WP2 Status

2nd CompactLight Annual Meeting,
Athens, 21 – 24 January 2020

Jim Clarke, STFC Daresbury Laboratory, on behalf of the WP2 team

WP2 FEL Science Requirements and Facility Design

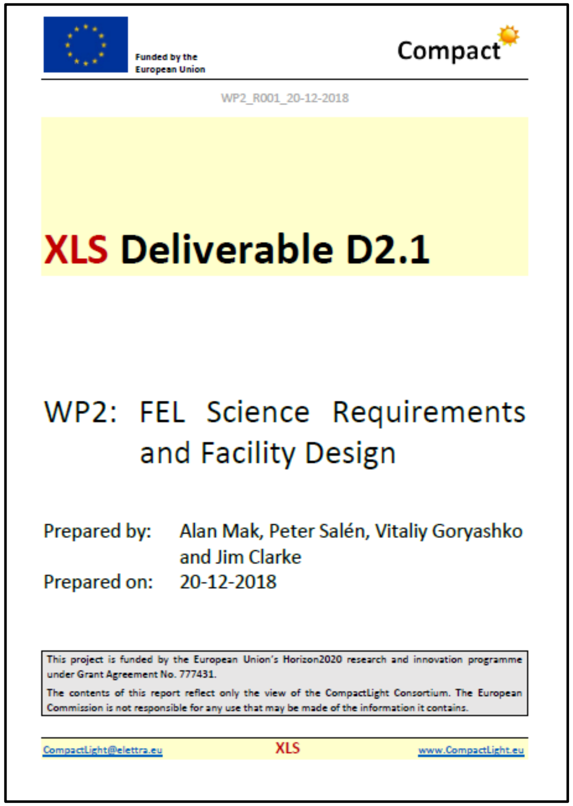
- ***The objective of WP2 is to provide the overall design of the hard X-ray FEL facility***
- **Description of work**
  - Starting from the performance specification of the FEL, based on user-driven scientific requirements, the aim of WP2 is to identify and choose the most appropriate technical solutions for the FEL considering cost, technical risk and performance.
  - WP 2 is broken down into three tasks, each with a single deliverable

WP2 FEL Science Requirements and Facility Design

- **Task 2.1 -** FEL user scientists and potential users will provide specification for the X-ray FEL output parameters (in terms of wavelength range, pulse energy, polarisation, beam structure, pulse duration, synchronisation to external laser, etc.).

- **Deliverable 2.1** - A report summarising the requests from the users and defining the performance specifications for the FEL, **(31/12/18).**

- **Task Leader – Vitaliy Goryashko, Uppsala University**



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WP2_R001_20-12-2018

XLS Deliverable D2.1

WP2: FEL Science Requirements and Facility Design

Prepared by: Alan Mak, Peter Salén, Vitaliy Goryashko and Jim Clarke

Prepared on: 20-12-2018

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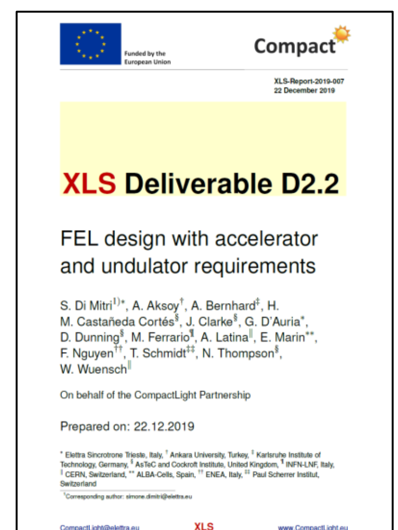
WP2 FEL Science Requirements and Facility Design

- **Task 2.2 -** The outcome of the previous task will be used by FEL experts (working closely with WP3, 4, & 5) to define the FEL system, with the accelerator and undulator requirements that are needed to achieve the specification (electron energy, bunch charge, peak current, emittance, energy spread, period, field strength, etc.). Then the task will identify and choose the most appropriate technical solutions considering cost, technical risk and performance. *The other WPs make recommendations for all the technical solutions which are then agreed within this task.*

- **Deliverable 2.2** - A report summarising the FEL design, with the accelerator and undulator requirements to achieve the specification, i.e. electron energy, bunch charge, peak current, emittance, energy spread, undulator parameters, etc., **(31/12/19).**

- **Task Leader – Simone DiMitri, Sincrotrone Trieste**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XLS-Report-2019-007
22 December 2019

XLS Deliverable D2.2

FEL design with accelerator and undulator requirements

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On behalf of the CompactLight Partnership

Prepared on: 22.12.2019

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WP2 FEL Science Requirements and Facility Design

- **Task 2.3 –** Engineers, accelerator physicists, undulator and RF experts will receive machine specification from FEL experts and will then design a user facility capable of achieving these requirements. Regular contact and iterations between the FEL experts, engineers, accelerator and undulator designers will be essential to achieve an optimised design. The Hard X-ray FEL ***conceptual design report*** will also include options for Soft Xray FEL and Compton Source. *WP2 has responsibility to ensure facility design is self consistent.*

- **Deliverable 2.3** - The conceptual design report for a Hard X-ray FEL facility, including cost estimates, with options for Soft X-ray FEL and Compton Source, **(31/12/20).**

- **Task Leader – Neil Thompson, STFC Daresbury Laboratory**

- **This is the primary deliverable for CompactLight and the focus of the year ahead**

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Facility Parameters

Table 1: Main parameters of the CompactLight FEL.

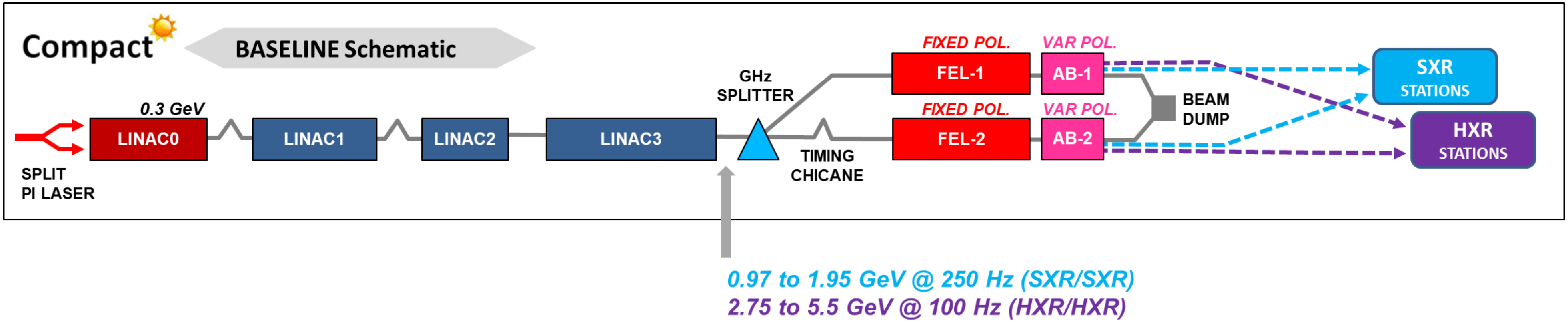
Parameter	Unit	Soft-x-ray FEL	Hard-x-ray FEL
Photon energy	keV	0.25 – 2.0	2.0 – 16.0
Wavelength	nm	5.0 – 0.6	0.6 – 0.08
Repetition rate	Hz	1000	100
Pulse duration	fs	0.1 – 50	1 – 50
Polarization		Variable, selectable	Variable, selectable
Two-pulse delay	fs	±100	±100
Two-colour separation	%	20	10
Synchronization	fs	<10	<10

D2.1 report is available at http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-374175

Baseline Layout

“Dual Mode Linac” – single linac, single klystron

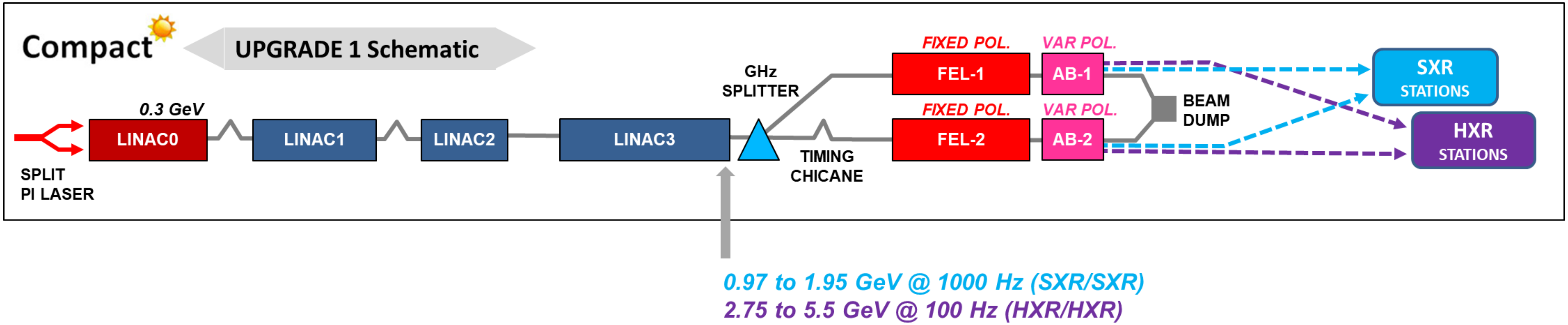
Every RF pulse contains two bunches



Upgrade 1 Layout

“Dual Source Linac” – single linac, two klystrons

Every RF pulse contains two bunches

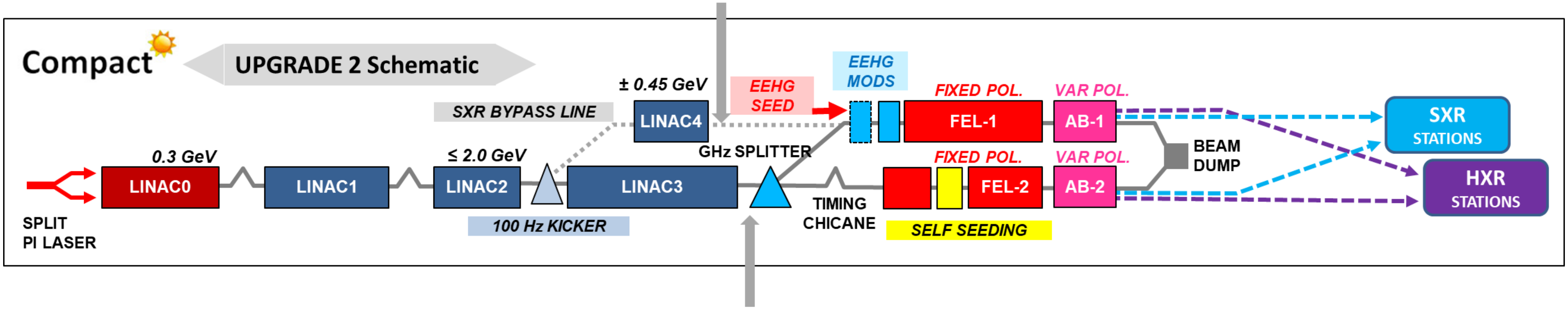


Upgrade 2 Layout

“Dual Source Linac” – single linac, two klystrons

Every RF pulse contains two bunches

0.97 to 1.95 GeV @ 100 Hz (SXR/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)

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Electron *vs.* photon beam energy

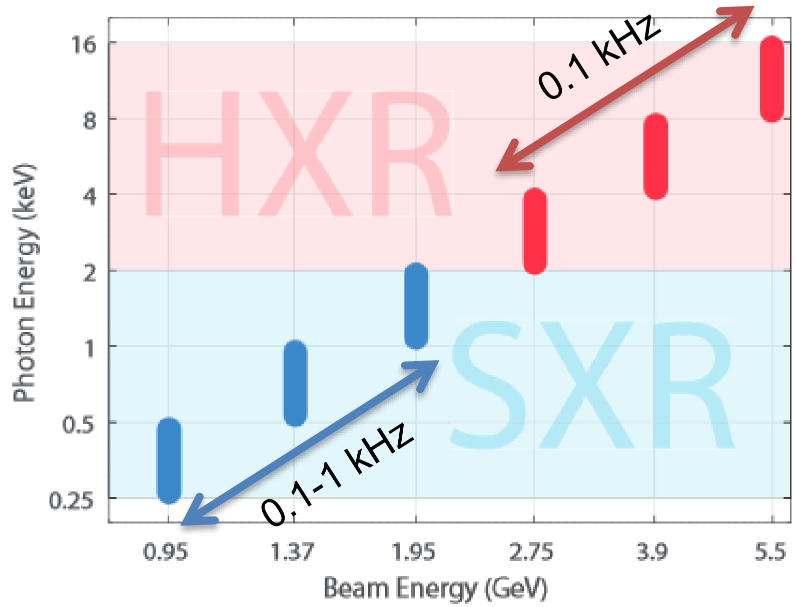
Table 5: Electron beam parameters at undulator entrance.

Parameter	Value
Max. Energy	5.5 GeV @ 100 Hz
Max. Peak Current	5 kA
Norm. Slice Emittance	0.15 μm rad
Bunch charge	< 100 pC
Bunch duration (RMS)	< 50 fs
Slice Rel. Energy Spread	10^{-4}
Max. repetition rate	1 kHz

- State-of-the-art injector
- Main challenge w.r.t. existing facilities: *1 kHz*

Table 11: Photon energy ranges and corresponding discrete electron beam energies at the undulator to cover the whole CompactLight spectral range. A minimum peak brilliance of $10^{33} ph/s/mm^2/mrad^2/0.1\%bw$ is considered. Linear polarization only is assumed.

Parameter	Unit	SXR			HXR		
Repetition rate	kHz	0.1, 0.25, 1			0.1		
Photon energy range	keV	0.25-0.5	0.5-1	1-2	2-4	4-8	8-16
Electron beam energy	GeV	0.97	1.37	1.95	2.75	3.9	5.5
Minimum peak current	kA	0.35	0.65	0.93	1.5	2.5	5
Slice energy spread (RMS)	%	0.05	0.04	0.03	0.02	0.015	0.01
Normalised slice emittance (RMS)	μm rad	0.2					
Bunch charge	pC	75					



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Injector baseline & upgrade

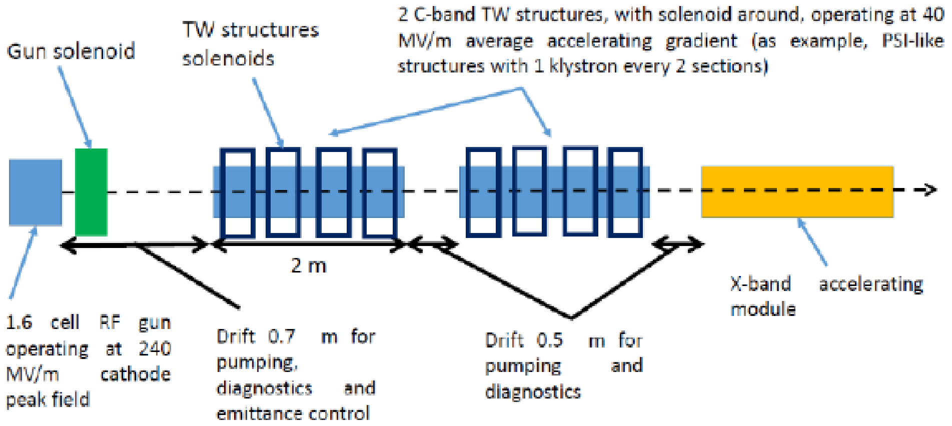

Table 3: Injector beam parameters.

Parameter	At gun exit	At L0 exit	Units
Repetition rate	0.1, 0.25, 1		kHz
Charge	75		pC
Proj. norm. emittance (RMS)	0.15 (x), 0.15 (y)		μm rad
Energy	6	280	MeV
Rel. enegry spread (RMS)	0.7	0.5	%
Bunch duration (RMS)	1.2	0.4	ps
Peak current (core)	20	60	A

- **Baseline:** C-band inj. + Ka-band linearizer
- **Upgrade:** X-band inj. + Ka-band linearizer

- ❑ Both guarantee 0.1 – 1 kHz rep. rate
- ❑ Transverse emittance at 1 kHz can be relaxed
- ❑ X-band inj. is more compact and utilizes same RF technology of the main linac
- ❑ The linearizer supports the optional velocity bunching as well

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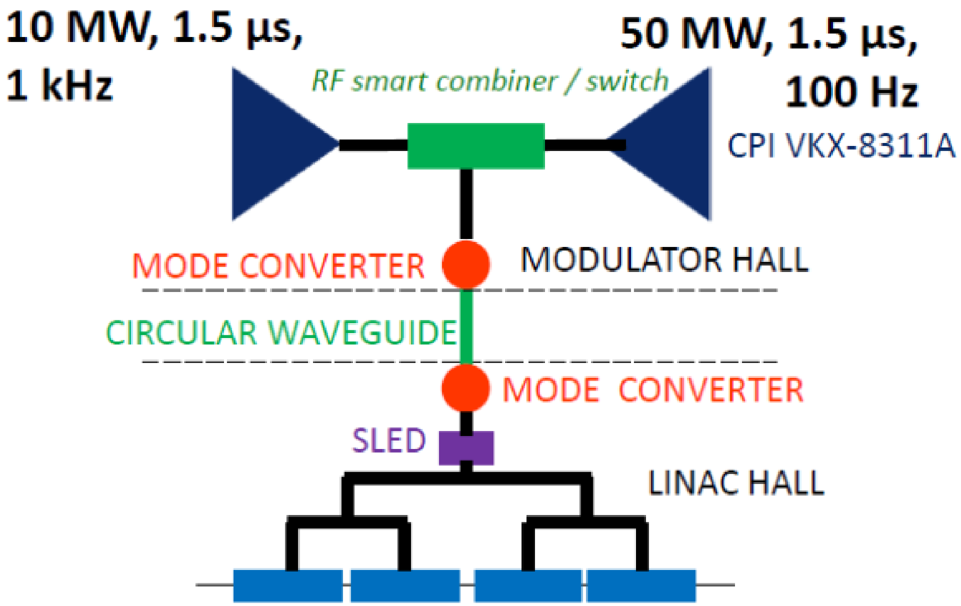
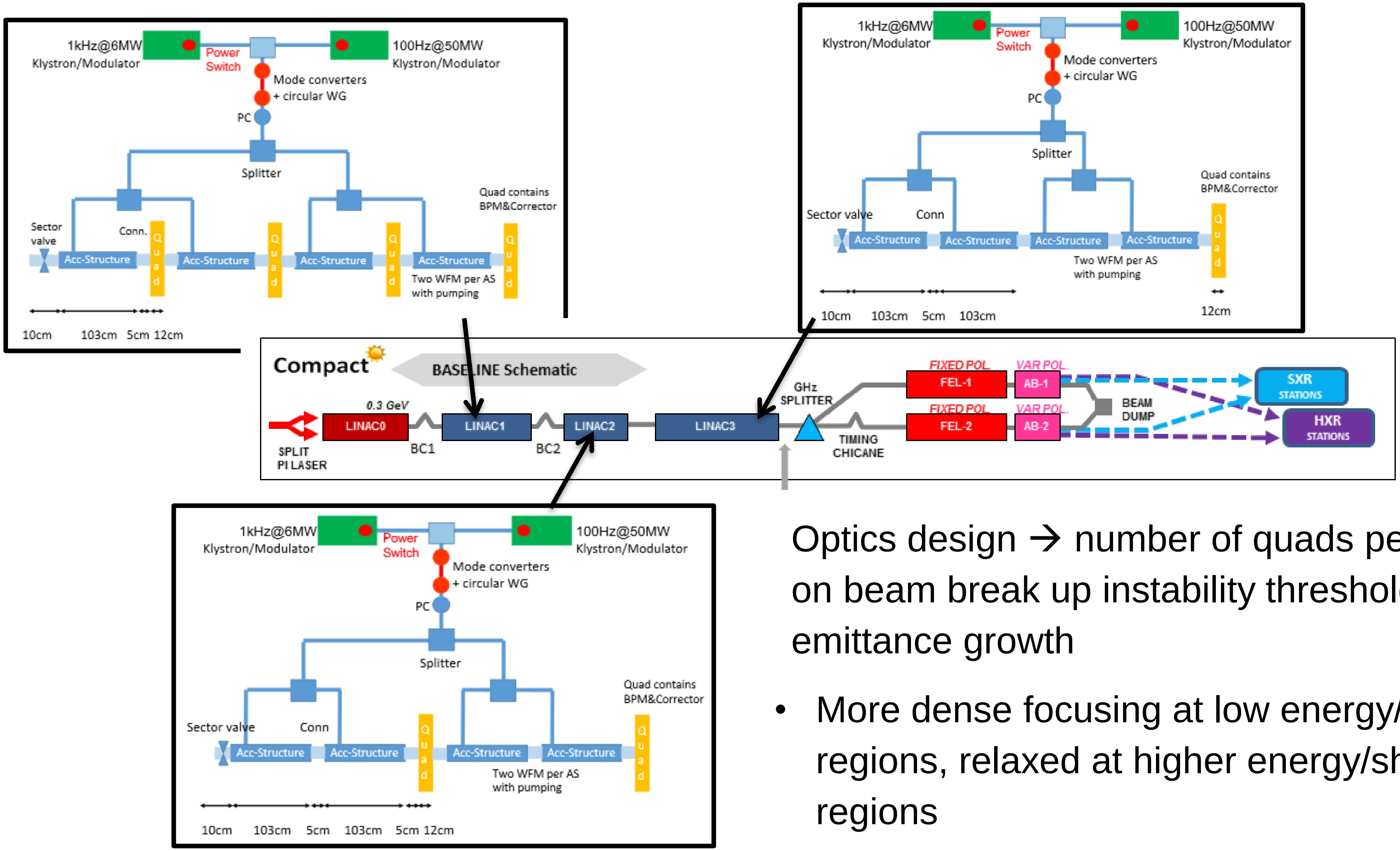
Main linac: RF distribution

- **Baseline:** "dual mode" for 0.1 & 0.25 kHz rep. rate
- **Upgrades:** "dual source" for up to 1 kHz rep. rate

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



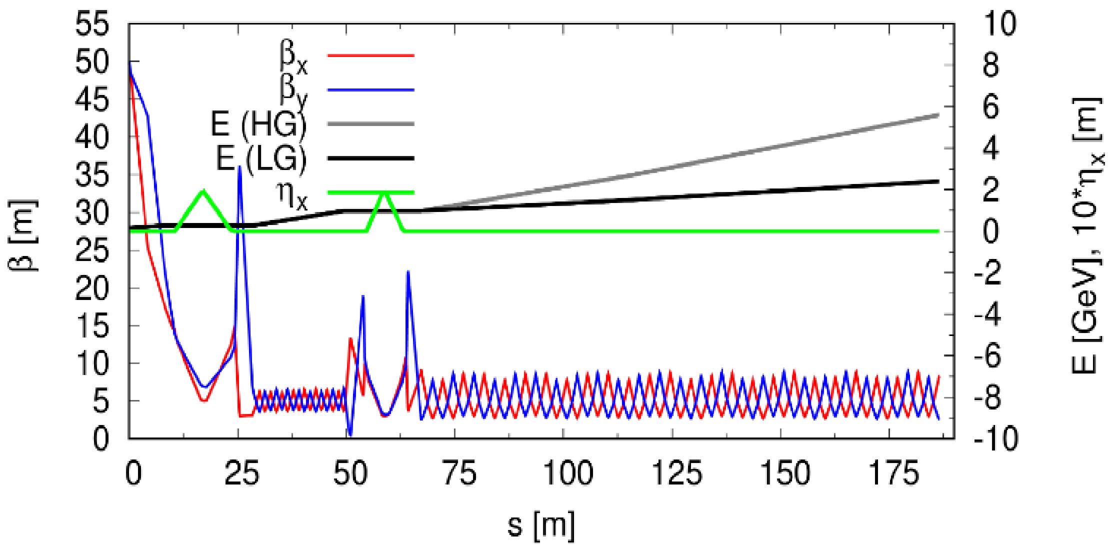
Main linac: modules

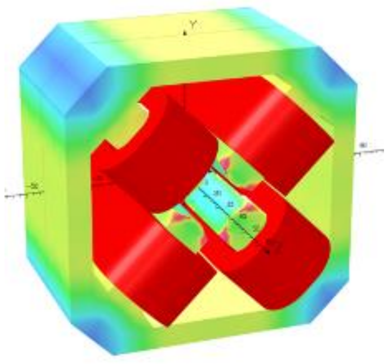


Optics design → number of quads per cavity, depends on beam break up instability threshold, *i.e.*, projected emittance growth

- More dense focusing at low energy/long bunch regions, relaxed at higher energy/shorter bunch regions
- The linac fill factor is in the range 70%-85%

Main linac: optics design





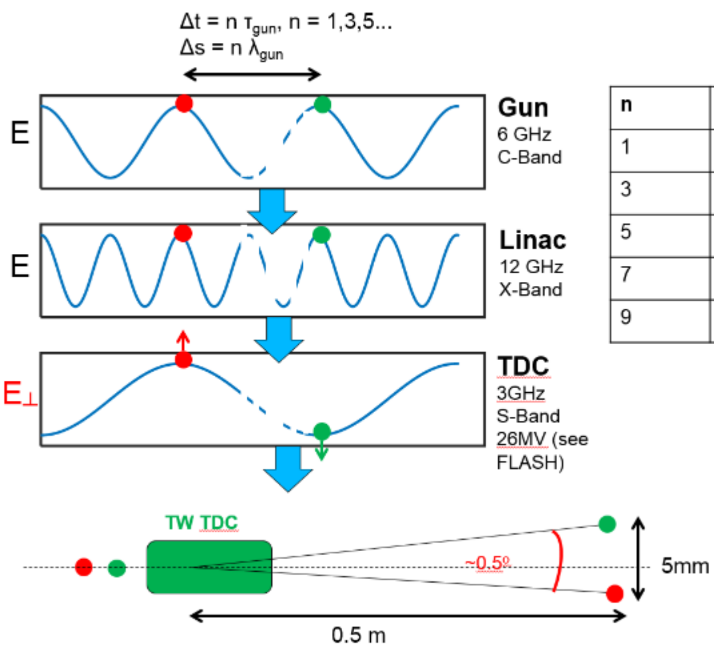
Quadrupole + correction coils

Table 6: Magnetic compressors parameters.

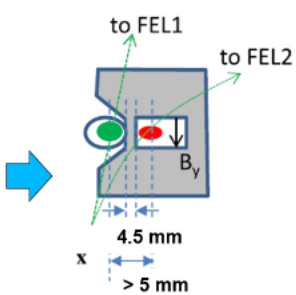
Parameter	Unit	BC1	BC2
Beam energy	GeV	0.25-0.3	1.4-1.6
Compression factor		10-15	5-10
Max. peak current at exit	kA	0.7	5
Min. bunch duration at exit (RMS)	fs	25	2
Max. $\|R_{56}\|$	mm	32	9
Max. rel. energy spread (RMS)	%	2	1.5
Geometry		chicane	chicane
Dipole bending angle	mrad	52.8	36.7
Dipole magnetic arclength	m	0.4	0.4
Total length	m	13.1	8.5
Tweaking quadrupoles		yes	yes

- ❑ > 70% RF-to-magnets filling fraction
- ❑ <50 µm-quads, <100 µm-RF misalignment errors
- ❑ 7 m average betatron functions
- ❑ 2 4-dipole chicanes for bunch compression

Twin bunches : concept

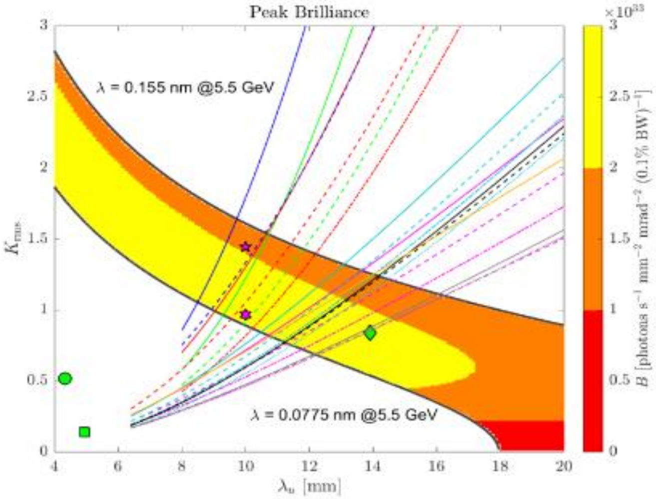


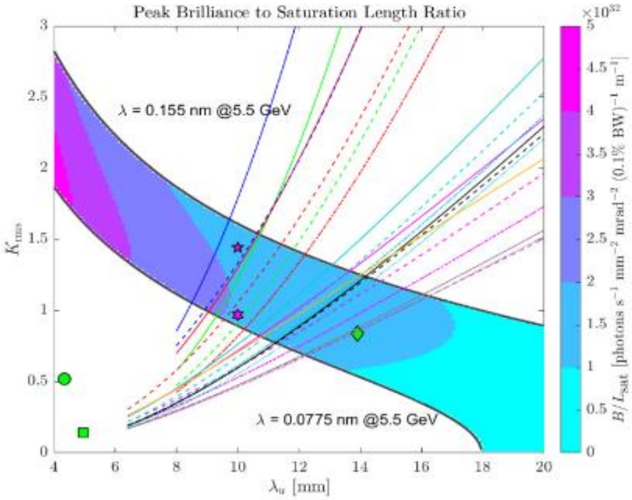
n	Δt	Δs
1	166 ps	50 mm
3	500 ps	150 mm
5	833 ps	250 mm
7	1.16 ns	350 mm
9	1.5 ns	450 mm



1. **Twin bunches** at the injector, separated by **0.83 ns** (e.g., 5 C-band cycles)
2. 30 MV S-band **TDC + septum** for splitting at high energy
3. High energy **dog-leg, 20 m x 2.5 m** footprint
4. High energy **chicane (10 m)** and **split-and-delay** photon beamline for synchronization.

Undulator: criterions





* tuning across photon energies will primarily be achieved by undulator scanning rather then electron energy scanning, in order to maximize efficient operation of the facility. Given that both SXR and HXR regimes require a factor of 8 photon energy scaling to be covered with a few discrete electron beam energies, the undulator should provide a factor of 2 wavelength tuning;
* variable, selectable polarization in both SXR and HXR range;
* two-colour operation achieved by double bunches sent to separate undulators. The required wavelength tuning of 10-20% is satisfied by the 2-fold wavelength tuning specified above;
* the ratio of FEL peak brilliance and saturation length should be maximized, as it is an index of performance vs. compactness;
* the FEL peak brilliance should be maximized by itself because there is a specific user requirement for a minimum brilliance;
* the aforementioned figures of merit should be maximized for a maximum electron beam energy lower than any other present x-ray FEL facility, and in particular lower than at SwissFEL for a higher maximum photon energy.

Undulator: final choice

Table 10: Results of GENESIS time-dependent simulations.

Parameter	CPMU	Delta	Hybrid	SCU
Saturation power [GW] (pulse average)	9.1	8.9	7.6	9.8
Saturation length [m]	24.5	26.5	29.1	15.6
Sat. pulse energy [μJ]	49	48	29	54
FWHM bandwidth [10^{-3}]	0.987	0.975	0.996	1.16
Peak brightness [10^{33} × × ph/s/mm^2/mrad^2/0.1%bw]	2.39	2.37	1.98	2.18

Table 12: FEL-1 and FEL-2 undulator parameters.

Parameter	Unit	Main radiator	Afterburner
Technology		SCU	IV-CPMU
Period length	mm	13	17
Minimum full gap	mm	4	3
Undulator parameter a_w		0.62–1.32	0.3–1.5
Maximum field on-axis	T	1.1	1.2
Segment length	m	1.8	1.8
Module length	m	2.3	2.0
Total length	m	37	6
Polarization		circular	variable

- **Baseline, Upgrade-1:** SASE
- **Upgrade-2:** EEHG SXR, self-seeding HXR

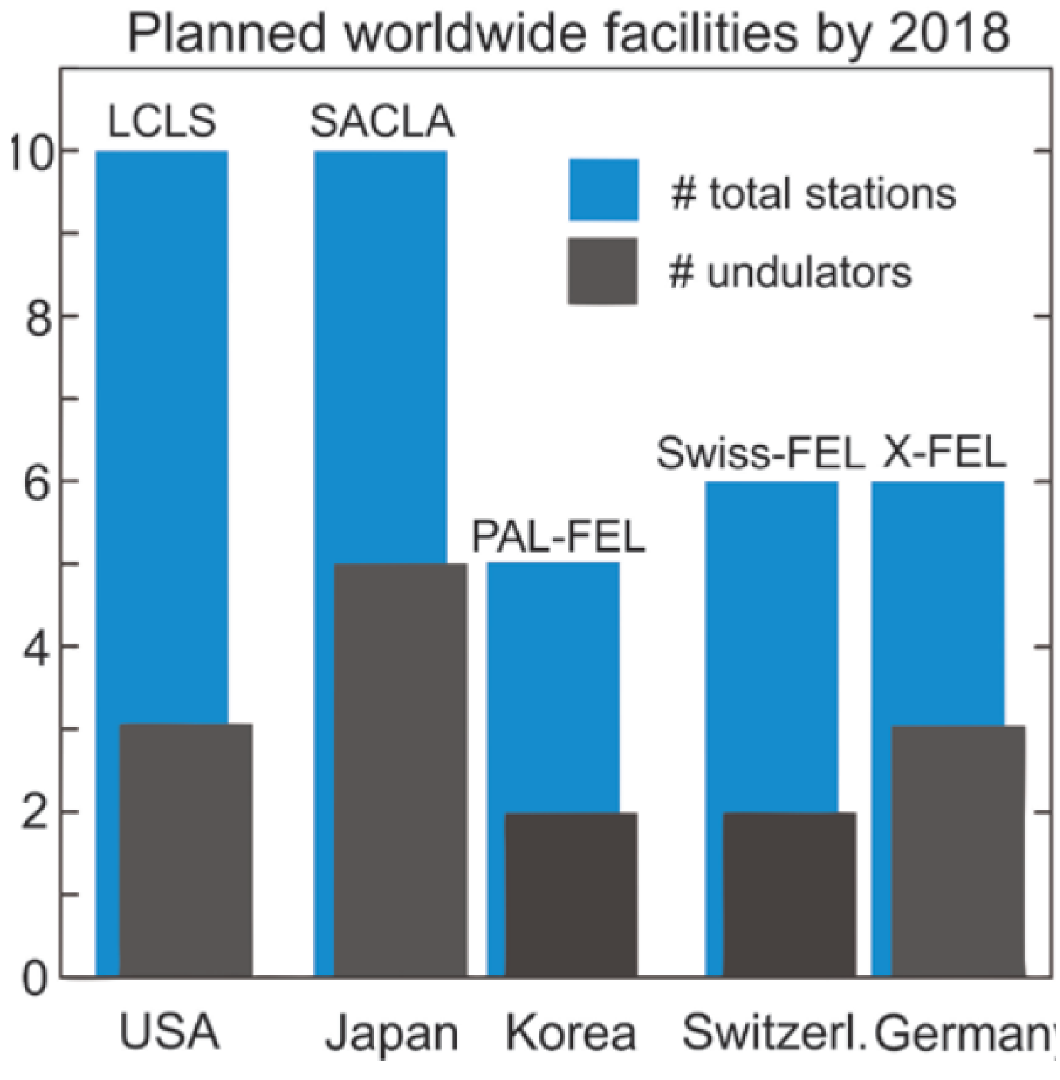
- ❑ FEL-1 and FEL-2 are identical
- ❑ × 2 λ-tuning range at each of the 6 fixed e-beam energies
- ❑ Helical SCU + in-vacuum CPMU afterburner

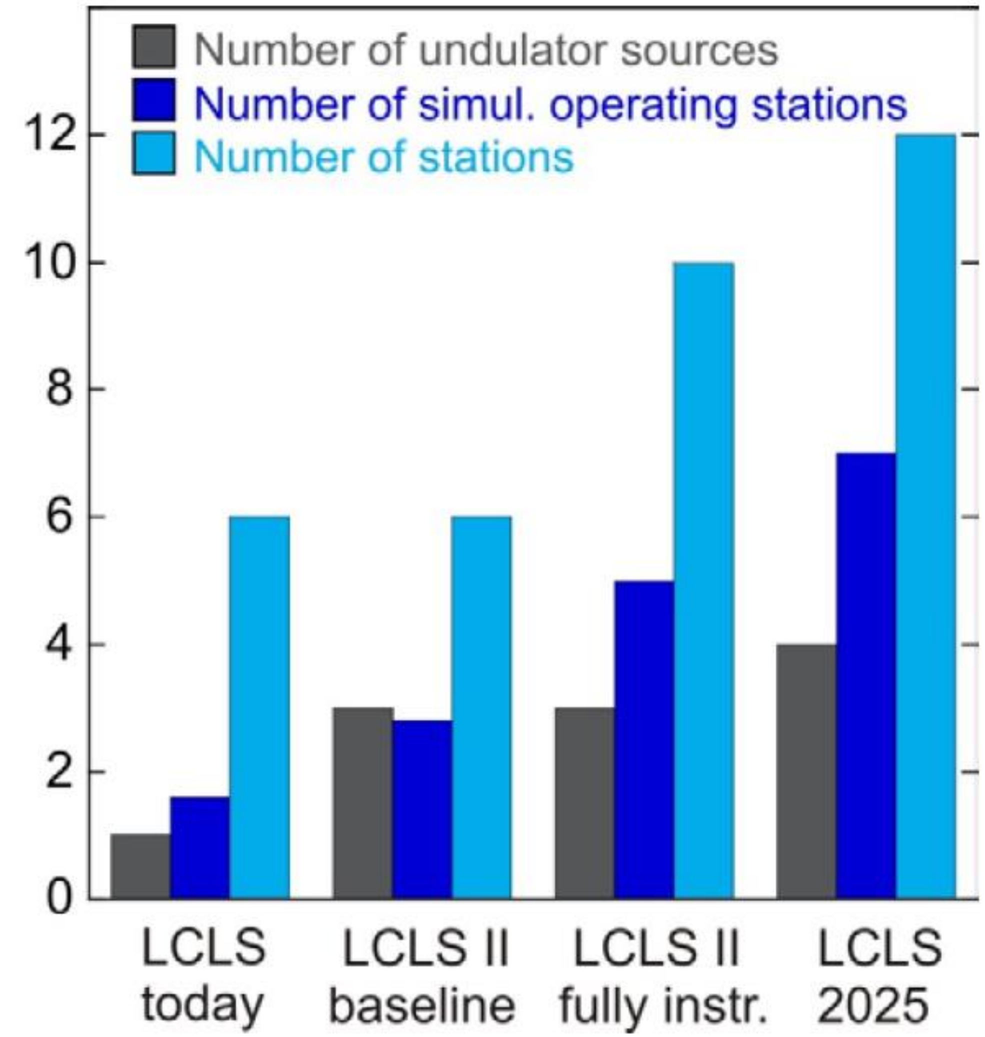
Aspects of the beamline design

- **End stations: how many and how to distribute**
- **FEL characteristics: beam size, fluence, Rayleigh length**
- **Focused beam size and demagnification**
- **X-ray damage and photon shutter**
- **Critical angle and location of end stations**
- **Example of the photon beam distribution at the sample**
- Two-colour operation and synchronization
- Incoupling of external lasers
- Photon diagnostics
- Experimental area
- Basic 1D and 3D CAD
- Safety

Vitaliy Goryashko

Facility trend: 3 stations/undul. Compact





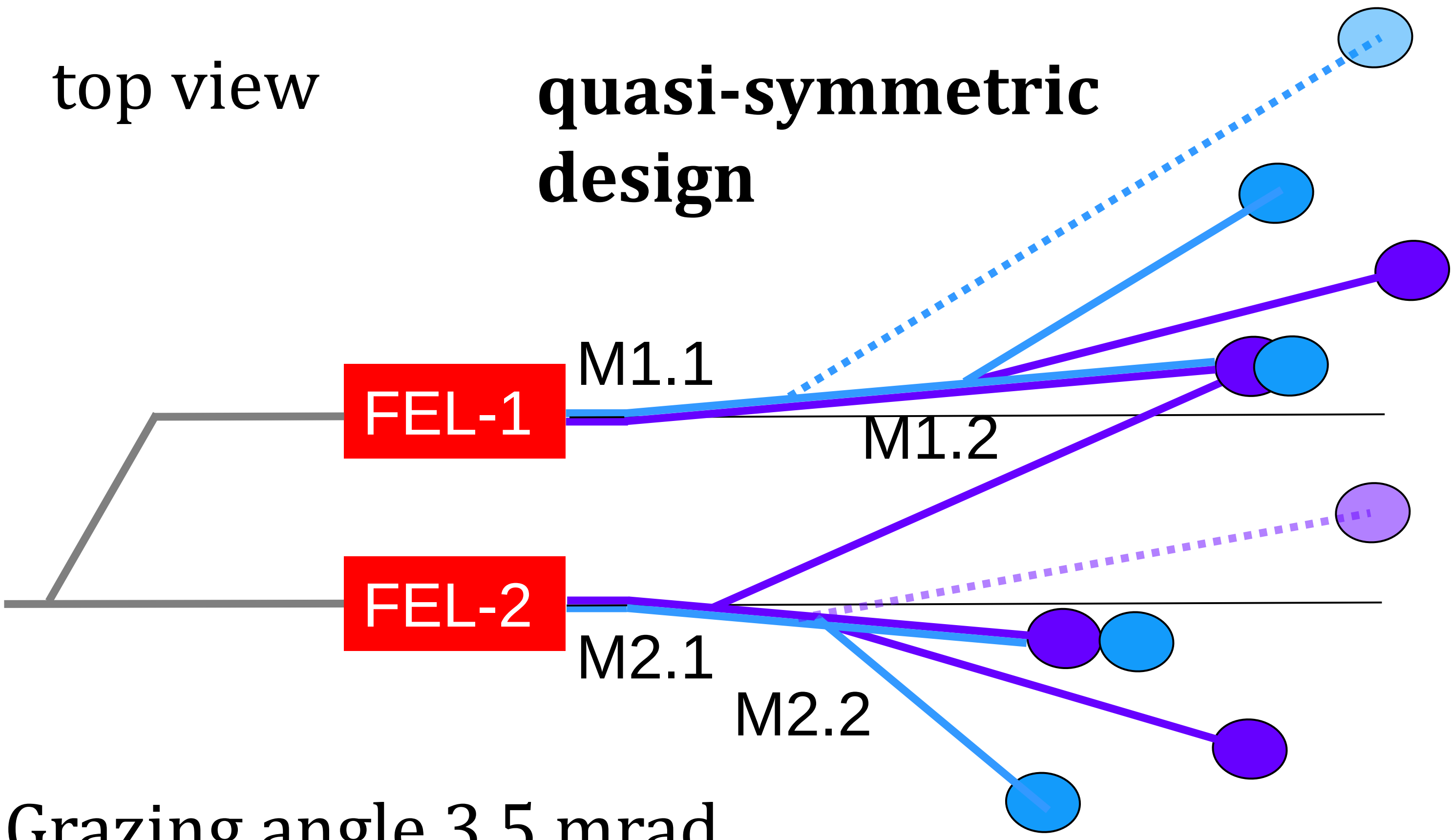
Figures are taken from “Science driven instrumentation for LCLS II”

3 end stations per undulator to maximize the beam time to users.

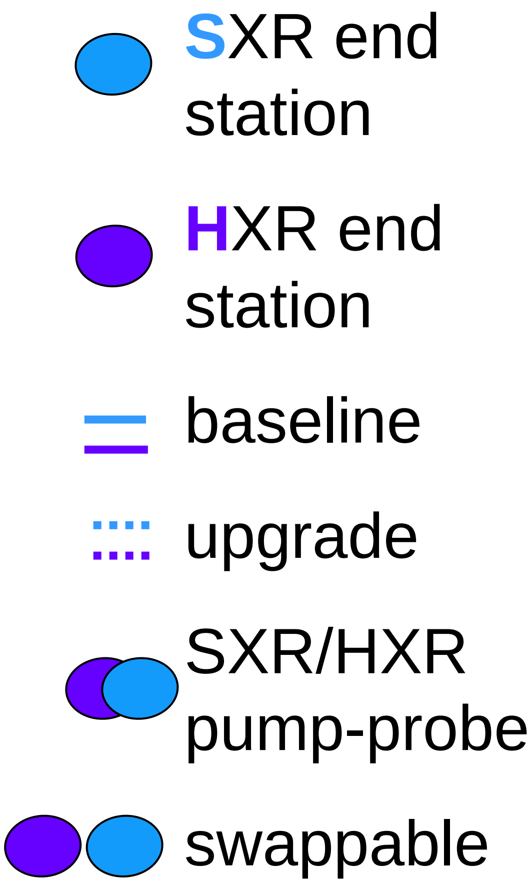
Baseline A

top view

quasi-symmetric design



- Two end stations for each FEL is **a must**.
- Stay out of bremsstrahlung



Grazing angle 3.5 mrad for HXR

FEL-1 branch is dominated by **S**XR end stations.
FEL-2 branch is dominated by **H**XR end stations.
8 end stations at the start to maximize beam time.

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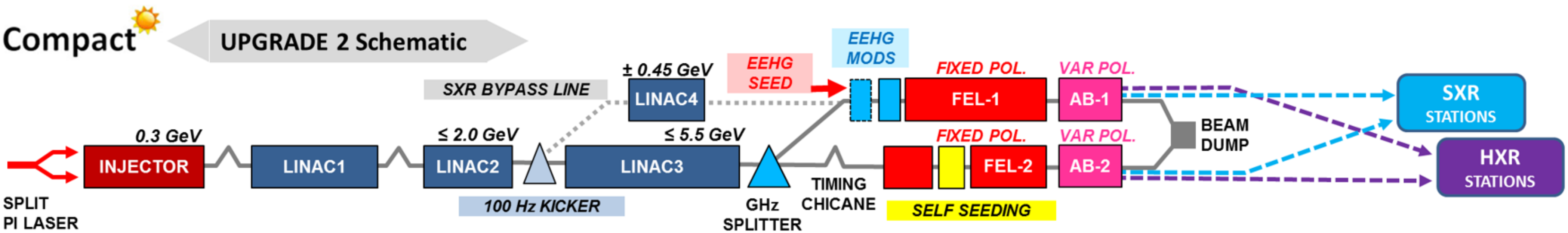
Facility layout in numbers (3/3)



Following numbers are along the upgrade 2 FEL-2 path

XLS Upgrade 2 - "FEL2" path			**energy gain per X-band module in M**			**234**	
Area of machine	**Assembly**	**# items**	**length in m**	**tot length**	**accumul**	**E gain in MeV**	**accumul**
Timing chicane	Chicane	1	20.00	20.00	203.99		5682
	Diagnostics section	1	2.00	2.00	205.99		5682
Light production	FEL-2	1	29.10	29.10	235.09		5682
	AB-2	1	5.00	5.00	240.09		5682
	deflector	1	3.00	3.00	243.09		5682
Seperator	Di-Pol	1	5.00	5.00	248.09		5682
(Beam dump)		1	5.00	5.00	253.09		5682
Light recombination		1	50.00	50.00	303.09		5682
Experimental lines		1	100.00	100.00	403.09		5682
		total		403.09	m	5682	MeV

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2020 CDR Proposed Schedule

Date	Task/Milestone	Responsibility of..
January 31	Complete document structure set up in Overleaf	WP2
June 30	All WP reports complete	All
July 31	1st complete draft which includes all material submitted by WP leaders	All
During August/September	Cross checking for consistency, errors and omissions	All
	Layout editing, style editing, editing for consistency	WP2
September 30	1st complete edited draft.	WP2
During October	Corrections	WP2 + All
October 30	2nd complete edited draft	WP2
December 1	Submission to EU (pre-Christmas)	WP1
January 2021	Online publication (and printed copy?) once approved by EU.	WP1/2
Later 2021	Journal submission	WP1/2

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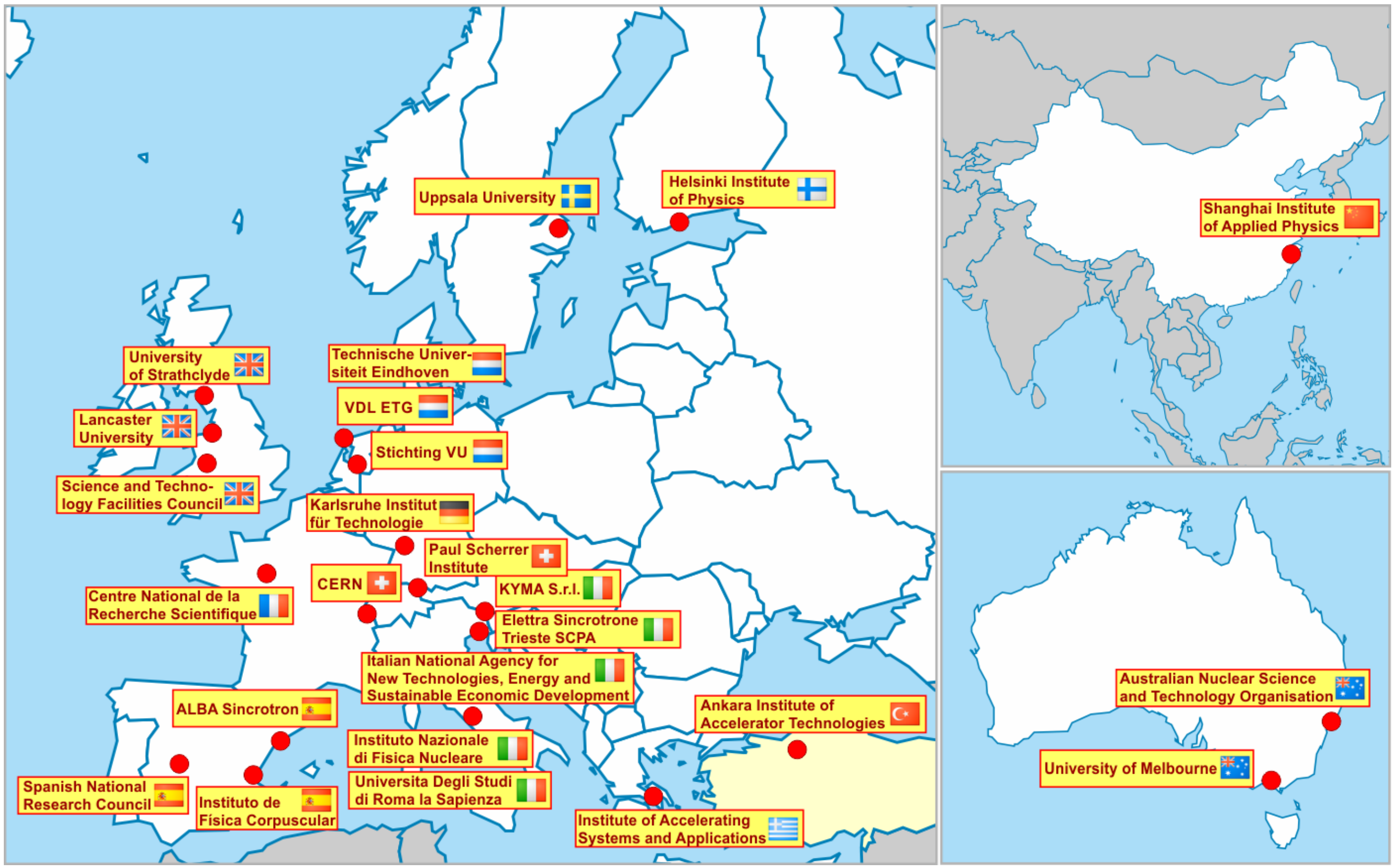

CompactLight is funded by the European Union's Horizon2020 research and innovation programme under Grant Agreement No. 777431.