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The CompactLight (XLS) Project

Objectives & Results

On behalf of the XLS Collaboration

LEDS2023 Workshop, ENEA Frascati

3-5 October 2023

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The CompactLight Collaboration

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Participant		Organisation Name	Country
1	ST (Coord.)	Elettra – Sincrotrone Trieste S.C.p.A.	Italy
2	CERN	CERN - European Organization for Nuclear Research	International
3	STFC	Science and Technology Facilities Council – Daresbury Laboratory	United Kingdom
4	SINAP	Shanghai Inst. of Applied Physics, Chinese Academy of Sciences	China
5	IASA	Institute of Accelerating Systems and Applications	Greece
6	UU	Uppsala Universitet	Sweden
7	UoM	The University of Melbourne	Australia
8	ANSTO	Australian Nuclear Science and Tecnology Organisation	Australia
9	UA-IAT	Ankara University Institute of Accelerator Technologies	Turkey
10	ULANC	Lancaster University	United Kingdom
11	VDL ETG	VDL Enabling Technology Group Eindhoven BV	Netherlands
12	TU/e	Technische Universiteit Eindhoven	Netherlands
13	INFN	Istituto Nazionale di Fisica Nucleare	Italy
14	Kyma	Kyma S.r.l.	Italy
15	SAPIENZA	University of Rome "La Sapienza"	Italy
16	ENEA	Agenzia Naz. per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile	Italy
17	ALBA-CELLS	Consorcio para la Construccion Equipamiento y Explotacion del Lab. de Luz Sincrotron	Spain
18	CNRS	Centre National de la Recherche Scientifique CNRS	France
19	KIT	Karlsruher Institut für Technologie	Germany
20	PSI	Paul Scherrer Institut PSI	Switzerland
21	CSIC	Agencia Estatal Consejo Superior de Investigaciones Científicias	Spain
22	UH/HIP	University of Helsinki - Helsinki Institute of Physics	Finland
23	VU	VU University Amsterdam	Netherlands
24	USTR	University of Strathclyde	United Kingdom
25	UniTov	University of Tor Vergata	Italy
26	USTR	Bilfinger Noell GmbH	Germany
Third Parties		Organisation Name	Country
AP1	OSLO	Universitetet i Oslo - University of Oslo	Norway
AP2	ARCNL	Advanced Research Center for Nanolithography	Netherlands
AP3	NTUA	National Technical University of Athens	Greece
AP4	AUEB	Athens University Economics & Business	Greece
AP5	KyTe	KYMA TEHN. DOO	Slovenia

CompactLight

(http://www.compactlight.eu)

A design study funded by EU

under the Horizon2020

Research & Innovation Programme

GA No. 777431

Total budget 3M€

23 International Labs./Universities
3 Private companies
5 Associated partners

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
Switz.	1
Finland	1
Norway	1 Ass. Part.
Slovenia	1 Ass. Part.
Internat.	1

XLS Objectives

The key objective of the CompactLight Design Study was to demonstrate the feasibility of a compact and cost-effective FEL facility using innovative accelerator technologies based on:

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

The FEL specifications have been driven by its potential users, taking into account the photon characteristics needed for their current and desired future experiments.

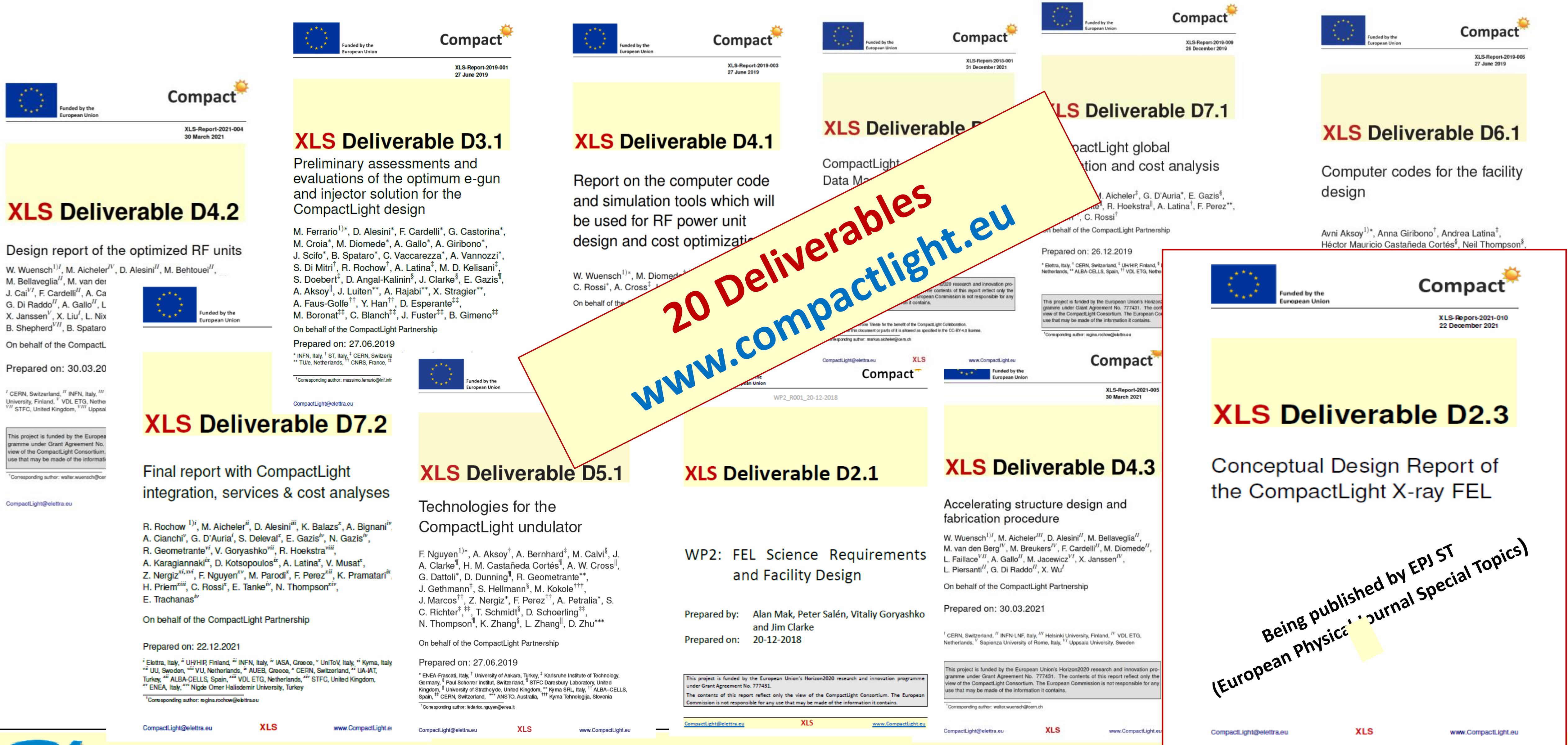
Users' wish list:

- High FEL stability in pulse energy and pulse duration
- FEL synchronization better than 10 fs
- Photon pulse duration less than 50 fs
- **A repetition rate from 1 Hz up to 1 kHz**
- FEL pump-probe capabilities with a large photon energy difference
- Small focused spot size
- Variable polarization, linear and elliptical
- Tunability up to higher photon energies
- Two-bunch operation
- Two-color pulse generation

- A soft X-ray (SXR) FEL able to deliver photons from 5.0 nm to 0.6 nm (0.25 keV to 2 keV) operating up to 1 kHz repetition rate (high rep rate);

- A hard X-ray FEL source (HXR) ranging from 6.0 Å to 0.8 Å (2 keV to 16 keV) with maximum 100 Hz repetition rate (low rep rate).

Deliverables



Final Review Meeting with EU

CompactLight started in 2018 and was completed in March 2022 with the final review meeting held with the EU Commission: https://indico.cern.ch/event/1130038/

Overall assessment:

"Project has achieved most of its objectives and milestones for the period with relatively minor deviations…….".

Significant results linked to dissemination, exploitation and impact potential:

"……The project represents an exceptional contribution to accelerator (X-FEL) technologies in terms of the development of a compact and lower-cost FEL facility, with the resulting positive economic, environmental, energy consumption, and other socio-economic impacts. The adoption of innovative photoinjector, high-gradient accelerating structures, and short period superconducting undulators, all successfully described in the submitted deliverables produced during the reporting period (especially relevant being D2.3 reporting the Conceptual Design Report of the facility), present clear industrialization potential………."

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Facility dimensions & costs

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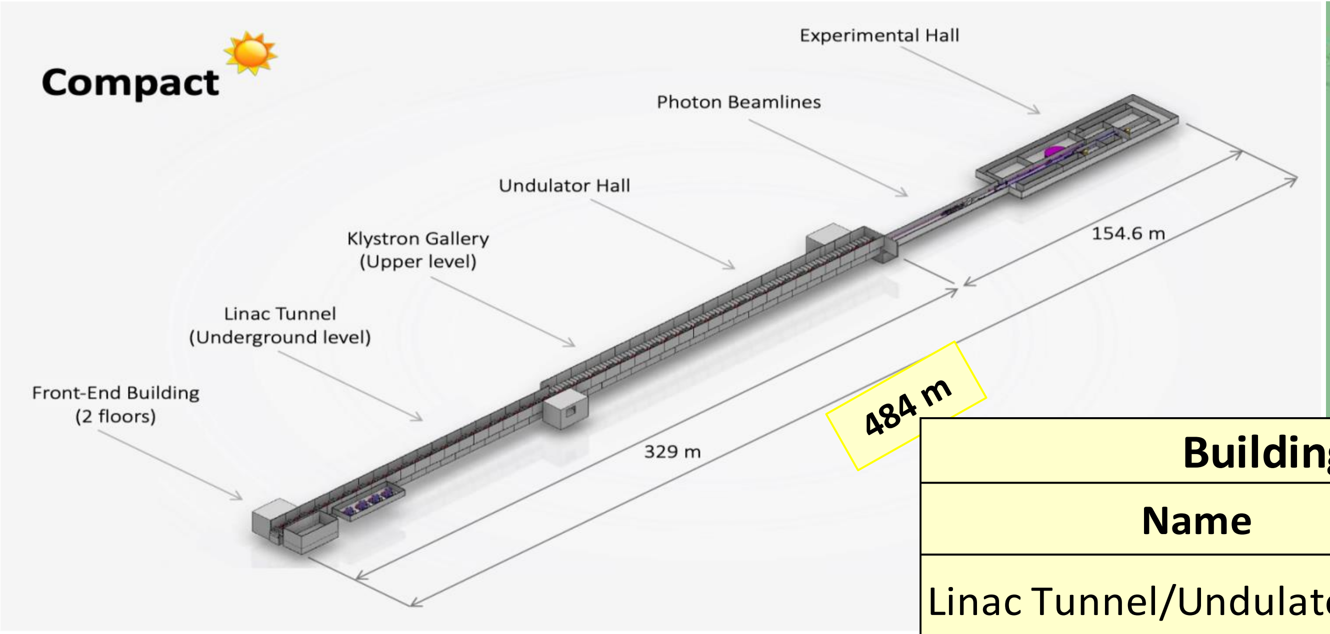
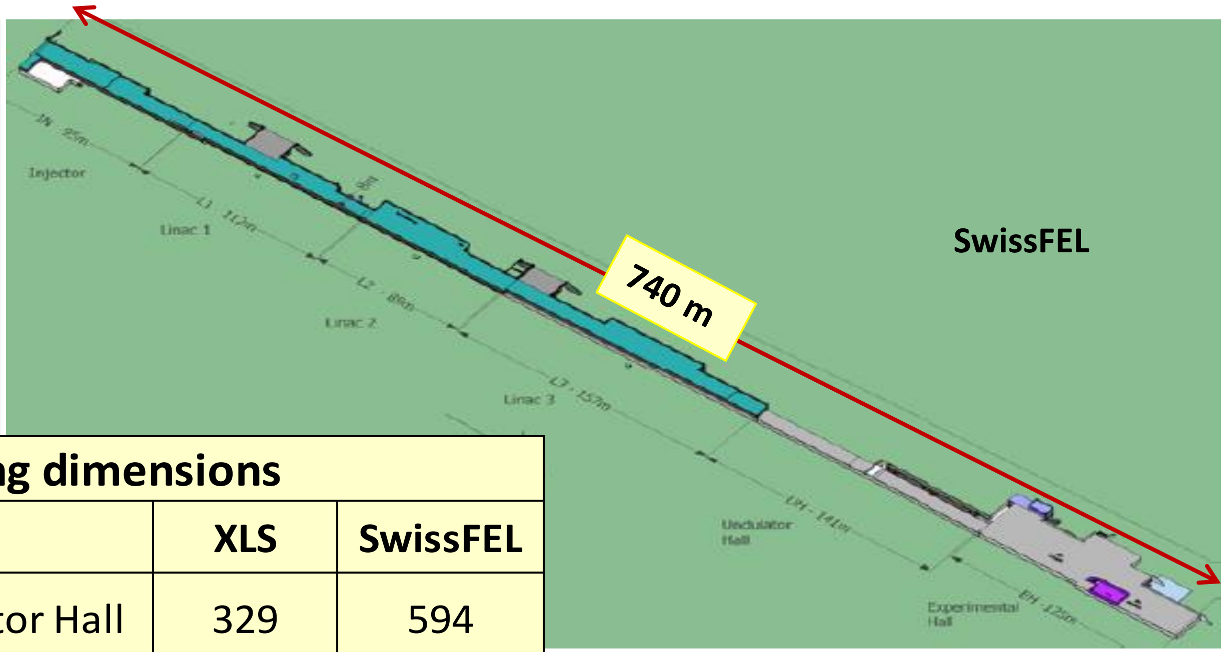




Building dimensions		
Name	**XLS**	**SwissFEL**
Linac Tunnel/Undulator Hall	329	594
Experimental Hall	155	146
TOTAL	**484**	**740**

Footprint → ≈ 35% shorter than SwissFEL

Complexity → macro-components design as ”building blocks” or ”standard units” to assemble for a vast number of applications

Efficiency → normal-conducting facilities that can operate at high rep. rates, (kHz regimes)

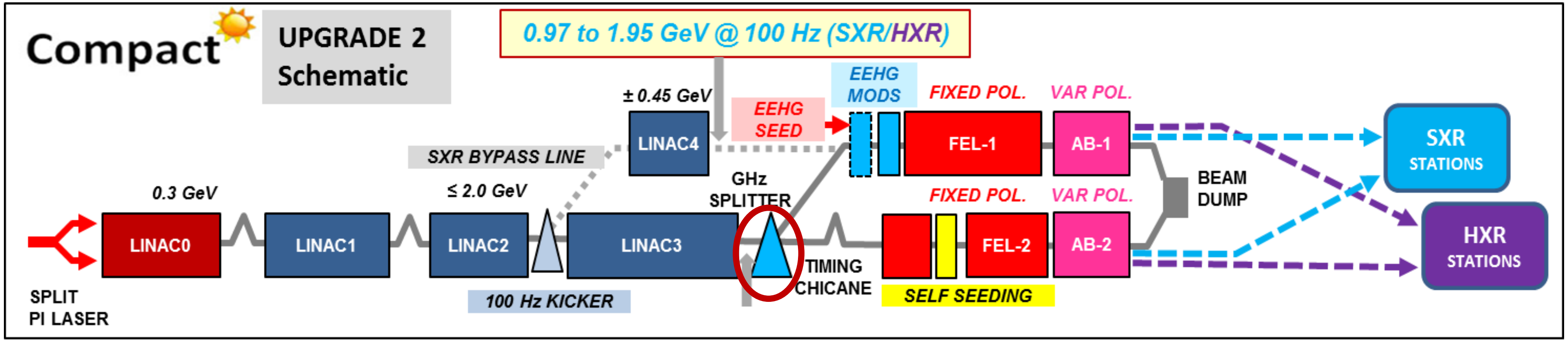
Cost → ≈ 25% cost reduction

CompactLight layout

Soft X-ray (SXR) FEL able to deliver photons from 5.0nm to 0.6nm (0.25 keV to 2 keV)

+

Hard X-ray FEL source (HXR) ranging from 6.0Å to 0.8 Å (2 keV to 16 keV)



Operating modes

- ✓ *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**

$<E_{acc}>$ = 65 MV/m @ 100 Hz

$<E_{acc}>$ = 30.4 MV/m @ 1 kHz

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Operating modes, output energies & repetition rates

Operating mode	FEL1 Wavelength	FEL2 Wavelength	L0/L1/L2/L3 Rep rate (Hz)	L3 Output Energy (GeV)	L4 Repet. rate (Hz)	L4 Output Energy (GeV)
BASELINE						
Baseline HH	HXR	HXR	100	2.75 – 5.5	-	-
Baseline SS	SXR	SXR	250	< 2.0	Up to 250	0.95 – 1.95
UPGRADE 1						
Upgrade1 HH	HXR	HXR	100	2.75 – 5.5	-	-
Upgrade1 SS	SXR	SXR	1000	< 2.0	Up to 1000	0.95 – 1.95
Upgrade 2 – All modes from Upgrade 1 plus SXR & HXR @100Hz at the same time						
Upgrade2 SH	SXR	HXR	100	2.75 – 5.5	100	0.95 – 1.95

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Operating parameters

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e⁻ beam (HXR)

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

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	1000	100
Pulse duration	fs	0.1 – 50	1 – 50
Polarization		Variable, selectable	Variable, selectable
Two-pulse delay	fs	±100	±100
Two-colour separation	%	20	10
Synchronization	fs	<10	<10

Scientific and Industrial Impact

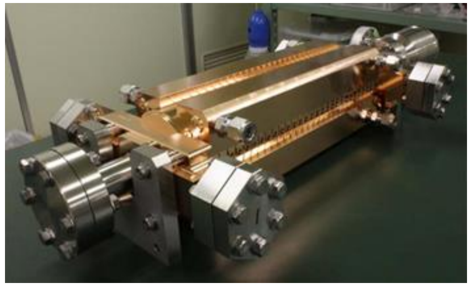
"The project has delivered outstanding results with significant immediate or potential impact in both science and industry"

New accelerator sub-systems specifically designed for CompactLight

- **Electron source**
  - Innovative C-band (6.0 GHz) photo-injector
  - Operating gradient up to 180 MV/m
  - Dual bunch operation (75 pC/e-bunch)
  - Normalized emittance ≤ 0.2mmmrad
- **Accelerating structure**
  - New X-band structure @11.994MHz, 0.9 m long, 106 cavities
  - Average iris radius 3mm
  - Operating gradient up to 65 MV/m
- **Beam linearizer**
  - Ka-band system, operating at 36 GHz
  - 300 mm TW structure, with an integrated gradient of 12.7MV
  - RF source (3MW) Multi-Beam Klystron/Gyro-Klystron
- **Sub-Harmonic deflecting system**
  - TM110 sub-harmonic deflecting structure, S-band (3 GHz)
  - Bunch spacing 1.5 or 2.5 S-band RF cycles RF (6 or 10 X-band cycles)
  - Transverse beam separation at the septum 2.5 mm
- **Undulator chain**
  - Innovative helical superconducting undulator, 13mm period/4.2mm gap
  - APPLE X afterburner, 19mm period/5mm gap

New sub-systems design

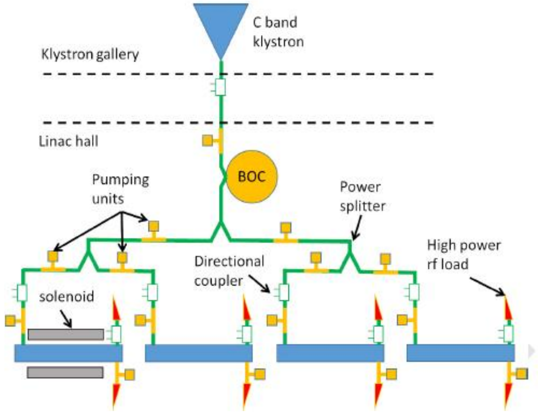
C-band photoinjector



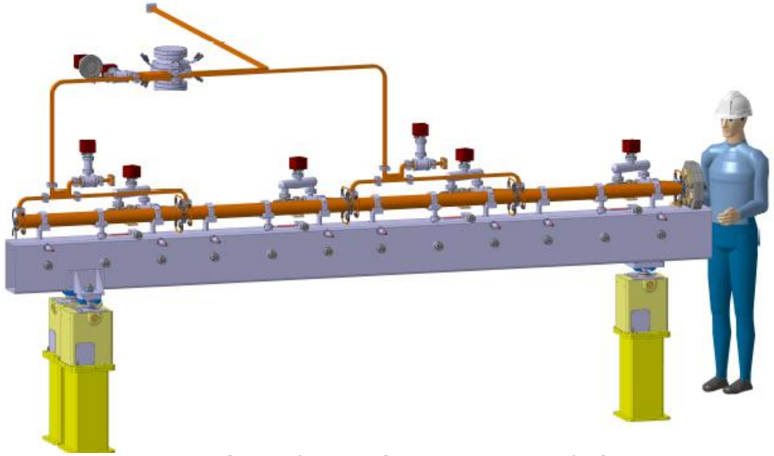
C- and X-band accelerating structures

Two prototypes under construction in the context of the I.FAST project

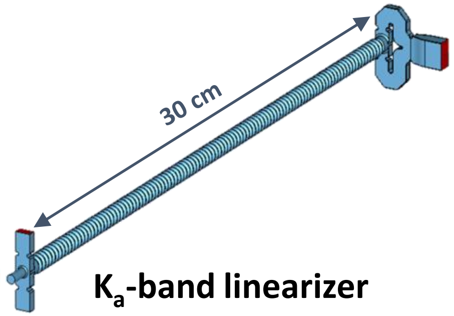
Helical SC Undulator 30 cm model



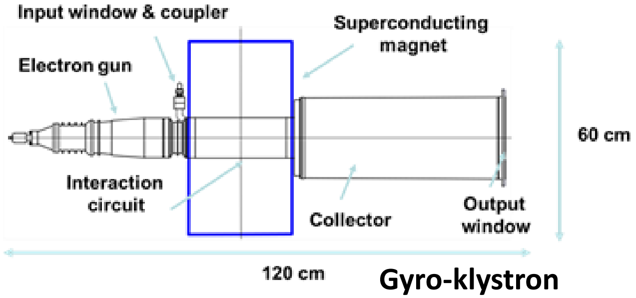
C-band accelerating module



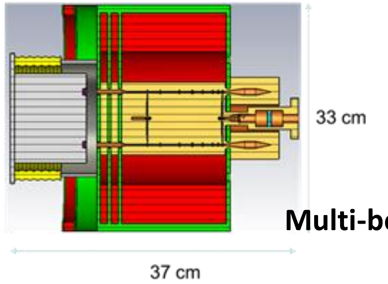
X-band accelerating module



K_a-band linearizer



Gyro-klystron

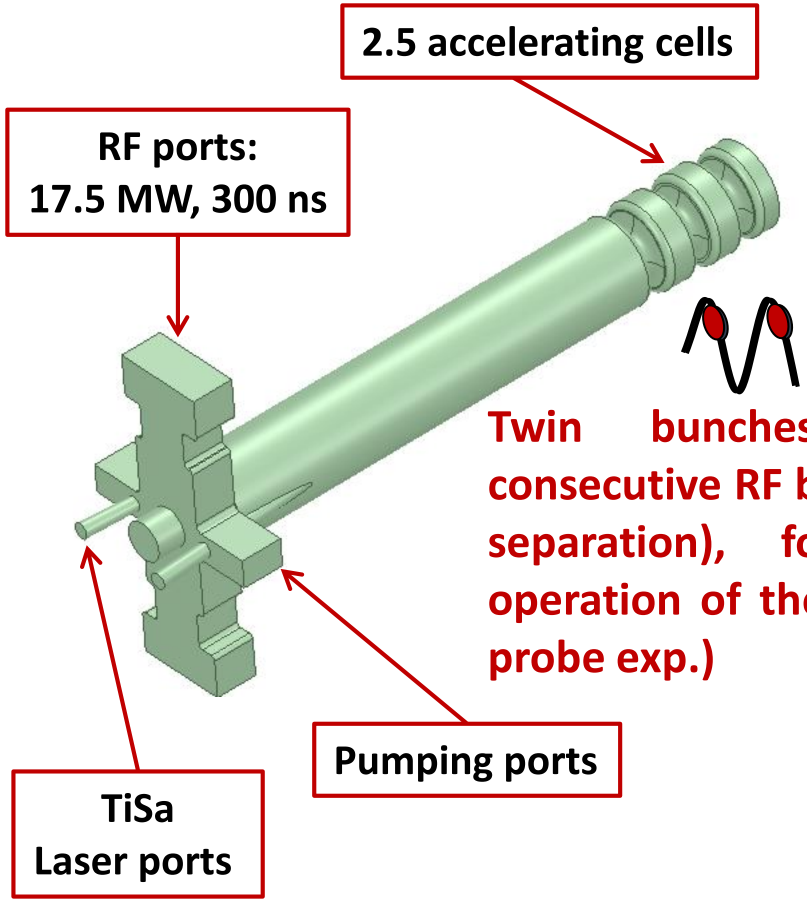


Multi-beam klystron

K_a-band RF sources

The XLS Collaboration is also strongly promoting with industry the development of C- and X-band high power RF sources that can operate up to 1 KHz

XLS C-band photoinjector



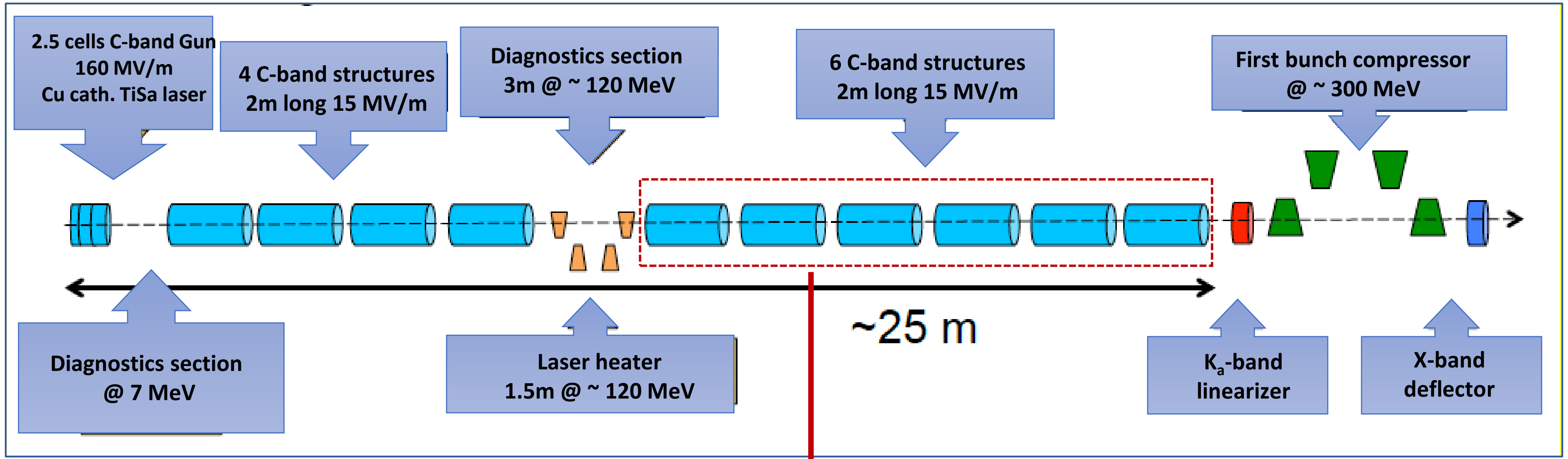
Twin bunches, sitting in near consecutive RF buckets (hundred's of ps separation), for the simultaneous operation of the two FEL lines (pump-probe exp.)

E_{cath}	160 MV/m
$\Delta f_{\pi/2-\pi}$	≈ 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 D. Alesini

Full C-band injector

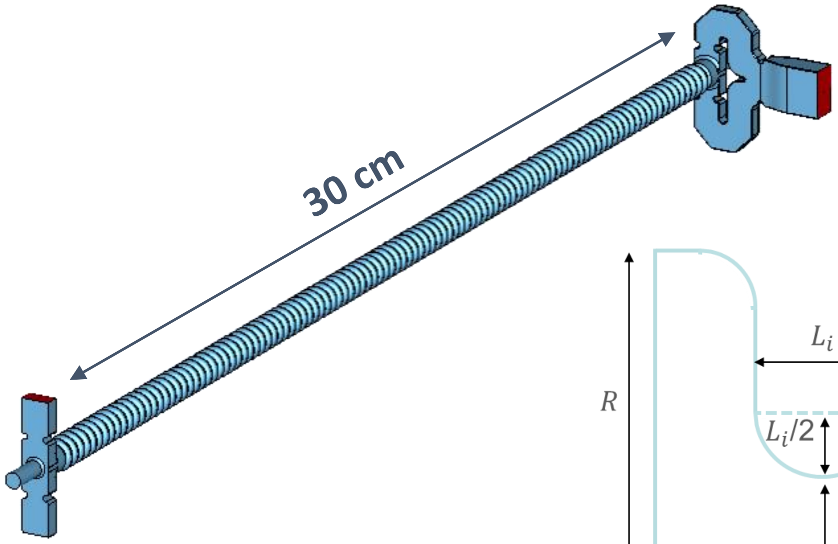
Same injector for High and Low repetition rate operations (1 KHz and 100 Hz)

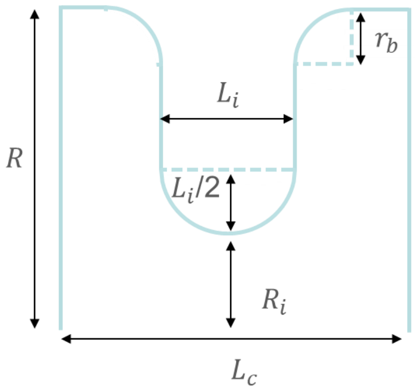


Possible replacement of the last 6 C-band stuctures
with 4 X-band structures @30 MV/m for the 1 KHz operation

Courtesy M. Ferrario

36 GHz linearizer





Parameter	$\varphi = {}^{2\pi}/_{3}$	$\varphi = {}^{5\pi}/_{6}$	$\varphi = {}^{6\pi}/_{7}$	Units
Freq.		36		GHz
Q	4392	5251	5365	--
r_L	106	109	109	MΩ/m
v_g	0.122	0.138	0.145	c
α_0	0.7	0.5	0.5	m^{-1}
E_p^*	2.6	3.1	3.0	MV/m
R	3.96	3.86	3.85	mm
R_i		2.00		mm
L_c	2.78	3.47	3.57	mm
L_i		0.60		mm
r_b		1.00		mm

*normalized to $E_z = 1\ MV/m$

A 30 cm structure provides the required voltage (12.75 MV) with the 15 MW of RF power supplied by the RF source and pulse compressor.

- Accelerating gradient: 41.7 MV/m
- Maximum surface E field: 108 MV/m

Courtesy by G. Burt and A. Castilla

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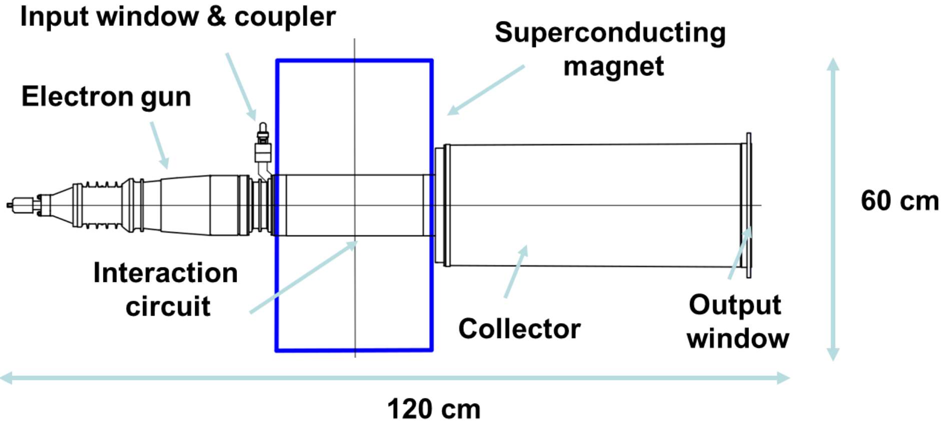
Ka-band RF sources

Two possible designs could provide ~3 MW at 1 kHz:

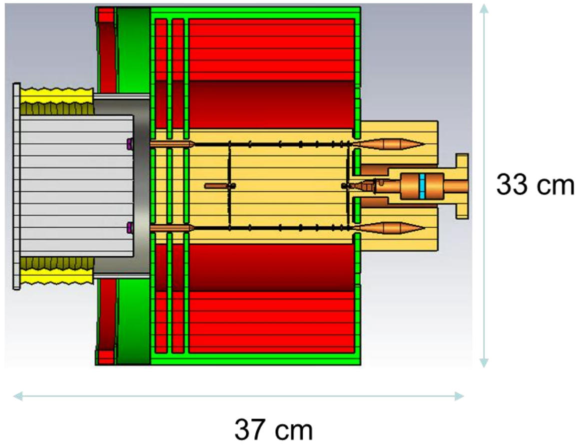
a) **gyro-klystron**

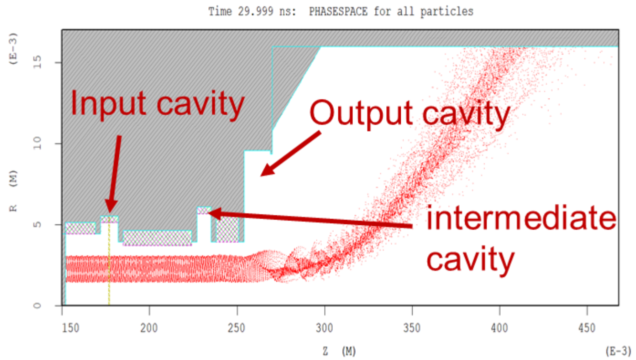
b) **multi-beam klystron**

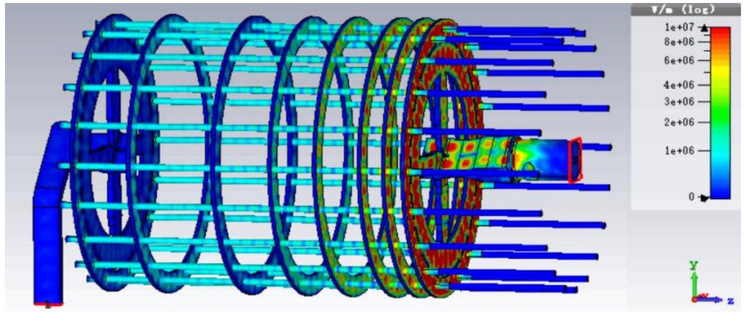
Gyro-klystron



Multi-beam klystron







Courtesy by G. Burt

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Dual bunch operation

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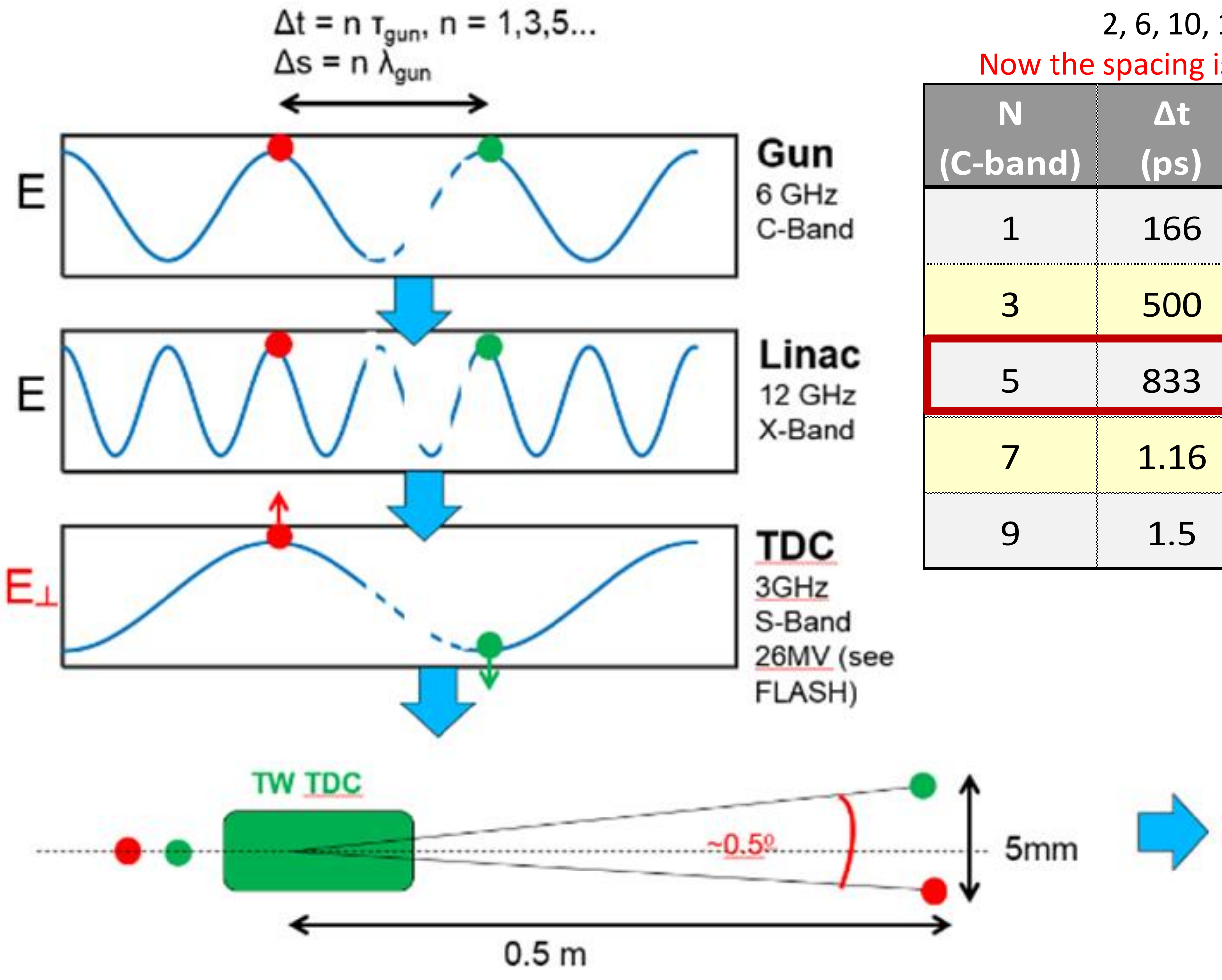
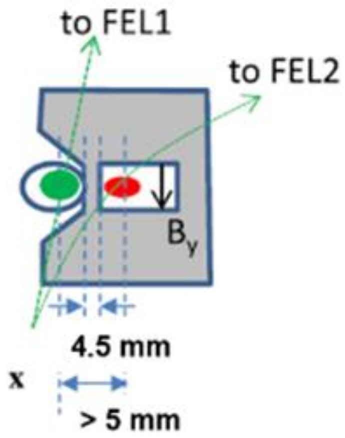
Pulse splitting options for a simultaneous operation HXR/SXR



Spacing between the two bunches should be:
2, 6, 10, 14… X-band rf cycle
Now the spacing is fixed to 10 X-band rf cycles

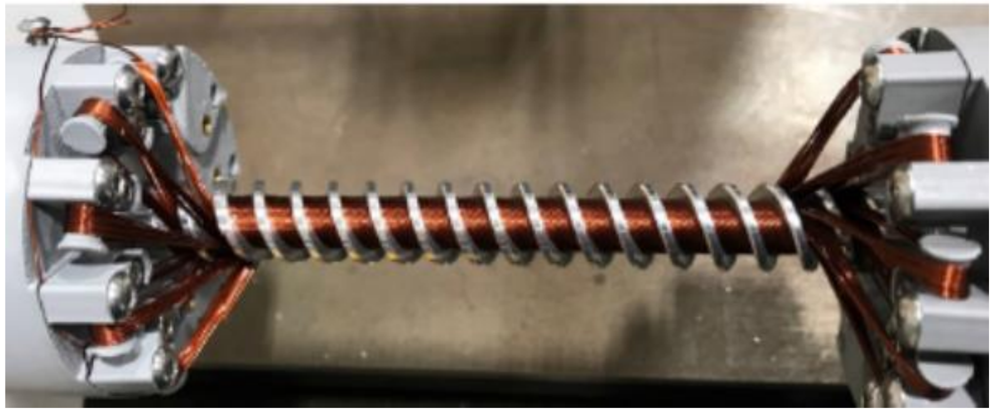
N (C-band)	Δt (ps)	Δs (mm)	→	N (X-band)
1	166	50		2
3	500	150		6
5	833	250		10
7	1.16	350		14
9	1.5	450		18



Undulators

Both Soft and Hard X-Ray configurations foresee a SASE line based on Helical SCUs plus an Afterburner line based on Apple-X undulators

SC helical undularor	Value	Unit
Period length	13	mm
Length (including matching periods)	1.755	mm
Magnetic gap	4.2	mm
Beam pipe bore diameter	3	mm
a_w (8 keV)	1.33	
a_w (16 keV)	0.617	
Bmax on axis	1.09	T



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

Courtesy B. Shepherd

Scientific impact

- **EuPraxia@SPARC_Lab** at INFN-LNF (IT), an ESFRI project for plasma acceleration and a FEL facility, that will make extensive use of the CompactLight technology, employing the X-band accelerating module, X-band components for beam diagnostics and manipulation, and short-period superconducting undulators.

- **FREIA Laboratory at Uppsala University, Sweden**, intends to develop a compact femtosecond X-ray source, envisioned to provide local users with laser-like X-ray radiation. This will bring the power of these unique instruments also to universities and small laboratories for new scientific applications.

Key sub-systems and Industrial impact I

RF structures:

There are already several initiatives involving industry in prototyping sub-systems designed in the context of CompactLight. This will be very beneficial to EU industry, which will gain great competitiveness in a strategic and rapidly evolving technology area:

- Two prototypes of C-band photoinjector, designed by INFN in the framework of the CompactLight Collaboration, will be built and tested within the I.FAST project by INFN and PSI.

- Two prototypes of the CompactLight X-band accelerating section will be built and tested, at high gradient and high repetition rate, within the I.FAST project (Elettra, CERN and INFN).

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XLS prototype accelerating structure construction

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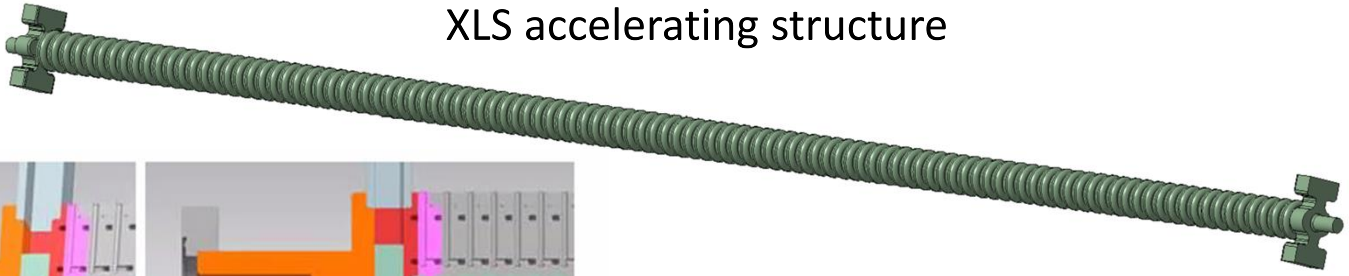
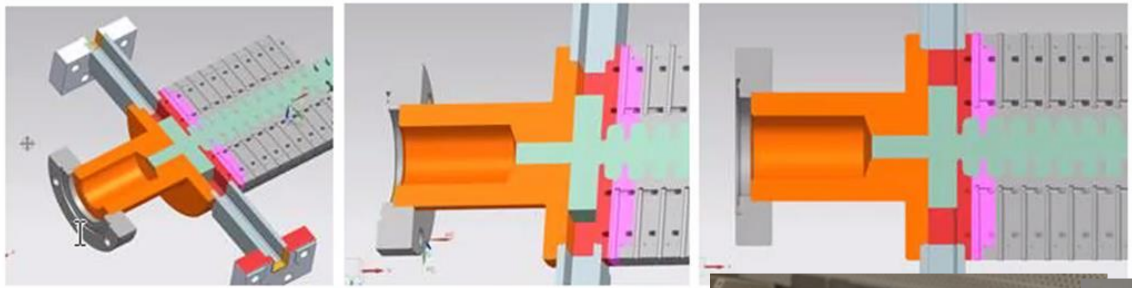
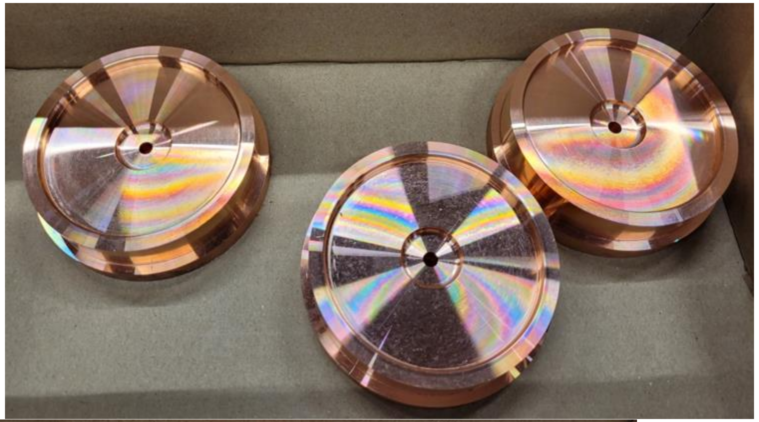
XLS accelerating structure



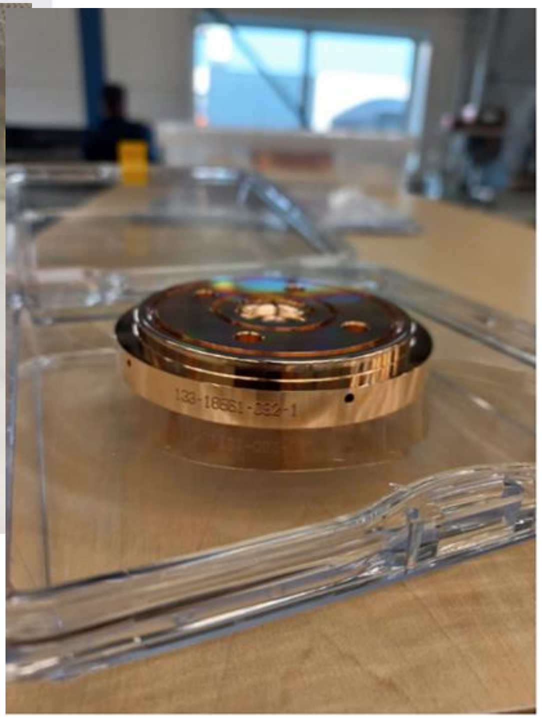


RF couplers



RF couplers

Single cell with cooling pipes



Courtesy M. van den Berg

Key sub-systems and Industrial impact II

X-band high power RF sources:

Great effort is under way by industry and research laboratories to develop the next generation of high power and high efficiency RF power sources (I. Syratchev, CERN).

- Canon, with the support of CERN, has already developed a 10 MW high-efficiency klystron.
- In addition, Canon is already on the market with medium power high repetition rate X-band klystrons, at 20 MW and 25 MW, with a repetition rate up to 400 Hz.
- CPI is now producing a prototype of a high-efficiency version of its 50MW klystron with the support of I. Syratchev. They have also plans to develop medium power tubes (20-25 MW).
- Recently, Thales has also shown interest in developing medium-power, high-repetition-rate X-band RF sources.

Conclusions and outlook

- The XLS Collaboration is determined to continue its activities well beyond the end of its H2020 contract, improving the partnership and maintaining its leadership in compact acceleration and light production, strong of the experience gained in the four years of the project.

- Periodic meetings and workshops will be organized to promote exchanges among the members of the Collaboration and the Scientific Community, to foster further developments in the field of very compact photon sources.

Note:
In addition to the applications already mentioned at European level, subsystems designed in the context of CompactLight have already been adopted outside Europe. For example, SXFEL and DCLS in China have recently completed the production of components for a C-band photoinjector and an X-band lineariser.

Acknowledgements

My special thanks to:

- The EU Commission, for supporting the project.
- All the CompactLight Collaboration members for the excellent work carried out.
- In particular to R. Rochow, A. Latina and all the WP leaders for their continuous support.

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Thank you!

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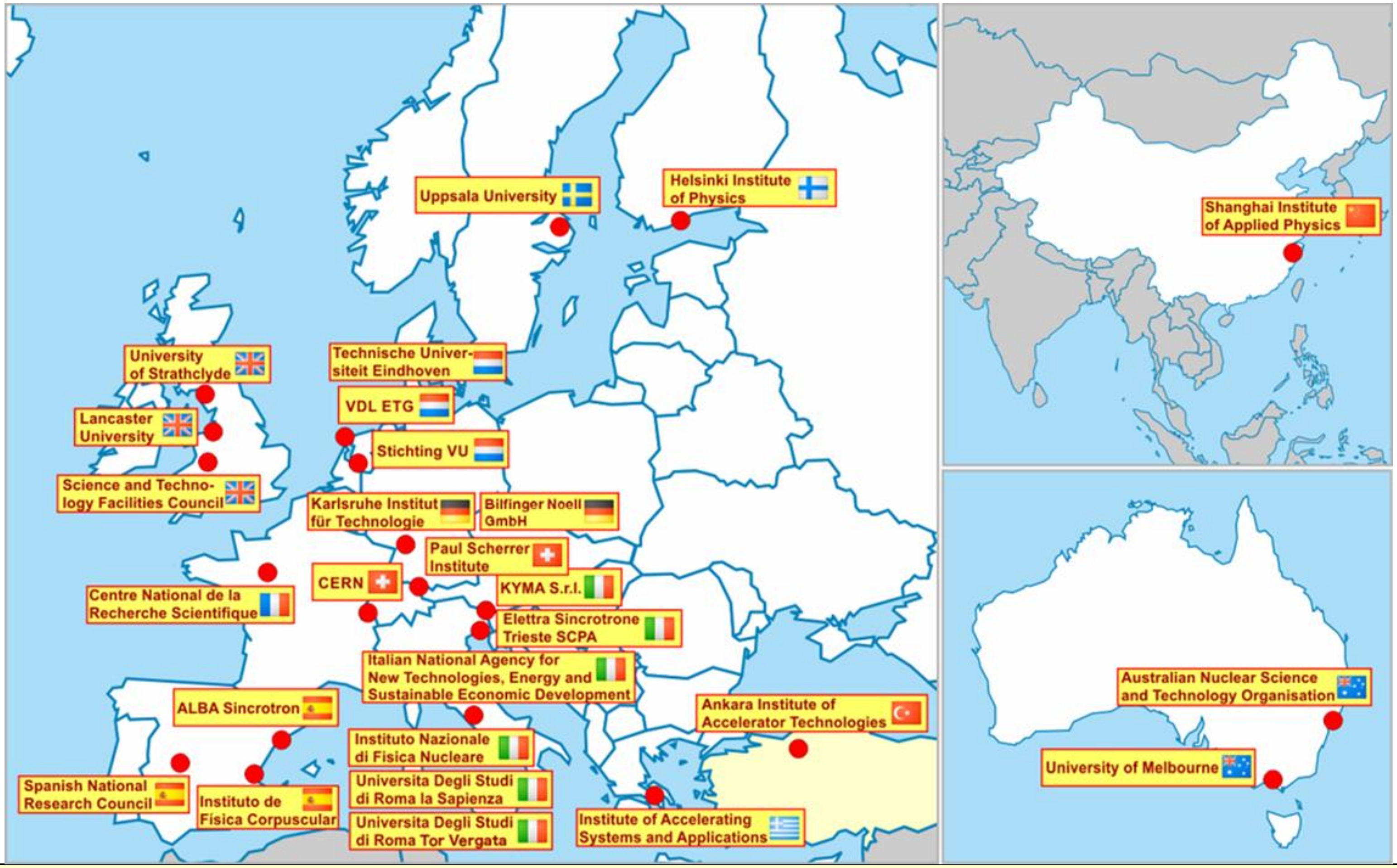

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