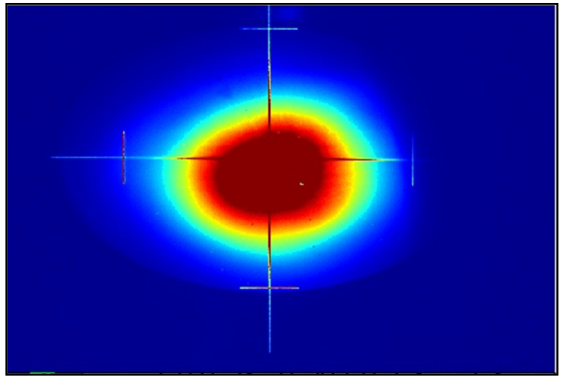
FLASH as an FEL User Facility

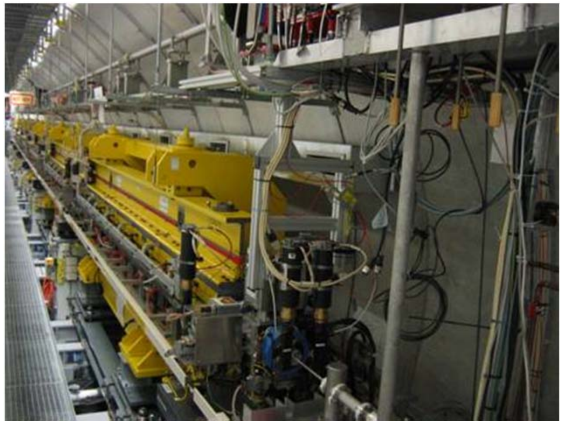
FLASH.
Free-Electron Laser
in Hamburg

FLASH free-electron laser user facility at DESY

Siegfried Schreiber
DESY

FLASH Accelerator Workshop, DESY, Germany, 4-Oct-2011





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FLASH at DESY in Hamburg

FLASH. Free-Electron Laser in Hamburg

FLASH today

FLASH at DESY in Hamburg

FLASH. Free-Electron Laser in Hamburg

> Single-pass high-gain SASE FEL
  - **SASE = self-amplified spontaneous emission**
> Photon wavelength range from vacuum ultraviolet to soft x-rays
> Free-electron laser user facility since summer 2005
  - 1st period: Jun 2005 – Mar 2007
  - 2nd period: Nov 2007 – Aug 2009
  - 3rd period: Sep 2010 – Sep 2011
  - 4th period: scheduled for 2012
> FLASH is also a test bench for the European XFEL and the International Linear Collider (ILC)
> FLASH II, a second undulator beam line under construction

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FLASH layout

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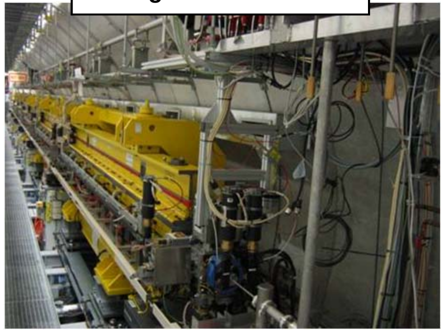
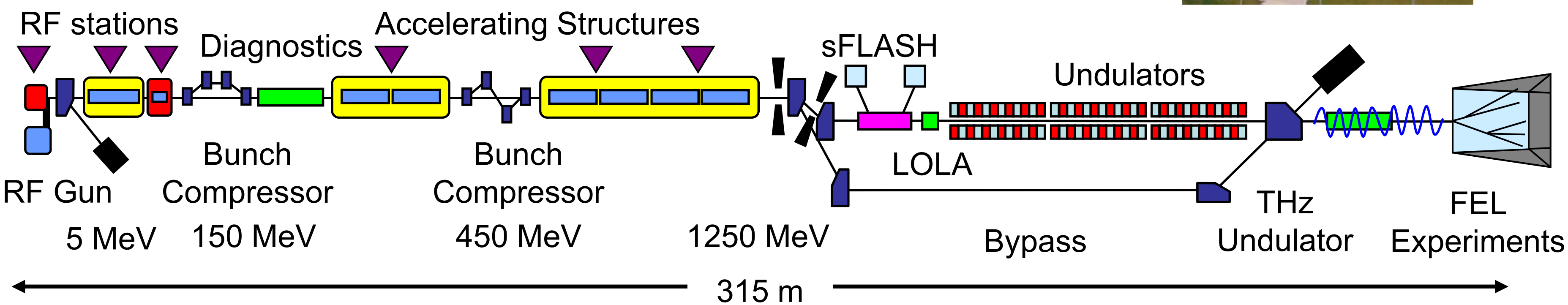
> 3rd harmonic cavity 3.9 GHz

> TESLA type superconducting accelerating modules

> Fixed gap undulator
> length ~ 27 m



> FEL Experimental Hall



> Normal conducting 1.3 GHz RF gun
> Ce_2Te cathode
> Nd:YLF based ps photocathode laser

> Diagnostics and matching

> sFLASH undulators

> FEL Experimental Hall

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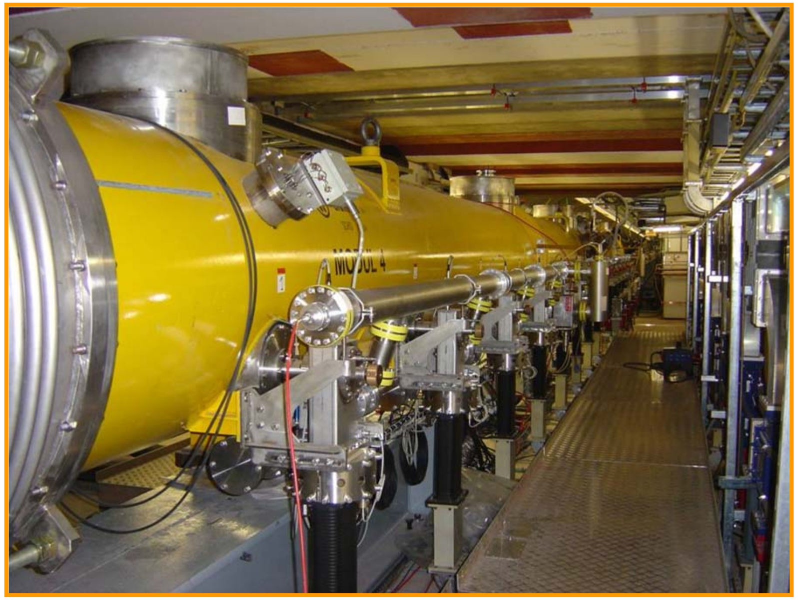
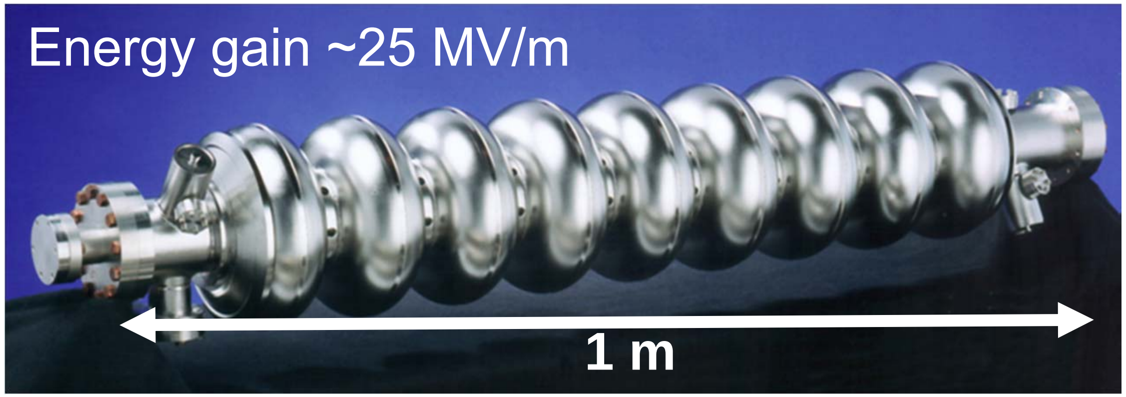
FLASH Accelerator

- FLASH uses TESLA technology
- Seven accelerating modules:
  each with eight 9-cell superconducting cavities operated at 1.3 GHz
- Burst mode:
  acceleration for 800 µs at 10 Hz
- Efficient acceleration due to high Q ~ 10^{10}
  (loaded Q = 2 x 10^{6})





Last Energy upgrade in 2010

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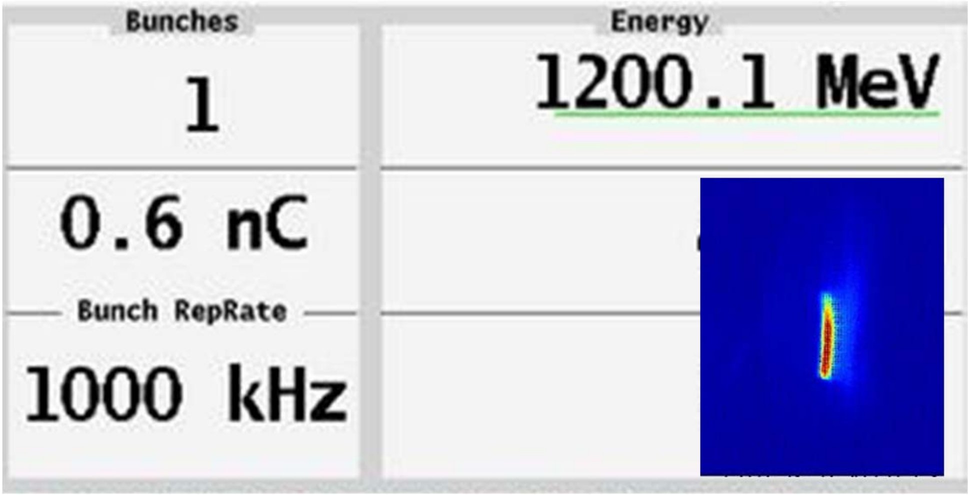
- Originally designed for 1 GeV and a wavelength of 6.4 nm
- Upgrade 2009/10:
- Installation of a 7th superconducting accelerating module
    - Prototype module for the European XFEL
    - Cryostat from China
    - Energy reach 240 MeV

1.2 GeV demonstrated with beam in May 2010



Last upgrade: new 3.9 GHz cavities (3rd harmonic)

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> New 1st accelerating module with improved cavities and Piezo tuners

> 3rd harmonic module with four nine-cell superconducting cavities operated at 3.9 GHz

- with RF system and LLRF regulation
- built at FNAL (Fermilab) in a collaboration with DESY

Fermilab DESY

First Lasing in the Water Window

FLASH Undulators

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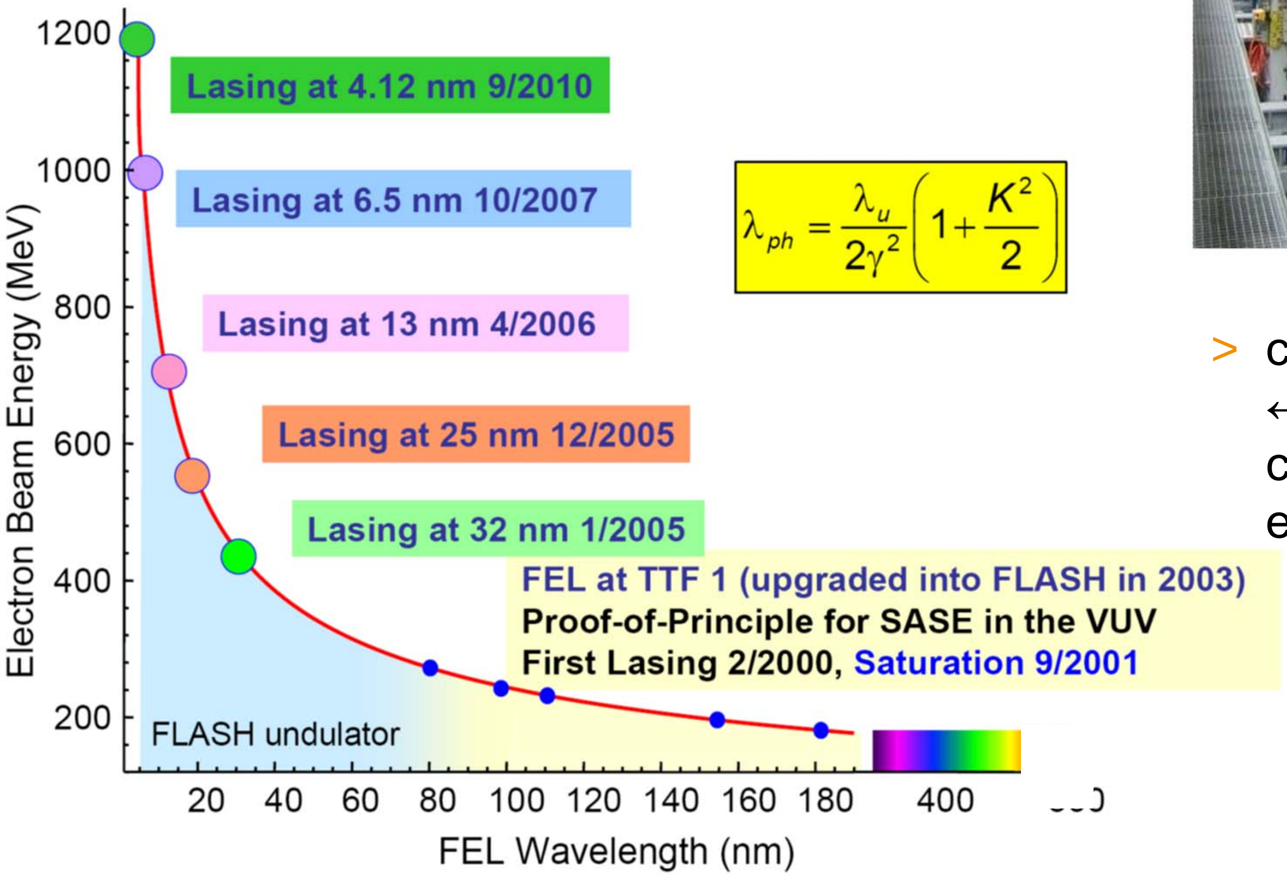
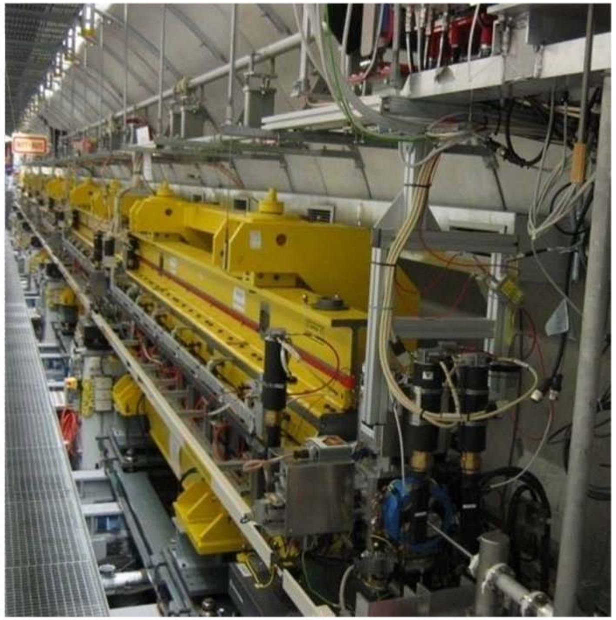
- 6 undulator modules, total length 27 m
- Fixed gap of 12 mm
  - permanent NdFeB magnets
  - peak B = 0.48 T, K = 1.23, period of 27.3 mm



$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



- change of wavelength ↔ change of electron beam energy

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FLASH reaches the water window

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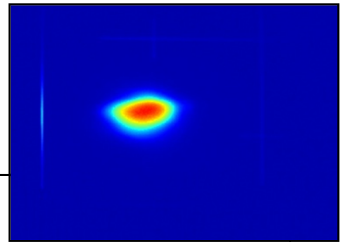
- On 25-Sep-2010 we have been able to increase the beam energy to 1250 MeV
- First lasing at a wavelength of 4.12 nm in the fundamental



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WASSERFENSTER.

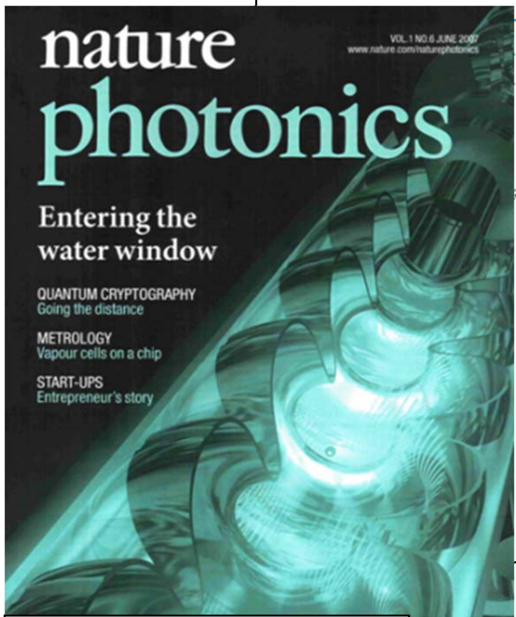
Home / Aktuelles / DESY News / 2010 / Wasserfenster

Hamburg 28.09.2010

FLASH eröffnet den Blick durchs Wasserfenster

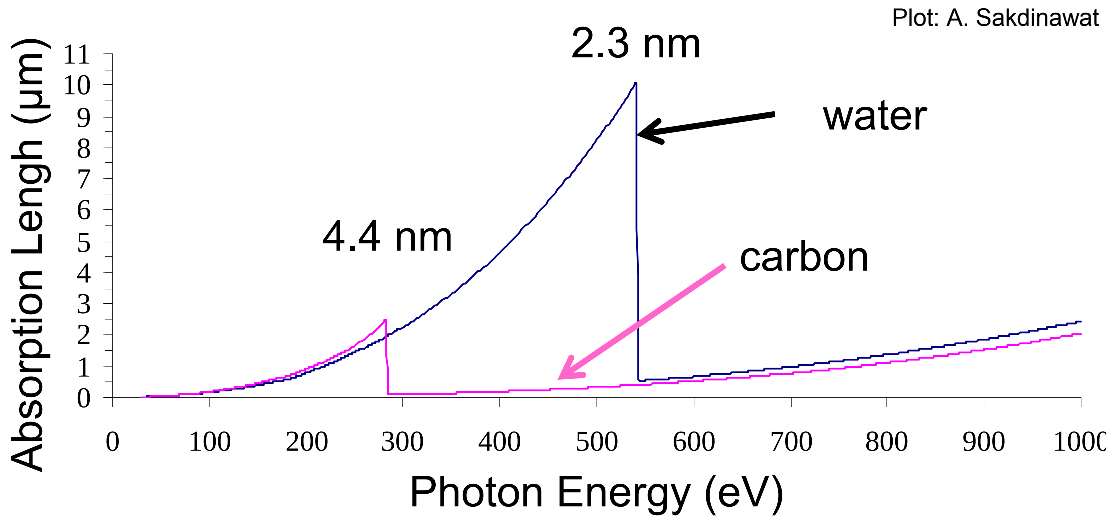
Der Freie-Elektronen-Laser FLASH (Free-Electron Laser in Hamburg) hat einen neuen Rekord aufgestellt: Am Wochenende hat die FLASH-Beschleunigermannschaft den FEL mit einer Elektronenenergie von 1,25 Giga-Elektronenvolt betrieben und so eine Wellenlänge von 4,12 Nanometern erzielt. Damit hat FLASH zum ersten Mal in seiner Grundwellenlänge Laserlicht im so genannten Wasserfenster erzeugt – bisher war dies nur mit Oberschwingungen des Lasers erreicht worden. Die kurzwelligen Lichtblitze hatten eine durchschnittliche Energie von 70 und eine Spitzenenergie von 130 Mikrojoule.

Der Plot für Experten: Das Spektrum eines FLASH-Blitzes bei 4,12 Nanometern Wellenlänge.



Nature photonics **1** (2007) 336

The Water Window



- The water window is the wavelength region between the K (1s) absorption edges of Oxygen (λ_{O2} = 2.3 nm, 543 eV) and Carbon (λ_C = 4.37 nm, 284 eV)
- Carbon absorbs the FEL radiation, water becomes more and more transparent
- Now also at FLASH, in-vivo experiments with biological probes in water solution, study of carbon containing molecules, etc.

SASE Parameters for 4.3 nm

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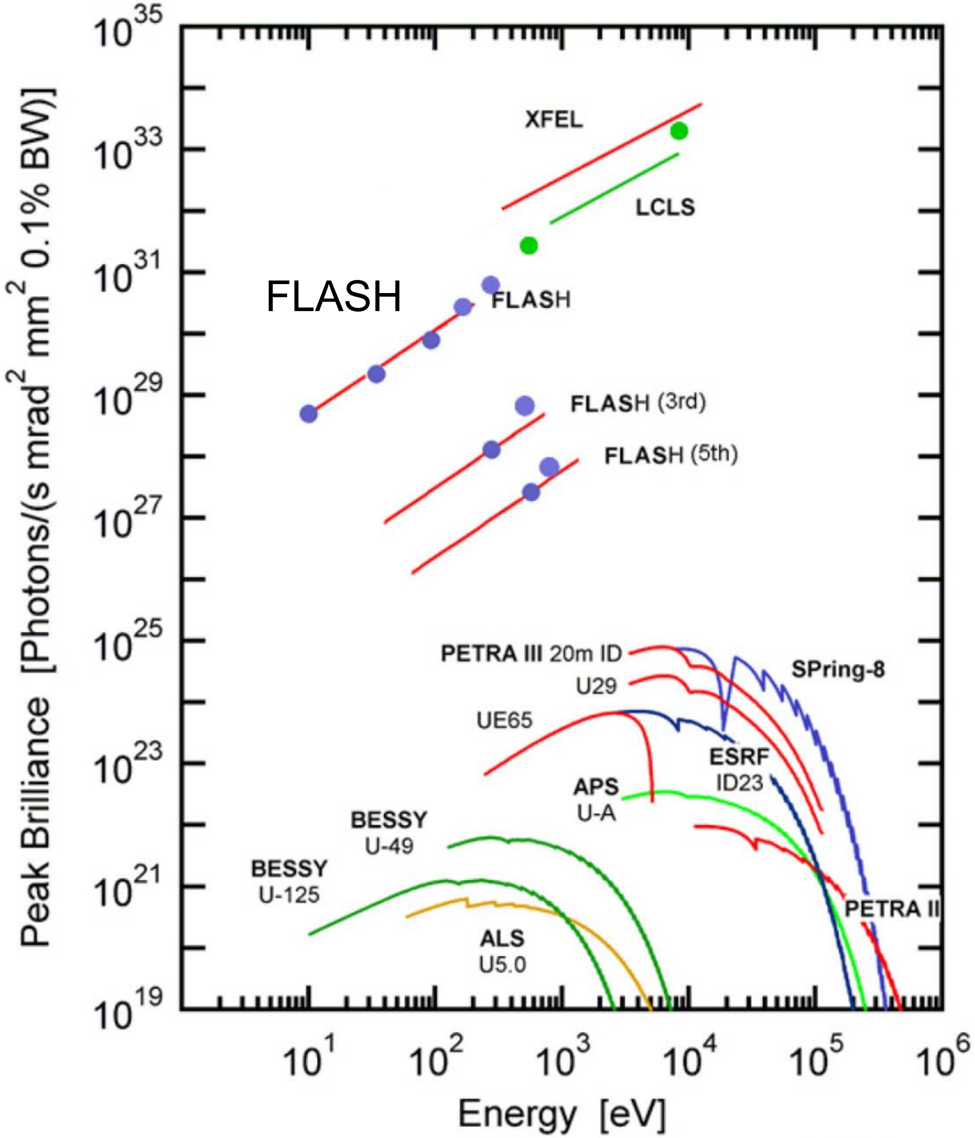
Preliminary data for 4.3 nm:

- Energy 160 µJ (av.)
- Peak power ~ 2 GW (estimate)
- bandwidth ~1 % fwhm
- Peak Brilliance

  B ~ 10^{30} - 10^{31} photons/s/mrad^2/mm^2/0.1%bw



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How FLASH might look like tomorrow

No decision on a FLASH upgrade beyond FLASH II has been made so far – what is presented here is my view of the mid term future for FLASH.

For the next POF period, an increase in energy and duty cycle has been proposed.

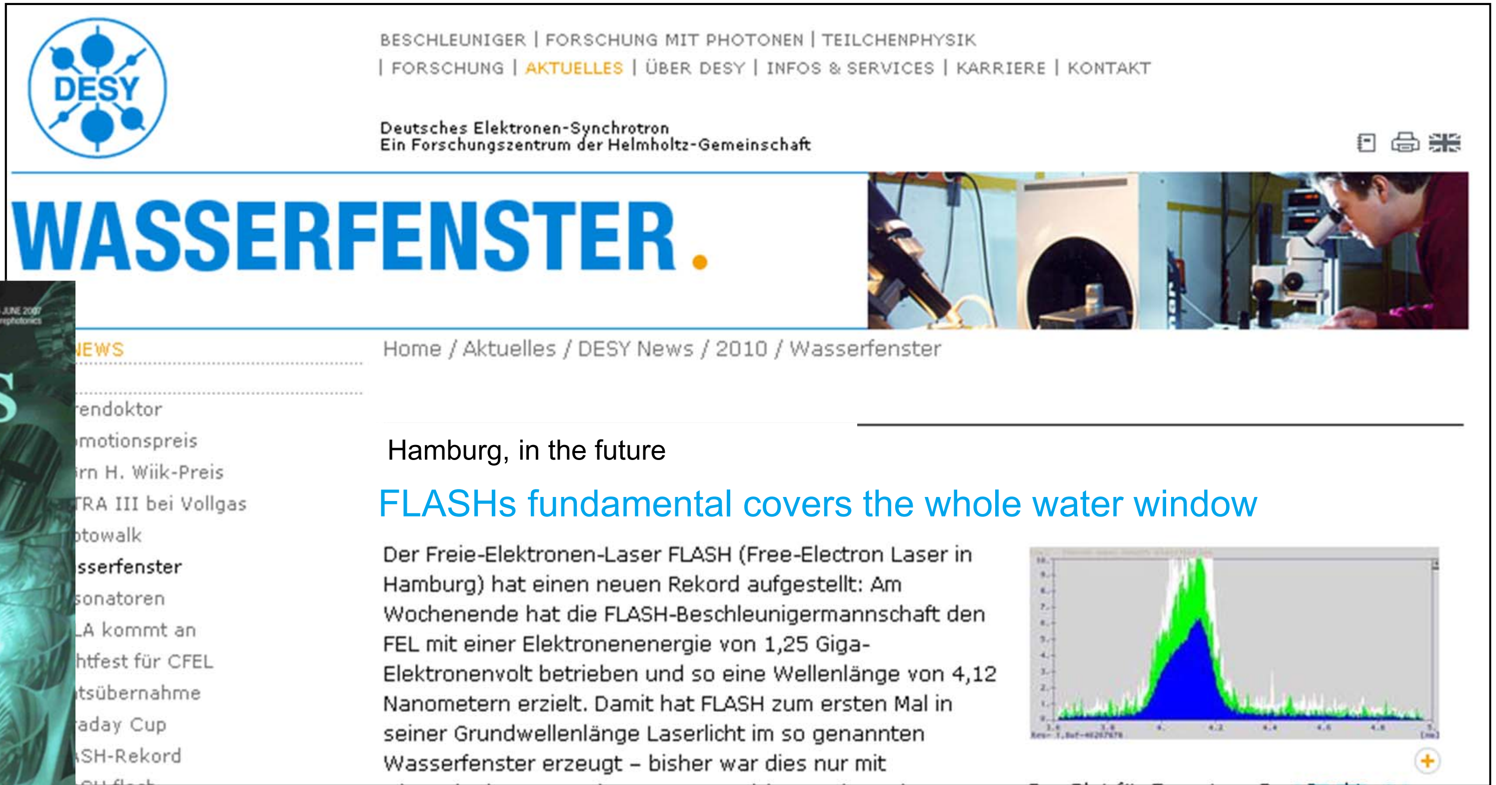
We have a good chance for a next upgrade after the start-up of the European XFEL.

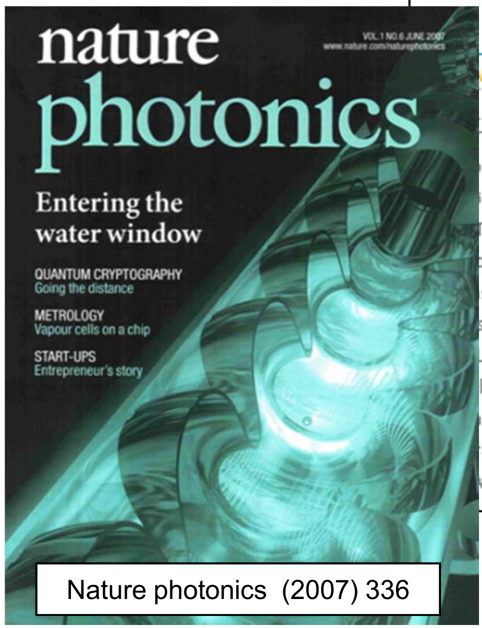
FLASH V. covering the water window

> Extending the wavelength range of FLASH is most useful for experiments

> Cover the whole water window with the 1st harmonic down to 2.3 nm

> Extend to the 'magnetic' window down to 1.x nm with switchable polarization





Nature photonics (2007) 336

FLASH fixed gap Undulators

FLASH V.
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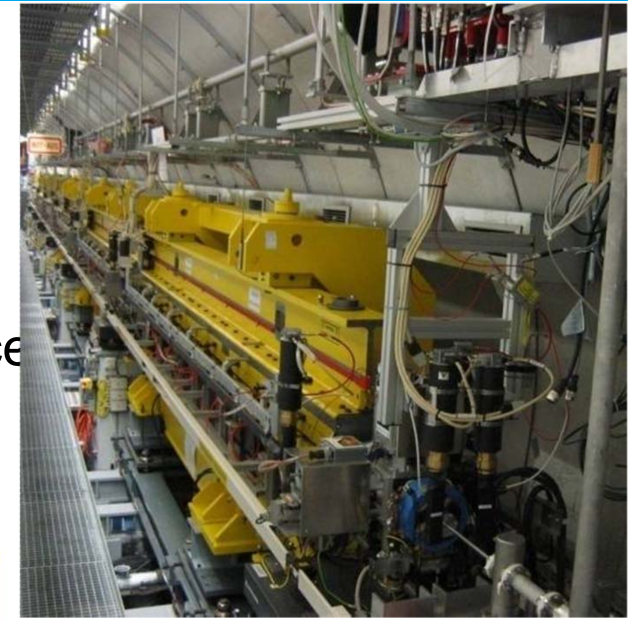
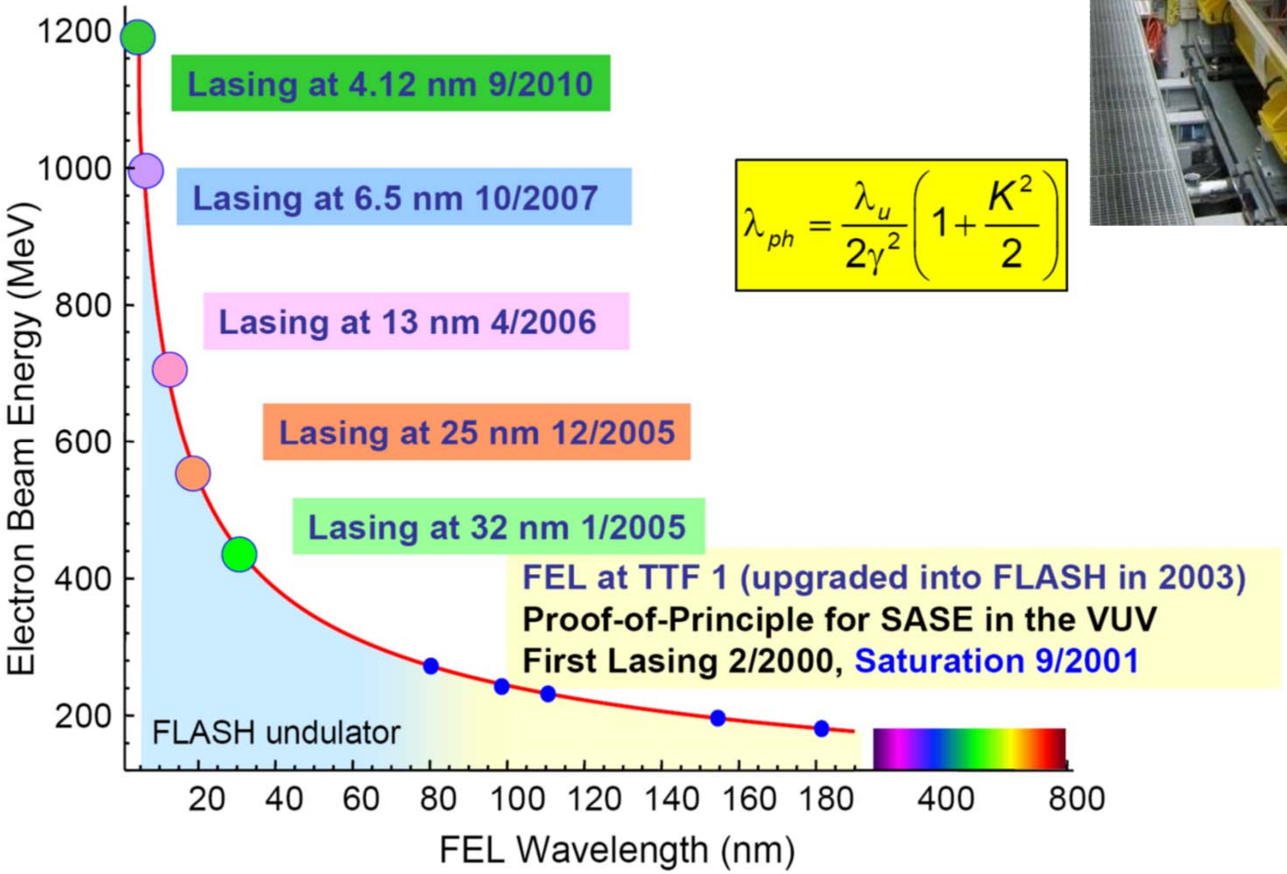


- With the given fixed gap undulators
  - peak B = 0.48 T, K = 1.23, period of 27.3 mm
- E = 1.65 GeV → 2.3 nm (542 eV)
- Gain length stays within 30 m - for a good emittance



$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

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FLASH with variable gap undulators

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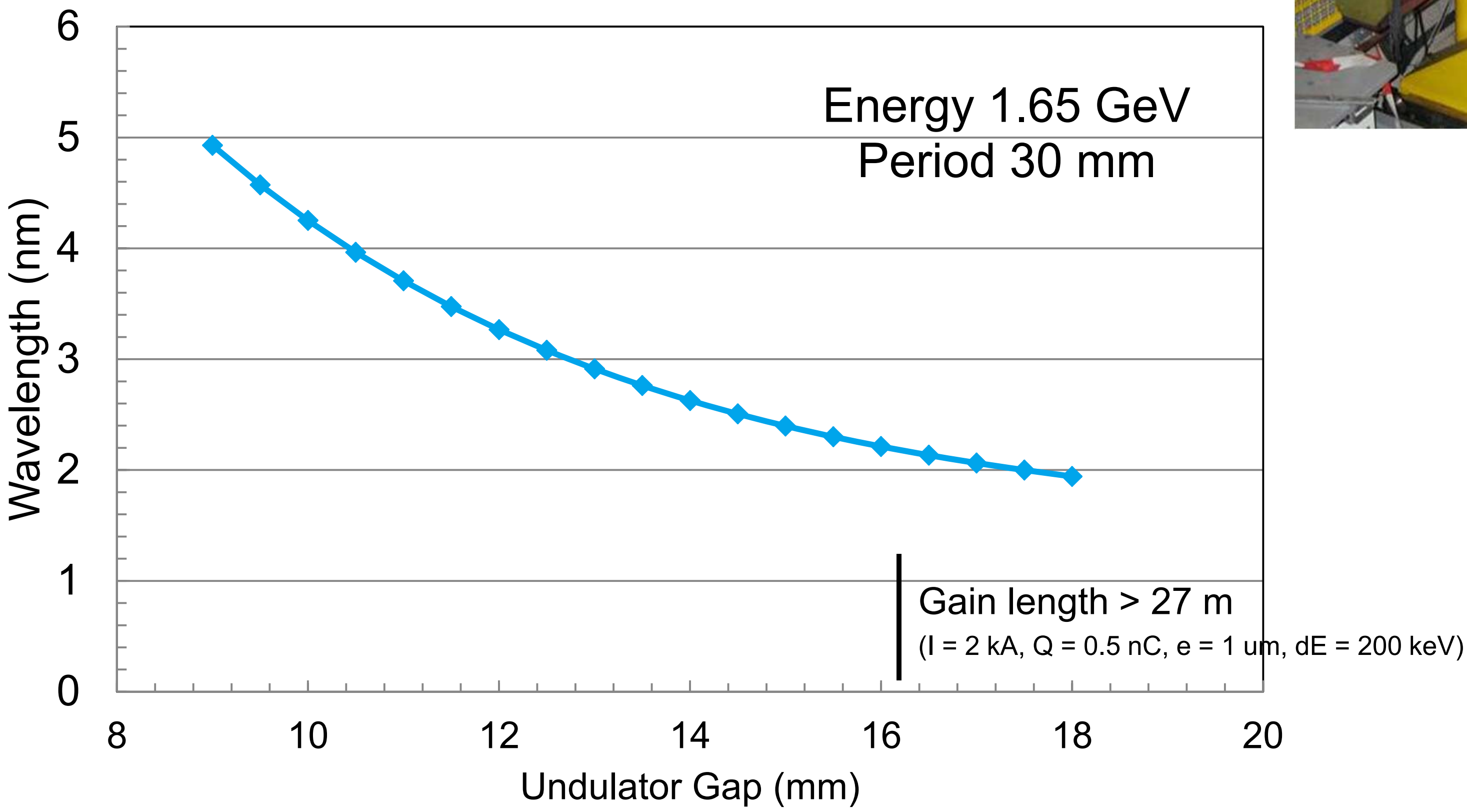
- A possibility would be to use variable gap
- Example: 30 mm period at 1.65 GeV
- Tuning over the whole water window



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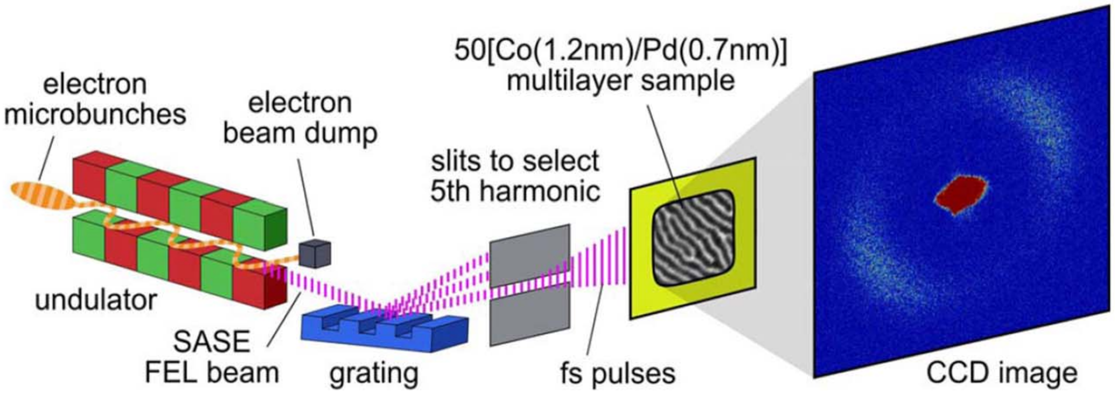
Polarization

> Polarization control is an asset for many experiments

> At the same time, wavelength below 2 nm are required

> Helical undulator as a 2nd harmonic afterburner with polarization switch option to reach 1.2 nm with acceptable number of photons per pulse

Example:
Resonant magnetic scattering with soft x-ray pulses from a free-electron laser operating at 1.59 nm



C. Gutt *et al.*, Phys. Rev. B **79**, 212406 (2009)

Additional Issues

> sFLASH moves to FLASH2 or FLASH3

> LOLA is set-up to be measure an arbitrary bunch in the train in a monitor like fashion – fast kicker/septum to dispersive section

> Phase stabilizer cavity

> Laser heater

> 3 injector lasers, two with optimal performance (XFEL-type, 4.5 MHz, flat hat), one laser for special beams

> Online photon diagnostics: energy (GMD before limiting aperture), position (GMD), spectrum, pulse length, arrival time, steering

> Diagnostics able to measure as low as 10 pC bunch charge

> … and many other

FLASH is an FEL User Facility

FLASH V. Free-Electron Laser in Hamburg

- Single-pass high-gain SASE FEL
- Seeding options
- Polarization
- Photon wavelength range from vacuum ultraviolet to soft x-rays – including the water window
- Delivers 4500 hours/year beam time for user experiments

  A year has 8760 h.
- FLASH3 as a third undulator beamline includes a plasma accelerated section to boost the beam energy beyond the reach of FLASH
- 1000 hours/year are accelerator studies at various locations of FLASH

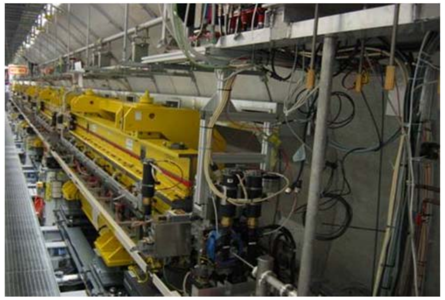
FLASH V. layout

FLASH V.
Free-Electron Laser in Hamburg

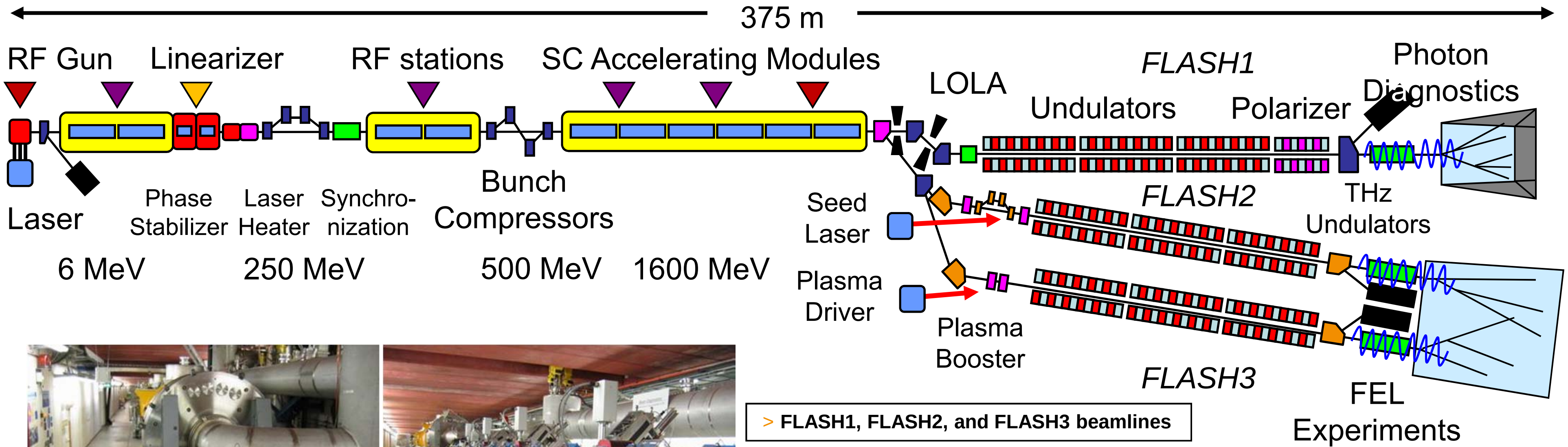
> 3rd harmonic cavities 3.9 GHz

> high duty cycle super-conducting accelerating modules

> variable gap undulators



> FEL Experimental Halls



> FLASH1, FLASH2, and FLASH3 beamlines

> High duty cycle 1.3 GHz RF gun
> 3 photocathode lasers

> Advanced electron beam diagnostics
> Improved bunch compression

Energy upgrade

FLASH V.
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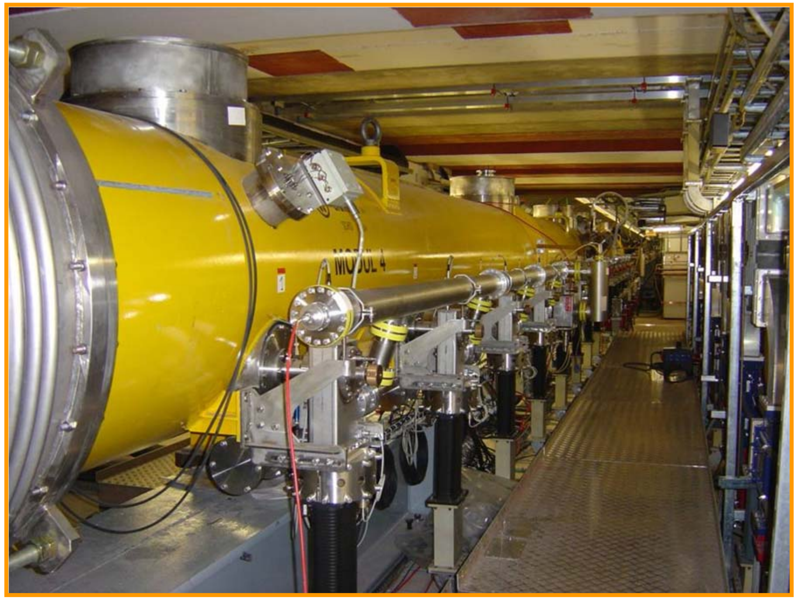
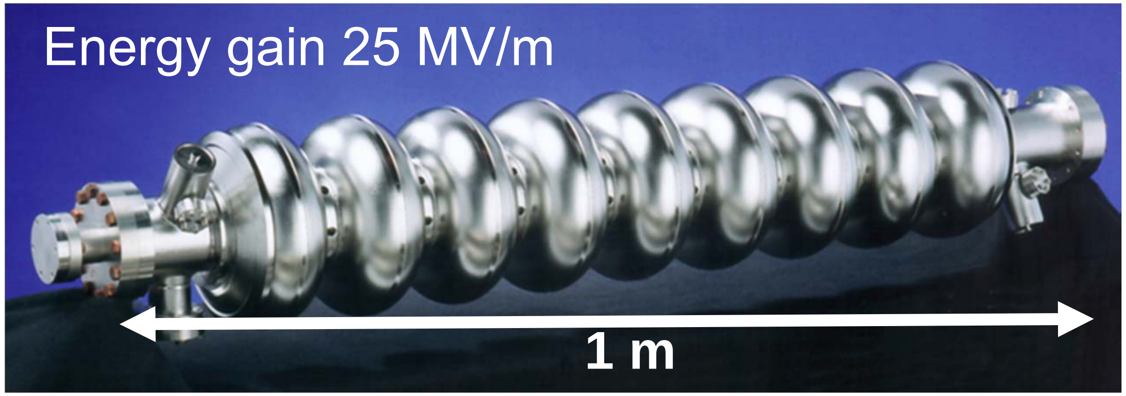
> 8 cavities per module, 25 MV/m
  Energy gain of 1 module 200 MeV
> A minimum of 2 new modules are required to achieve 1.6 GeV
> Taking into account bunch compression, an additional module before BC1 would be helpful
> Otherwise, new ACC2/3 mandatory





Energy upgrade to 1.6 GeV

- Add two new modules upstream to the existing string ACC4/5/6/7
- Use RF-station 8 in cryo annex
- Extend linac towards injector, refurbish ACC2/3
- Rearrange bunch compression
  - Add one module (same RF-station)
  - 250 MeV at BC1
  - Lower R56 (less timing jitter)
  - More flexibility with ACC39 by addin
    3.9 cavities
  - Laser heater
  - Fast phase stabilizer cavity

1.6 GeV demonstrated with beam in 2018

Extension of hall 3 towards south

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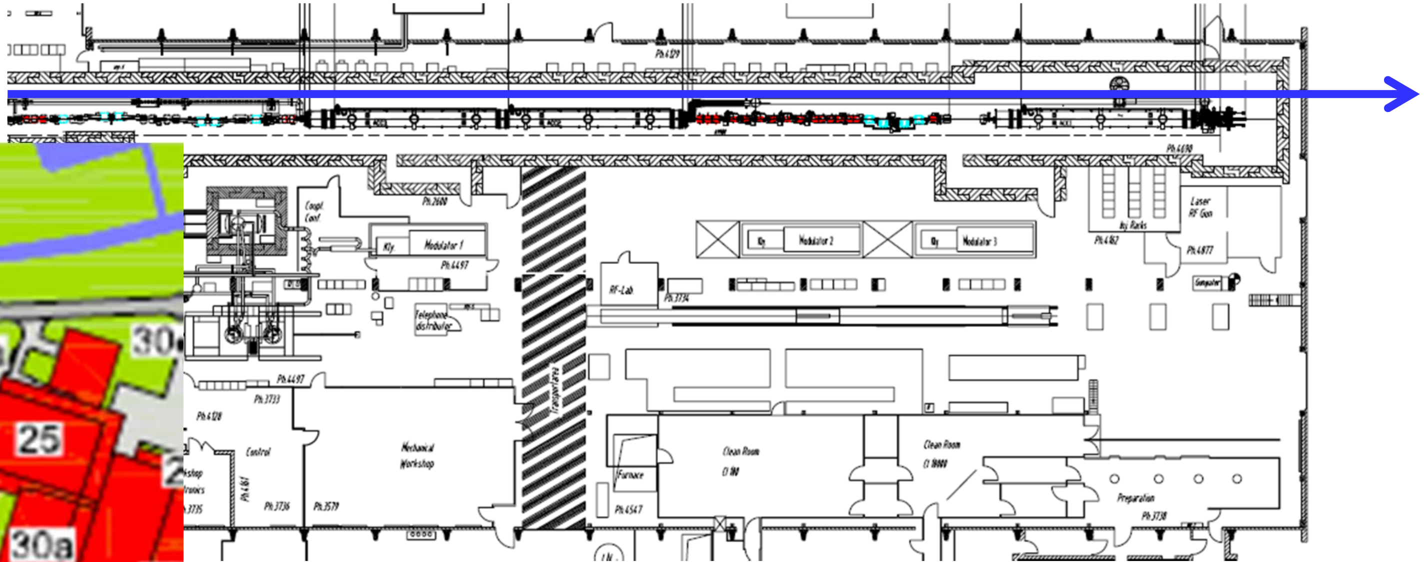
> Estimate of required additional length 3 x 13 m + 10 m overhead = 50 m



> New injector including new laser rooms

> An extension with of 50 m seams to interfere with 27a – must be avoided

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Laser heater to mitigate microbunch instabilities

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> An important finding is, that the microbunching instability is very sensitive to a small uncorrelated energy spread of the electron beam

gain G ~ exp($-\sigma_\gamma^2$)

$$G = Ck|R_{56}|\frac{I_0|Z(k)|}{\gamma_0 I_A Z_0}\exp\left(-\frac{1}{2}C^2k^2R_{56}^2\frac{\sigma_\gamma^2}{\gamma_0^2}\right).$$

> In order to fully suppress the instabilities, Saldin et al. propose to increase the uncorrelated energy spread to about 20 keV

> Method: applying a strong damping with resonant laser-electron interaction in an undulator - the so-called laser heater

> The energy modulated beam goes through the bunch compressor where these coherent energy modulations are quickly dissipated, leading to the effective ''heating'' of the beam

[E. L. Saldin, E. A. Schneidmiller, M. V. Yurkov,
Longitudinal space charge-driven microbunching instability in the TESLA Test Facility linac, Nucl. Inst. Meth. **A 528**, 355 (2004)]

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Possible layout

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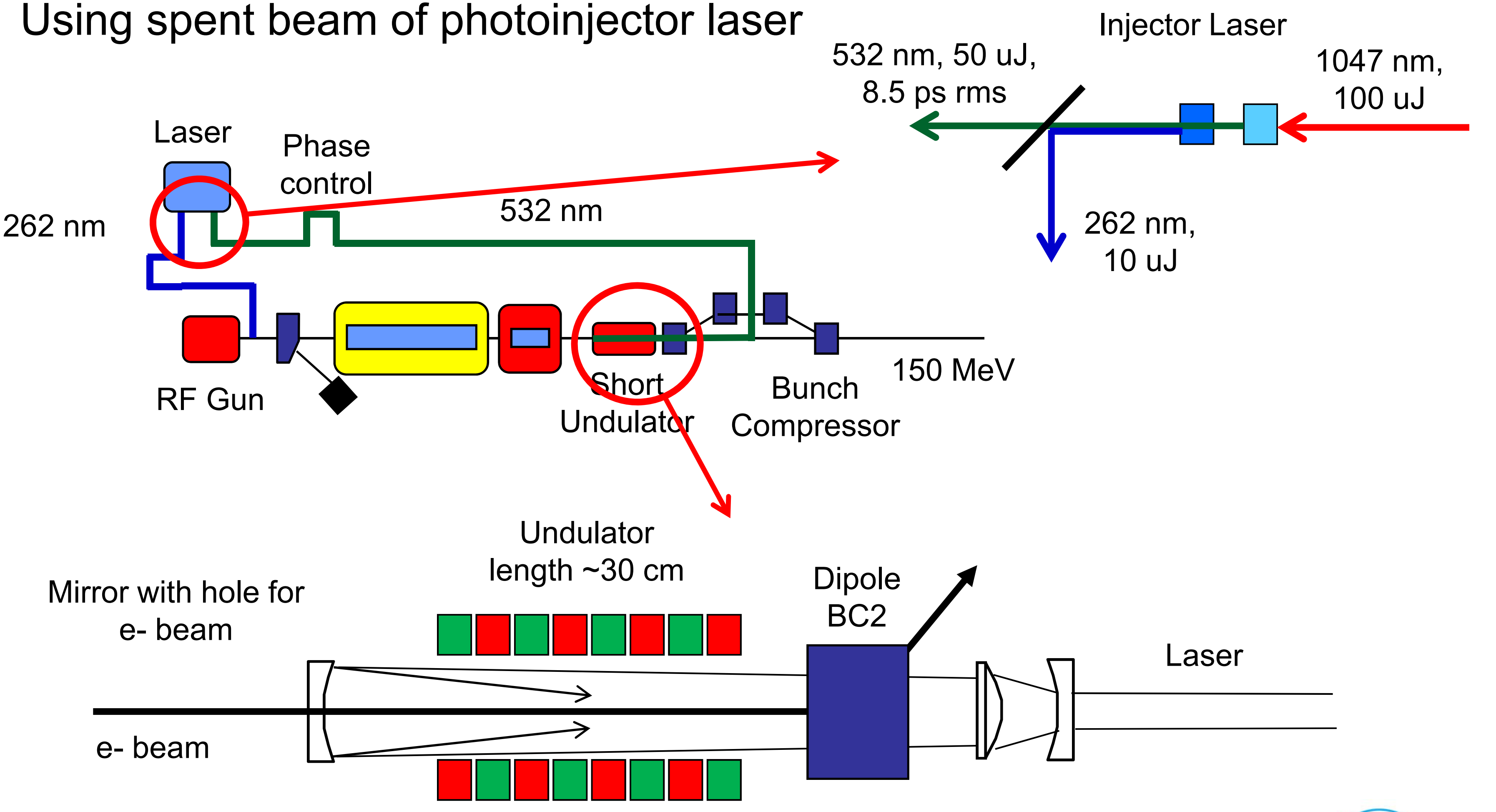
- Short undulator with 10 periods of 3 cm before BC2
- Using spent beam of photoinjector laser



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Main Parameters

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Laser	
Wavelength	523 nm
Pulse length (rms)	8 ps
Power	1 MW
Spent beam from photoinjector laser	

Undulator	
Number of periods	10
Period	30 mm
Peak field	0.5 T
Variable gap, nominal	12 mm

- Induced energy modulation 15 to 20 keV – to be determined experimentally
- Variable gap to adjust for possible changes in energy and to have the possibility to remove it from the beam
- Beta function (present optics) ~ 16 … 25 m -> beam size ~0.3 … 0.4 mm

Higher Duty Cycle

Motivation: Driven by Experiments with Photons

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> Many experiments require large distance between bunches
  - For instance those using time of flight detectors would be happy with bunch distances of 10 μs, but cannot cope with 1 μs

> We run with 50 kHz / 100 kHz / 200kHz / 250 kHz / 500 kHz/ 1 MHz

> Many experiments would profit from higher train repetition rate

Requested Pulse Pattern		
Single bunch		47 %
multi-bunch with different bunch spacing		53 %
Requested FEL pulse duration		
	< 50 fs fwhh	28 %(*)
	50 -100 fs	54 %
	not critical, but high intensity	18 % (**)

(*) 72 % multi-bunch (**) mostly multi-bunch

What are the options?

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in Hamburg

Repetition rate

> Increase the repetition rate from 10 Hz to 25 Hz
  - Similar as proposed for the European XFEL
  - This brings the cryo load and RF at their estimated limit – to be evaluated in detail

RF pulse length

> Lengthen the RF pulses by some factors

> For the present 0.8 ms, only 800 pulses/sec with 100 kHz

> Real cw operation of RF and beam with for example 1 kHz or even 1 MHz beam repetition rate
  - Similar to the NGLS (LBNL) proposal
  - Requires new accelerating modules, not realistic for FLASH

Longer RF pulse limits – just a glance

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> In general, for longer RF pulses we need to keep the beam current and the accelerating gradient smaller

> As an example:

- A reduction in beam current from 4.5 mA (4.5 MHz, 1 nC) to 0.1 mA (100 kHz, 1 nC) reduces the required generator power from 165 kW to 94 kW
- Reducing the gradient from 25 to 20 MV/m reduces to 61 kW
- (200 kHz detuning assumed – standard FLASH cavity parameters, no detuning: 122/52/33 kW)
- Maximum power for our circulators (per pulse): 350 kW,
- With a 5 MW klystron: ~250 kW per cavity

> Staying with lower currents, gives room for a moderate increase in pulse length by a factor of 4 at most (keeping average power)

> With a reduction to 20 MV/m and 10 modules installed, we can just keep the wavelength reach (10 x 160 MeV)

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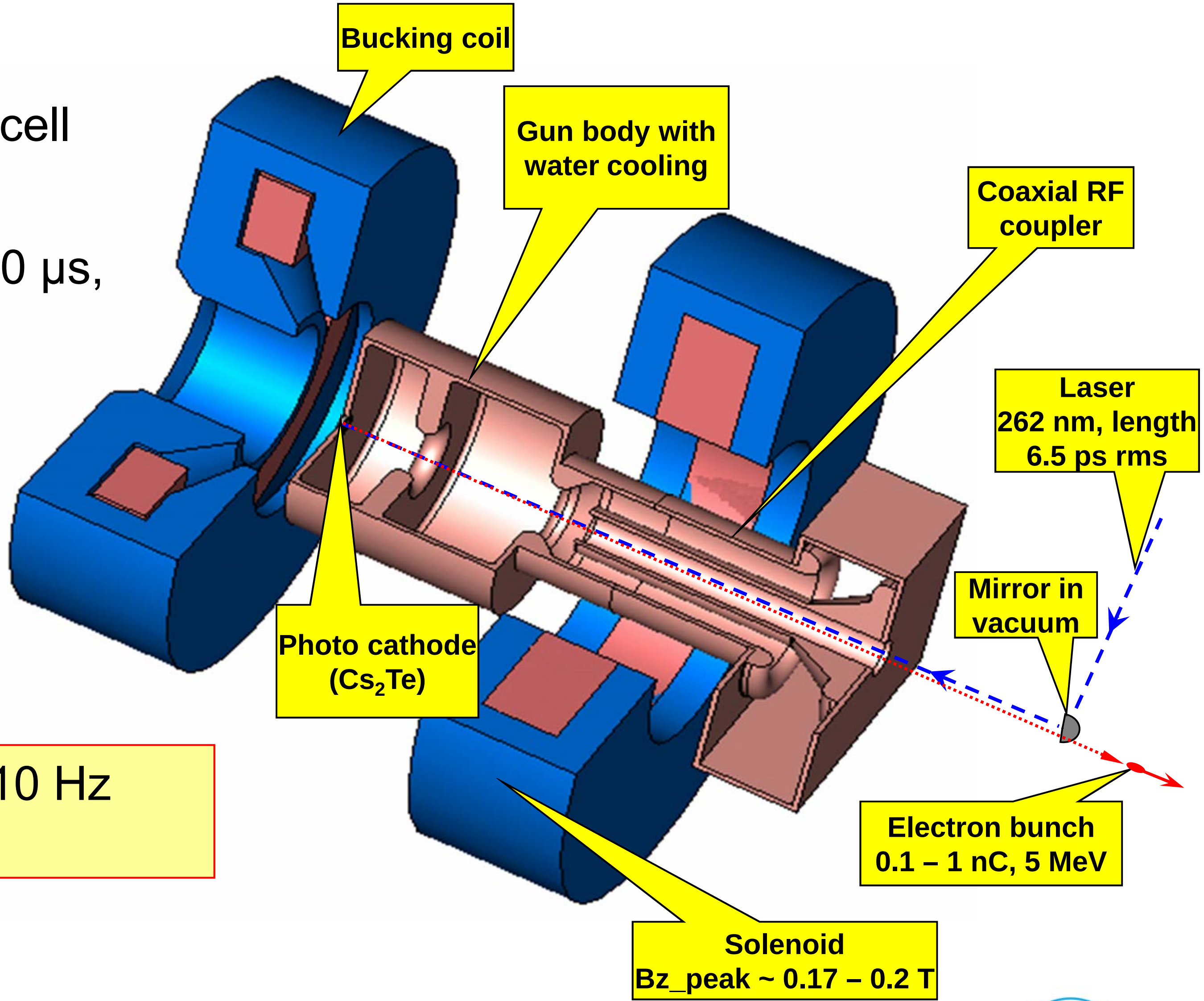
Limitation due to RF Gun

- RF gun: 1.3 GHz copper cavity, 1 ½ cell
- RF power 6 MW, RF pulse length 850 μs, 10 Hz
- Design for an average power of 50 kW

8 ms with 5 MW at 10 Hz
= 400 kW !



Comb pulsed RF with FLASH RF gun

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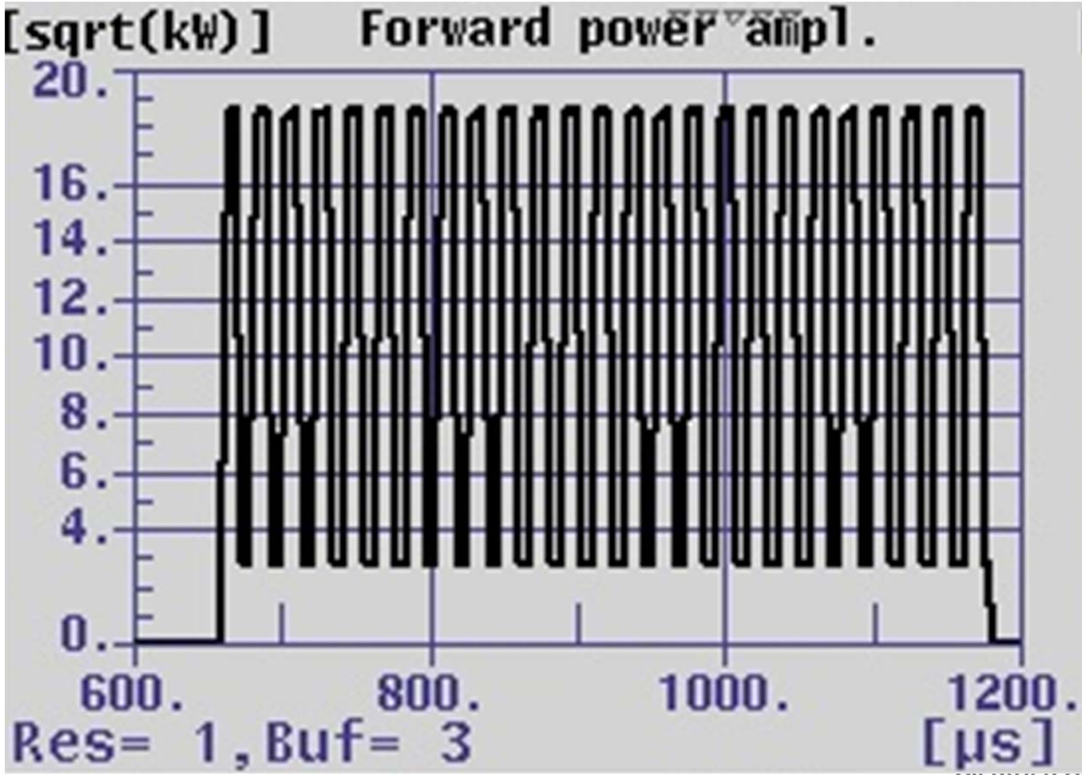
- > Pulsing RF within a long RF pulse (PiP or comb mode)
- > Tests at FLASH: rf gun pulsed with 12 us on / 10 us off
- > With 4 MW, 10 Hz, this would allow 2.5 ms long combs for 50 kW
  → good for 100 bunches/train only (1 bunch per comb tooth)



Comb tooth width determined by filling time of ~ 2 us

With 3.8 MW 10 Hz, 1.3 ms are possible

Superconducting gun would be the better option, may be cold gun

Some FLASH V Parameters

FLASH V.
Free-Electron Laser in Hamburg

Beam Energy	0.5 – 1.65 GeV
Normalized emittance (proj.,1 nC)	1 mm mrad (larger for FLASH2/3)
Energy spread	0.2 MeV
Peak Current	> 2 kA
Bunches per second	up to 36000 (4.5 MHz)
Bunch Charge	0.02 – 1.5 nC
Undulators	
Fixed gap FLASH SASE undulators	27.3 mm, 12 mm gap
Variable gap as an option	30 mm, 9 – 15 mm gap
Helical undulator	2nd harmonic afterburner
Radiation	SASE
Wavelength range (nm)	2.3 – 25, FLASH 2 up to 60 nm
High duty cycle option*	
Repletion rate	25 Hz
RF Pulse length (100 kHz beam)	3 ms

*requires high duty cycle RF gun

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Summary

FLASH V. Free-Electron Laser in Hamburg

- Most important for FLASH is the upgrade in wavelength reach to cover the whole water window
- FLASH1 from 2.3 nm to 25 nm with an energy of 500 MeV to 1.65 GeV
- FLASH2 covers wavelengths from 4 to 60 nm with variable gap undulators and seeding options
- Polarization for very short wavelength with an helical undulator as a 2^{nd} harmonic afterburner
- This closes the wavelength gap to the European XFEL
- Accelerating modules are added by extending the linac upstream
- Upgrade of the injector, especially the compression scheme
- Increase of duty cycle requires more effort and is with the given hardware only possible in moderate steps
- Especially the RF gun requires a substantial upgrade