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Compact

Multi-mode operation of CompactLight

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Elettra – Sincrotrone Trieste

on behalf of the CompactLight (XLS) Collaboration

CLIC Mini Week,
30 September to 1 October 2020

Outline

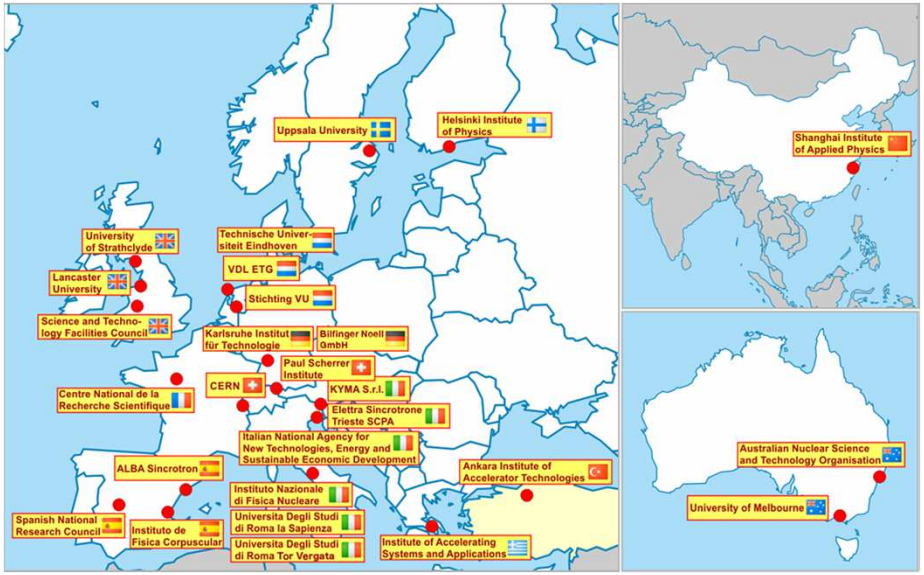
- **The CompactLight project:**
  - **The XLS Collaboration**
  - **Aims & Motivations**
- **FEL parameters**
- **FEL schemes and photon availabilities**
- **Linac operating modes**
- **XLS high repetition rate potentials:**
  - **Compact X-ray sources for multidisciplinary applications (i.e. medical imaging).**
- **Conclusions**

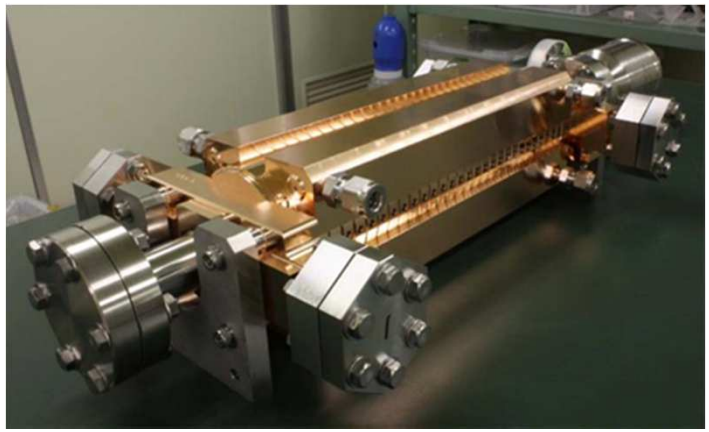
The CompactLight project

Compact

- CompactLight (***http://CompactLight.eu***) is an EU funded design study aimed at promoting the construction of the next generation FEL based photon sources with innovative accelerator technologies.
- The objective is the design of a 5.5 GeV X-band linac, based on the CLIC technology, to drive a FEL facility with soft and hard x-ray options.

The CompactLight Collaboration





CompactLigh parameters at full energy

Parameter	Value
Max energy	5.5 GeV @100 Hz
Peak current	5 kA
Normalised emittance	0.2 mm.mrad
Bunch charge	< 100 pC
RMS slice energy spread	10^{-4}
Max photon energy	16 keV
FEL tuning range at fixed energy	×2
Peak spectral brightness @16 keV	10^{33} ph/s/mm^2/mrad^2/0.1%bw

FEL Parameters

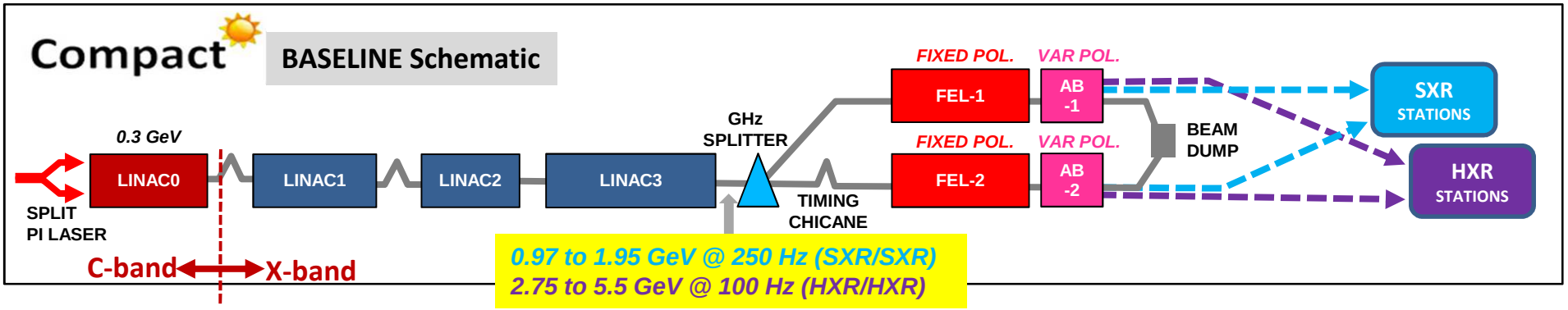
The facility design and FEL Parameters have been driven by User's requirements and associated science case

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-colour separation	%	20	10
Synchronization	fs	< 10	

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

Would be unique and very desirable features of XLS design!

Baseline FEL Layout



1st scenario 1 klystron x LINAC Module with pulse shortening

Ref. CPI VKX-8311A

50 MW, 1.5 µs, 100 Hz **$\langle E_{acc} \rangle$ = 65 MV/m**	→
50 MW, 150 ns, 250 Hz **$\langle E_{acc} \rangle$ = 32 MV/m**	

- SLED bypassed
- Linac energy reduced by a factor ~2 @ 250 Hz rep rate
- Max rep rate very much dependent on modulator rise/fall time τ_{trans}
- Klystron operated always at its nominal working point.

Courtesy J. Clarke

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Upgraded FEL layouts

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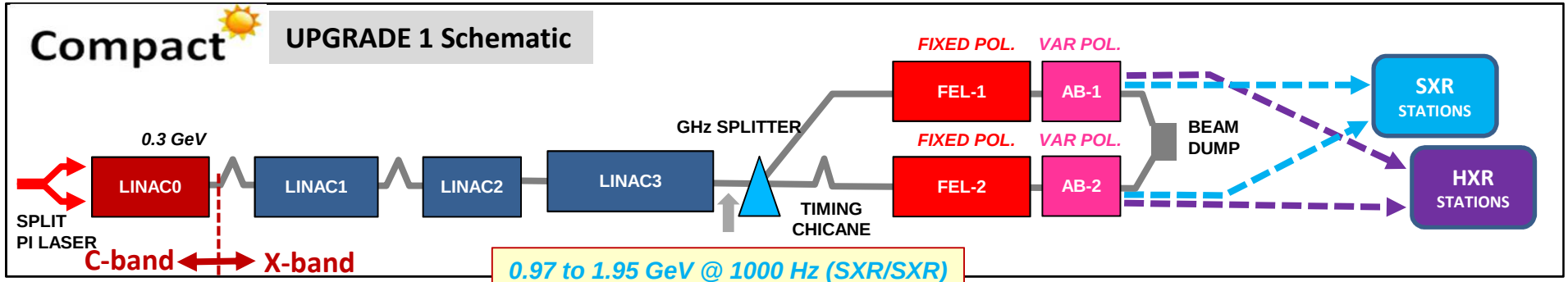
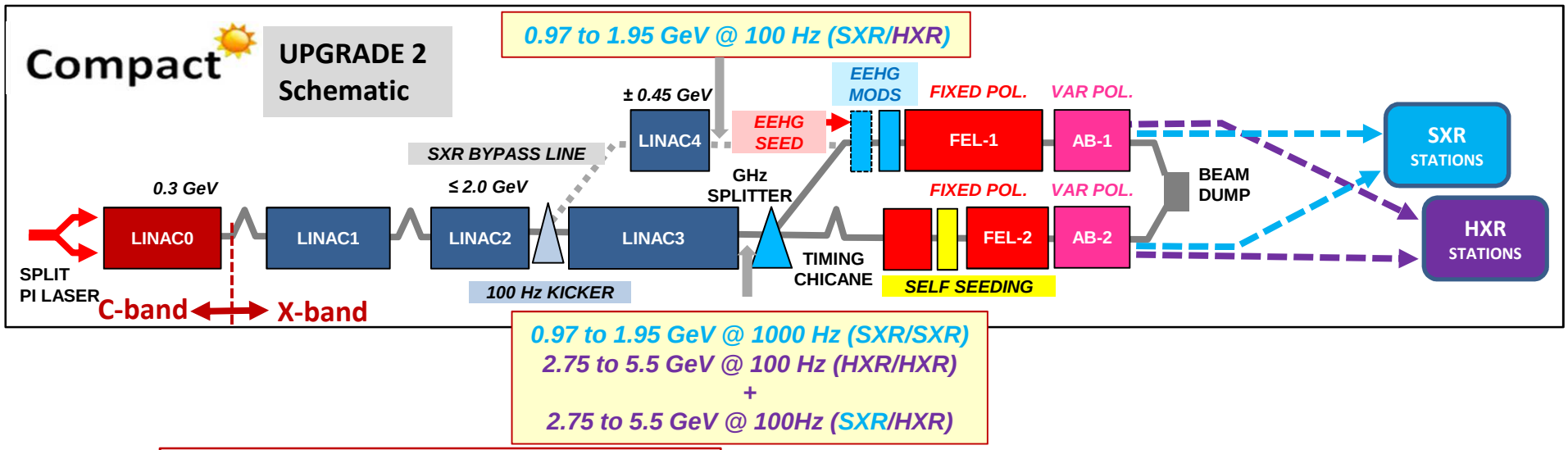




2 klystrons x LINAC Module:
- **CPI VKX-8311 @ 50 MW**
- **CPI (Canon E37113*) @ 10 MW**

*Currently at 6.0 MW

→ $\langle E_{acc} \rangle$ = 65 MV/m @ 100 Hz
$\langle E_{acc} \rangle$ = 30.4 MV/m @ 1 kHz

Courtesy J. Clarke

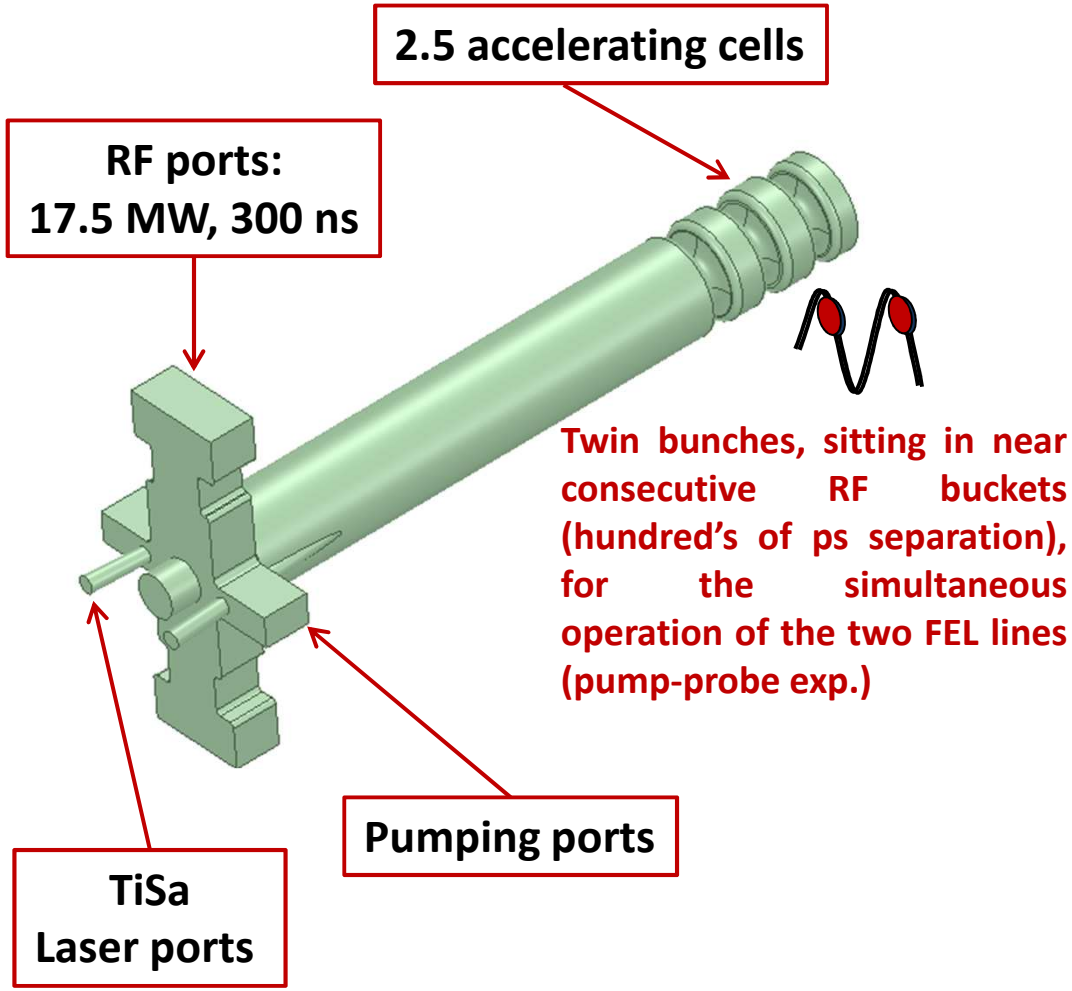
XLS FEL operating modes

Operating Mode	FEL-1 λ-range	FEL-2 λ-range	L0-L1-L2-L3 Rep.Rate [Hz]	L3 Final E [GeV]	L4 Rep.Rate [Hz]	L4 Final E [GeV]
BASELINE						
B-HH	0.6 - 0.08 nm		100	2.75-5.5		
B-SS	5.0 - 0.6 nm		250	0.95-1.95		
B-HH	0.6 - 0.08 nm		100	2.75-5.5		
UPGRADE-1						
U1-HH	0.6 - 0.08 nm		100	2.75-5.5		
U1-SS	5.0 - 0.6 nm		1000	0.95-1.95		
UPGRADE-2: U1 plus extra mode						
U2-SH	5.0-0.6 nm / 0.6-0.08 nm		100	2.75-5.5	100	0.95-1.95

Legenda:

B = Baseline	**HH** = Twin Hard X-ray pulses
U1 = Upgrade 1	**SS** = Twin Soft X-ray pulses
U2 = Upgrade 2	**SH** = Soft and Hard X-ray pulses simultaneous

C-band photoinjector

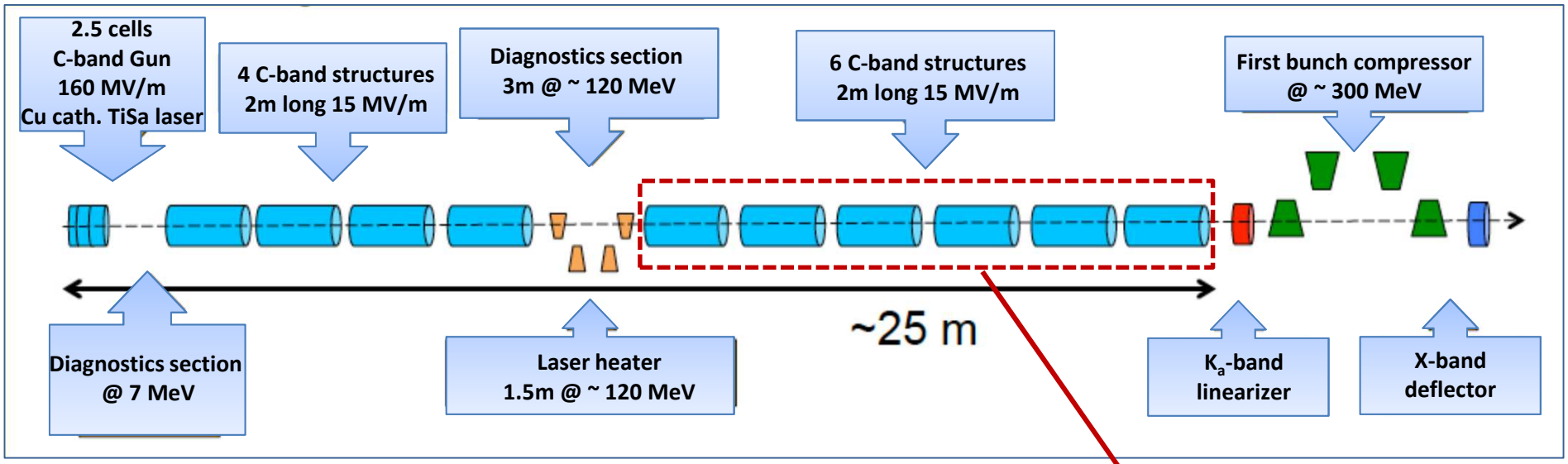


E_{cath}	160 MV/m
$\Delta f_{\pi/2\text{-}\pi}$	≈ 52 MHz
Q_0	11600
β	3
Filling time (τ_F)	160 ns
P_{diss} @160MV/m	9.7 MW
$E_{CAT}/\sqrt{P_{diss}}$	51.4 [MV/m/(MW)$^{0.5}$]
Rep. Rate	1000 Hz
Peak Input power P_{IN}	17.5 MW
Pulsed heating (T_{puls})	<20 °C
RF pulse length (T_{RF})	300 ns
Av diss power (P_{av})	2300 W

Courtesy M. Diomede

Full C-band injector

Same injector for High and Low repetition rate operations (1 KHz and 100 Hz)

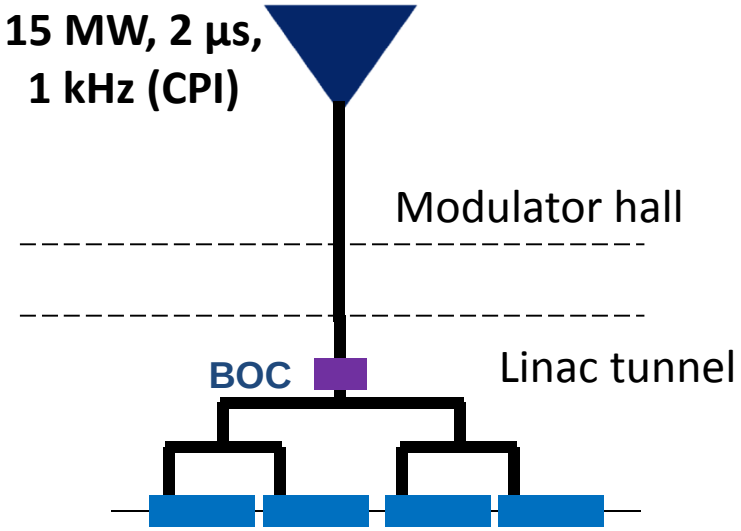


Possible replacement of the last
6 C-band stuctures
with 4 X-band structures @30 MV/m
for the 1 KHz operation
(evaluation ongoing)

Courtesy M. Ferrario

C-band module

RF System	
Operating frequency [GHz]	5.996
Klystron pulse length [us]	2
Klystron peak power [MW]	15
Pulse rate [pps]	1000
Q0 of BOC	216000
Qe of BOC	19100

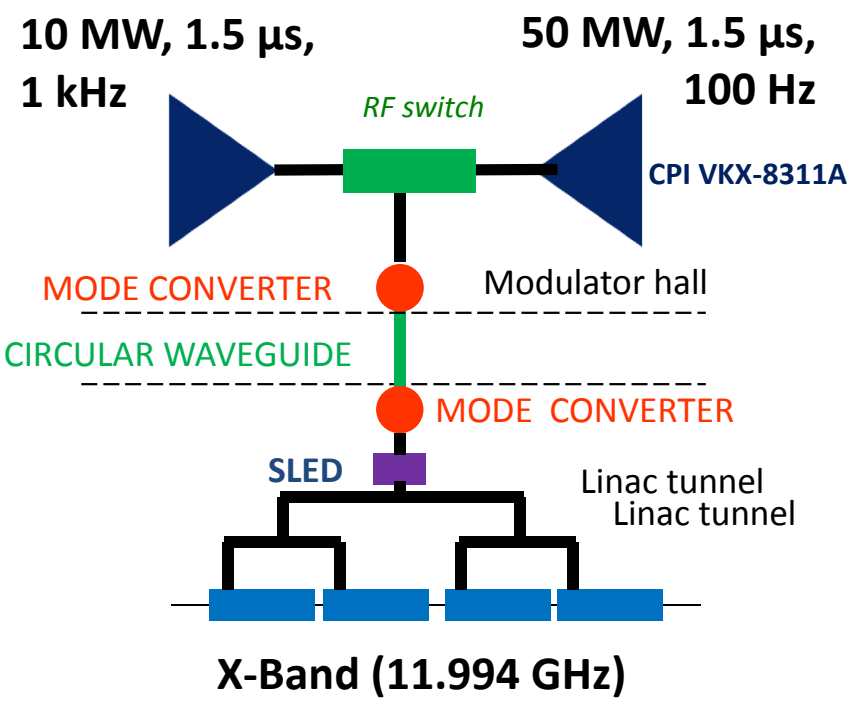


Acc. Structure	
Phase advance	2pi/3
Cell length [mm]	16.667
Number of cells	120
Total length [m]	2
Average iris radius [mm]	6.6
Tapering angle [deg]	0.02
Iris radius (first - last) [mm]	6.943 – 6.257
Shunt imp. [MΩ/m]	71 - 77
Q	9986 - 9943
Group velocity/c [%]	2.4 – 1.6
Filling time [ns]	336
Repetition rate [Hz]	1000
Avg. acc. gradient [MV/m]	15
Kly. Power per module [MW]	9

Courtesy M. Diomede

X-band module

Compact



Frequency [GHz]	**11.994**		
RF pulse (250 Hz) [µs]	1.5 (0.15)		
Average iris radius <a> [mm]	3.5		
Iris radius a [mm]	4.3-2.7		
Iris thickness t [mm]	2.0-2.24		
Structure length L_s [m]	0.9		
Unloaded SLED Q-factor Q_0	180000		
External SLED Q-factor Q_E	23300		
Shunt impedance R [MΩ/m]	85-111		
Effective shunt Imp. R_s [MΩ/m]	349		
Group velocity v_g/c [%]	4.7-0.9		
Filling time [ns]	146		
Repetition rate [Hz]	100	250	1000
SLED	ON	OFF	ON
Kly. Power per module [MW]	44	44	9
Avg. acc. gradient [MV/m]	65	30	30

Courtesy M. Diomede

10 MW @ 11.9942 GHz Klystron Designs

Parameter	Minimum	Nominal	Maximum	Units
RF Operating Frequency	----	11.9942	----	GHz
Peak Power Output	10	10.27	----	MW
Average Power Output	20	20.54	23.6	kW
DC to RF Efficiency	38	43	----	%
Beam Voltage	----	185	195	kV
Beam Current	----	127.31	137.76	a
Average Beam Power		70.66	80	kW
Micro-Perveance	1.55	1.6	1.65	$a/V^{3/2}$
RF Power Gain	48	54	----	dB
RF Input Drive Power	----	40	200	w
Pulse Width (video)	7.5	----	----	us
Pulse Width (RF)	2.0	----	5.0	us
Pulse Repetition Frequency	50	----	400	Hz
Video Duty Factor	----	0.3	----	%
RF Duty Factor	----	0.2	----	%
Instantaneous Saturated Bandwidth < 0.2dB Power Variation	----	>40	----	MHz
VSWR Tolerance	----	----	1.2:1	----

Predicted (1-D code) minimum, nominal, and maximum operational parameters for a typical 10 MW pulsed klystron

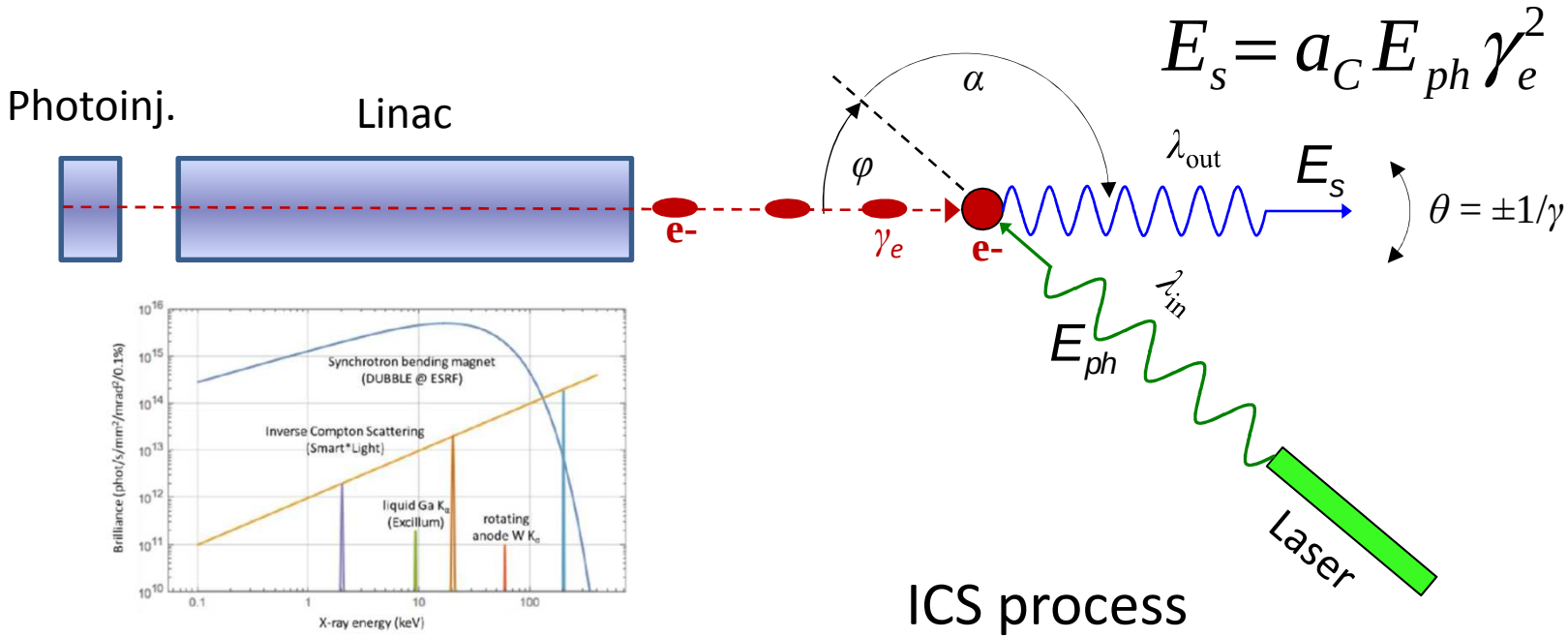
Preliminary Design of 15 MW, 5.996 GHz Klystron

Parameter	Minimum	Nominal	Maximum	Units
RF Operating Frequency	----	5.996	----	GHz
Peak Power Output	15	15.4	----	MW
Average Power Output	20	20.54	50	kW
DC to RF Efficiency	42	45	----	%
Beam Voltage	----	220	230	kV
Beam Current	----	154.7	165.4	a
Average Beam Power		170	190	kW
Micro-Perveance	1.45	1.5	1.55	$a/V^{3/2}$
RF Power Gain	49	54	----	dB
RF Input Drive Power	----	70	160	w
Pulse Width (video)	5.0	----	----	us
Pulse Width (RF)	2.0	----	3.0	us
Pulse Repetition Frequency	400	----	1000	Hz
Video Duty Factor	----	0.3	----	%
RF Duty Factor	----	0.2	----	%
Instantaneous Saturated Bandwidth < 0.2dB Power Variation	----	>6	----	MHz
VSWR Tolerance	----	----	1.2:1	----

Predicted (1-D code) minimum, nominal, and maximum operational parameters for a typical 15 MW, 5.996 GHz pulsed klystron

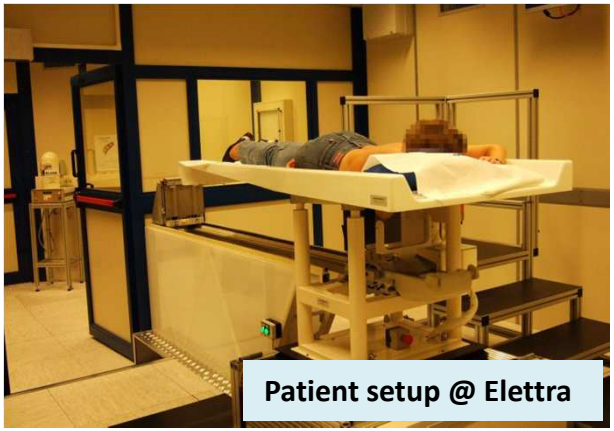
CPI Communications & Power Industries

The XLS design, with the challenging target to extend the operation of the RF systems up to 1 KHz, will also have a major impact on very compact X-ray sources, for multi-disciplinary applications, based on Inverse Compton Scattering (ICS). Despite they have lower photon fluxes, if compared to large-scale Synchrotron facilities, ICS nowadays are becoming very attractive, for their potentials, costs and extremely reduced footprint.



Smart Light (TU/e)

Biomedical applications I (patients)

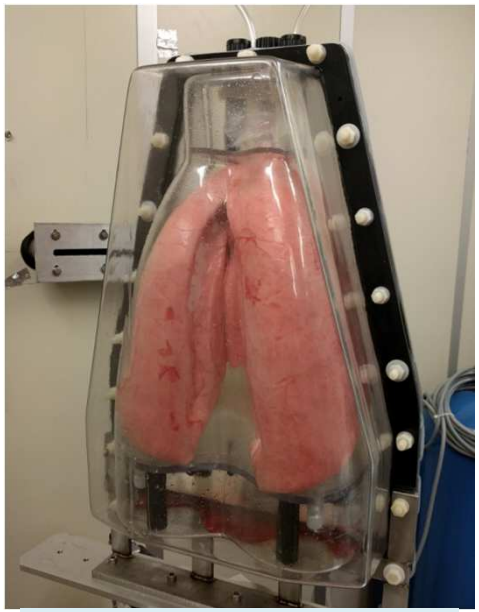


Patient setup @ Elettra

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

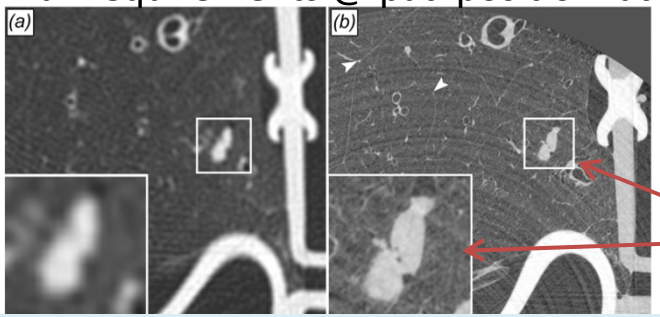
Note: at a Synchrotron: need for vertical scan of the patient



Phantom with porcine lungs

Lung CT imaging *(early detection of lung cancer, idiopatic fibrosis, fibrotic consequences of COVID-19 pneumonia)*

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



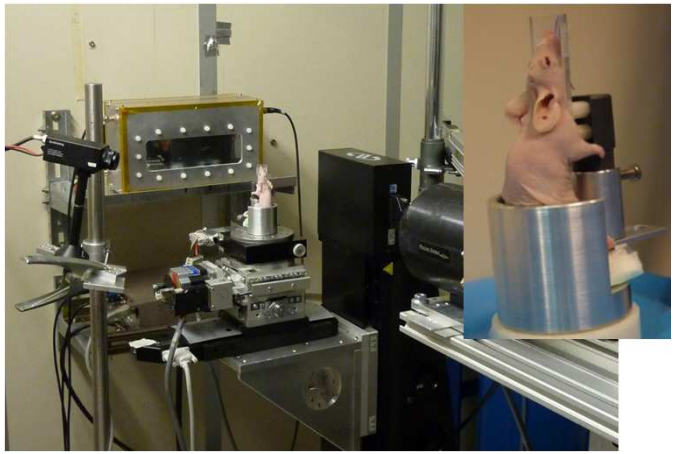
Note: at a Synchrotron: need for vertical scan of the patient

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).

Courtesy G.Tromba

Biomedical applications II (pre-clinical)

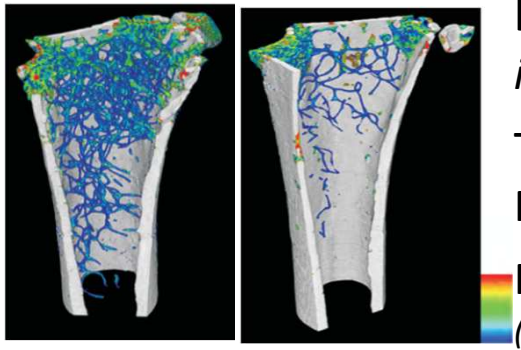


Imaging of small animals *(studies of animal models mimiking human diseases)*

Typical X-ray 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



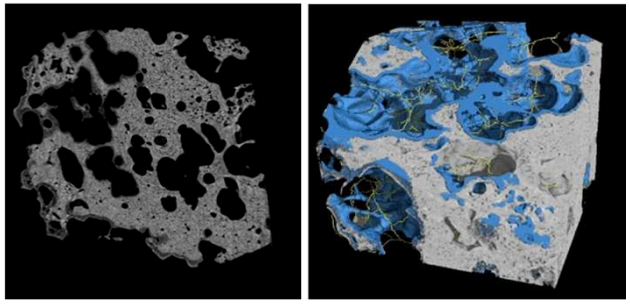
High resolution Imaging of tissues and organs *(virtual histology, in-vitro imaging)*

Typical X-ray 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

Courtesy G.Tromba

Conclusions

- ✓ Thanks to all the Partners, the XLS project is running well, according to the time schedule.
- ✓ Advanced and challenging FEL schemes have been proposed with a wide range of operating modes, including the simultaneous operation of HXR/SXR at 100 Hz.
- ✓ Operation with two bunches and up to 1 KHz repetition rate expected.
- ✓ The objective to extend the machine operation up to 1 KHz pave the way for further applications of the XLS technology.

Thank you!

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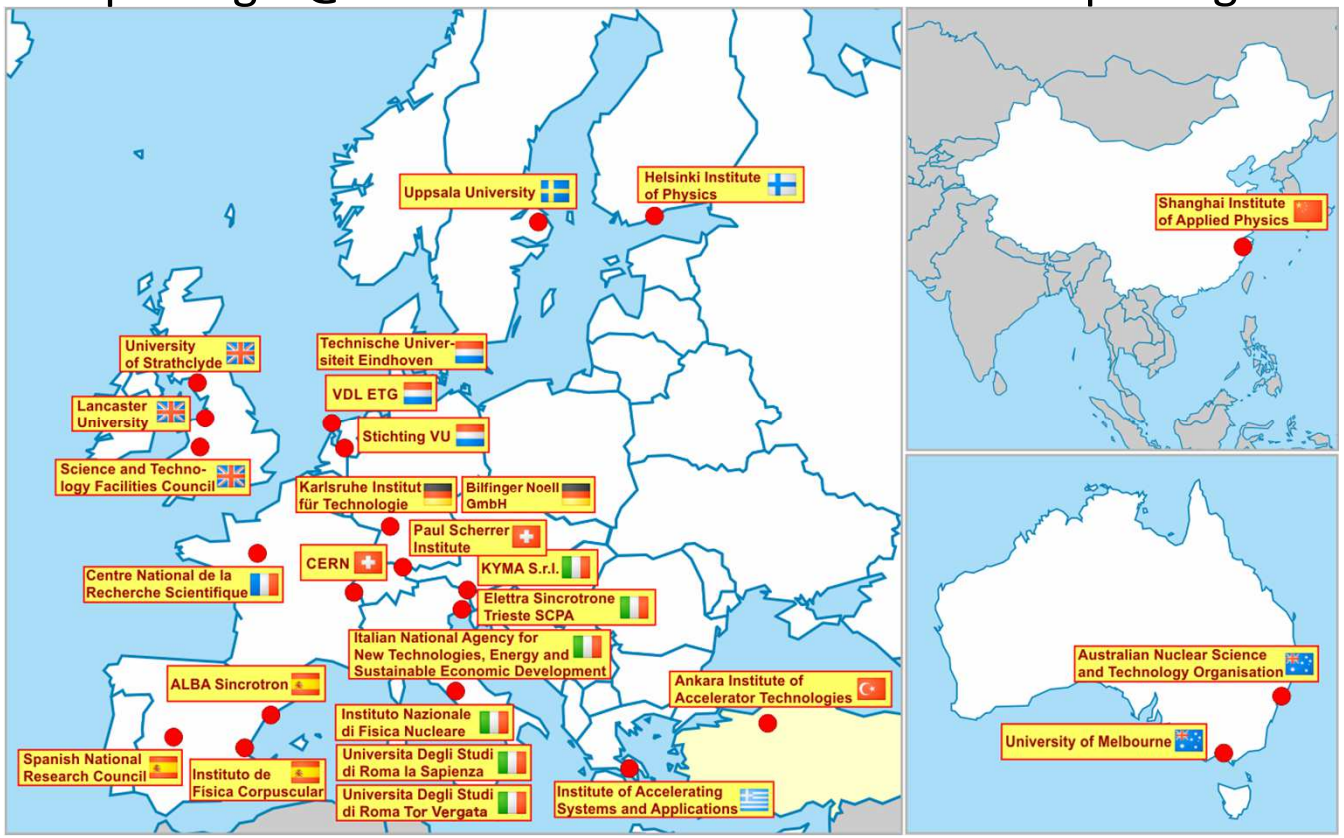

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