First Beam Heating at FLASH

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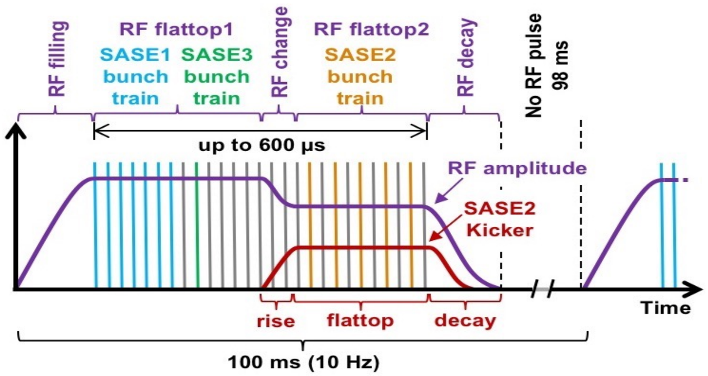
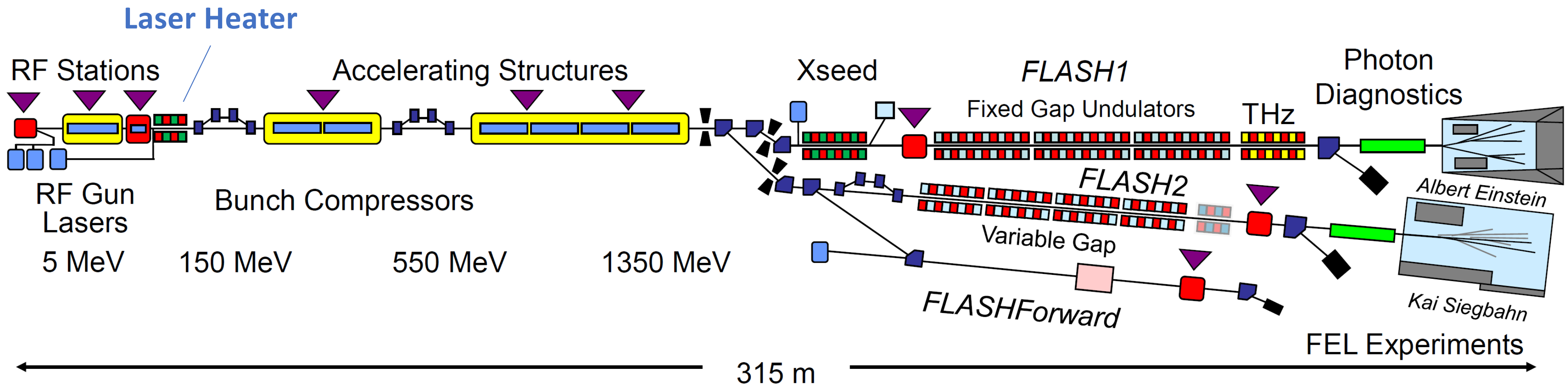
FLASH @ DESY

super-conducting linear accelerator

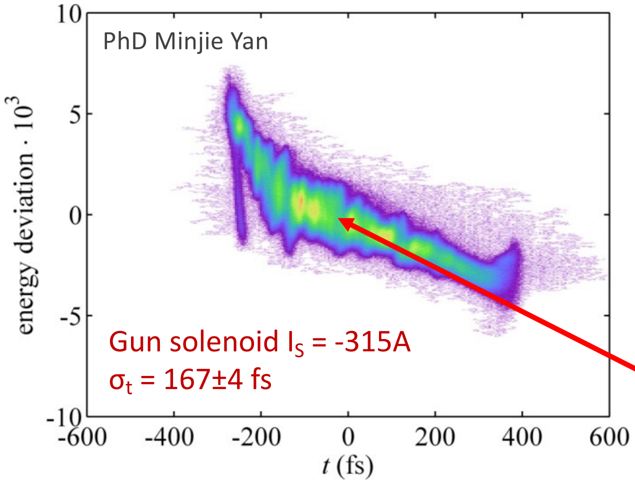




A Laser Heater has been installed in the injector at FLASH in the shutdown 2021/2022

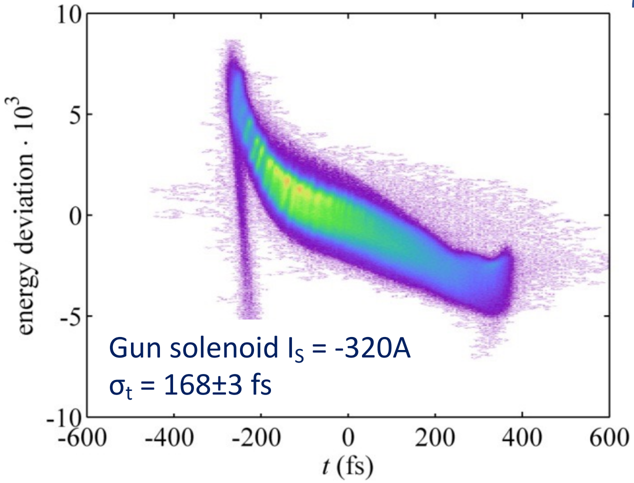
Why Laser Heater: Micro-bunching Instability

Long. Phase Space with TDS

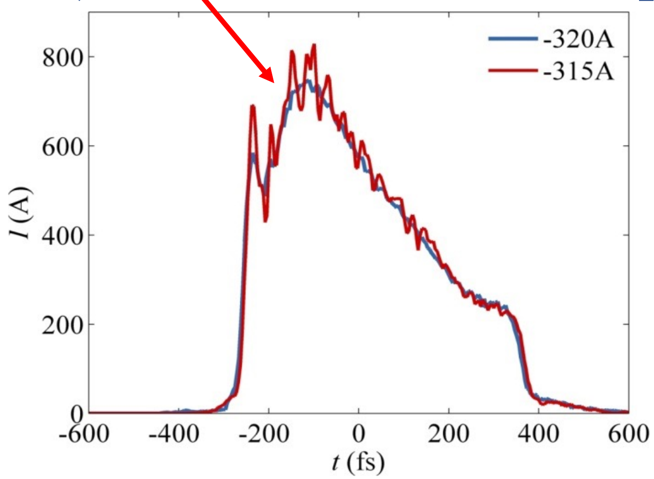


- High-gain Free-Electron Lasers require electron bunches with ~kA for lasing
- Random charge density modulations at the gun can be amplified
  => during bunch compression
  => due to longitudinal space charge
- This **micro-bunching instability** can drastically degrade the lasing process
  => SASE but especially external seeding processes

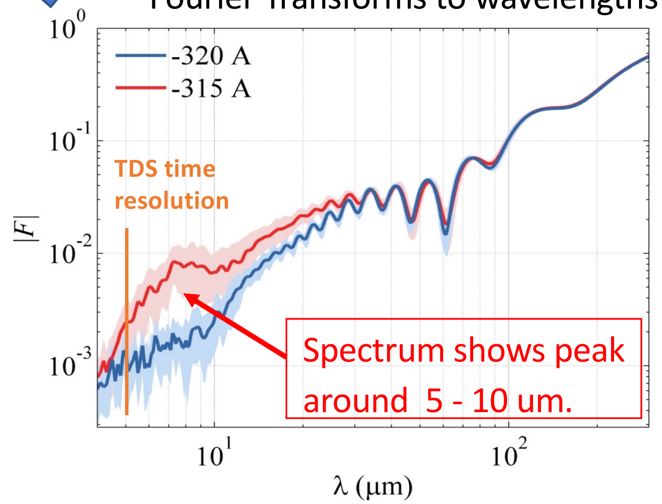
Micro-bunching



Current Profiles



Fourier Transforms to wavelengths



Microbunching Instability at FLASH: How to cure

2003

TESLA-FEL-2003-02

May 2003

Longitudinal Space Charge Driven Microbunching Instability in TTF2 linac

E.L. Saldin [a], E.A. Schneidmiller [a], M.V. Yurkov [b]

Abstract

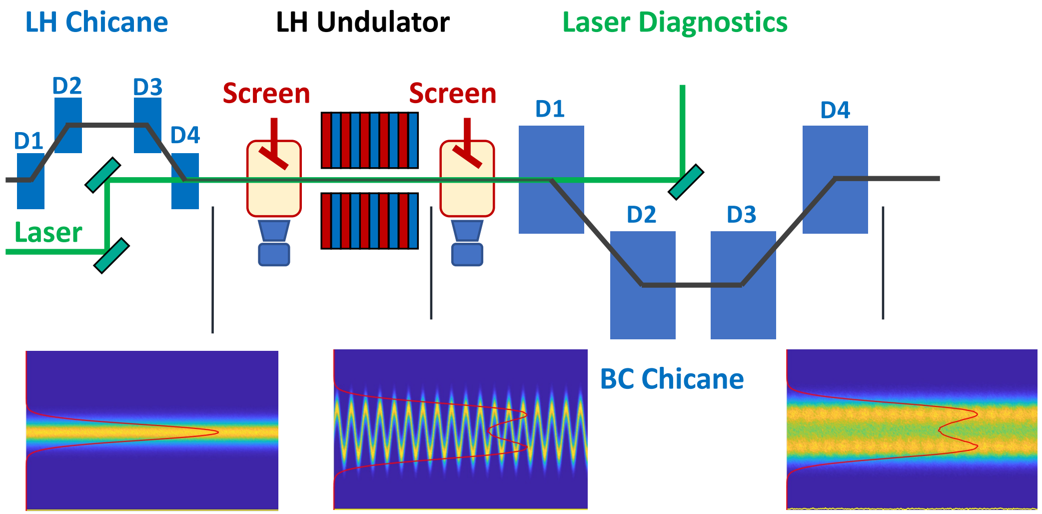
In this paper we study a possible microbunching instability (amplification of parasitic density modulations) in the TESLA Test Facility (Phase 2) linac. A longitudinal space charge field is found to be the main effect driving the instability. Analytical estimates show that initial perturbations of beam current in the range 0.5-1 mm will be amplified by a factor of a few hundred after the beam passed two bunch compressors. A method to suppress the instability is discussed.

How to cure the microbunching instability:

As for the amplification mechanism itself, an effective way to suppress the gain is to increase local energy spread since the gain critically depends on this parameter. For instance, increase of the energy spread at TTF2 up to 15-20 keV would eliminate the instability.

... A simple method to control the energy spread at low energy would be to use FEL type modulation of the beam in optical wavelength range by a laser pulse in an undulator. Then the beam goes through the bunch compressor where these coherent energy modulations are quickly dissipated, leading to the effective "heating" of the beam [4]. For illustration we present here a nu-

Shutdown 2021/2022



A look to other Facilities

LCLS

• 2004: Design: https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.7.074401

• 2010: Commissioning: https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.13.020703

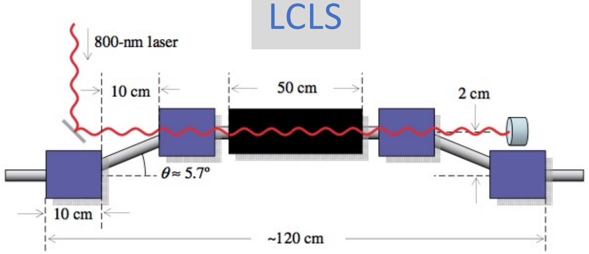
FERMI@Elettra

• 2014: Commissioning: https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.17.120705

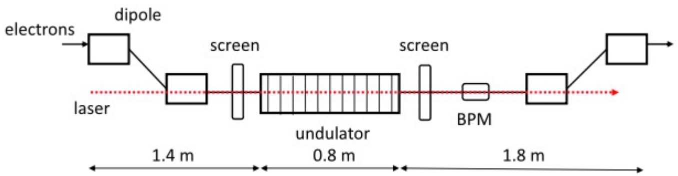
PAL-XFEL

• 2017: Commissioning: https://www.sciencedirect.com/science/article/pii/S0168900216311214

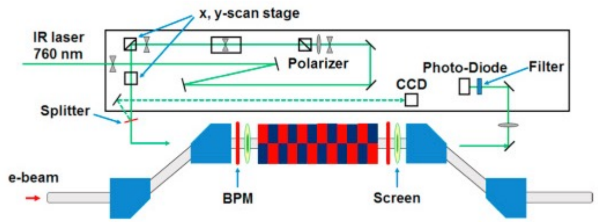
LCLS



FERMI

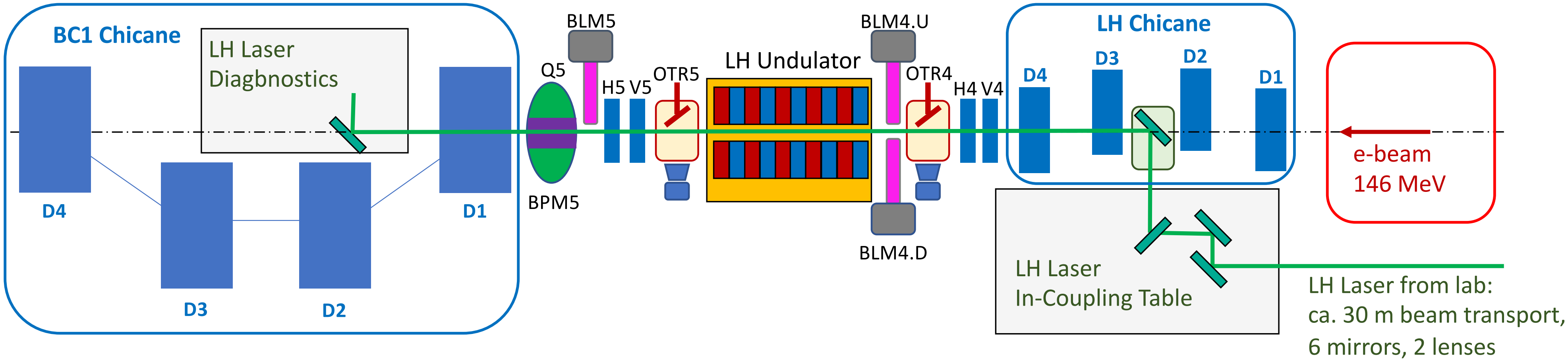


PAL-XFEL

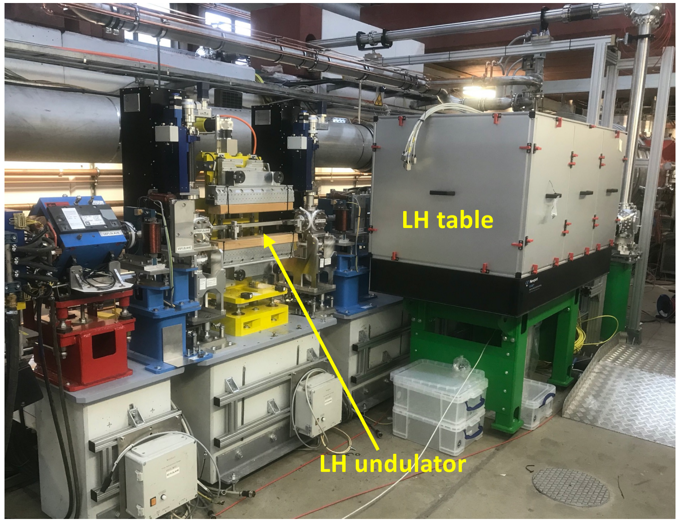


- LH undulator in a small chicane (easy for in- and out-coupling of the LH laser beam (TiSa: ~800 nm))
- R_{52} of 2^{nd} part of LH chicane is used to ‘smear out’ the energy modulation
- Risk of residual density modulation in BC that is not smeared out completely => ‘trickle’ heating (see LCLS 2010)

FLASH2020+ LH Layout



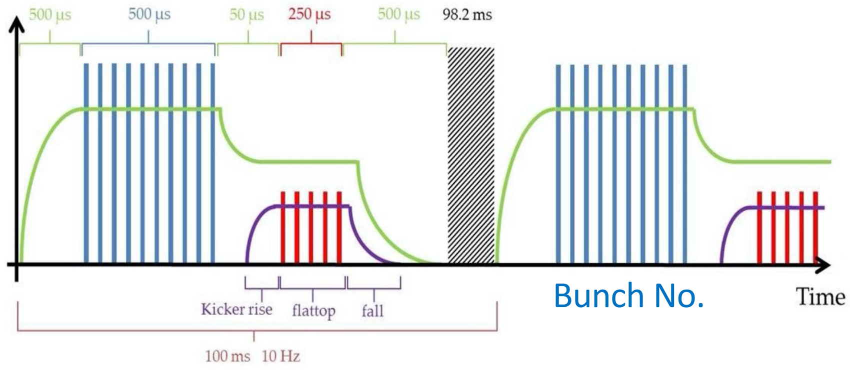
- **LH undulator in dispersive-free straight section**
  => to avoid beam tilts due to energy chirp for bunch compression
  => on-axis in-coupling of the LH laser
  => **In-vacuum mirror** and **LH chicane** to bend the beam around
- **Dedicated LH laser system in the green**
- **LH Undulator**
  => Radiation losses due to high duty cycle of superconducting accelerator
  => optimize for **'large' minimum gap**
  => use radiation hard magnet material: **SmCo** (~ 90% of NdBFe)



LH Laser and Laser Beamline

- **LH Laser wavelength in the green at 532 nm**
  => effective 'smearing out' of the induced energy modulation
  => reduces risk of 'trickle' heating
  => requires dedicated laser system
- **Mimic electron bunch pattern**
  => burst of up to 800 pulses at 1.0 MHz at 10 Hz rep rate
- **Laser architecture identical European XFEL photo injector laser**
  => hybrid Yb:fiber / Nd:YVO4 laser system
  => operating at 1064 nm and frequency-doubled to 532 nm
  => low bandwidth pulses with ps pulse duration
  => proven technology and high reliability (99% availability since 2017)
- **Laser peak power in the green about 2 MW**
  => smaller compared to all other facilities
  => BUT leads to high peak and average pulse energies in the IR!
- **Transport of LH Laser pulses**
  => from the laser lab about 50 m in evacuated beamline
  => 1:1 imaging telescope

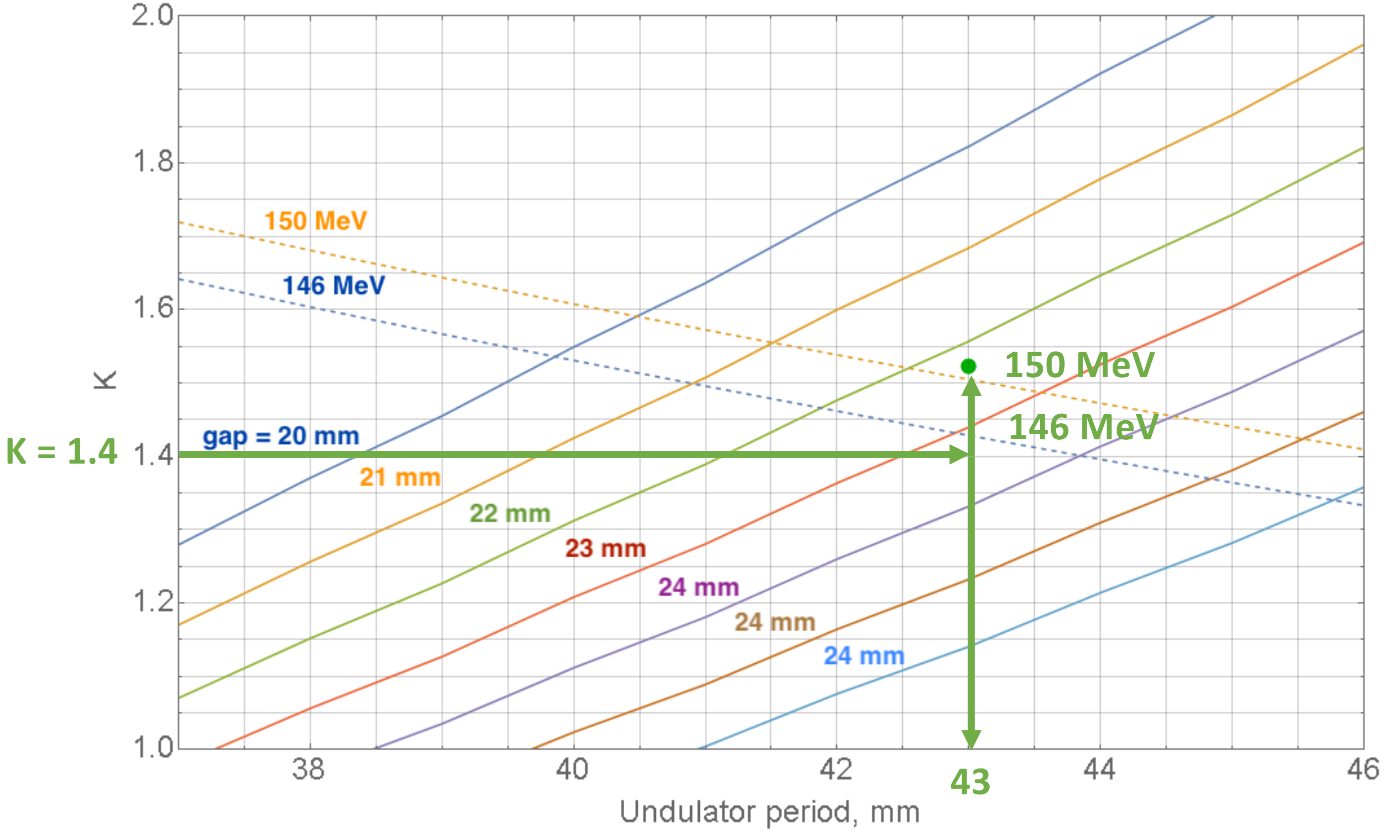
FLASH Time Pattern

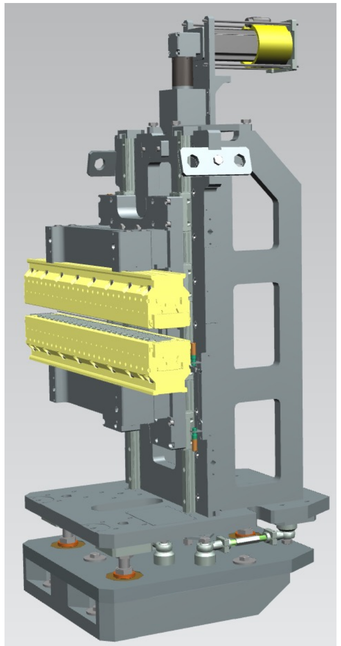


Parameter	Symbol	Unit	Value
Laser wavelength	λ_L	nm	532
Pulse duration (FWHM)	T_L	ps	8
Peak power (nominal)	P_L	MW	2
Repetition Rate	f_{burst}	Hz	10
Burst lengths	T_{burst}	ms	0.8
Intra-burst rep rate	f_{pulse}	MHz	1.0

LH Undulator

1. Maximize **energy modulation** scales with **K *$JJ(K)$ * λ_u* N_u ~ K * L_u => k = 1.**4 @146 MeV
2. Maximize **min. gap**: To reduce radiation losses at the LH undulator vacuum chamber
3. Choose radiation hard magnet material => **SmCo** (~10% less remanence than NdFeB)





=> Period = 43 mm

=> min. gap = 22 mm

Max. number of periods that fit into available space (566 mm)

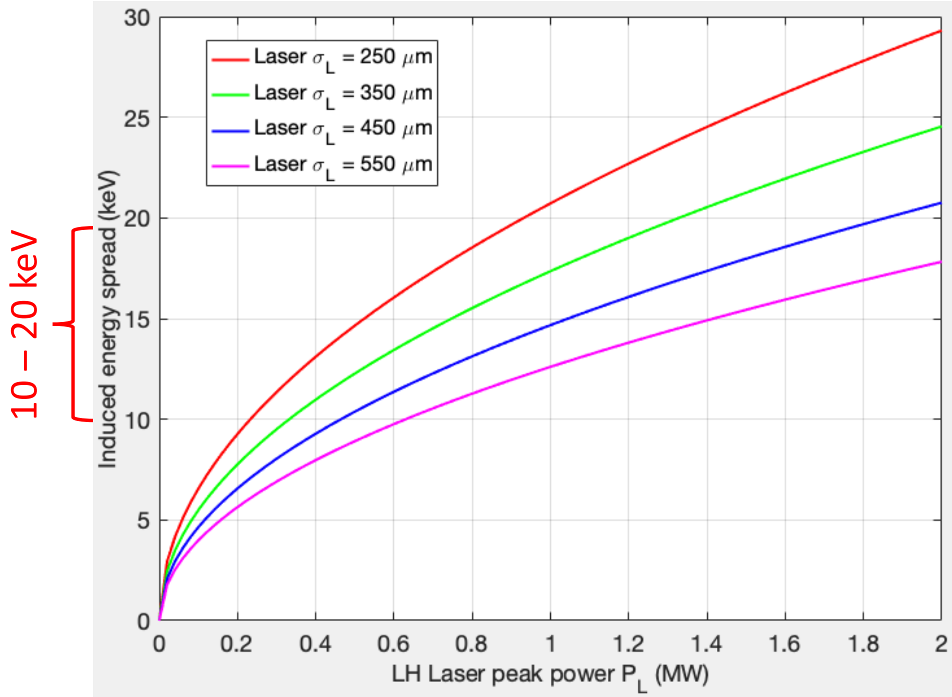
=> N = 11

LH modelling: Induced (slice) Energy Spread

Z. Huang *et al*, Phys. Rev. STAB, vol. 13, no. 2, p. 020 703, 2010.

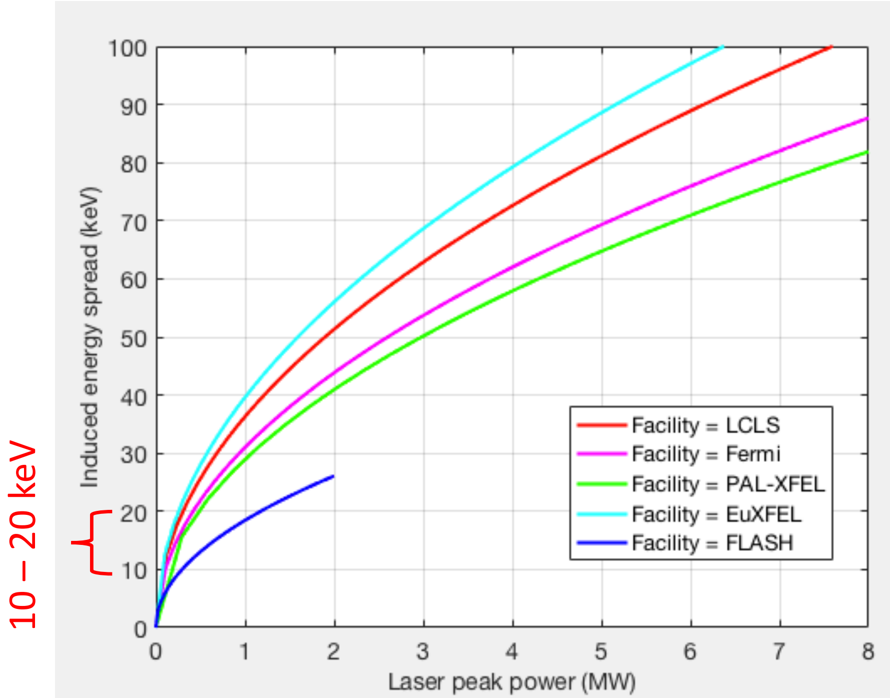
$$\sigma_{\Delta E}(P_L) = \frac{mc^2}{\sqrt{P_0}} \cdot \frac{K \cdot JJ(K) \cdot L_u}{\gamma} \cdot \sqrt{\frac{\sigma_L^2}{2(\sigma_x^2+\sigma_L^2)}}\frac{1}{\sigma_L} \cdot \sqrt{P_L}$$

Different laser beam sizes



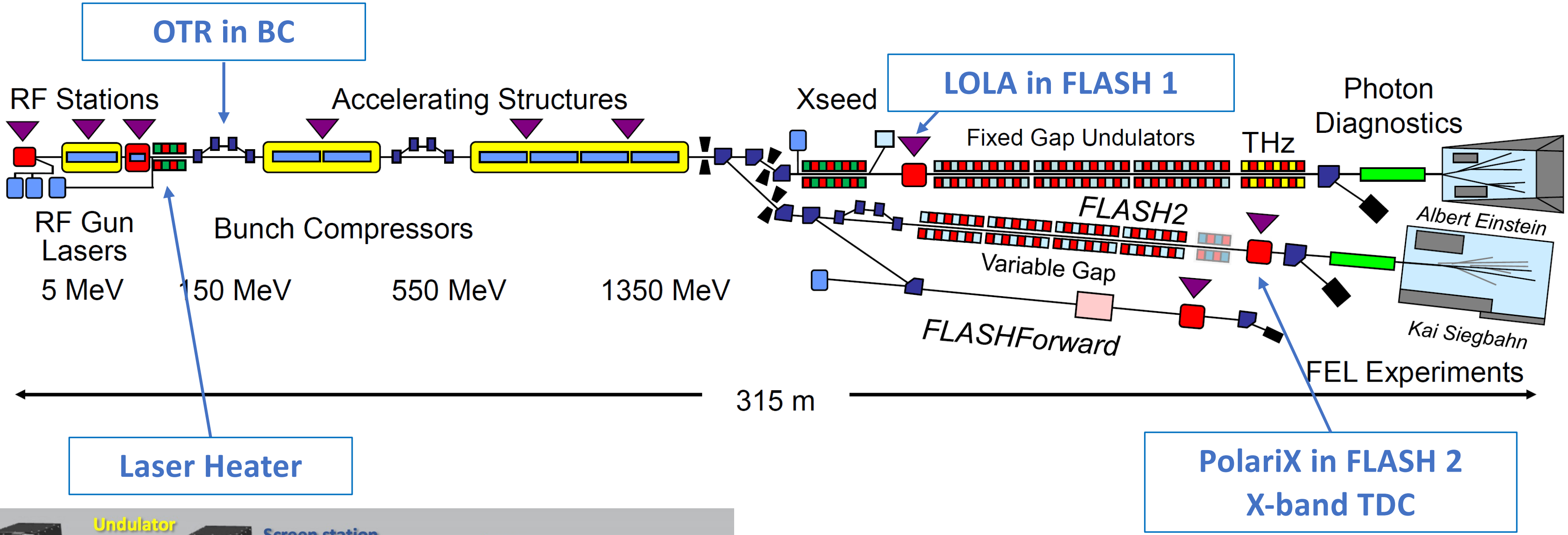
Not much overhead in laser peak power
can become challenging for finding timing overlap

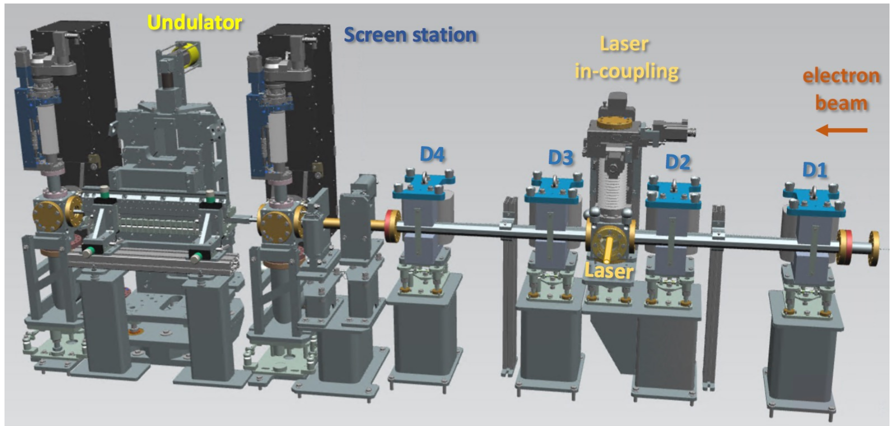
Comparison with other facilities
Data from publications
Matched laser and e-beam sizes



Note: FLASH has largest γ and σ_L
Other facilities have huge overhead in laser power

Laser Heater Diagnostics: OTR screen and TDS LOLA and PolariX





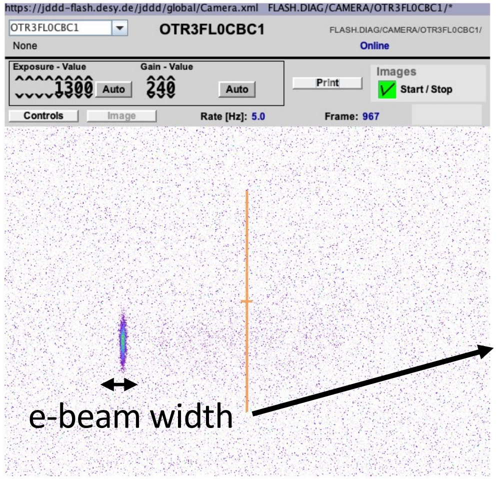
Laser Heater Commissioning

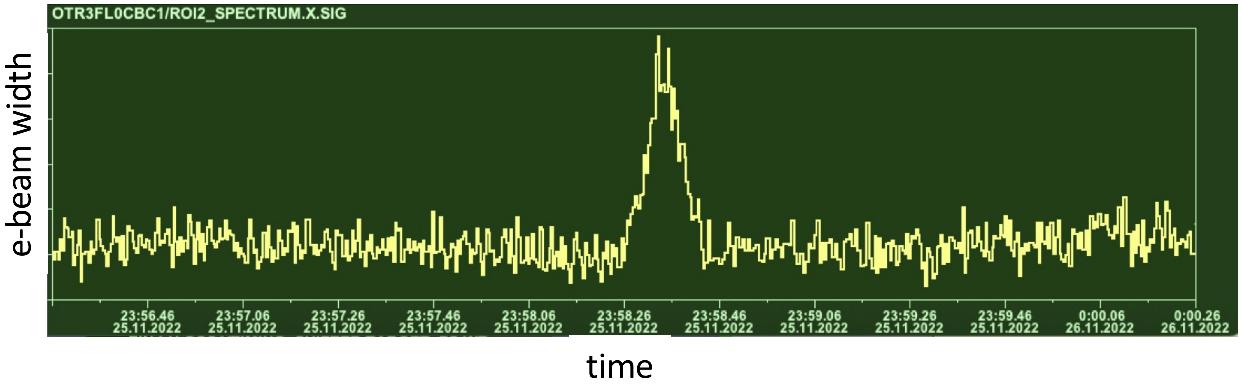
- Temporal Overlap: Fine timing (~ps) of LH Laser with
  - Induced energy spread in a dispersive section => **OTR in BC1**

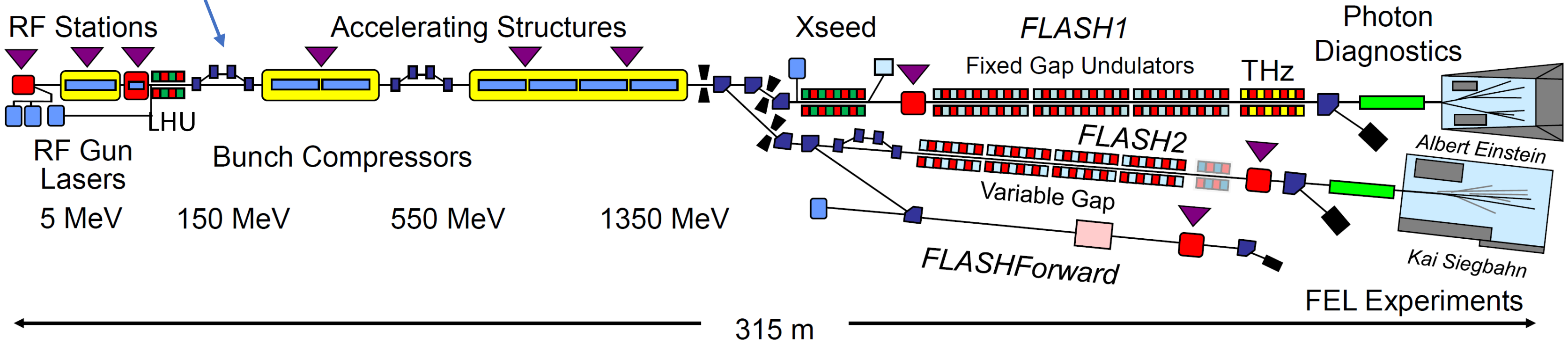
- Increased energy spread = Temporal overlap
- First heating of e-beam: 25/11/22 at 23:58

Optimized beam for minimum beam width:
- Accelerator settings
- Focusing with Quadrupol

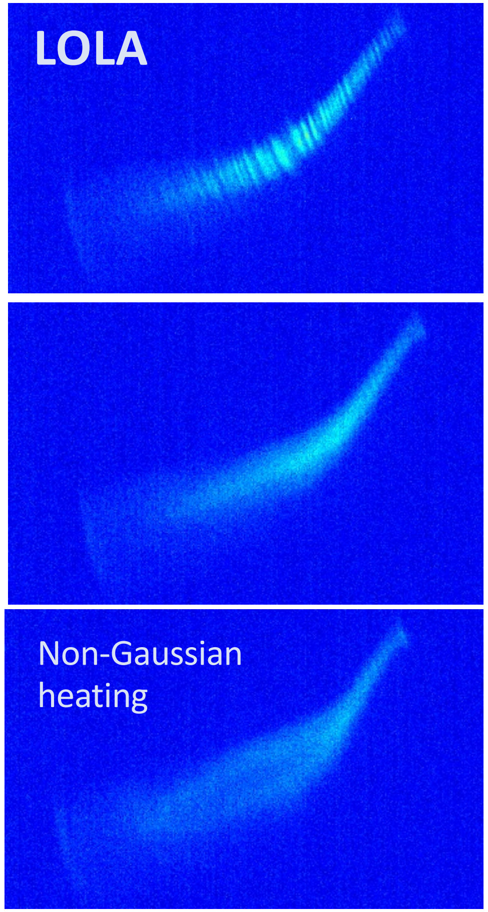
OTR in BC1







LH Commissioning: LOLA and PolariX



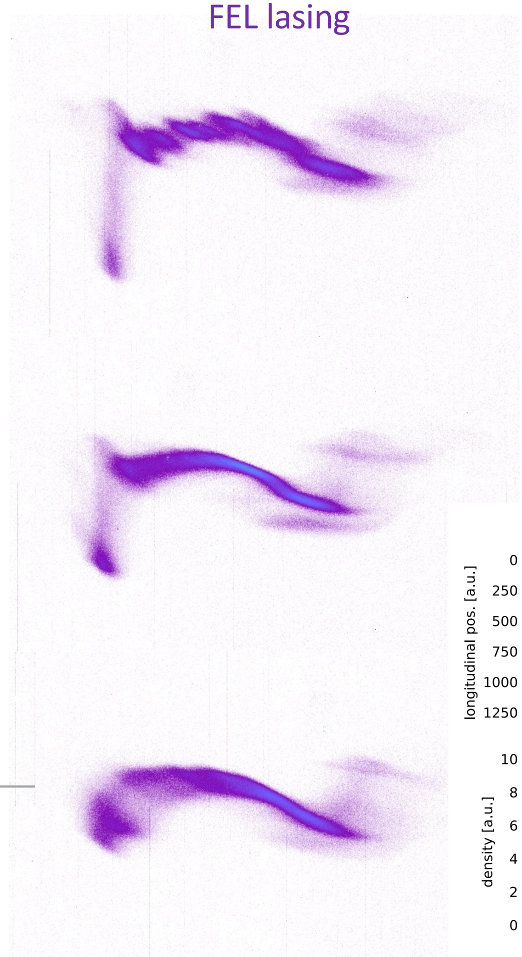
LH off
Strong MBI

LH low intensity
MBI washed out

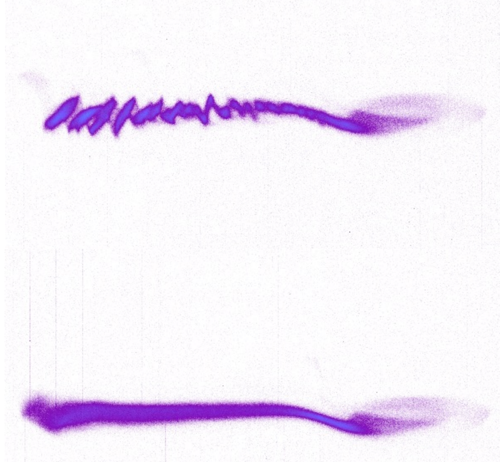
LH full intensity
e-beam „blown up“

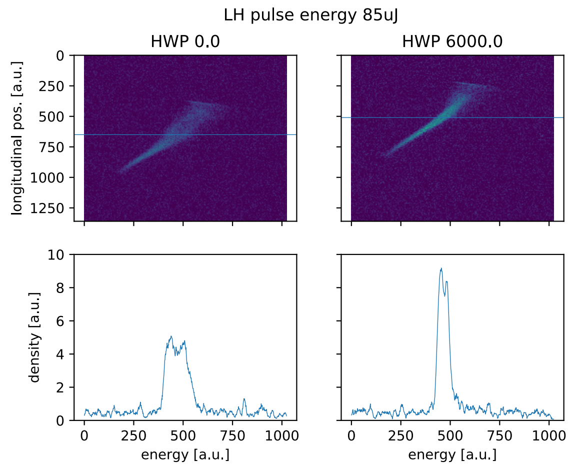
PolariX

FEL lasing



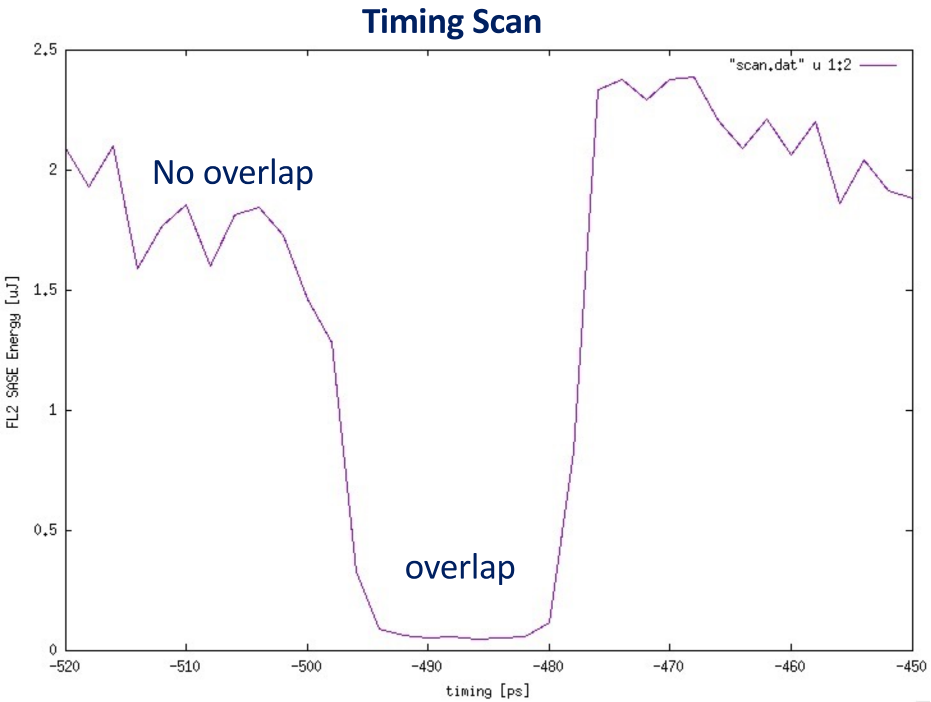
Bunch „optimized“ for MBI



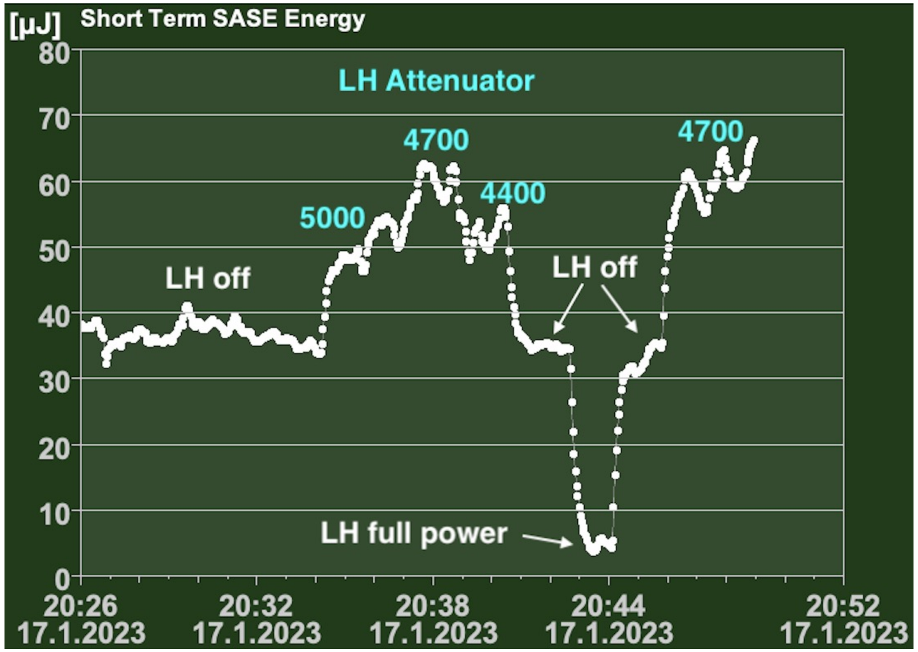


LH Commissioning: Effect on FEL process

1) LH full intensity: e-beam „blown up“ => SASE destroyed

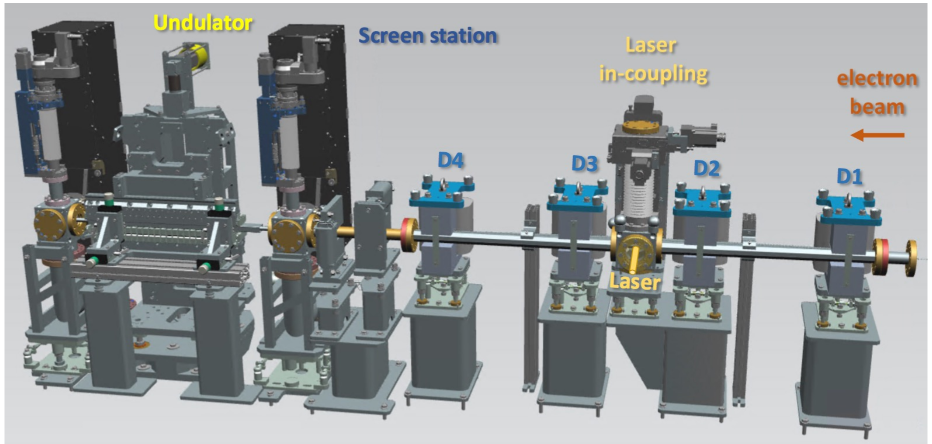


2) Optimize Laser Heater power for FEL



Summary & Outlook

- LH System was installed within FLASH2020+ Upgrade
  => suppress microbunching and enable high rep-rate seeding
- Next steps
  - Study effect on FEL lasing
  - Study effect during Seeding Experiment
  - Long-term stability studies



Comparison of parameters:

Parameter	Symbol	Unit	LCLS-2010	Fermi-2014	PAL-2017	EuXFEL-2017*	FLASH2020+
Beam Energy	E_b	MeV	135	96	138	130	146
Laser wavelength	λ_L	nm	758	783	760	1030	532
Undulator period	λ_u	mm	54	40	50	74	43
Undulator K value	K		1.38	0.86	1.5	1.27	1.43
Number of periods	N		10	12	9	10	11
Bunch length (RMS)	σ_t	ps	2.5	3	1.5	4.6	< 6
Pulse duration (FWHM)	T_L	ps	10 - 20	8 - 15	8	22	11 (20)
Peak power (nominal)	P_L	MW	~23 (0.6)	~20 (0.1)	~30	~10	2