The CompactLight Design Study (XLS)

www.compactlight.eu

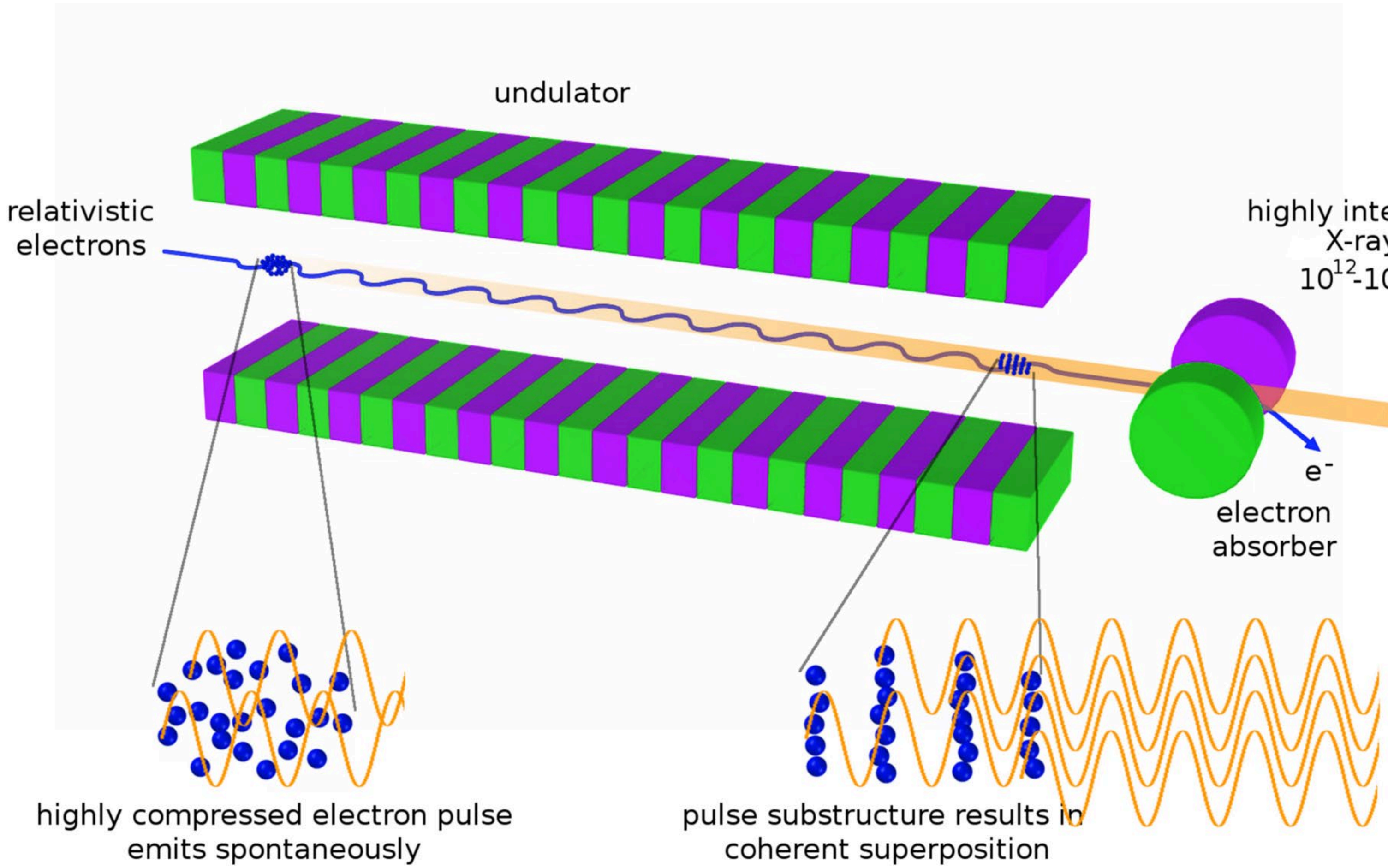
Horizon2020 - Work Programme 2016 – 2017
Research & Innovation Action (RIA)
INFRADEV-1-2017 Design Studies
[01/01/2018 – 31/12/2021]

Andrea Latina (CERN)

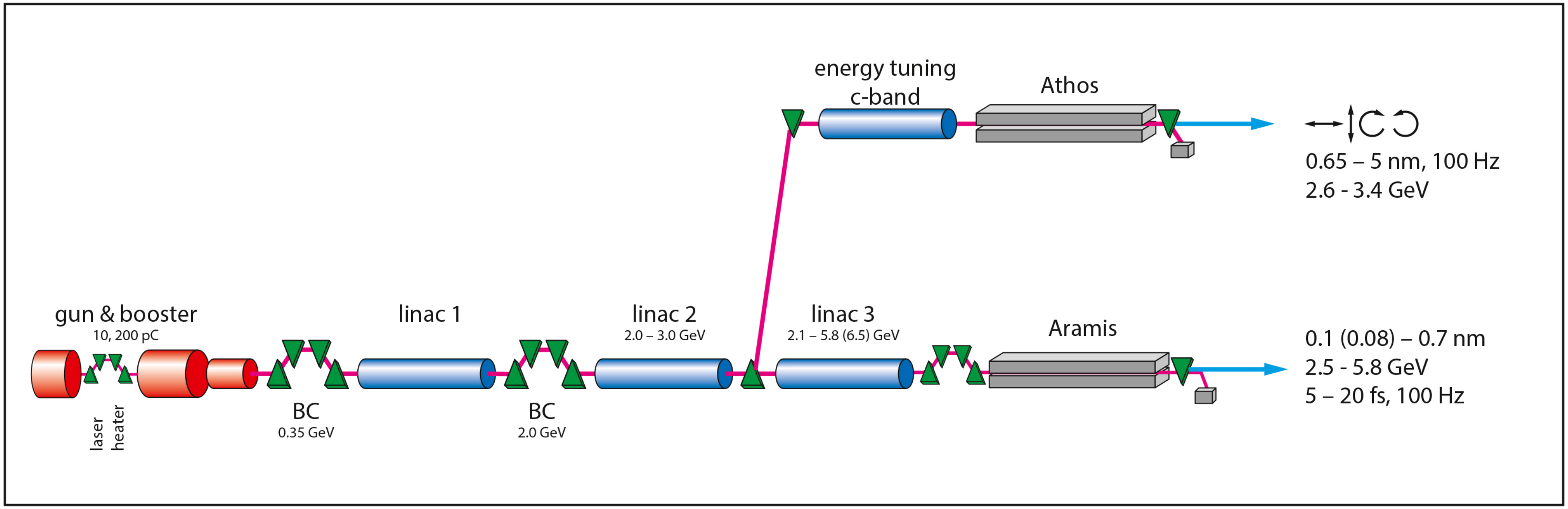
on behalf of the CompactLight Collaboration

Highly-compressed electron bunches

as sources of intense X-rays

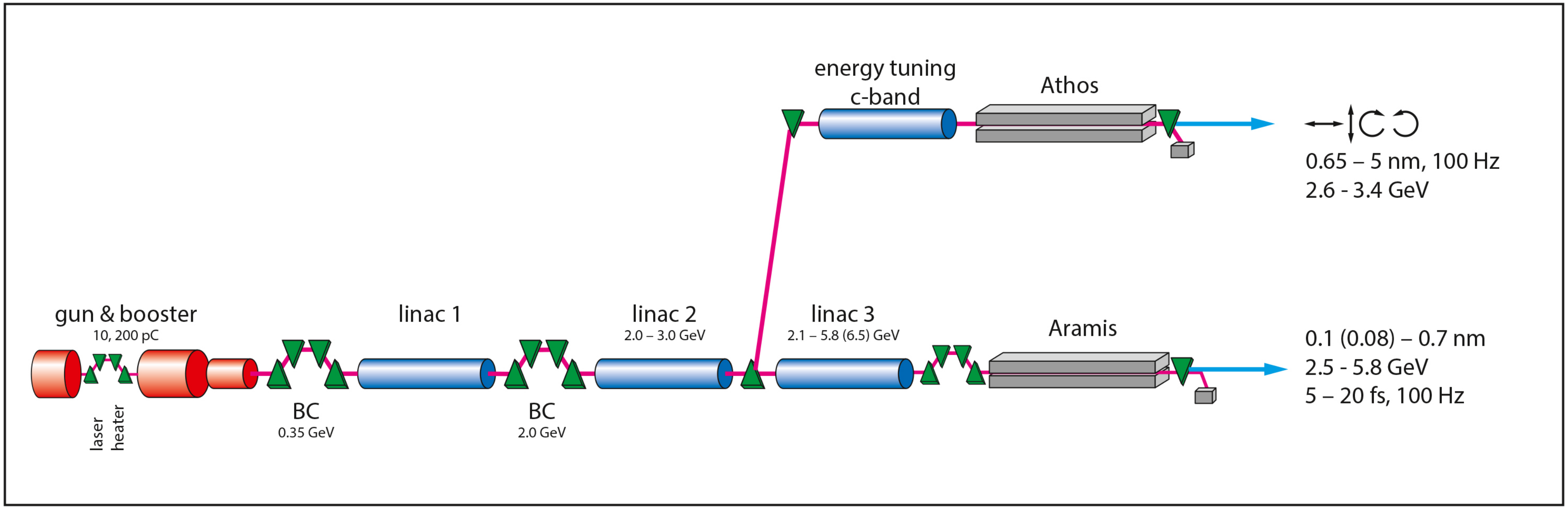


E.g., SwissFEL @ PSI



E.g., SwissFEL @ PSI

Main parameters	
Wave length	1A -50Å
Photon energy	0.25-12 keV
Pulse duration	1fs - 20fs
e Energy	5.8 GeV
e Bunch charge	10 - 200 pC
Repetition rate	100 Hz



SwissFEL Facility

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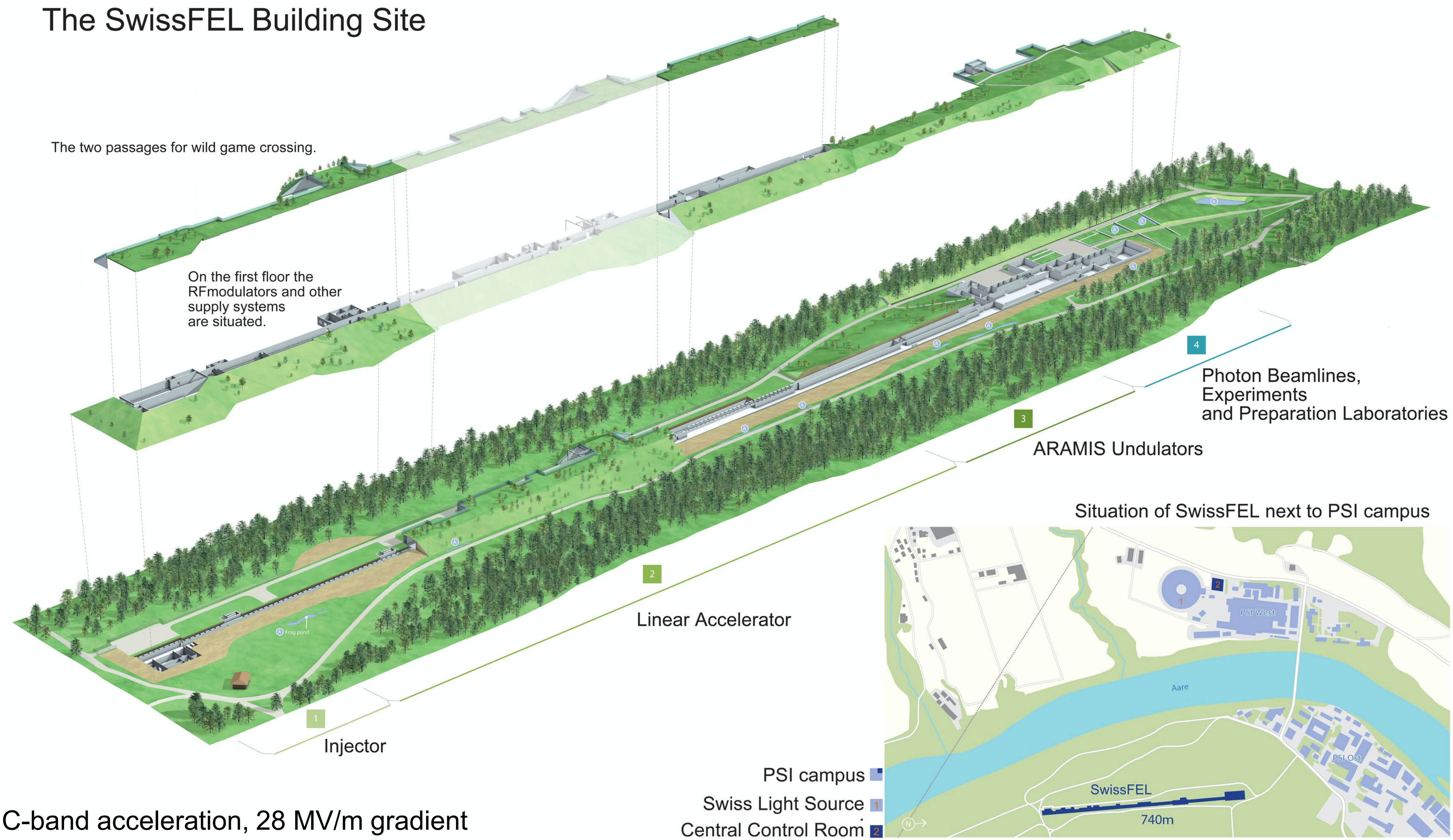

C-band acceleration, 28 MV/m gradient

The facility has a total length of 740 m

The CERN Compact Linear Collider (CLIC)

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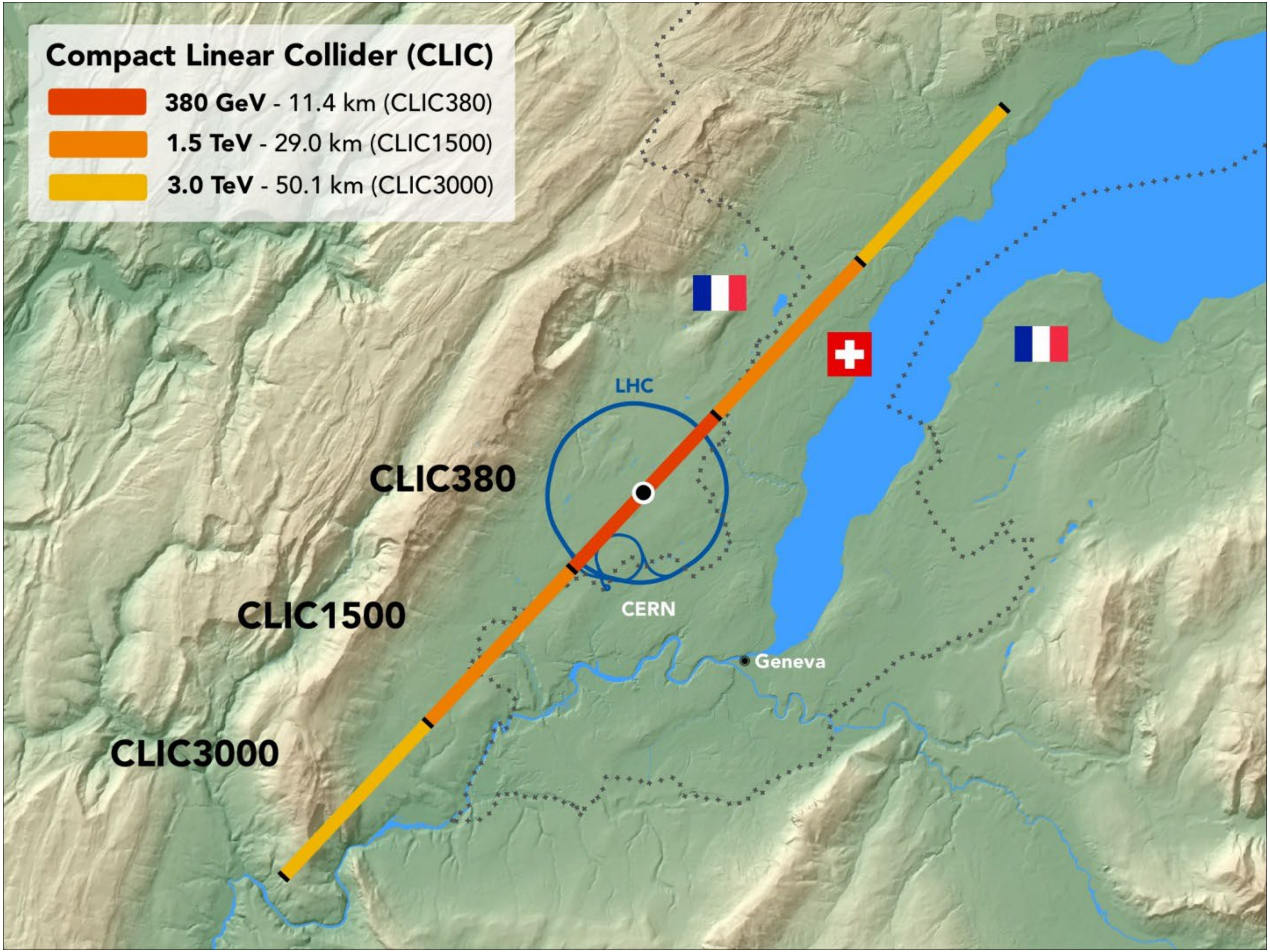
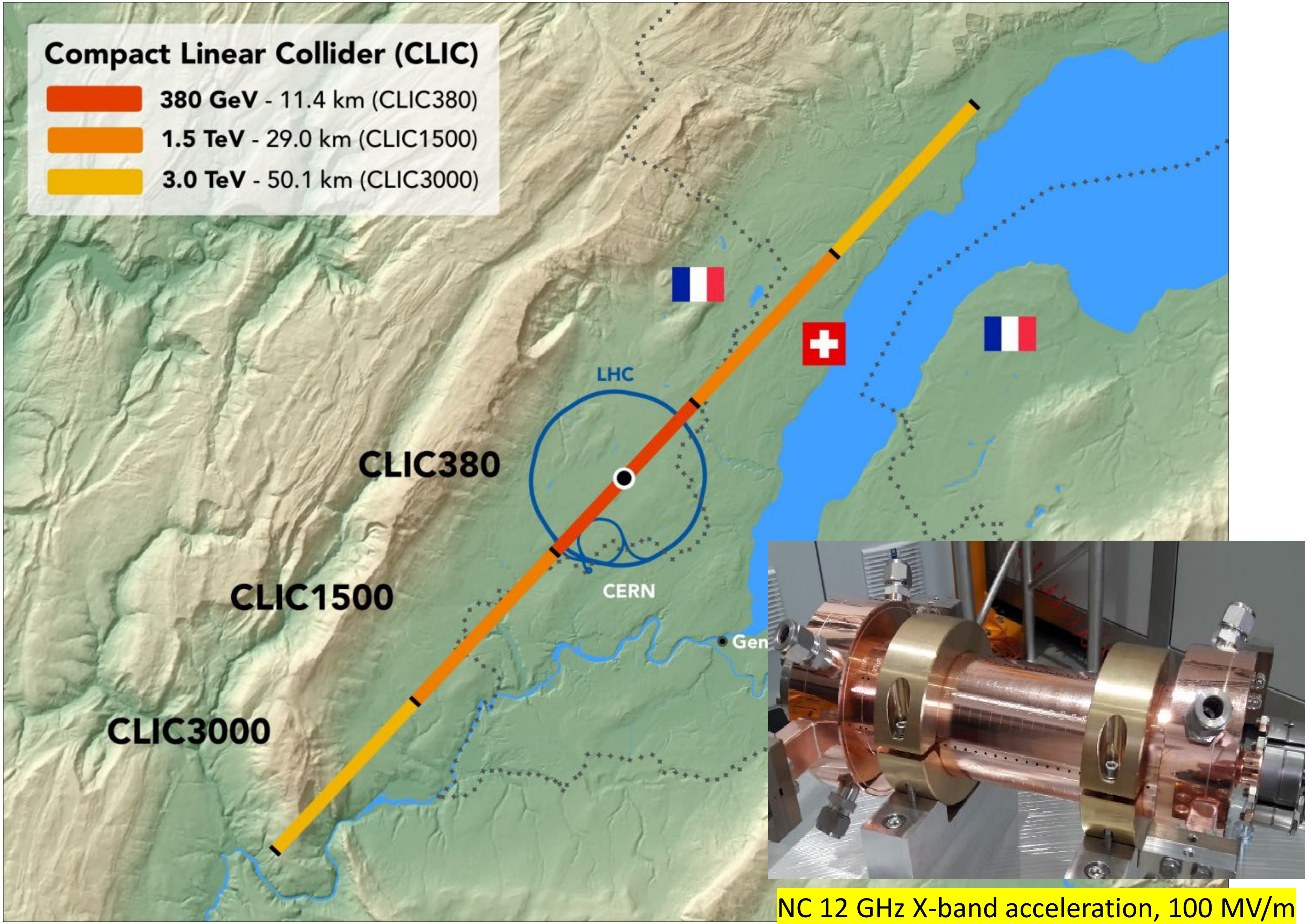


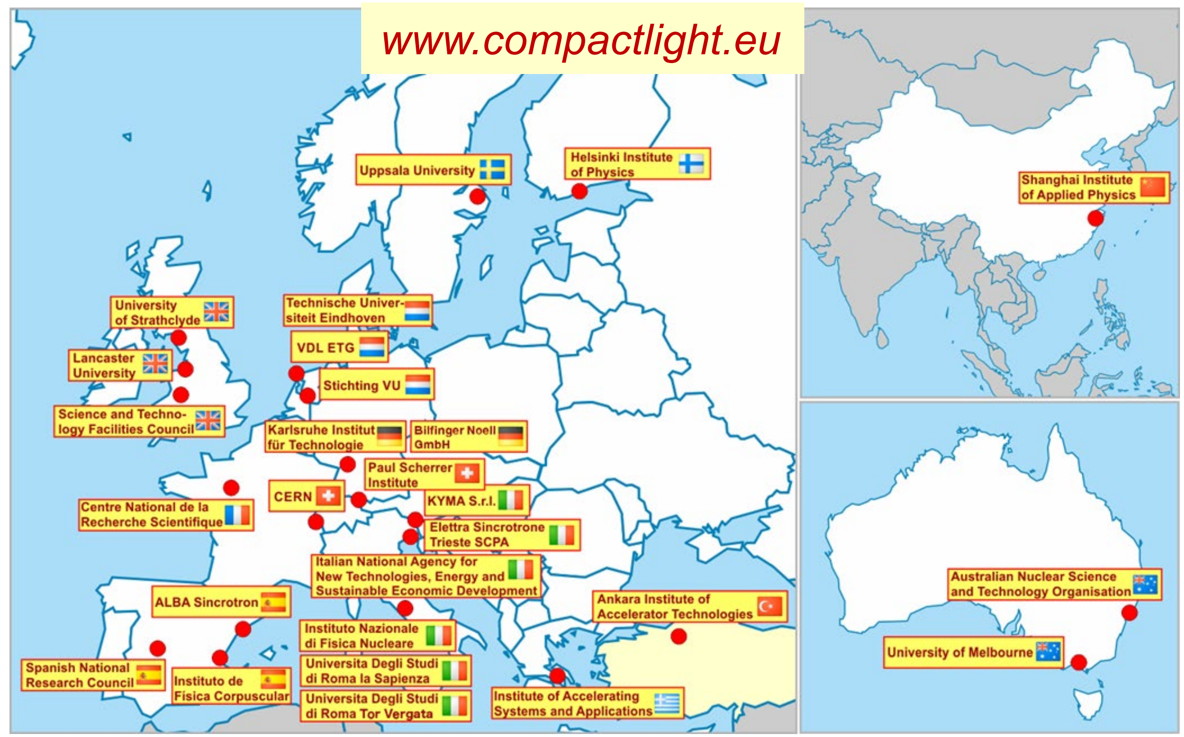
The CERN Compact Linear Collider (CLIC)

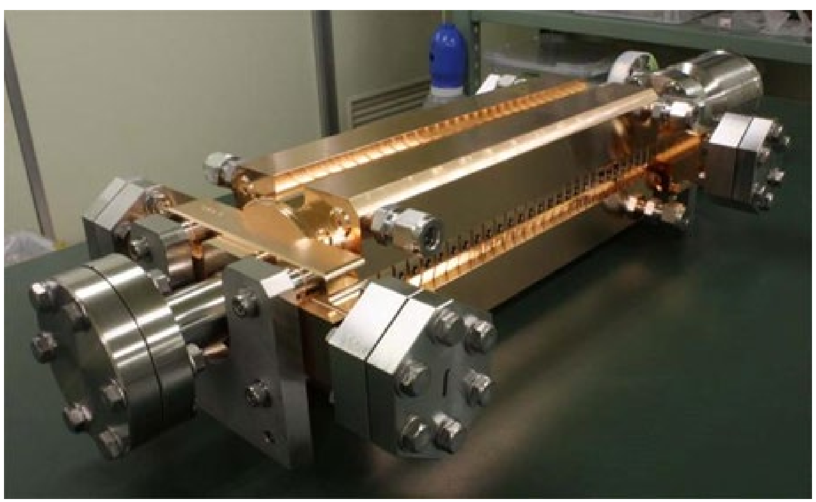


NC 12 GHz X-band acceleration, 100 MV/m

The CompactLight Collaboration

- The XLS Collaboration gathered 26 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.

We made use of the latest concepts for:

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

Collaboration Partners

Compact

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

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

Technical WPs Structure

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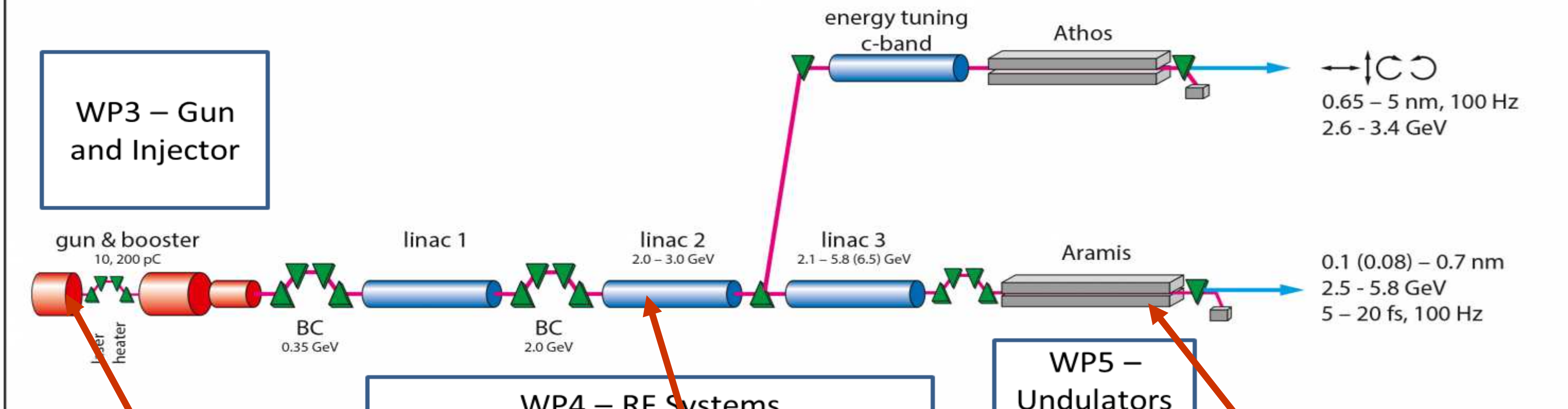
WP2 – FEL Science requirements and Facility Design

WP6 – Beam Dynamics and Start to End Simulations

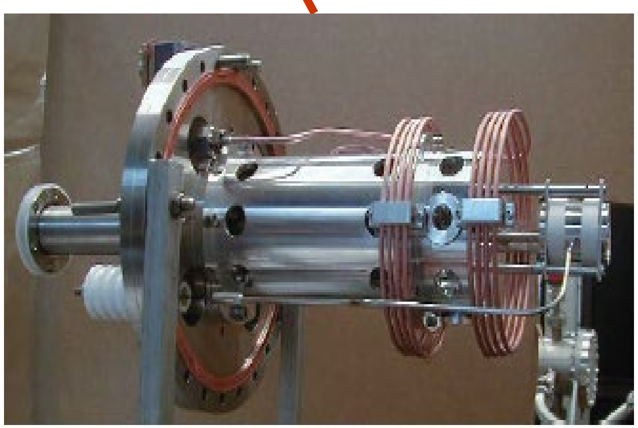
WP8 - Diagnostics

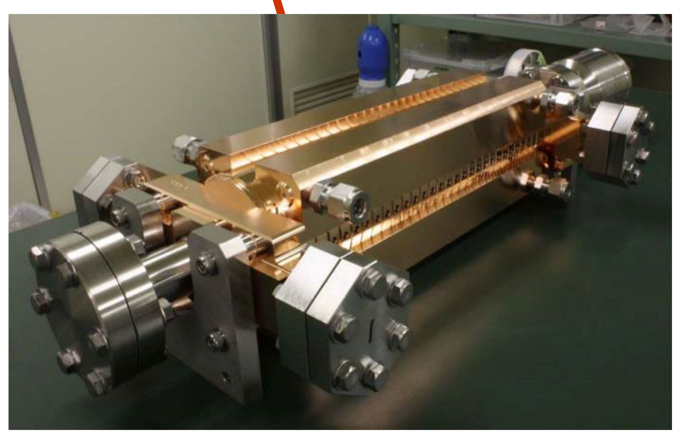
WP3 – Gun and Injector

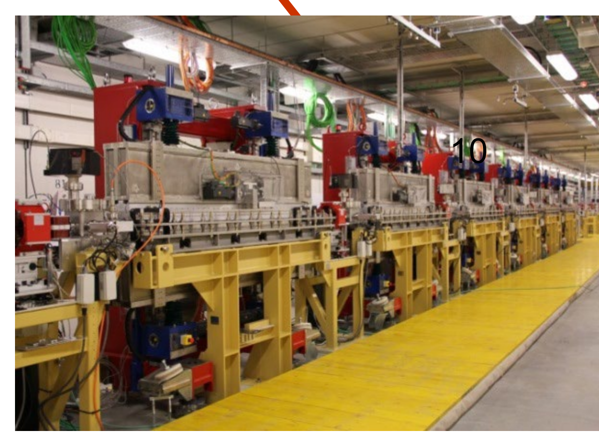


WP4 – RF Systems

WP5 – Undulators and Light Production

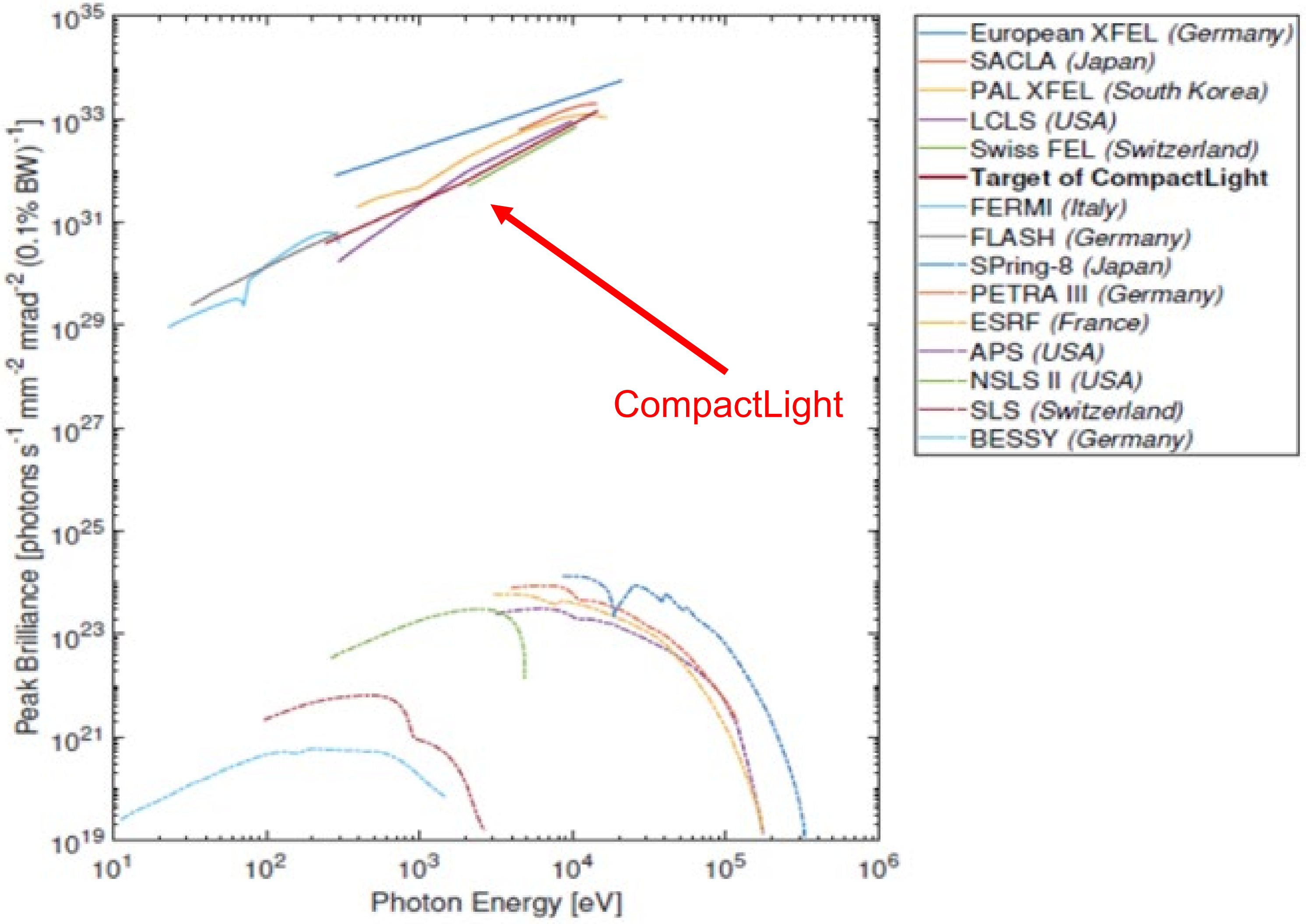






CompactLight performance

Estimated XLS performance compared with other existing facilities



FEL radiation 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-colour operation**
- **Simultaneous HXR/SXR operation**

These will be unique and highly desirable features of XLS design

Operational parameters

Main electron beam and FEL parameters

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

Two-bunch train

RF operational scenarios:
- B: dual mode (Baseline)
- U1, U2: 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 baseline

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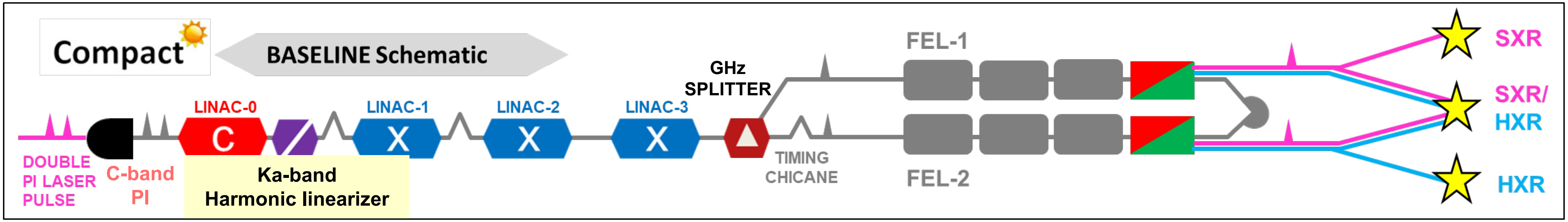
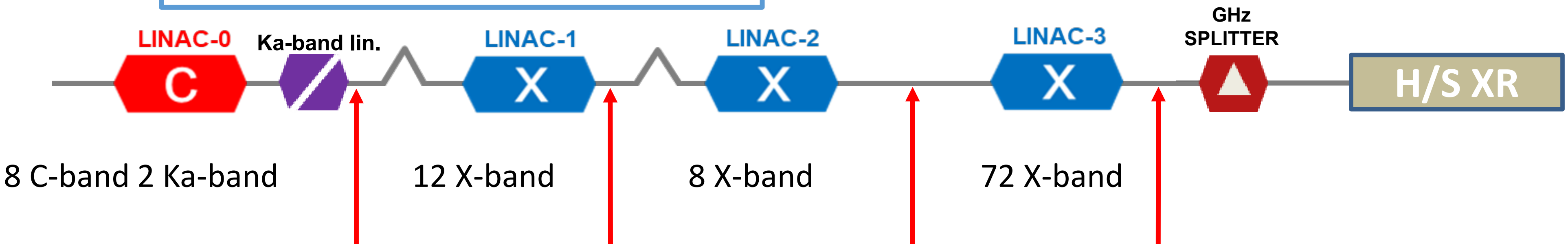


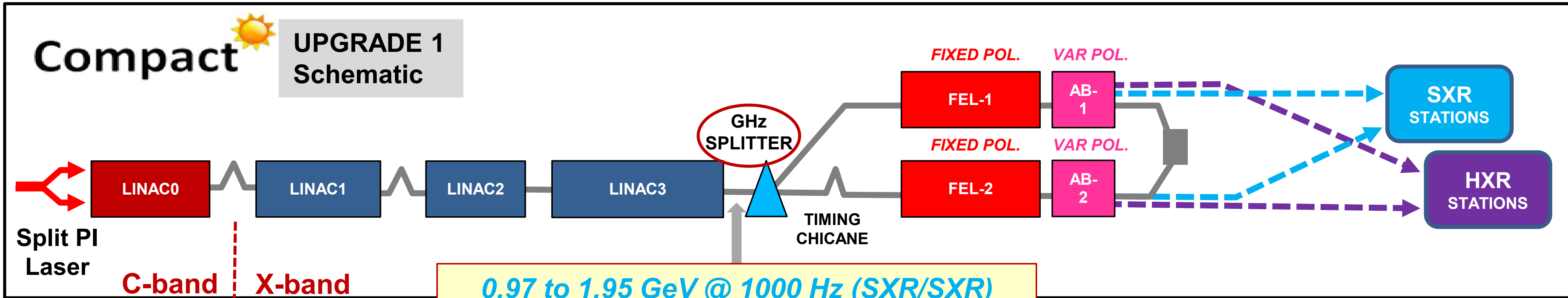
Main linac, length ~250 m



100 Hz	300 MeV	0.98 GeV	1.43 GeV	5.50 GeV	→ Hard X-ray
250 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 for 250/1000 Hz

CompactLight upgrades



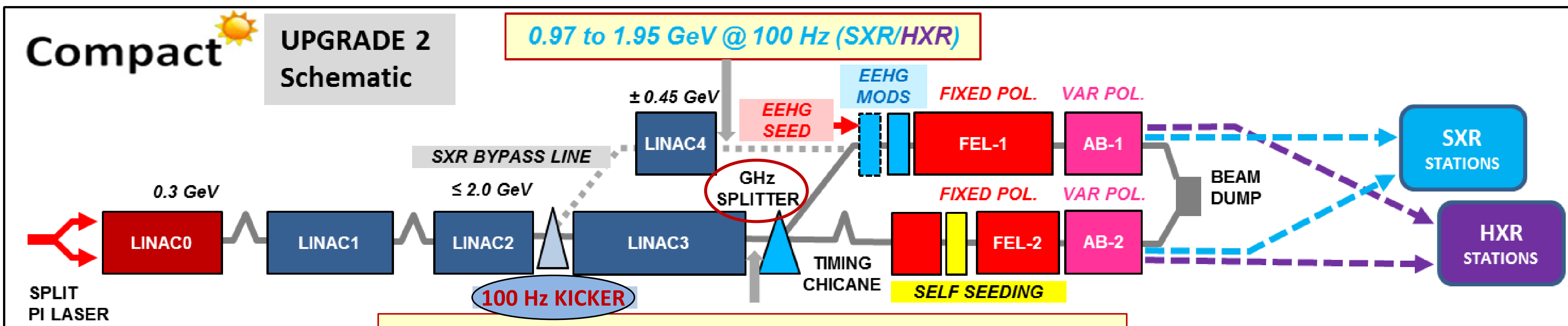
0.97 to 1.95 GeV @ 1000 Hz (SXR/SXR)
2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)

2 klystrons x LINAC Module:

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

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

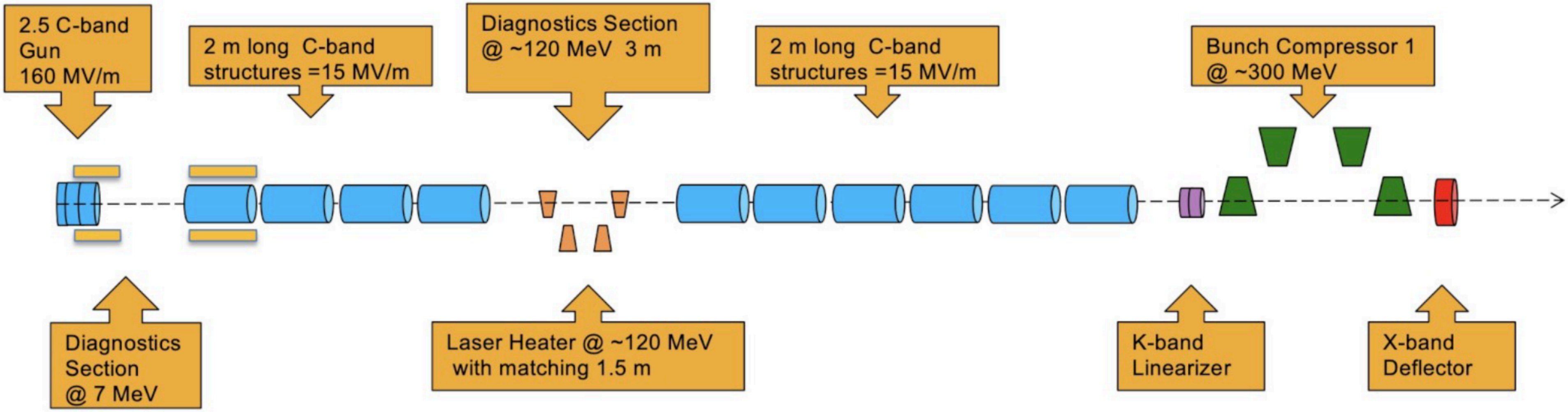
$\langle E_{acc} \rangle$ = 30.4 MV/m @ 1 kHz



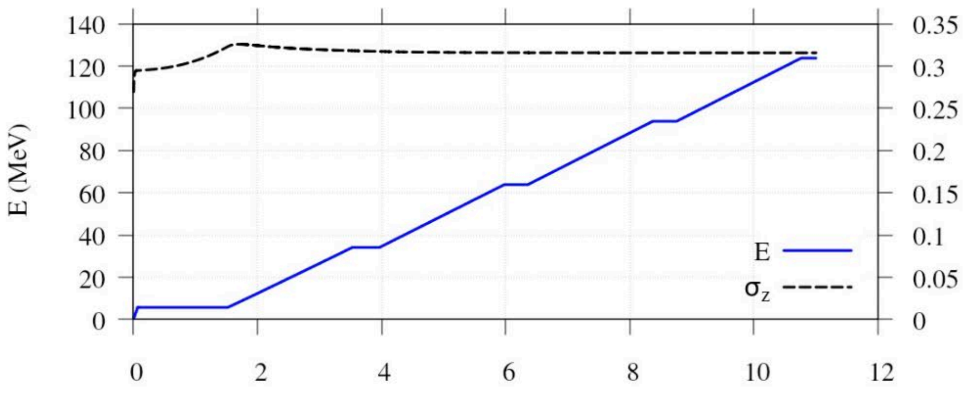
0.97 to 1.95 GeV @ 1000 Hz (SXR/SXR)
2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)
+
2.75 to 5.5 GeV @ 100Hz (SXR/HXR at the same time)

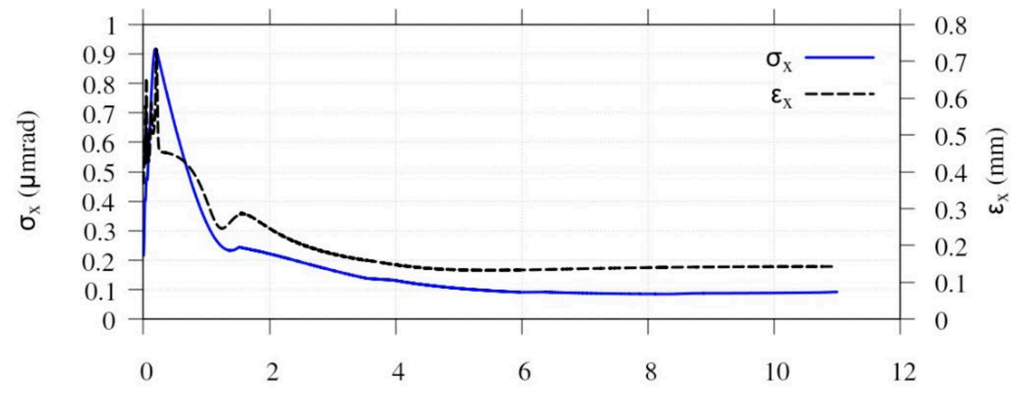
Injector and Linac0

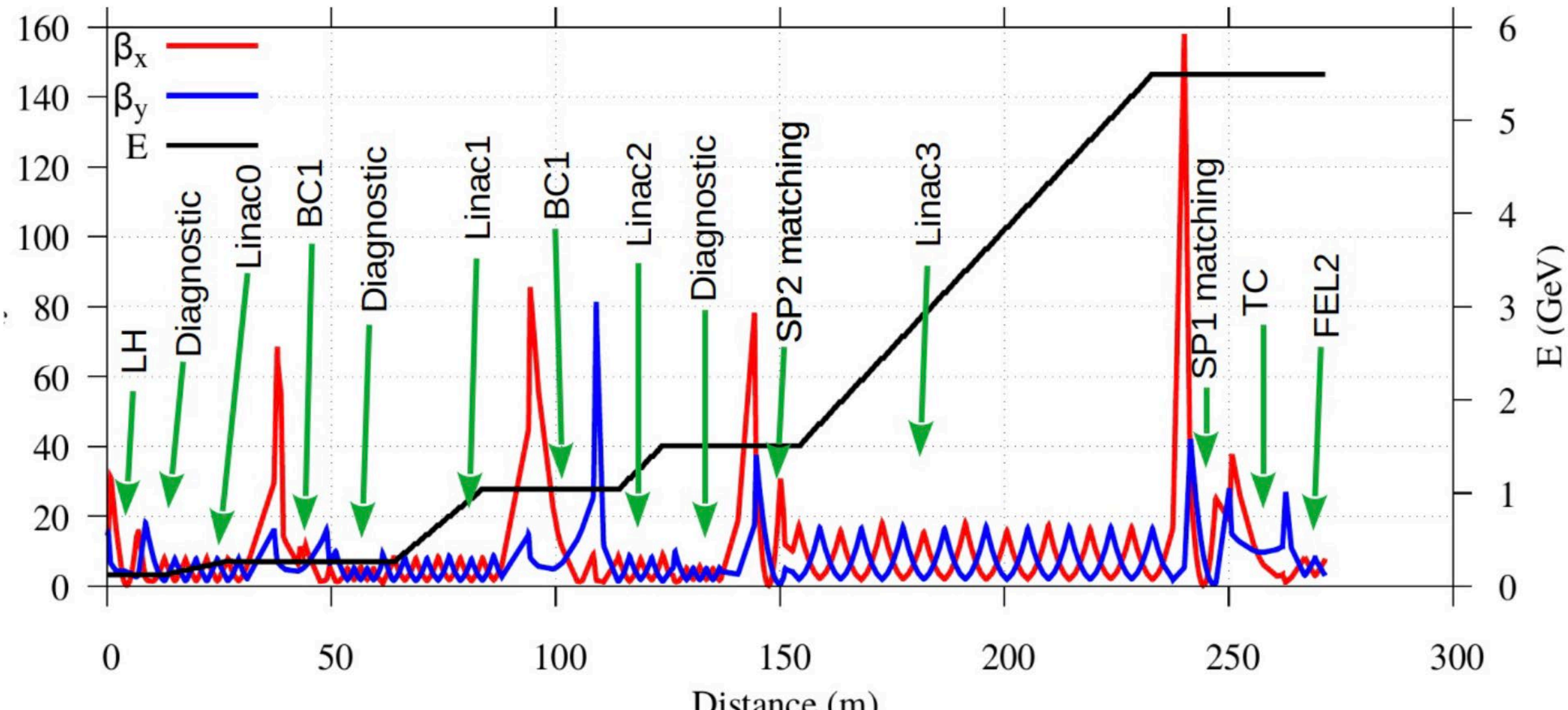
Parameter	Unit	After VB and/or BC-1
Charge Q	pC	75
Beam energy	MeV	300
RMS Bunch Duration σ_t	fs	350
Peak Current	A	60
RMS Energy Spread	%	0.5
Projected RMS Norm. Emittance	μm	0.2
Repetition Rate	Hz	100–1000



Injector and Linac Beam Dynamics







Higher-harmonic linearizer

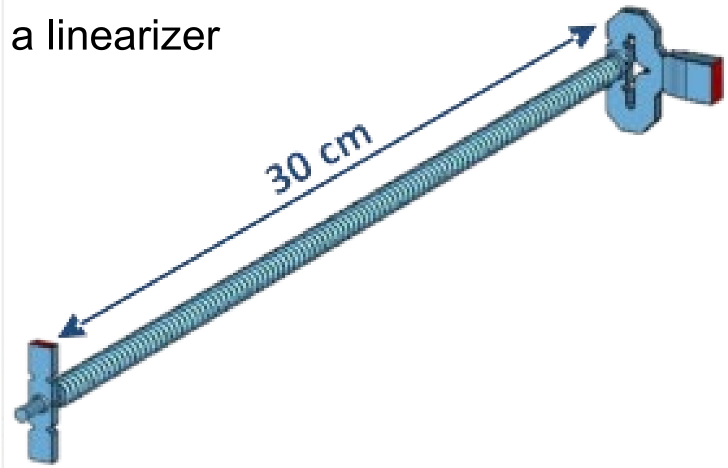
Longitudinal phase space linearization can be achieved using a linearizer

$$V_{\mathrm{lin}} = \frac{1}{h^2} V_{\mathrm{main}} \cos(\phi_{\mathrm{main}})$$

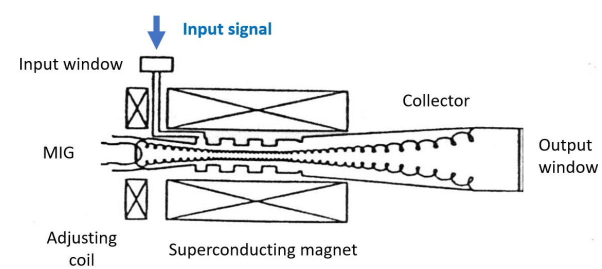
We chose *h=6,* 36 GHz RF

Parameter	**Value**	**Units**
Active length l	300	mm
Phase advance ϕ	$2\pi/3$	rad
Number of cells	108	–
Filling time τ	8.4	ns
Frequency f	36	GHz
Compressed power P	15	MW
Design gradient E_{acc}	42.5	MV/m
Peak surface field E_p	109.2	MV/m
Peak surface field B_p	189.1	mT
Modified Poynting vector S_c	4.84	W/μm^2

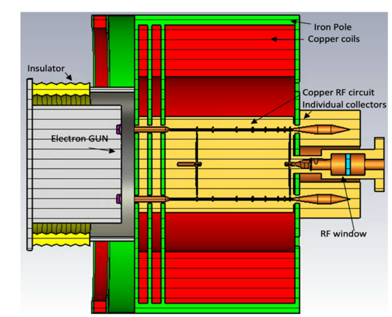
Average iris aperture <a> = 2 mm



Ka-band RF sources

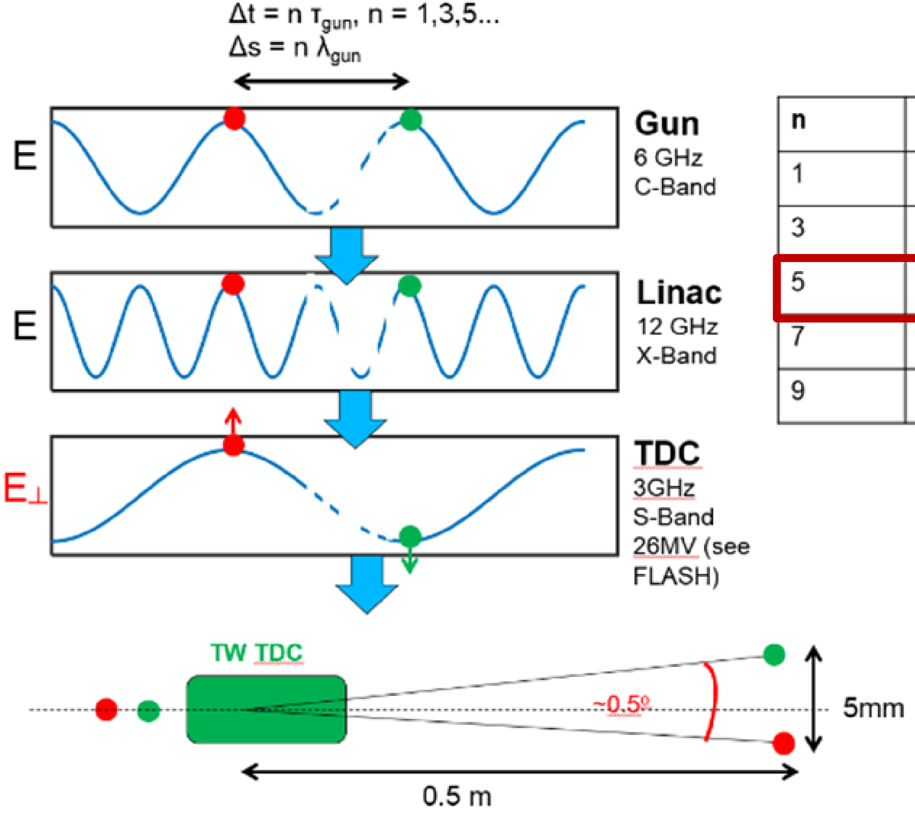


Gyro-klystron

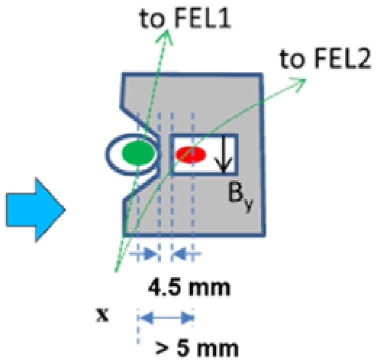


Multi-beam klystron

Pulse splitting options for a simultaneous operation HXR/SXR



n	Δt	Δs
1	166 ps	50 mm
3	500 ps	150 mm
5	833 ps	250 mm
7	1.16 ns	350 mm
9	1.5 ns	450 mm



Main accelerating structure

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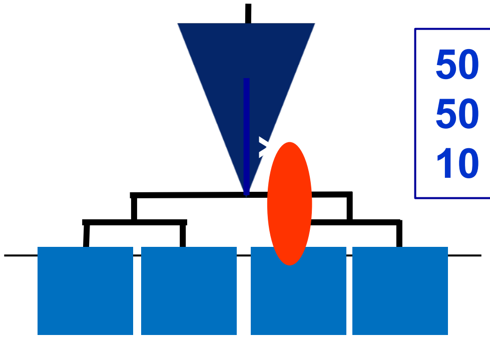
RF system parameter and layouts done for 100 Hz baseline, 100/250 Hz dual mode and 100/1000 Hz dual klystron



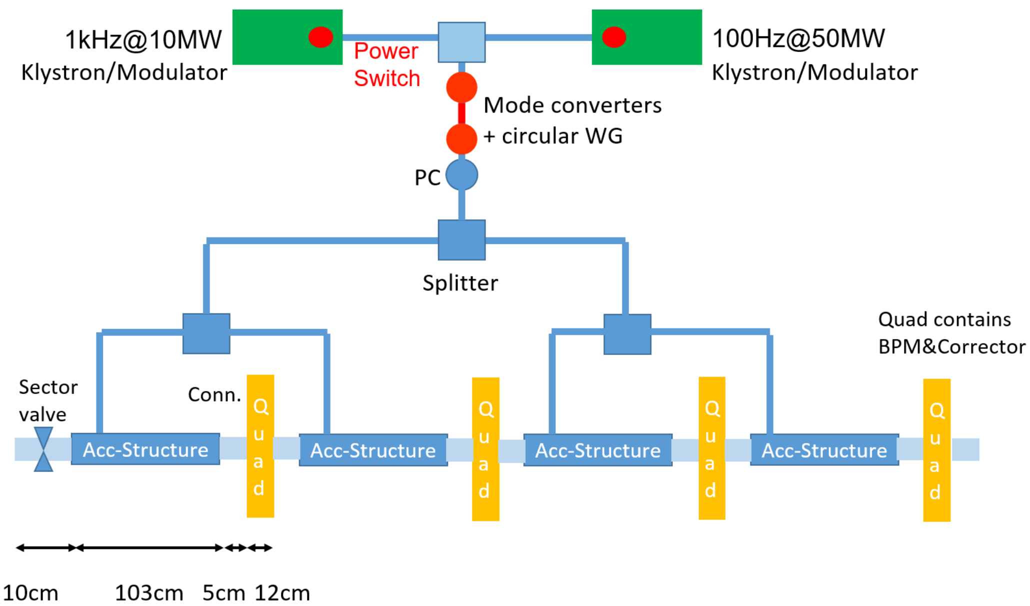
50 MW, 1.5 μs, 100 Hz
50 MW, 150 ns, 250 Hz
10 MW, 1.5 μs, 1 KHz

	Rep. rate [Hz]		
	100	250	1000
Average gradient <G> [MV/m]	65	32	30.4
Max klystron available out. power [MW]	50	50	10
Req. klystron power per module [MW]	39	42.5	8.5
RF pulse length [μs]	1.5	0.15	1.5
SLED	ON	OFF	ON
Av. diss. power per structure [kW]	1	0.31	2.2
Peak input power per structure [MW]	68	10.6	14.8
Av. Input power per structure [MW]	44	10.6	9.6
Module energy gain [MeV]	234	115	109

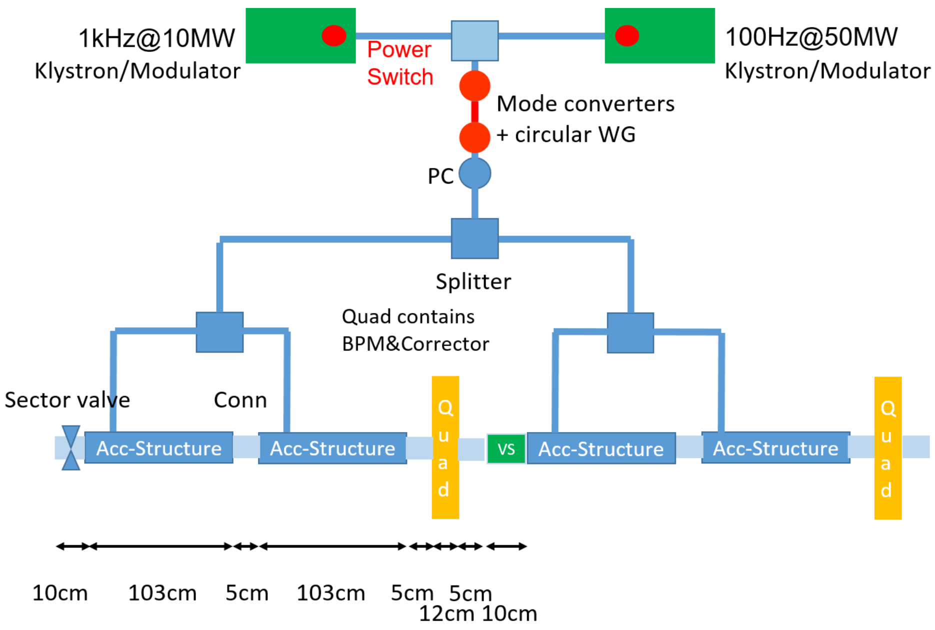
Parameter	Value
Frequency [GHz]	11.9942
Phase advance per cell [rad]	$2\pi/3$
Shunt impedance R [MΩ/m]	90-131
Effective shunt Imp. R_s [MΩ/m]	387
Group velocity v_g [%]	4.7-1.0
P_{out}/P_{in}	0.215
Filling time [ns]	144
Number of cells per structure	108
Unloaded SLED Q-factor Q_0	180000
External SLED Q-factor Q_E	23000
# structures per module N_m	4
Module active length L_{mod} [m]	3.6
Average iris radius <a>	3.5
Iris radius input-output [mm]	4.3-2.7
Structure length L_s [m]	0.9

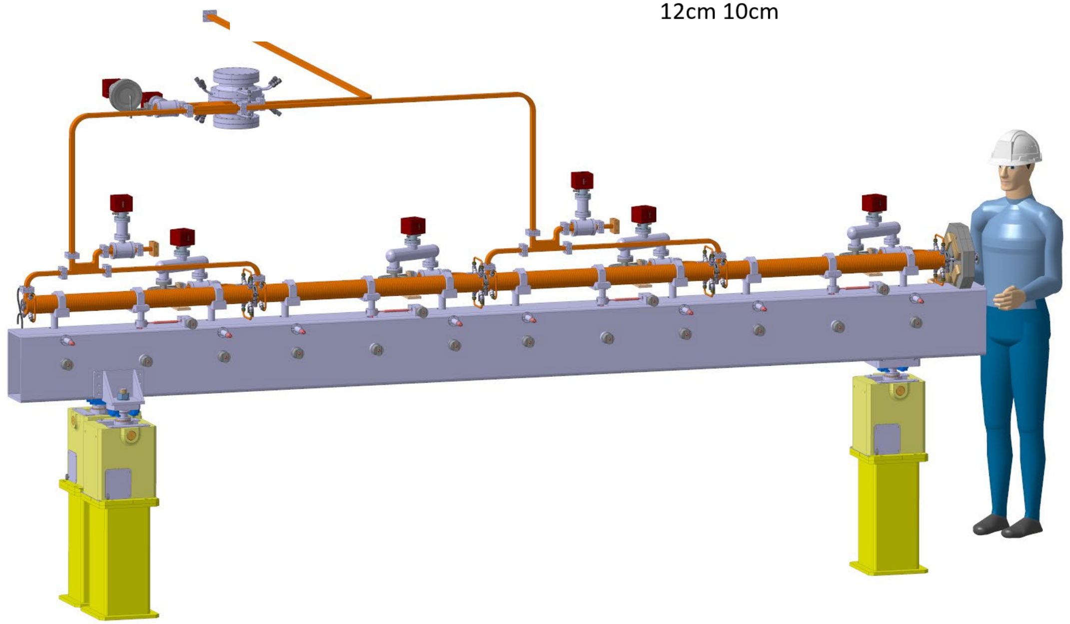
Main linac module

Low-energy module



High-energy module





Main linac beam dynamics

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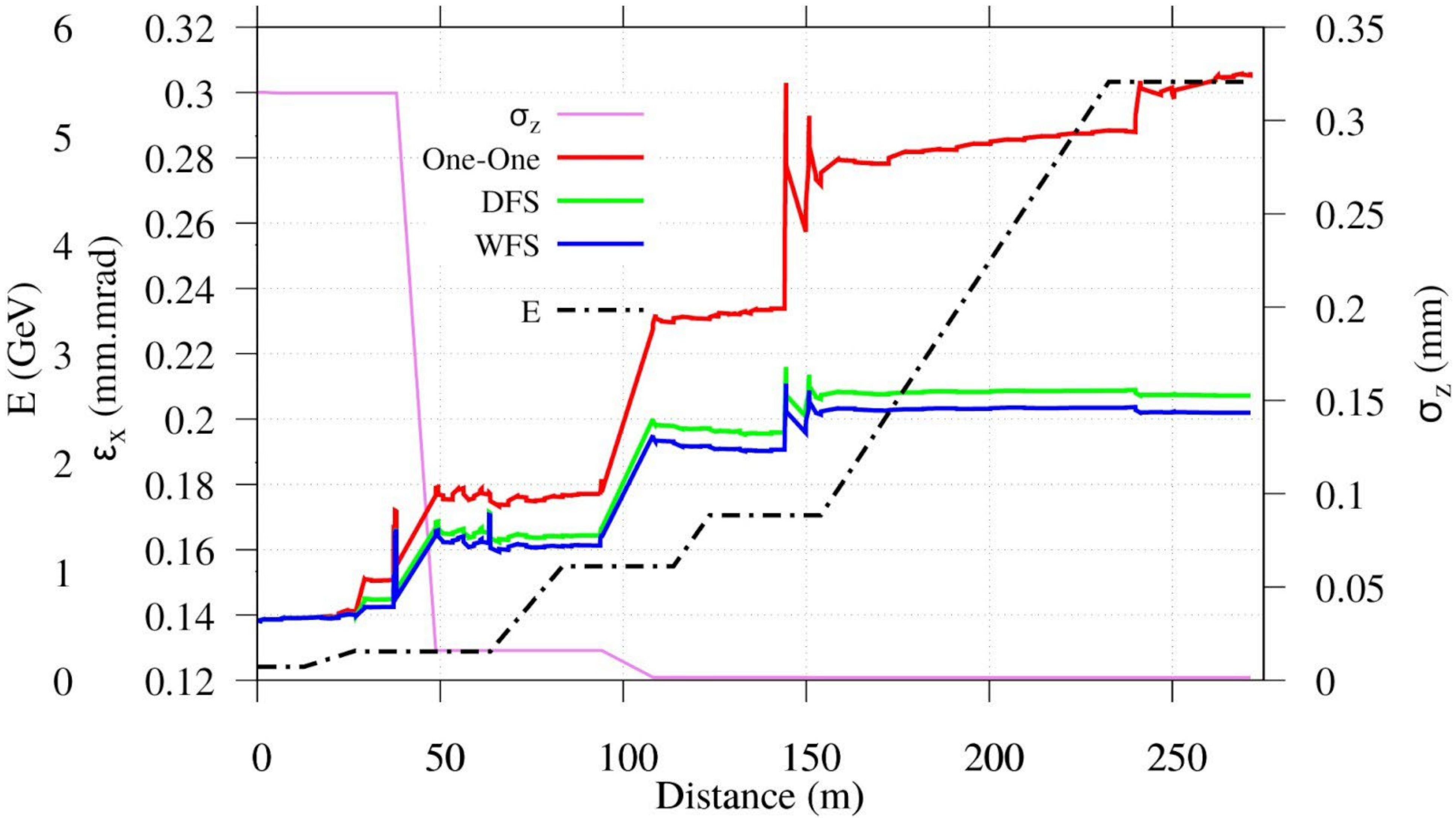
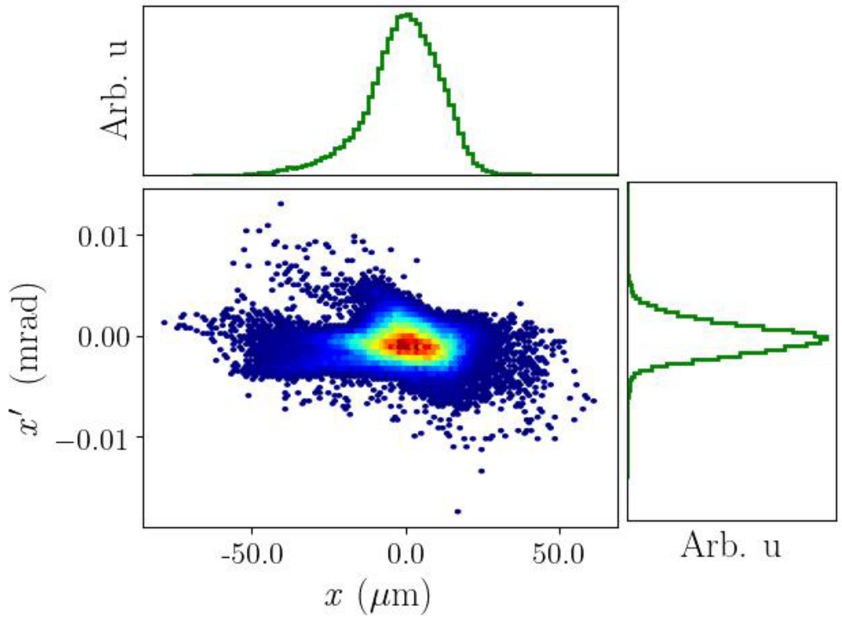
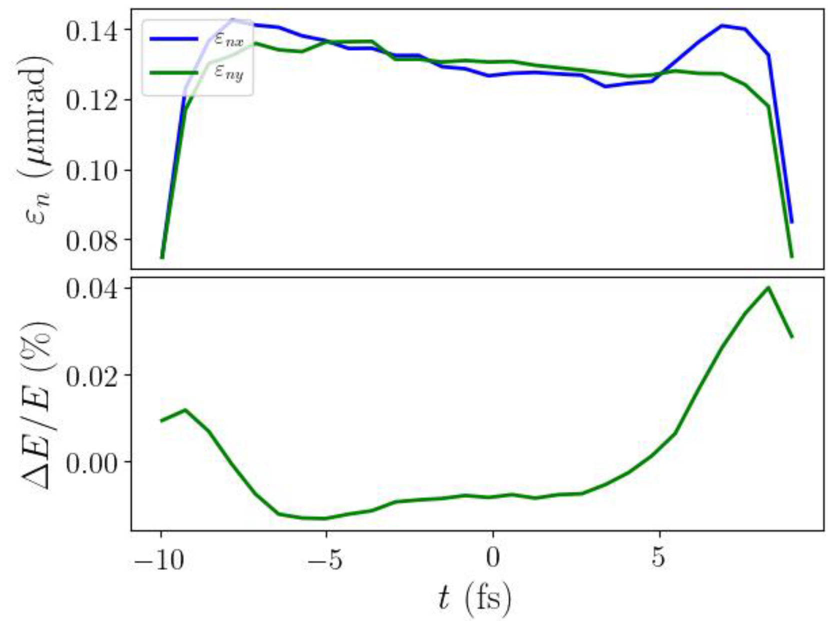
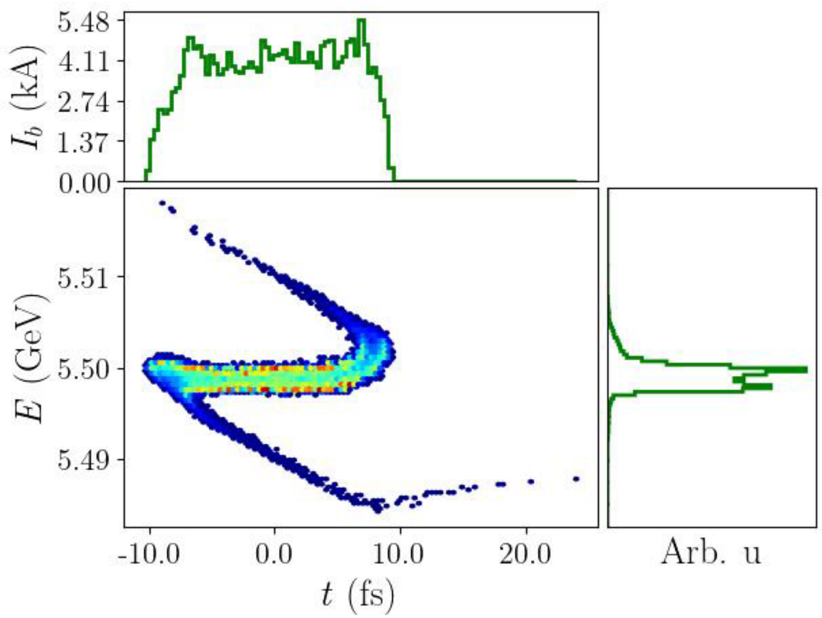
Beam performance under the effects of misalignments: 100 μm rms 200 μrad rms, all elements.
Average of 100 random configurations.



Main beam profile

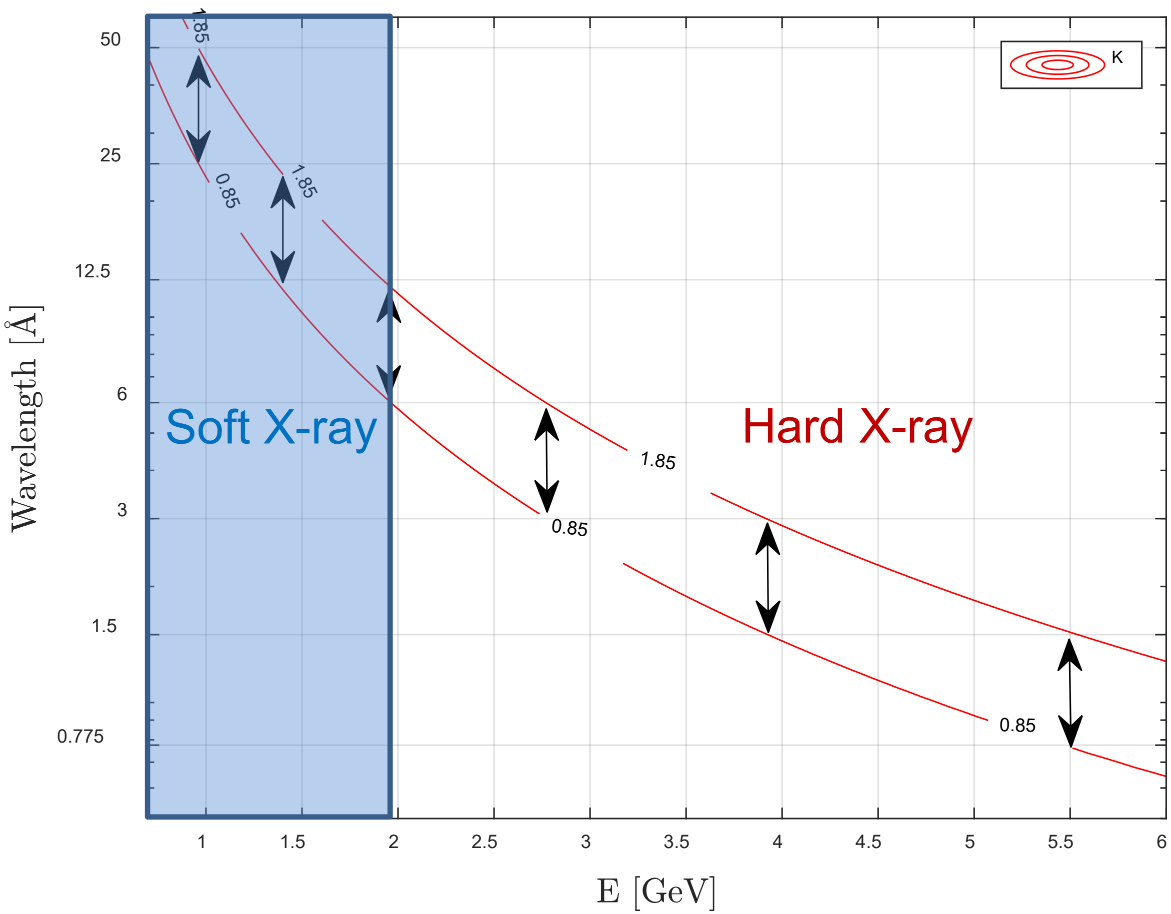






Parameter	Unit	Value
E	GeV	5.50
$\varepsilon_{n,x}$	μmrad	0.217
$\varepsilon_{n,y}$	μmrad	0.148
ε_z	MeV.ps	0.01
σ_x	mm	0.013
σ_y	mm	0.007
σ_t	fs	5.195
σ_E	MeV	1.67
$\Delta E/E$	%	0.030

Undulator parameters



Both undulator lines have identical parameters, so K is tuneable to provide a factor of 2 wavelength tuning for both Soft X-ray and Hard X-ray

$\lambda_u \approx 13mm$

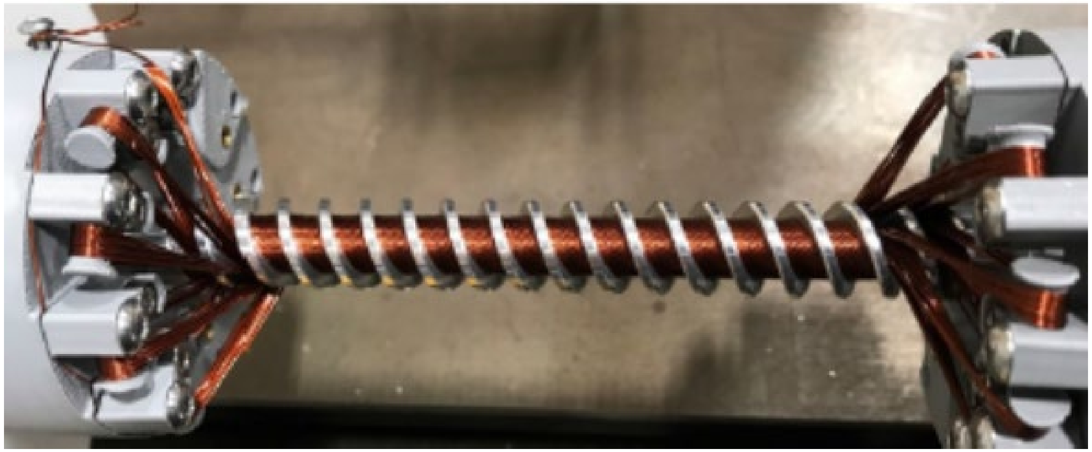
$K_u \approx 0.85\text{-}1.85$

- Soft X-ray
  $E_{beam} \approx 1.0 / 1.4 / 1.95GeV$
  (~3 discrete working points @increased rep.rate, TBC)

- Hard X-ray
  $E_{beam} \approx 2.75 / 3.9 / 5.5GeV$
  (~3 discrete working points @100Hz)

Both Soft and Hard X-Ray configurations foresee a SASE line based on Helical Super-Conductive Undulator 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 of B. Shepherd (STFC)

Summary of Beam Parameters

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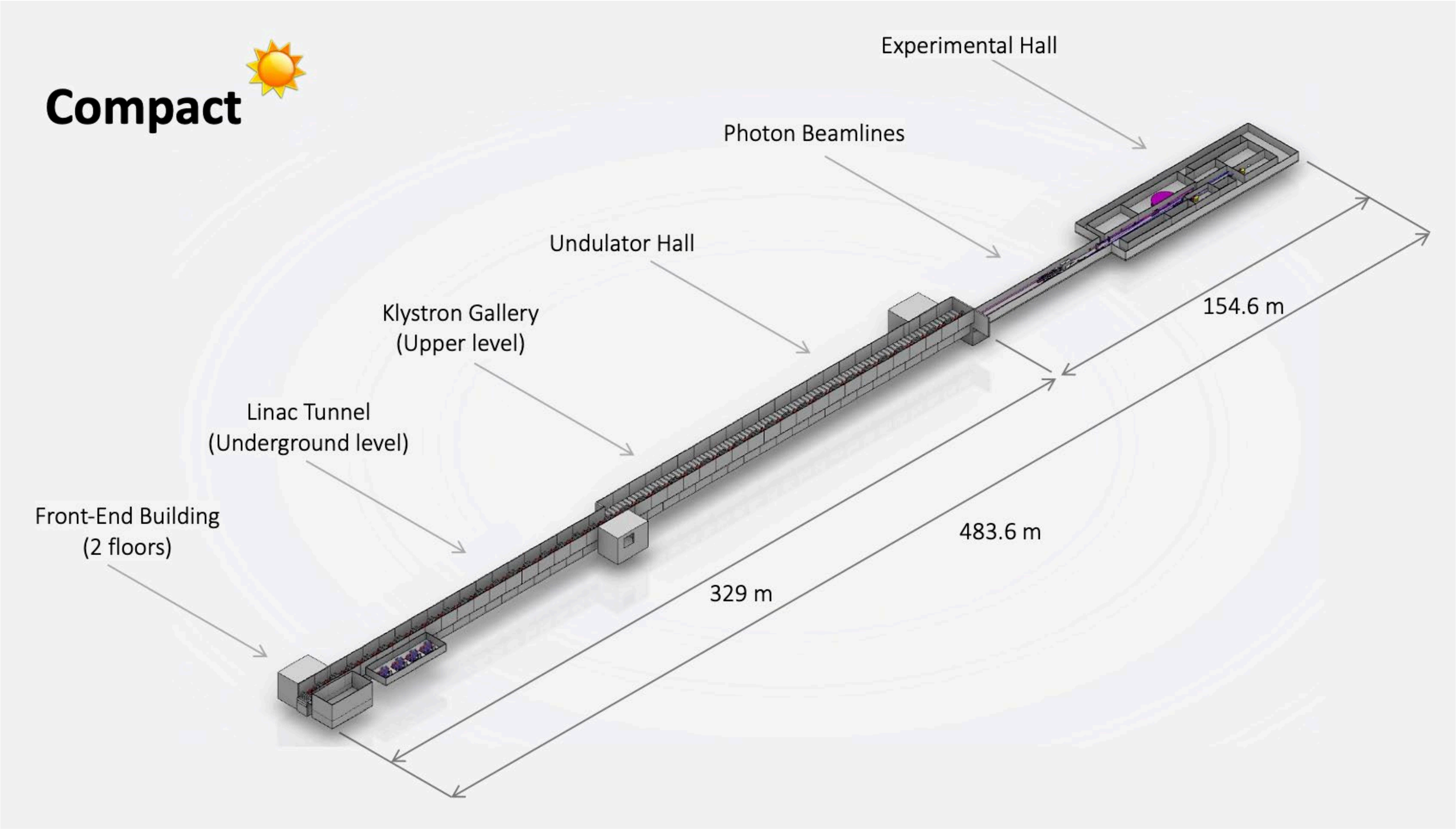
Operating modes

Operating mode	FEL1 Wavelength	FEL2 Wavelength	L0/L1/L2/L3 Rep rate (Hz)	L3 Output Energy (GeV)	L4 Rep rate (Hz)	L4 Output Energy (GeV)
BASELINE						
B-HH	HXR	HXR	100	2.75 – 5.5		
B-SS	SXR	SXR	250	0.97 - 1.95		
UPGRADE 1						
U1-HH	HXR	HXR	100	2.75 – 5.5		
U1-SS	SXR	SXR	1000	0.97 – 1.95		
UPGRADE 2 – ALL MODES FROM UPGRADE 1 PLUS EXTRA MODE						
U2-SH	SXR	HXR	100	2.75 – 5.5	100	0.97 – 1.95

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					

Facility layout



CompactLight as an accelerator toolkit

CompactLight has been conceived as an accelerator toolbox

- Hi-rep. rate C-band injector
- X-band Linac module
- Ka-band linearizer
- Undulators

We studied two cases

- Inverse-Compton Scattering source (ICS)
- Short soft X-ray FEL facility

An ICS source based on CompactLight

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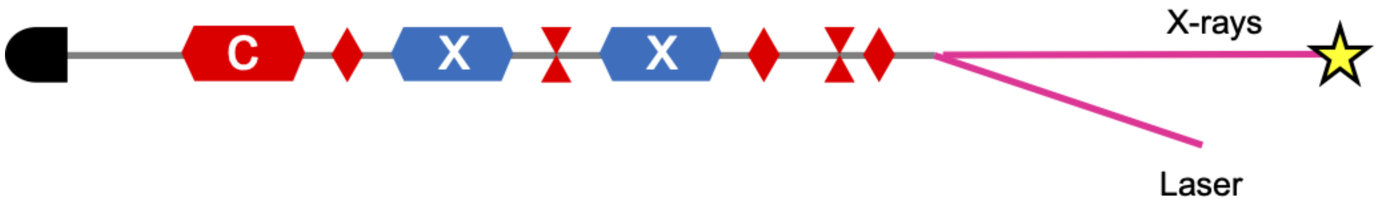
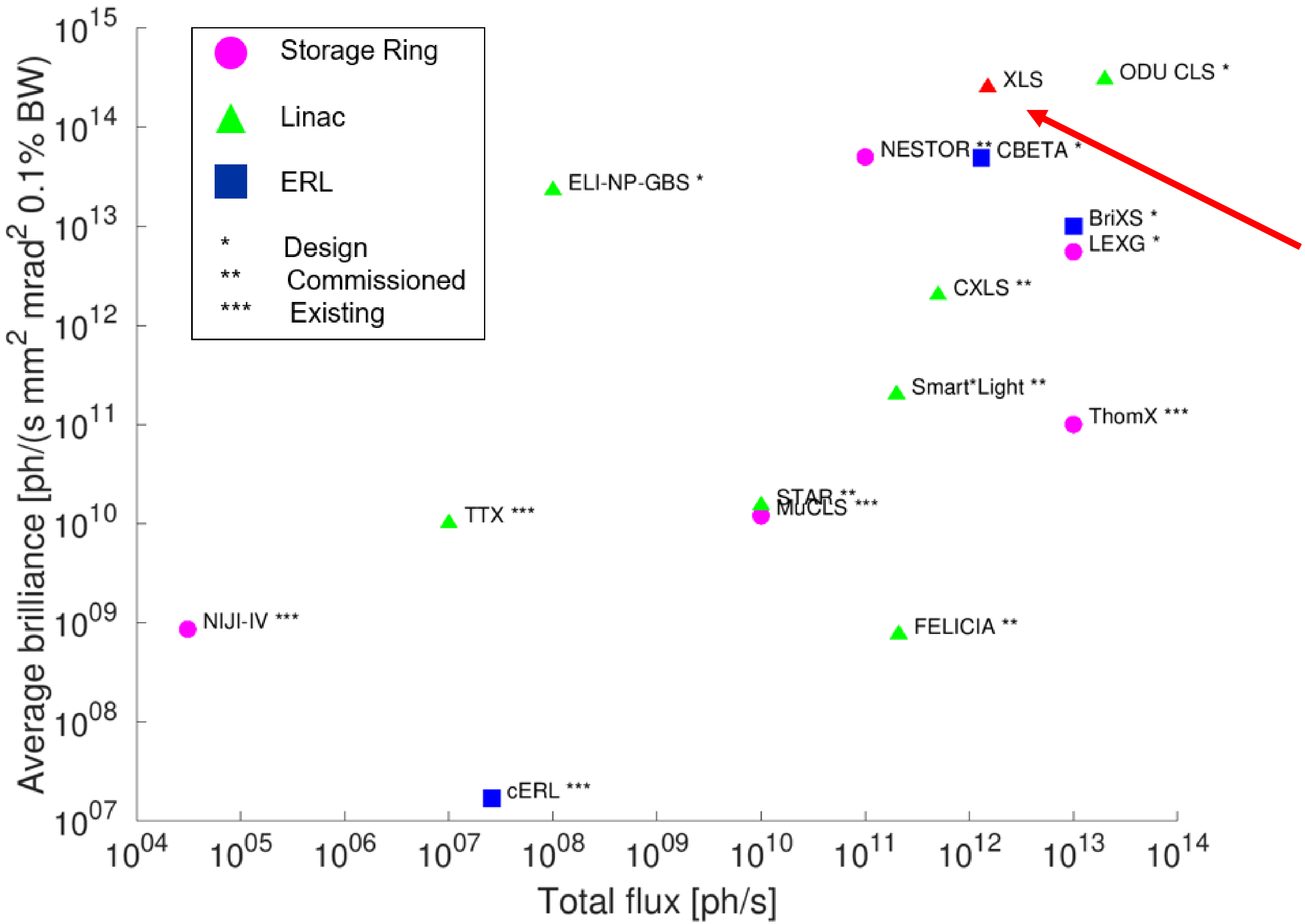


Parameter	Symbol	CompactLight	Unit
Electron beam energy	E_e	100	MeV
Collision frequency	f_{eff}	50,000	s^{-1}
Bunch charge	Q	200	pC
Rel. energy spread	σ_e/E_e	5	‰
Norm. emittance	ϵ_x/ϵ_y	0.35/0.39	mm mrad
Electron spot size	$\sigma^*_{e,x}/\sigma^*_{e,y}$	5.56/12.34	µm
Laser pulse energy	E_p	50	mJ
Laser spot size	$\sigma^*_{\text{laser},x}/\sigma^*_{\text{laser},y}$	4.71/4.71	µm
Crossing angle	ϕ	2	°
Source size	$\sigma^*_{\text{X-ray},x}/\sigma^*_{\text{X-ray},y}$	3.59/4.40	µm
Total flux	$\dot{N}_\gamma$	8.62×10^{11}	ph/s
Average brilliance	$\mathcal{B}$	1.85×10^{14}	[1]

[1] ph/(s mm^2 mrad^2 0.1%BW).

A High-Energy and High-Intensity Inverse Compton Scattering Source Based on CompactLight Technology MDPI Photonics, April 2022, https://www.mdpi.com/2304-6732/9/5/308

A CompactLight-based ICS

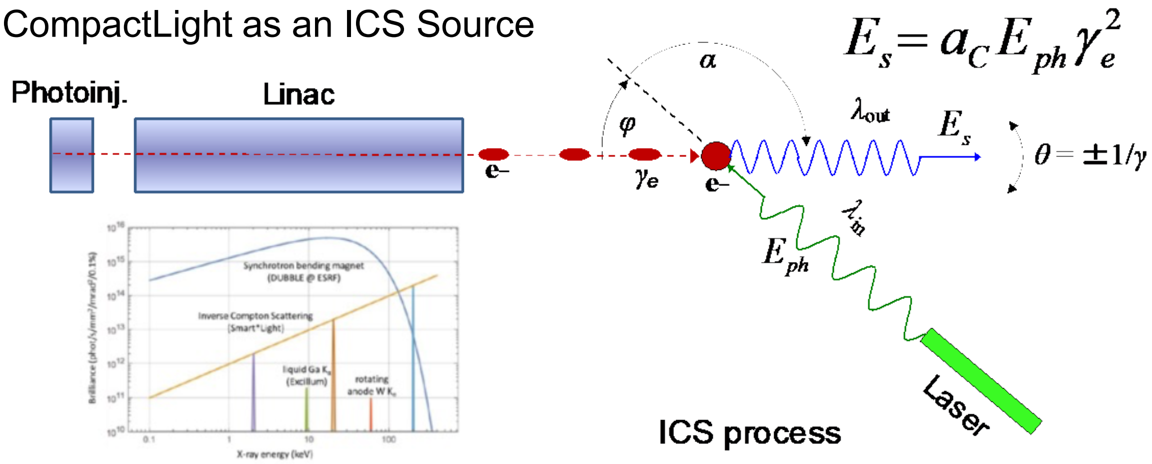


A High-Energy and High-Intensity Inverse Compton Scattering Source Based on CompactLight Technology MDPI Photonics, April 2022, https://www.mdpi.com/2304-6732/9/5/308

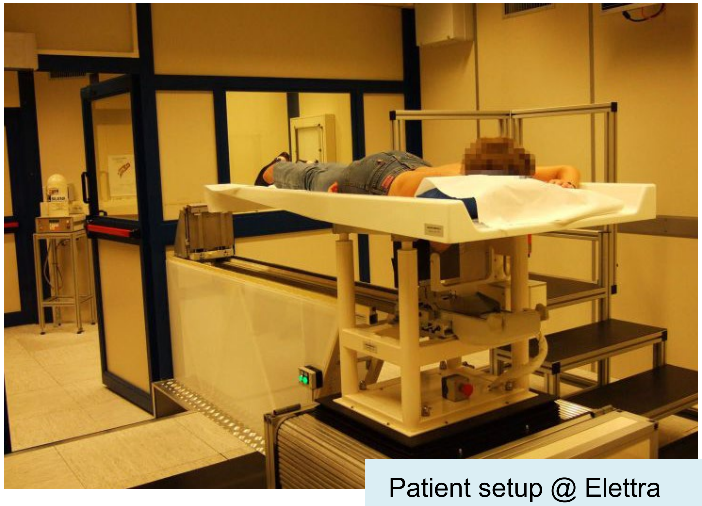
Biomedical applications

Compact

CompactLight as an ICS Source



Smart Light (TU/e)


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 5×10^7 ph/mm²/s

Lung CT imaging *(early detection of lung cancer, lung fibrosis)*
Typical X-ray energy range: 60-70 keV
Field of view (hor x vert.): ~ 50 cm x 50 cm or ~15-20 cm x 15cm (local area, single lobe)

Imaging of small animals *(studies of animal models mimicking human diseases)*
Typical X-ray energy range: 15-30 keV
Field of view (hor x vert.): ~3-15 cm x 10-20 cm

High resolution Imaging of tissues and organs *(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

Courtesy of G. Tromba (Elettra)

CompactLight follow ups

Compact

- ✓ CompactLight published its Conceptual Design Report in early 2022:

  https://zenodo.org/record/6375645

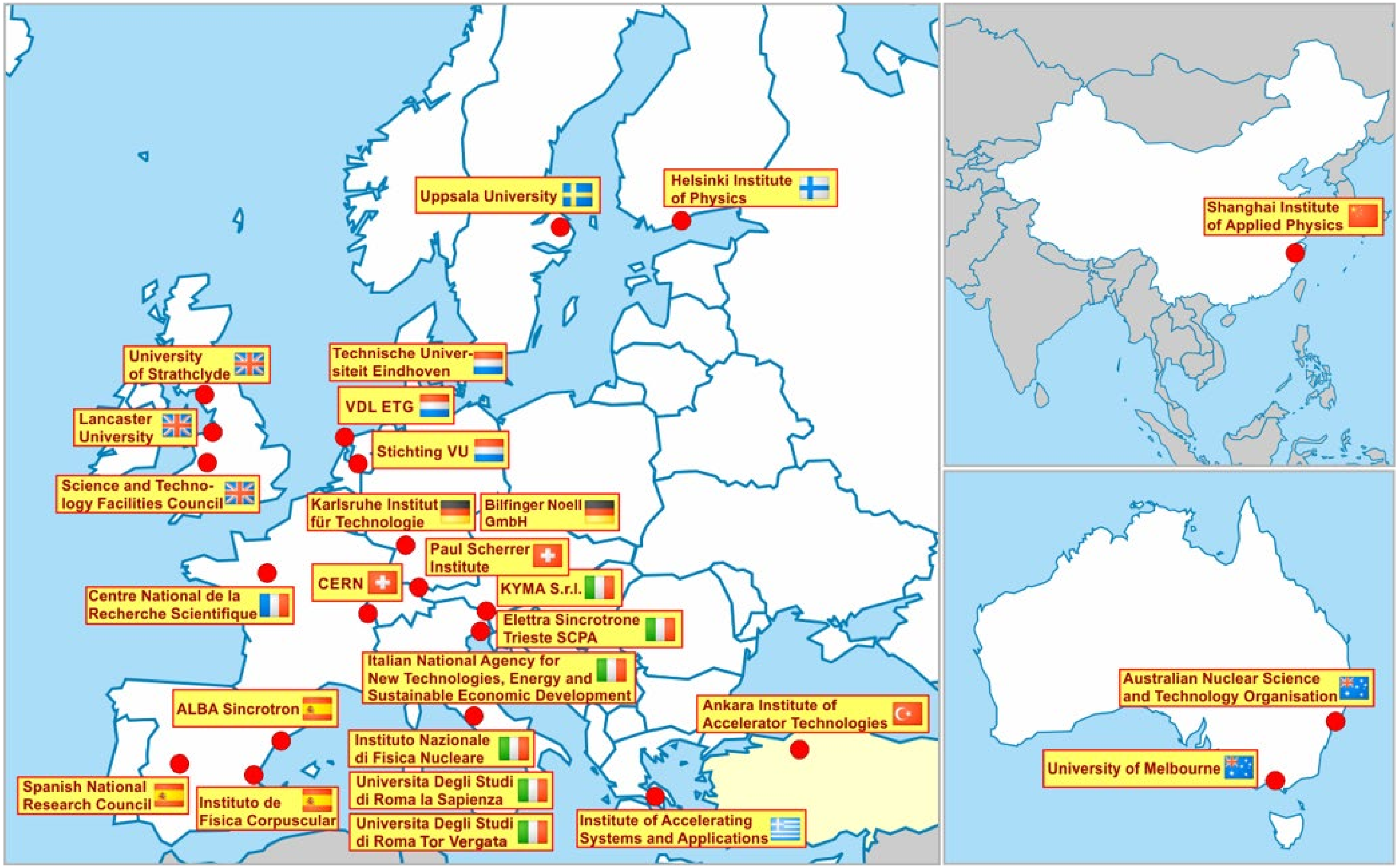
- ✓ We are part of Horizon Europe I.FAST project
  - ✓ Manufacturing two CompactLight X-band structures
- ✓ Collaboration will continue:
  - ✓ Periodic meetings
  - ✓ Development of high repetition rate X-band power sources
  - ✓ Design of an Inverse-Compton Scattering source and compact FEL

Summary

Compact

- ✓ CompactLight offers advanced and challenging FEL schemes with a wide range of operating modes, using affordable, efficient, compact technology:
  - ✓ Simultaneous operation of HXR and SXR at 100 Hz
  - ✓ C-band injector, two-bunch operation up to 1 kHz
  - ✓ Compact X-band linac up to 65 MV/m gradient
  - ✓ Ka-band linearizer at 36 GHz
  - ✓ Compact super-conductive undulators
- ✓ The facility operation up to 1 kHz will pave the way for further applications of the XLS technology
- ✓ The application of CompactLight technology offers the possibility to assemble also smaller machines like Inverse-Compton Scatteromg sources with a wide range of applications

Thank you!



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