TWENTIETH LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS August, 19-25, 2021
MOSCOW STATE UNIVERSITY

The XLS-CompactLight Design Study

Federico Nguyen – August 25th 2021*
on behalf of the XLS-CompactLight Collaboration

* ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Fusion and Technology for Nuclear Safety Department

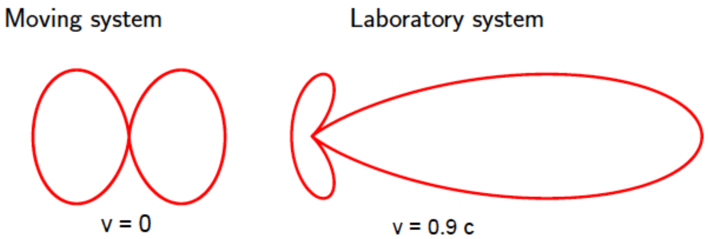
Outline

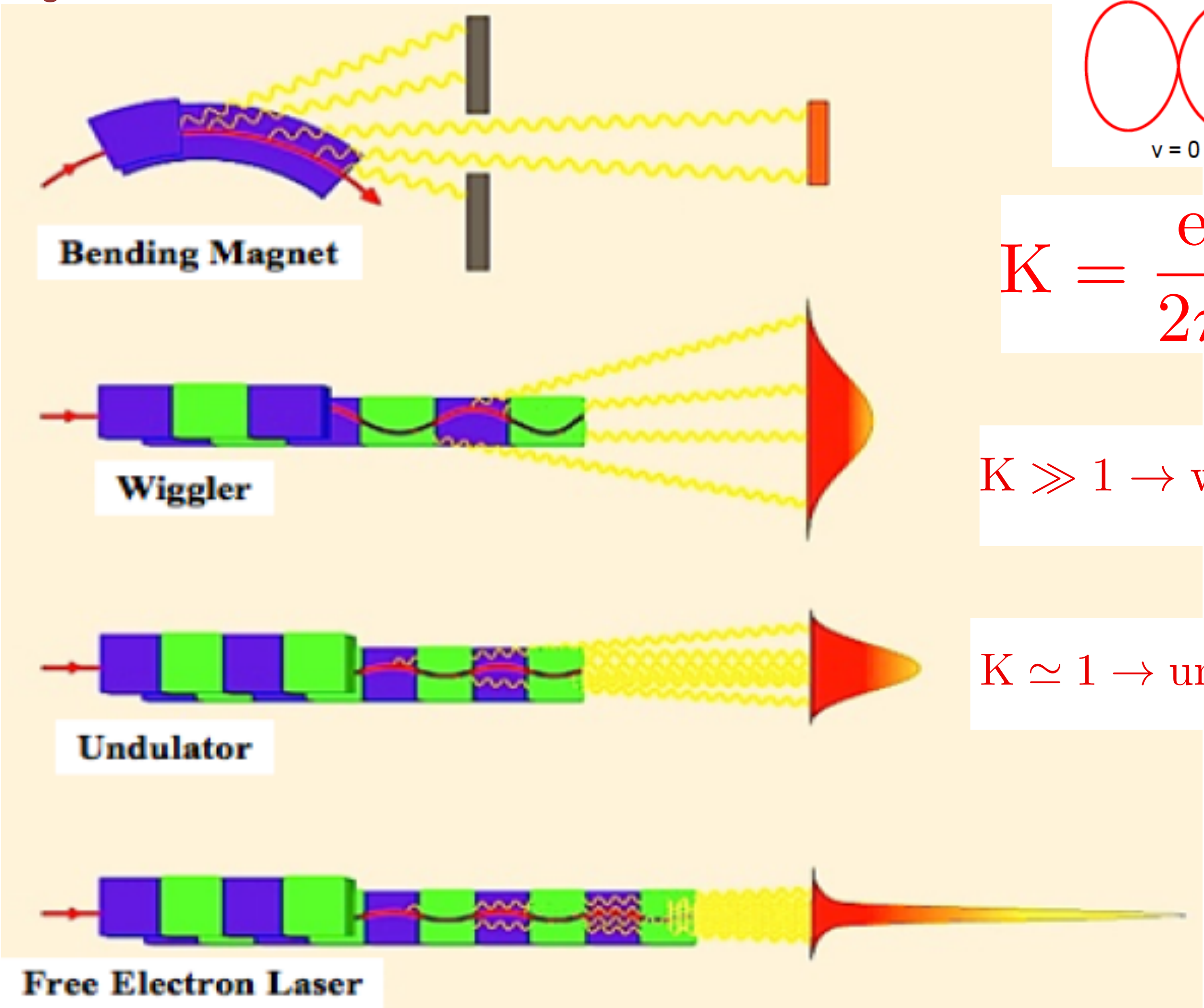
- ✓ **Introduction: (two) Free-Electron Laser (FEL) applications**
- ✓ **The XLS-CompactLight project**
- ✓ **Technology driver: short period undulators**
- ✓ **User driver: FEL performance**
- ✓ **Conclusions & outlook**

Funded by the European Union

Light emission in insertion devices

For each device: an electron beam entering the magnet insertion





$$K = \frac{eB\lambda_u}{2\pi m_e c}$$ = **deflection strength**

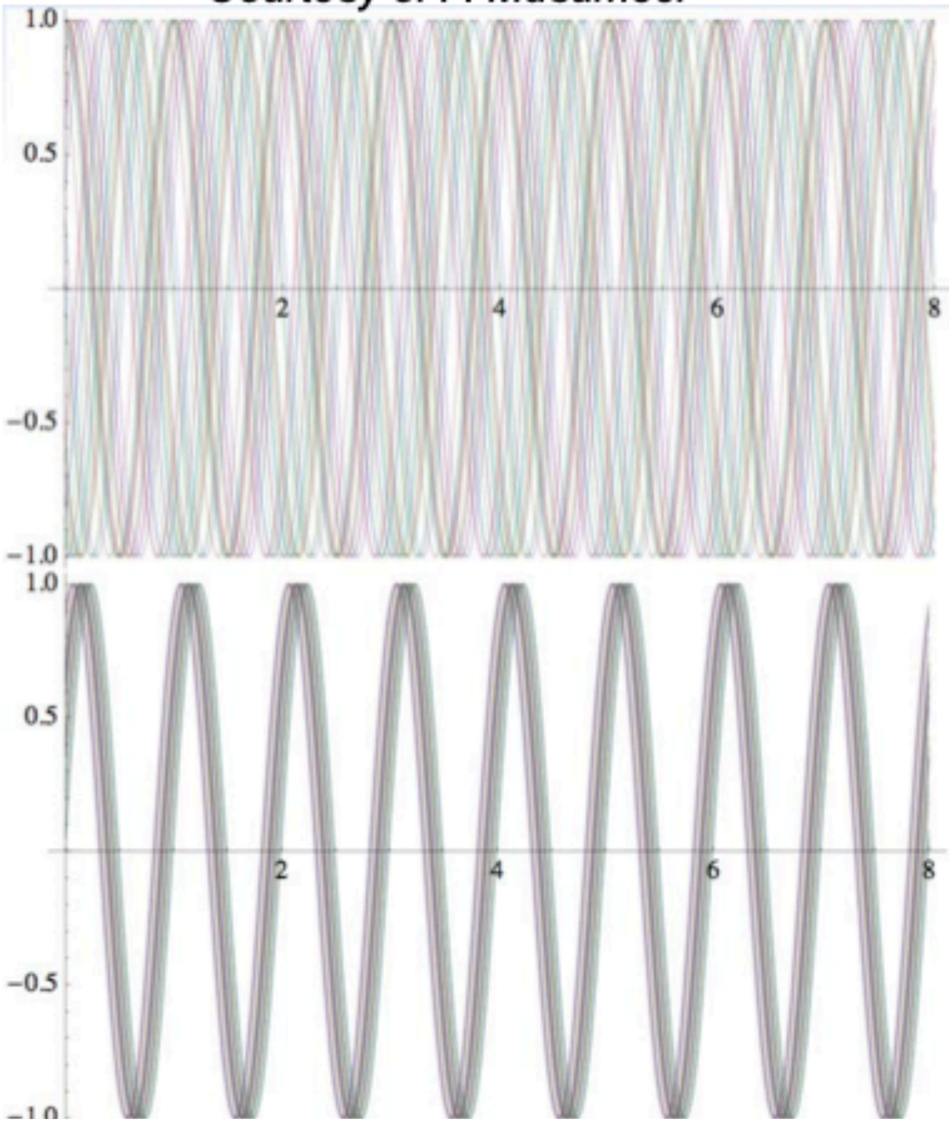
$$K \gg 1 \rightarrow \text{wiggler}: \quad \text{also } \theta \gtrsim \frac{1}{\gamma}$$

$$K \simeq 1 \rightarrow \text{undulator}: \quad \theta \sim \frac{1}{\gamma\sqrt{N_u}} < \frac{1}{\gamma}$$

High quality e-beam: bunching happens!

FEL: undulator & bunching

Courtesy of P. Musumeci



Disordered system: single electron wave trains superimpose with random phases: noise. ***Intensity ∝ N_e***

$$B = \frac{1}{N_e}\sum_{n=1}^{N_e}\exp(i\phi_n)$$

B → 1 is the perfect order

Ordered system: all single wave trains are in phase. ***Intensity ∝ N_e^2***

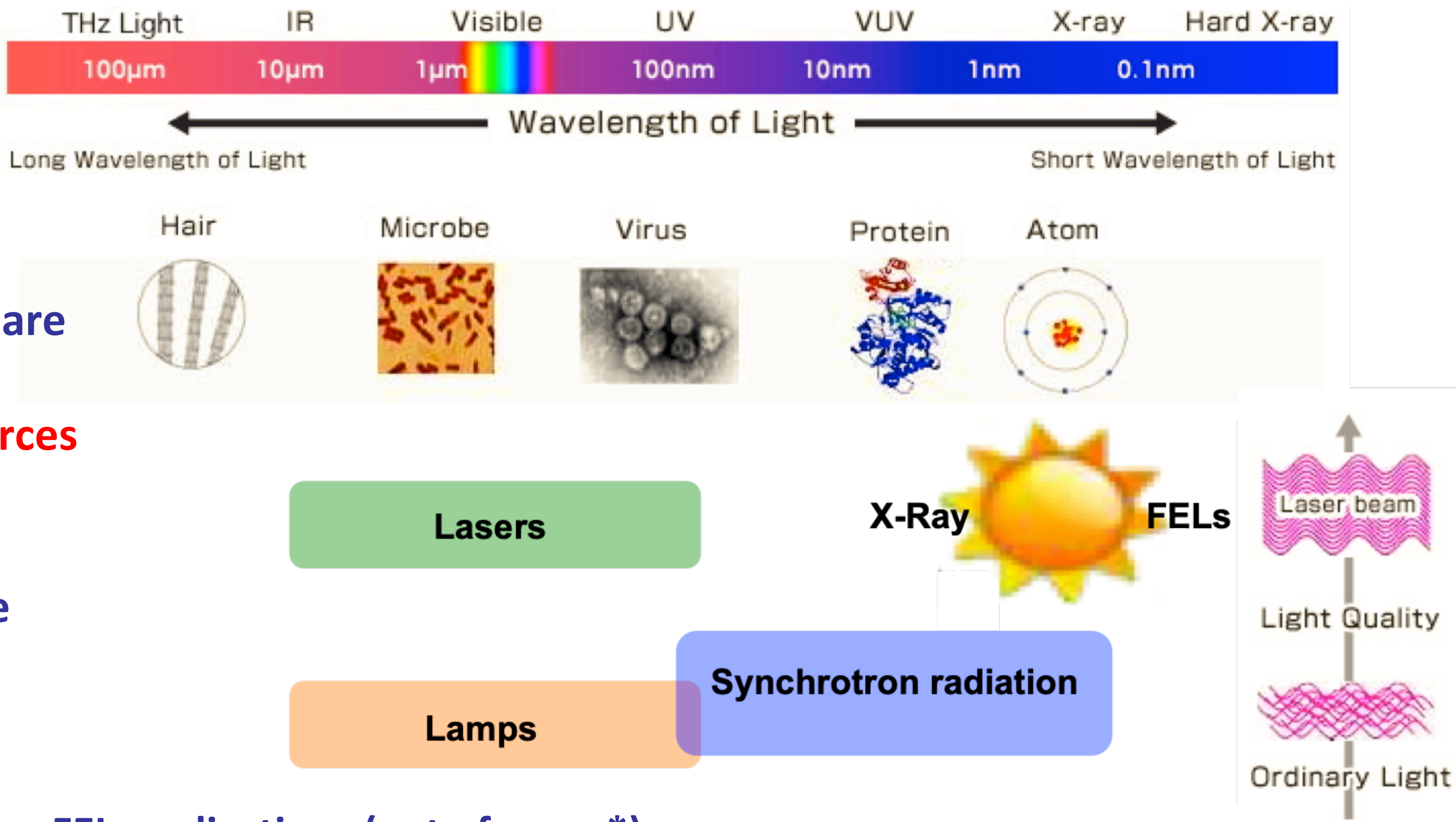
For an electron Gaussian bunch with rms length σ_0

$$N_e^2|B|^2 = N_e + N_e(N_e-1)e^{-\omega^2\sigma_0^2/c^2}$$

Bunching happens if

$$\sigma_0 \ll c/\omega = \lambda/(2\pi)$$

FEL: an accelerator to investigate matter



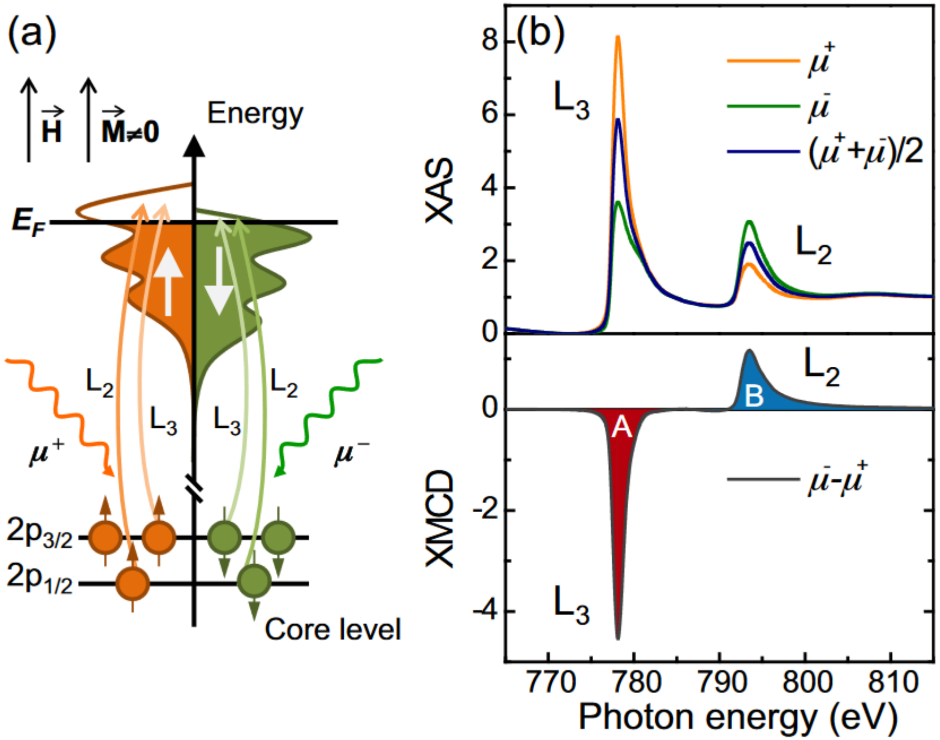
Particle Accelerators are used as coherent photon sources with applications in Physics, Chemistry, Biology and Medicine

Two target X-ray FEL applications (out of many*):

1. **Chemical properties through magnetic polarization**
2. **Coherent diffraction imaging of biological samples**

*A. Mak, P. Salén, V. Goryashko and J.A. Clarke, *FEL Science Requirements and Facility Design*, https://www.compactlight.eu/uploads/Main/D2.1_XLS_Specification.pdf

X-ray magnetic properties of materials



G. van der Laan & A.I. Figueroa / Coordination Chemistry Reviews **277** (2014) 95

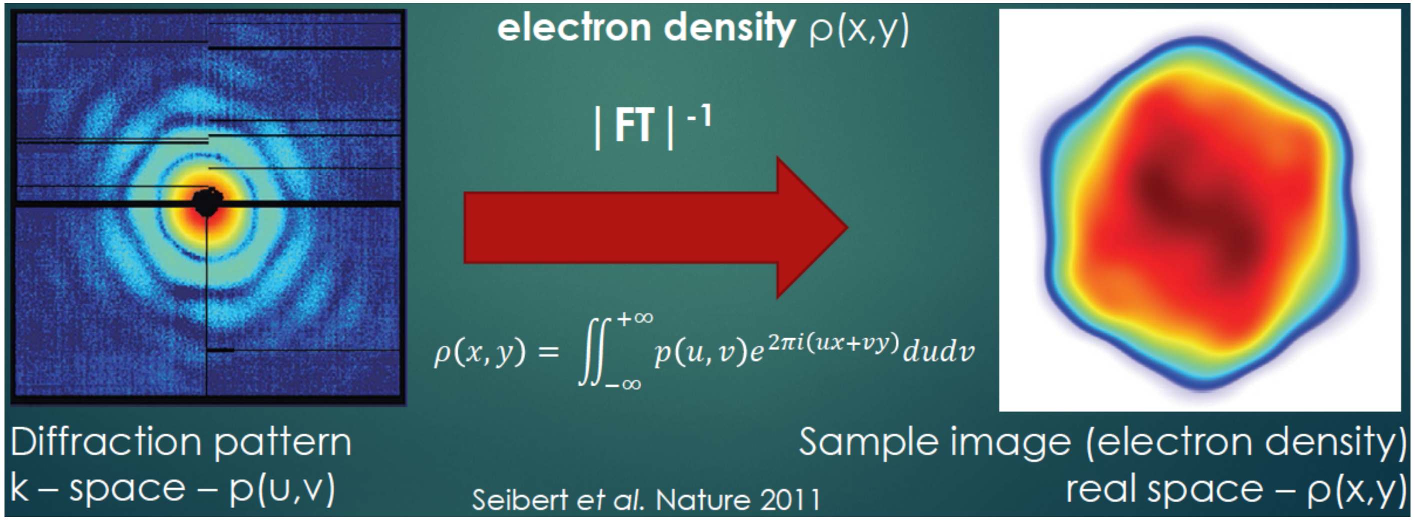
X-ray magnetic circular dichroism (XMCD) is the difference of X-ray absorption spectra (XAS) taken in a magnetic field:

left circularly polarized light –
right circularly polarized light

- **XMCD allows for element and site specific studies**
- **Great interest in ultrafast (< 1 ps) magnetic dynamics with switchable FEL polarization**

Edge		3*d* TM	4*d* TM	5*d* TM
K	$1s \to p$	5–11 keV	17–27 keV	65–81 keV
$L_{2,3}$	$2p \to d$	450–950 eV	2–4 keV	9–14 keV
$M_{2,3}$	$3p \to d$	30–125 eV	150–650 eV	1.7–3 keV
$N_{2,3}$	$4p \to d$	–	–	380–610 eV

Coherent imaging of biological samples



Coherent photons hit the sample, creating a diffraction pattern

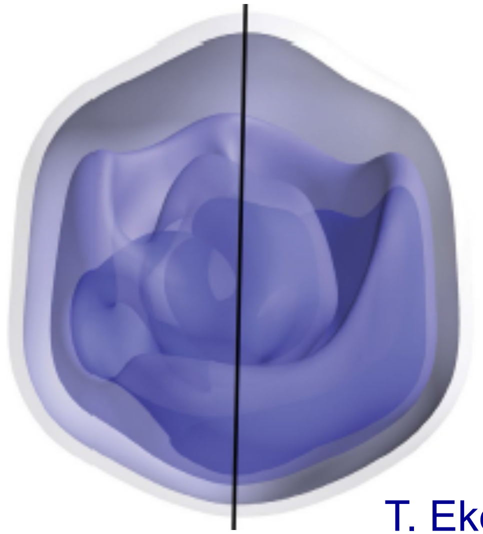
The detector image is the Fourier Transform of the sample electron density

3D images are obtained processing several diffraction patterns

The sample is destroyed by the FEL photons shot, so many identical samples are needed

Ideal technique to get 3D images of viruses in their native environment

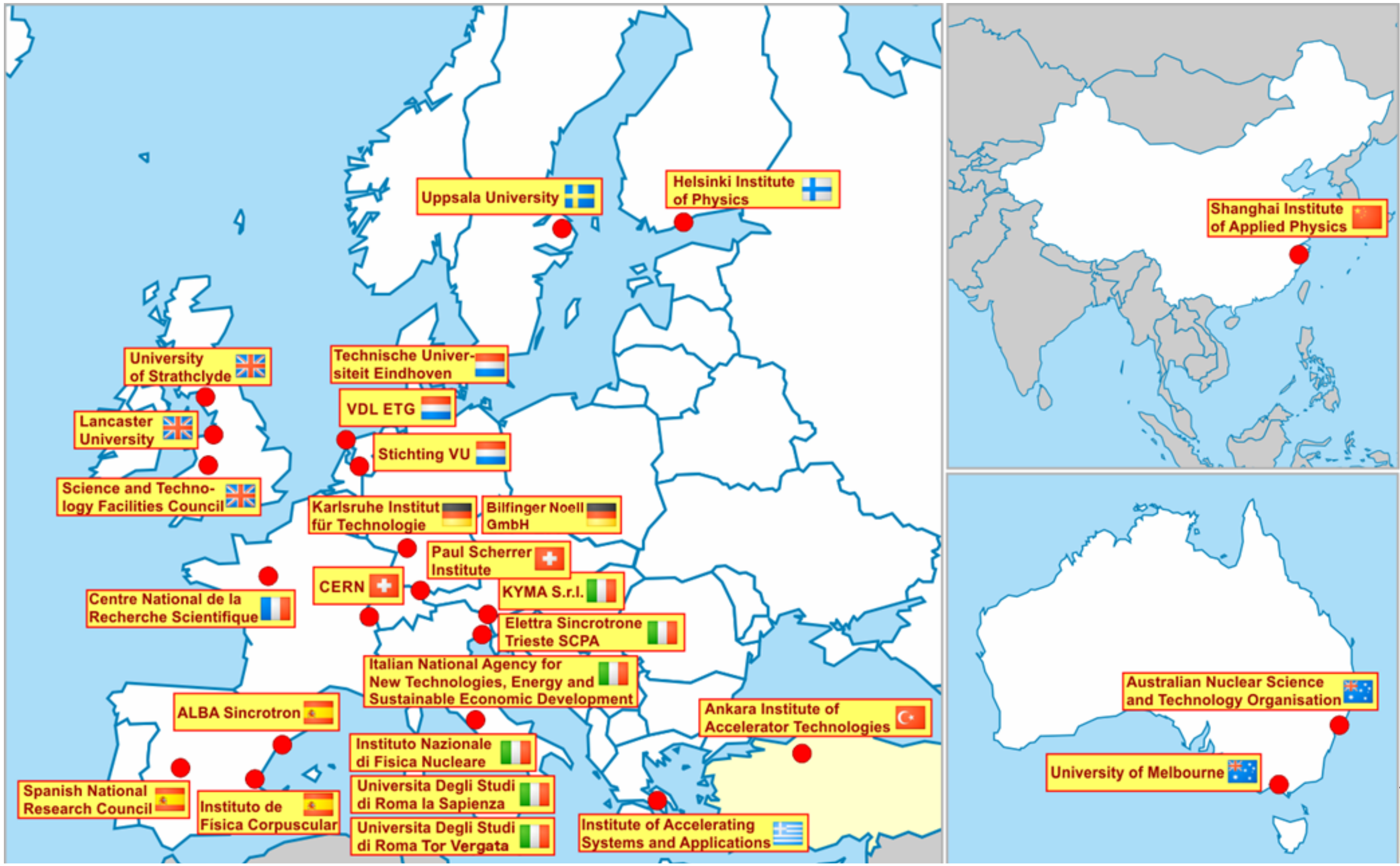
X-ray FEL virus 3D reconstruction



T. Ekeberg *et al.*
Phys. Rev. Lett. **114** (2015) 098102

The CompactLight (XLS) Collaboration

- **The XLS Collaboration gathers several International Institutions with the aim at promoting design and construction of the next generation FEL sources with innovative accelerator technologies**
- **The objective is the design of a 5.5 GeV beam energy X-band Linac, based on the CLIC technology, to drive an FEL facility with Soft and Hard X-ray options**



Italy	6
Neth.	3+1 Ass. Part.
UK	3
Spain	2
Australia	2
China	1
Greece	1+2 Ass. Part.
Sweden	1
Turkey	1
France	1
Germany	2
Switzerland	1
Finland	1
Norway	1 Ass. Part.
Slovenia	1 Ass. Part.
Internat.	1 CERN

26 Institutions
+ 5 Ass. Partners

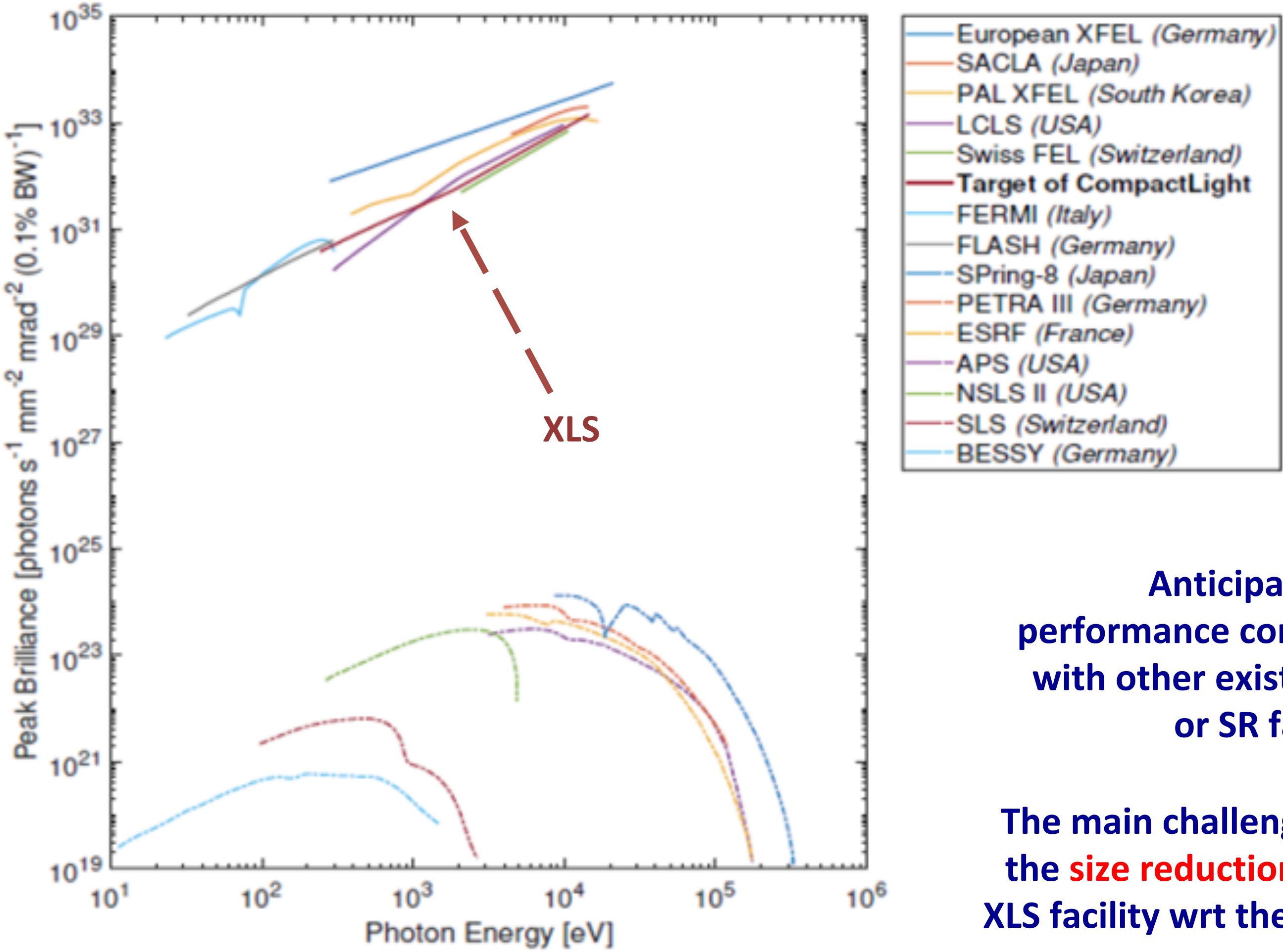
The XLS project goal

The main goal is to facilitate the widespread development of X-ray FEL facilities across Europe and beyond, by making them more affordable to construct and operate through the optimum combination of accelerator technologies

We plan to use of the most advanced concepts for:

- **High brightness electron photoinjectors**
- **Very high gradient accelerating structures**
- **Novel short period undulators**

Horizon2020 – Work Programme 2016-2017
Research & Innovation INFRADEV-1-2017 Design Studies
Duration: from 01.01.2018 through 31.12.2021, Grant amount: 3 M€



Anticipated XLS performance compared with other existing FEL or SR facilities

The main challenge is on the size reduction of the XLS facility wrt the others

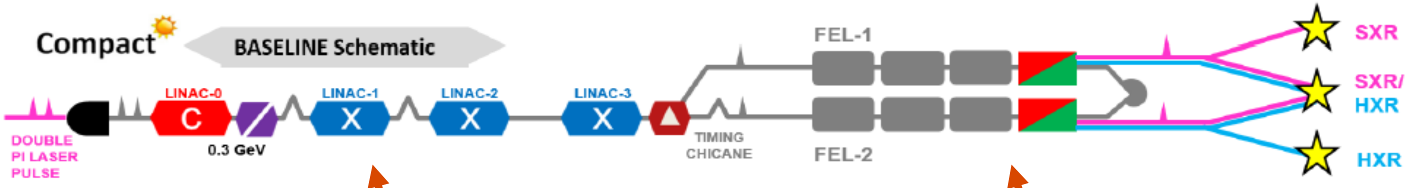
The more compact FEL → the more affordable and easy-to-implement facility → fit any University campus

The XLS project structure

WP2 – FEL Science requirements and Facility Design

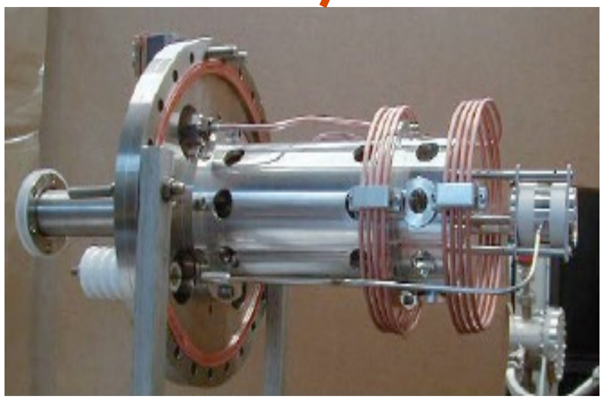
WP6 – Beam Dynamics and Start to End Simulations

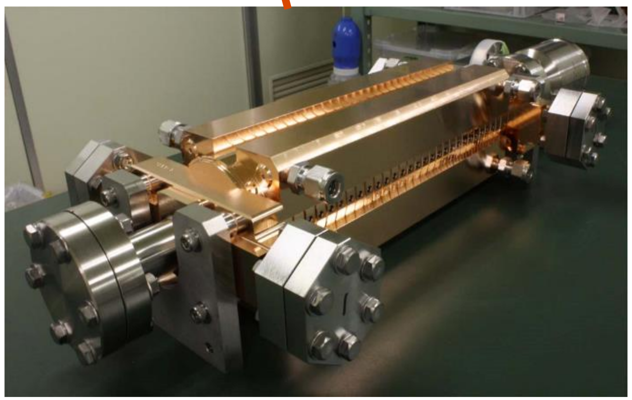
WP3 – Gun and Injector

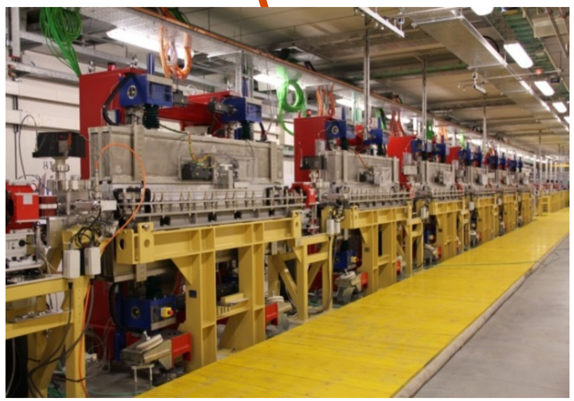


WP4 – RF Systems

WP5 – Undulators and Light Production







XLS parameter tables

Parameter	Unit	Soft x-ray FEL	Hard x-ray FEL
Photon energy	keV	0.25 - 2.0	2.0 - 16.0
Wavelength	nm	5.0 - 0.6	0.6 - 0.08
Repetition rate	Hz	100 to 1000	100
Pulse duration	fs	0.1 - 50	
Pulse energy	mJ	< 0.3	
Polarization		Variable - Selectable	
Two-pulse delay	fs	± 100	
Two-color separation	%	20	10
Synchronization	fs	< 10	

FEL parameter wishlist (from users' requirements and science cases):

- **Repetition rate up to 1 kHz**
- **Two colors operation**
- **Simultaneous SXR - HXR operation**

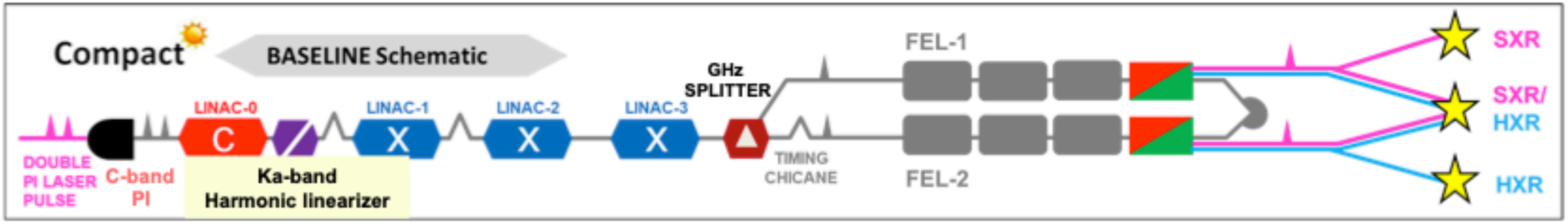
In addition: a peak brilliance of about 10^{31} SXR - 10^{33} HXR photons/s/mm^2/mrad^2/0.1%BW

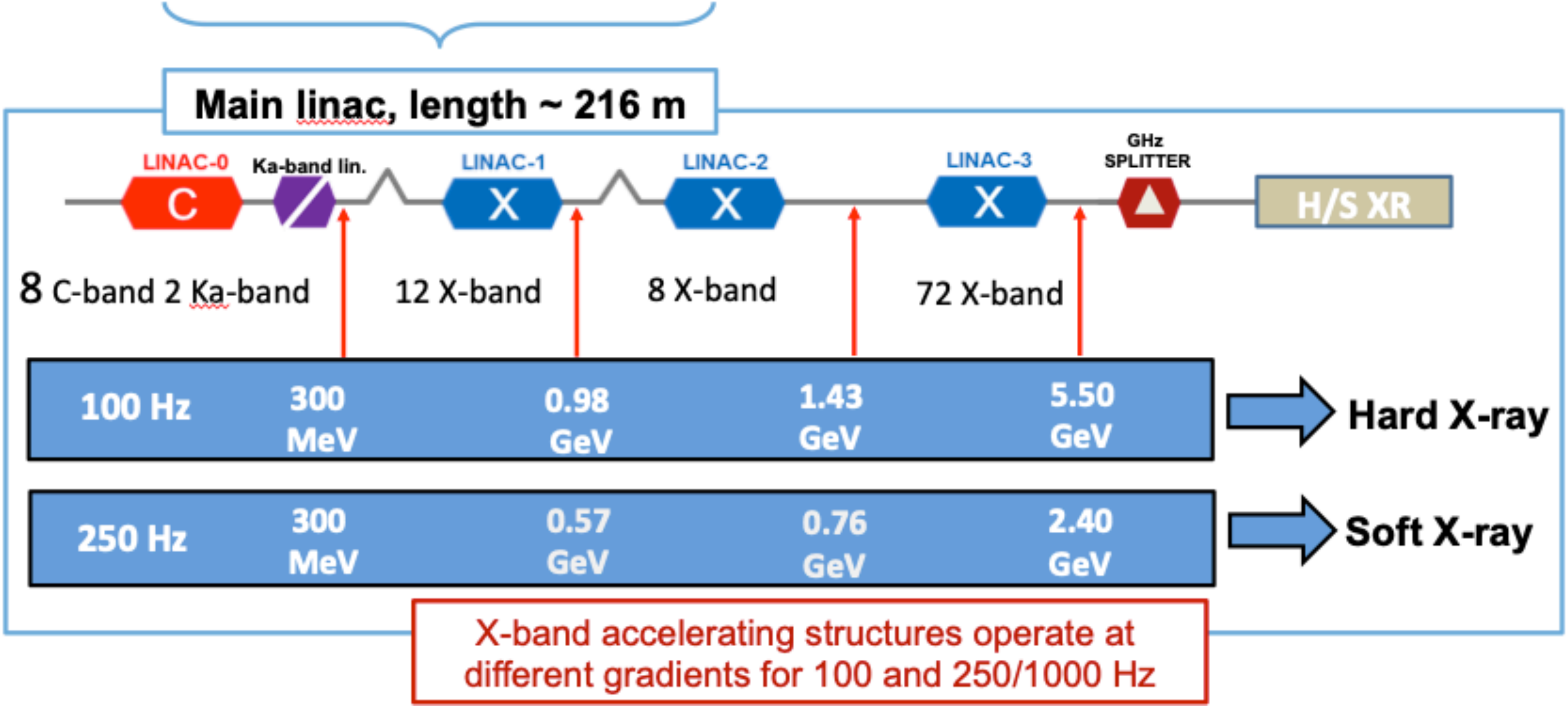
3 discrete beam working points:

Beam Parameters

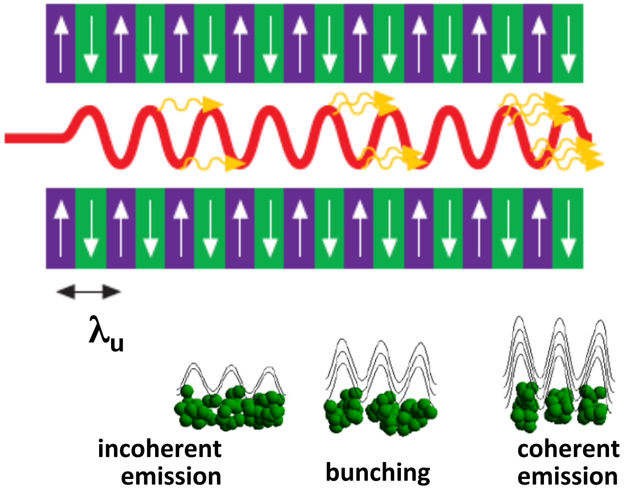
Parameter	Unit	Hard X-rays			Soft X-rays		
Beam Energy	GeV	5.5	3.9	2.75	1.95	1.37	0.97
Photon Energy Range	keV	16 - 8	8 - 4	4 - 2	2 - 1	1 - 0.5	0.5 - 0.25
Minimum Peak Current	kA	5.0	2.5	1.5	0.925	0.65	0.35
RMS Slice Energy Spread	%	0.01	0.014	0.02	0.028	0.04	0.056
Normalised Emittance	mm-mrad	0.2					
Bunch Charge	pC	75					

Linac baseline layout





FEL main character: magnetic undulator



$$K = \frac{eB\lambda_u}{2\pi m_e c} \simeq 0.94\ B[T]\ \lambda_u[cm]$$ → **resonant wavelength**

$$\lambda_R = \frac{\lambda_u}{2\gamma^2}\left(1 + a_u^2\right)$$

$$a_u = K/\sqrt{2}\,(a_u = K)$$

for planar (helical) undulators

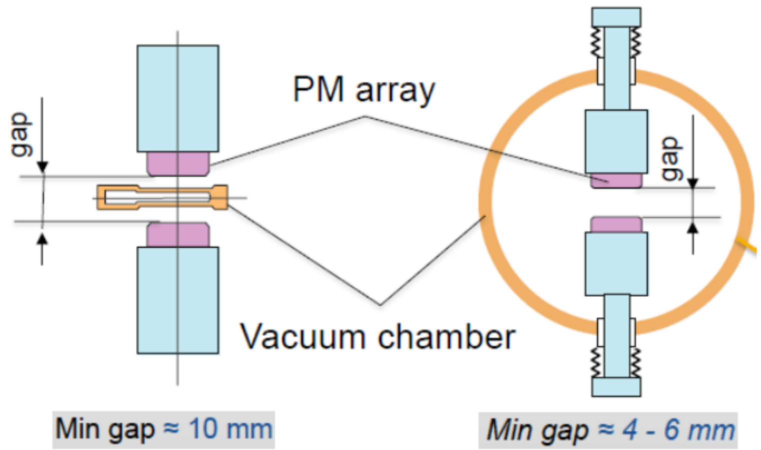
Magnetic field also a function of λ_u, and gap

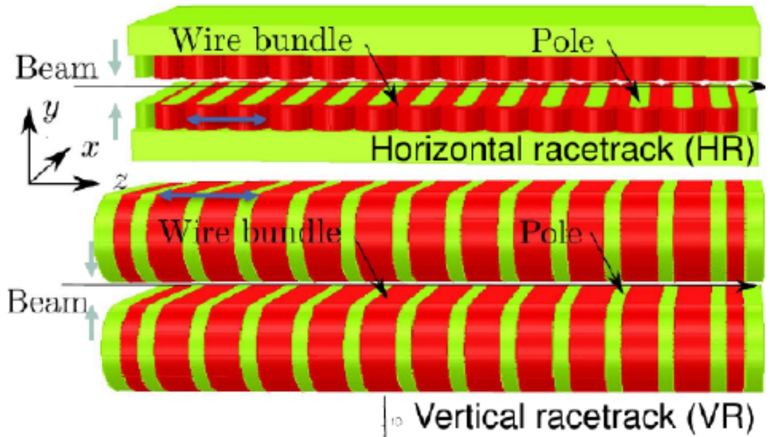
$$B \propto \exp\left[-a\left(\frac{g}{\lambda_u}\right) + b\left(\frac{g}{\lambda_u}\right)^2\right]$$

oscillations are confined in a plane (→ linearly polarized light) or follow a helix (→ circularly polarized light)

Several undulator configurations have been scrutinized and compared on the basis of technology readiness and FEL performance

Courtesy of J. Chavanne





PMU out-of-vacuum structures:

PMU room temperature and cryogenic in-vacuum devices.

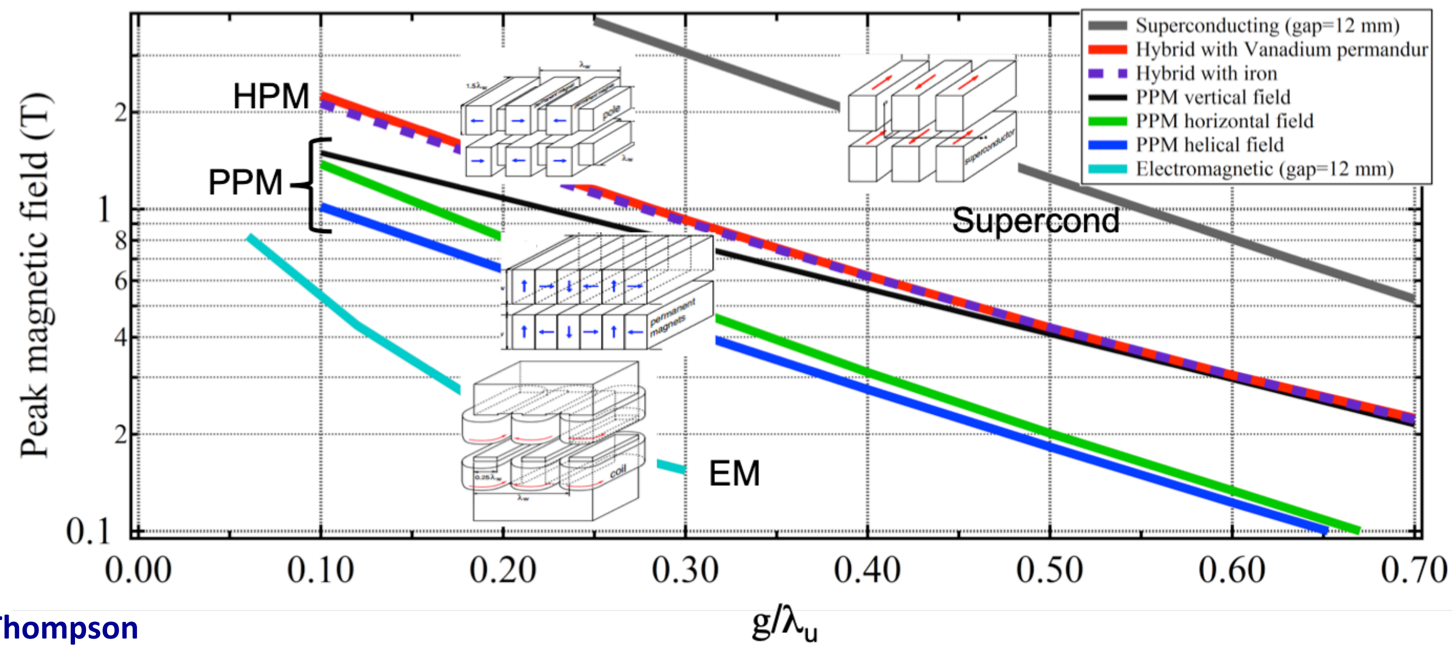
SCU low temperature NbTi and Nb_3Sn structures.

SCU high temperature wound tapes and bulk structures.

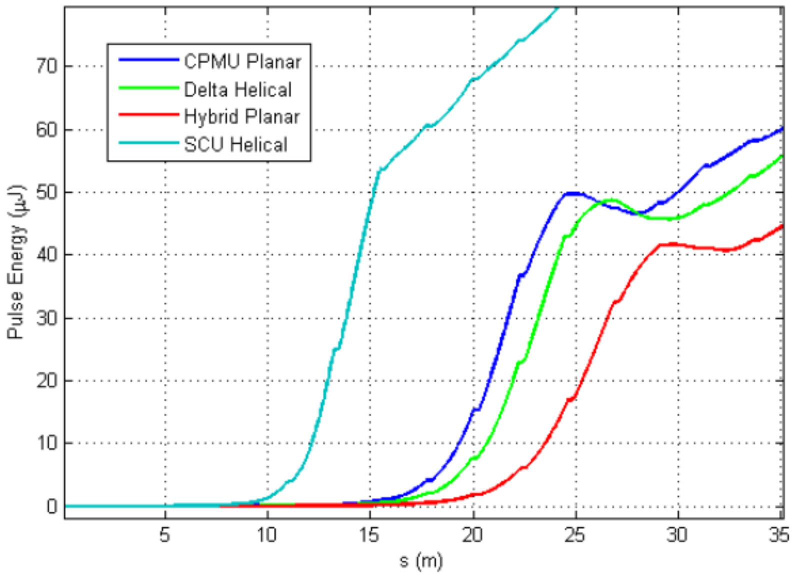
Funded by the
European Union

Undulator technology selection criteria

Compact



Courtesy of N. Thompson

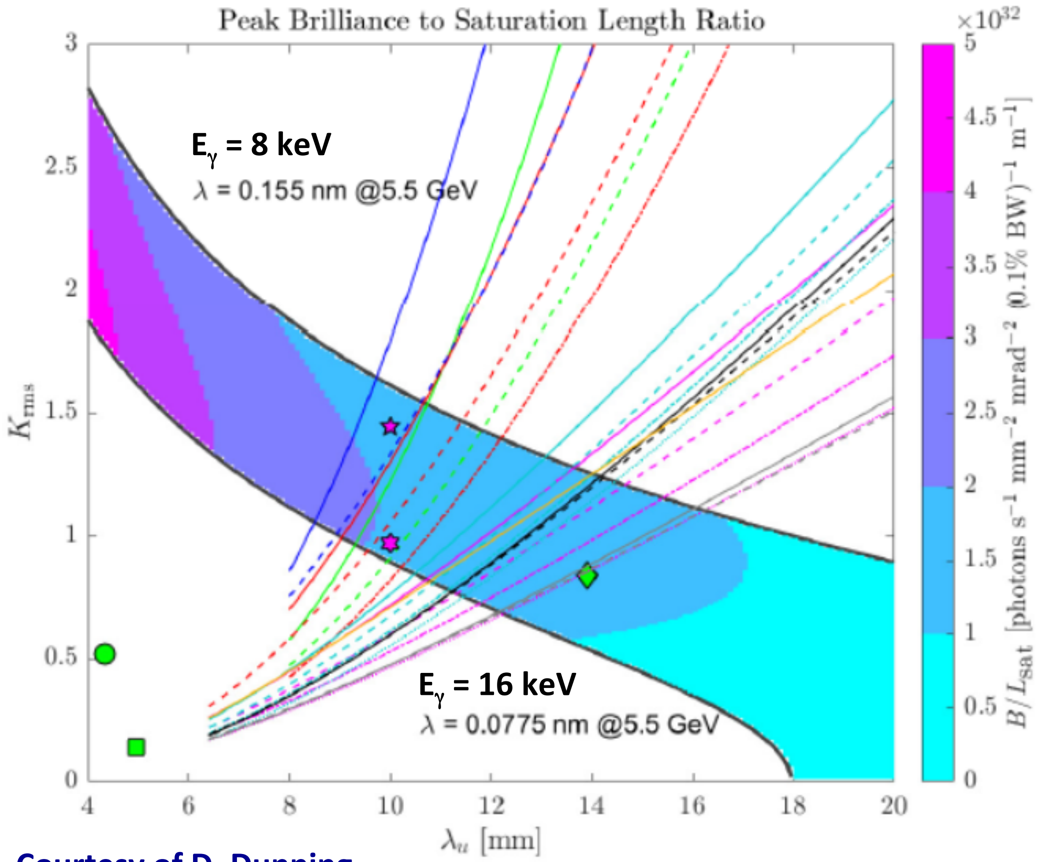


- **In general, SCUs provide larger magnetic field at the same gap, period → the same short wavelength (or high photon energy) will be covered with higher K strength and magnet field values**
- **This translates into a higher FEL interaction → higher photon pulse energy & shorter length by which the optimum (saturation) FEL power is reached at the end of the exponential growth: saturation length L_{sat}**
- **This expectation is confirmed by the FEL full 3D simulation with the XLS electron beam parameters**

Funded by the European Union

XLS requests & considerations on undulators

Compact



Courtesy of D. Dunning

- ✓ **Both Hard and Soft X-ray FEL lines should have the same undulator devices**
- ✓ **In both cases, a factor 2 wavelength tuning (varying the magnet gap or the SC coil current) is requested**
- ✓ **The maximum peak brilliance and the shortest saturation length (would like a *bright & compact source*) are desired: maximum B/L_{sat} ratio**
- ✓ **Each line curve is an undulator configuration or technology that is weighted by its B/L_{sat} ratio: the most performant ones are high temperature superconducting devices, but they are not considered mature enough to be deployed in a FEL user facility**
- ✓ **The choice is a NbTi helical superconducting undulator**

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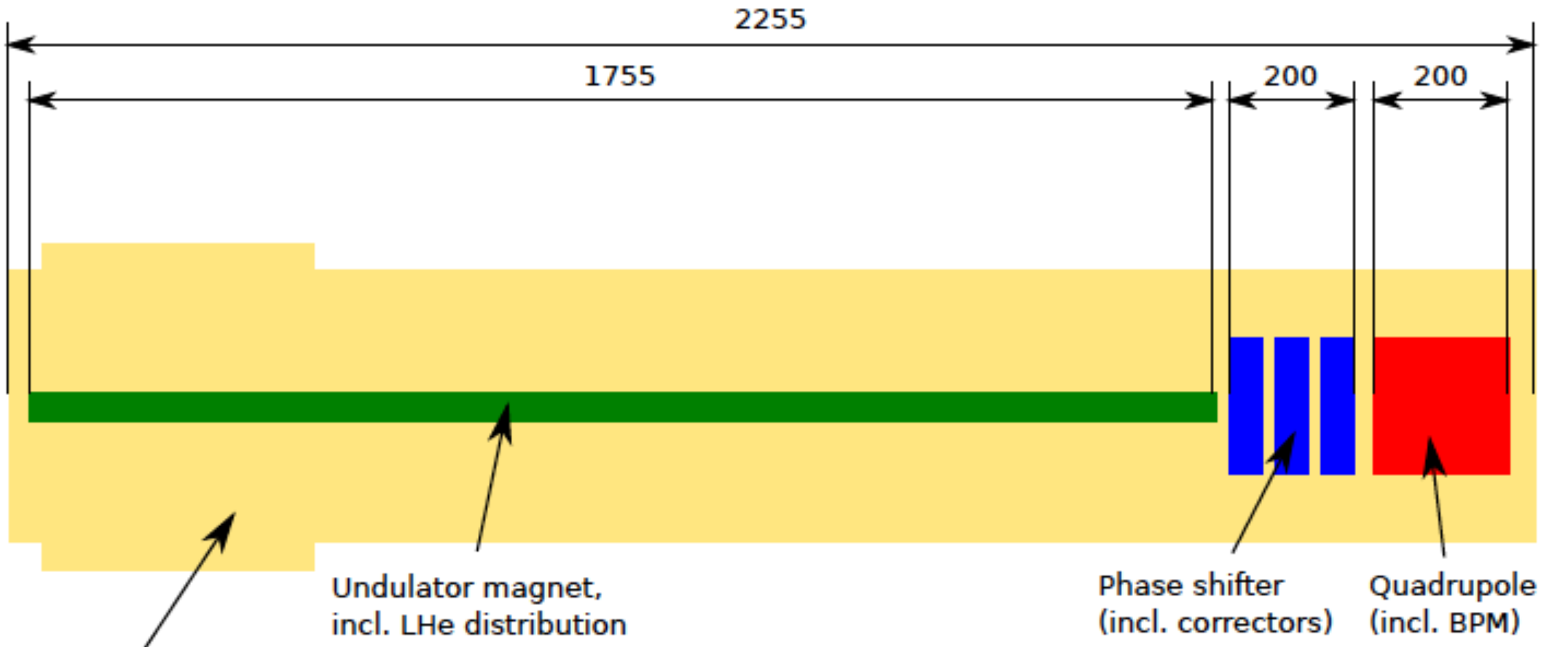
Helical SCU design

Compact



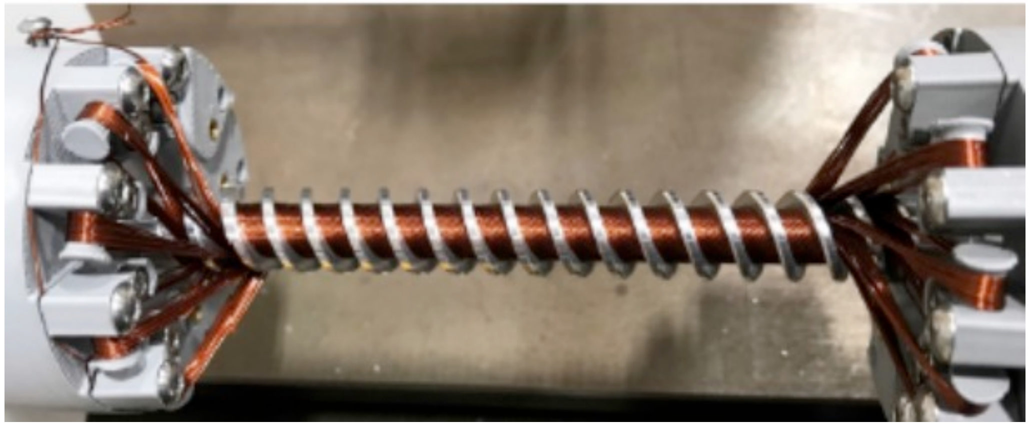
Courtesy of
A. Bernhard

Vessel e.g. DN 400,
consisting of 6-way cross,
tube, bellow

▶ requirement for 1 XLS-FEL line:

Cooling power @ 4.2 K ~40 W

Period length	13	mm
Length (including matching periods)	1.755	mm
Magnetic gap	4.2	mm
Bmax on axis	1.09	T



Winding trials ongoing at RAL on a 30 cm model, 13 mm period

Full former wound with copper wire, starting ← with SC wire

Courtesy of B. Shepherd

Considerations on variable polarization

Important to have variable and selectable polarization, to operate XMCD experiments as an example

I. Variable polarization undulator for the full undulator line
   - Straight-forward
   - Not achievable for some technologies (e.g. CPMU and SCU).

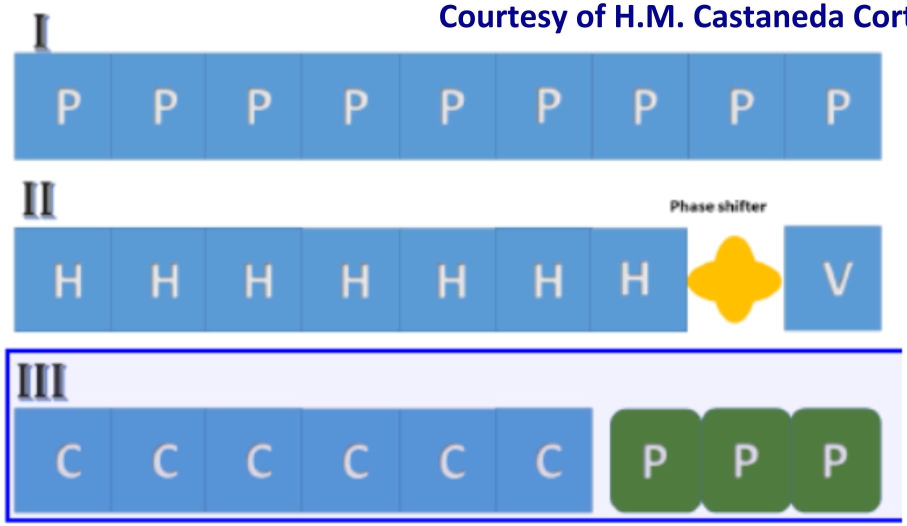
II. Crossed undulator technique
   - Any undulator can be used.
   - Relatively low degree of polarisation.

III. Undulator plus after-burner(AB)
   - Any undulator can be used.
   - The afterburner then sets the shortest wavelength achievable.

The choice is: scheme III

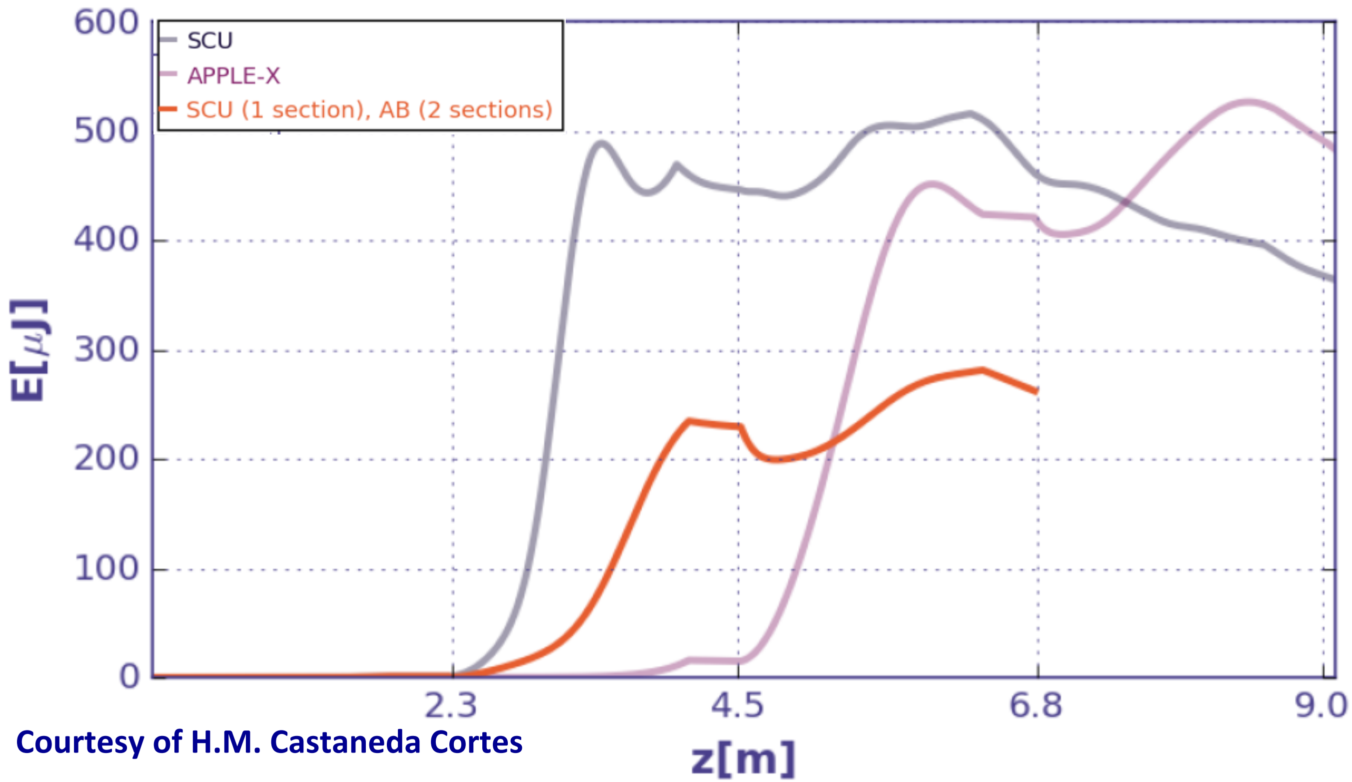
- ✓ Less expensive than scheme I
- ✓ More efficient than scheme II

Courtesy of H.M. Castaneda Cortes



- ❑ Helical SCU with fixed circular polarization
- ❑ Permanent magnet afterburner with variable polarization

Variable polarization FEL performance



Courtesy of H.M. Castaneda Cortes

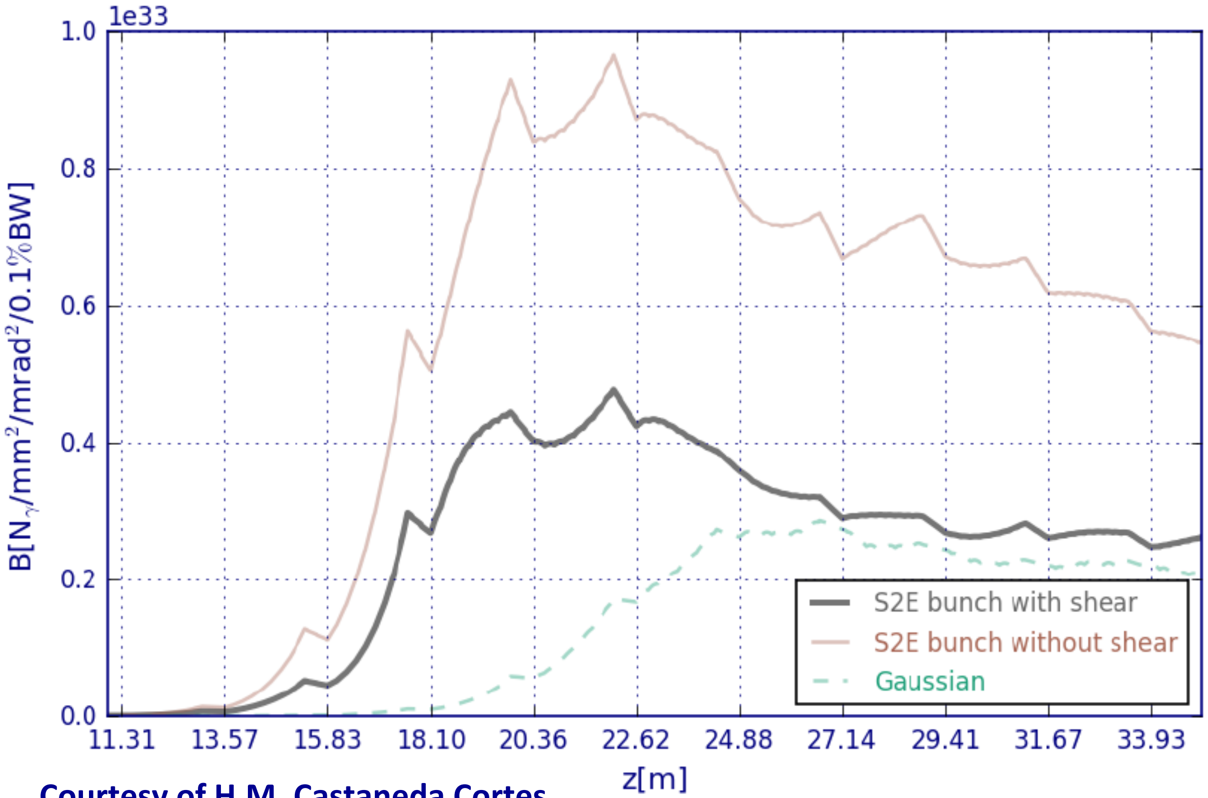
Comparison of FEL pulse energy growth among SCU only, AB only & XLS (SCU+AB) configurations, targeting E_γ = 250 eV

- ✓ **XLS (SCU+AB) has a growth shorter (~ 40%) than AB only and slightly longer (~ 13%) than SCU only, that has <u>no variable polarization</u>**
- ✓ **At the price of delivering about 2.5 times lower pulse energy, but still in the ballpark of ~ 200 μJ, and having polarization switch control as a unique bonus**

Start-2-end HXR performance

- ✓ **Wish to prove that the upper FEL photon energy limit 16 keV is feasible with the full chain of the beam transport from the cathode through the last undulator exit**

- ✓ **Most of the beam quality deteriorating sources due to collective effects – *i.e.* coherent synchrotron radiation (CSR), bunch space charge and wakefields – are accounted for in the full transfer line**



Courtesy of H.M. Castaneda Cortes

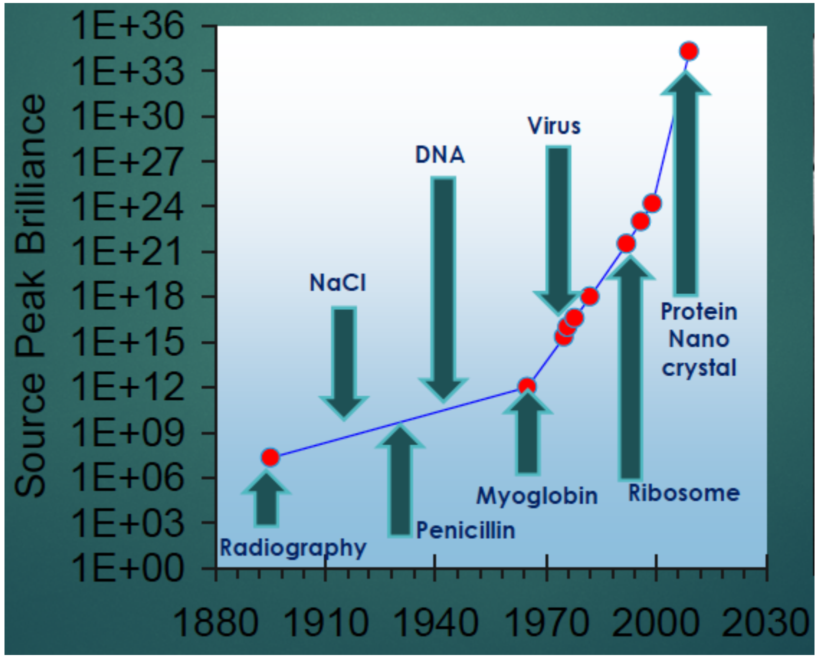
At undulator entrance, the beam exhibits a transverse deformation along bunch length due to CSR → causing FEL gain degradation along the undulator line

Still the peak brilliance stays in the ballpark of about 5 x 10^{32} photons/s/mm^2/mrad^2/0.1%BW

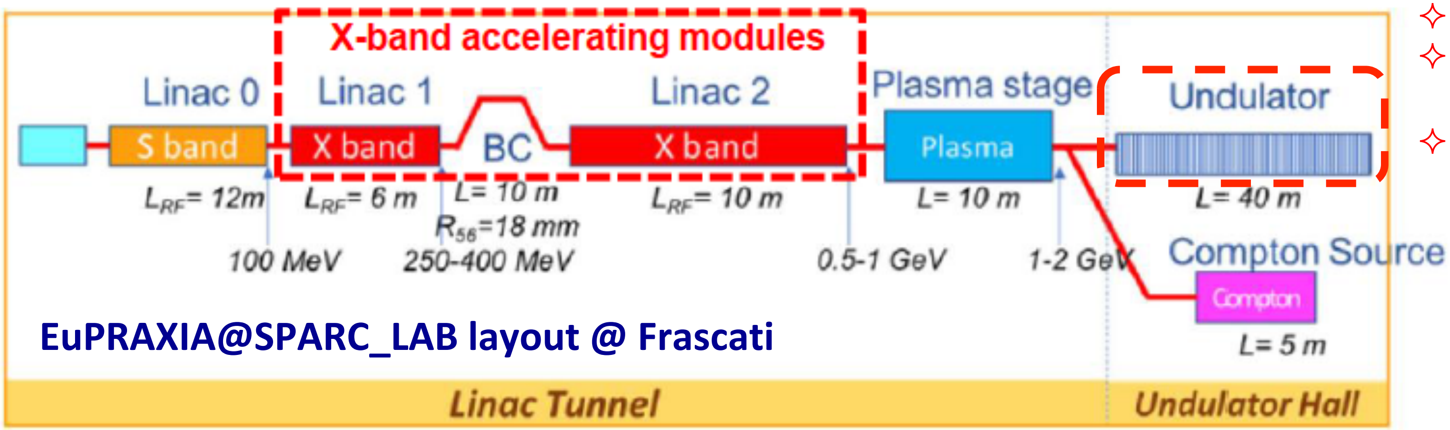
Conclusions

- ✓ **XLS will offer challenging FEL schemes with a broad range of operating modes, by means of affordable and compact X-band technology (see also CLIC studies), *e.g.* simultaneous operation of HXR and SXR at 100 Hz, and SXR up to 1 kHz**
- ✓ **A thorough and comprehensive FEL analysis selected NbTi superconducting undulators as the magnets technology (addressed alternatives: cryogenic PM, low temperature NbSn, high temperature structures)**
- ✓ **FEL 3D simulation with selectable polarization in the SXR proven to meet the requirements**
- ✓ **Full start-2-end simulation embedded with effects degrading the beam quality proved that the peak brilliance requested for probing biological samples is within reach**

Please, stay FEL-tuned!



XLS technology implementation: EuPRAXIA Compact



- NbTi SCU will be an option
- INFN-Fermilab-ENEA collaboration
- Planar prototype under construction

ESFRI announces new RIs for Roadmap 2021

30.06.2021

PRESS RELEASE

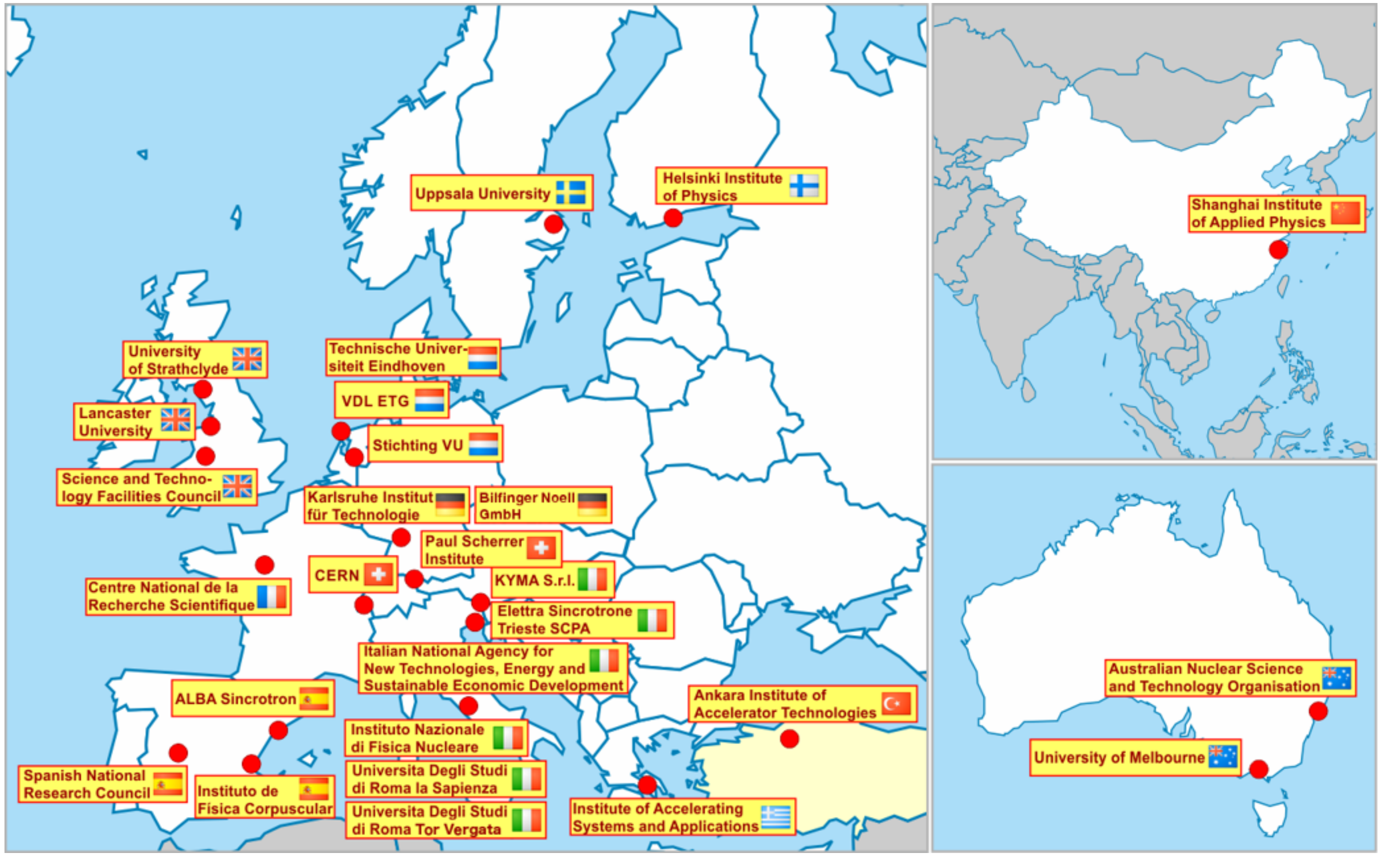
ESFRI announces the 11 new Research Infrastructures to be included in its Roadmap 2021

€4.1 billion investment in excellent science contributing to address European challenges

- **EuPRAXIA** - European Plasma Research Accelerator with Excellence in Applications, a distributed, compact and innovative accelerator facility based on plasma technology, set to construct an electron-beam-driven plasma accelerator in the metropolitan area of Rome, followed by a laser-driven plasma accelerator in European territory.

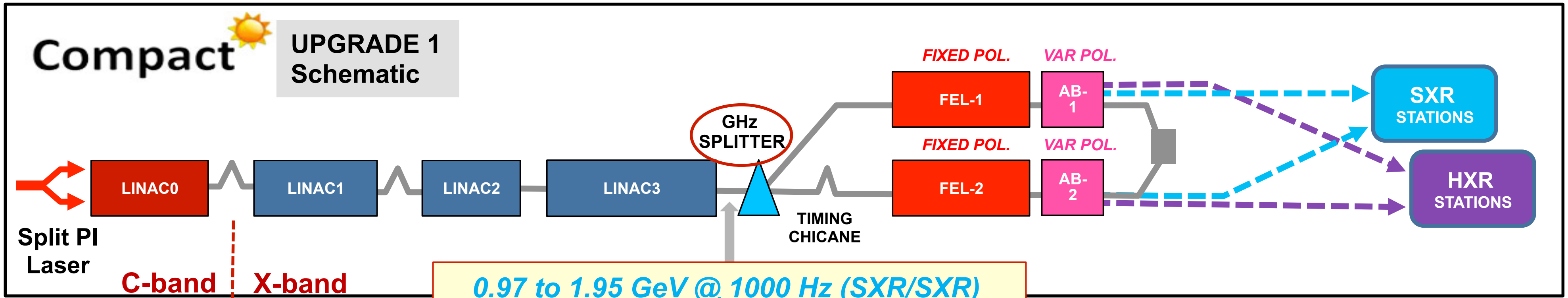
Thank you!

CompactLight@elettra.eu www.CompactLight.eu

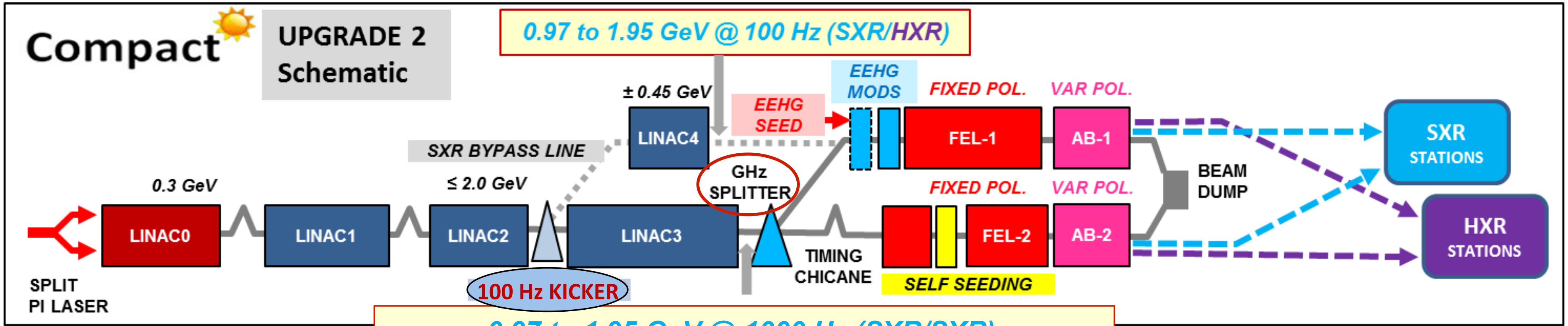


CompactLight is funded by the European Union's Horizon2020 research and innovation programme under Grant Agreement No. 777431.

XLS upgraded layout



0.97 to 1.95 GeV @ 1000 Hz (SXR/SXR)
2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)



0.97 to 1.95 GeV @ 1000 Hz (SXR/SXR)
2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)
+
2.75 to 5.5 GeV @ 100Hz (SXR/HXR at the same time)

2 klystrons x LINAC Module:

- **CPI VKX-8311 @ 50 MW**
- **CPI (Canon E37113*) @ 10 MW**

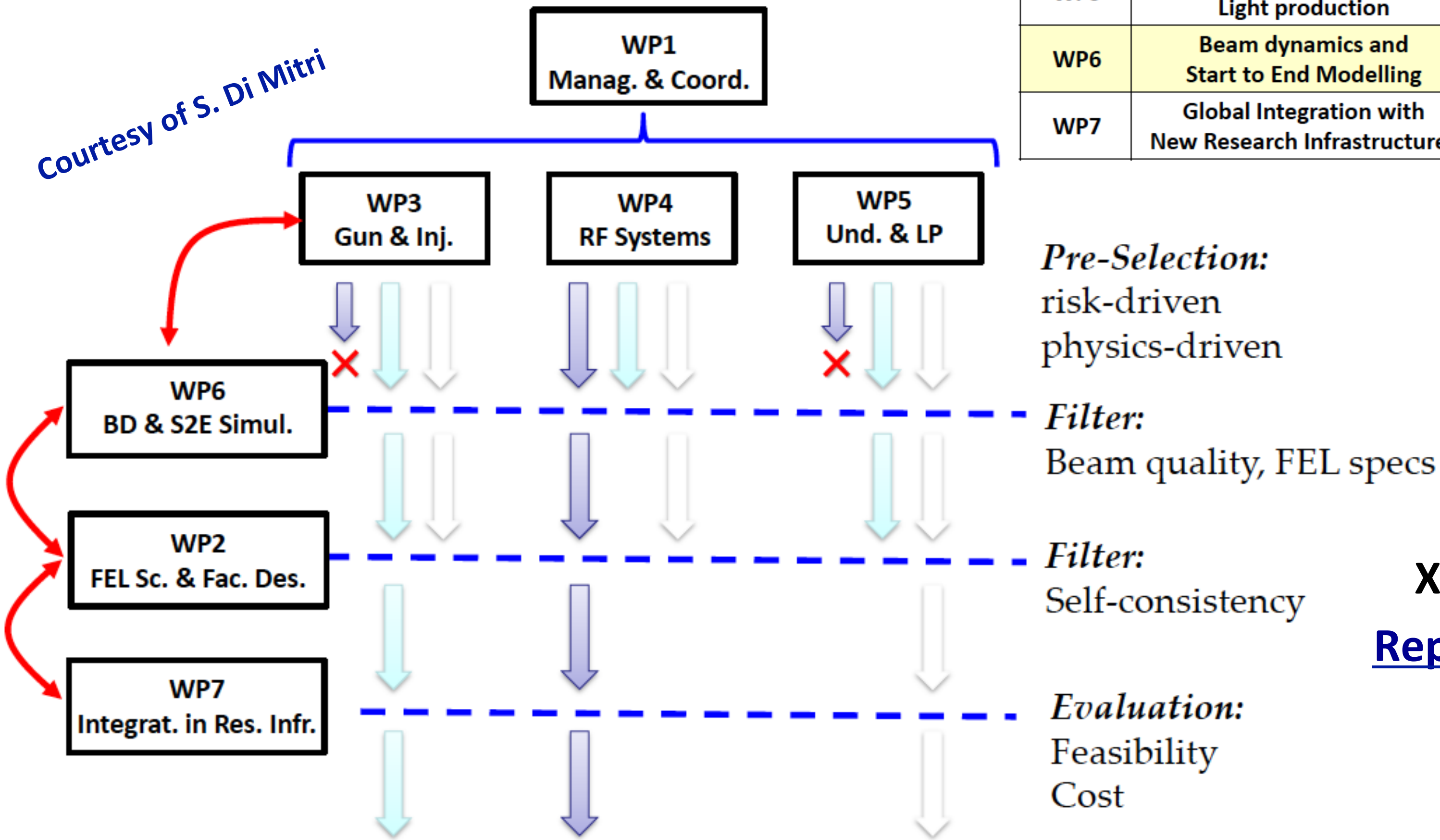
$\langle E_{acc} \rangle$ = 65 MV/m @ 100 Hz

$\langle E_{acc} \rangle$ = 30.4 MV/m @ 1 kHz

The XLS work packages

Technology options surveyed and down-selected on the basis of Physics performance & feasibility, risks and costs: in a way very similar to High Energy Physics experiments when deciding their sensors or detectors technology

Work Package		Lead Participant	Person Months
WP1	Project management and Technical Coordination	Elettra - ST	32
WP2	FEL Science Requirements and Facility Design	STFC	68
WP3	Gun and Injector	INFN	76
WP4	RF systems	CERN	78
WP5	Undulators and Light production	ENEA	81
WP6	Beam dynamics and Start to End Modelling	UA-IAT	78
WP7	Global Integration with New Research Infrastructures	Elettra - ST	27
		Total Person Months	440



XLS Conceptual Design Report to be released by December 31st 2021