 3rd hamonic cavities will render more than **20 hours of lifetime**

What ALBA II will provide

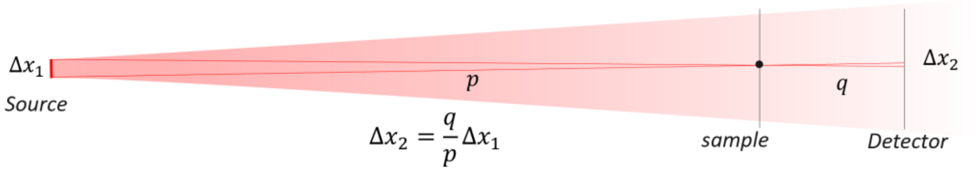
Full infrastructure to tackle the grand challenges of our time for the Spanish and European users

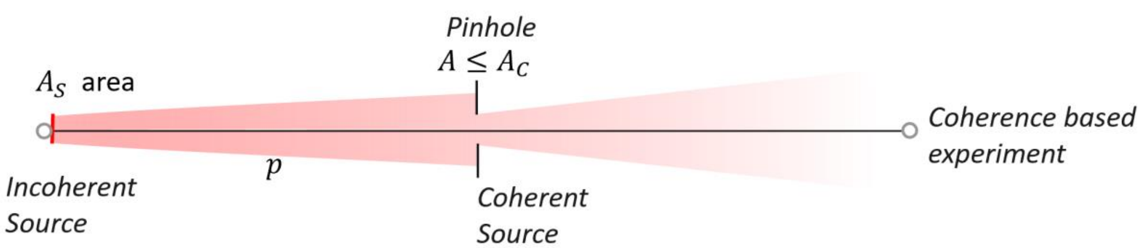
ALBA II combines the excellence and availability of the user program of ALBA with the development of full characterization suites for characterizing multi-lengthscale problems

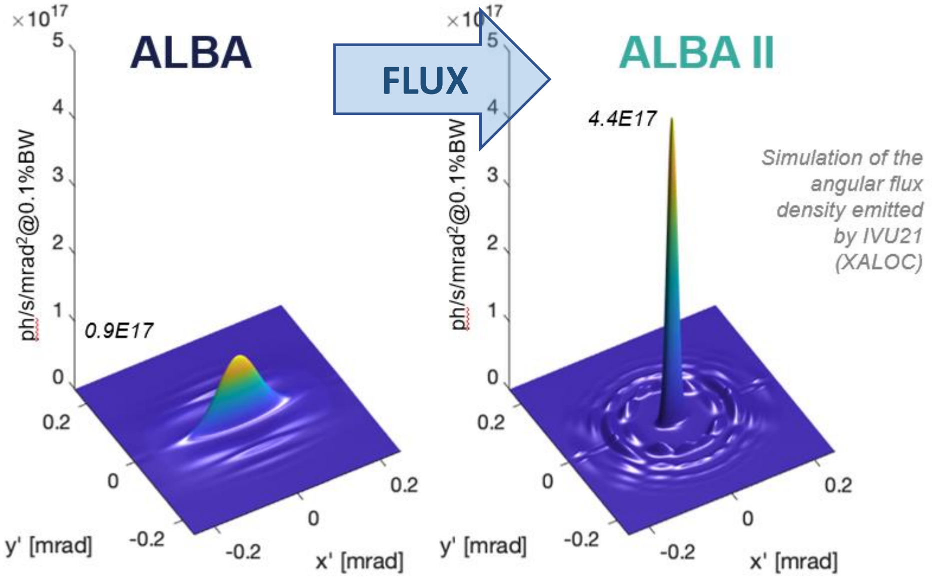
- Enhanced **microscopy** capabilities
- **Multimodal methodologies** to address complex development tasks
- **High throughput capabilities** and big-data connectivity for fast innovation
- And **optimized operando env**ironments to optimize functional materials and devices

Evolution from 3rd to 4th generation synchrotrons

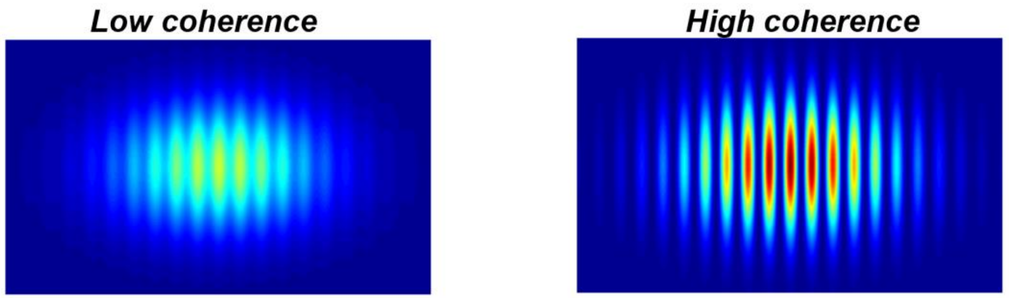
increase in Brilliance, flux, coherence of synchrotron light by orders of magnitude – boosted by long photon paths







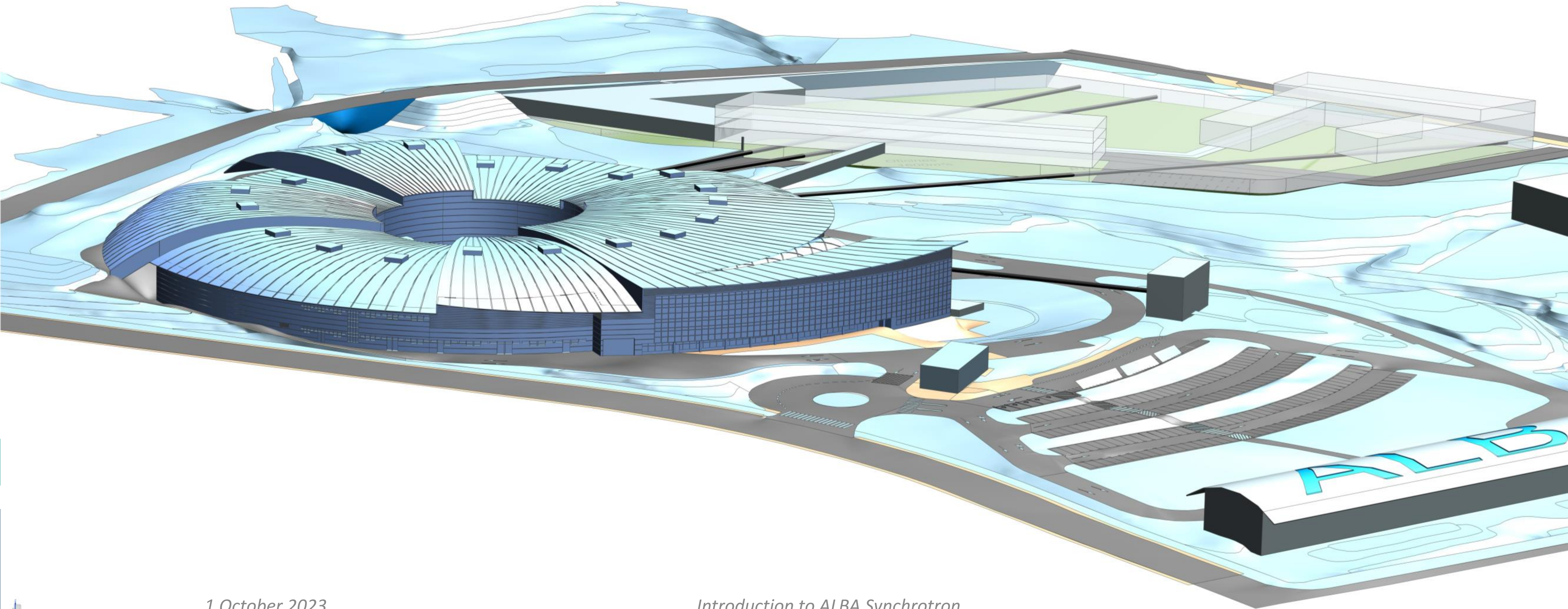
Most basic example: Young's Double slit interference



$$A_C(p) = \frac{(\lambda p)^2}{A_S}$$

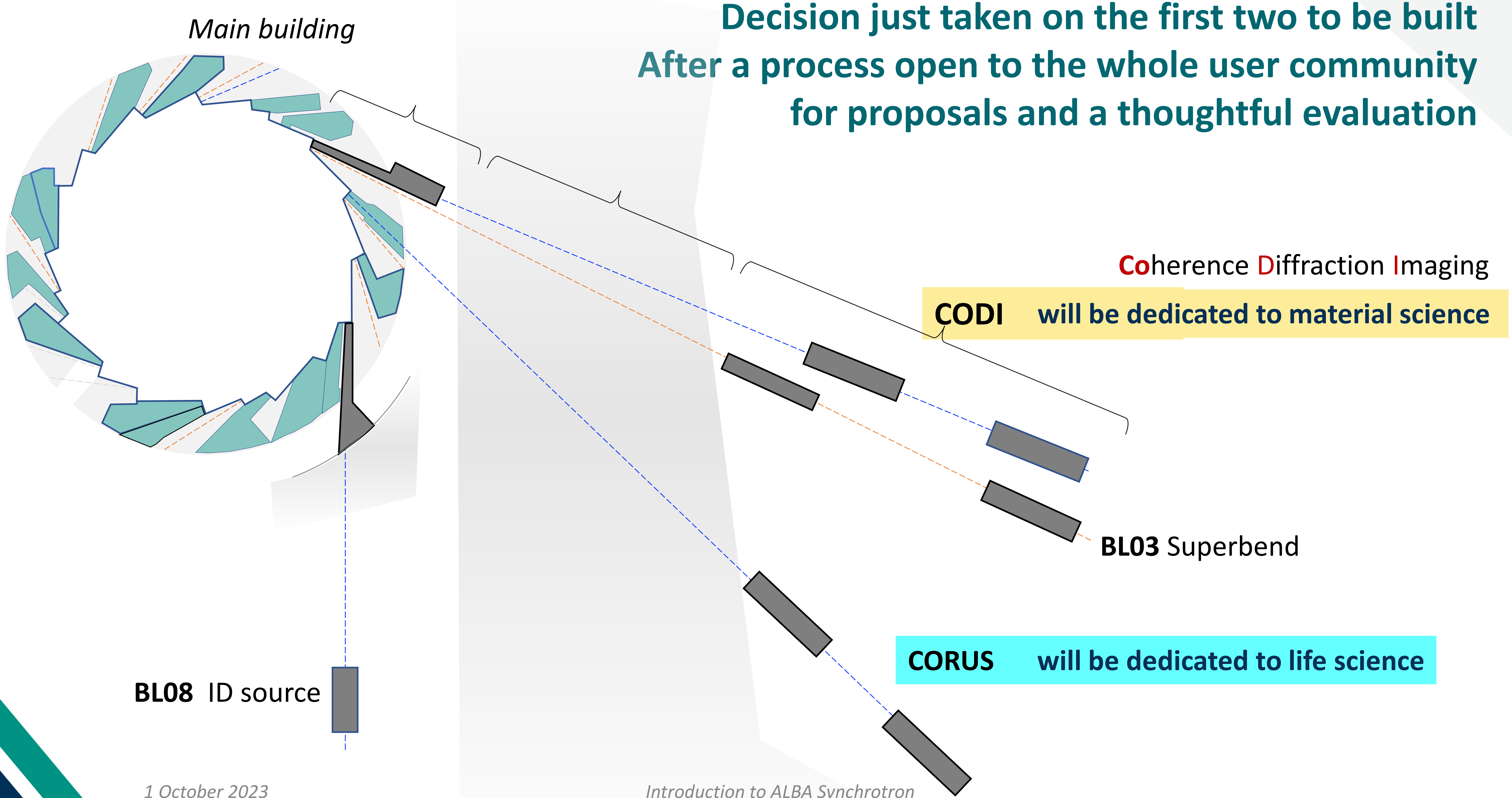
ALBA II – enlarging the infrastructure

New plots have been assigned to ALBA for building long BLs



Long Beamlines

Decision just taken on the first two to be built
After a process open to the whole user community for proposals and a thoughtful evaluation

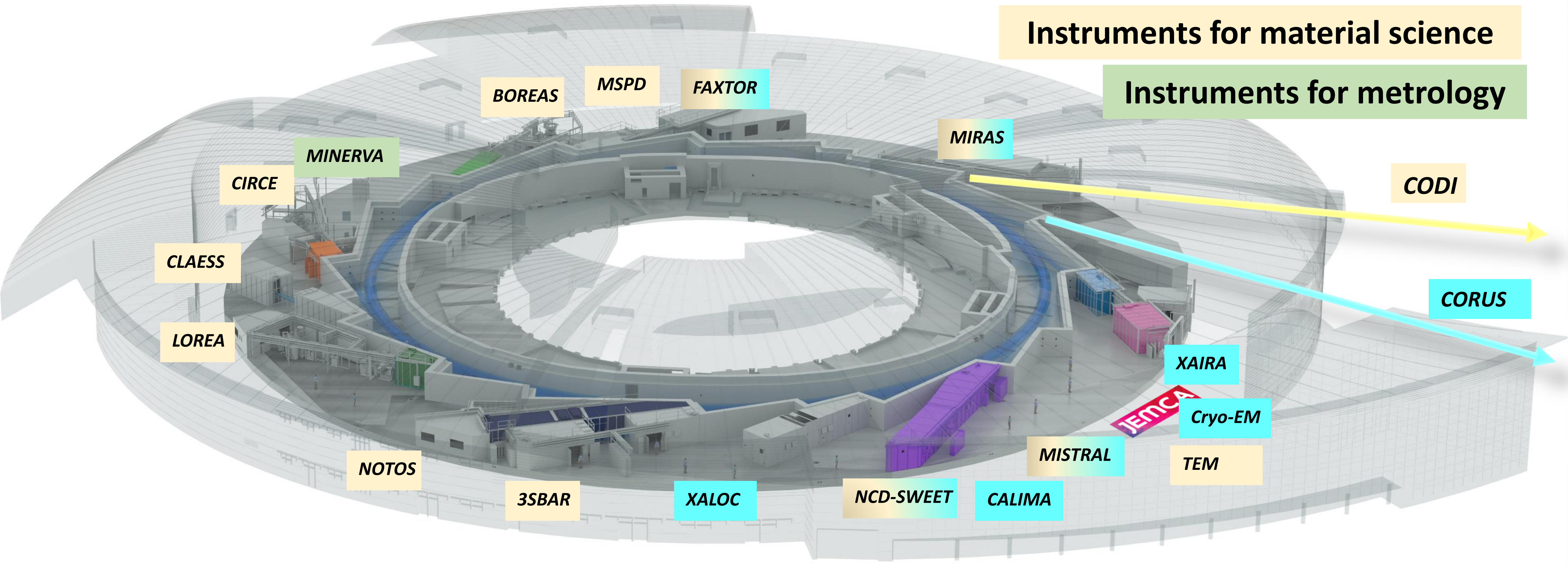


BEAMLINES at ALBA II (2031)

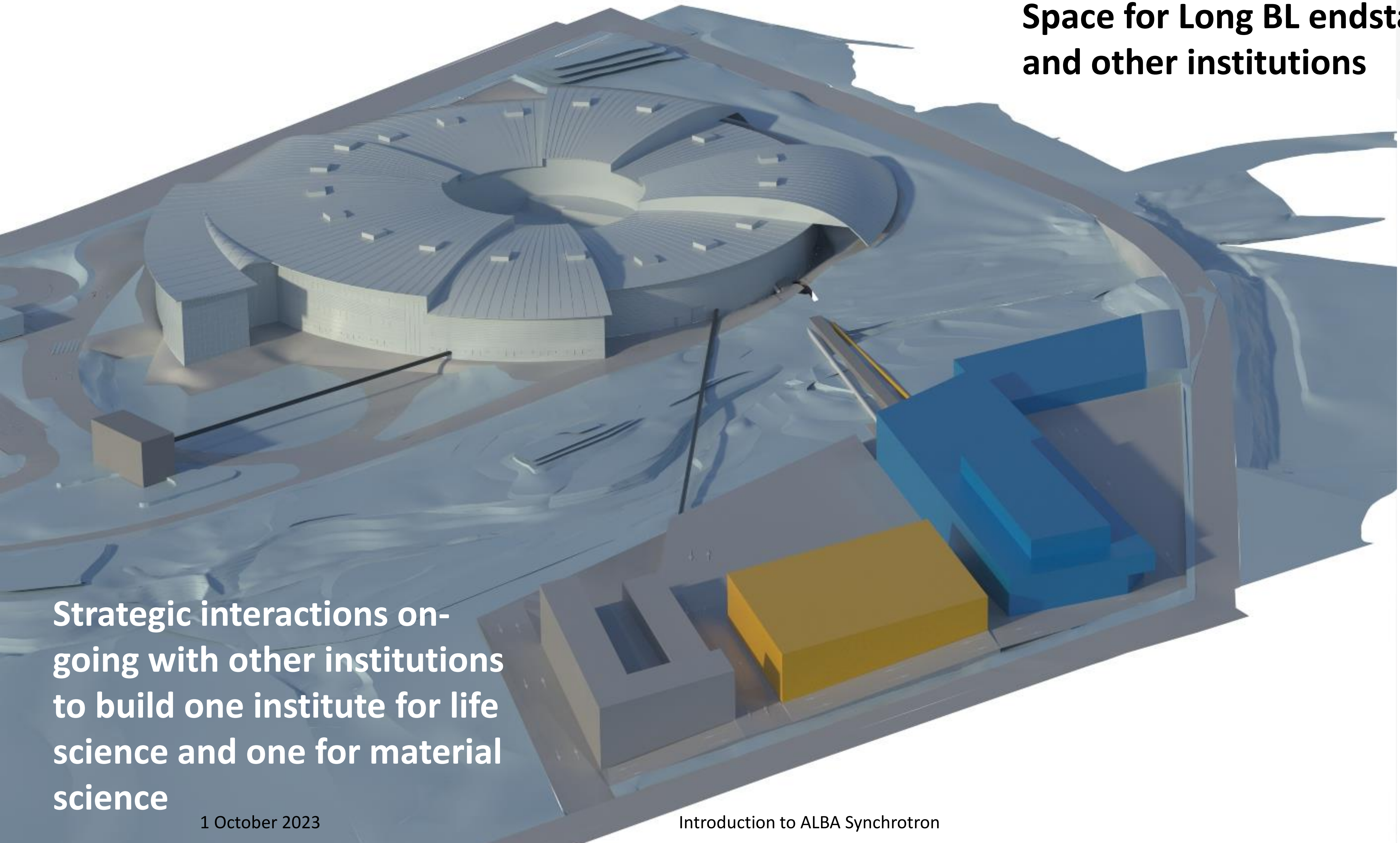
Instruments for life science

Instruments for material science

Instruments for metrology



Space for Long BL endstations and other institutions

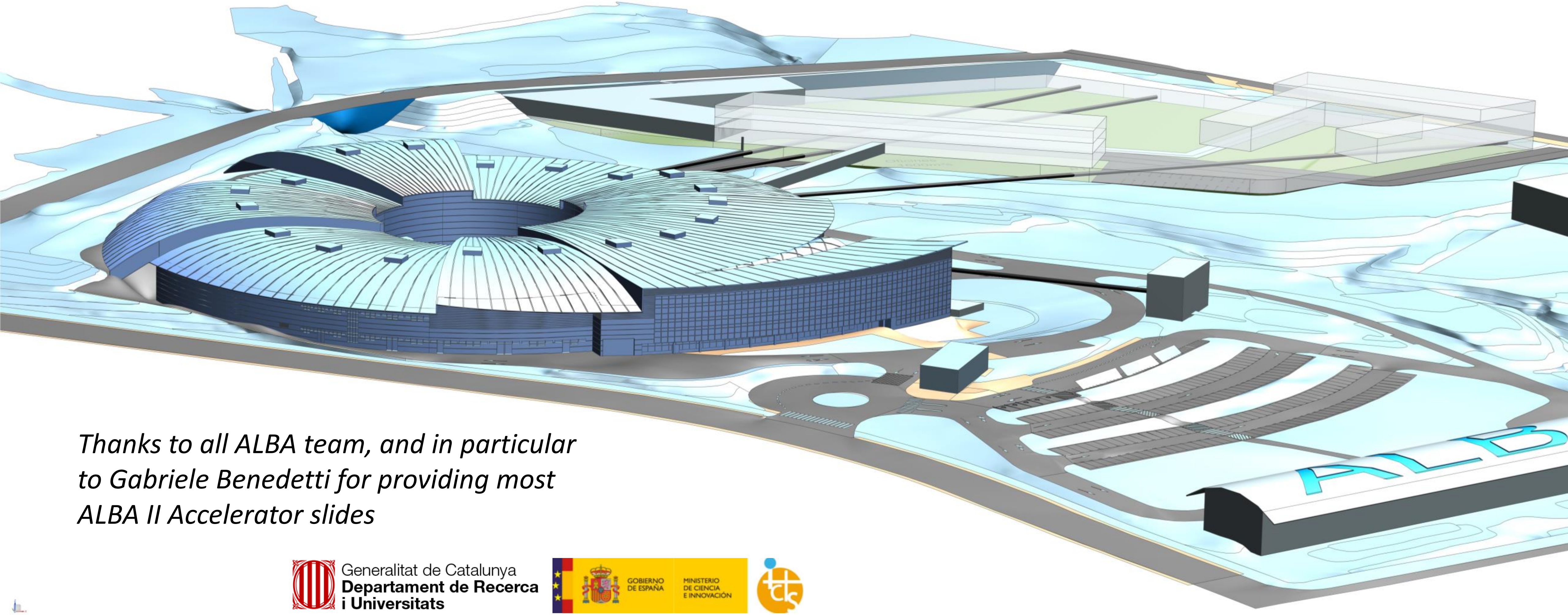


Strategic interactions on-going with other institutions to build one institute for life science and one for material science

Looking forward to your visit on 5 October

Questions welcome

We are hiring:
https://public.cells.es/jobs/#!/jobs



Thanks to all ALBA team, and in particular to Gabriele Benedetti for providing most ALBA II Accelerator slides

Generalitat de Catalunya
Departament de Recerca i Universitats

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