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CompactLight with ICS focus, future ideas

Gerardo D'Auria

Elettra – Sincrotrone Trieste

on behalf of the CompactLight (XLS) Collaboration

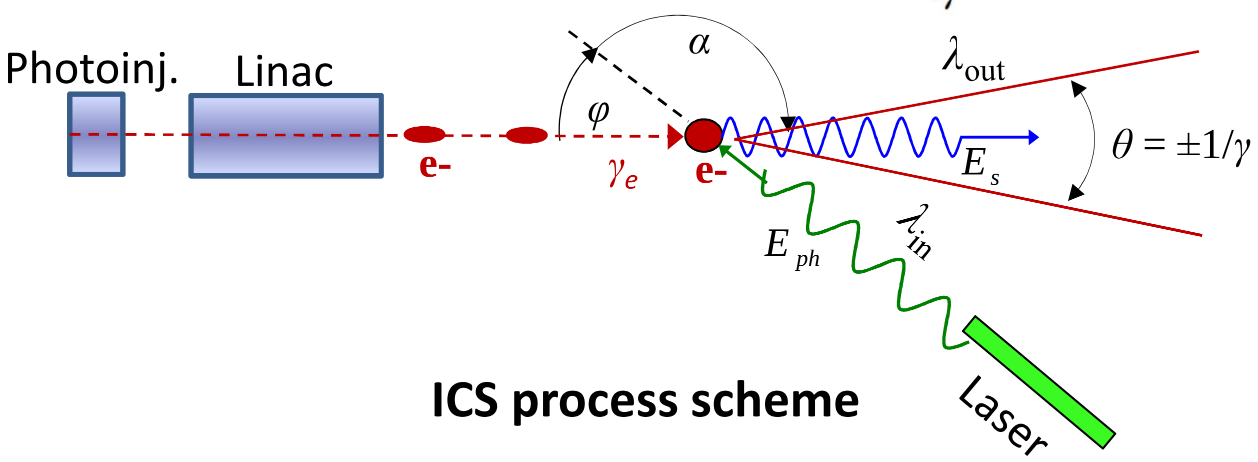
CLIC Project meeting
5 October 2021

Inverse Compton Sources (ICS)

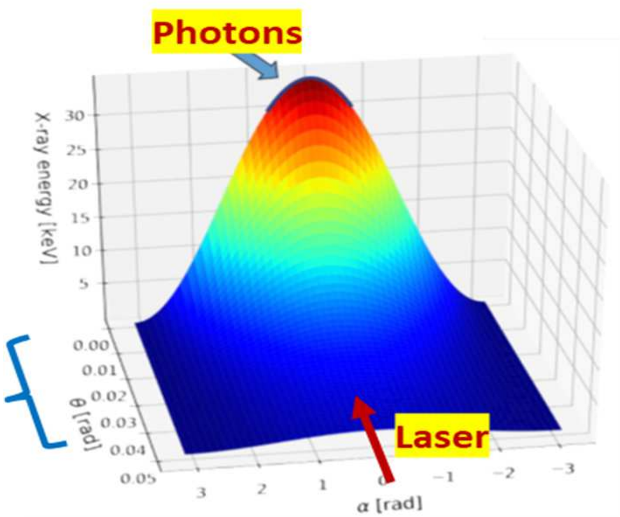
Recent advances in laser and linear particle accelerator technology have enabled development of compact X-ray light sources that use the Inverse Compton Scattering (ICS) for generating high-energy photons.

The process, based on the collision of a relativistic electron beam bunch with an intense laser pulse, can produce photons above 1 keV, up to a few MeV.

$$\lambda_x = \frac{\lambda_0}{4\gamma^2}(1+\gamma^2\theta^2)$$



ICS process scheme



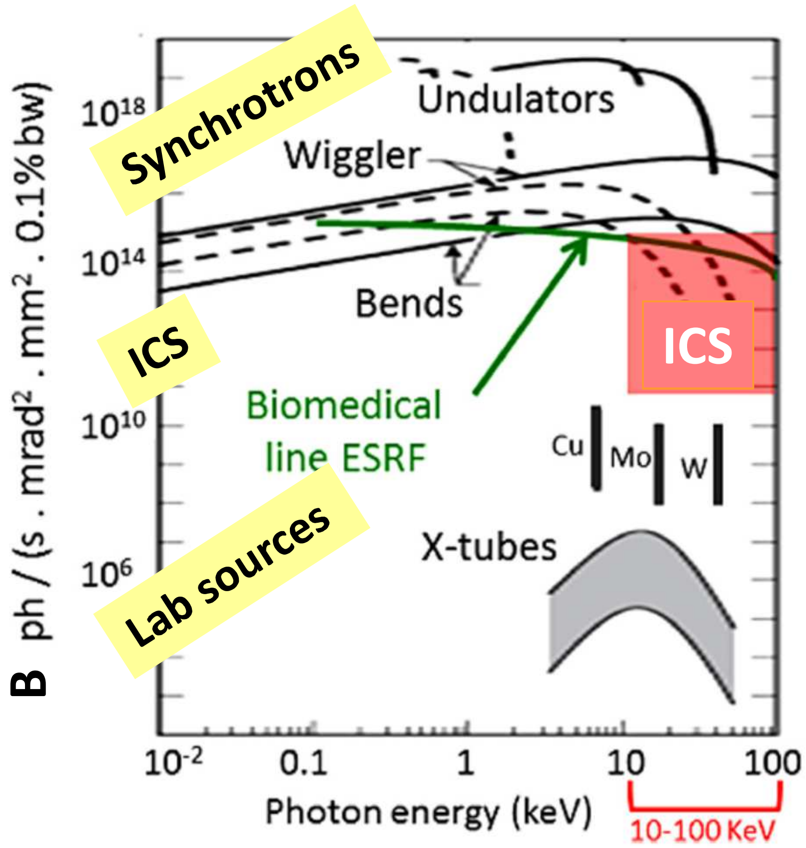
ICS main features

Although ICS cannot compete with large synchrotron light sources or high power FELs in term of brilliance, their diffusion is greatly increasing due to some aspects that make these facilities very attractive.

In particular:

- **A quasi-monocromatic source, with tunable wavelength from soft to hard X-ray as well as a pulsed structure closely coupled to the laser pulse duration, ranging from pico to femto-seconds.**
- **A dramatic reduction in size and cost of the overall system (compared to the large and expensive Synchrotron and FEL facilities), that can be easily installed in university campus, small laboratories, hospitals, etc.**
- **A wide range of applications in medicine, cultural heritage, industry, homeland security (i.e. phase contrast imaging, electronic chip manufacturing, nuclear materials assay through Nuclear Resonant Fluorescence - NRF, etc.).**

Brightness comparison



Synchrotrons & FELs	**Large and expensive, limited access**
	High power, high monochromaticity and coherence
	Flux of photons
	Low costs, lab. size (hospital, univ...)
Compact Compton Sources	**Compactness (~100 m^2)**
	Tunable wavelength
	High X-ray energy range (keV to MeV)
	Brightness (10^{11}-10^{15} ph/s/mm^2/mrad^2)
X-ray tubes	**Lack of power, monochromaticity and coherence**
	Laboratory size

K. Dupraz_ThomX

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ICS source projects - examples

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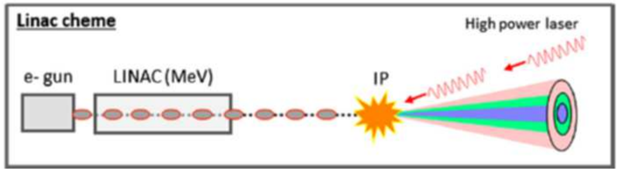
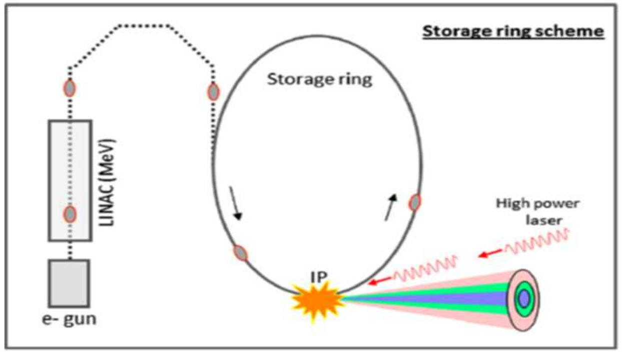
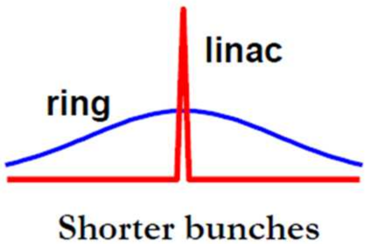
Main machine configurations



Linac



Storage Rings & Energy recovery Linacs



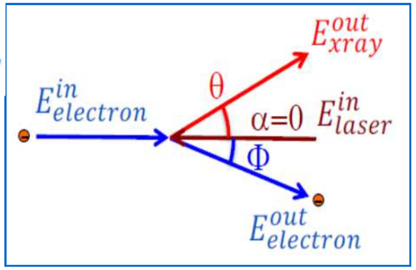
Name	Electron source	Energy (MeV)	Bunch charge (pC)	X-ray energy (keV)	Total flux (ph/s)	Brilliance (ph/s/mm^2/$mrad^2$)
CXLS	Linac_X	7	100	12,4	5,0E+11	2,0E+12
Smart*Light	Linac_X	5	10-100	60-120	5,0E+10	2,6E+10
ODU CLS	SC-Linac	25	10	1,2-12	2,0E+13	3,0E+14
TTX	Linac_S	46,7	200	30-50	1,0E+07	1,0E+10
ELI-NP-GBS	Linac_C	520	0,25	200-2.000	1,0E+08	2,3E+13
ThomX	SR	50-70	50	45-90	1,0E+13	1,0E+11
MuCLS	SR	29-45	250	15-35	3,0E+10	5,0E+11
HIγS	SR		40	1.000-2.000	5,0E+7 5,0E+8	
CBETA	ERL	150	32	33.5-427	1,3E+12	4,9E+13
cERL	ERL	20	0.355	6,95	1,0E+10	
BriXS	ERL	30-100	100-200	20-180	1.0E+11 1.0E+13	1.0E+13 1.0E+14

For medical applications Φ_{ph} (N_{ph}/sec) > 1.0 E+10 (to be able to acquire an X-ray image in a fraction of a second)

V. Muşat

Photon flux

How many X-ray photons/second, $\dot{N}_x$ can be produced?



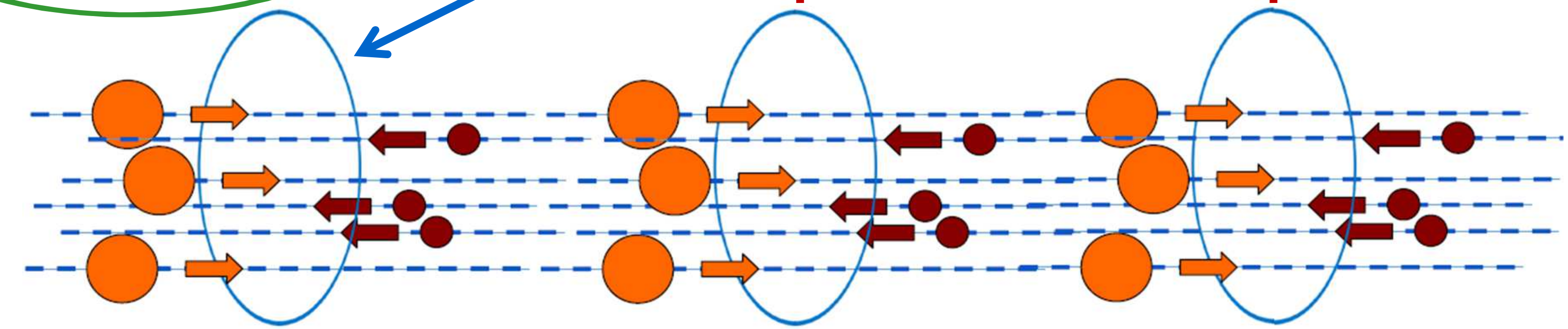
N_e = No of electrons
N_L = No of laser photons

$$\dot{N}_x = \sigma_{Th} \cdot \frac{N_e N_L}{4\pi\sigma_{eL}^2} \cdot f_{CLS}$$

Thomson cross section

$\sigma_{Th} = \frac{8\pi}{3} r_e^2$ = 6.65E-29m^2

Repetition frequency



$\sigma_e * \sigma_L$ spot size at IP

K. Achterhold_MuCLS

ICS source with XLS linac

First study of an ICS source based on CompactLight technology

(Vlad Muşat)

Parameters of ICS source with one CompactLight linac module and ODU CLS' 1 MW laser

Parameter	Quantity	Units
Beta function (at the IP), β^*	0.1	mm
Crossing angle, ϕ	2	deg
Bunch repetition frequency, f	1	kHz
Nb of bunches per train	2	
Effective repetition frequency, f	2	kHz
Electron kinetic energy, E_{el}	250-300	MeV
Energy spread, $\delta E/E$	5	‰
Bunch length, σ_z	1	ps
Bunch charge, Q_{pc}	75	pC
Normalised emittance, ϵ_x^N, ϵ_y^N	0.15, 0.15	mm mrad
Pulse energy	10	mJ
Pulse length, τ	0.67	ps
Wavelength, λ	1000	nm
Laser spot size, w_0	3.2	μm
Total flux, $\mathcal{F}$	4×10^9	ph/s
Average brilliance, $\mathcal{B}$	2×10^{12}	ph/(s mm2 mrad2 0.1% BW)

Using one CompactLight linac X-band module and ODU CLS' 1 MW laser, a **total flux in the order of 10^9 ph/s** could be reached, along with a brilliance in the order of **10^{12} ph/(s mm^2 mrad^2 0.1% BW)**.

To be improved!!!

How to overcome this limit

Parameter	Quantity	Units
Beta function (at the IP), β^*	0.1	mm
Crossing angle, ϕ	2	deg
Bunch repetition frequency, f	1	kHz
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Total flux, $\mathcal{F}$	4×10^9	ph/s
Average brilliance, $\mathcal{B}$	2×10^{12}	ph/(s mm2 mrad2 0.1% BW)

→ Nb of bunches per train: **50** (5 ns spaced)

→ Bunch charge: **100 (200!) pC**

→ Laser spot size: **10 µm**

Using one CompactLight linac X-band module and ODU CLS' 1 MW laser, a **total flux in the order of ≈ 10^{11} ph/s** could be reached, along with brilliance in the order of **≈ $4 \cdot 10^{13}$ ph/(s mm^2 mrad^2 0.1% BW)**

A gain of two order of magnitude on Flux and Brilliance

To go further

More X-ray flux:
- ↑ Bunch repetition rate
- ↑ e- beam charge
- ↑ Laser power

Less X-ray divergence:
- ↓ e^- emittance

Smaller source spot size:
- ↓ Laser beam waist size
- ↓ e^- beam spot size

Ingredients to go further

#	Sub-systems	Technology	Parameters of interest	Expected improvements
1	Hi brightness electron sources	Photoinjector (X-band) DC gun	− Multibunch operation − High repetition rate	10 - 50 bunches (5 ns spaced); Q/bunch >100 pC; t_{bunch} < 1 ps; macropulse rep. rate ≥ 1.0 KHz; ε_n < 1 mm mrad
2	RF power generators	X-band	Peak power	≥ 15 MW
			RF pulse length	≥ 1.0 μsec
			Efficiency	≥ 60 %
			Repetition rate	≥ 1.0 KHz
3	Diagnostics and beam manipulation	Synchroniz. systems Transv. deflect. struct.	X-band	Femto-sec systems
4	Focusing elements	Permanent magnet quads	Field at interation point	> 100T/m
5	Laser system	Laser system at the interation point	Multibunch/burst operation	KHz/MHz operation with high average power: − λ < 1 μm mrad, − t_b <1 ps

Medical applications

Multi-scale multi-resolution X-ray imaging for bio-medical research

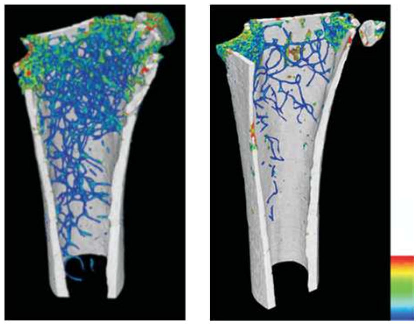
Monochromaticity
Energy tuning/optimization
K-Edge Subtraction imaging

Spatial coherence
Phase contrast imaging

High brilliance
Beam collimation

High Fluxes
Dynamic imaging

Compact source



"In vitro" - high resolution imaging – virtual histology

Applicable to study tissues, organs, sizes on the order of some millimiters, typical pixel size ~ 0.6-5 µm

Pre-clinical - Imaging of animals

Studies on organs, animal models
Typical pixel size: 9 µm (for ex-vivo) to 100 µm (in-vivo)

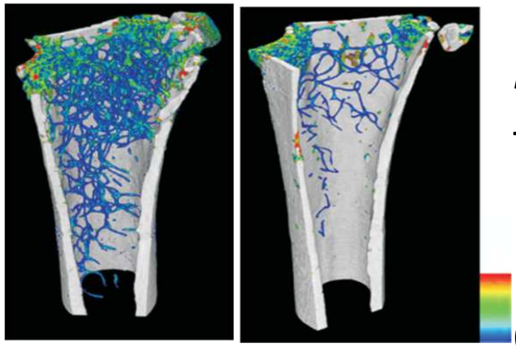
Clinical – Applications to patients

Research protocol, find best compromise between dose & image quality, pixel sizes : 50 – 100 µm

Radiation dose

G.Tromba

Biomedical applications I (pre-clinical)



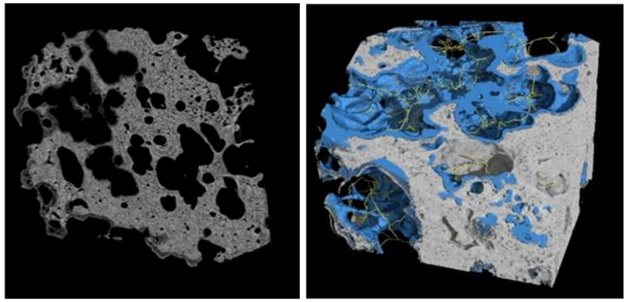
High resolution Imaging of tissues and organs *(virtual histology, in-vitro imaging)*

Typical energy range: 10-30 keV (also pink beam)
Field of view (hor x vert.): ~ 1-3 cm x 0.5 cm

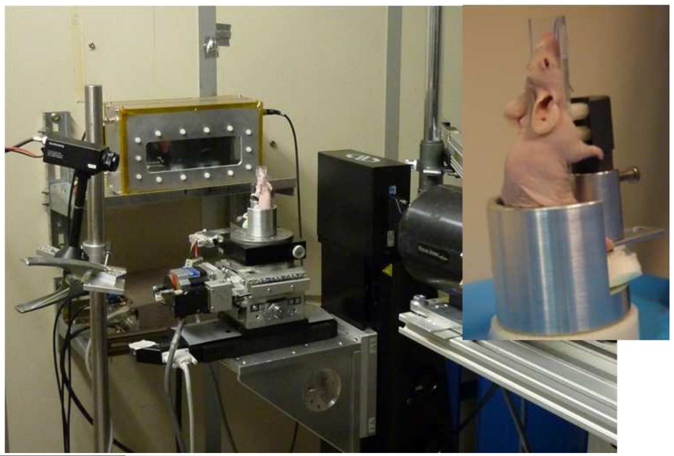
Flux requirements @ sample position: at least 10^9 ph/mm²/s
(Better with higher fluxes to shorten CT scans and allow for dynamic CT studies)

Effects of microgravity on trabecular structure of mice femurs
(Left:control, right: animal exposed to microgravity

S. Tavella et al, PlosONE, March 2012.



Visualizing new bone formation in Scaffold - slice and 3D rendering



Imaging of small animals *(studies of animal models mimiking human diseases)*

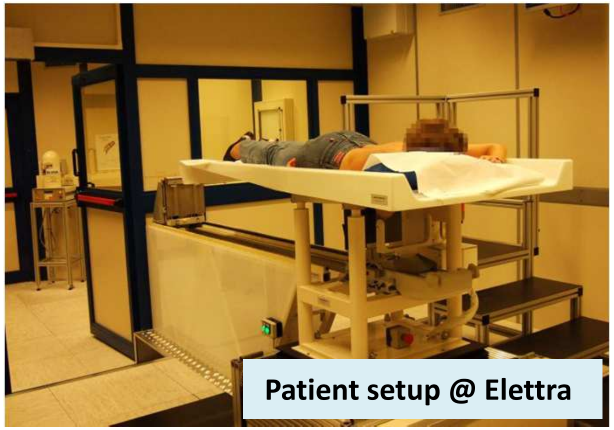
Typical energy range: 15-30 keV
Field of view (hor x vert.): ~3-15 cm x 10-20 cm

Flux requirements @ sample position: at least 10^8 ph/mm²/s

Note: at a Synchrotron: need for vertical scan of the sample

G.Tromba

Biomedical applications II (patients)



Patient setup @ Elettra

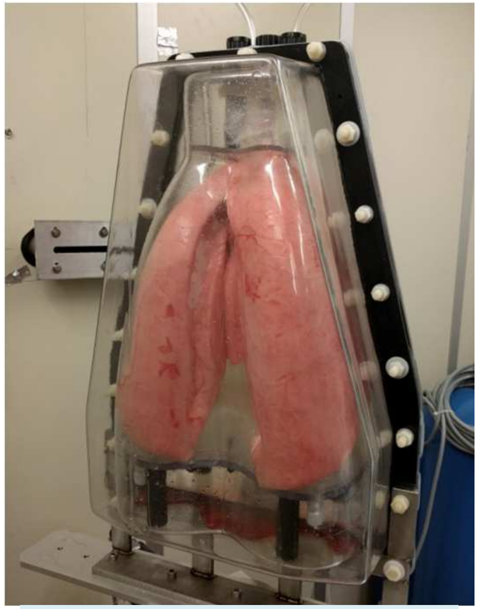
Breast CT imaging *(early detection of breast cancer)*

Typical X-ray energy range: 30-40 keV
Field of view (hor x vert.): ~ 15-20 cm x 15 cm
Flux requirements @ pat. position: at least $5x10^7$ ph/mm²/s

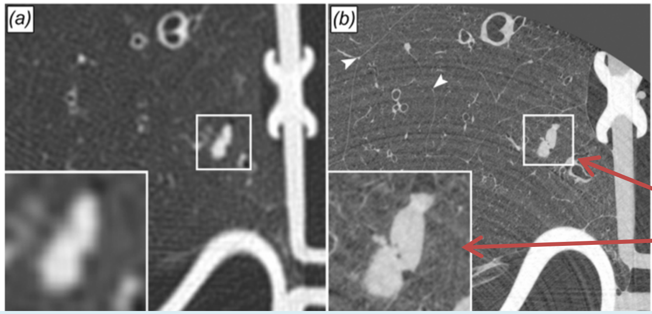
Note: at a Synchrotron: need for vertical scan of the patient

Lung CT imaging *(early detection of lung cancer, idiopatic fibrosis,...)*

Typical X-ray energy range: 60-70 keV
Field of view (hor x vert.): ~ 50 cm x 50 cm or
~ 15 cm-20 cm x 15 cm (local area, single lobe)
Flux requirements @ pat. position: at least $5x10^7$ ph/mm²/s



Phantom with porcine lungs



Note: at a Synchrotron: need for vertical scan of the patient

Artificial nodule (agarose)

CT slice of porcine lung with simulated nodule in agarose – Clinical unit scan (a), Elettra scan (b): improved visibility in the PHC image - W.Wagner et al.: J.Synchrotron Rad. 25, (2018).

G.Tromba

Cnclusions

- **Despite Inverse Compton Scattering (ICS) sources have lower photon fluxes if compared to large-scale Synchrotron facilities, they are becoming very attractive for many applications (i.e medical imaging, cultural heritage, industry, homeland security, etc)**
- **ICS are also more compact and cost effective w.r.t. huge infrastructures, like FELs and Synchrotron facilities, and suitable for Laboratory and University installations.**
- **Great efforts are currently underway at many International Laboratories to improve their performance (i.e. photon flux, brightness).**
- **In this context, the XLS design, with the challenging target to extend the operation of the RF systems up to 1 kHz, will have a major impact for the expected improvements.**

Announcement

A workshop focused on:

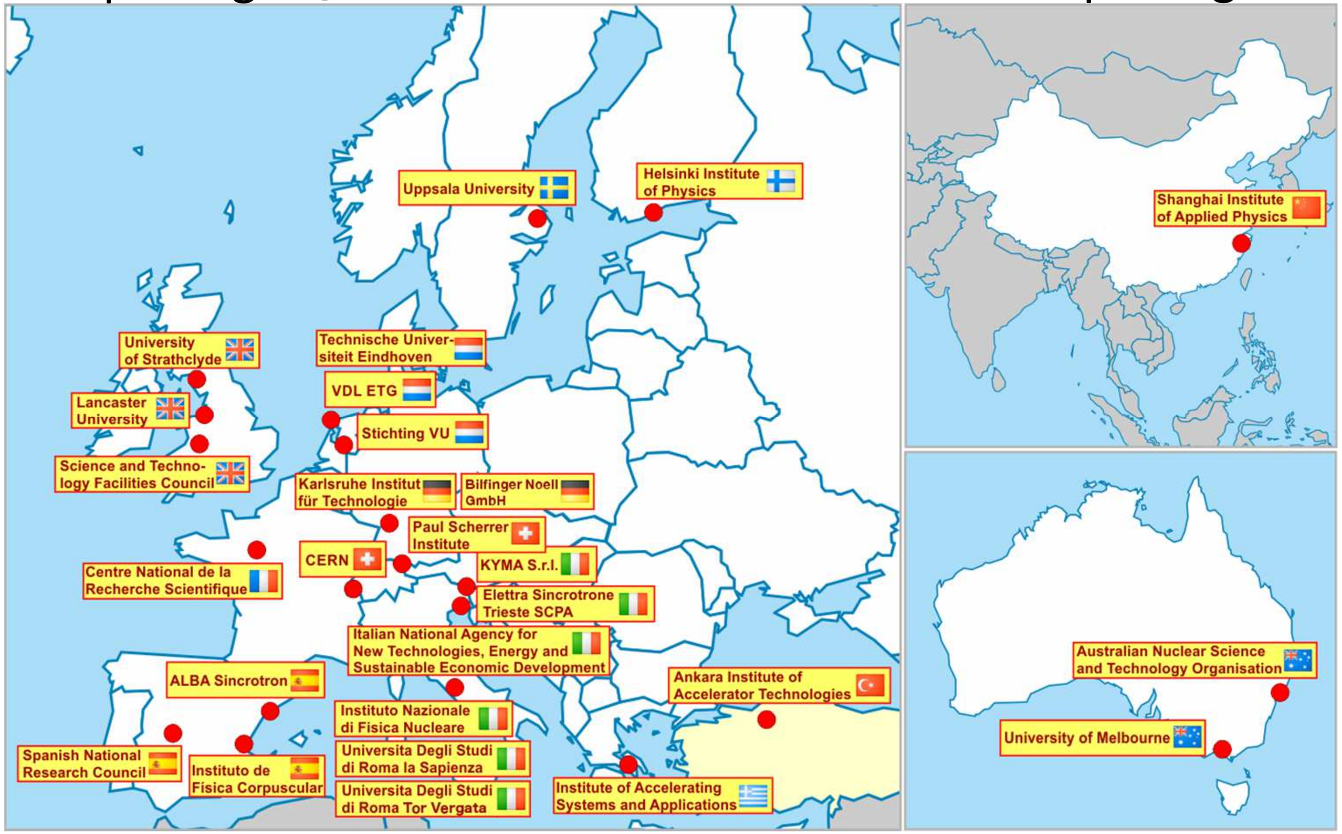
"Complementary use of the XLS technology"

will be organized, from *remote,* in the week of 8-12 Nov 2021.

You are very welcome to attend it and participate to the discussion, please spread out the info.

Thank you!

CompactLight@elettra.eu www.CompactLight.eu



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