CompactLight:

Bunch compression, microbunching instability and seeding aspects

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LEDS 2023 – ENEA, Frascati, Italia – 2-5 October 2023

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- Bunch compression
- Micro-bunching instability
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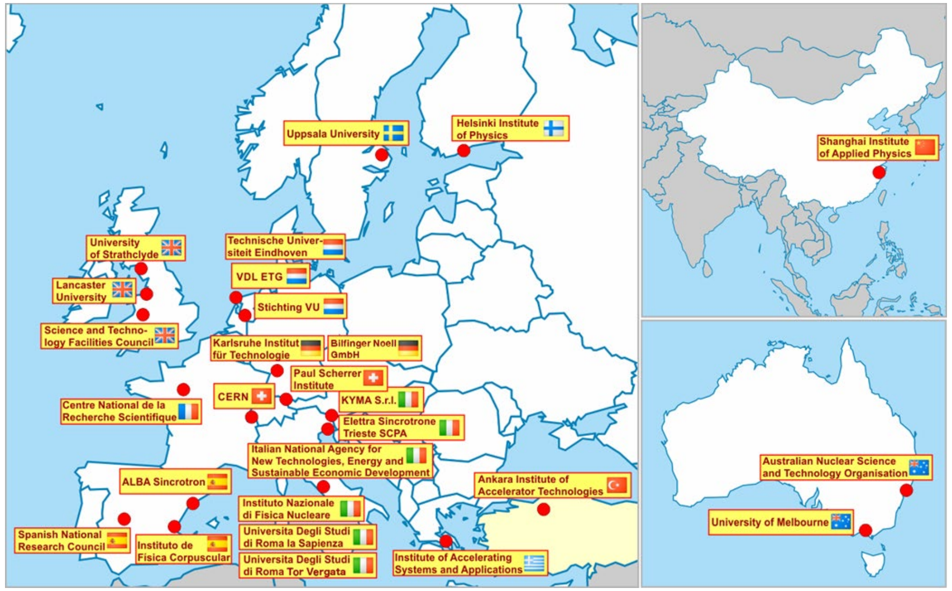
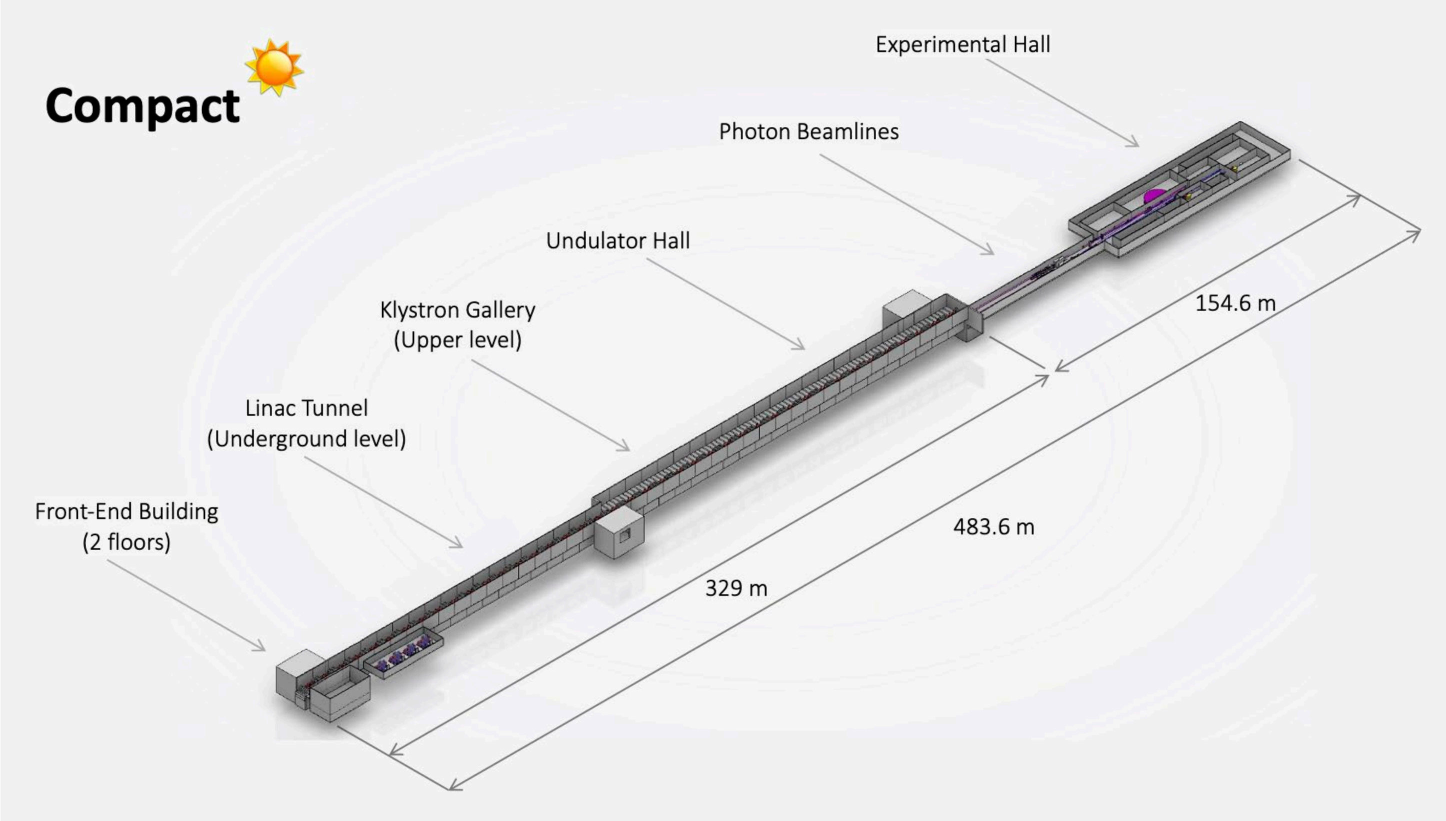
Compact Light

High-brilliance, compact FEL based on innovative, next generation technologies

- High-rep rate photoinjectors -> high-flux, high-brilliance
- X-band linac -> high energy and compactness
- Novel undulator concepts -> compactness

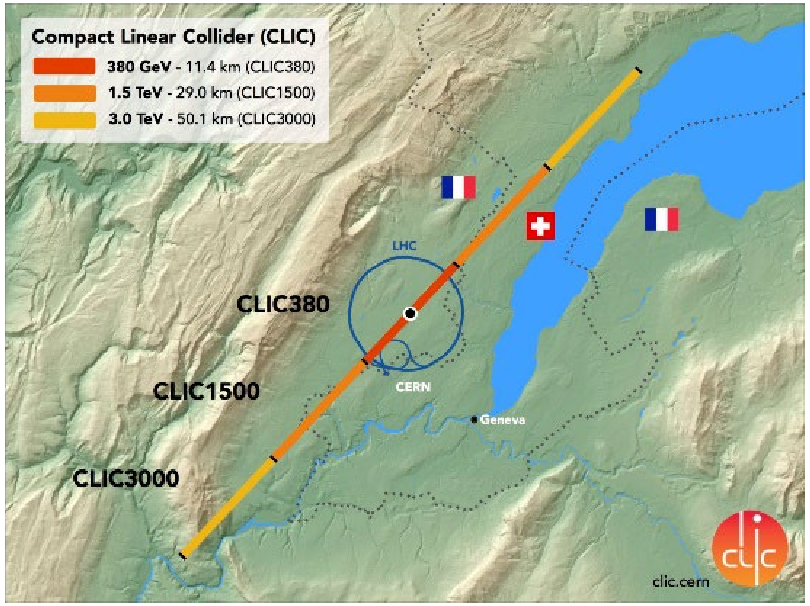


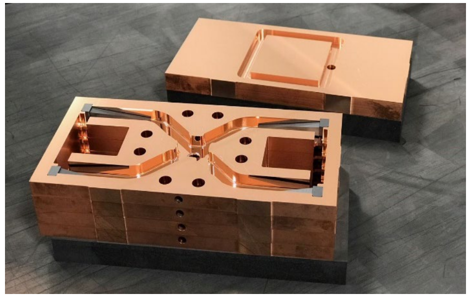


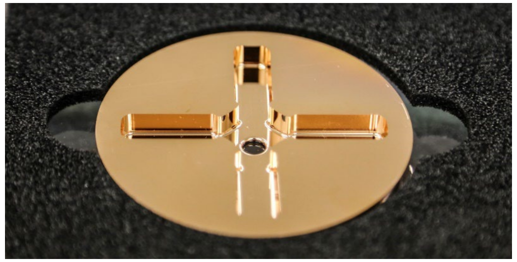
The result is a facility feauting a 5.5 GeV X-band linac that drives two FEL lines for soft and hard X-ray options.

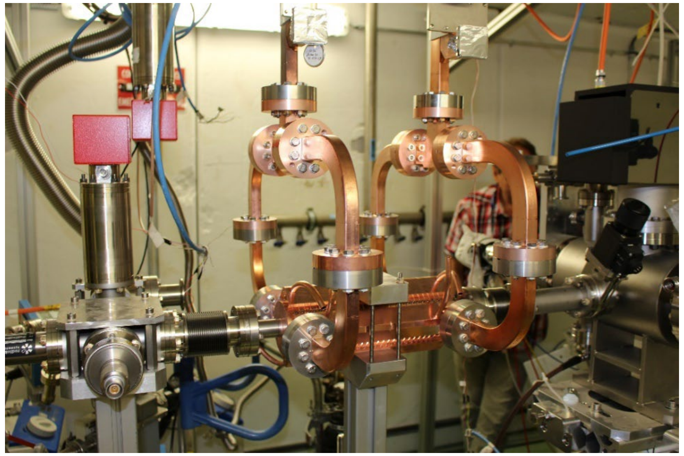
The CDR is available online: https://zenodo.org/record/6375645

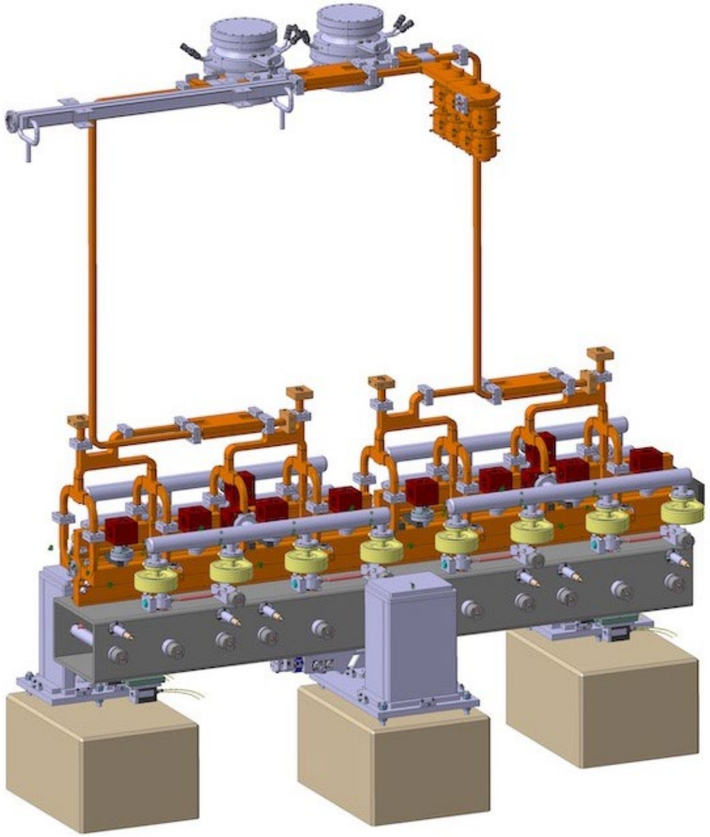
Enabling technology: X-band acceleration









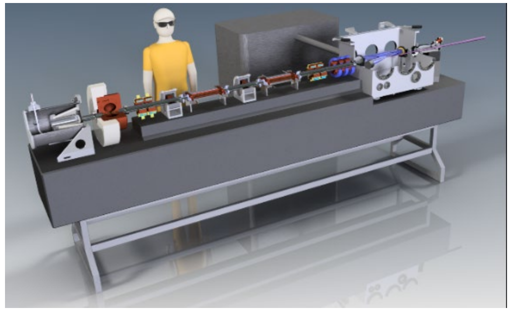


1m long accelerator structure is sufficient for generating up to ~100 keV monochromatic X-ray beams

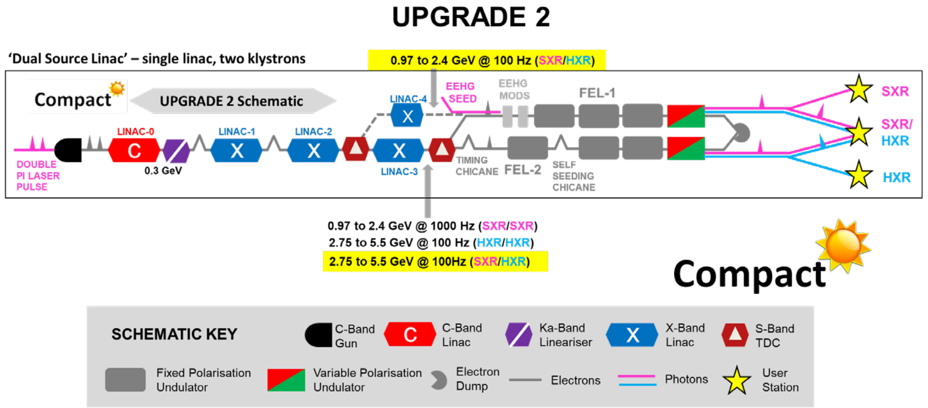
CLIC design study at CERN

- Very high-accelerating gradient to make compact facility - 100 MV/m accelerating gradient - 12 GHz - normal conducting
- Efficiency a design goal from the beginning

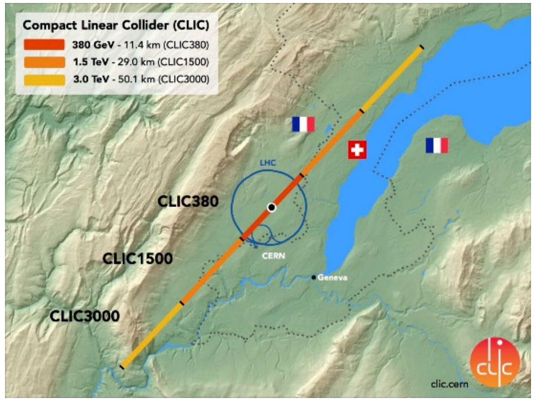
X-band and high-gradient applications



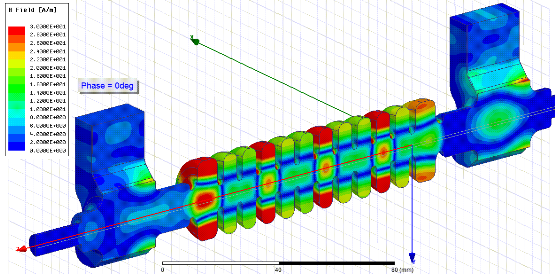
Light sources - ICS sources

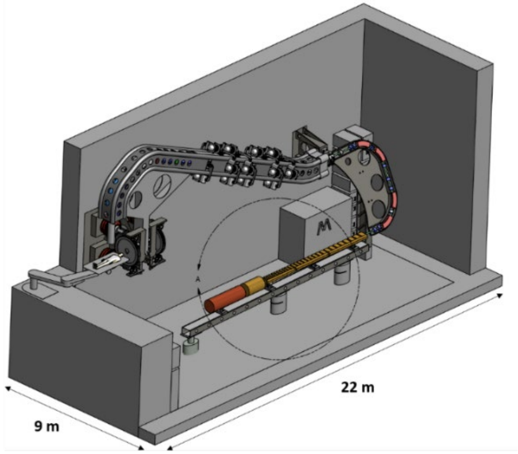


Light sources - XFEL

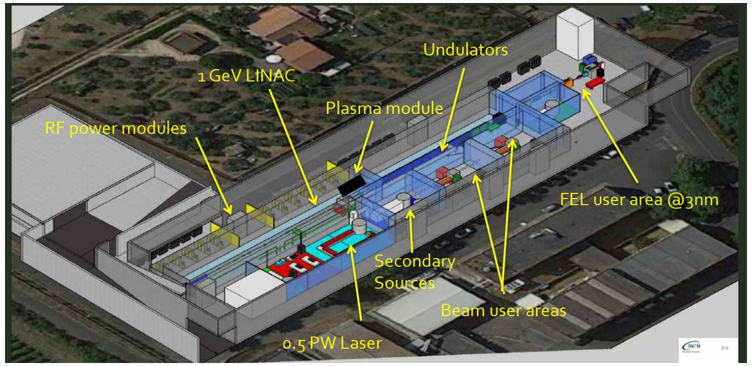


Linear collider

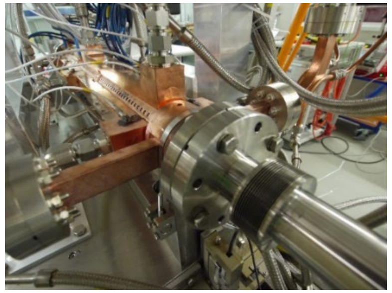




Medical applications

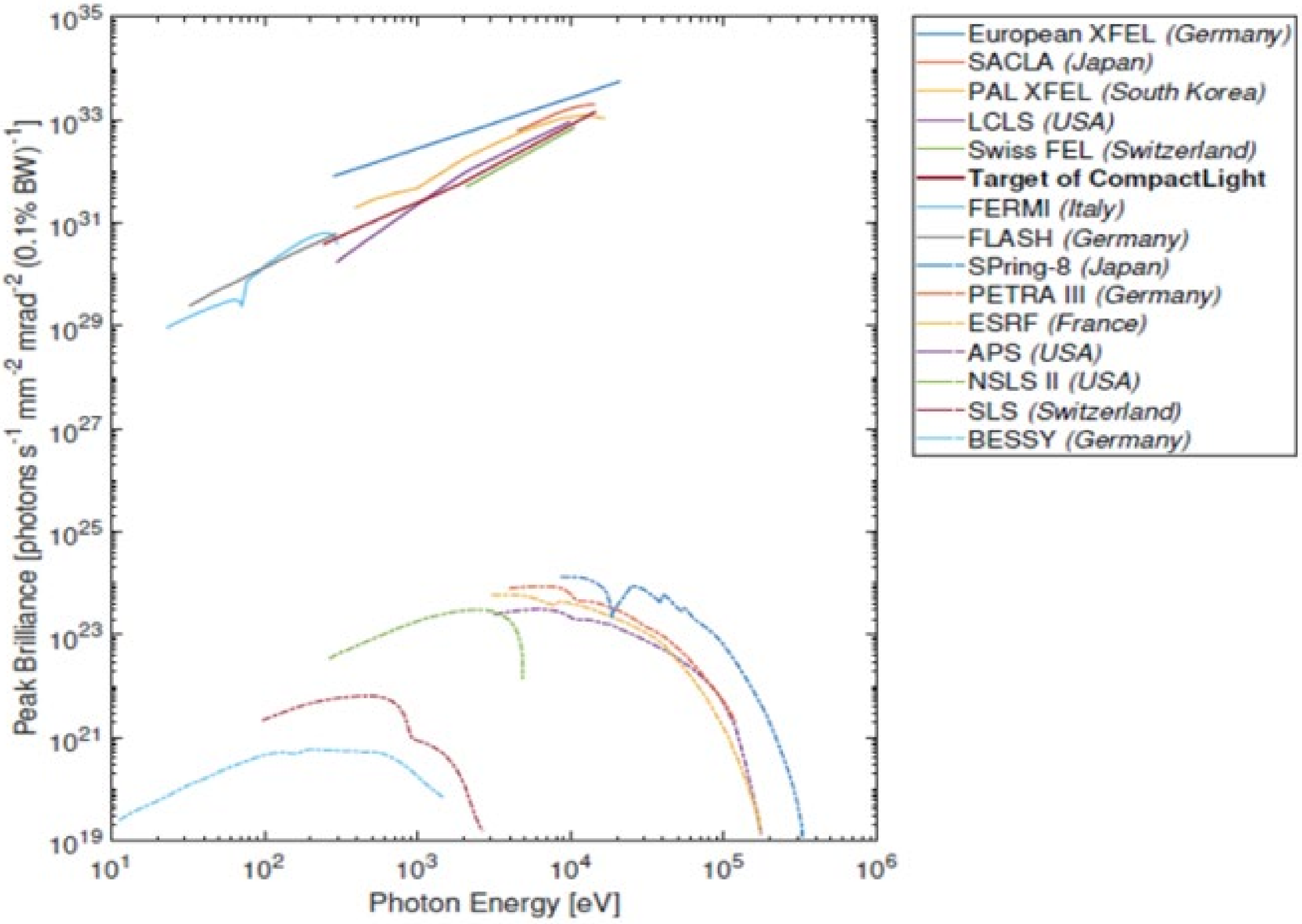


GeV-range research linacs

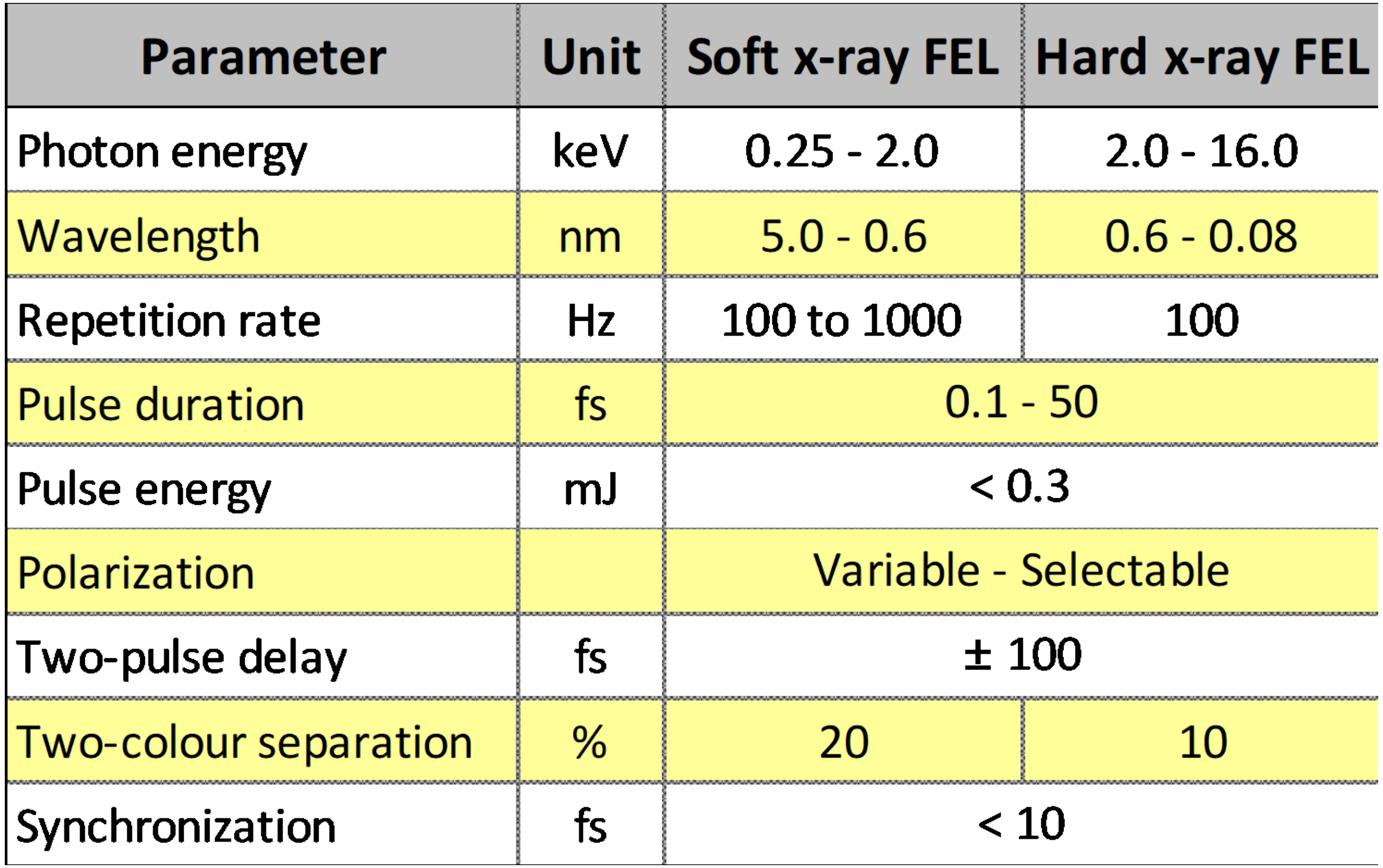


Beam manipulation

Estimated performance of CompactLight



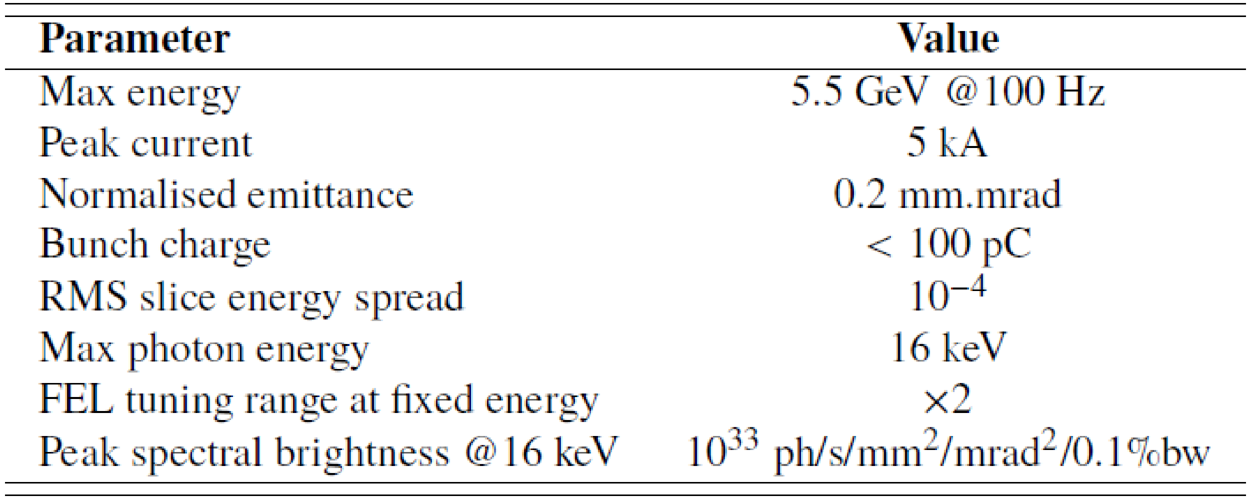
Photon performance



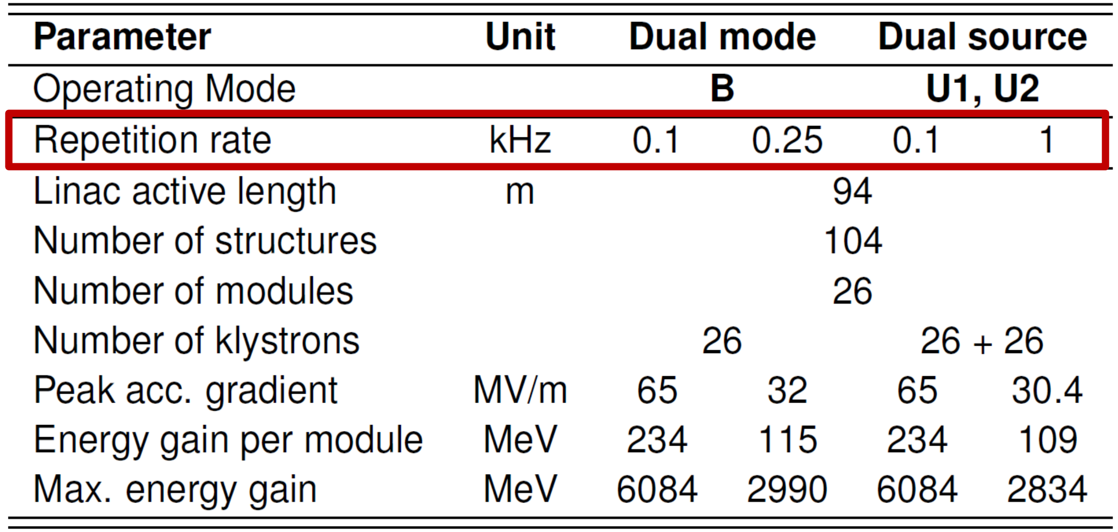
Parameter	Unit	Soft x-ray FEL	Hard x-ray FEL
Photon energy	keV	0.25 - 2.0	2.0 - 16.0
Wavelength	nm	5.0 - 0.6	0.6 - 0.08
Repetition rate	Hz	100 to 1000	100
Pulse duration	fs	0.1 - 50	
Pulse energy	mJ	< 0.3	
Polarization		Variable - Selectable	
Two-pulse delay	fs	± 100	
Two-colour separation	%	20	10
Synchronization	fs	< 10	

Linac operational parameters

Electron beam parameters at the undulator entrance (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

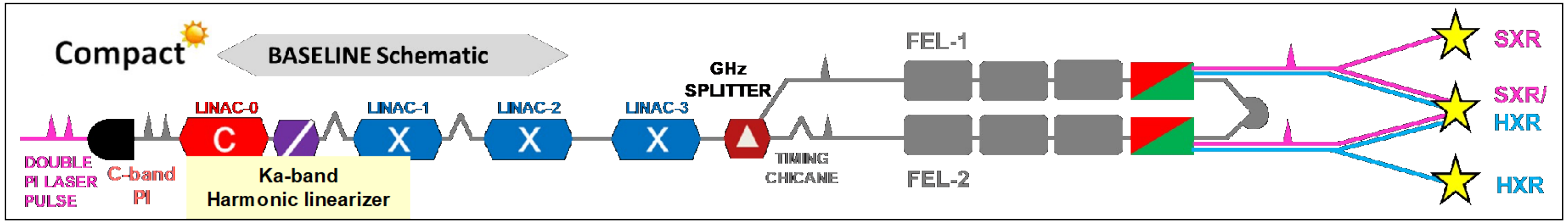


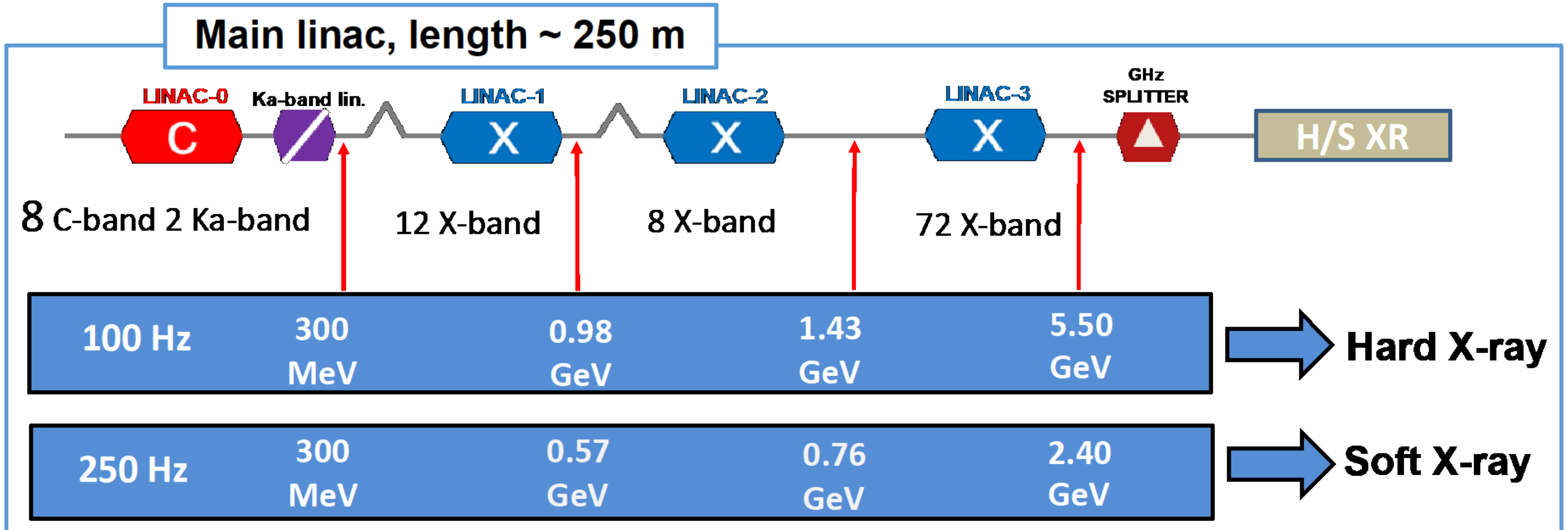
Parameter	Unit	Dual mode		Dual source	
Operating Mode		B		U1, U2	
Repetition rate	kHz	0.1	0.25	0.1	1
Linac active length	m	94			
Number of structures		104			
Number of modules		26			
Number of klystrons		26		26 + 26	
Peak acc. gradient	MV/m	65	32	65	30.4
Energy gain per module	MeV	234	115	234	109
Max.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

RF operational scenarios:

- **B: dual mode (Baseline)**
- **U1, U2: dual source (Upgrade 1 & 2)**

CompactLight baseline





Main linac, length ~ 250 m

8 C-band 2 Ka-band

12 X-band

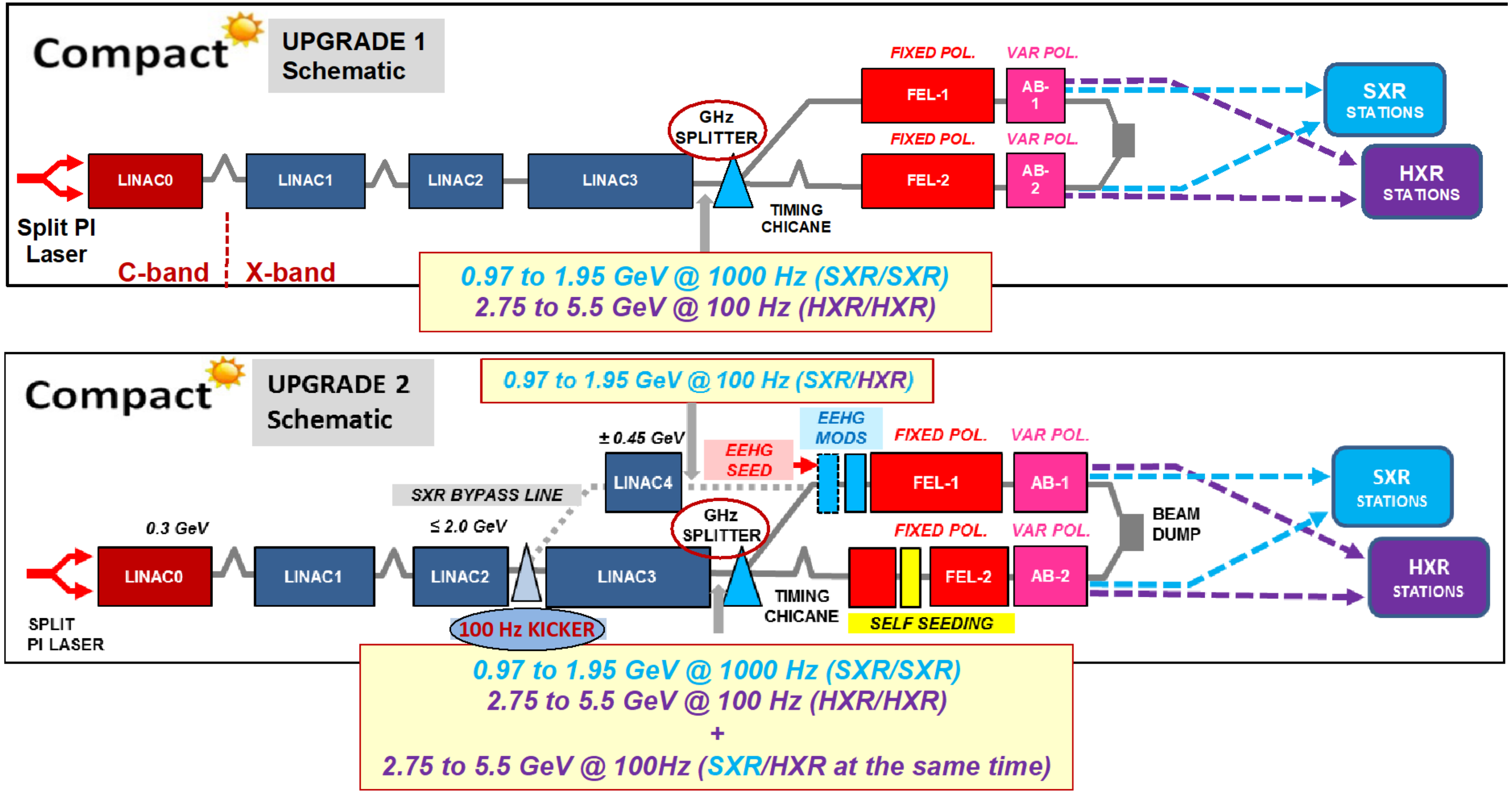
8 X-band

72 X-band

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)

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 at the same time)

2 klystrons x LINAC Module:

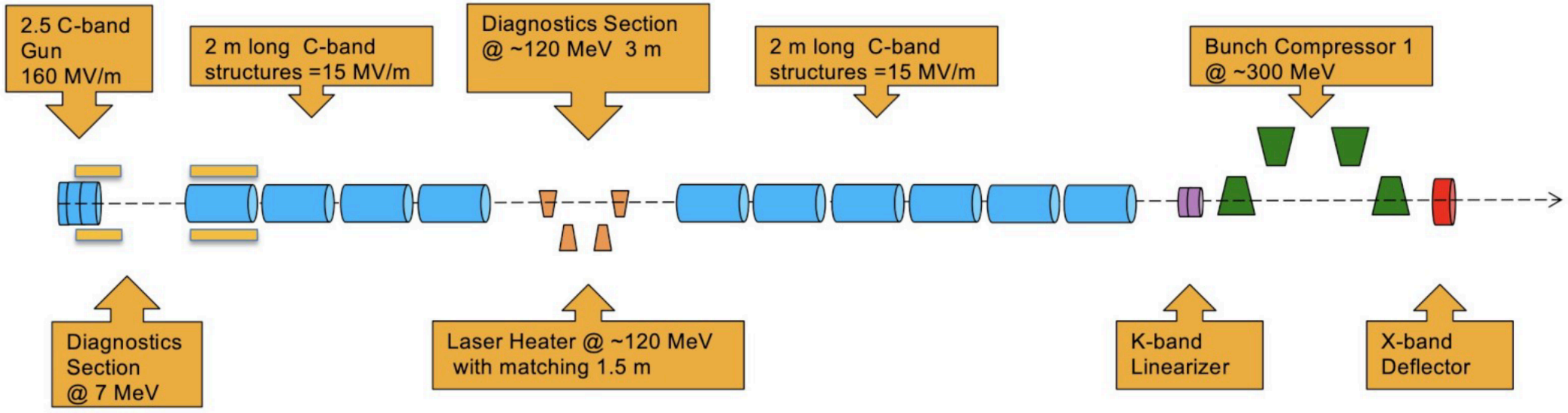
- **CPI VKX-8311 @ 50 MW**
- **CPI (Canon E37113*) @ 10 MW**

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

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

C-band Injector

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



2.5 C-band Gun 160 MV/m

2 m long C-band structures =15 MV/m

Diagnostics Section @ ~120 MeV 3 m

2 m long C-band structures =15 MV/m

Bunch Compressor 1 @ ~300 MeV

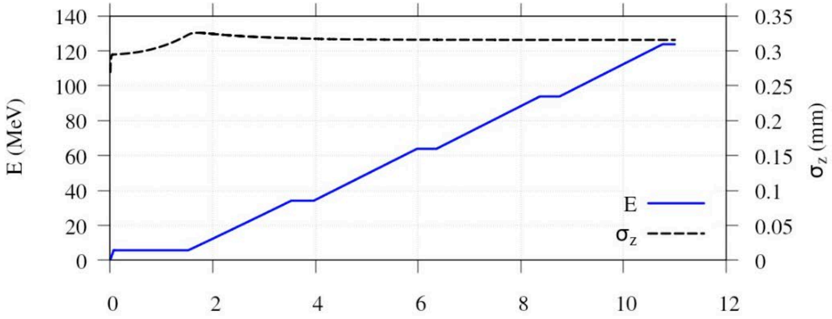
Diagnostics Section @ 7 MeV

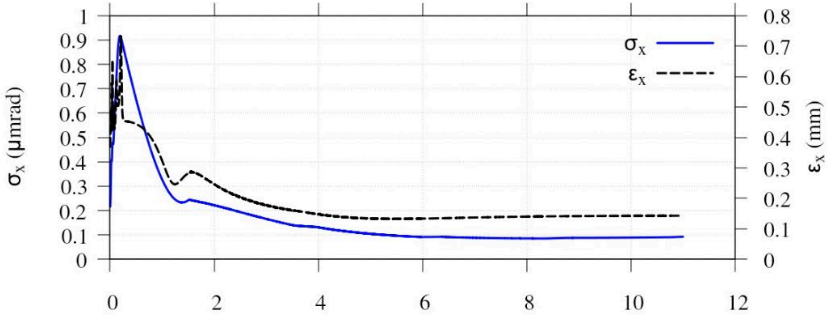
Laser Heater @ ~120 MeV with matching 1.5 m

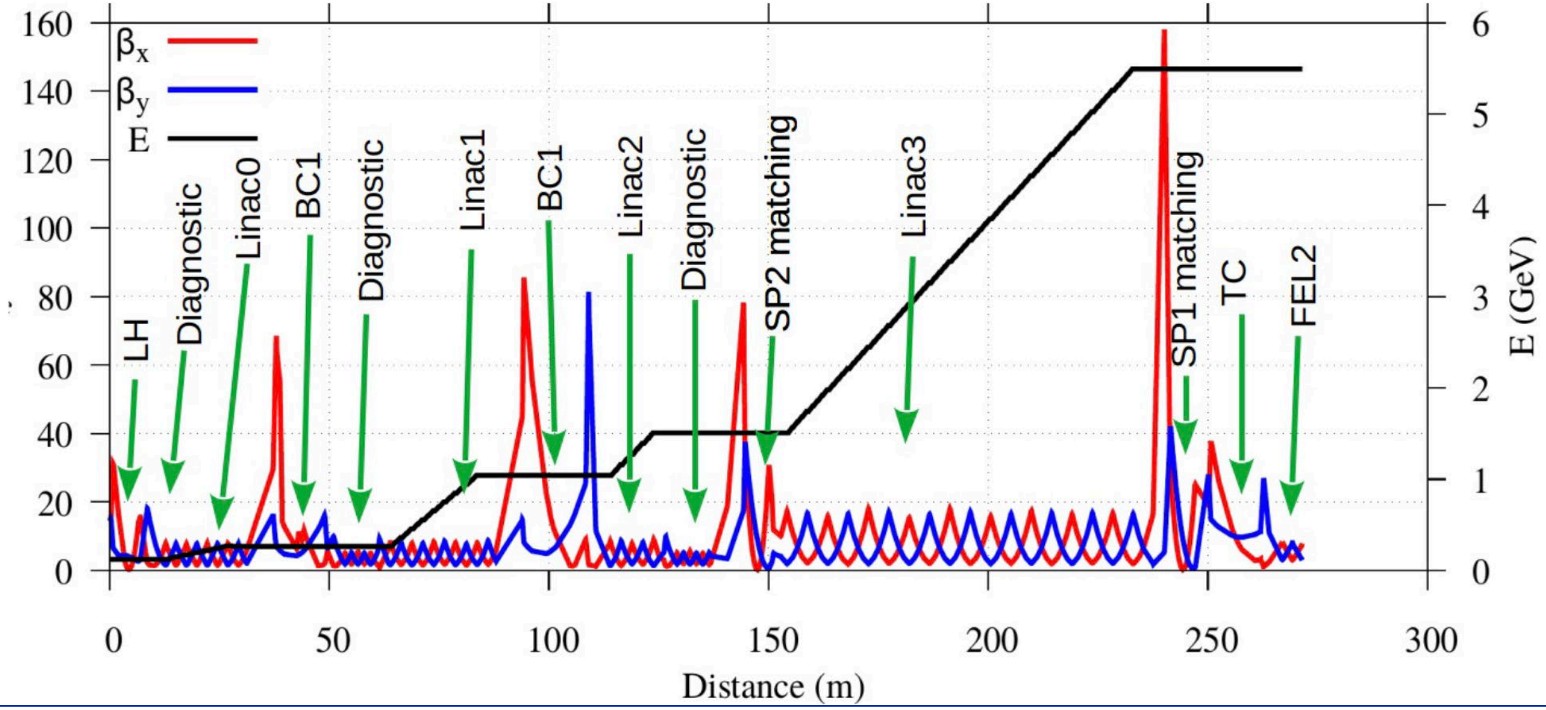
K-band Linearizer

X-band Deflector

Start-to-end beam dynamics design







Bunch compressors

The goal is the compression of a **75-pC bunch charge** accelerated to **5.5 GeV**, giving a **peak current of about 5 kA**. This corresponds to a rms bunch length

$$\sigma_z = 15 \text{ fs} \cdot c = 4.5 \text{ um}$$

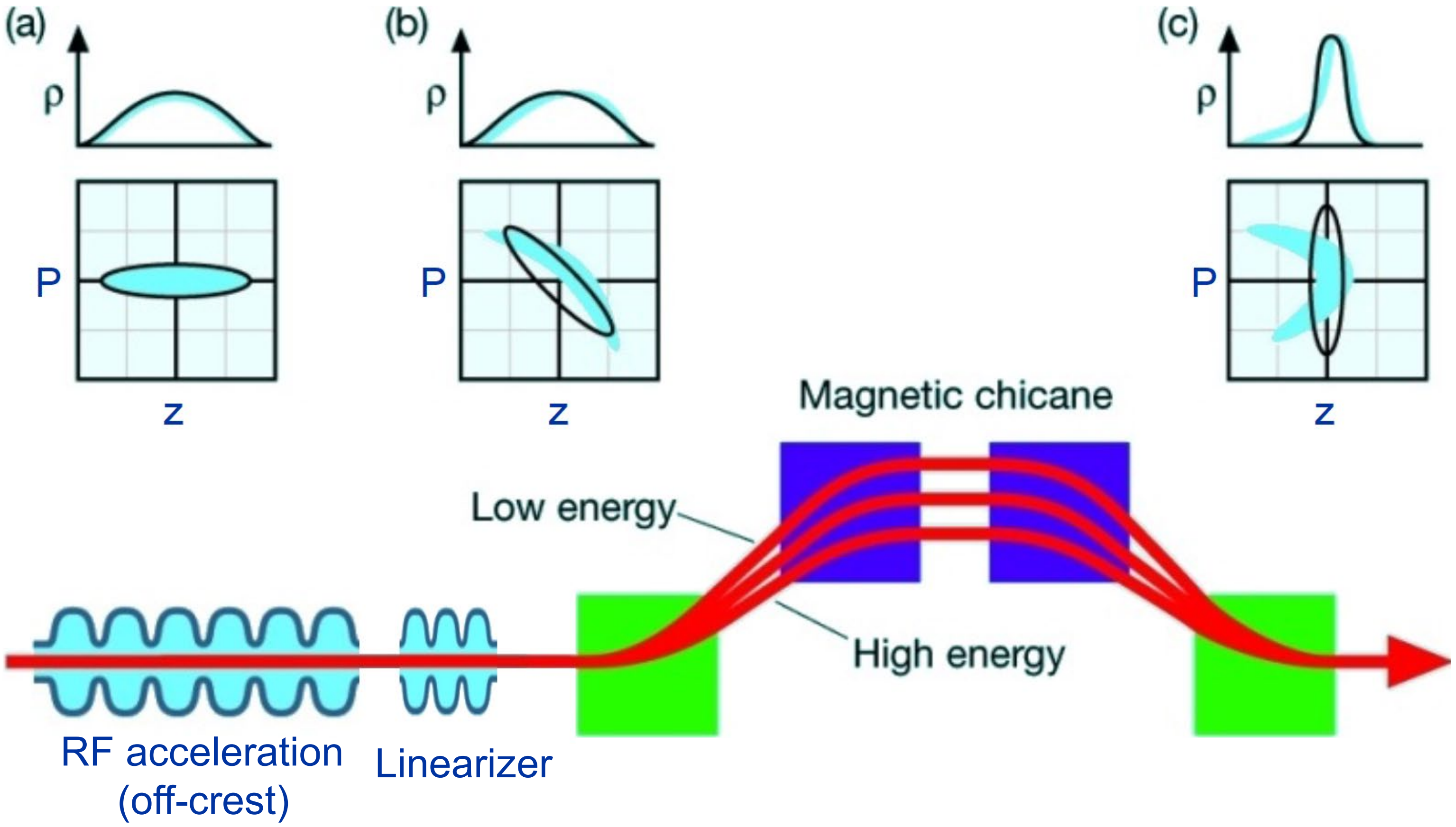
A two-stage compression system is used, with two bunch compressors: one between Linac0 and Linac1 and one between Linac1 and Linac2.

BC1 uses the **C-band Linac0** to accelerate the beam to 300 MeV and a **Ka-band lineariser** at **36 GHz** before a 4-dipole chicane.

BC2 uses the **X-band Linac1** to accelerate the beam to 1.2 GeV and 4-dipole chicane. The correlated energy spread is later corrected in **Linac2**, balancing it off using wakefield effects and slightly off-crest RF acceleration.

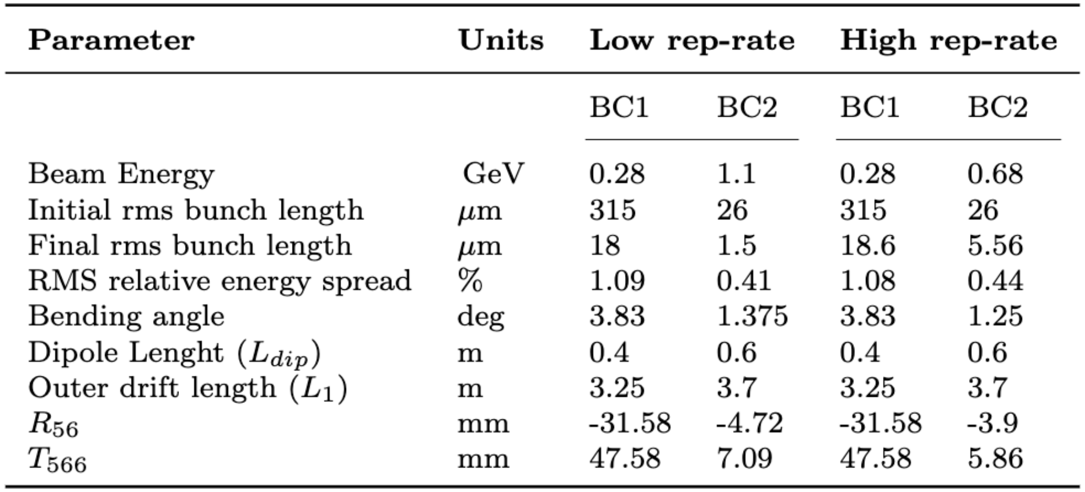
Bunch compression

(a) An RF stage of acceleration provides energy chirp and optionally acceleration (C-band, 6 GHz)
(b) A high harmonic linearizer corrects for nonlinear correlations (Ka-band, 36 GHz)
(c) A magnetic 4-dipole chicane completes the longitudinal phase-space rotation

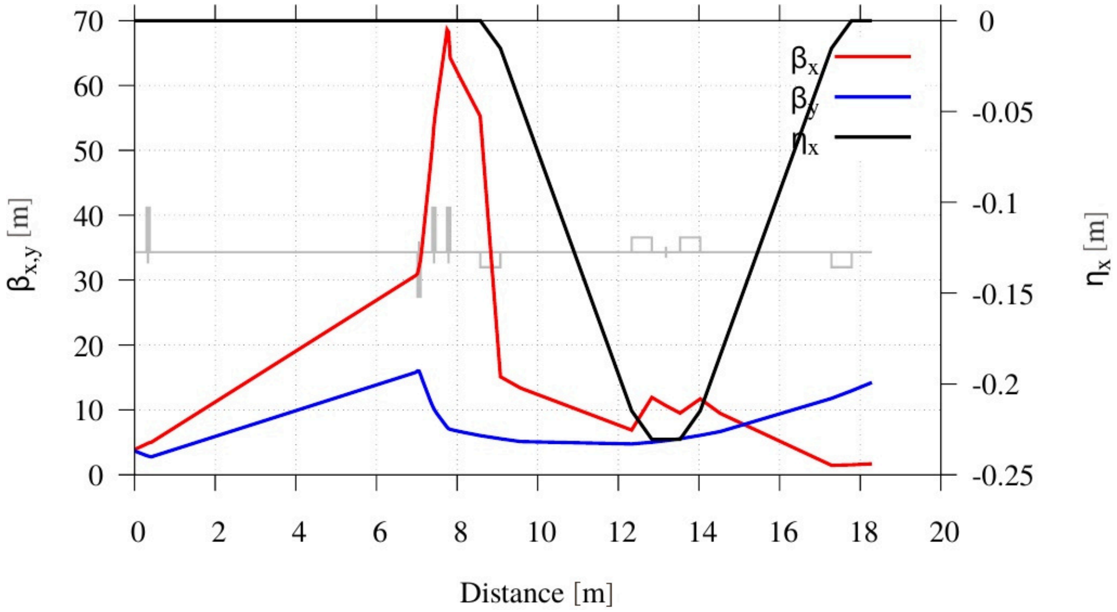


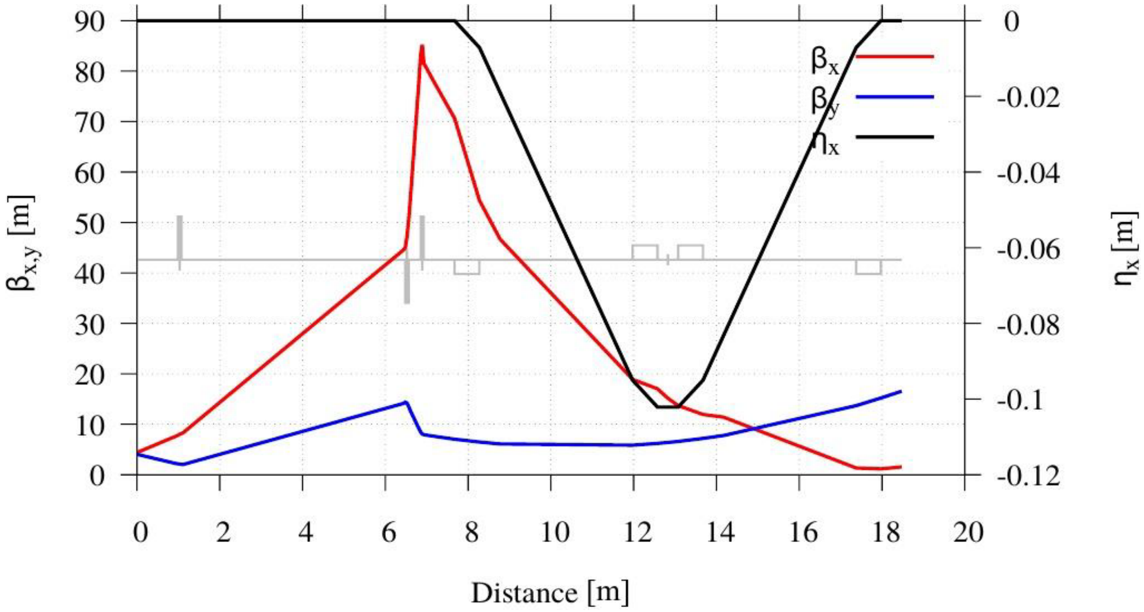
Bunch compressors

Requirements
- Compression factors between 10 and 20
- Minimise CSR effects (energy spread, emittance growth)
- Minimise chromatic effects
- Minimise space-charge-induced emittance growth (BC1)
- Achieve the target energy
- Minimizing nonlinear effects



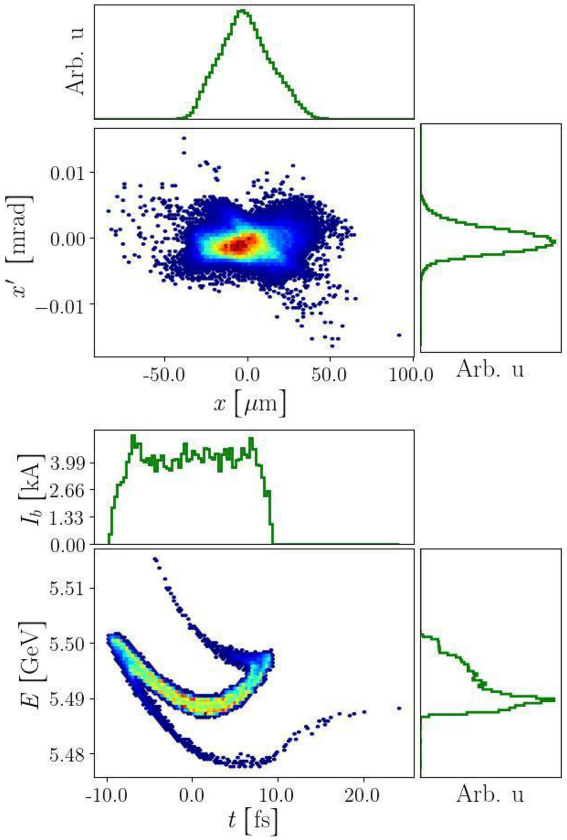
Parameter	Units	Low rep-rate		High rep-rate	
		BC1	BC2	BC1	BC2
Beam Energy	GeV	0.28	1.1	0.28	0.68
Initial rms bunch length	μm	315	26	315	26
Final rms bunch length	μm	18	1.5	18.6	5.56
RMS relative energy spread	%	1.09	0.41	1.08	0.44
Bending angle	deg	3.83	1.375	3.83	1.25
Dipole Lenght (L_{dip})	m	0.4	0.6	0.4	0.6
Outer drift length (L_1)	m	3.25	3.7	3.25	3.7
R_{56}	mm	-31.58	-4.72	-31.58	-3.9
T_{566}	mm	47.58	7.09	47.58	5.86

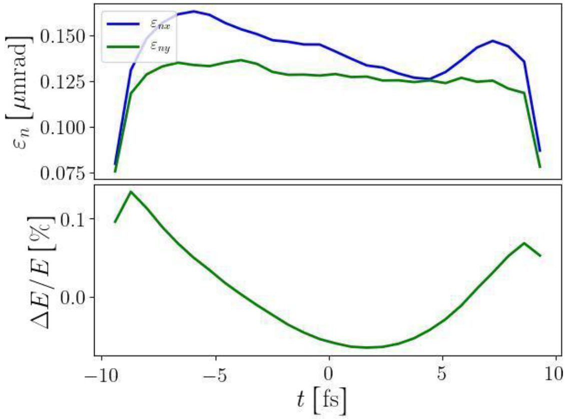




Electron bunch at undulators entrance

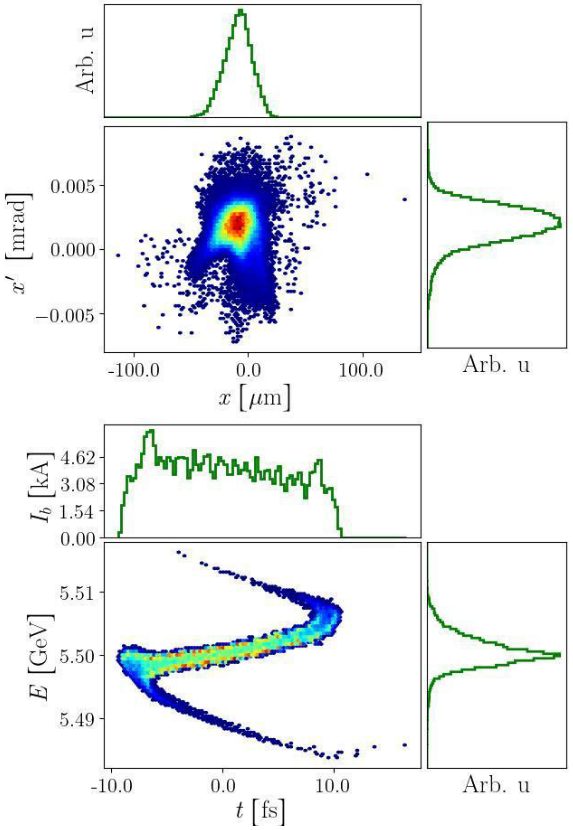
FEL1

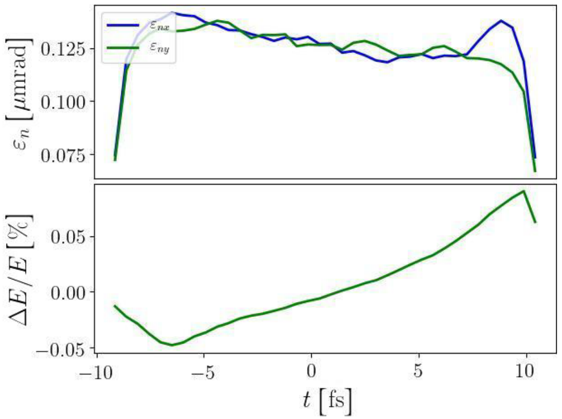




Parameter	Unit	Value
E	GeV	5.49
$\varepsilon_{n,x}$	μmrad	0.221
$\varepsilon_{n,y}$	μmrad	0.147
ε_z	MeV.ps	0.02
σ_x	mm	0.015
σ_y	mm	0.007
σ_t	fs	5.155
σ_E	MeV	3.53
$\Delta E/E$	%	0.064

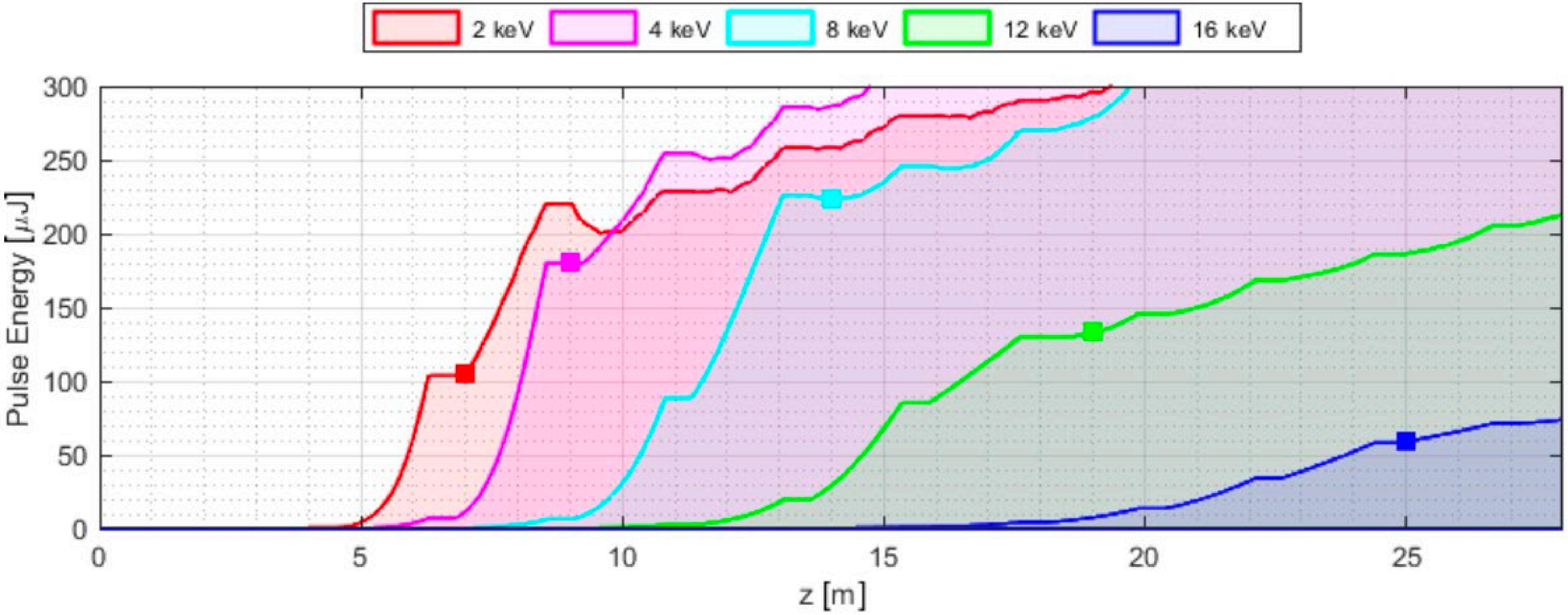
FEL2





Parameter	Unit	Value
E	GeV	5.50
$\varepsilon_{n,x}$	μmrad	0.177
$\varepsilon_{n,y}$	μmrad	0.149
ε_z	MeV.ps	0.01
σ_x	mm	0.012
σ_y	mm	0.007
σ_t	fs	5.420
σ_E	MeV	2.52
$\Delta E/E$	%	0.046

Undulator performance simulation



Pulse energy growth for HXR FEL operation using the nominal bunch.

Saturation is achieved in less than 25 meters

Microbunching instability

The micro-bunching instability (MBI) is a longitudinal, collective instability which occurs in electron beams during the operation with short bunches. In linacs, the microbunching instability is commonly studied in two regimes distinguished by the beam energy.

Low energy: from the gun until the ultra-relativistic regime, where the current modulation for wavelengths smaller than the bunch length is reduced and a momentum modulation is generated.

High energy: where the current modulation is increased basically only in the bunch compressors (the beam is too rigid to increase the current modulation in drifts and cavities) and more momentum modulation is cumulated.

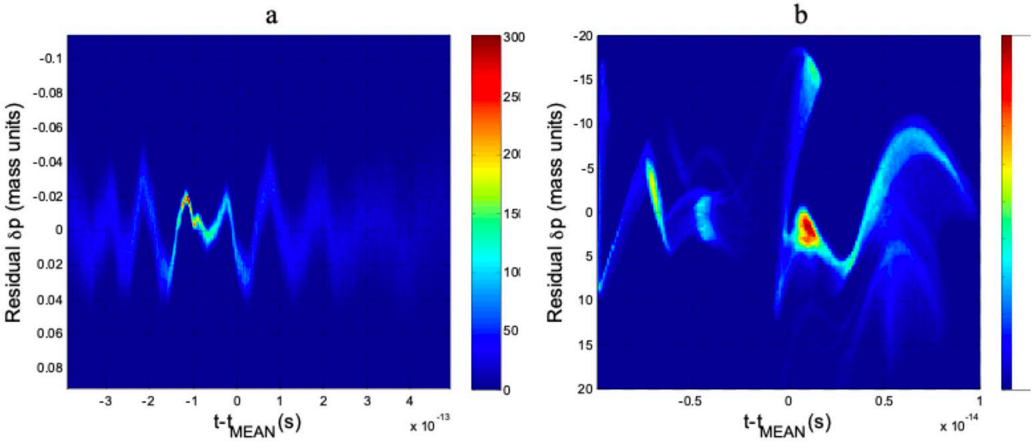


Figure 3: Start-to-end simulation. Residual momentum of the real shape bunch tracked to (a) the entrance of BC1 and (b) the Aramis undulators.

The complex dynamics during the instability lead to fluctuations in the emitted CSR as well as in the bunch length and energy spread and therefore also the horizontal bunch size.

[Figure] S. Bettoni, B. Beutner, V. Goryashko, Microbunching instability studies in SwissFEL, IPAC2012

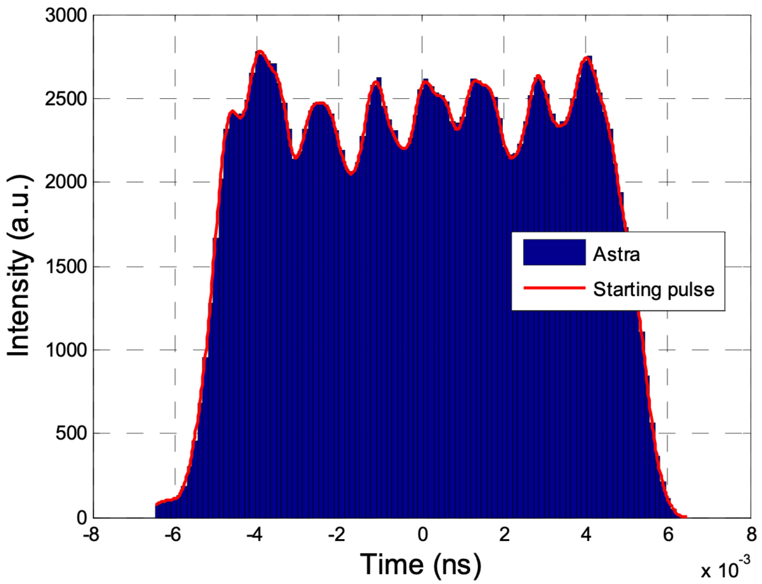
Sources of microbunching instability

The microbunching instability is expected to start at the **photoinjector**, from a density modulation caused by **shot noise in the photoinjector's laser temporal profile** and **cathode imperfections**, then the current modulation for wavelengths smaller than the bunch length is reduced and a momentum modulation is generated.

As the beam travel towards the RF structures, this time modulation couples with th **longitudinal space-charge force**, and the longitudinal modulation becomes **energy modulation**.

At higher beam energy, microbunching occurs also in the **bunch compressors' chicanes**, due to CSR-induced effect, which also causes emittance growth in the transverse plane, and is further amplified by the bunch length compression.

It cabe be reduced by clever design, or by introducing a laser heater.

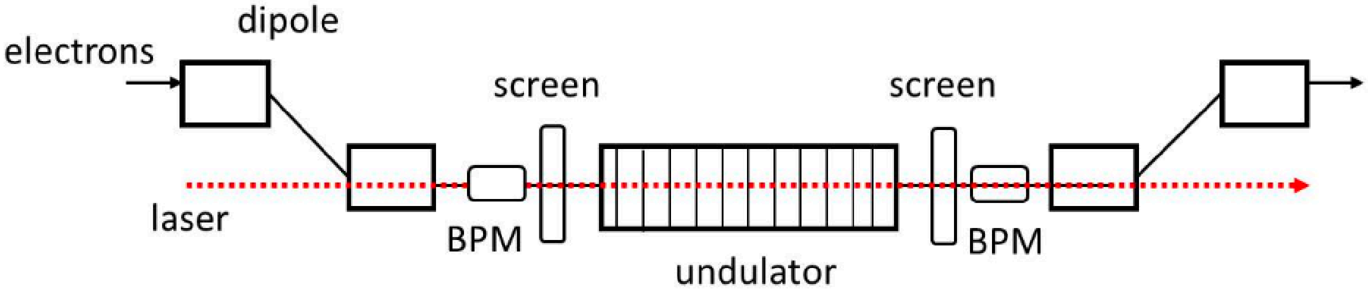


Longitudinal laser profile measured at the SwissFEL Injector Test Facility (SITF)

[1] C.-Y. Tsai, S. Di Mitri, D. Douglas, R. Li, and C. Tennant, Conditions for coherent-synchrotron-radiation-induced microbunching suppression in multibend beam transport or recirculation arcs, PRAB 20, 024401 (2017)
[2] S. Bettoni, B. Beutner, V. Goryashko, Microbunching instability studies in SwissFEL, IPAC2012 [figure]

Laser heater

To control the MBI, Saldin et al. proposed the addition of a device commonly referred to as a ”laser heater”. This device adds a controlled amount of incoherent energy spread to the electron beam and suppresses further MBI growth via energy Landau damping.



The laser is a small portion of the 800 nm Ti:Sa photocathode laser, before it is upconverted to UV. Its pulse length lasts for 20 ps FWHM, largely enough to cover the entire bunch length.

The undulator consists of eight 40 mm long periods and a peak field of 0.4 T. The vertical gap can be remotely changed to resonantly match the external laser wavelength for electron beam energies in the range 100−140MeV.

The 4-dipole chicane has two objectives: (1) it allows the laser to be transversely aligned to the electron beam and perfectly overlapped with it; (2) it smears out the laser-induced energy modulation and transforms it into an uncorrelated energy spread.

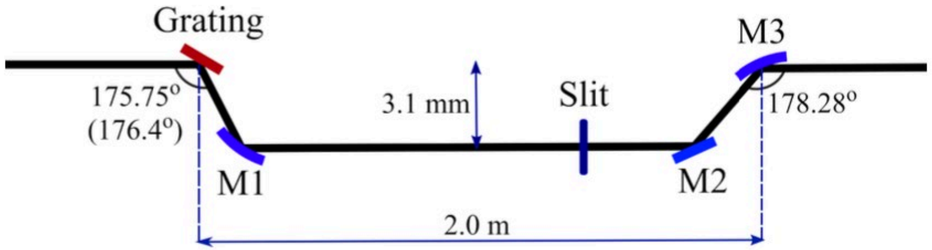
S. Di Mitri

Seeding aspects

CompactLight Upgrade-2 includes **self-seeding options** for both the **HXR** and **SXR** beamlines. The generic method is that the FEL pulse is extracted at some point along the undulator line before saturation and filtered to reduce its spectral width, hence increasing its coherence length.

The filtered pulse is then used as a seed and injected into the second section of the undulator line to be amplified to saturation. The method used to filter the pulse depends on the wavelength regime.

In the SXR, a compact grating monochromator is used. This replaces one undulator module:



In the HXR, a diamond crystal with the crystal orientation is adjusted such that a notch is taken out of the spectrum at the appropriate photon energy.

In both cases, in a **small chicane** around the optical elements diverts the electron beam to **overlap with the seed pulse** in the second undulator section. The chicane also the effect **of smearing out the FEL-induced MBI** through long. dispersion.

SXR and HXR Self-seeding simulations

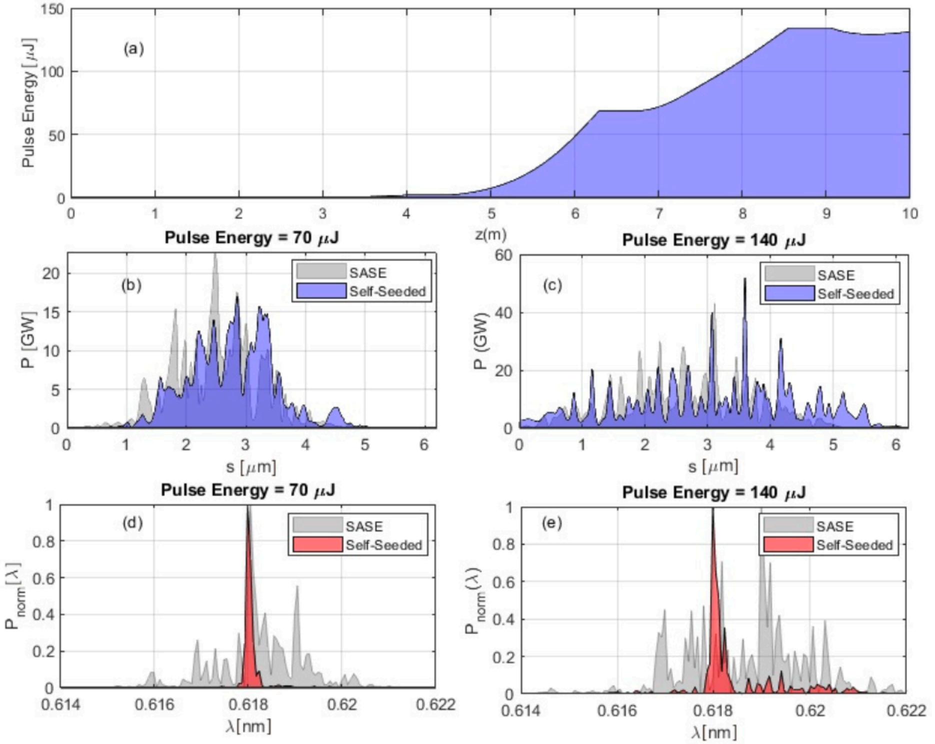


Fig. 26: SXR Self-Seeding simulation results for output at 2 keV: (a) Growth of pulse energy vs distance z through second undulator section (b) Self-seeded pulse profile at $z = 6.5\,\mathrm{m}$ with pulse energy $70\,\mu\mathrm{J}$ (in blue) and equivalent SASE pulse of the same pulse energy (in grey) (c) Self-seeded pulse profile at $z = 8.5\,\mathrm{m}$ with pulse energy $140\,\mu\mathrm{J}$ (in blue) and equivalent SASE pulse of the same pulse energy (d) Spectra of $70\,\mu\mathrm{J}$ self-seeded pulse (red) and equivalent SASE pulse (grey). Both spectra were normalised to peak values. (e) Spectra of $140\,\mu\mathrm{J}$ self-seeded pulse (red) and equivalent SASE pulse (grey).

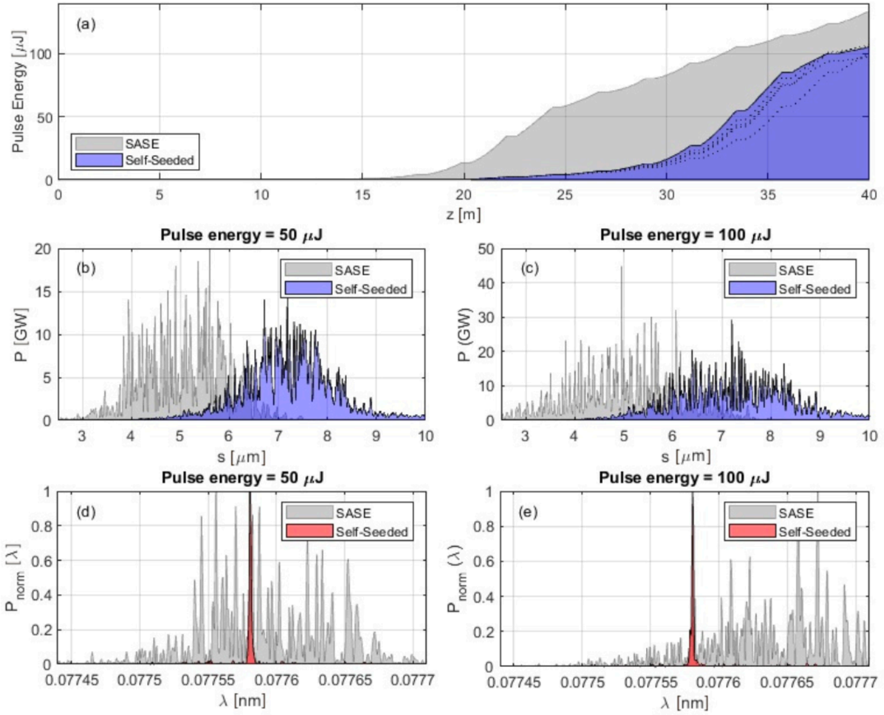
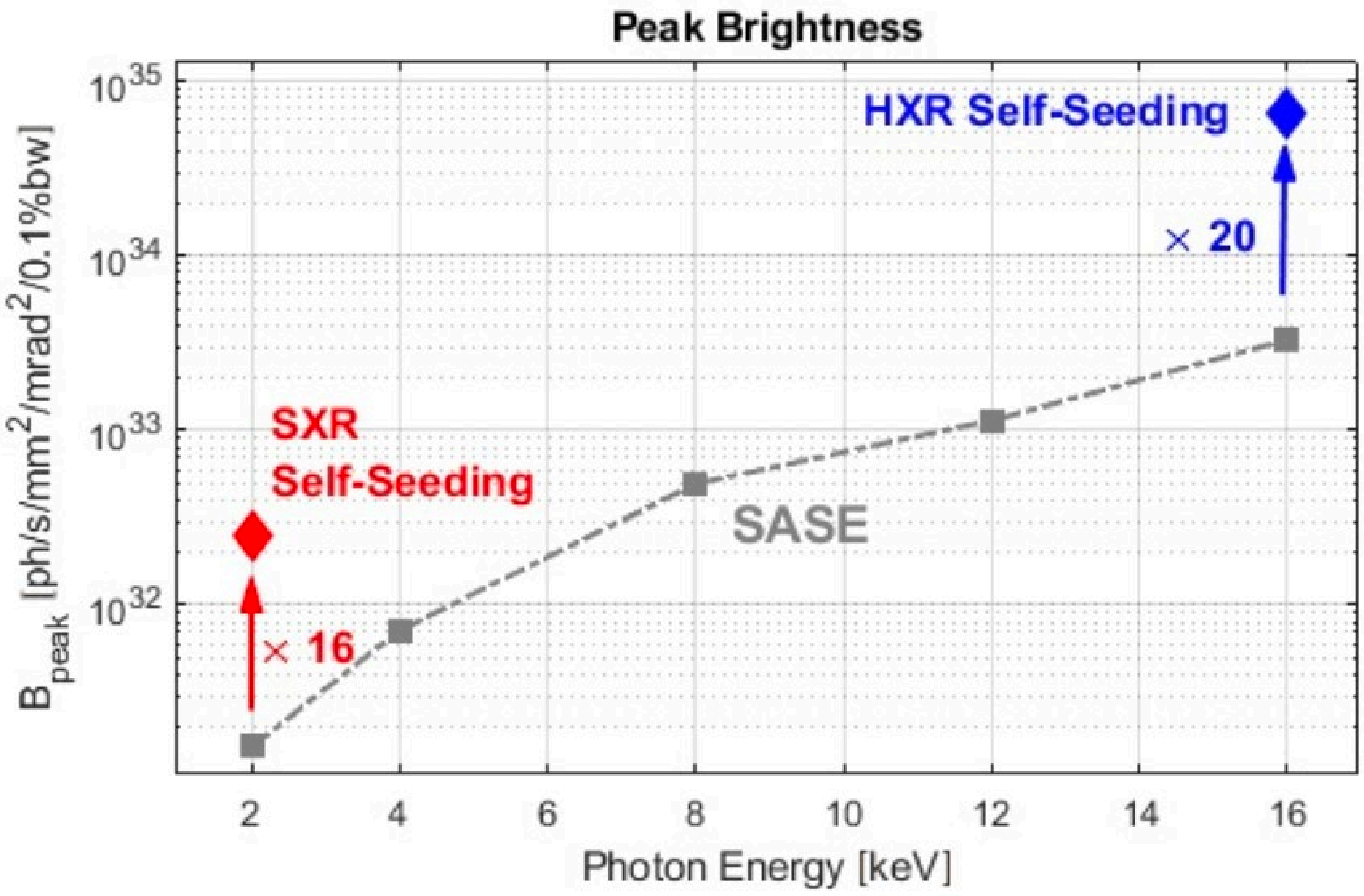


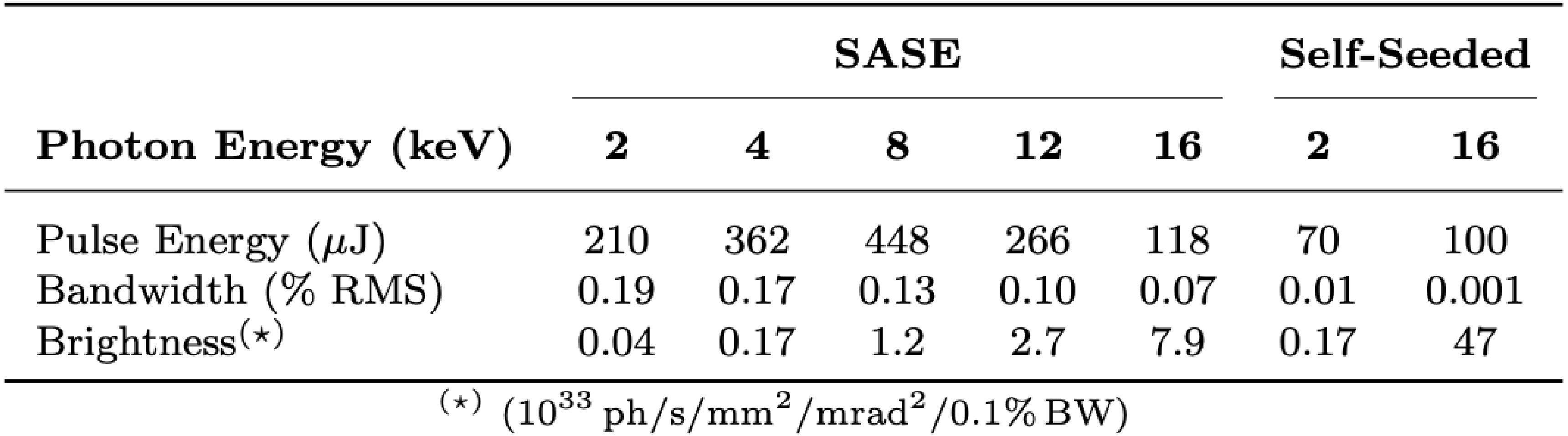
Fig. 29: HXR Self-Seeding simulation results for output at 16 keV: (a) Growth of pulse energy vs distance z from the start of the first undulator section (dashed lines are other shot-noise cases) (b) Self-seeded pulse profile at $z = 33.5\,\mathrm{m}$ (6 modules/13.1 m in the second stage) with pulse energy $50\,\mu\mathrm{J}$ (in blue) and equivalent SASE pulse of the same pulse energy (in grey) (c) Self-seeded pulse profile at $z = 38.0\,\mathrm{m}$ (8 modules/17.6 m in the second stage) with pulse energy $100\,\mu\mathrm{J}$ (in blue) and equivalent SASE pulse of the same pulse energy (d) Spectra of $50\,\mu\mathrm{J}$ self-seeded pulse (red) and equivalent SASE pulse (grey). Both spectra were normalised to peak values. (e) Spectra of $100\,\mu\mathrm{J}$ self-seeded pulse (red) and equivalent SASE pulse (grey).

Peak brightness enhancement with Self-seeding



The electron bunch is an ideal Gaussian current profile with constant nominal slice parameters.

Summary of the estimated CompactLight performance in SASE and Self-seeded modes



	SASE					Self-Seeded	
Photon Energy (keV)	**2**	**4**	**8**	**12**	**16**	**2**	**16**
Pulse Energy (μJ)	210	362	448	266	118	70	100
Bandwidth (% RMS)	0.19	0.17	0.13	0.10	0.07	0.01	0.001
Brightness$^{(\star)}$	0.04	0.17	1.2	2.7	7.9	0.17	47

$^{(\star)}$ $(10^{33}\ \mathrm{ph/s/mm^2/mrad^2/0.1\%\,BW})$

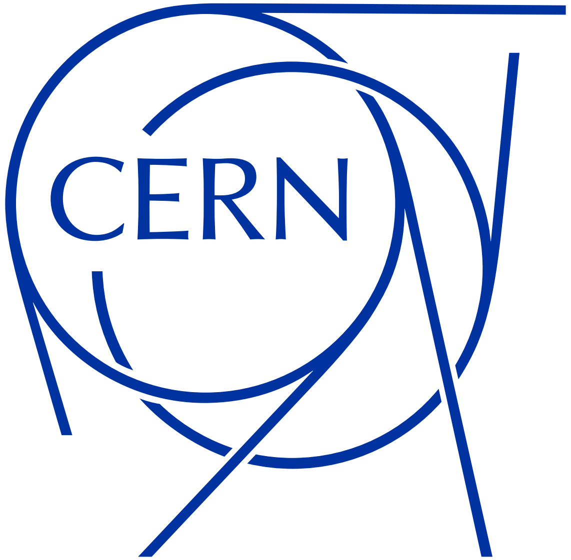
Summary and Conclusions

The CompactLight collaboration produced a 360-page long Conceptual Design Report, where the next generation of compact FEL is presented, based on novel technologies to design arguably the most advanced yet compact and cost-efficient FEL worldwide.

Unique features like two-colour operation, simultaneous SXR and HDR make it a unique facility.

MBI was taken into account by design, as well as self-seeding options to enhance the photon performance of CompactLight both in the soft- and in the hard- X-ray options.

The CDR is available online: https://zenodo.org/record/6375645 (now being published)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