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Compact

The CompactLight Design Study

http://CompactLight.eu

Gerardo D'Auria

Elettra- Sincrotrone Trieste

on behalf of the CompactLight Collaboration (XLS)

13th International Workshop on Breakdown Science and High-Gradient Technology, HG2019
19-22 April 2021

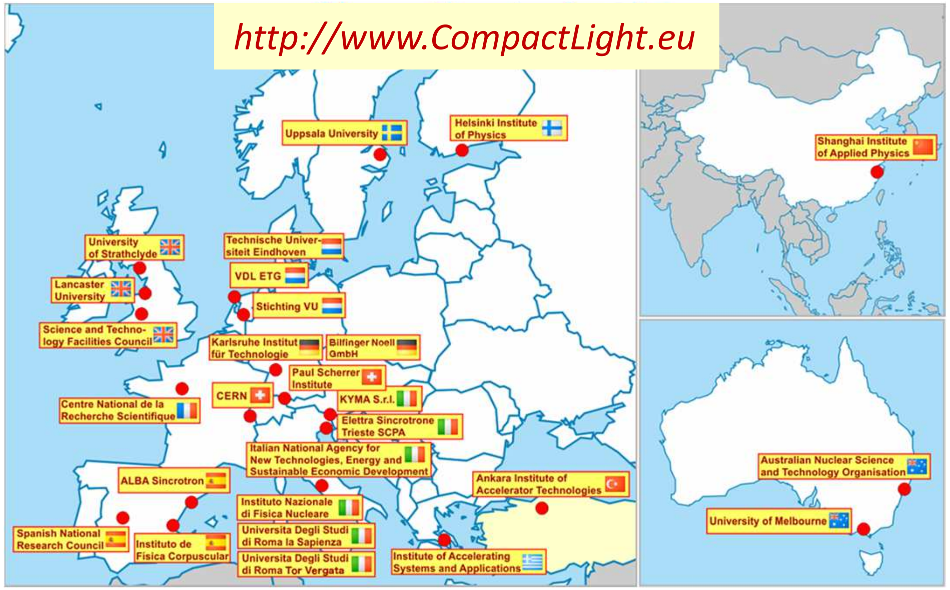
Outline

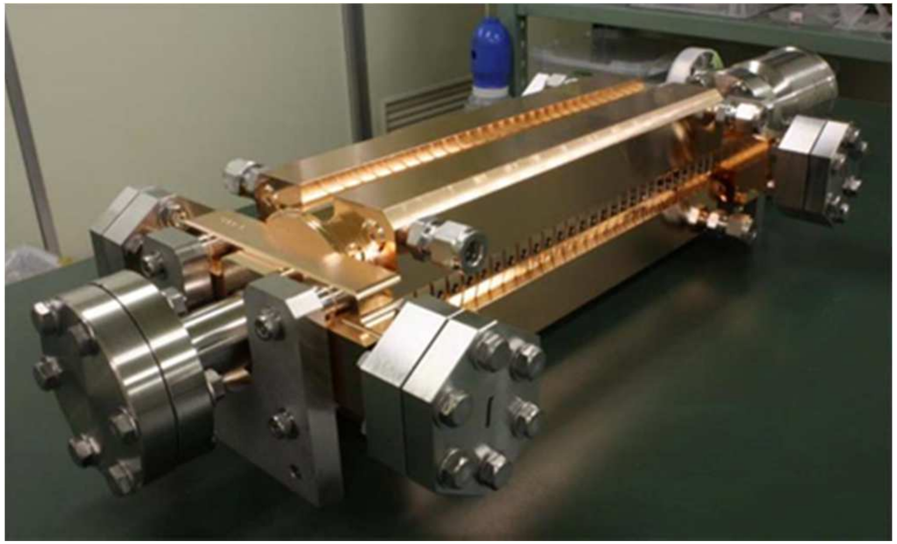
- Context
  - The XLS Collaboration
  - Aims & Motivations
- Timeline & Deliverables
- Work Packages
- Facility design
  - Facility layout
  - Expected performance
  - Ongoing activities

The XLS Collaboration

- The XLS Collaboration gathers several International Laboratories with the aim to promote the design and 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.





Our aim 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 an optimum combination of emerging and innovative accelerator technologies:

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

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XLS Partners

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 Instritut 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 Techn. DOO	Slovenia

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

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Gantt chart_Meetings & Deliverables

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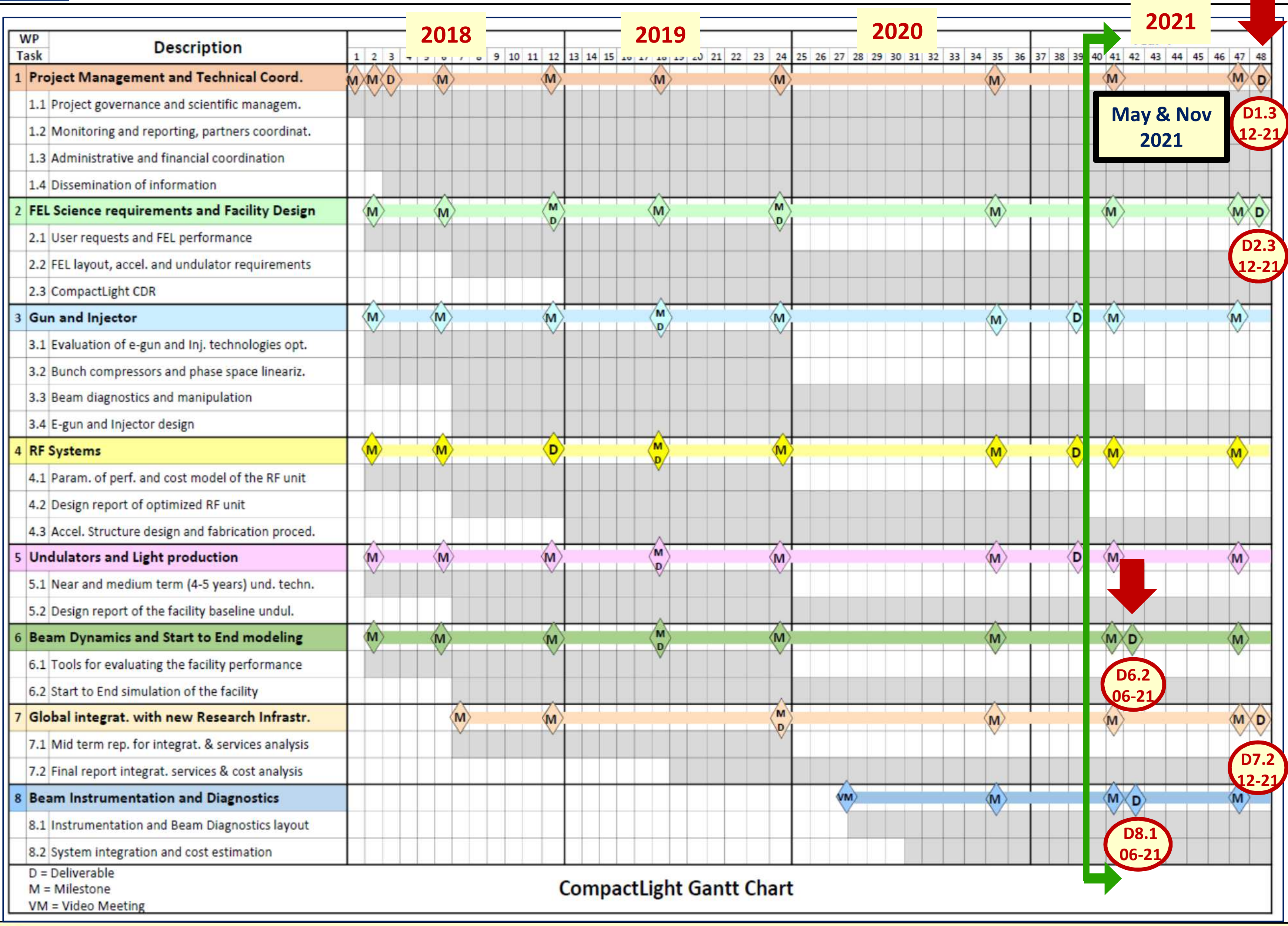
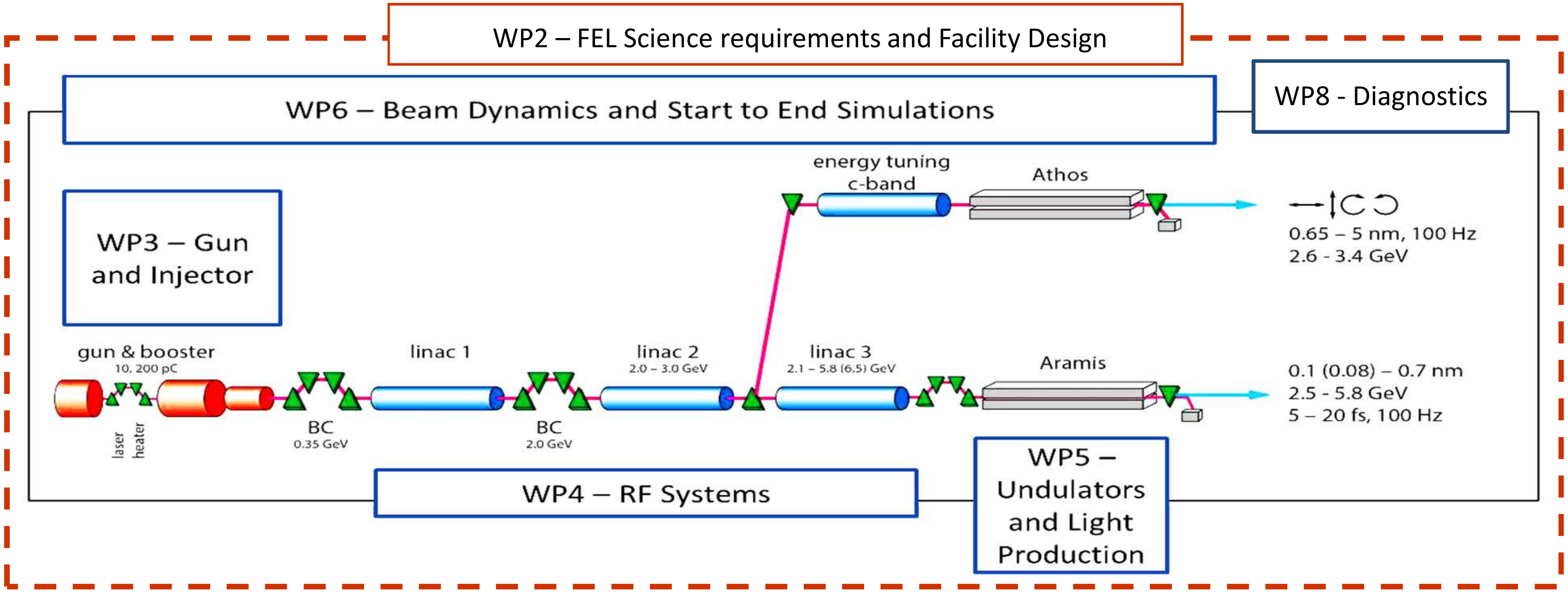


Deliverables

Status	Del.	Deliverable name	WP Lead part.	Type Del. date	Year
OK		CompactLight Public Website.	WP1-ST	DEC-PU-M3	2018
OK	D1.2	Data Management Plan	WP1-ST	ORDP-PU-M6	2018
OK	D2.1	Report providing users requirements and FEL performance specification.	WP2-STFC	R-PU-M12	2018
OK	D3.1	Evaluation report of the optimum e-gun and injector solution for the XLS CDR.	WP3-INFN	R-PU-M18	2019
OK	D3.2	A review report on the bunch compression techniques and phase space linearization	WP3-INFN	R-PU-M18	2019
OK	D4.1	Computer code report for RF power unit design and cost optimization.	WP4-CERN	R-PU-M18	2019
OK	D5.1	A review report comparing the different technologies for the CompactLight undulator.	WP5-ENEA	R-PU-M18	2019
OK	D6.1	Review report on the most advanced computer codes for the facility design	WP6-UAIAT	R-PU-M18	2019
OK	D2.2	Report summarizing the FEL design with accelerator and undulator requirements.	WP2-STFC	R-PU-M24	2019
OK	D7.1	Mid-term report with CompactLight global integration and cost analysis	WP7-ST	R-PU-M24	2019
		COVID 19 pandemic ---> 2020 Deliverables postponed to 2021			
OK	D3.3	Design report of the injector diagnostics/beam manipulations based on a X-band cavities	WP3-INFN	R-PU-M39	2021
OK	D3.4	E-gun and injector Design Report with diagnostics and phase space linearizer	WP3-INFN	R-PU-M39	2021
OK	D4.2	Design report of the optimized RF unit	WP4-CERN	R-PU-M39	2021
OK	D4.3	Report on RF unit design and fabrication procedure	WP4-CERN	R-PU-M39	2021
OK	D5.2	Conceptual Design Report of the undulator	WP5-ENEA	R-PU-M39	2021
30 June	D6.2	Final report with start to end facility simulations	WP6-UAIAT	R-PU-M42	2021
30 June	D8.1	XLS electron and photon beam biagnostics	WP8-UniTor	R-PU-42	2021
31 Dec.	D7.2	Final report with CompactLight global integration analysis, services and cost.	WP7-ST	R-PU-M48	2021
31 Dec.	D2.3	Hard X-ray FEL Conceptual Design Report.	WP2-STFC	R-PU-M48	2021
31 Dec.	D1.2	Production of a short monograph summarizing the Conceptual Design Report.	WP1-ST	R-PU-M48	2021

WPs Structure

Work Package		Lead Participant	Person Months
WP1	Project management and Technical Coordination	Elettra - ST (G. D'Auria)	32
WP2	FEL Science Requirements and Facility Design	STFC (J. Clarke)	68
WP3	Gun and Injector	INFN (M. Ferrario)	76
WP4	RF systems	CERN (W. Wuensch)	78
WP5	Undulators and Light production	ENEA (F. Nguyen)	81
WP6	Beam dynamics and Start to End Modelling	UA-IAT (A. Aksoy)	78
WP7	Global Integration with new Research Infrastructure	Elettra - ST (R. Rochow)	27
WP8	Beam Diagnostics and Instrumentation	UniTor (A. Cianchi)	27
		Total	456



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FEL parameters

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The facility design and FEL Parameters have been driven by Users' requirements and associated science cases

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

These will be unique and very desirable features of XLS design

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CompactLight Performance

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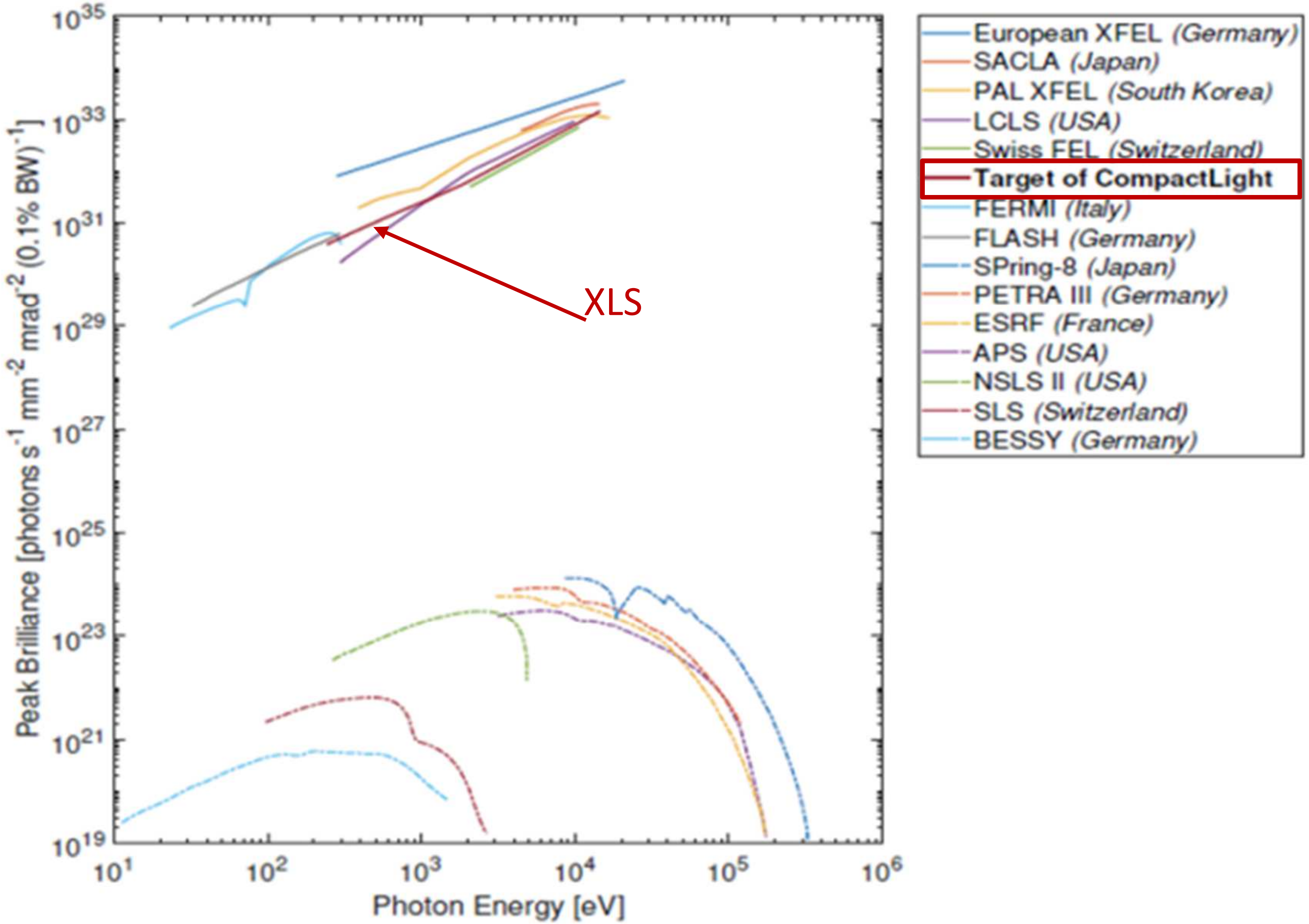
Anticipated XLS performance compared with other existing facilities



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Linac operating parameters

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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	$\times 2$
Peak spectral brightness @16 keV	10^{33} ph/s/mm^2/mrad^2/0.1%bw

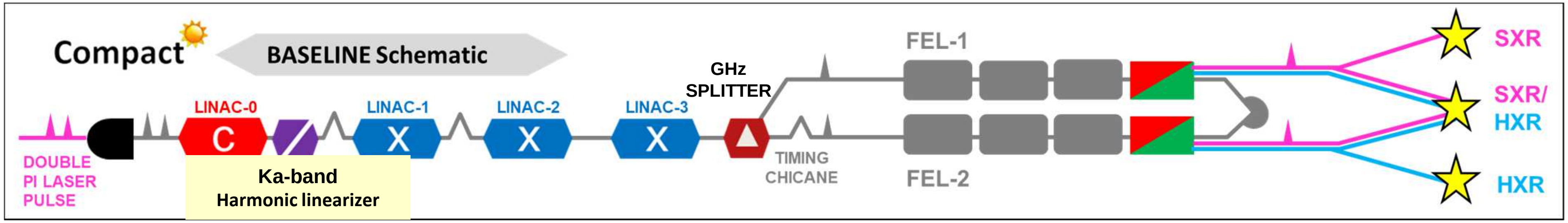
Electron beam parameters at the undulator entrance (HXR)

RF operating scenarios:

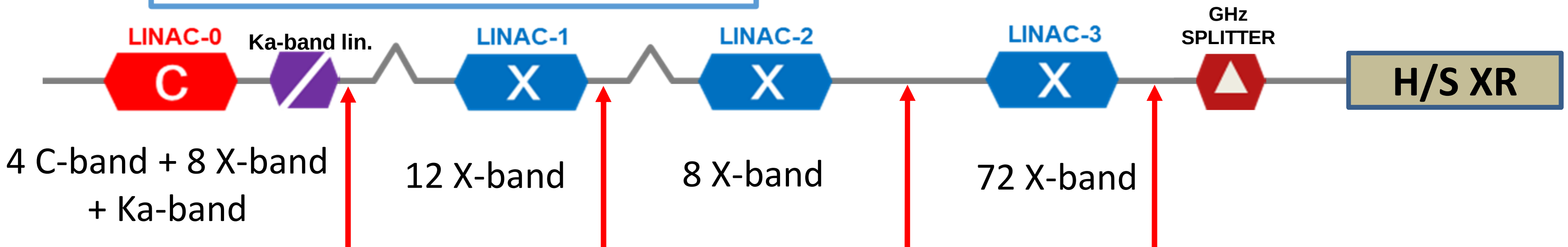
- **B: dual mode (Baseline)**
- **Dual source (Upgrade 1 & 2)**

Parameter	Unit	Dual mode		Dual source	
Operating Mode		B		U1, U2	
Repetition rate	kHz	0.1	0.25	0.1	1
Linac active length	m	94			
Number of structures		104			
Number of modules		26			
Number of klystrons		26		26 + 26	
Peak acc. gradient	MV/m	65	32	65	30.4
Energy gain per module	MeV	234	115	234	109
Max. energy gain	MeV	6084	2990	6084	2834

Linac layout



Main linac, lenght ~ 216 m



100 Hz	300 MeV	0.98 GeV	1.43 GeV	5.50 GeV	→ Hard X-ray
1000 Hz	300 MeV	0.57 GeV	0.76 GeV	2.40 GeV	→ Soft X-ray

X-band accelerating structures operate at different gradients for 100 and 1000 Hz

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XLS baseline layout

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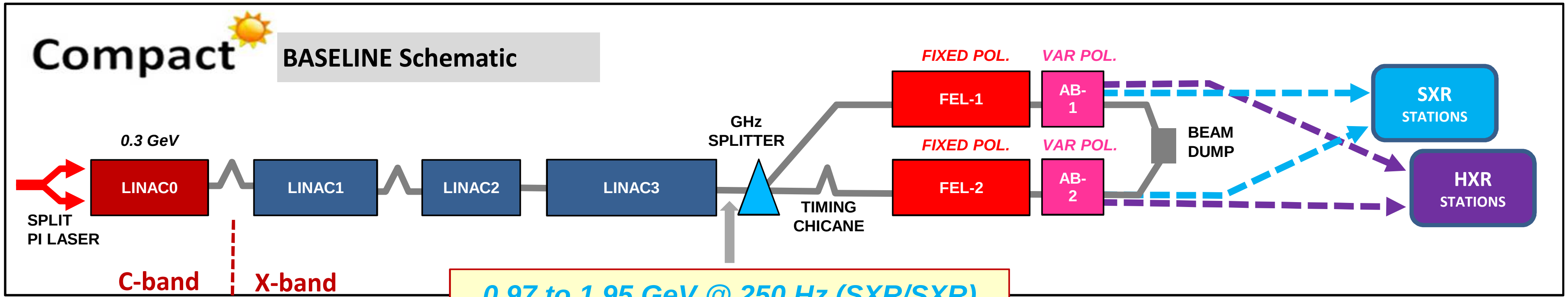

0.97 to 1.95 GeV @ 250 Hz (SXR/SXR)
2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)

1 klystron x LINAC Module operating in dual mode with pulse shortening

Ref. CPI VKX-8311A

HXR		SXR
50 MW, 1.5 μs, 100 Hz $<E_{acc}> = 65$ MV/m	→	50 MW, 150 ns, 250 Hz $<E_{acc}> = 32$ 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 T_{trans}
- Klystron operated always at its nominal working point

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XLS upgraded layouts

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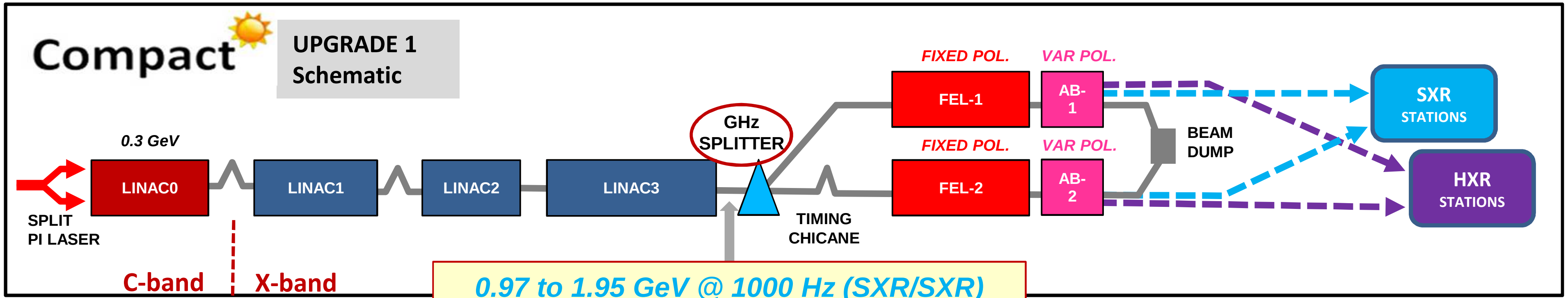
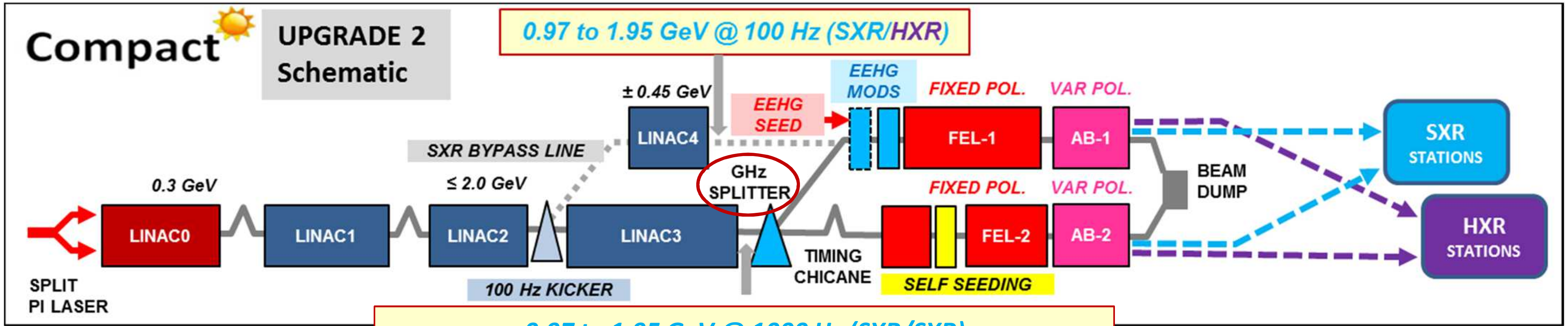


0.97 to 1.95 GeV @ 1000 Hz (SXR/SXR)
2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)



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

Operating modes, output energies & repetition rates

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

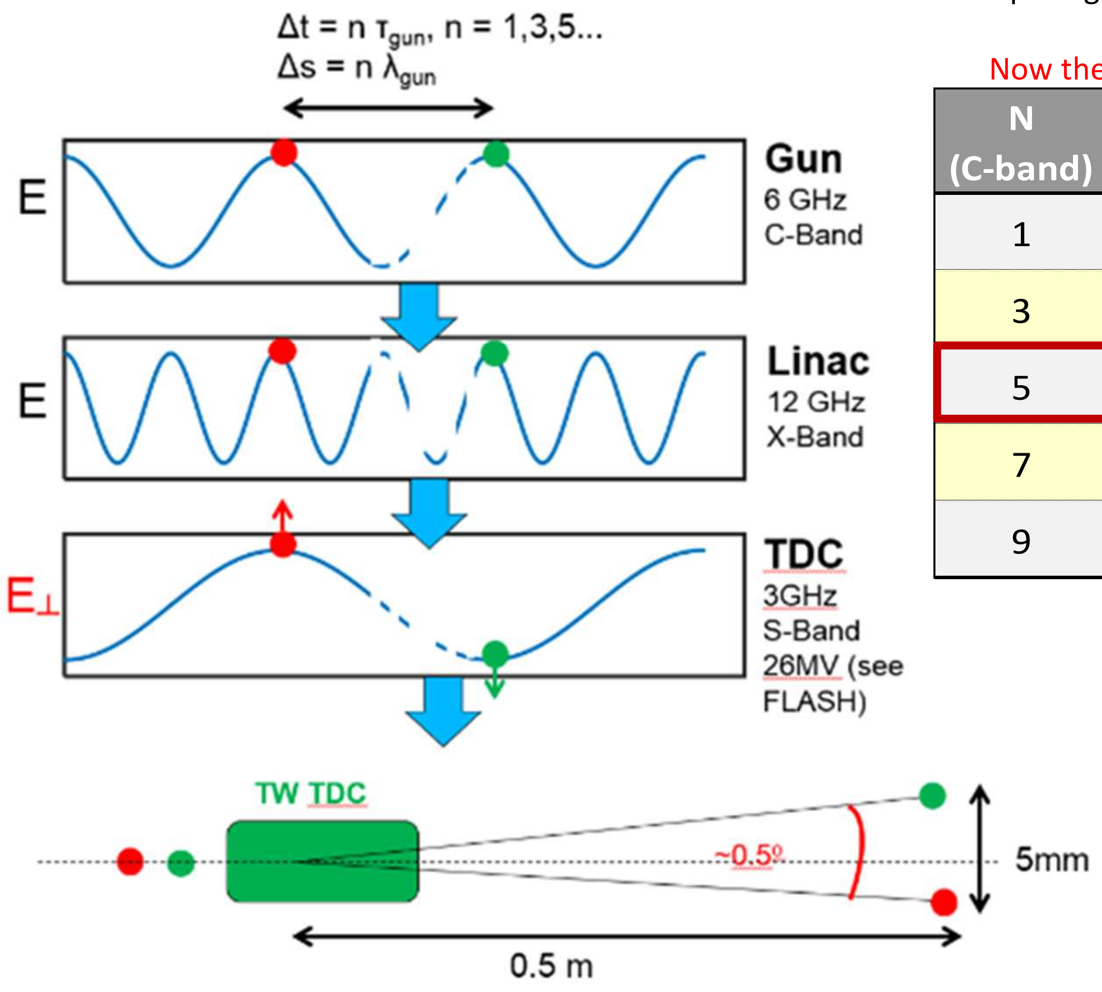
Legenda:

B = Baseline
U1 = Upgrade 1
U2 = Upgrade 2

HH = Twin Hard X-ray pulses
SS = Twin Soft X-ray pulses
SH = Soft and Hard X-ray pulses simultaneous

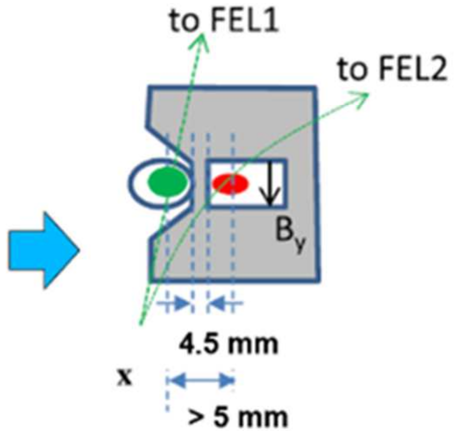
Dual bunch operation

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

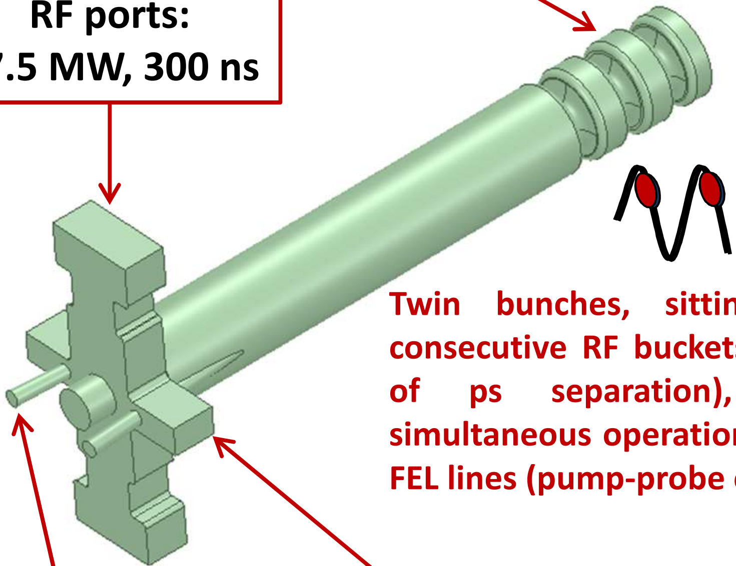
N (C-band)	Δt (ps)	Δs (mm)	N (X-band)
1	166	50	2
3	500	150	6
5	833	250	10
7	1.16	350	14
9	1.5	450	18



C-band photoinjector

2.5 accelerating cells

RF ports:
17.5 MW, 300 ns



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.)

TiSa
Laser ports

Pumping ports

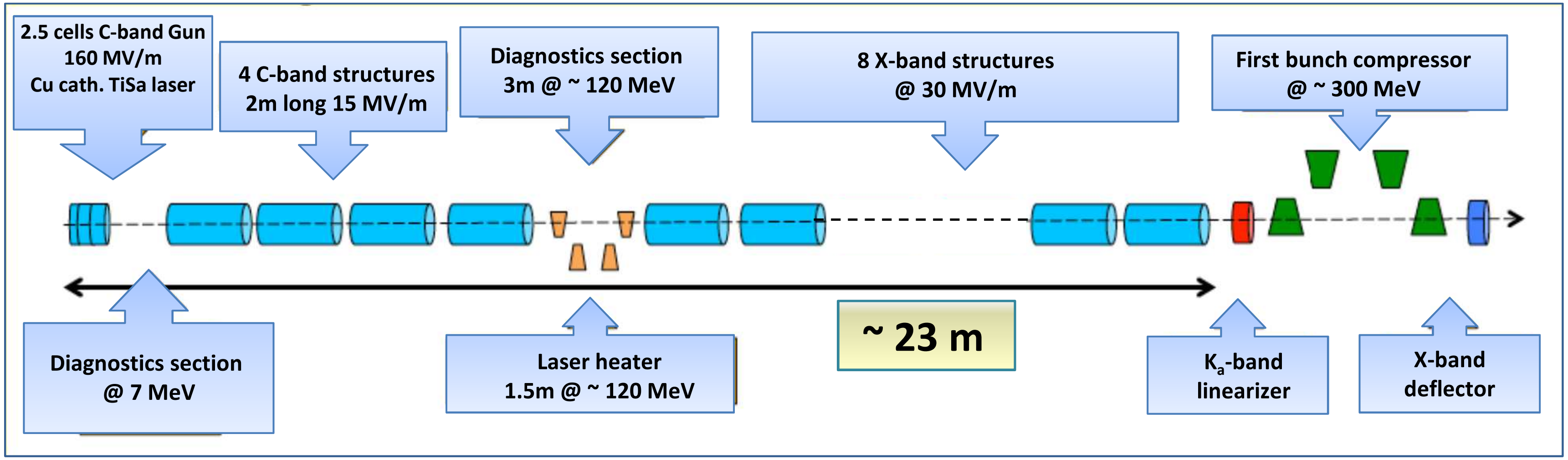
E_{cath}	160 MV/m
$\Delta f_{\pi/2-\pi}$	≈ 52 MHz
Q_0	11600
β	3
Filling time (τ_F)	160 ns
P_{diss} @160MV/m	9.7 MW
$E_{CAT}/\sqrt{P_{diss}}$	51.4 [MV/m/(MW)$^{0.5}$]
Rep. Rate	1000 Hz
Peak Input power P_{IN}	17.5 MW
Pulsed heating (T_{puls})	<20 °C
RF pulse length (T_{RF})	300 ns
Av diss power (P_{av})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

Courtesy M. Diomede

C-band injector

Same injector for **High and Low** repetition rate operations

(1 KHz and 100 Hz)



Courtesy M. Ferrario

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C-band RF module

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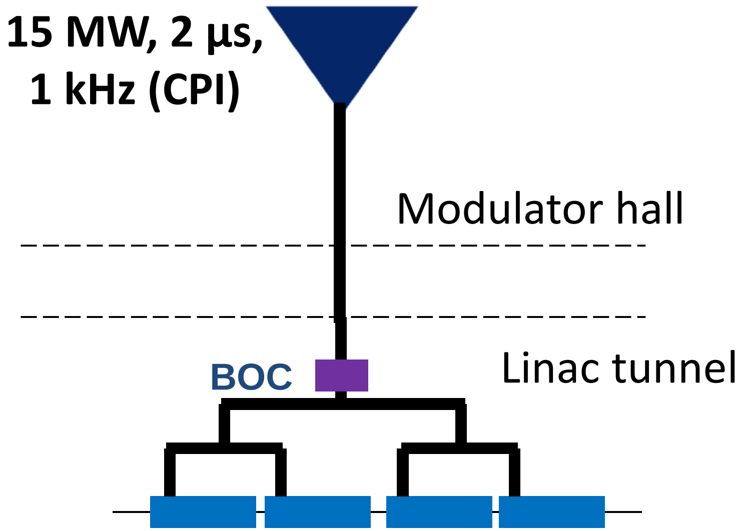
RF System	
Operating frequency [GHz]	5.996
Klystron pulse length [us]	2
Klystron peak power [MW]	15
Pulse rate [pps]	1000
Q0 of BOC	216000
Qe of BOC	19100



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

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X-band RF module

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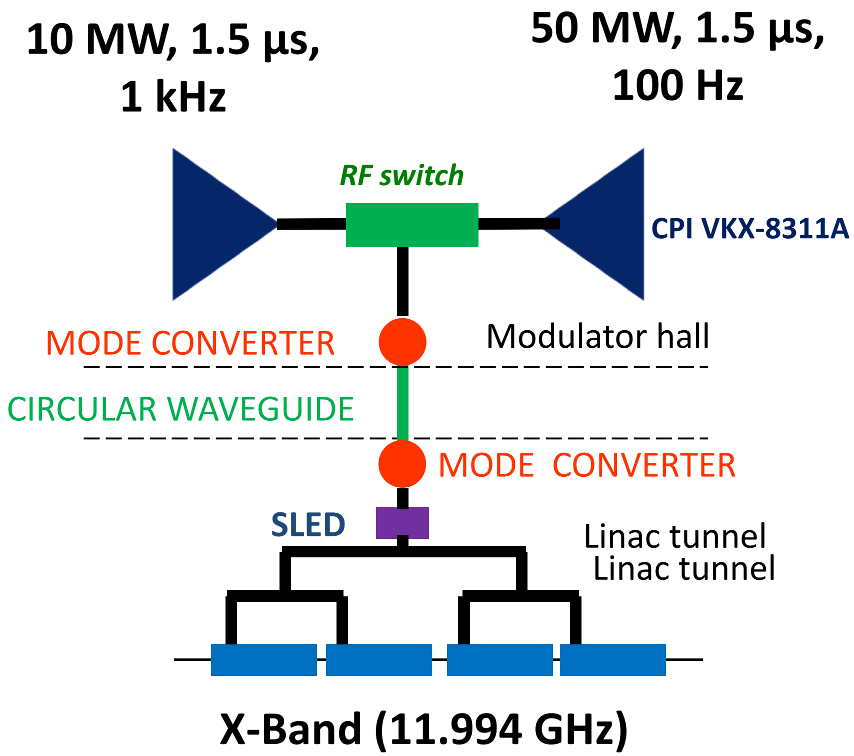
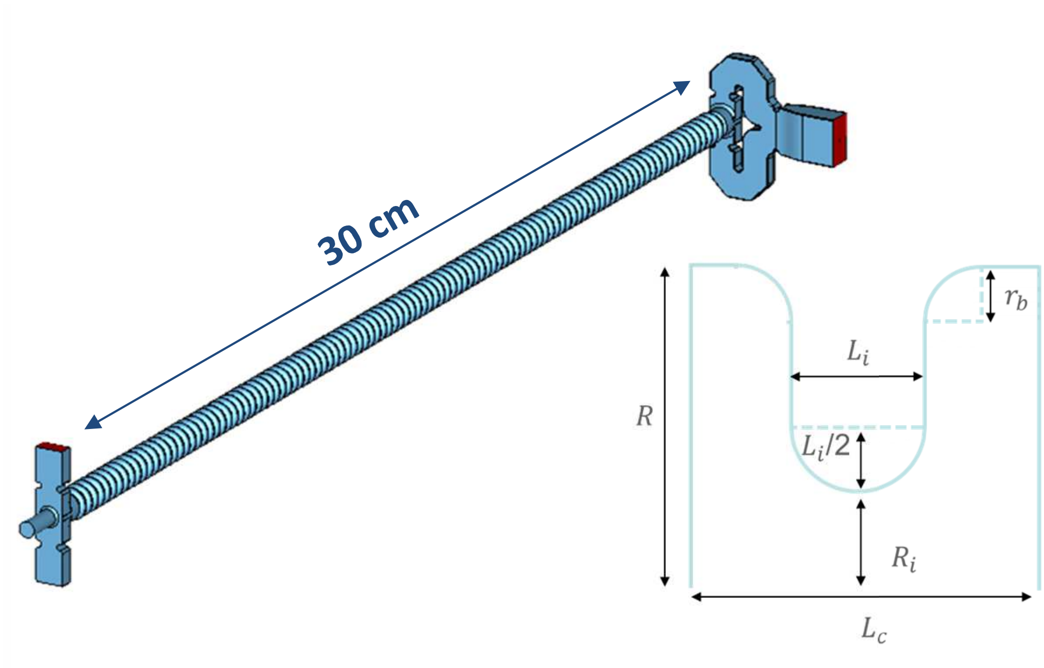


Frequency [GHz]	**11.994**		
RF pulse (250 Hz) [μs]	1.5 (0.15)		
Average iris radius <a> [mm]	3.5		
Iris radius a [mm]	4.3-2.7		
Iris thickness t [mm]	2.0-2.24		
Structure length L_s [m]	0.9		
Unloaded SLED Q-factor Q_0	180000		
External SLED Q-factor Q_E	23300		
Shunt impedance R [MΩ/m]	85-111		
Effective 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

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

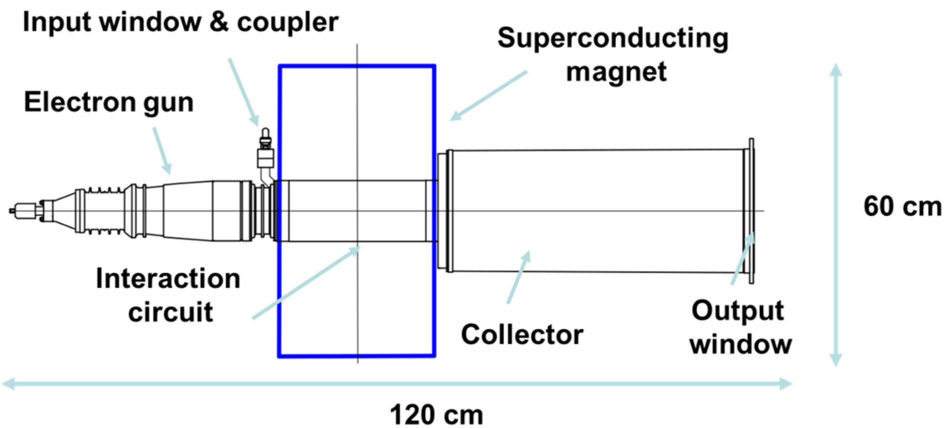
Ka-band RF sources

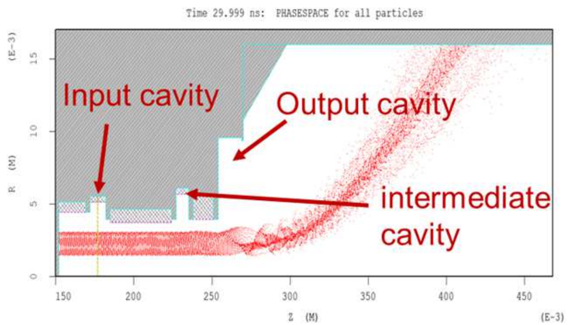
Two possible designs could provide ~3 MW at 1 kHz:

a) **gyro-klystron**

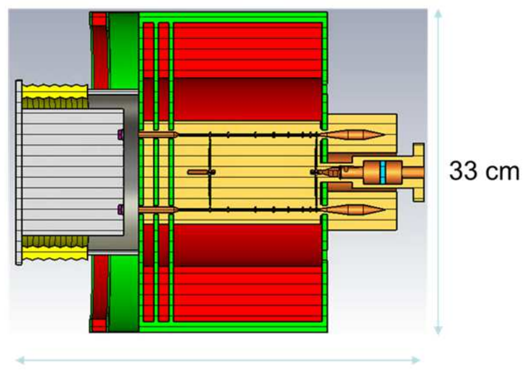
b) **multi-beam klystron**

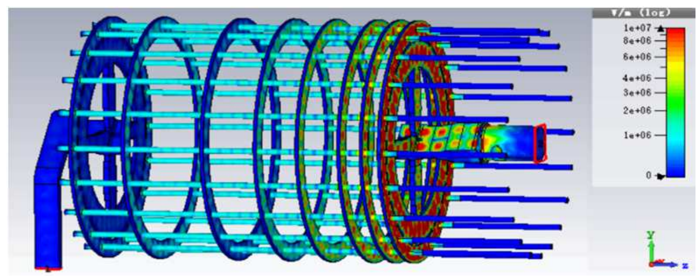
Gyro-klystron





Multi-beam klystron



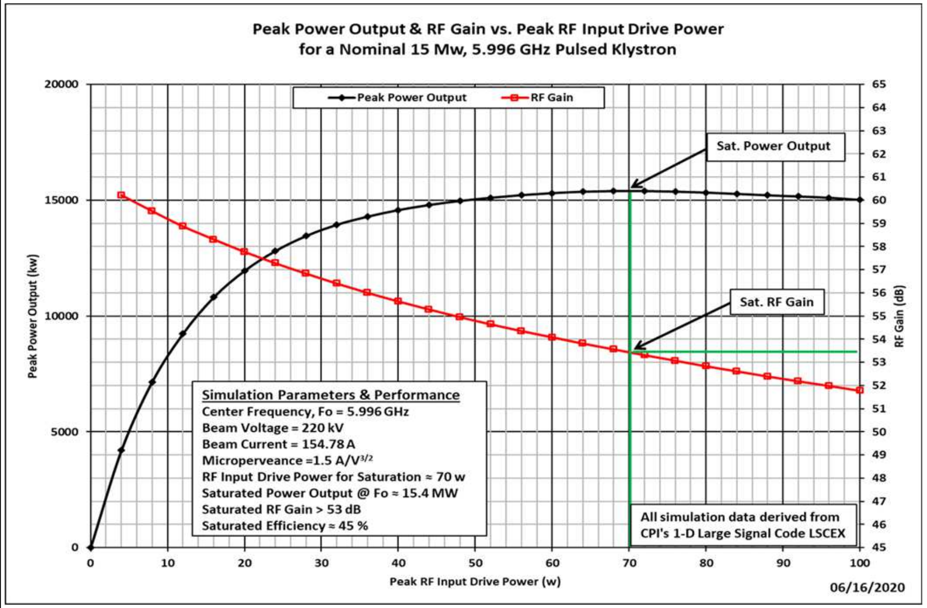


Courtesy by G. Burt, A. Cross, I. Syratchev

C-band klystron developments

Preliminary design of a 15 MW, 5.996 GHz klystron (p.r.r. up to 1KHz)

Parameter	Min	Nom	Max	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 Freq.	400	----	1000	Hz
Video Duty Factor	----	0.3	----	%
RF Duty Factor	----	0.2	----	%
Instantaneous Saturated BW < 0.2dB power variat.	----	>6	----	MHz
VSWR Tolerance	----	----	1.2:1	----



Courtesy of CPI Comm. & Power Ind.

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X-band klystron developments

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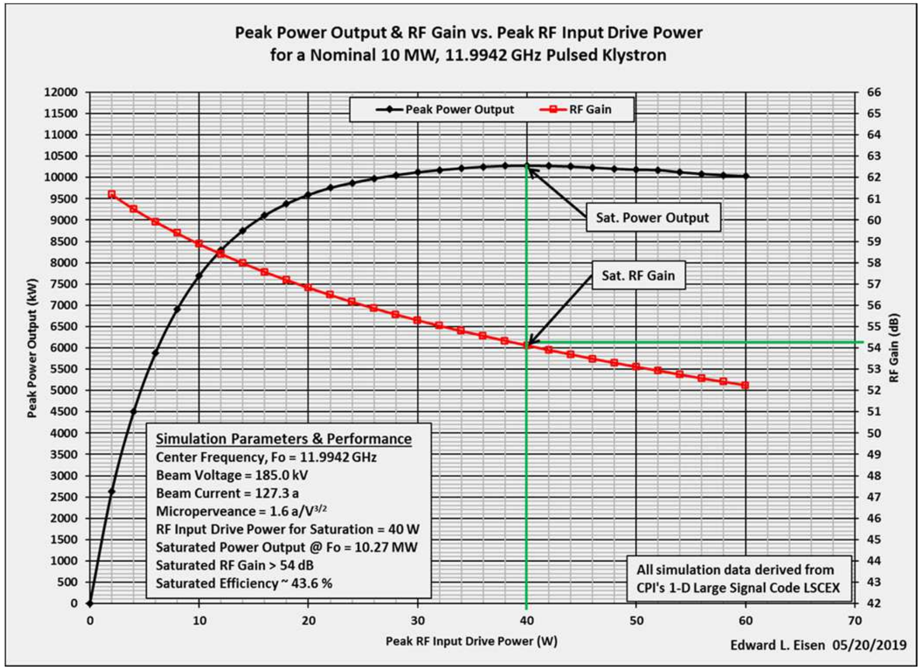
Preliminary design of a 10 MW, 11.9942 GHz klystron (p.r.r. up to 1KHz)

Parameter	Min	Nom	Max	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 Freq.	50	----	400	Hz
Video Duty Factor	----	0.3	----	%
RF Duty Factor	----	0.2	----	%
Instantaneous Saturated BW < 0.2dB power variat.	----	>40	----	MHz
VSWR Tolerance	----	----	1.2:1	----

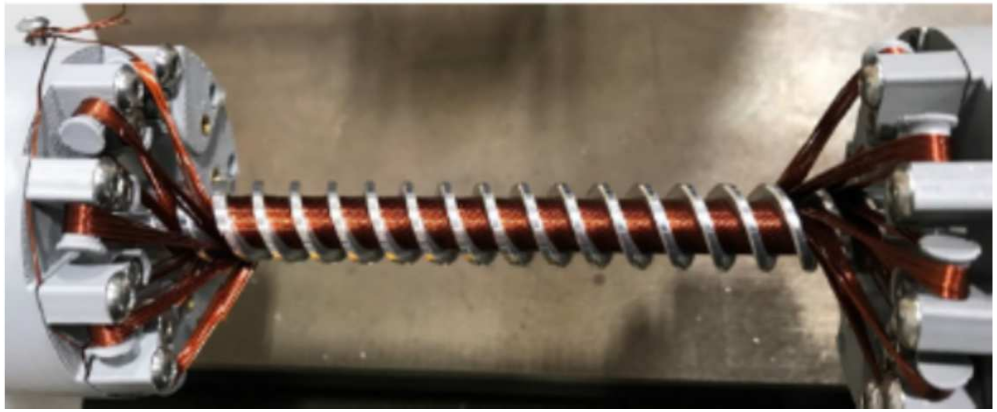


Courtesy of CPI Comm. & Power Ind.

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

Conclusions

- ✓ Project is running well and all the WPs are progressing according to the time schedule.
- ✓ CompactLight will offer advanced and challenging FEL schemes with a wide range of operating modes, using affordable, efficient, normal conductive RF X-band technology and SC undulators.
  - Operation with two bunches up to 1 KHz.
  - Simultaneous operation of HXR and SXR at 100 Hz.
- ✓ The extension of the machine operation up to 1 KHz will represent a big step forward for the FEL community and will pave the way for further applications of the XLS technology.

Thank you!

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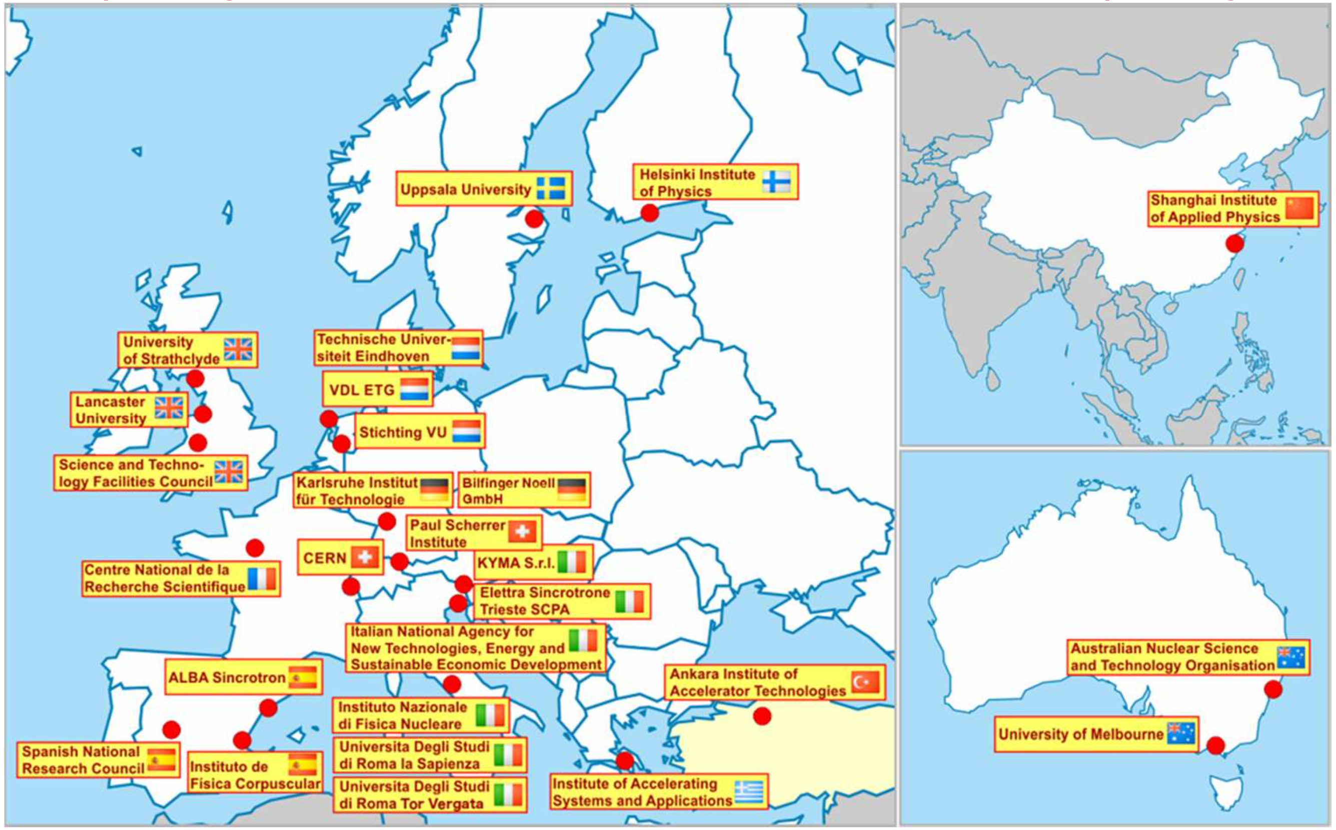

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