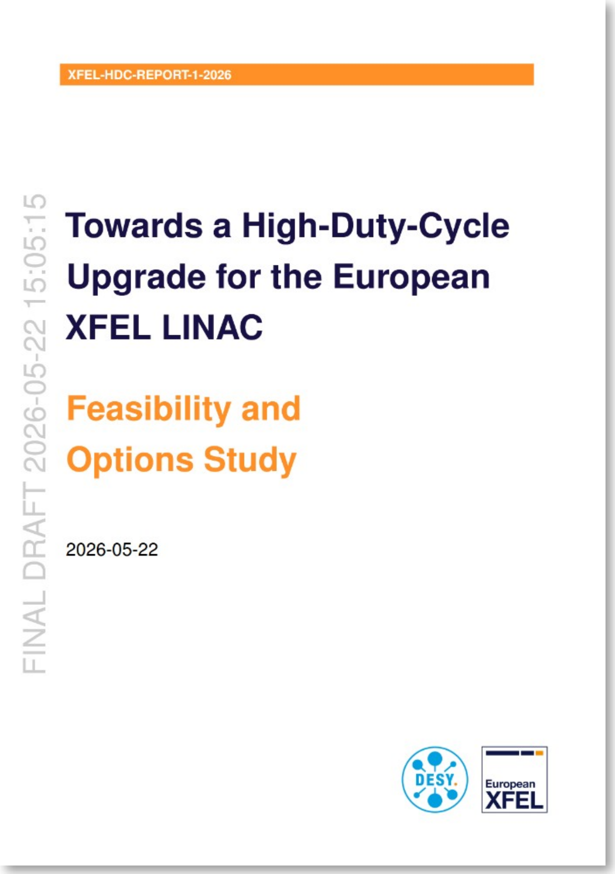
Extending the parameter range of European XFEL
The feasibility and options study

Winni Decking – DESY/MXL

Schenefeld, 28.05.26


XFEL-HDC-REPORT-1-2026

FINAL DRAFT 2026-05-22 15:05:15

Towards a High-Duty-Cycle Upgrade for the European XFEL LINAC

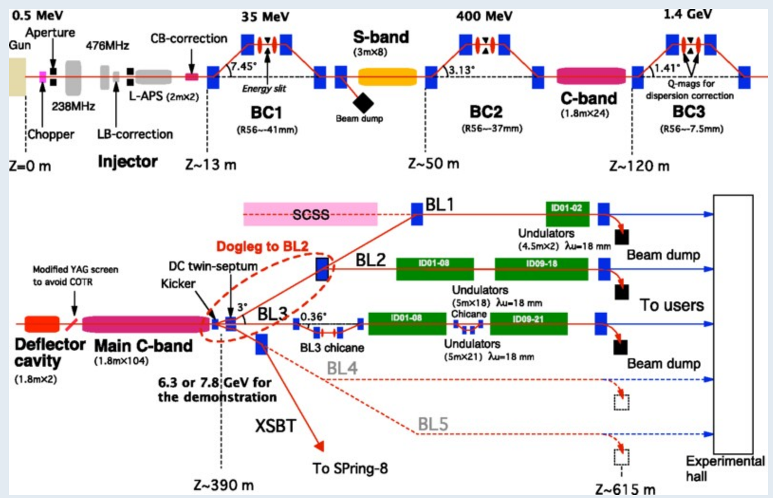
Feasibility and Options Study

2026-05-22

European XFEL

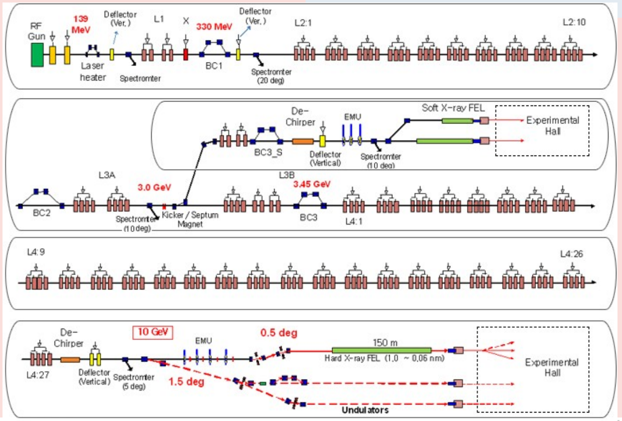
HELMHOLTZ

The HXR FEL landscape in 10 years



SACLA:

- 8 GeV NC 50 Hz, 2 undulators (+1 SXR fed by 0.5 GeV linac)
- Upgrade: Space for 2 more undulators in hall, rumors for upgrade to kHz NC RF, change to photo-injector
- Biggest asset: world leading optics



PalFEL:

- 10 GeV NC 50 Hz, 2 undulators (SXR/ HXR)
- Upgrade: ambitions for 3rd undulator, 2 bunch operation, increase to 100 Hz
- Biggest asset:

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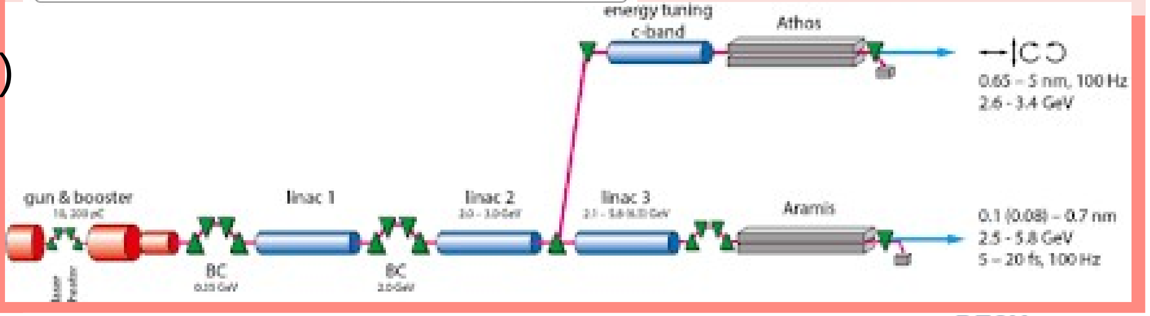
ppalli ppalli



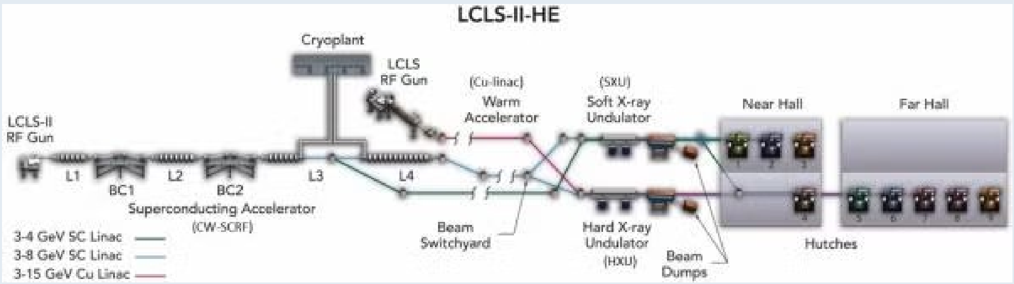
SwissFEL:

- 5.8 GeV NC 100 Hz two bunch, 2 undulators (SXR/HXR)
- Upgrade: injector rebuild, 7 GeV linac upgrade, preparation for 3rd undulator
- Biggest asset: tailored to special modes

The HXR FEL landscape in 10 years

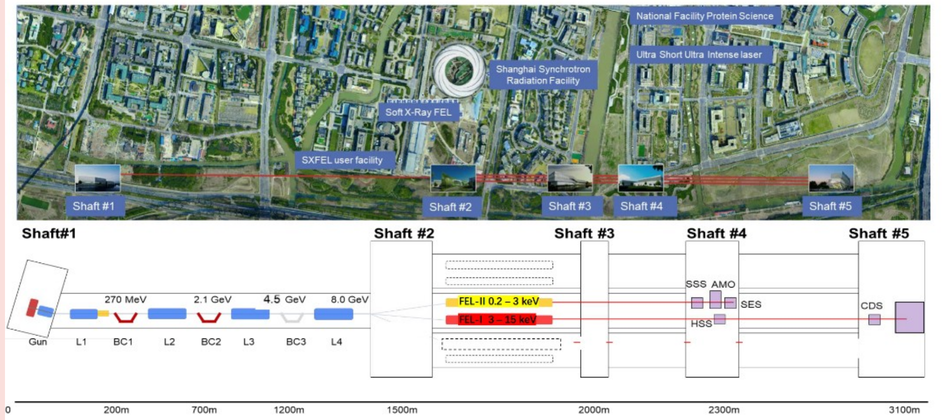
LCLS:

- 8 GeV SC CW, 14 GeV NC 60 Hz, 2 undulators (SXR/ HXR)
- Upgrade: Low emittance injector for higher photon energies & LCLS-X (more beamlines)
- Biggest asset: CW accelerator for many beamlines, NC high energy accelerator for high photon energies



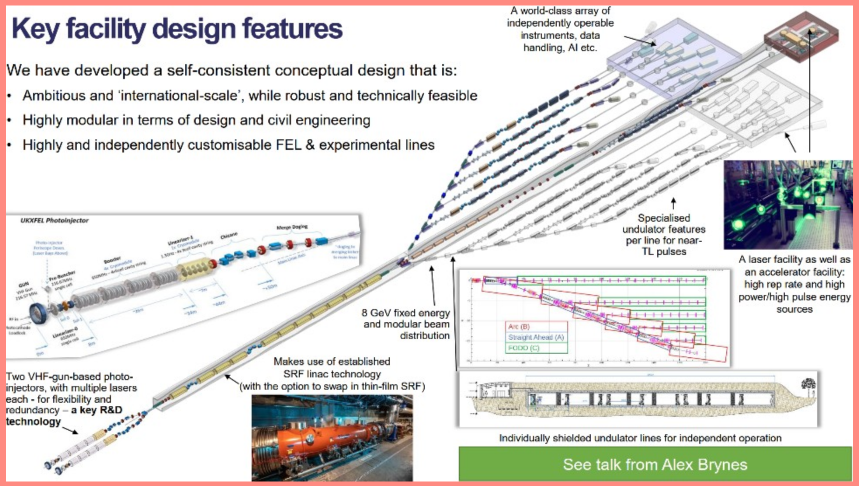
SHINE:

- 8 GeV SC CW, 2 undulators (SXR/HXR)
- Upgrade: Low emittance injector & 3rd short period (superconducting) undulator
- Biggest asset: Already three undulator tunnels build, so extension to many beamlines straightforward



UKFEL (study):

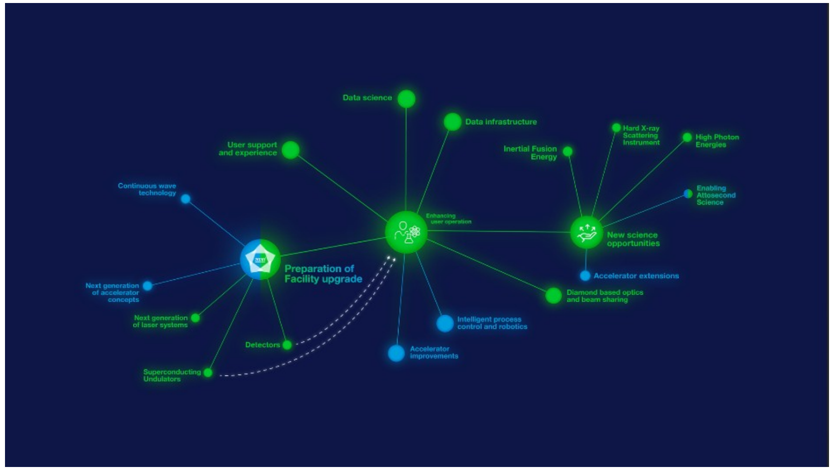
- 8 GeV SC CW, 10 tailored radiators
- Biggest asset: Thorough analysis of UK user needs and match to tailored radiators



The HXR FEL landscape in 10 years

European XFEL:

- 17 GeV SC burst mode, 3 undulators (SXR/ HXR)
- Upgrade/Strategy:
  - Harvest
  - superconducting undulators - high photon energies
  - short pulses (SA1-3)
  - Twin bunches
  - Hafen
  - …
- Biggest asset:
  - 2 empty tunnels
  - Longest accelerator, highest electron energy, longest undulators
  - Ultra stable, multiplexing since 2019, …
  - Technology leader in many areas
  - **It’s ours**



What can we do with the linear accelerator

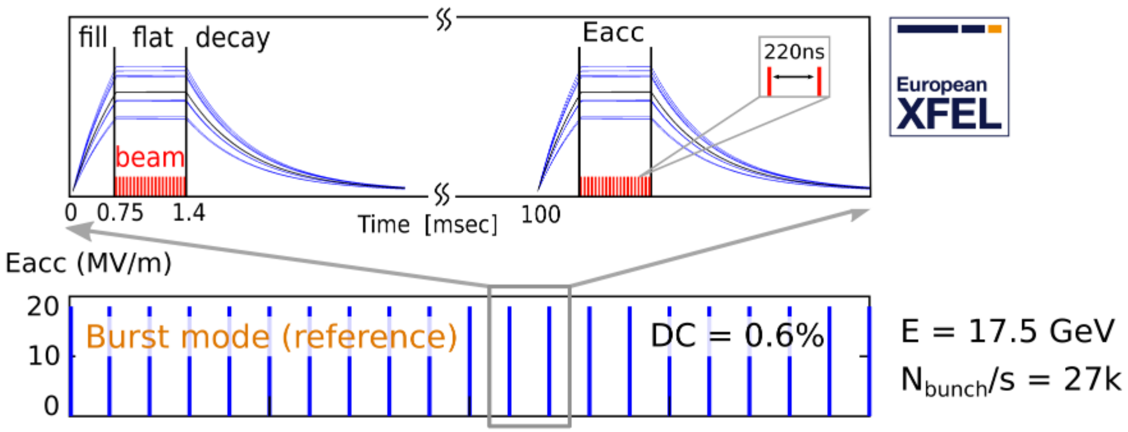
- This is not a facility layout / proposal
- It describes options for a modification of the superconducting linear accelerator to increase the

duty cycle: percentage of beam* on per time unit

- Benefits:
  - Create more electron bunches/photon pulses per second
  - Distribute photon pulses over a longer time period with larger spacing
- Note: the beam power usually does not increase over what is possible at EuXFEL today, thus also the maximum number of photons will not increase

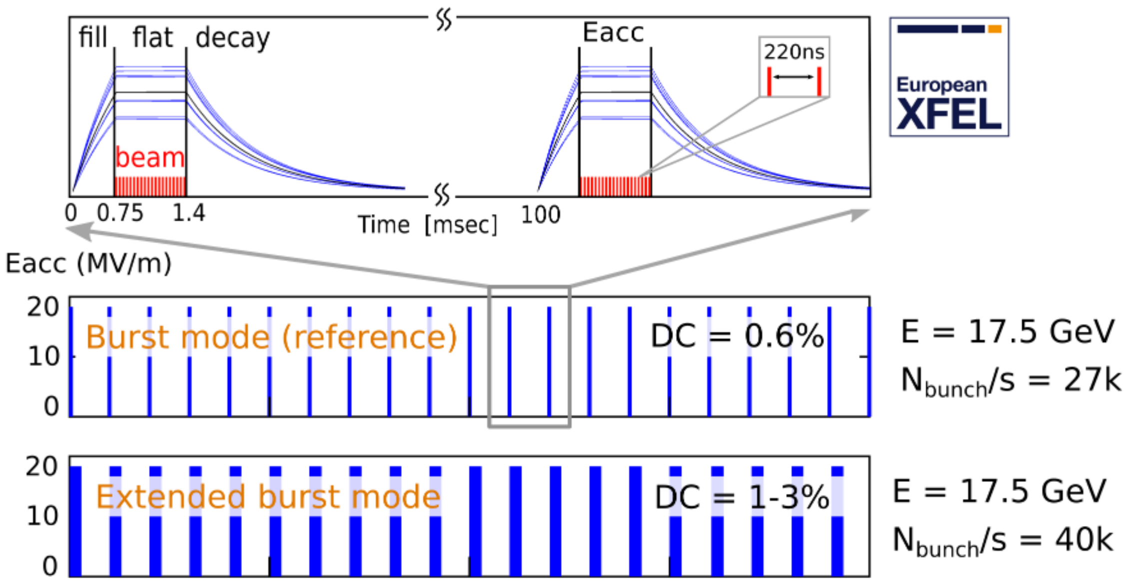
* Cryo and RF specialists define duty cycle often as percentage of RF on per unit time

Change the way how the RF is operated



→ **TODAY**

Change the way how the RF is operated



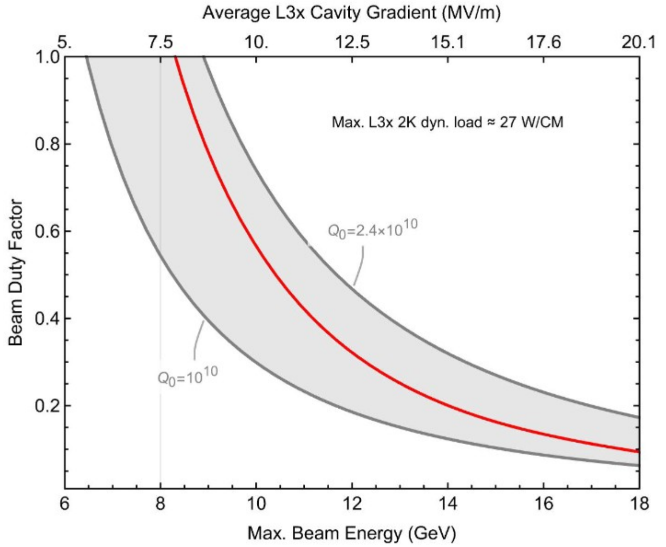
→ **TODAY**

Extended RF Burst Principal Limitations (at 17.5 GeV beam energy)

Approx. beam duty cycle limit	Limiting HW	Way out
1 %	RF Gun	New RF Gun
1.5 %	Cryo Plant	Operate 2nd (redundant) cryo plant string (+ 3 MW) + new cold box
1.8 %	High Power RF System	New HPRF
3 %	Cryo Module (2 phase pipe)	New Cryo Modules

- An approx. 1% duty cycle in the burst mode seems to be a reasonable limit for reliable and sustainable operation, with the new GUN5 we already increased from 0.6% to 0.8%

Higher Duty Cycle with new, modified cryo modules



Similar to LCLS-II / SHINE approach

- Optimized 2-phase He transport
- Improved cavity quality factor → reduced dynamic 2K load

1) Rebuild the entire linac for max energy reach at CW operation

- Very high cost ~1B€ (or more), very long dark time

2) Rebuild only L1+L2 (+new 2nd injector), keep L3 (optionally extend it by 16 modules from old L1+L2)

- CW high gradient in L1+L2 with high-performance modules, keep beam energy up to BC-II constant @ ~2. – 2.5GeV, very beneficial for beam dynamics
- L3 in CW mode at low gradient and/or higher g pulsed mode with possibly increased d.c.

Prospects for CW and LP operation of the European XFEL in hard X-ray regime

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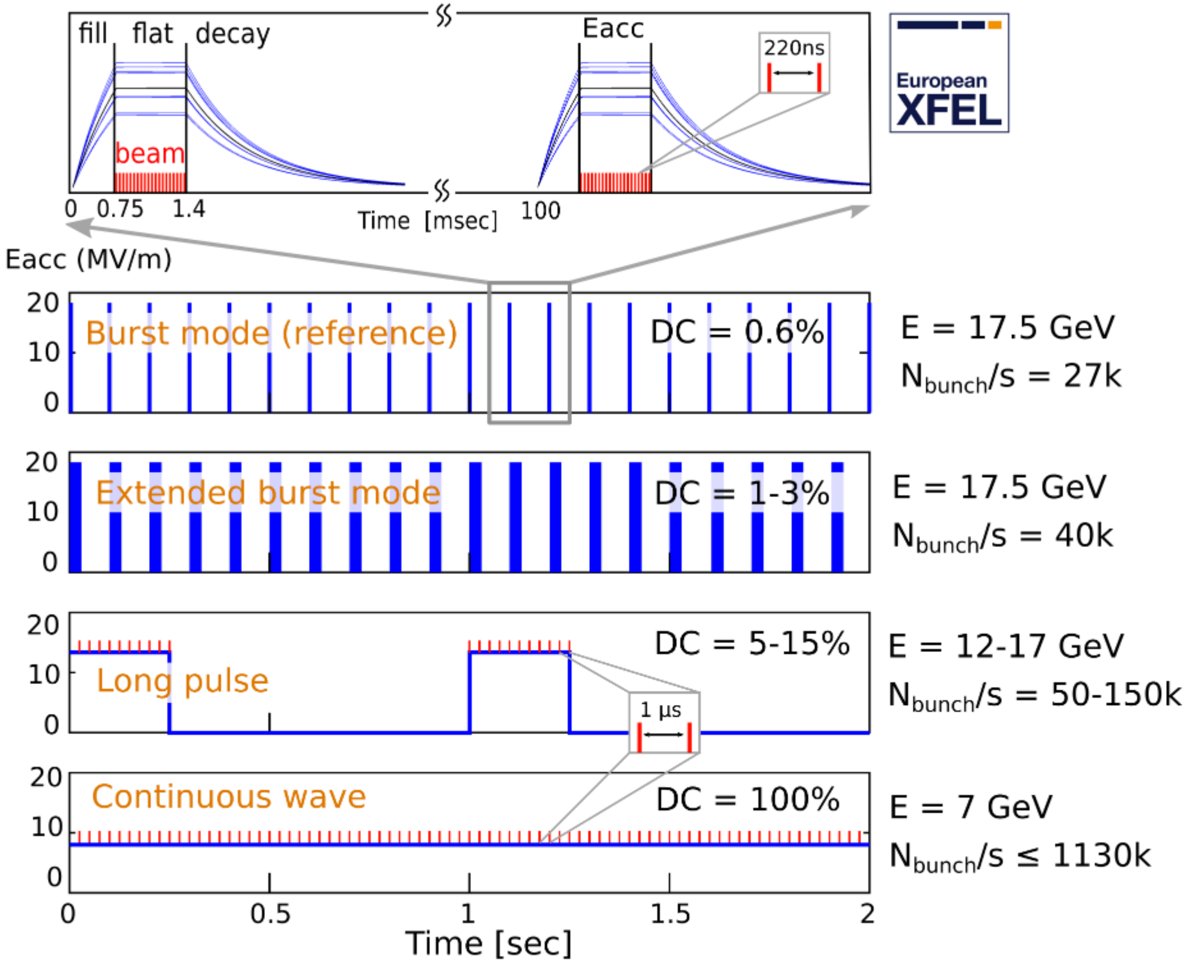
Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany

NIM A 768 (2014)

R&D for the High Duty-Cycle program (i.e. CW and Long Pulse)



→ **TODAY**

High Duty Cycle (HDC)

Since 11/2022 detailing out the High Duty Cyle Concept

Reminding / writing / editing – thanks Nick

2026	6th XFEL-HDC workshop (FOS report re-view) – Jork	24-25.11.2025	Report content review
2025	5th XFEL-HDC workshop (FOS scope re-view) - DESY	23-24.04.2025	Report scope review
2024	4th XFEL HDC workshop (Mozartsäle, Hamburg) (Indico)	8-9.12.2024	Writing kick-off & initial discussion with ‘photon’ users
2023	3rd Workshop (Jork retreat) November 2023	2023-11-21	Focus on controls&diagnostics
	2nd Workshop (Jork retreat) March 2023	28-29.03.2023	Focus on injector
2022	First XFEL CW Operations Mini-Workshop	1-2.11.2022	Define 6 working groups and work plan


Hotel Altes Land

Top Level Scope of the study – be world leading in 10 years

Criteria	Rational	Importance
Maximum energy for CW operation should be 8 GeV	Compete with LCLS-II-HE and SHINE	High
Maximum energy in long-pulse mode should be 16 GeV	Maintain the unique high-energy capabilities of EuXFEL	High
Beam repetition rate should be 1 MHz	Capability to support ~10 undulators with the preferred repetition rate of 100 kHz	High
Electron source should deliver 100 pC bunches with an emittance of ~0.2 mmmrad	FEL performance should be comparable to present parameters (~1 mJ at ~10 keV)	High
Reuse existing installations/infrastructure	Propose an economic and sustainable upgrade path	Medium
Maintain current burst mode capabilities	Support current operation modes	Low

Table 1.1: Top level scope (requirements) driving the High Duty Cycle *Feasibility and Options Study*.

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Maintain current burst mode capabilities	Support [illegible]	

Table 1.1: Top level scope (requirements) driving the High Duty Cycle *Feasibility and Options Study*.

Dropped early because of operational and technical incompatibilities

Working Groups

2. General scope and top level parameters (Winni Decking, Nick Walker)

   Develop parameters and scope from basic scaling laws

Beam parameters				
Beam energy	GeV		8	16
Beam duty factor			100 %	10 %
Average bunch rate	/s		10^6	10^5
Bunch repetition rate	MHz		1	1
Pulse repetition rate	Hz			1
Beam pulse length	ms			100
Bunch charge	pC		100	100
Beam current	µA		100	100
LINAC parameters		L1/L2 (CW)	L3x (CW)	L3x (LP)
Beam energy	GeV	2	8	16
Gradient	MV/m	20	7.5	17.6
Max. off-crest phase (1)		40°		
RF duty factor		100 %	100 %	12 % (2)
Cryogenic				
Cavity Q_0 (3)		3×10^{10}	1.8×10^{10}	1.14×10^{10}
Cryo 2 K dyn. load / module	W	114	27	27
Cryo total 2 K dyn. load	W	1820	2590	2590
RF parameters				
Q_{ext}		6×10^7	1×10^7	1×10^7
Max. detuning ($\pm\Delta f$) (4)	Hz	10	10	10
Max. P_{for} per cavity	kW	4.8	2.0	9.3
Cavities per amplifier		1	8	8
Number of amplifiers		128	96	96
Max. P_{for} per amp. (5)	kW	7.3	23.5	112.1
AC-RF efficiency		≥60 %	≥40 %	≥60 %
RF AC power / amplifier	kW	12.1	58.8	22.4
Total RF AC power	MW	1.6	5.6	2.2

Table 2.4: Key parameters for the high-duty-cycle accelerator upgrade. CW and the highest-energy LP working points are shown. notes: (1) On-crest operation assumed for L3x (off-crest operation for energy management is included in margin). (2) Assumes 20 ms fill time. (3) L1/L2 value is design specification for new CW-optimised cavities. (4) Assumed peak to peak. (5) Assumes a 50 % power margin.

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3. Cryogenic solutions (Tobias Schnautz, Kay Jensch)

   How to cope with the increased heat load

No.	Topic	No.	Topic
1	Bypass Problem	4	L3x configuration
2	Level Elevation	5	Compatibility tests
3	CM design for L1 and L2	6	HDC Cryoplant's option

Table 3.3: Important topics to be studied.

Working Groups

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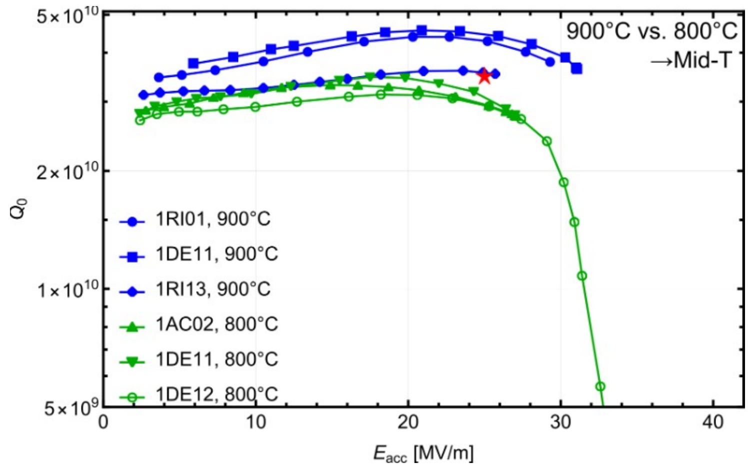
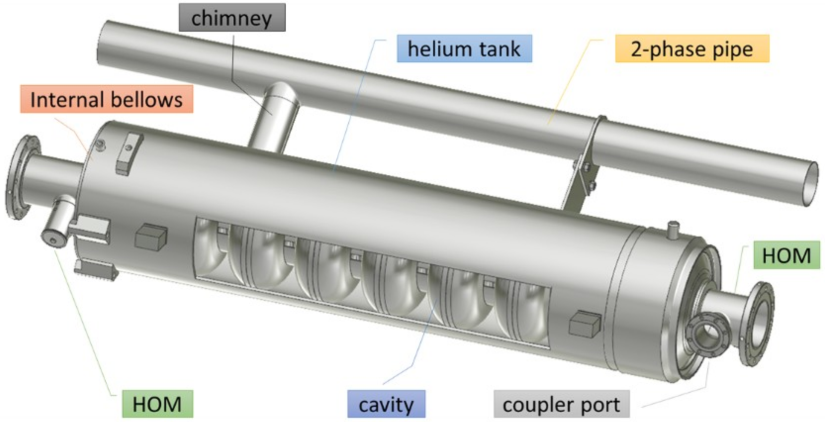
3. Cryogenic solutions (Tobias Schnautz, Kay Jensch)

   How to cope with the increased heat load

4. CW-optimized 1.3 GHz modules (Serena Barbanotti, Lea Steder, Detlef Reschke)

   How to build a CW optimized cryo-module & how to modify the existing power couplers





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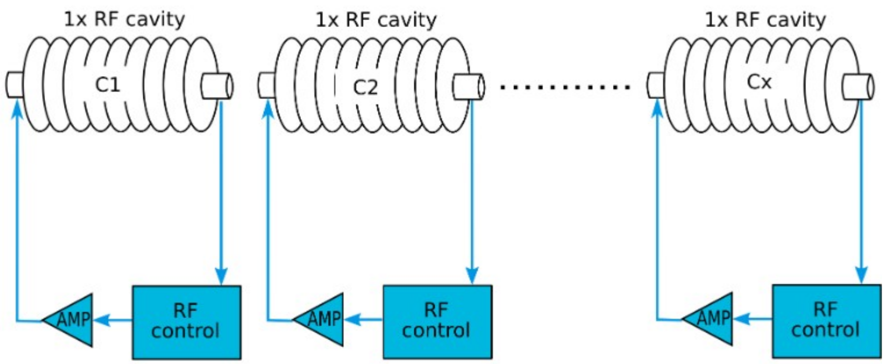

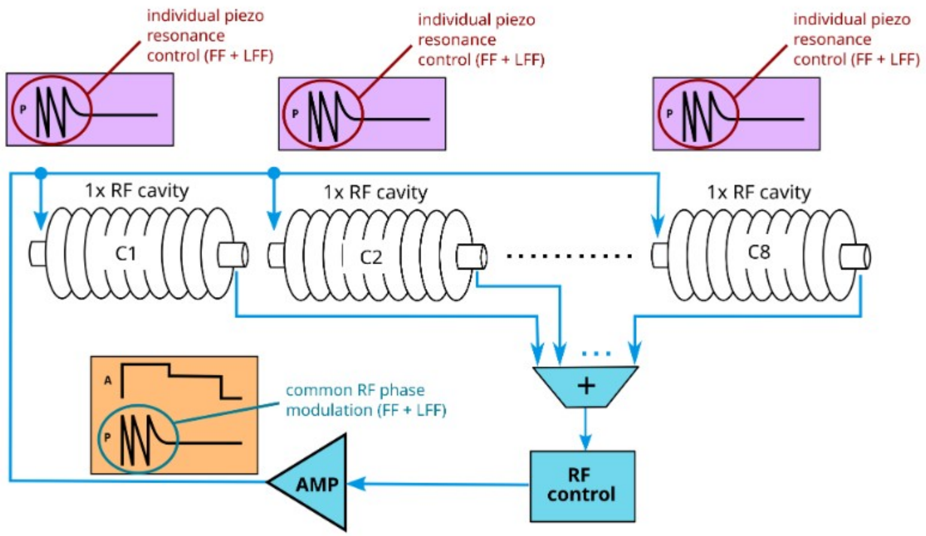

Working Groups

2. General scope ... ck Walker)
   Develop param...
3. Cryogenic solu...
   How to cope w...
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   How to build a ... he existing powe...
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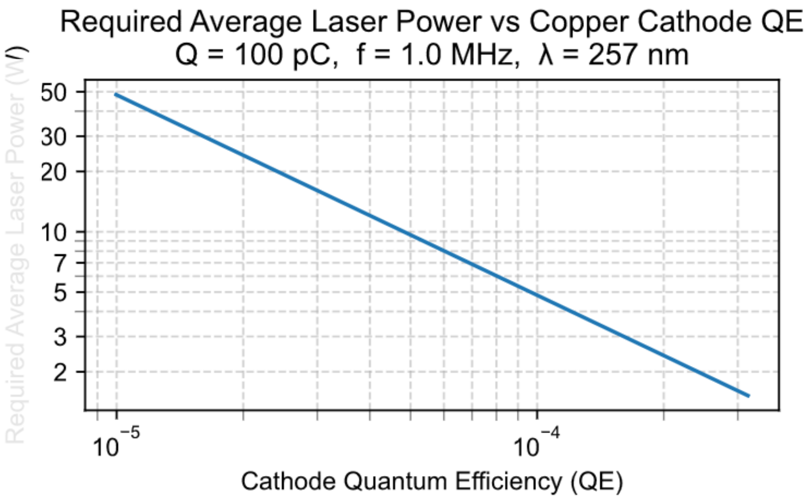
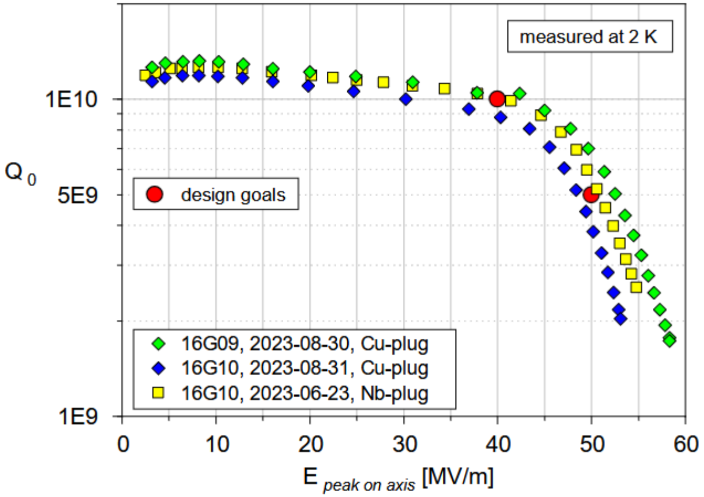
   How to build an RF system capable of CW and pulsed mode into the existing
6. CW Photoinjector (Dmitry Bazyl, Mikhail Krasilnikov, Elmar Vogel)
   How to develop a CW injector with sufficient beam quality and beam current





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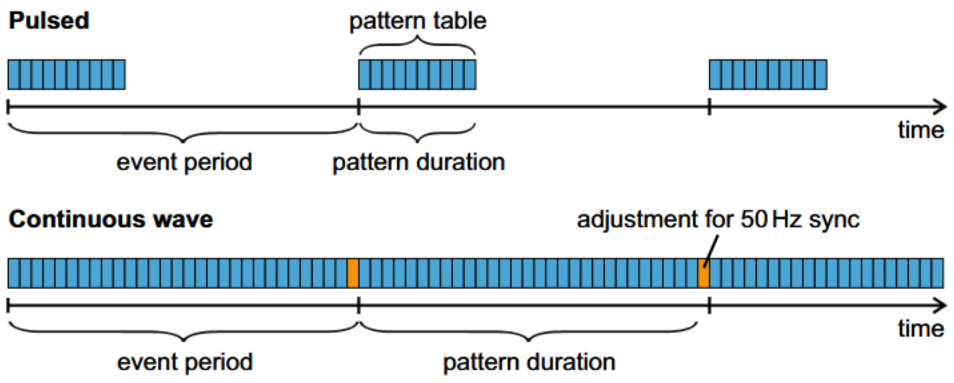

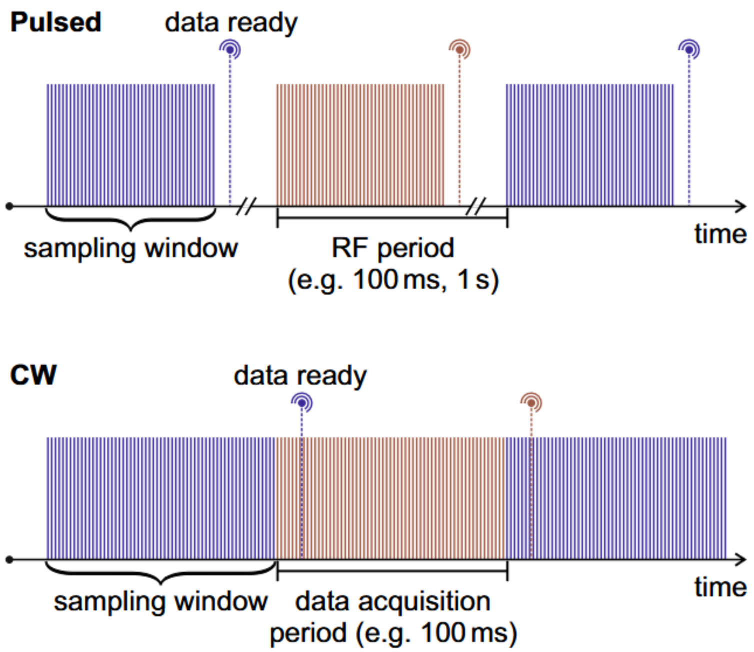

6. CW Photoinjector (Dmitry Bazyl, Mikhail Krasilnikov,

   How to develop a CW injector with sufficient beam quality and beam current

7. Timing and Controls (Lars Froehlich, Tim Wilksen)

   How to deal with a continuous and increased data stream

Working Groups

System	Sum	Subsystem	Injector	XTL	XTDs
Dosimetry	578	RadFets	3	48	376
Screens	~70	simple	3		
		complete	7	26	18
		dump	1	4	5
		compressor		3	
Loss monitors	~490	BLM	19	230	240
		BHM	1	1	2
Wire scanners	14			6	8
Charge	~50	Faraday Cup	4		
		Toroid	6	15	15
		Dark current monitor	2	7	
BPM system	~ 460	Button	10	164	131
		Cavity Ø 10 mm			107
		Cavity Ø 40.5 mm	3	18	2
		Reentrant	1	23	
		Button Compressor		3	

System	Sum	Subsystem	Injector	XTL	XTDs
Arrival-time monitors	12	BAC(*)	0/1	0/1 ?	
		BAM	1/0 ?	6/6	3/3
		LAM(*)	0/1	-	-
Bunch length and profile monitors	5	EOSD	1/0	2/2	-
		BCM(*)	-	4/4	-
		THz spectrometer(*)	-	1/1	-
Longitudinal phase space monitors	6	TDS	1/1	2/2 ?	-
		passive streaker	-	-	3/3 ?

8. Diagnostics and Feedbacks (Marie Kristin Czwalinna, Dirk Lipka)

Identify challenges and chances coming with the increased duty cycle

Working Groups

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High Duty Cycle Upgrade

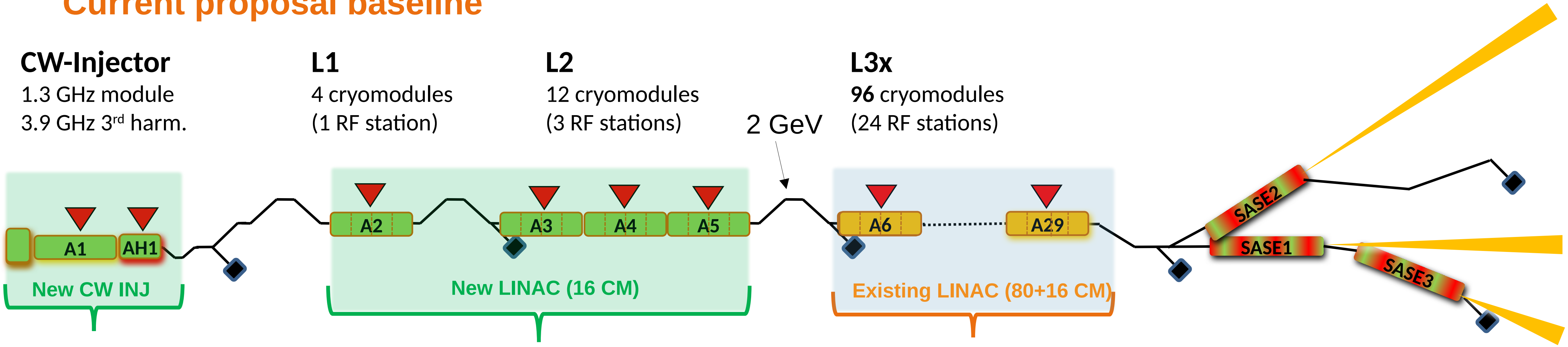
Current proposal baseline

CW-Injector
1.3 GHz module
3.9 GHz 3rd harm.

L1
4 cryomodules
(1 RF station)

L2
12 cryomodules
(3 RF stations)

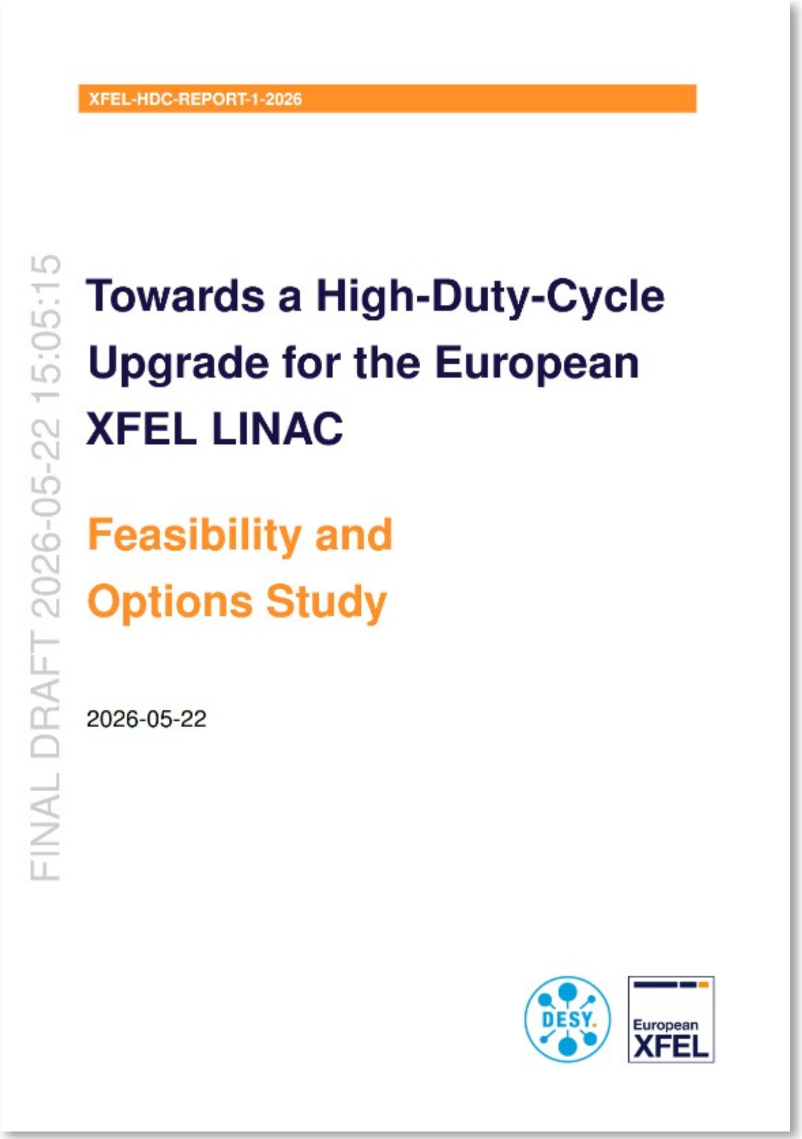
L3x
96 cryomodules
(24 RF stations)



New SRF injector
TS4i
How to maintain beam quality

16x new CW-cryomodules
Based on new high-Q_0 cavities
How to modify the cryomodules

Maximum heat load supported by 2 phase pipe ?
What are the limits of our existing CMs
Maximum RF power supported by input couplers ?
How to optimize their operation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Feasibility and Options Study

2026-05-22

DESY. European XFEL

- Summarizes 3.5 years of work
- 6 workshops
- 6 test stands in operation or under construction
- Approx. 35 FTE/year
- 180 page document
  - Overall concept, workackages technical descriptions, summary of further R&D
- Still in Draft state, core messages are there, will be finalized after November 27 MAC meeting

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2026-05-22

Thank You !

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