Funded by the
European Union

Compact

The CompactLight Project (XLS)

Andrea Latina

On behalf of the CompactLight collaboration

Aims and Objectives

"The possibility of producing low charge (pC range), ultra-short (sub-micrometer), electron bunches with small emittance and high brightness, opens new possibilities to design and build **compact, lower cost FELs**, to produce high intensity, femtosecond long, coherent X-ray pulses in a wide wavelength range".

C. Pellegrini, "Compact, cheap, better", ICFA FLS 2010

With CompactLight we plan to design **a Hard X-ray Facility** using the very latest concepts for:

a. ***High brightness electron photoinjectors***
b. ***Very high gradient accelerating structures***
c. ***Novel short period undulators.***

The XLS Collaboration

The XLS Collaboration is an initiative among several International Laboratories aimed at promoting the construction of the next generation FEL based photon sources with innovative accelerator technologies

H2020 Design Studies (2018-2020)

http://compactlight.eu

Funded by the
European Union

List of Participants

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

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

Italy	5
Neth.	3+1
UK	3
Spain	2
Australia	2
China	1
Greece	1+2
Sweden	1
Turkey	1
France	1
Germany	1
Switz.	1
Finland	1
Norway	0+1
Internat.	1

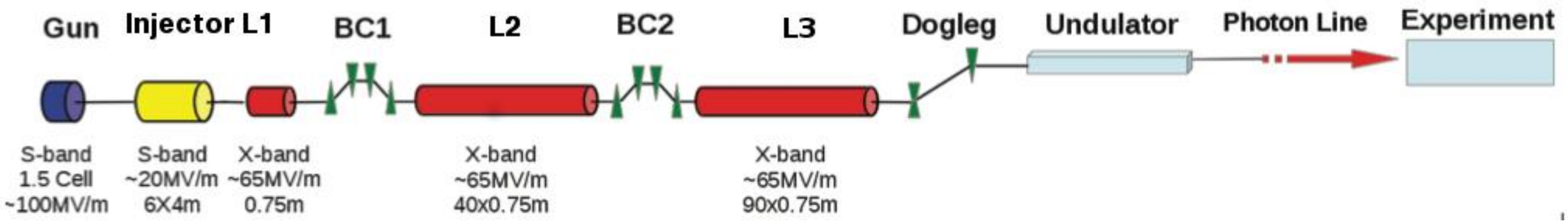
Aims and Objectives II

The New Facility, compared with Current Facilities, will benefit from:

i. A lower electron beam energy, due to the enhanced undulator performance.
ii. Being significantly more compact due to lower energy and high gradient structures.
iii. Having a much lower electrical power demand than current facilities.
iv. Having much lower construction and running costs.

This will facilitate the widespread development of X-ray FEL Facilities across Europe and beyond, by making their construction and operation costs more affordable through an optimum combination of emerging and innovative accelerator technologies.

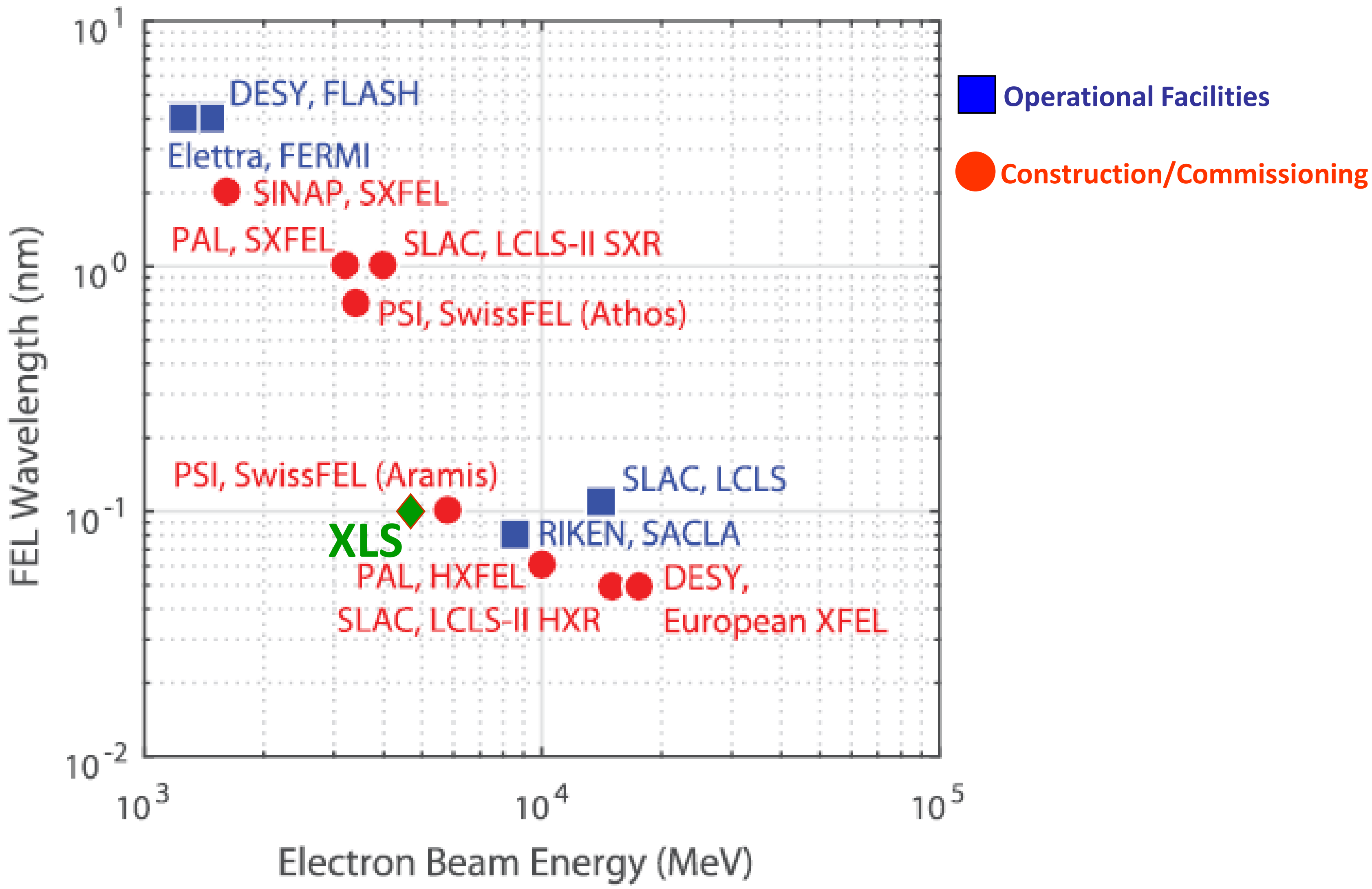
CompactLight Layout & Parameters



Preliminary Parameters and Layout of XLS hard X-ray FEL facility

Parameter	Value	Unit
Minimum Wavelength	0.1	nm
Photons per pulse	$>10^{12}$	
Pulse bandwidth	<<0.1	%
Repetition rate	100 to 1000	Hz
Pulse duration	<1 to 50	fs
Undulator Period	10	mm
K value	1.13	
Electron Energy	4.6	GeV
Bunch Charge	<250	pC
Normalised Emittance	<0.5	mrad

FEL Facilities



E.A. Seddon et al.

Interests for X-ray FELs

FEL Facilities	Institutes
Hard X-ray	STFC, PSI, UA-IAT, SINAP, UoM, ANSTO
Soft X-ray	ELETTRA-ST, INFN
Compton Sources	TU/e, ANSTO
Upgrading of existing Facilities	ELETTRA-ST, INFN

CERN has no direct interest in Synchrotron Light Sources and FELs, but the activities on CompactLight will have strong return value for the CLIC project: i.e. accelerator and RF components optimization, technical developments with industry, costs reduction, etc.

Sub-systems	Institutes
Accelerating Structures	CERN, SINAP, UU, VDL-ETG, PSI, CSIC, UH/HIP, USTR
Undulators	ENEA, STFC, KIT, CERN, PSI, KYMA, ALBA-CELLS, UU, VU
Beam diagnostics and manipulation	ST, CERN, STFC, SINAP, IASA, UU, UA-IAT, ULANC, INFN, SAPIENZA, INFN, PSI, ALBA-CELLS, CNRS

XLS Work Packages

Work Package		Lead Participant	Person Months	Start Month	End month
WP1	Project management and Technical Coordination	Elettra - ST	32	1	36
WP2	FEL Science Requirements and Facility Design	STFC	68	2	36
WP3	Gun and Injector	INFN	76	2	36
WP4	RF systems	CERN	78	2	36
WP5	Undulators and Light production	ENEA	81	2	36
WP6	Beam dynamics and Start to End Modelling	UA-IAT	78	2	36
WP7	Global Integration with New Research Infrastructures	Elettra - ST	27	6	36
		Total Person Months	440		

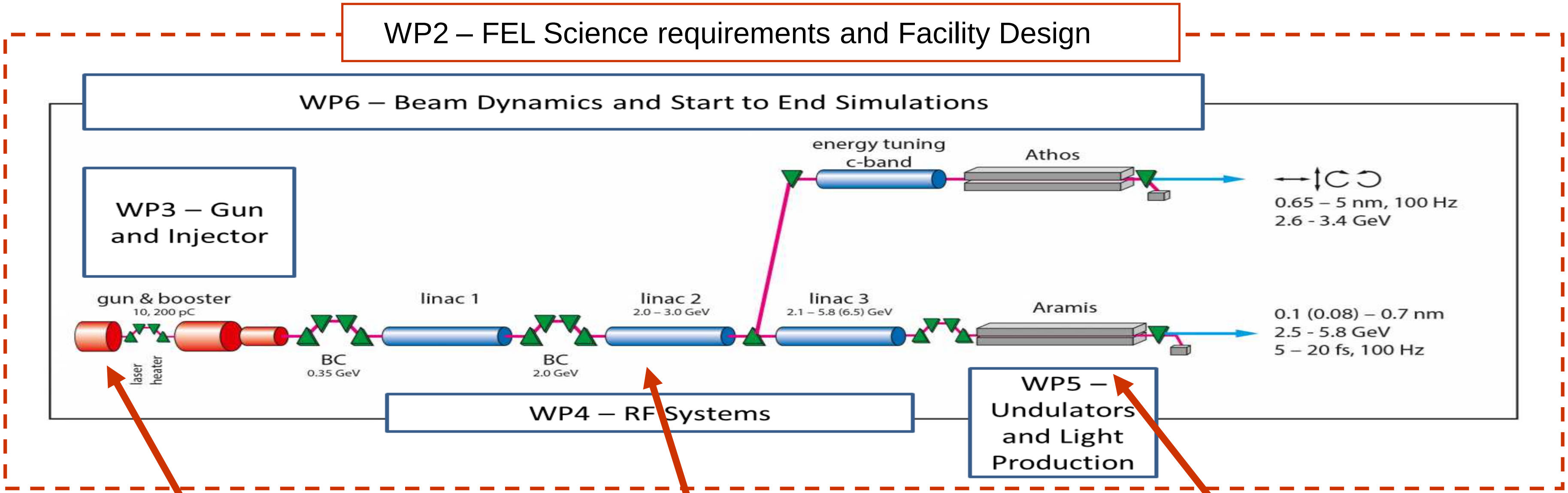
XLS Specific Goals

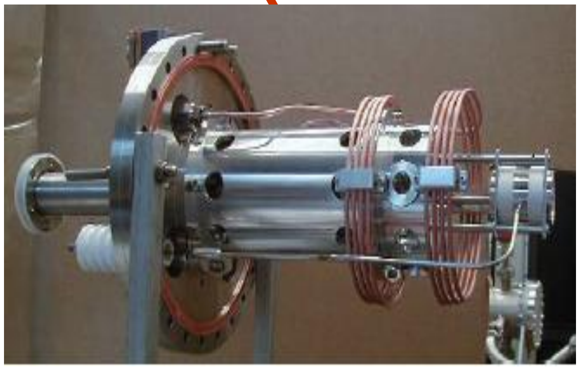
- **Based on user-driven scientific requirements, determine the overall design and parameters for an ideal X-band driven FEL for Hard X-rays, with options for Soft X-ray FEL and Compton Source (WP2).**
- Design the main machine sub-assemblies required, including e-Gun, RF power units and power distribution systems, accelerating structures and undulators (WPs 3 to 5).
- Specify the key parameters of the machine including beam structure, lattice, geometric layout, mechanical tolerances, magnetic transverse focusing, required diagnostics, while identifying a solution as common as possible (WP6).
- Gathering the user demands on FELs and accelerator upgrades, in the near and mid-term future, emphasizing the needs from European laboratories and global partners, develop plans for an harmonious integration within new Research Infrastructures (WP7).

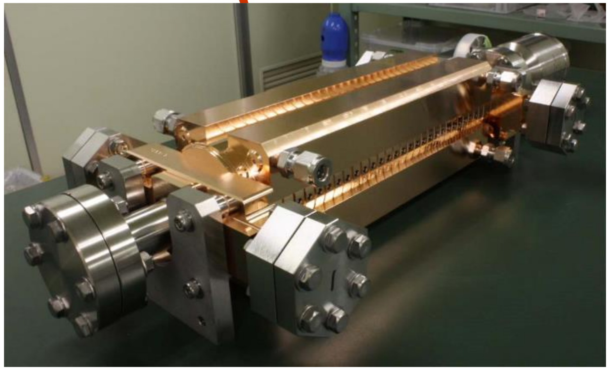
Funded by the European Union

WPs Relationship

Compact







Bring together technology advances in key accelerator systems for XFEL

Funded by the
European Union

Compact

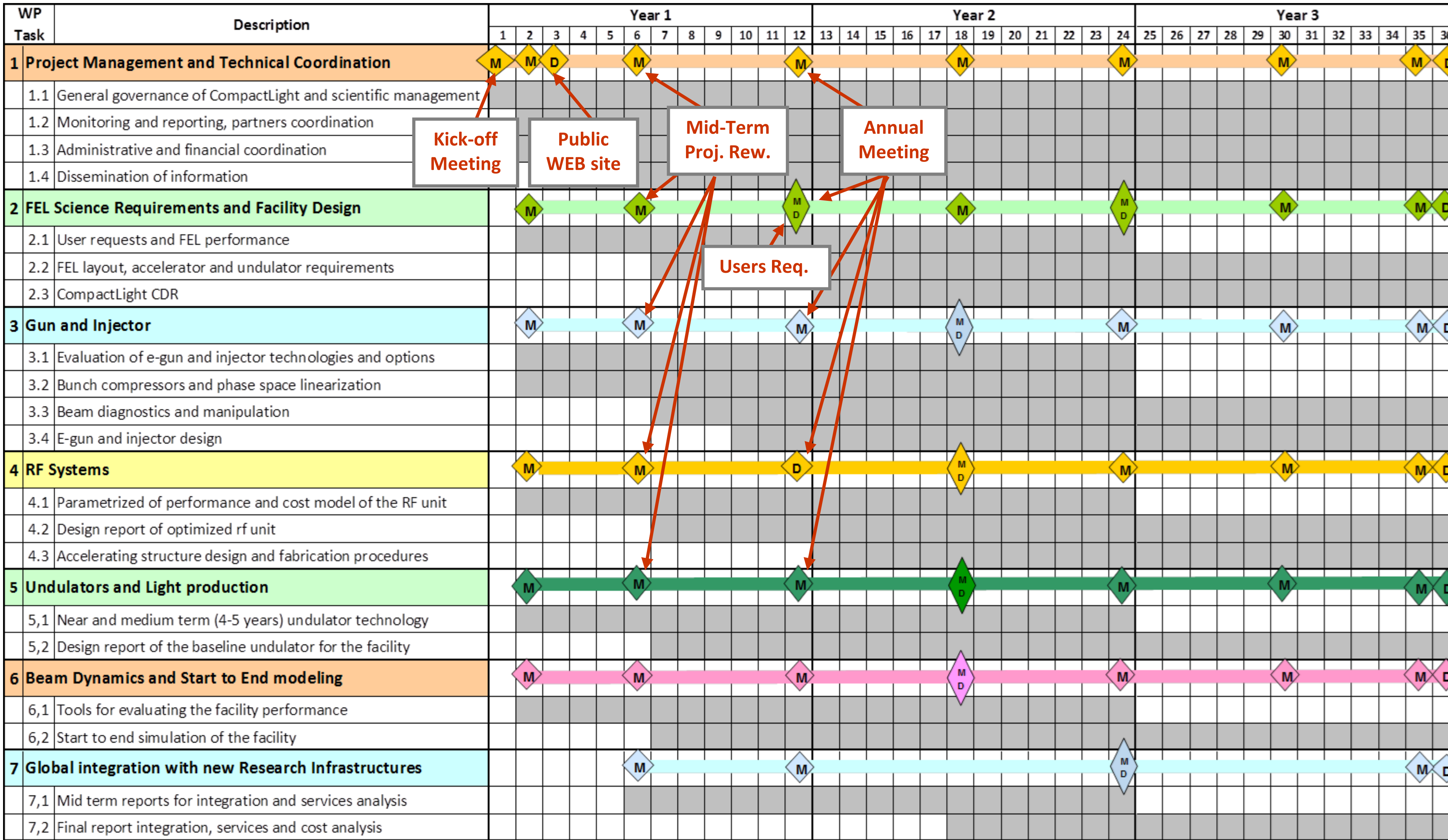
WPs Ongoing activities

E.A. Seddon et al.

Funded by the European Union

Time plan, Milestones and Deliverables

Compact



CompactLight Gant chart

Funded by the European Union

ALBA

Compact

First XLS - CompactLight Annual Meeting

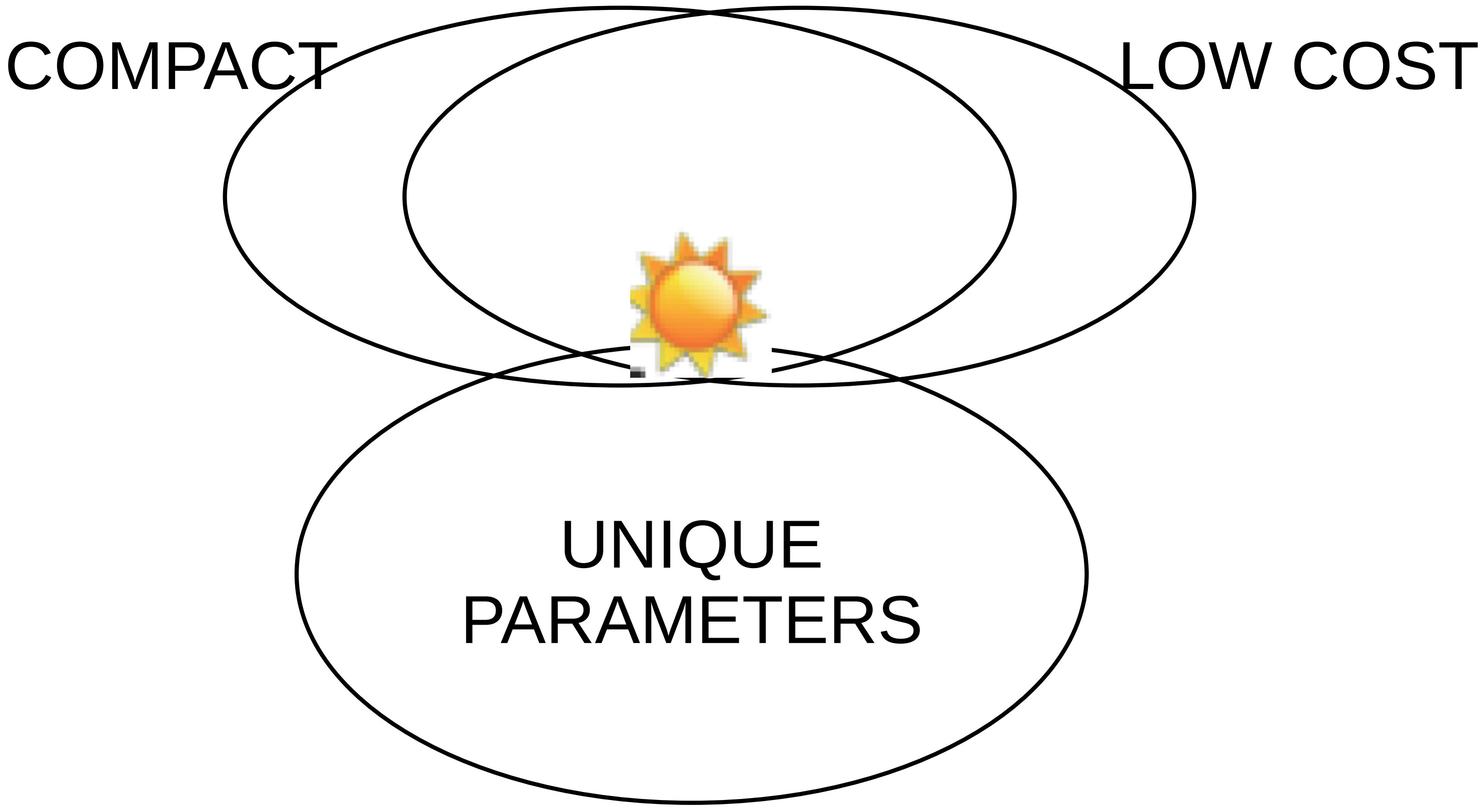
10-12 December 2018
Europe/Madrid timezone

XLS Users Meeting: 27-28 Nov 2018 at CERN

	Welcome: Welcome		*18-3-008 - CLIC Meeting room, CERN*	13:30 - 13:40
	The CompactLight Project		*18-3-008 - CLIC Meeting room, CERN*	13:40 - 14:00
14:00	XLS layout and performance		*18-3-008 - CLIC Meeting room, CERN*	14:00 - 14:20
	Ultrafast X-ray spectroscopy of molecular systems and solid materials	*Majed Chergui*	*18-3-008 - CLIC Meeting room, CERN*	14:20 - 14:40
	Resonant spectroscopies at Compact FELs	*Claudio Masciovecchio*	*18-3-008 - CLIC Meeting room, CERN*	14:40 - 15:00
15:00	Femtosecond X-ray experiments for chemical dynamics research	*Christian Bressler*	*18-3-008 - CLIC Meeting room, CERN*	15:00 - 15:20
	X-ray imaging, spectroscopy and diffraction: a user's ultrafast dream	*Stefano Bonetti*	*18-3-008 - CLIC Meeting room, CERN*	15:20 - 15:40
16:00	Coffee Break with Discussion in Working Groups		*18-3-008 - CLIC Meeting room, CERN*	15:40 - 16:40
17:00	Round table discussion		*18-3-008 - CLIC Meeting room, CERN*	16:40 - 18:00
18:00				

):00	Serial crystallography and single particle imaging with XFELs: Overview and photon beam requirement	*Adrian Mancuso*		
	Time-resolved serial MX correlated with emission spectroscopy	*Allen Orville*		09:20 - 09:40
	Ultrafast X-ray scattering in correlated materials	*Matteo Savoini*		09:40 - 10:00
):00	Scientific case of the EUPRAXIA@SPARC_LAB	*Augusto Marcelli*		10:00 - 10:20
	High energy density science with X-Ray FELs	*Justin Wark*		10:20 - 10:40
	Attosecond science with X-ray FELs	*Jon Marangos*		10:40 - 11:00
l:00	**Coffee Break with Discussion in Working Groups**		***18-3-008 - CLIC Meeting room, CERN***	**11:00 - 12:00**
2:00	Round table discussion and wrap up		*18-3-008 - CLIC Meeting room, CERN*	12:00 - 13:30
3:00				

The CompactLight prime objective is to generate a compact & low cost FEL facility design



Funded by the European Union

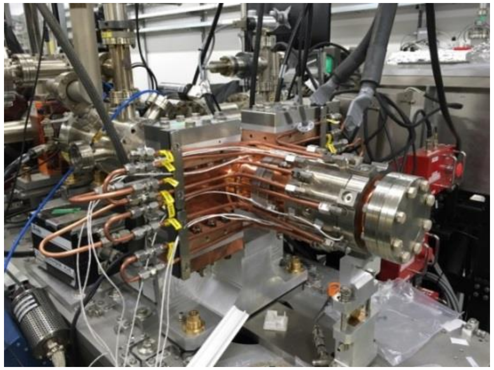
FEL Specifications

	Soft x-ray	Hard x-ray
Photon energy [keV] (min-max)	0.25 - ~2	~2 - 16
Wavelength [nm] (max-min)	5 - 0.6	
Repetition rate [Hz]	1000	100
Maximum pulse energy [mJ]	Competitive with other FELs	Competitive with other FELs
Number of photons		
Pulse duration [fs]	0.1 – 50	
Polarisation (at experiment)	Variable, selectable	Variable, selectable
Two-colour pulses: time separation [fs]	-20 -> +40	
Two-colour pulses: photon energy variation (max. of E2/E1)	2 (270-530eV), 1.2 for the rest of the range	1.1

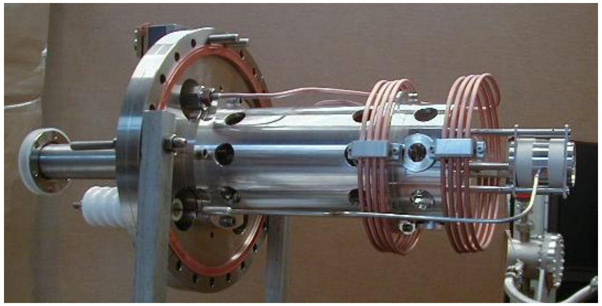
WP3: Gun & Injector

Tasks:

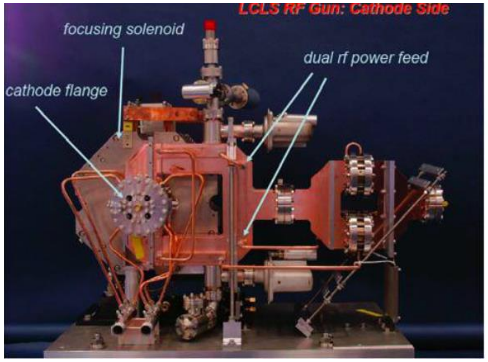
- Review State of the art Gun/Injector (S, C, X-band) and pick the best for XLS
- Develop of novel high-repetition rate gun/injector (with K-band linearizer)



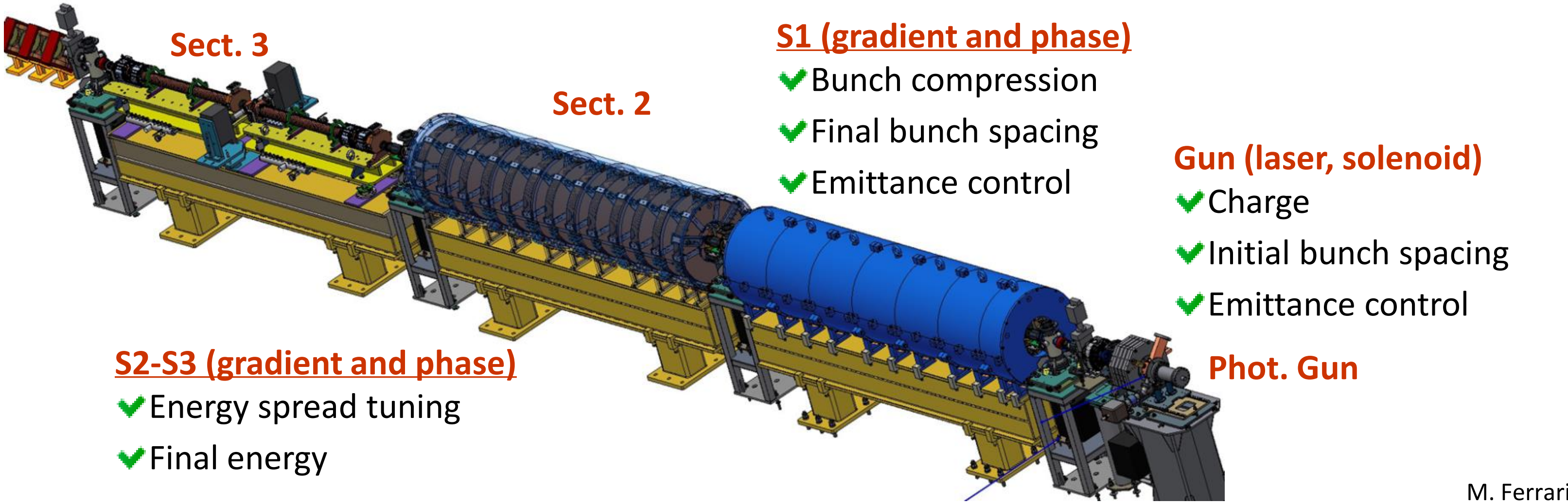
400Hz S-band rf gun in CLARA



Ultra-low emittance electron source, TU/e



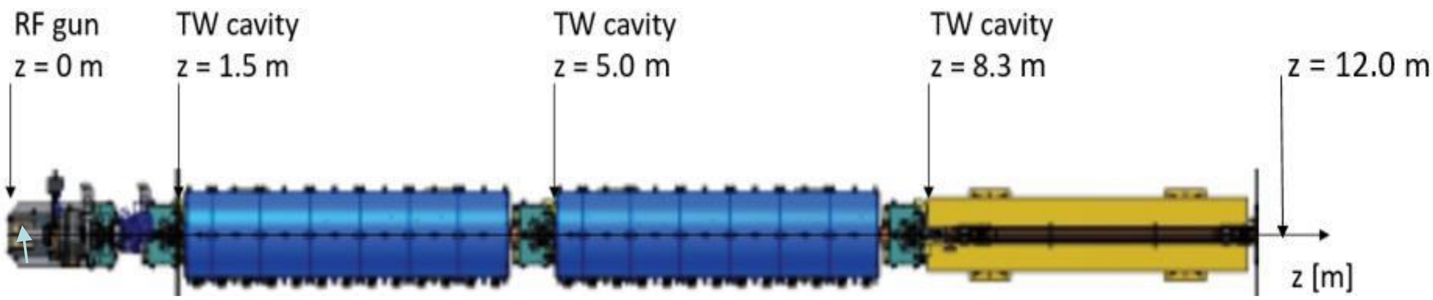
LCLS S-band rf gun



M. Ferrario

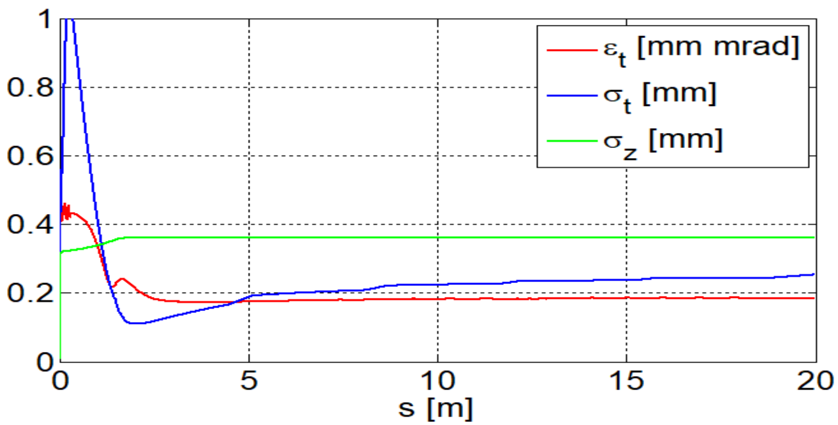
S-Band Injector (Q=75pC)

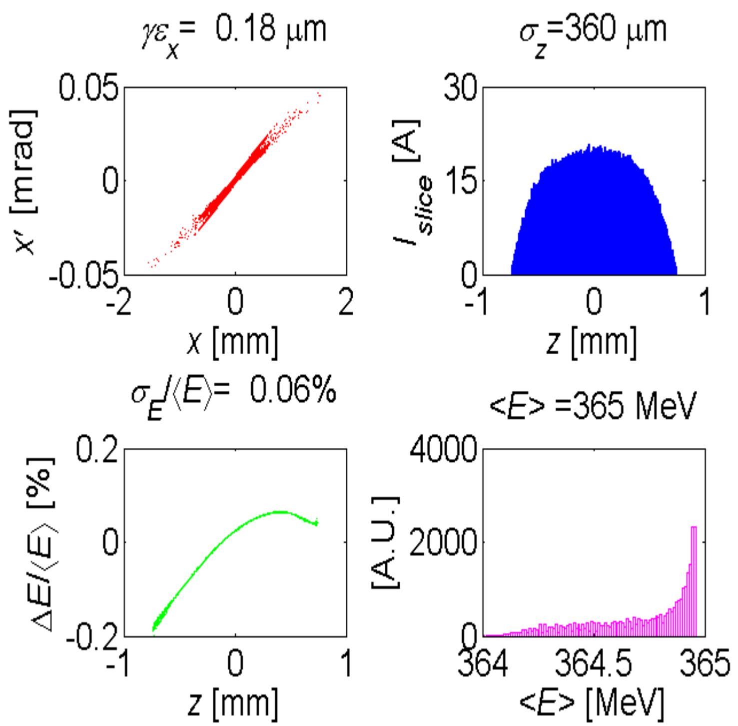
A.Giribono



1.6 Cell S-band gun
Epeak=120 MV

S-band TW SLAC type





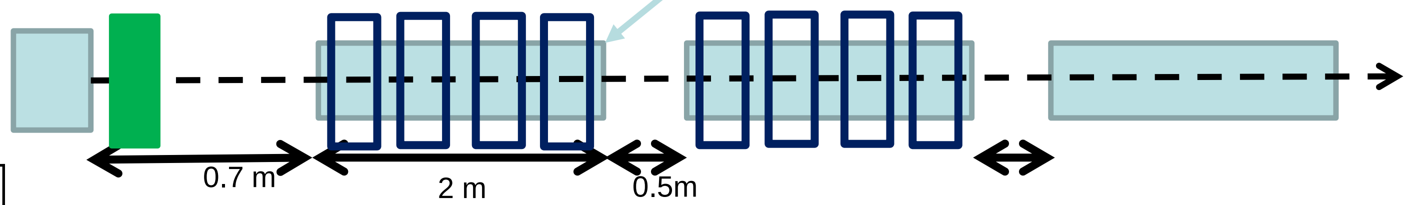
C-Band Injector (Q=100pC)

1.6 cell RF gun operating at 240 MV/m cathode peak field

Gun solenoid

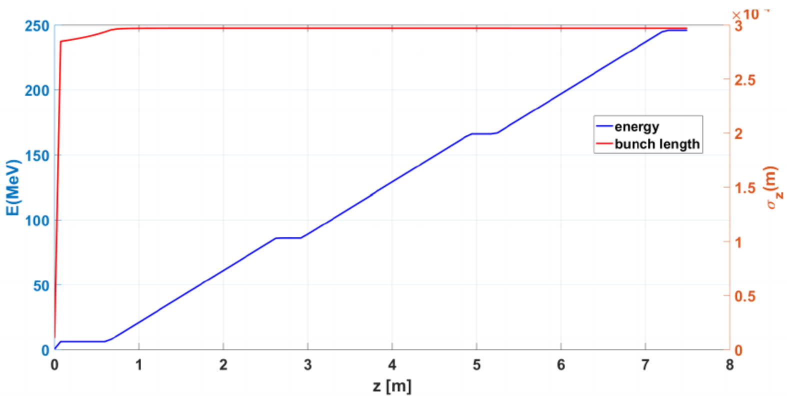
TW structures solenoids

2 C-band TW structures, with solenoid around, operating at 40 MV/m average accelerating gradient (as example, PSI-like structures with 1 klystron every 2 sections)

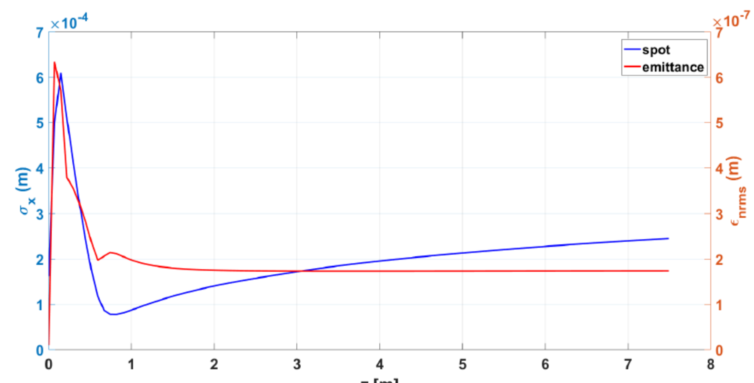


Laser/cathode parameters	
Pulse length	3.8 ps (Uni)
Spot size radius	324 μm (Uni)
Thermal emit	0.9 μm/mm

M. Croia



$\sigma_{z,final} \approx 300\ \mu m$



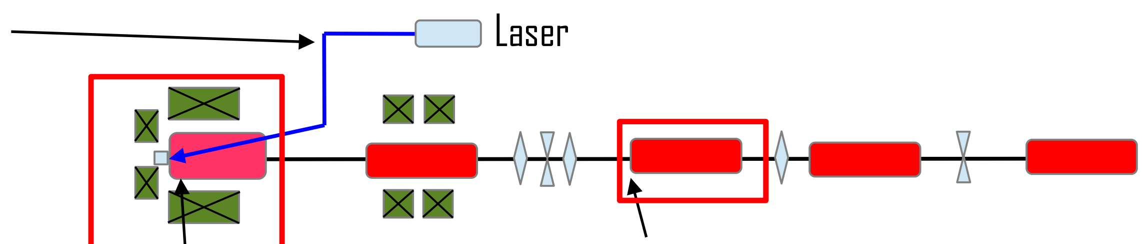
$\epsilon_{n,rms,final} \approx 174\ nm$

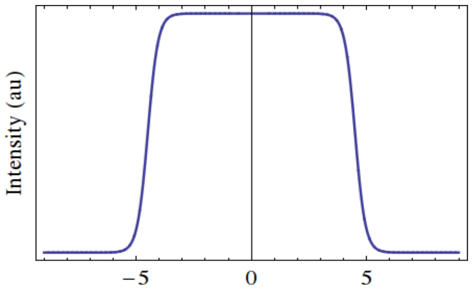
Funded by the European Union

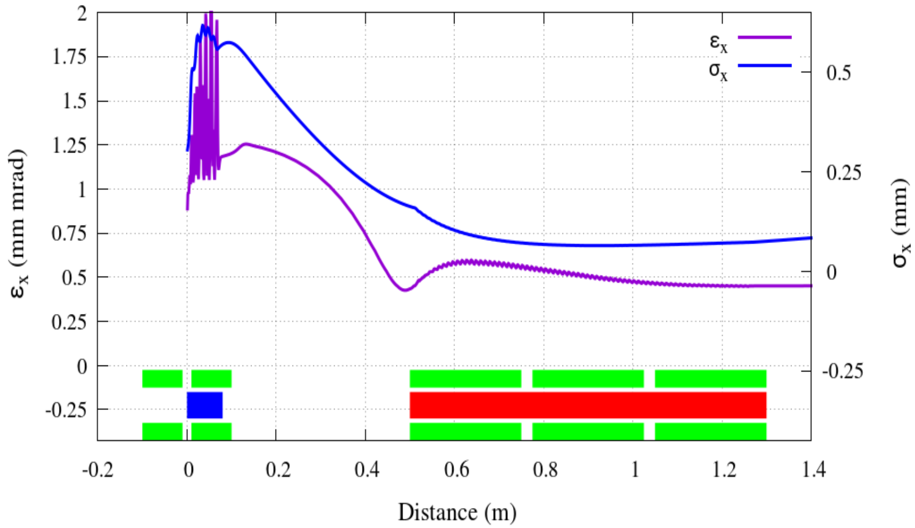
X-Band Injector (Q=250 pC)

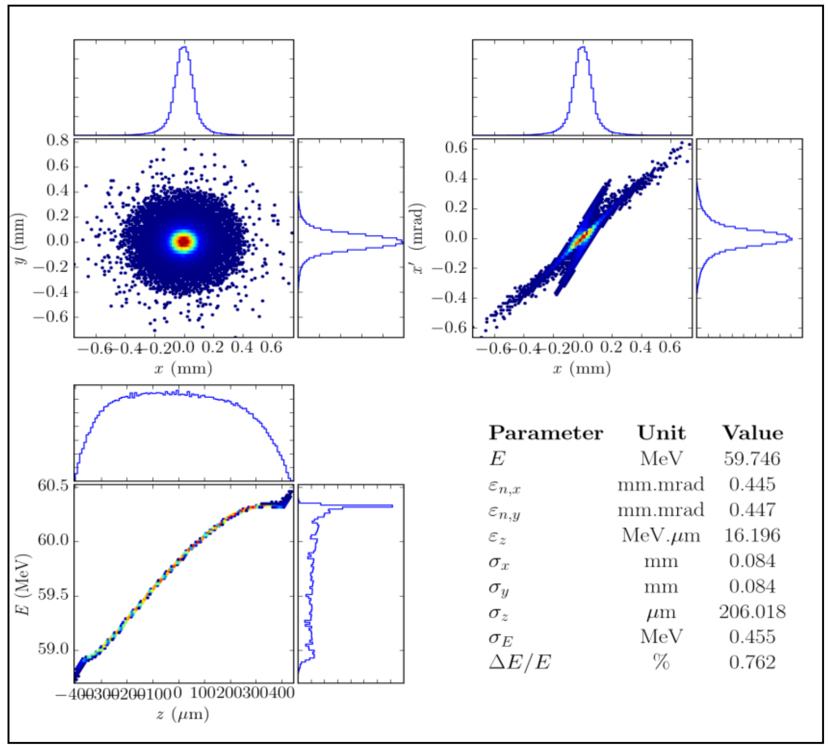
Compact

σ_z = 3 ps (FWHM)
$\sigma_{x,y}$ = 0.3 mm









Parameter	Unit	Value
E	MeV	59.746
$\varepsilon_{n,x}$	mm.mrad	0.445
$\varepsilon_{n,y}$	mm.mrad	0.447
ε_z	MeV.μm	16.196
σ_x	mm	0.084
σ_y	mm	0.084
σ_z	μm	206.018
σ_E	MeV	0.455
$\Delta E/E$	%	0.762

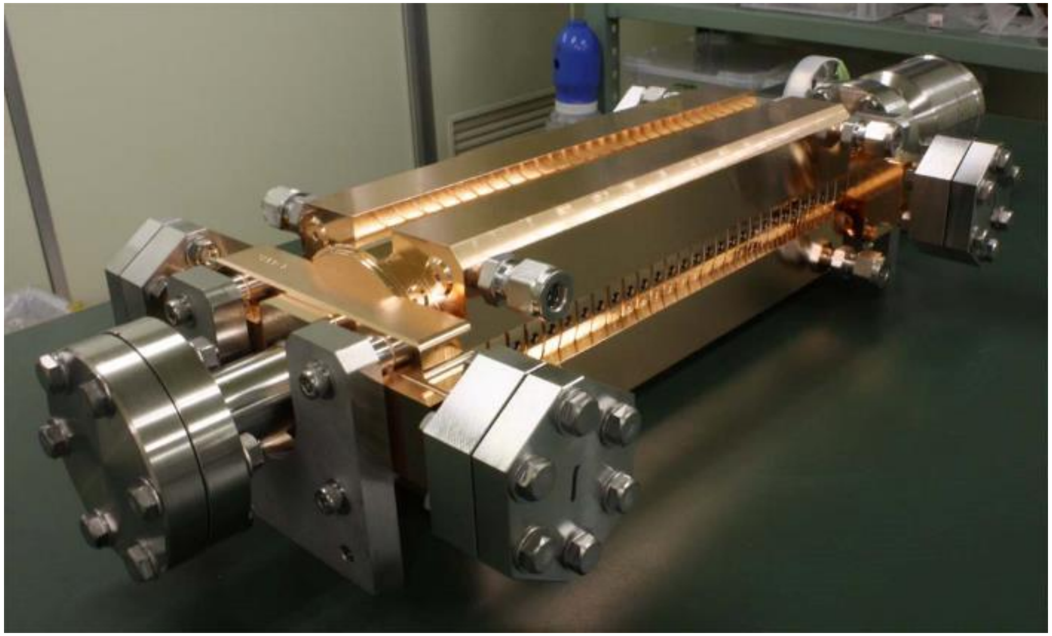
A. AKSOY

Linac gradients for most recent X-ray FELs

European XFEL (Germany)	24 MV/m	Superconducting L-band
Swiss FEL (Switzerland)	28 MV/m	Normal-conducting C-band
SACLA (Japan)	35 MV/m	Normal-conducting C-band

CLIC accel. structure:

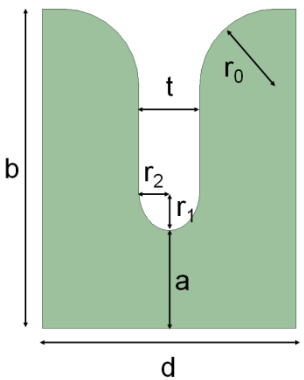
- **Normal-conducting X-band**
- **Gradient 100 MV/m**
- **Input power ≈50 MW**
- **Pulse length ≈200 ns**
- **Repetition rate 50 Hz**



XLS target: 65-70 MV/m

W. Wuensch

50 MW, 1.5 μs

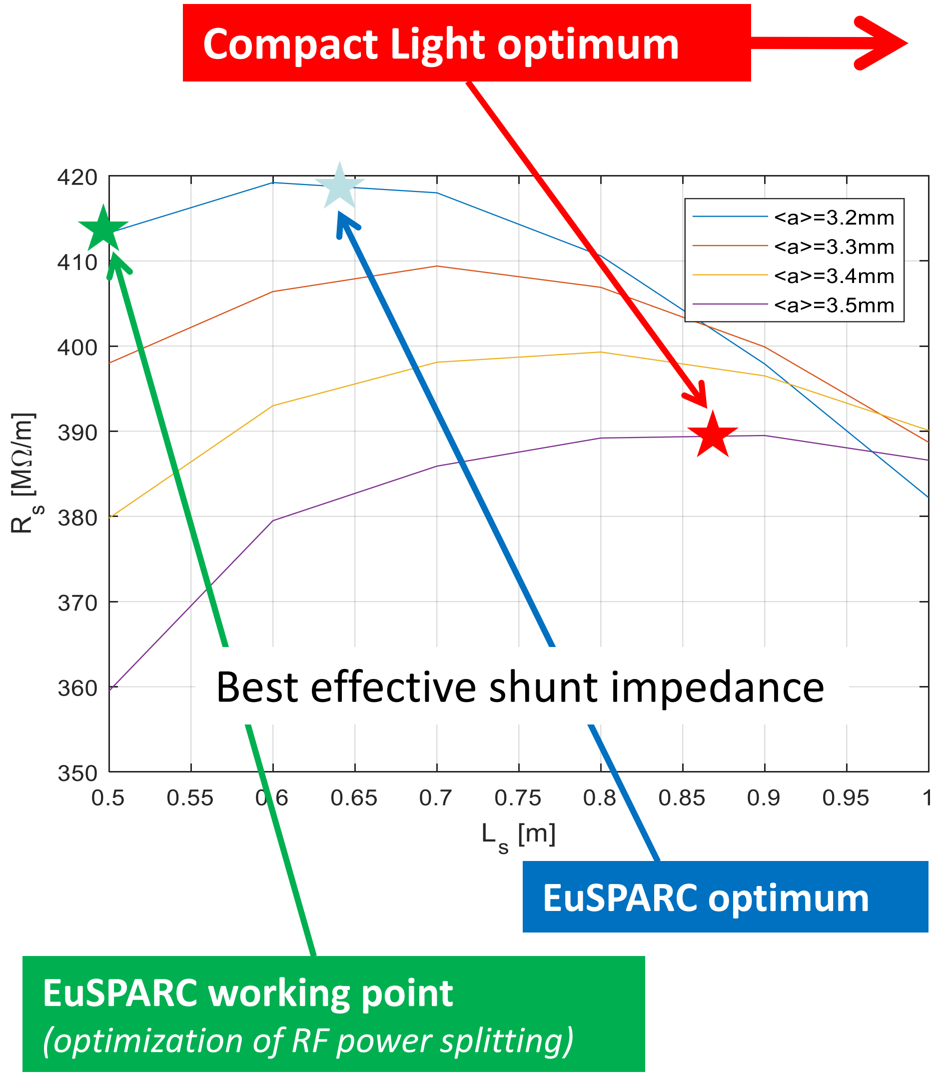


- Baseline accelerating gradient: **65 MV/m** → ***Trade-off between machine compactness and RF power requirements***
- RF system and pulse compressor characteristics
- Average iris radius: **3.5 mm** → ***Beam dynamics requirements (BBU threshold)***
- Electromagnetic parametric study of the TW cell
- Effective shunt impedance optimization by a 2D scan of the total length and the iris tapering
- Check of modified Poynting vector values @ nominal gradient
- Design a realistic RF module including power distribution network
- Finalize the electromagnetic (input and output couplers) and mechanical design

Iterations among these various steps are typically required.

A. GALLO

XLS Accel. Struct. optimization

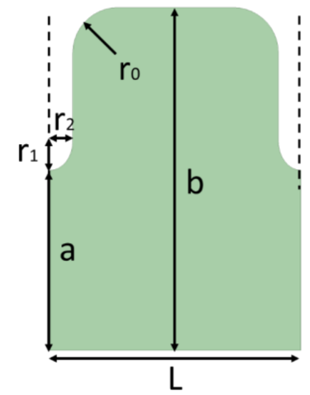


Freq. of 2π/3 mode [GHz]	**11.9942**
Average iris radius <a> [mm]	3.5
Total length of the TW structure L_s [m]	0.9
RF pulse [μs]	1.5
Average gradient <G> [MV/m]	**65**
Linac Energy gain E_{gain} [GeV]	4.5
Linac active length L_{act} [m]	69.2
Unloaded SLED Q-factor Q_0	180.000
External SLED Q-factor Q_E	21400
Iris radius a [mm]	4.3-2.7
Group velocity v_g [%]	4.5-1.0
Effective shunt Imp. R_s [MΩ/m]	**389**
Filling time t_f [ns]	140
Input power per structure P_{k_s} [MW]	9.8
Structures per module N_m (input power per module P_{k_m} [MW])	**4 (39)**
Total number of structures N_{tot}	**80**
Total number of klystrons N_k	**20**

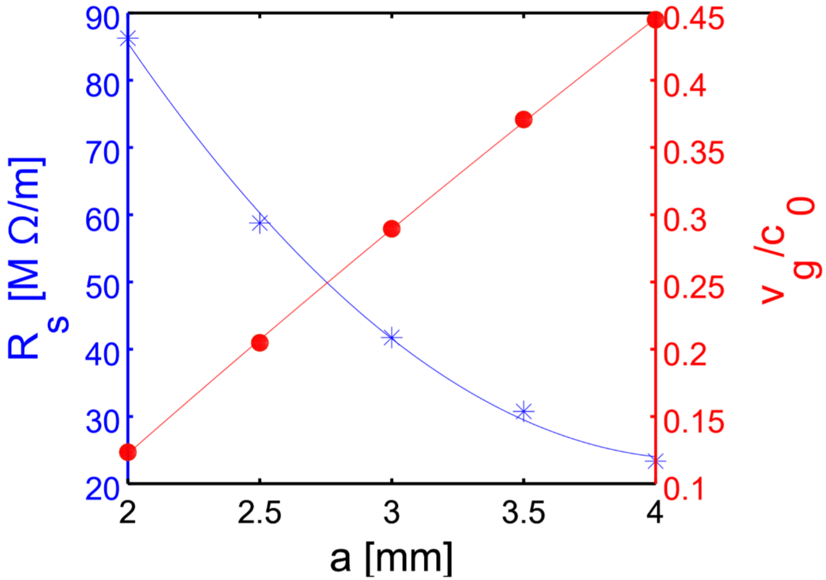
A. Gallo

Ka-band structure at CERN

- Structure analytical optimization
  - Working at 36 GHz, 2π/3 mode
  - Constant impedance structure
  - Consistent with Lancaster's results



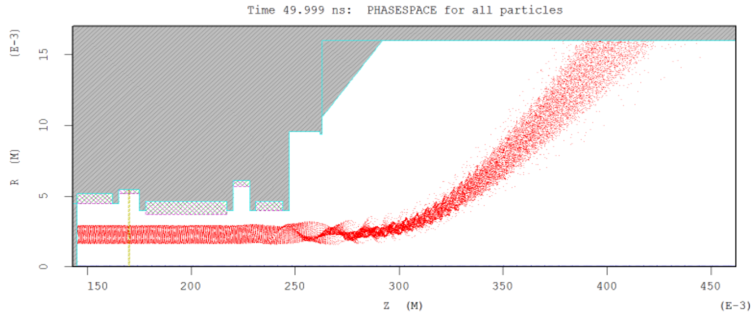
Geometrical parameters	
a [mm]	≥ 2
b [mm]	≥ 3.8869
L [mm]	2.778 (2π/3 mode)
r_0 [mm]	0.8
t [mm]	0.6

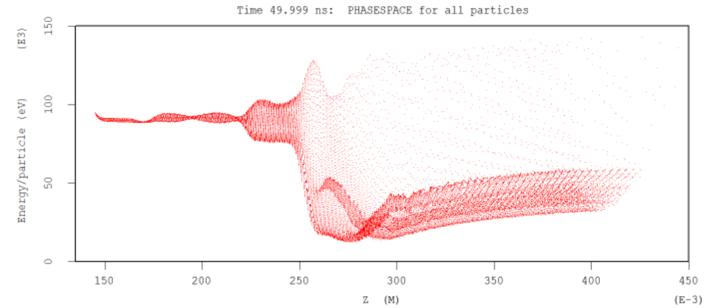


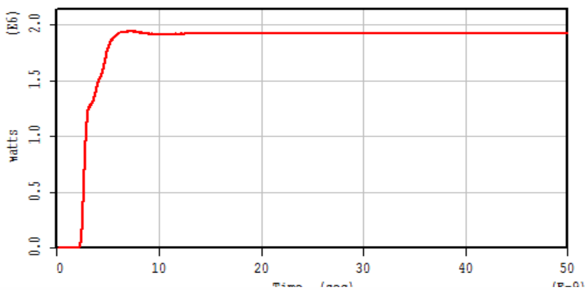
X. WU

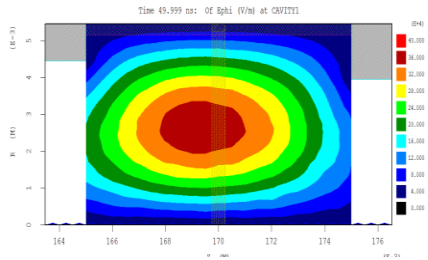
PIC simulations results

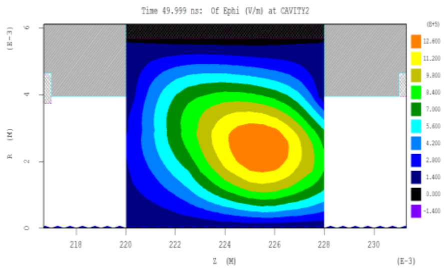
University of

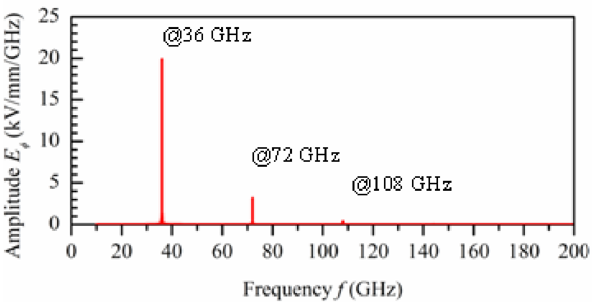


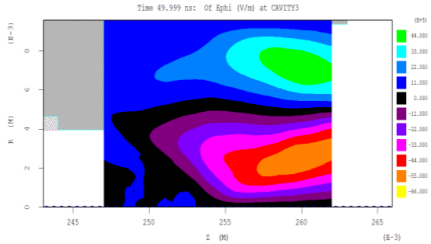




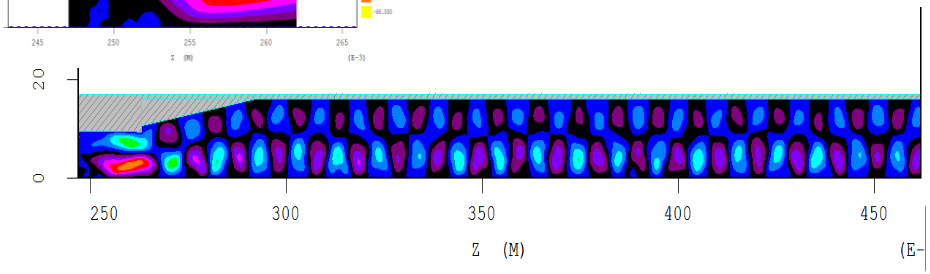








Output cavity



SUPA

A. CROSS

Comparative studies of *ambitious* undulators on the timescale of 4-5 years: e.g. cryo- permanent-magnet, super-conductive undulators, …

Cory PM Undulator
HZB/UCLA

ENEA-INFN

S. C. Undulator KIT

F. Nguyen

Funded by the European Union

Undulator parameters

Compact

Soft X-ray case working parameters

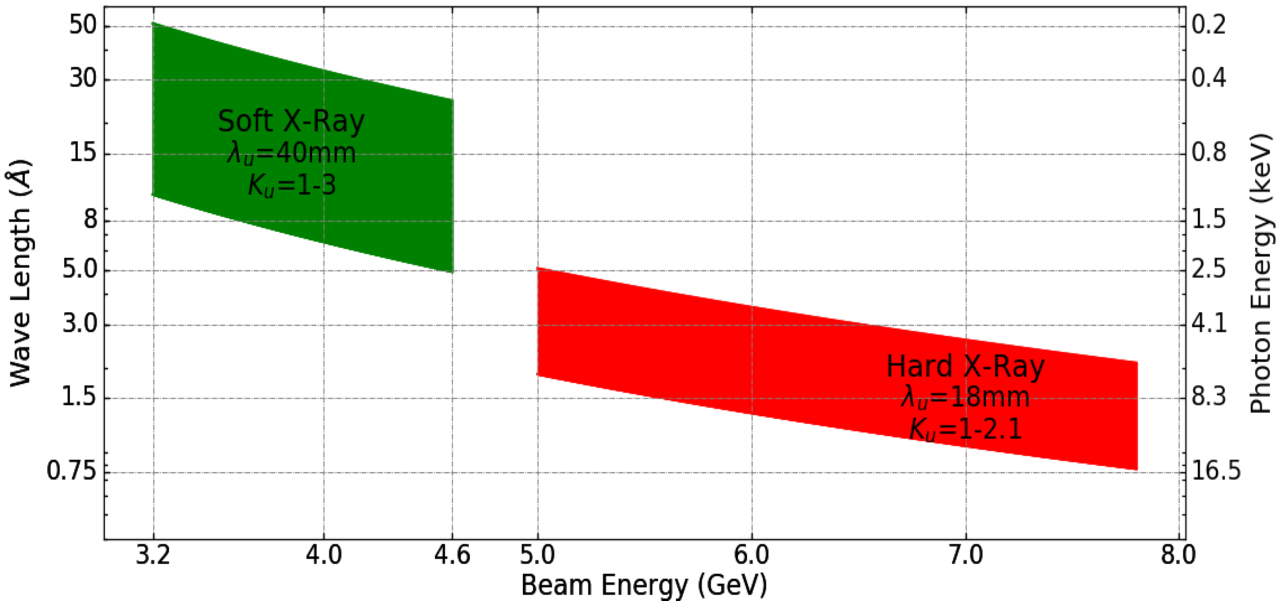
Undulator parameters	
undulator period	1.7 cm
undulator gap	3 mm
deflection parameter (RMS)	1.9
Bunch parameters	
beam energy	4 GeV
pulse duration (FWHM)	10 fs
bunch charge	20 pC
peak current	1.9 kA
norm. emittance	0.12 mm×mrad
energy spread	0.01 %
Potential reach	
FEL wavelength ($\hbar\omega$)	0.66 nm (1.9 keV)
N_γ/pulse	5.6×10^{11}
E_{FEL}/pulse	0.2 mJ
saturation length	21 m

Hard X-ray case working parameters

Undulator parameters	
undulator period	1.3 cm
undulator gap	3 mm
deflection parameter (RMS)	1.17
Bunch parameters	
beam energy	9 GeV
pulse duration (FWHM)	7.5 fs
bunch charge	75 pC
peak current	9 kA
norm. emittance	0.12 mm×mrad
energy spread	0.01 %
Potential reach	
FEL wavelength ($\hbar\omega$)	0.05 nm (25 keV)
N_γ/pulse	2.5×10^{11}
E_{FEL}/pulse	1 mJ
saturation length	25 m

F. Nguyen

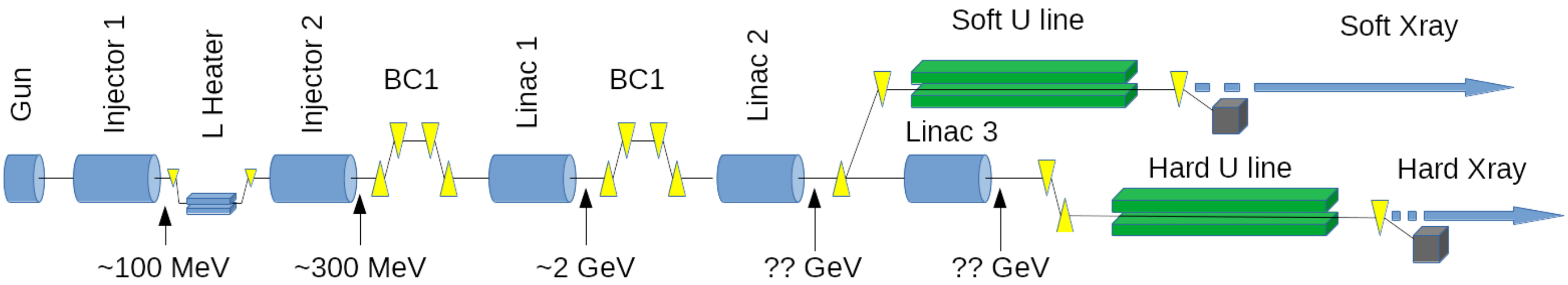
WP6: Start-to-End modelling



- Perform start-to-end simulations, which cover the beam transport from the cathode to the FEL exit, for Soft X-Ray & Hard X-Ray, including mechanical tolerance studies.
- Provide key parameters and performance estimates of the overall facility.
- Define the basis for technology choices for critical components and for developing detailed designs of subsystems and components.
- Develop tools for modeling the machine, as the basis for the final integrated performance studies.

A. Aksoy

XLS flavours



#	Gun	Acc	Lnz	BC1	Acc	BC2	Acc	Undulator
1	S-Band gun 3 GHz, 1.6? Cell 100 MV?	S-Band Acc 3 GHz, N? Cell 15 MV/m	X-Band Lnz 12 GHz, N? Cell G MV/m	BC1 Chicane	X-Band Acc 12 GHz, N? Cell G MV/m	BC2 Chicane	X-Band Acc 12 GHz, N? Cell G MV/m	Undulator λ_u ,*K*, *N?* section
2	C-Band gun 6 GHz, 3.6? Cell 200 MV?	C-Band Acc 6 GHz, N? Cell G MV/m	X-Band Lnz 12 GHz, N? Cell G MV/m	BC1 Chicane	X-Band Acc 12 GHz, N? Cell G MV/m	BC2 Chicane	X-Band Acc 12 GHz, N? Cell G MV/m	Undulator λ_u ,*K*, *N?* section
3	X-Band gun 12 GHz, 5.6? Cell 300 MV?	X-Band Acc 12 GHz, N? Cell G MV/m		BC1 Dogleg	X-Band Acc 12 GHz, N? Cell G MV/m	BC2 Chicane	X-Band Acc 12 GHz, N? Cell G MV/m	Undulator λ_u ,*K*, *N?* section
4	X-Band gun 12 GHz, 5.6? Cell 300 MV?	X-Band Acc 12 GHz, N? Cell G MV/m	K-Band lnz 36 GHz, N? Cell G MV/m	BC1 Chicane	X-Band Acc 12 GHz, N? Cell G MV/m	BC2 Chicane	X-Band Acc 12 GHz, N? Cell G MV/m	Undulator λ_u ,*K*, *N?* section

1D full X-band solution

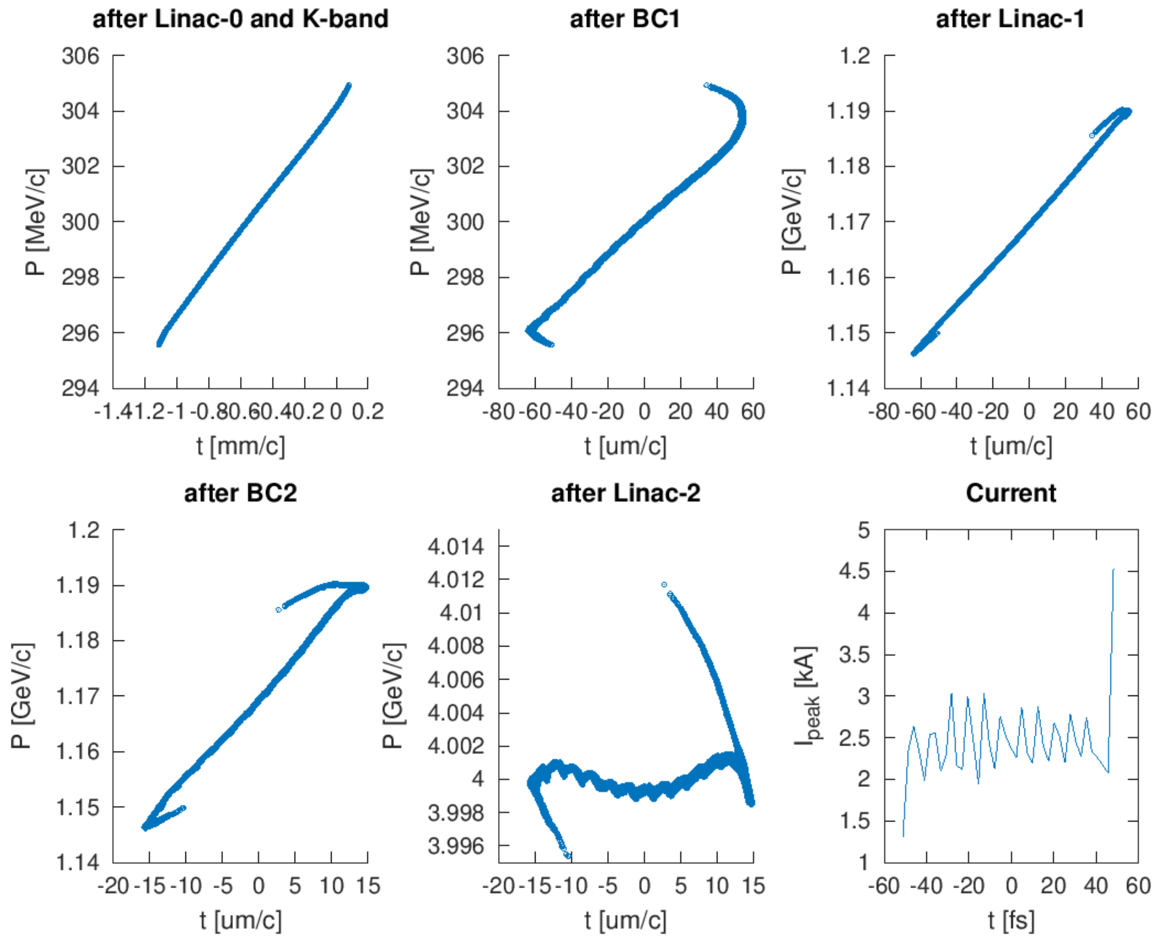
Frascati's XLS X-band structure ; Lancaster / CERN K-band structure

Bunch charge = 250 pC
Injector_sigmaz = 208 um

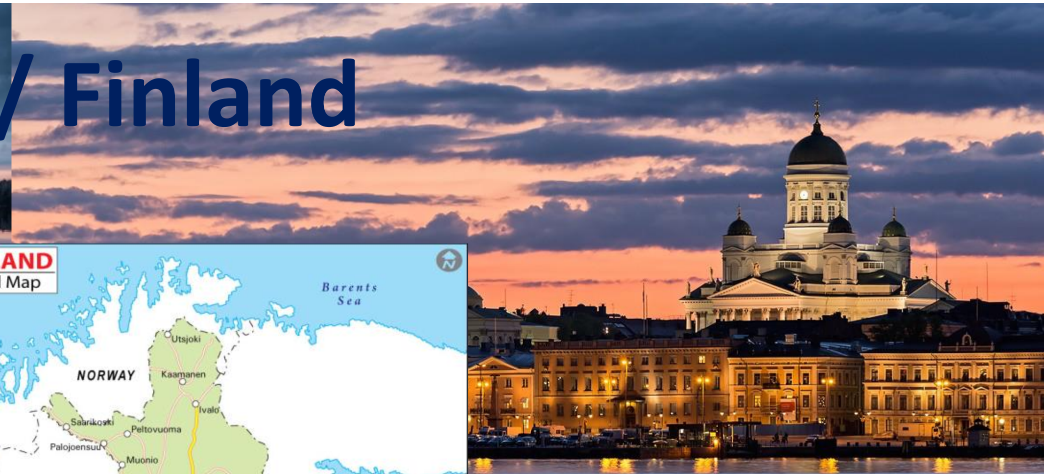
BC1_sigmaZ = 35 um
BC1_meanE = 300.0 MeV

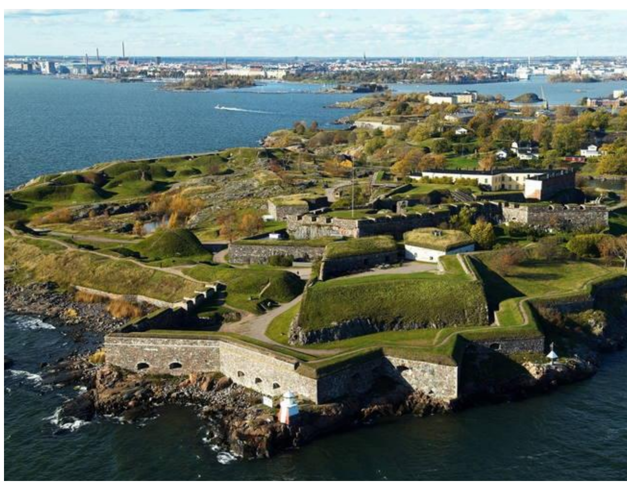
BC2_sigmaZ = 8 um
BC2_meanE = **1.2 GeV**
BC2_slice_sigmaE = 0.0007 GeV
BC2_slice_rel_Espread = 0.06 %

END_sigmaZ = 8 um
END_meanE = **4.0 GeV**
END_slice_sigmaE = 0.00012 GeV
END_slice_rel_Espread = 0.003 %



Helsinki / Finland





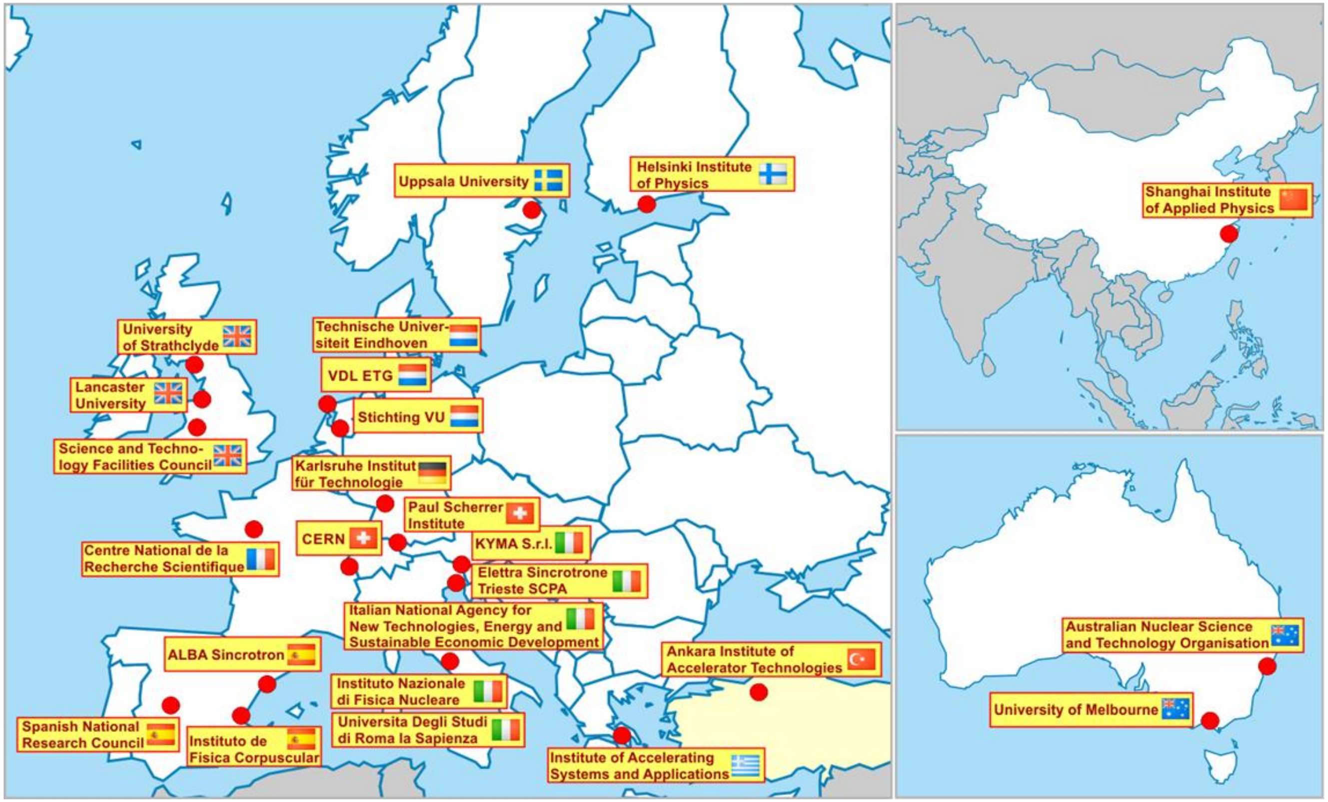
Funded by the European Union

Compact

Thank you!

CompactLight@elettra.eu

www.CompactLight.eu



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

Extras

CERN participation

WP2 - WP6:
- Facility design and beam dynamics, modelling, simulation, specifications and performance assessment
- Integration and cost optimisation

WP3:
- Linac and bunch compressors optics design and specifications (full X-band w/ K-band)

WP4: Work Package leader
- X-band structures and module design
- TW K-band Lineariser structure and coupler design. K-band pulse compression
- Design of standardized RF unit

WP5:
- Employ technical high-temperature superconductors (HTS) to superconducting undulators and wiggler for the Compact Linear Collider (CLIC) damping rings or the next generation of compact, highly brilliant light sources

WP1 - WP7:
- Support project management and coordination as well as CompactLight global integration for new RI (WP7)