Experience form FLASH: FEL Theory versus Experiment

M.V. Yurkov (DESY, Hamburg)

I. Introduction to FLASH facility.

II. Practical guide on analysis of SASE FEL operation.

III. TESLA Test Facility FEL, Phase I: nonlinear compression and production of ultra-short radiation pulses.

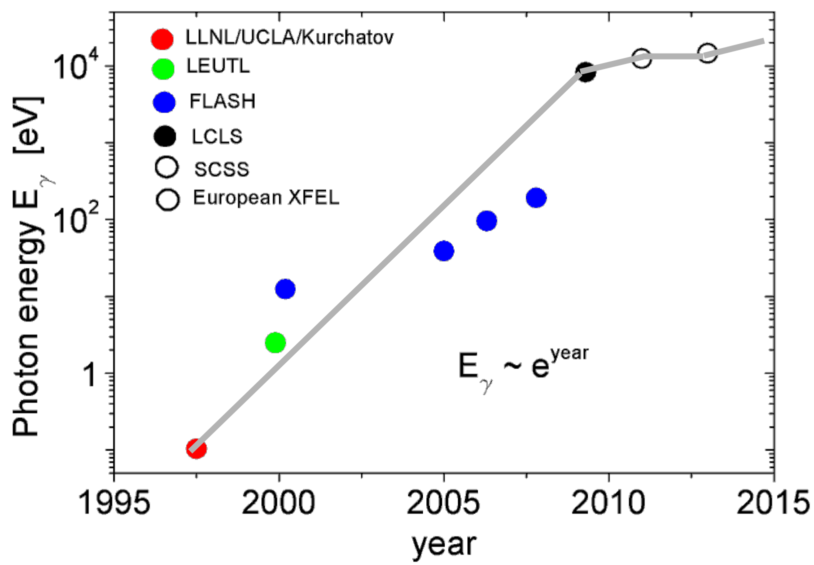
IV. Present day performance of FLASH: (i) Example from the program for production of ultra-short radiation pulses; (ii) Transverse coherence and pointing stability.

V. Development of statistical methods for measurements of the main parameters of SASE FEL radiation.

VI. Advanced developments: FIR undulator, optical afterburner for SASE FEL, optical replica synthesizer, undulator tapering for efficiency increase, reverse undulator tapering, harmonic lasing and harmonic lasing self-seeding, external seeding developments.

Evolution of SASE FELs

- First SASE FEL (12 μm wavelength) was put in operation at the UCLA (University of California, Los Angeles) in 1997.
- During the next decade there was permanent (nearly exponential) progress in the reduction of the wavelength. Milestones we achieved by Argonne National Laboratory (LEUTL, down to 385 nm), DESY (TTF FEL, FLASH, down to 4.x nm in the fundamental, and 1.6 nm in the 5th harmonic), SLAC (LCLS, down to 0.12 nm in the fundamental harmonic), SACLA (down to 0.07 nm).
- Several projects of hard x-ray FELs are on track: SwissFEL, PAL XFEL, European XFEL.



1997/1998: UCLA/LANL/RRCKI/SLAC experiment on a high-gain SASE FEL

1998: publication in PRL of two papers on UCLA/LANL/RRCKI/SLAC experiment raised hot debates in the FEL community:

Measurements of High Gain and Intensity Fluctuations in a Self-Amplified, Spontaneous-Emission Free-Electron Laser (Phys. Rev. Lett. 80 (1998) 289**)**

M. Hogan, C. Pellegrini, J. Rosenzweig, G. Travish, A. Varfolomeev,* S. Anderson, K. Bishofberger,

P. Frigola, A. Murokh, N. Osmanov,* S. Reiche, and A. Tremaine

Department of Physics and Astronomy, UCLA

(Received 1 July 1997)

Measurements of Gain Larger than 10^5 at 12 m**m in a Self-Amplified Spontaneous-Emission Free-Electron Laser (**Phys. Rev. Lett. 81 (1998) 4867**)**

M. J. Hogan, C. Pellegrini, J. Rosenzweig, S. Anderson, P. Frigola, and A. Tremaine

Department of Physics and Astronomy, UCLA

C. Fortgang, D. C. Nguyen, R. L. Sheffield, and J. Kinross-Wright

Los Alamos National Laboratory

A. Varfolomeev, A. A. Varfolomeev, and S. Tolmachev

RRC–Kurchatov Institute, Moscow, Russia

Roger Carr

Stanford Synchrotron Radiation Laboratory

(Received 29 April 1998)

1997/1998: UCLA/LANL/RRCKI/SLAC experiment on a high-gain SASE FEL

E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov,

Numerical simulations of the UCLA/LANL/RRCKI/SLAC experiment on a high-gain SASE FEL, Nucl. Instrum. and Meth. A 429 (1999) 197-201:

4. Conclusion

In conclusion, we should like to point out that there is no doubt that the UCLA/LANL experiment [1] is a proof-of-principle of a high-gain SASE FEL. Even though it was performed at a relatively long wavelength, the physics of its operation is described with the same equations as future VUV and X-ray SASE FELs. All the simulations presented in this paper have been performed with the simulation code developed for simulation of short-wavelength SASE FELs. It is seen that there is good agreement between theoretical predictions and experimental results, which forms a reliable base for the future design of short-wavelength SASE FELs.

Acknowledgements

We are extremely grateful to C. Pellegrini and A. Varfolomeev for providing us with experimental results and fruitful discussions. We wish to thank B. Faatz, J. Feldhaus, J. Krzywinski, G. Materlik, T. Moeller, C. Pagani, J. Pflueger, S. Reiche, J. Rossbach and J.R. Schneider for many useful discussions.

1997/1998: UCLA/LANL/RRCKI/SLAC experiment on a high-gain SASE FEL

M. Hogan et al., Phys. Rev. Lett. 81 (1998) 4867

TABLE I. Electron beam, undulator, and FEL characteristics.

Electron Beam	
Energy [MeV]	18
Charge per micropulse [nC]	0.3–2.2
Transverse spot size (σ) [μm]	115–145
Uncorrelated energy spread at 2 nC (σ) [%]	0.25
Pulse length (σ) [ps]	3–5.5
Peak current [A]	40–170
Undulator	
Period [cm]	2.05
Number of periods	98
Undulator parameter (K)	1.04
Betatron wavelength [m]	1.2
FEL	
Radiation wavelength [μm]	12
Field gain length at 2.2 nC [cm]	25

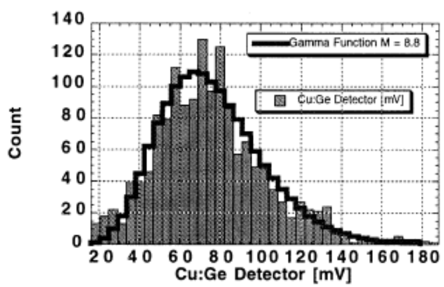


FIG. 5. Measured output intensity fluctuations for individual 2 nC micropulses compared to the predicted gamma distribution function. The mean value is 76 mV with a standard deviation of 28 mV corresponding to fluctuations on the order of 37%. Based on the FEL theory, we expect a gamma distribution function of M value 8.8 and fluctuations on the order 34%. For comparison, the fluctuations we might expect from micropulse to micropulse variations in charge are of the order of 2%. The gamma distribution function has been normalized such that the area under the curve is the same as the area of the histogram.

E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Nucl. Instrum. and Meth. A 429 (1999) 197

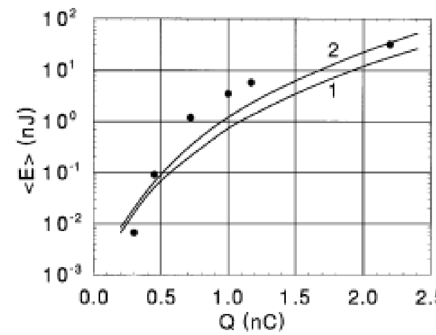


Fig. 3. Dependence of the averaged energy in the radiation pulse versus the bunch charge. Curves 1 and 2 correspond to the Gaussian and the parabolic axial beam profiles. The circles are experimental results [1].

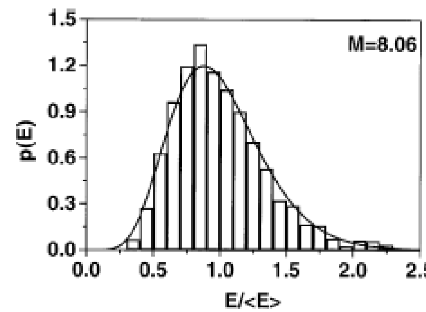


Fig. 5. Probability distribution of the energy in the radiation pulse at a bunch charge of 2.2 nC calculated over 2400 statistically independent runs. The solid curve represents a gamma distribution with $M = 8.06$.

More details can be found in: *The Physics of Free Electron Lasers* (Springer-Verlag, 1999) – Chap. 6.4 is devoted to analysis of the experiment using methodology described here.

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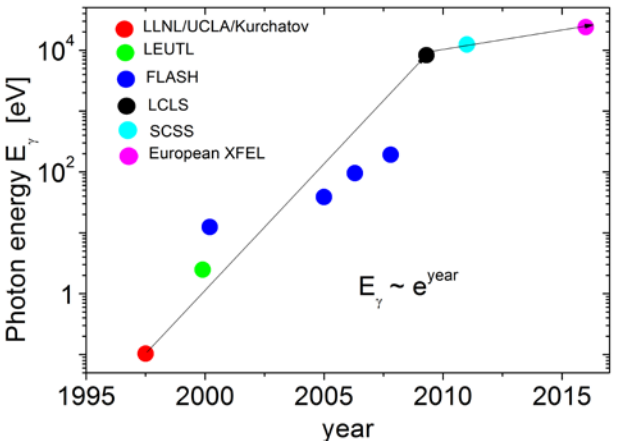
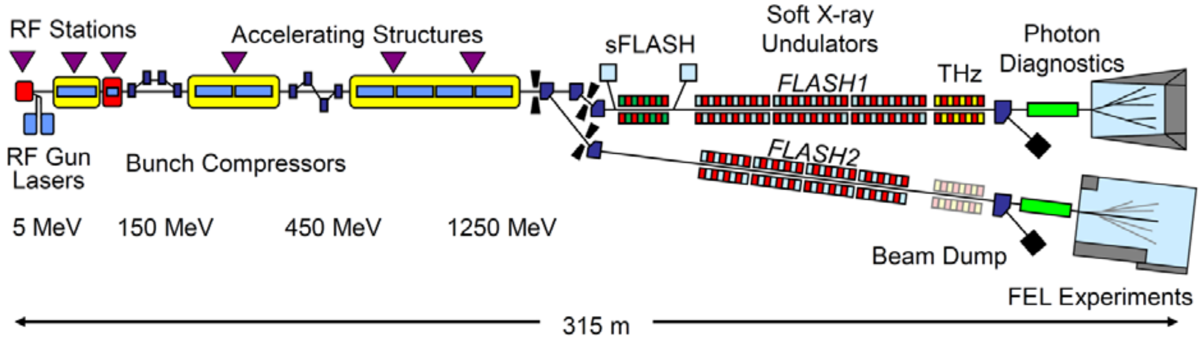
TESLA, ILC, FLASH, European XFEL

- FLASH (Free-electron -LASer in Hamburg) is a superconducting linear accelerator with free electron laser for radiation in the vacuum-ultraviolet and soft X-ray range of the spectrum.
- It originated from the TTF (TESLA Test Facility), which was built in 1997 to test the technology that was to be used in the planned linear collider TESLA, a project which was replaced by the ILC (International Linear Colider).
- At FLASH technology for the future-project European XFEL is tested as well as for the ILC.
- Five scientific instruments have been in use since the commissioning of the facility in 2004.
- Second stage, FLASH2 is under commissioning now. First lasing has been obtained in August, 2014, and first user operation started in 2016.

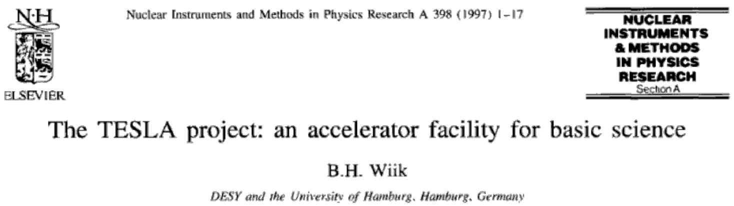


FLASH was leading SASE FEL facility during last decade.



1994: start of the TESLA Test Facility FEL

TTF FEL, Pase 1: proof of principle experiment of SASE FEL in the VUV (270 MeV, 80 nm)
TTF FEL, Phase 2: 6-120 nm & upgrade for the self-seeding option (1 GeV, 6 nm)
Linear collider with integrated x-ray laser facility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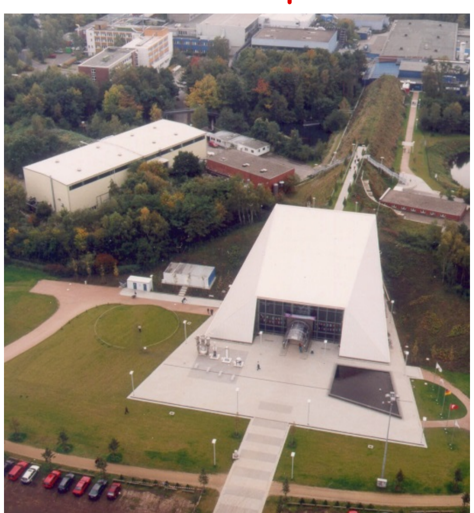
Nuclear Instruments and Methods in Physics Research A 398 (1997) 1–17
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

The TESLA project: an accelerator facility for basic science

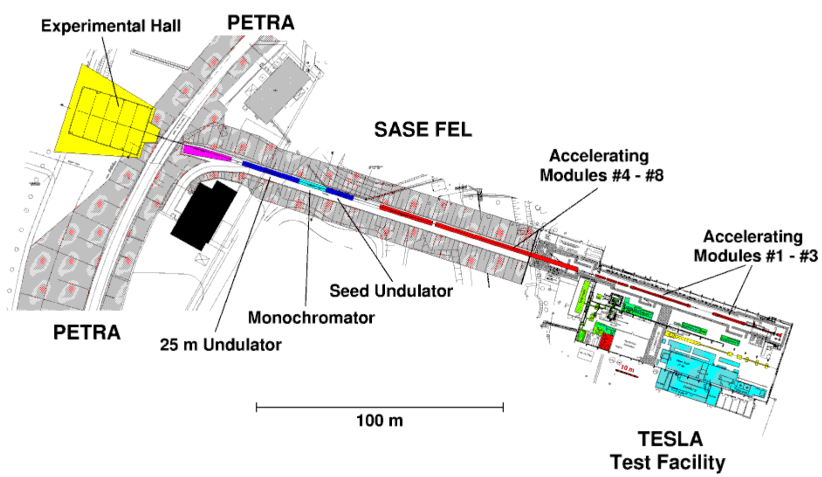
B.H. Wiik

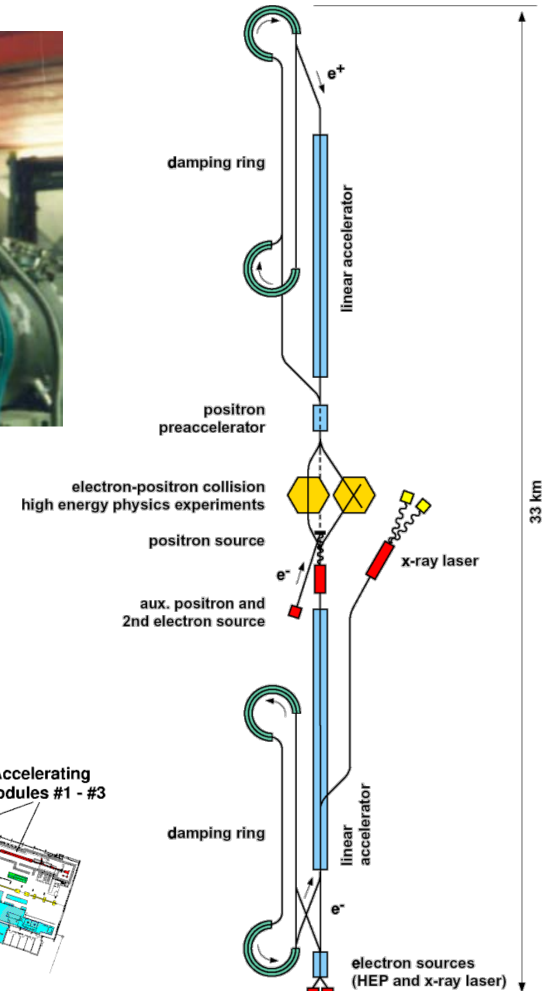
DESY and the University of Hamburg, Hamburg, Germany

TTF FEL at Expo 2000

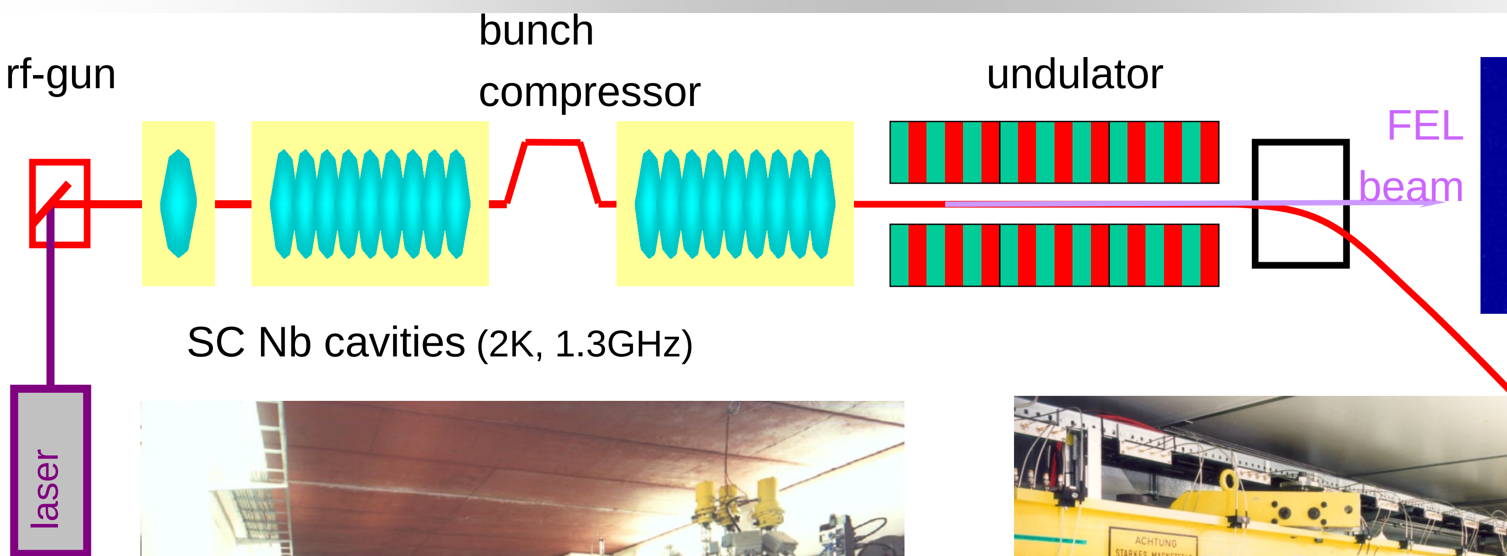


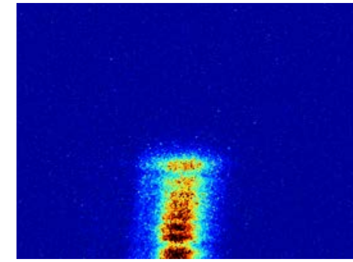
Bjoern Wiik, 1994

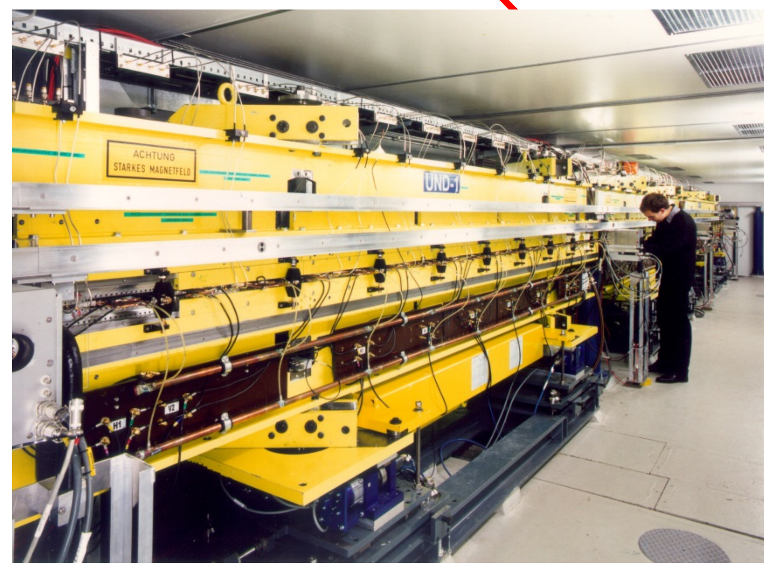




1994-2001: TESLA Test Facility FEL, Phase 1





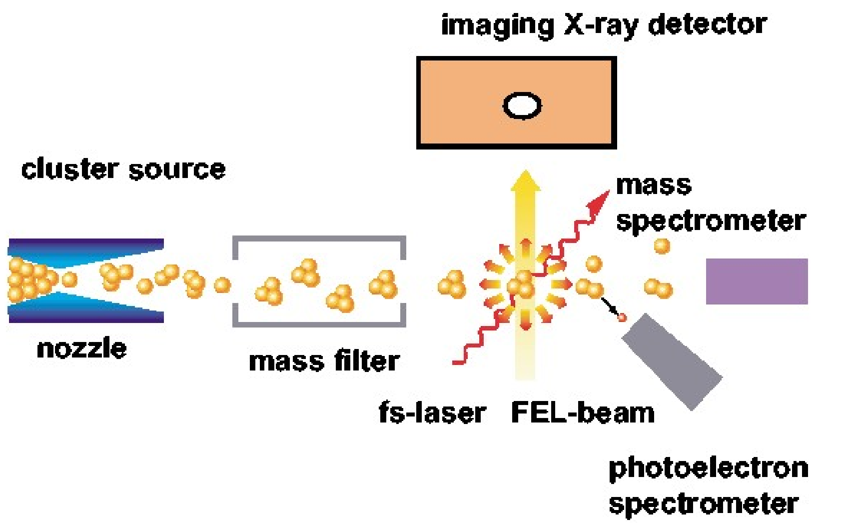


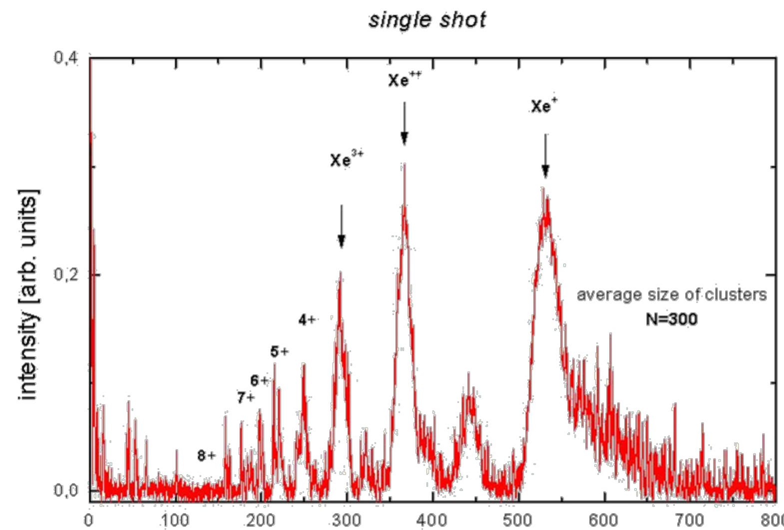
Energy	270 MeV
Rep. rate	1-5 Hz
Macropulse duration	1 ms
Micropulse rep. rate	2.25 MHz

Period	2.73 cm
Module length	4.5 m
Number of modules	3

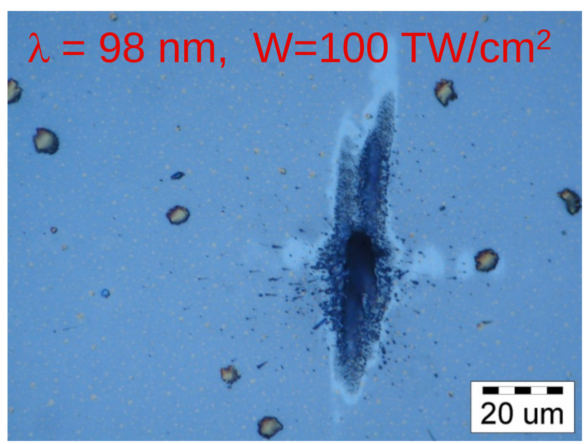
2001: TESLA Test Facility FEL, Phase 1
Pioneer user's experiments

H. Wabnitz et al., Nature, 420, 482-485 (2002): Coulmb explosion of clusters

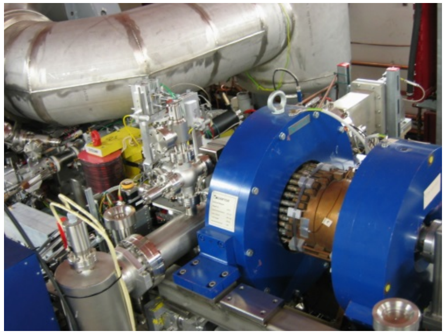
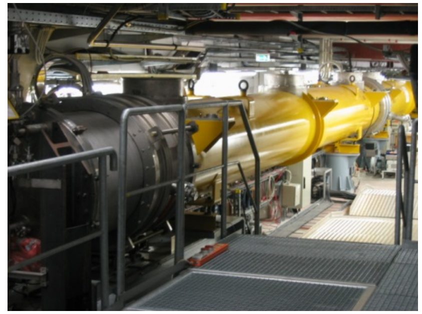


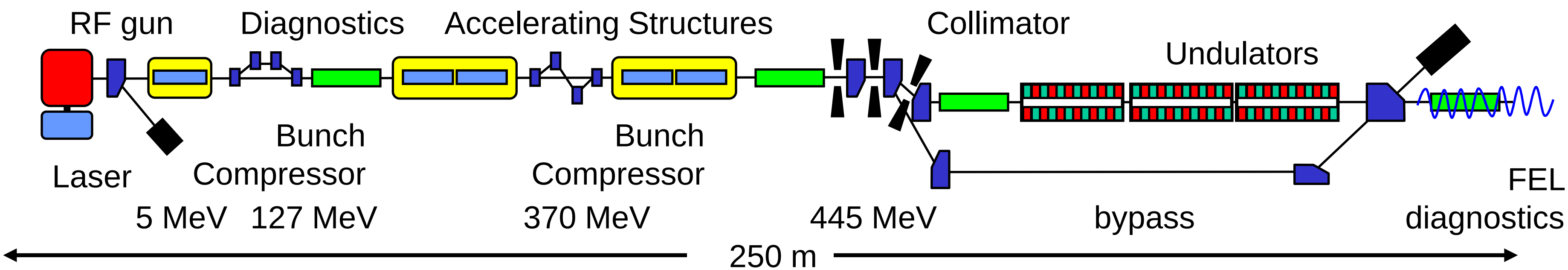


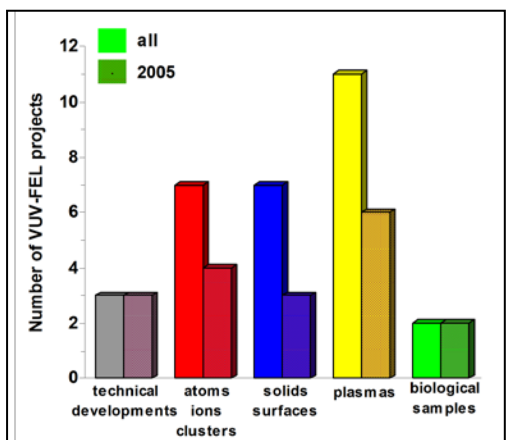
Jacek Krzywinski et al.: Au film (15 nm) on Si substrate irradiated by a single SASE pulse

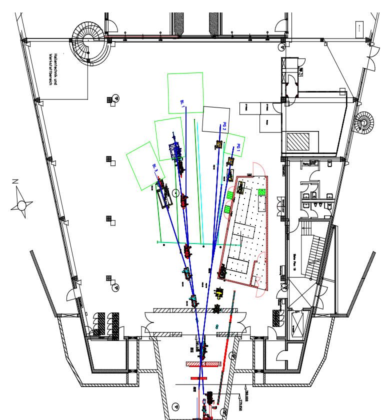


2005: VUV FEL (FLASH)
First soft x-ray FEL user facility

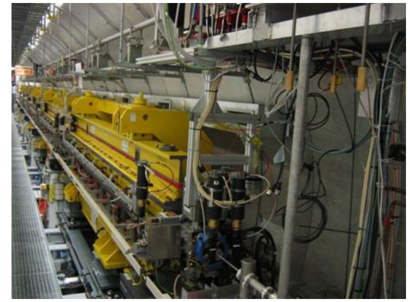
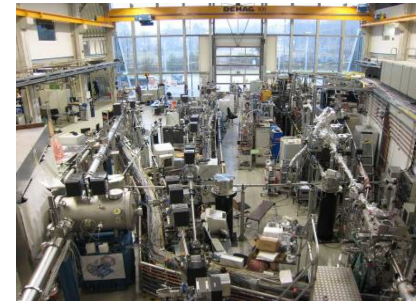



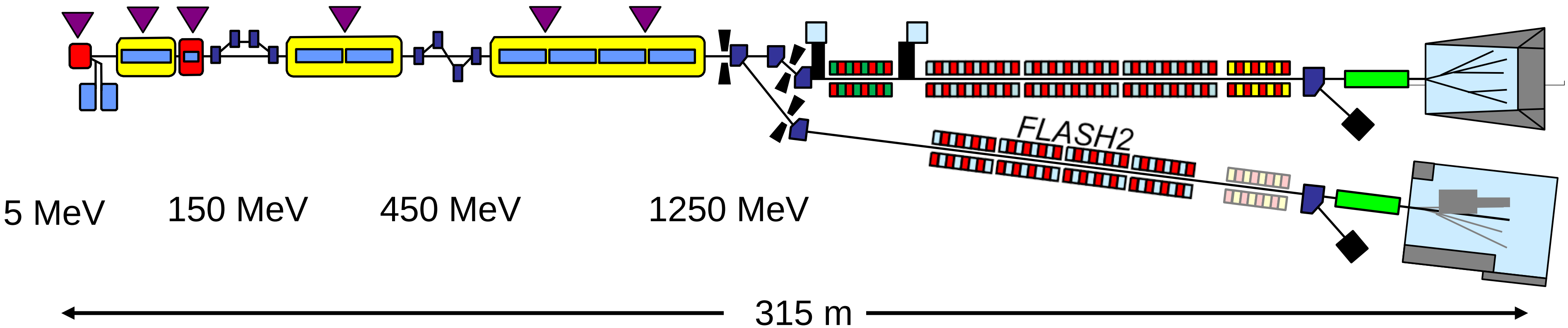




FLASH facility in 2016

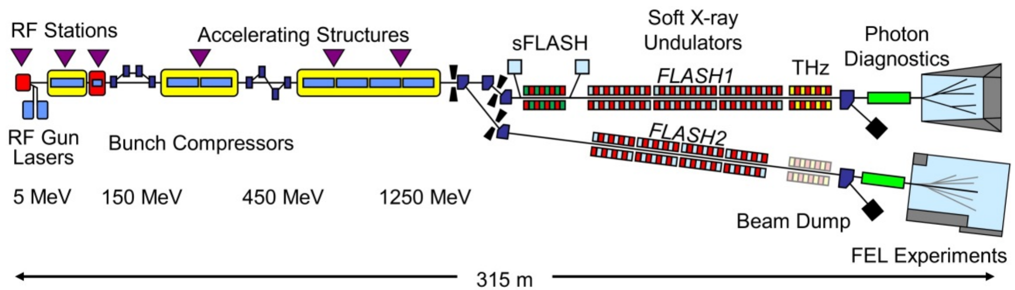


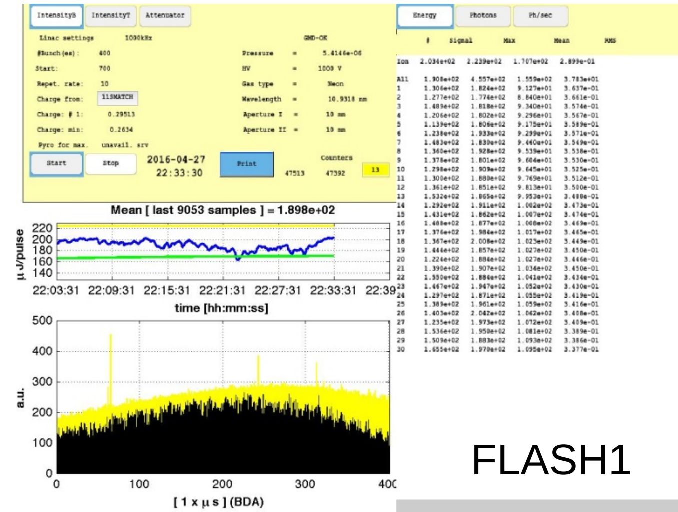



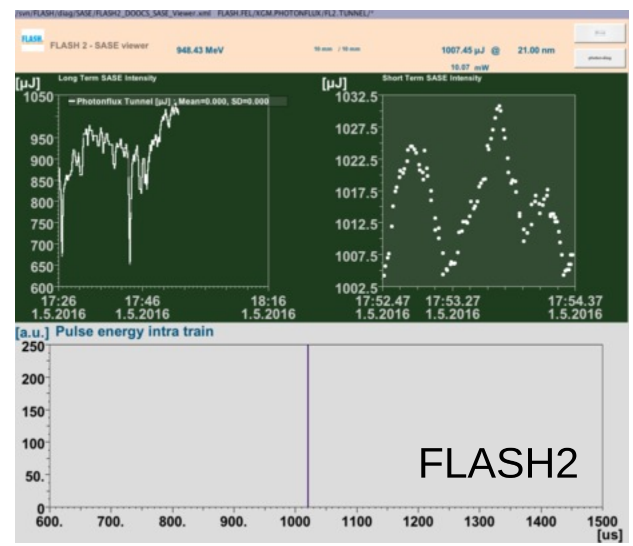





FLASH facility in 2016







Linac: SRF burst, 1 msec x 10 Hz

Energy	[GeV]	0.5-1.25
Length	[m]	315

Undulators:

	Period	Length	
FLASH1:	2.73 cm	27 m (6 x 4.5 m modules)	fixed gap
FLASH2:	3.14 cm	30 m (12 x 2 m modules)	variable gap

Radiation:

Wavelength [nm] 4.1-55 (FLASH1), 3.x-8.x (FLASH2)

Up to 0.8 W average radiation power

Up to 1 mJ average radiation pulse energy

A few 10 fs to a few 100 fs pulse duration

A few GW peak radiation power

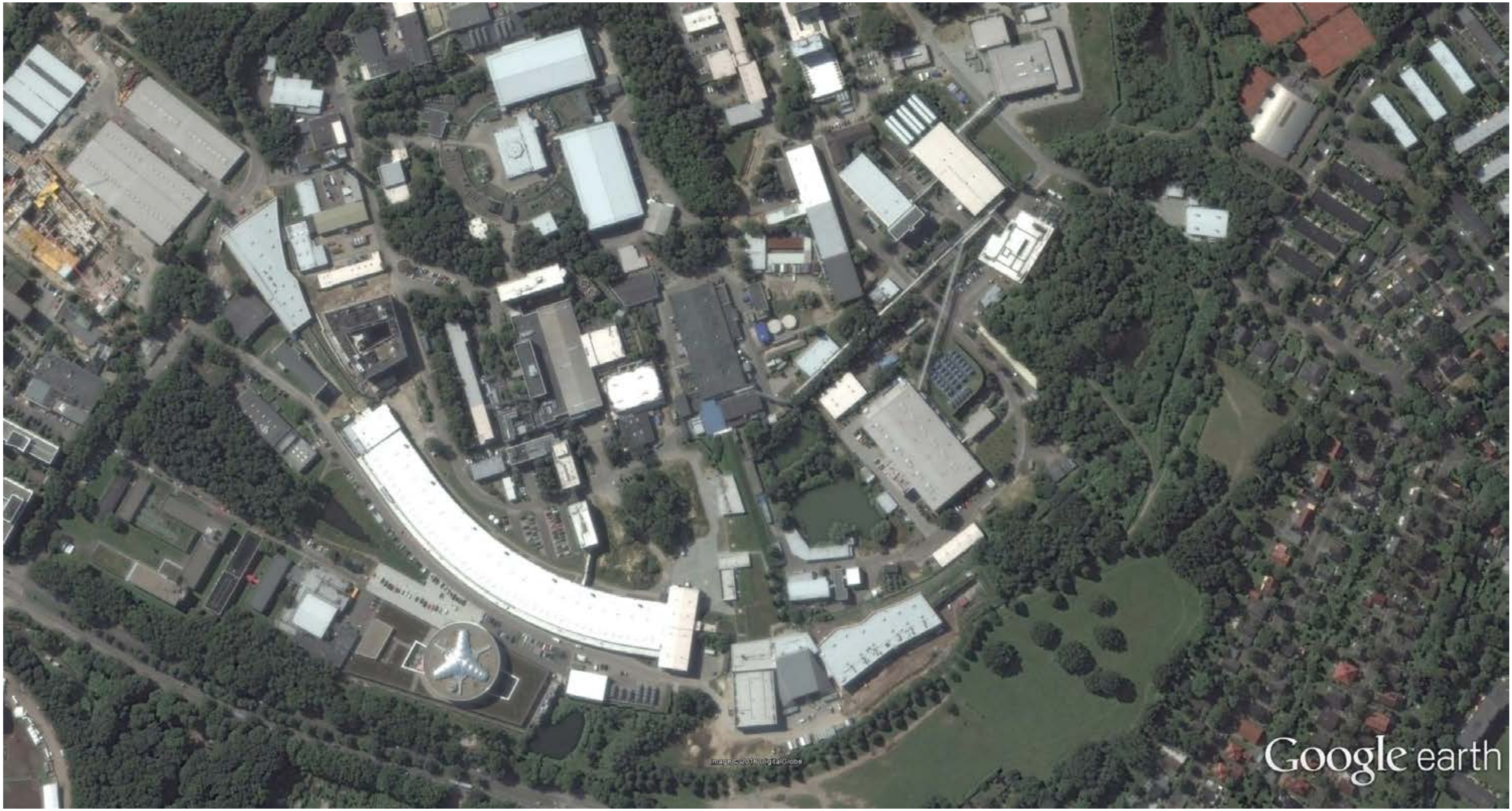
Up to 5000 pulses per second

DESY areal view in August, 2015

PETRA III: East Hall, Max von Laue Hall (left), Nord Hall (left)

FLASH: 1.25 GeV SC linac, FLASH and FLASH2 experimental hall (center)

European XFEL: AMTF, cryogenic plant and injector (top-right)



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Analysis of experimental results

Collection of experimental data:

- Parameters of the electron beam: energy, energy chirp, emittance, energy spread, axial profile. Individual data for each bunch: energy, charge, orbit.
- Measurements related to machine jitters: slow drifts (e.g., rf phases), and bunch-to-bunch (energy, charge, orbit, compression).
- Photon beam parameters: pulse energy, spectra, images of radiation pulses.
- SASE FEL gain curve and fluctuations of the radiation pulse energy.
- Measurement of higher harmonic content.

Four levels of analysis:

- Analysis of physical parameters.
- Quick semi-analytical analysis of parameter space: allows to define physical consistency of measured parameters. It is usually performed on-line with collecting experimental data.
- Detailed analysis of experimental data and determination of the main SASE parameters (pulse duration, pulse shape, mode content, coherence time, degree of transverse coherence). Gaiting of the results with jitter-sensitive machine parameters may be needed to isolate machine jitters.
- Simulations with S2E beam simulation tools and time-dependent FEL simulation codes. At these step we define parameters which are not observable directly from measurements.

Step 1: Analysis of physical parameters

- In the framework of the three-dimensional theory the operation of the FEL amplifier is described by the diffraction parameter B, the energy spread parameter $\hat{\Lambda}^2_{\mathrm{T}}$, the space charge parameter $\hat{\Lambda}^2_{\mathrm{p}}$, the betatron motion parameter $\hat{k}_\beta$, and the detuning parameter $\hat{C}$:

$$B = 2\Gamma\sigma^2\omega/c \ , \qquad \hat{k}_\beta = 1/(\beta\Gamma) \ , \qquad \hat{\Lambda}^2_{\mathrm{T}} = (\sigma_{\mathrm{E}}/\mathcal{E})^2/\bar{\rho}^2 \ , \qquad \hat{\Lambda}^2_{\mathrm{p}} = \frac{4\bar{\rho}}{B}\frac{1+K^2}{K^2A^2_{JJ}} \ , \qquad \hat{C} = C/\Gamma \ ,$$

with the gain parameter $\Gamma =$ and 3D FEL parameter $\bar{\rho}$:

$$\Gamma = \left[\frac{I}{I_{\mathrm{A}}}\frac{8\pi^2K^2A^2_{\mathrm{JJ}}}{\lambda\lambda_{\mathrm{w}}\gamma^3}\right]^{1/2} \ , \quad \bar{\rho} = \frac{\lambda_{\mathrm{w}}\Gamma}{4\pi} = \rho/B^{1/3} \ .$$

- Each parameter has clear physical sence reflecting power of the corresponding physical effect: diffraction, energy spread, betatron oscillations, detuning from resonance, see "The Physics of Free Electron Lasers" (Springer, 2000) for more details.

- Typically, space charge effects are small for short wavelength FELs (visible and shorter), but may play significant role for FELs operating in infrared wavelength range.

- The value of diffraction parameter $B = 1$ separates diffraction limited case (thin beam) and the wide beam.

- For the case of "cold" electron beam, $\hat{\Lambda}^2_{\mathrm{T}} \to 0$, $\hat{k}_\beta \to 0$, the operation of the FEL amplifier tuned to maximum gain is described by the only diffraction parameter B.

Step 2: Quick calculation of main FEL characteristics 1D Handbook

- FEL parameter ρ and number of cooperating electrons N_c:

$$\rho = \frac{\lambda_\mathrm{w}}{4\pi}\left[\frac{4\pi^2 j_0 K^2 A_\mathrm{JJ}^2}{I_A \lambda_\mathrm{w} \gamma^3}\right]^{1/3} , \qquad N_\mathrm{c} = I/(e\rho\omega) .$$

- Main properties of SASE FEL in the saturation can be quickly estimated in terms of ρ and N_c:

$$\text{The field gain length}: \quad L_\mathrm{g} \sim \lambda_\mathrm{w}/(4\pi\rho) ,$$

$$\text{Saturation length}: \quad L_\mathrm{sat} \sim 10 \times L_\mathrm{g} ,$$

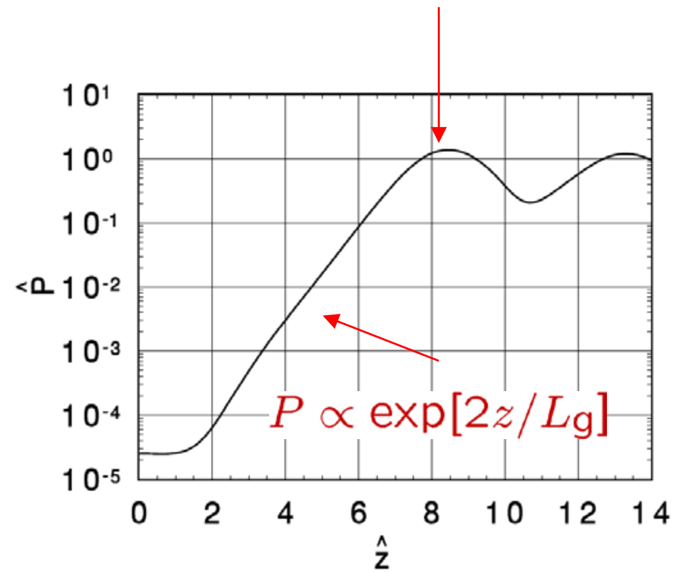
$$\text{Effective power of shot noise}: \quad \frac{W_\mathrm{sh}}{\rho W_\mathrm{b}} \simeq \frac{3}{N_\mathrm{c}\sqrt{\pi \ln N_\mathrm{c}}} ,$$

$$\text{Saturation efficiency}: \quad \rho ,$$

$$\text{The power gain at saturation}: \quad G \simeq \frac{1}{3} N_\mathrm{c}\sqrt{\pi \ln N_\mathrm{c}} ,$$

$$\text{Coherence time at saturation}: \quad \tau_\mathrm{c} \simeq \frac{1}{\rho\omega}\sqrt{\frac{\pi \ln N_\mathrm{c}}{18}} ,$$

$$\text{Spectrum bandwidth}: \quad \sigma_\omega \simeq \rho\omega\sqrt{\frac{18}{\ln N_\mathrm{c}}} .$$



Simple and physically transparent 1D formulae are useful for educational purpose. However, accuracy of estimations is poor (no energy spread and emittance effects). There is no hint on power of diffraction effects and spatial properties of the radiation.

Step 2: Quick calculation of main FEL characteristics 3D fitting formulae

Fitting formulae by Ming Xie:

- Gain length;
- Saturation length;
- Saturation power.

Physical model: axisymmetric electron beam, diffraction, energy spread, betatron oscillations, detuning.

Fitting formulae for optimized SASE FEL by ES&MY:

- Gain length and saturation length;
- Saturation power, radiation pulse energy;
- Radiation spot size and divergence;
- Radiation pulse duration;
- Coherence time and spectrum width;
- Number of modes in the radiation pulse and fluctuations of the radiation pulse energy;
- Degree of transverse coherence;
- Brilliance.

Physical model: axisymmetric electron beam, diffraction, energy spread, betatron oscillations. SASE FEL is tuned to maximum gain of the fundamental radiation mode.

Step 2: Quick calculation of main FEL characteristics Fitting formulae by Ming Xie

Gain length, saturation length, saturation power in 3D case in all parameter space: diffraction, energy spread, betatron oscillation, detuning

$$\frac{L_{1\mathrm{d}}}{L_{\mathrm{g}}} = \frac{1}{1+\Lambda} \qquad (19)$$

where

$$\Lambda = a_1\eta_{\mathrm{d}}^{a_2} + a_3\eta_{\varepsilon}^{a_4} + a_5\eta_{\gamma}^{a_6} + a_7\eta_{\varepsilon}^{a_8}\eta_{\gamma}^{a_9} + a_{10}\eta_{\mathrm{d}}^{a_{11}}\eta_{\gamma}^{a_{12}} + a_{13}\eta_{\mathrm{d}}^{a_{14}}\eta_{\varepsilon}^{a_{15}} + a_{16}\eta_{\mathrm{d}}^{a_{17}}\eta_{\varepsilon}^{a_{18}}\eta_{\gamma}^{a_{19}}$$

and the 19 fitting parameters are given in Table 1.

Table 1
Fitting parameters for gain length

$a_1 = 0.45$	$a_2 = 0.57$	$a_3 = 0.55$	$a_4 = 1.6$
$a_5 = 3$	$a_6 = 2$	$a_7 = 0.35$	$a_8 = 2.9$
$a_9 = 2.4$	$a_{10} = 51$	$a_{11} = 0.95$	$a_{12} = 3$
$a_{13} = 5.4$	$a_{14} = 0.7$	$a_{15} = 1.9$	$a_{16} = 1140$
$a_{17} = 2.2$	$a_{18} = 2.9$	$a_{19} = 3.2$	

$$L_{sat} = L_g \ln\left(\frac{P_{sat}}{\alpha P_n}\right) \qquad (2)$$

$$P_{sat} \approx 1.6\rho\left(\frac{L_{1d}}{L_g}\right)^2 P_{beam}. \qquad (7)$$

There are four scaling parameters [6] in Eq. (5): $\eta_{\mathrm{d}} = 1/F_{\mathrm{d}}$ is a diffraction parameter, where $F_{\mathrm{d}} = 2k_r\sigma_x^2/L_{1\mathrm{d}}$ is the Fresnel number of electron beam corresponding to a length scale of $L_{1\mathrm{d}}$; $\eta_\varepsilon = 4\pi(L_{1\mathrm{d}}/\lambda_\beta)k_r\varepsilon$ and $\eta_\gamma = 4\pi(L_{1\mathrm{d}}/\lambda_w)\sigma_\eta$ characterize the effective spread in longitudinal velocity due to emittance and betatron focusing and due to energy spread, respectively, where $\lambda_\beta = 2\pi\beta_f$, $\varepsilon = k_\beta\sigma_x^2$ is rms beam emittance and σ_η is relative rms energy spread; finally, $\eta_\omega = 4\pi(L_{1\mathrm{d}}/\lambda_w)\Delta\nu$ is a frequency detuning parameter. The Pierce para-

Ming Xie,
Exact and variational solutions of 3D eigenmodes in high gain FELs, Nucl. Instrum. and Meth. A 445 (2000) 59;
Design optimization for an X-ray free electron laser driven by SLAC linac, 1995 Particle Accelerator Conference

Step 2: Quick calculation of main FEL characteristics
Fitting formulae for optimized SASE FEL

- Typical procedure of optimization of short wavelength SASE FEL consists in optimization for the maximum gain of the fundamental (TEM_{00}) beam radiation mode. This case is referred as optimized SASE FEL (E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Opt. Commun. 235(2004)415):

- Gain length and optimum beta function:

$$L_{\mathrm{g}} \simeq 1.67 \left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_{\mathrm{w}})^{5/6}}{\lambda^{2/3}} \frac{(1+K^2)^{1/3}}{K A_{JJ}} (1+\delta) \,, \qquad \beta_{\mathrm{opt}} \simeq 11.2 \left(\frac{I_A}{I}\right)^{1/2} \frac{\epsilon_n^{3/2} \lambda_{\mathrm{w}}^{1/2}}{\lambda K A_{JJ}} (1+8\delta)^{-1/3} \,.$$

$$\delta = 131 \, \frac{I_A}{I} \, \frac{\epsilon_n^{5/4}}{\lambda^{1/8} \lambda_{\mathrm{w}}^{9/8}} \, \frac{\sigma_\gamma^2}{(K A_{JJ})^2 (1+K^2)^{1/8}} \,.$$

- Accuracy for the gain length fit is better than 5 % in the range of parameters

$$1 < \frac{2\pi\epsilon}{\lambda} < 5 \,, \qquad \delta < 2.5 \left\{ 1 - \exp\left[-\frac{1}{2} \left(\frac{2\pi\epsilon}{\lambda} \right)^2 \right] \right\}$$

- When technical limitations prevent organization of optimum focusing beta function, and $\beta > \beta_{\mathrm{opt}}$, the gain length is approximated as (E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. ST-AB 15, 080702 (2012)):

$$L_g(\beta) \simeq L_g(\beta_{\mathrm{opt}}) \left[1 + \frac{(\beta - \beta_{\mathrm{opt}})^2 (1+8\delta)}{4\beta_{\mathrm{opt}}^2} \right]^{1/6} \qquad \text{for} \quad \beta > \beta_{\mathrm{opt}}$$

- Fitting formulae are extended for harmonic lasing as well.

Step 2: Quick calculation of main FEL characteristics
Fitting formulae for optimized SASE FEL

- In the case of small energy spread characteristics of optimized SASE FEL written down in the normalized form are functions of two parameters, ratio of geomtrical emittance to the wavelength, and the number of electrons in the volume of coherence:

$$\hat{\epsilon} = 2\pi\epsilon/\lambda \ , \qquad N_{\mathrm{c}} = I L_{\mathrm{g}} \lambda/(e\lambda_{\mathrm{w}} c) \ .$$

- Dependence of the FEL characterestics on N_{c} is very slow, in fact, logarithmic. Approximately, with logarithmic accuracy they depend only on $\hat{\epsilon}$.

- In fact, the diffraction parameter B and the betatron oscillation parameter k_β are:

$$B \simeq 13 \times \hat{\epsilon}^{5/2} \ , \qquad k_\beta \simeq 0.154/\hat{\epsilon}^{3/2}$$

Step 2: Quick calculation of main FEL characteristics
Fitting formulae for optimized SASE FEL at saturation

Saturation length:

$$\hat{L}_{\rm sat} = \Gamma L_{\rm sat} \simeq 2.5 \times \hat{\epsilon}^{5/6} \times \ln N_{\rm c} \ ,$$

FEL efficiency:

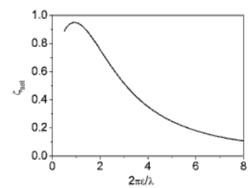
$$\hat{\eta} \ = \ P/(\bar{\rho} P_{\rm b}) \simeq 0.17/\hat{\epsilon} \ ,$$

Coherence time and rms spectrum width:

$$\hat{\tau}_{\rm c} \ = \ \bar{\rho}\omega\tau_{\rm c} \simeq 1.16 \times \sqrt{\ln N_{\rm c}} \times \hat{\epsilon}^{5/6} \ , \qquad \sigma_\omega \simeq \sqrt{\pi}/\tau_{\rm c} \ .$$

Degree of transverse coherence:

$$\zeta_{\rm sat} \ \simeq \ \frac{1.1\hat{\epsilon}^{1/4}}{1+0.15\hat{\epsilon}^{9/4}} \ ,$$



Degeneracy parameter:

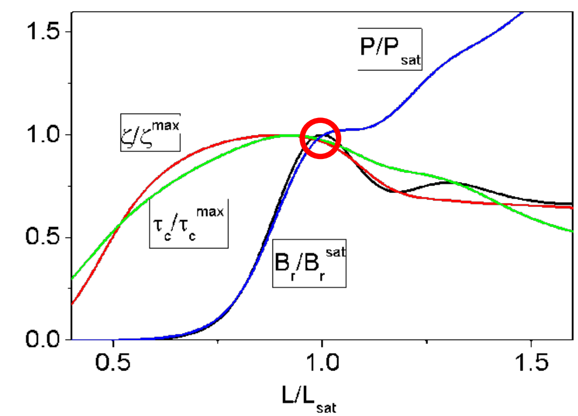
$$\hat{\delta} \ = \ \hat{\eta}\zeta\hat{\tau}_{\rm c}$$

Brilliance:

$$B_r \ = \ \frac{\omega d\dot{N}_{ph}}{d\omega} \frac{\zeta}{\left(\frac{\lambda}{2}\right)^2} = \frac{4\sqrt{2}c}{\lambda^3}\frac{P_{\rm b}}{\hbar\omega^2}\hat{\delta} \ .$$

FWHM spot size and FWHM angular divergence:

$$\Delta\hat{r}_{\rm FWHM} \ \simeq \ \ln(8.2/B^{1/5}) \ ,$$
$$\Delta\hat{\theta}_{\rm FWHM} \ \simeq \ \simeq \ln(3.3B^{1/3}) \ .$$



Normalizing parameters:

$$\Gamma \ = \ \left[\frac{I}{I_{\rm A}} \frac{8\pi^2 K^2 A_{\rm JJ}^2}{\lambda\lambda_{\rm w}\gamma^3}\right]^{1/2} \ , \qquad \bar{\rho} = \frac{\lambda_{\rm w}\Gamma}{4\pi} \ .$$

$$\Delta\hat{r}_{\rm FWHM} = \Delta r_{\rm FWHM}/(\sigma\sqrt{2}),$$

$$\Delta\hat{\theta}_{\rm FWHM} = \Delta\theta_{\rm FWHM}\lambda/(2\sqrt{2}\pi\sigma).$$

The diffraction parameter B:

$$B \simeq 13 \times \hat{\epsilon}^{5/2} \ ,$$

The betatron oscillation parameter k_β:

$$k_\beta \simeq 0.154/\hat{\epsilon}^{3/2} \ .$$

E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Opt. Commun. 281(2008)1179; 281(2008)4727 ; New Journal of Physics 12 (2010) 035010;
E.A. Schneidmiller, M.V. Yurkov, Proc. FEL2012 Conference, MOPD06.

Step 4: Simulations with S2E beam simulation tools and time-dependent FEL simulation codes

- Check of consistency of fine details of SASE FEL operation.
- Determination of parameters which can not be measured in the experiment. First of all this refers to slice properties of the radiation pulse (longitudinal and transverse intensity distributions).

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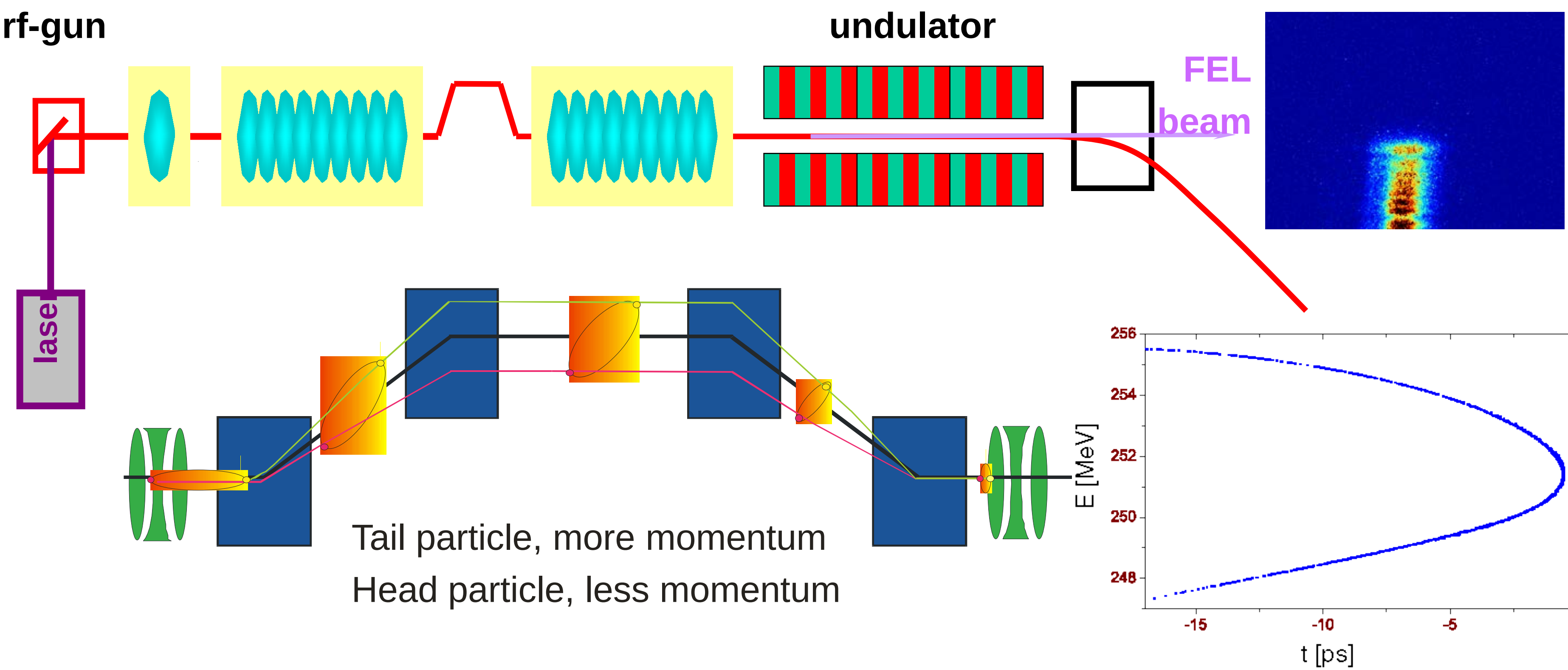
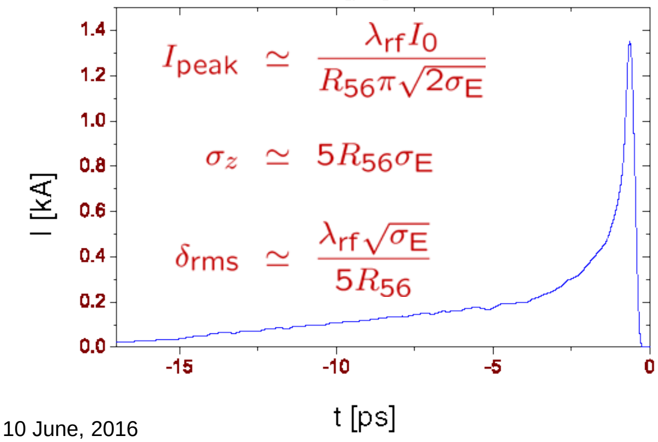
2001: TESLA Test Facility FEL, Phase 1
Saturation: Phys. Rev. Lett. 88(2002)10482



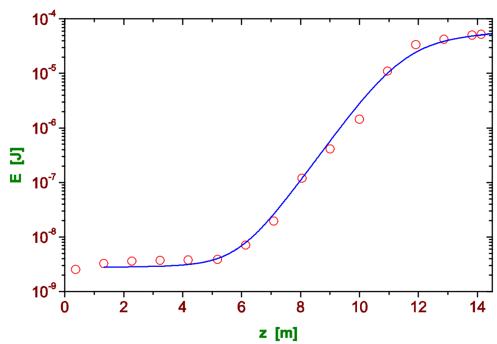
- The feature of TTF FEL was strongly nonlinear beam formation system.
- As a result, short spike in the head of electron bunch produced SASE FEL radiation.

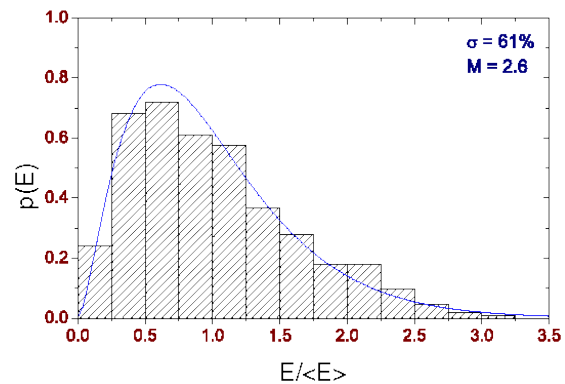


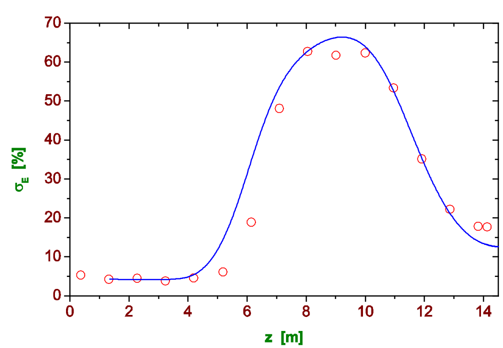
TESLA Test Facility FEL, Phase 1

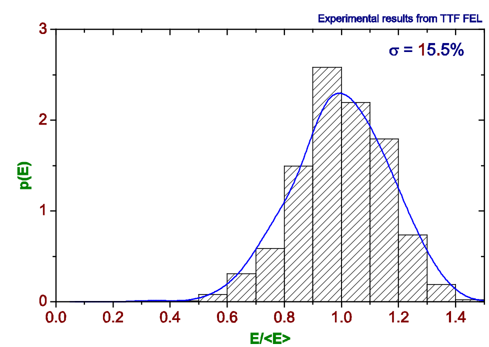
Saturation: Phys. Rev. Lett. 88(2002)10482

- Electron beam diagnostics at TTF did not allow to perform all required slice measurements of the electron beam parameters.
- Within uncertainty range of the electron beam parameters it was possible to select those which were consistent with measured FEL gain curve and fluctuations.
- Measured divergence of the radiation and spectrum were visibly wider than theoretical values.

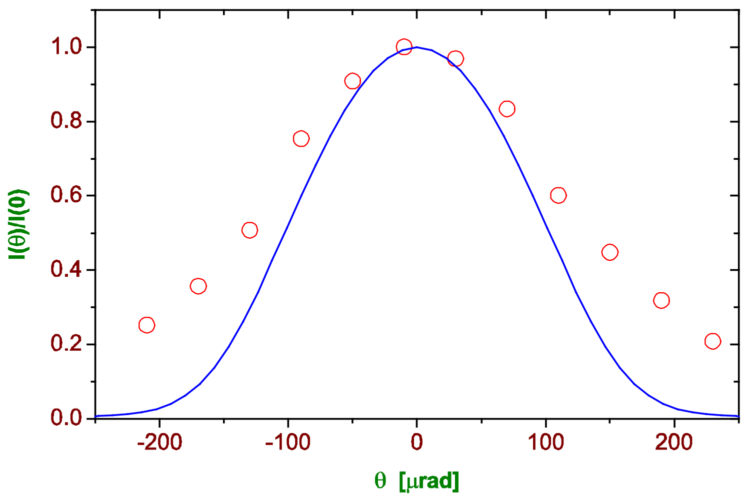


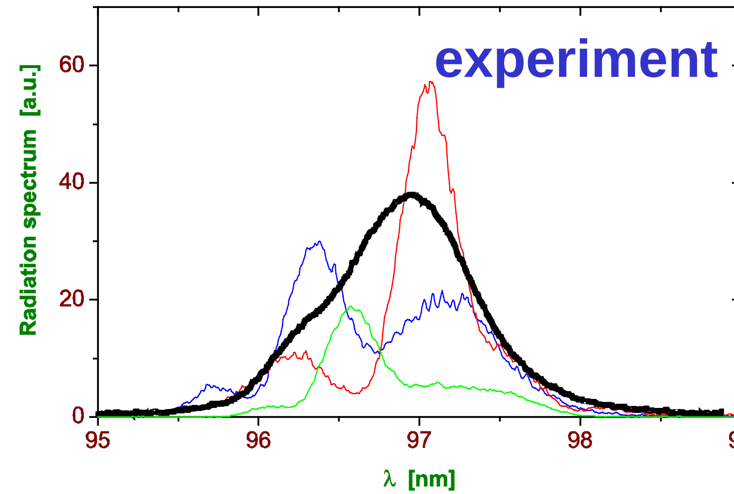


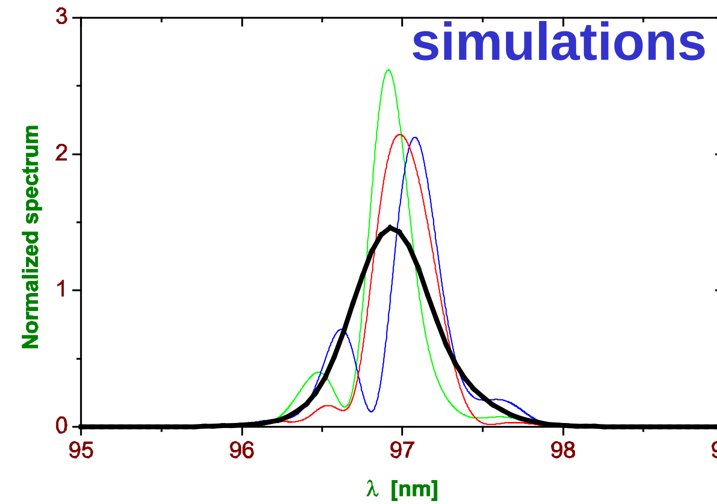




2001: TESLA Test Facility FEL, Phase 1
First iteration: Phys. Rev. Lett. 88(2002)10482







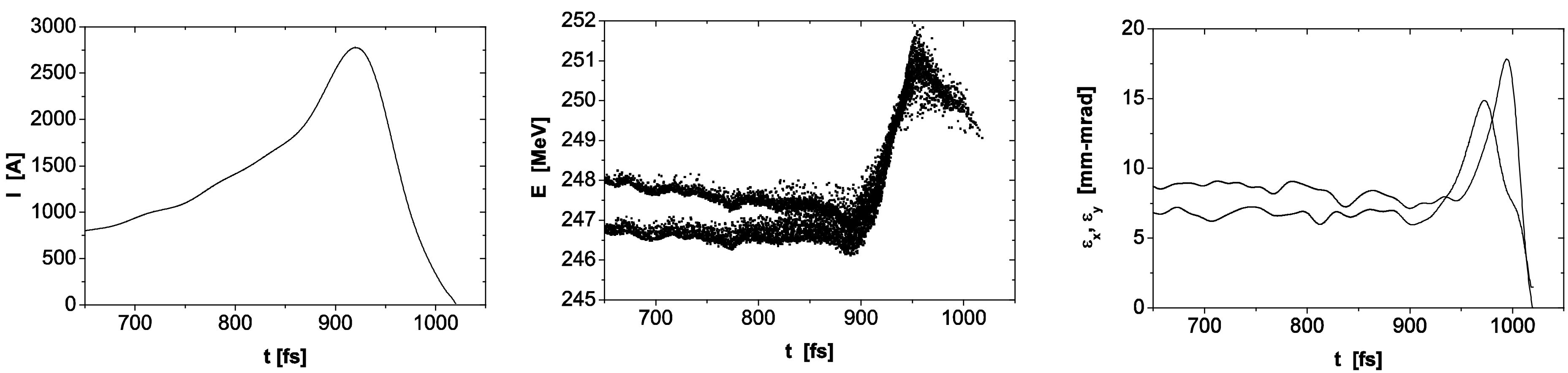
- ☹ Difference in angular divergence indicates on difference in the spatial structure of the radiation at the undulator exit.
- ☹ Visible disagreement between experimental and simulated spectra is a clear indication for higher value of beam current, or for large energy chirp along the bunch.

2001: TESLA Test Facility FEL, Phase 1
Extended analysis: Nucl. Instrum. Meth. A 530 (2004) 217

- To find the origin of difference between measured and simulated FEL parameters we launched dedicated study of the chain of simulation procedures from the cathode, trough the whole accelerator, and with final simulations of FEL performance with time-dependent FEL code FAST (M. Dohlus et al., Nucl. Instrum. Meth. A 530 (2004) 217).
- Our finding was strong influence of the space charge effects in the process of the formation of lasing spike:

$$\frac{d(\Delta\gamma)}{dz} \simeq 2.4 \frac{I}{I_A} \frac{\ln(\gamma\sigma_z/\sigma_r)}{\gamma^2\sigma_z}$$

missed in original studies which happened due significant overestimation of the slice energy spread at the exit of the electron gun.



ASTRA (DESY) - beam tracking with space charge (gun, ACC, drifts)

elegant (Argonne Natl. Lab.) - electron beam tracking in BC (including CSR)

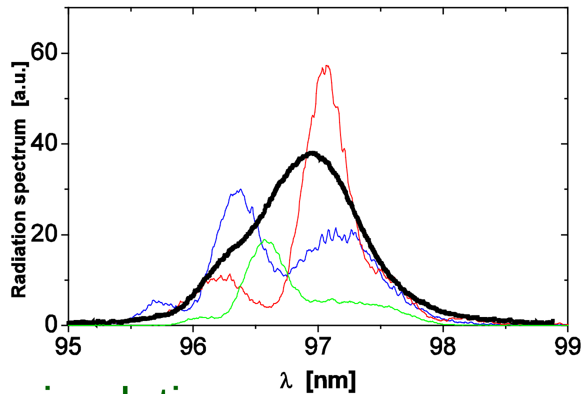
FAST (DESY/JINR) - time-dependent simulations of SASE FEL

2001: TESLA Test Facility FEL, Phase 1

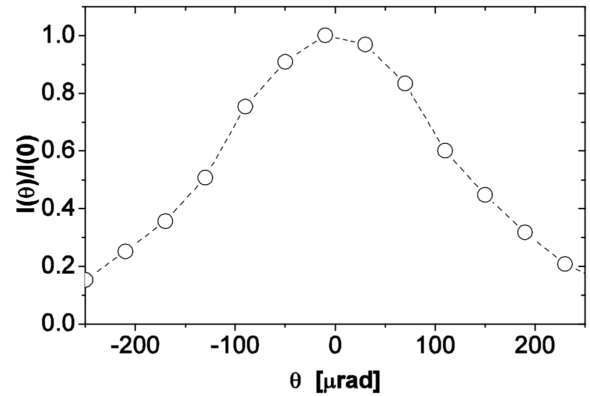
Extended analysis: Nucl. Instrum. Meth. A 530 (2004) 217

Experimental data

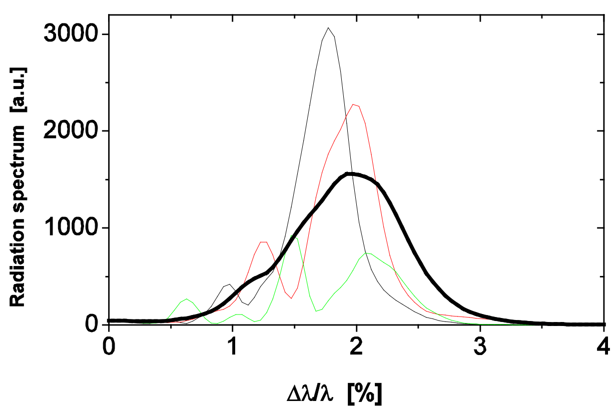
Spectra

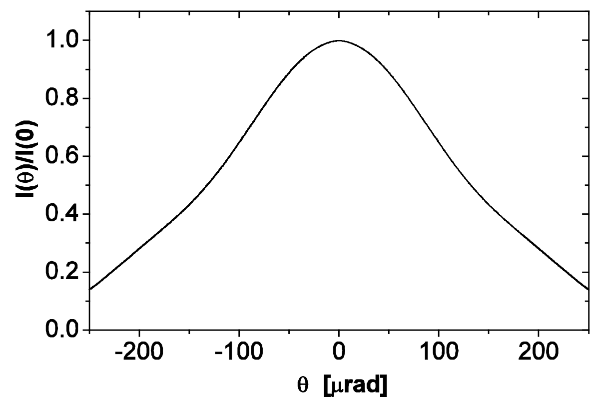


Angular divergence



Start-to-end-simulations





☺ It turned out that energy chirp along the lasing part was responsible for (1) widening of the spectrum, and (2) distortion of the beam radiation mode due to significant chirp on a scale of coherence length.

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Production of ultra-short radiation pulses

- The program for production of ultra-short electron pulses at FLASH has been launched several years ago by DESY and Hamburg University.
- Experiment has been performed on January, 11, 2013. Some results are presented at the FEL 2013 Conference:

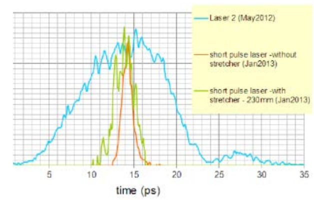
J. Roensch-Schulenburg, E. Hass, A. Kuhl, T. Plath, M. Rehders, J. Rossbach, G. Brenner, C. Gerth, U. Mavric, H. Schlarb, E. Schneidmiller, S. Schreiber, B. Steffen, M. Yan, M.V. Yurkov, Short SASE-FEL Pulses at FLASH, Proc. FEL2013 Conference, New York, USA, 2013, tupso64. http://accelconf.web.cern.ch/AccelConf/FEL2013/papers/tupso64.pdf

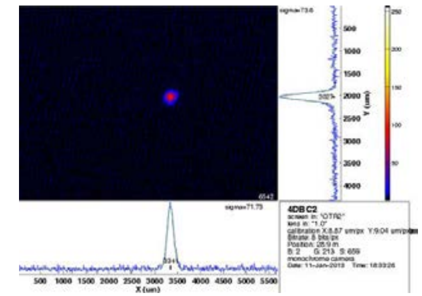
Extended analysis have been presented at the IPAC2016 Conference (report ID: MOPOW013).

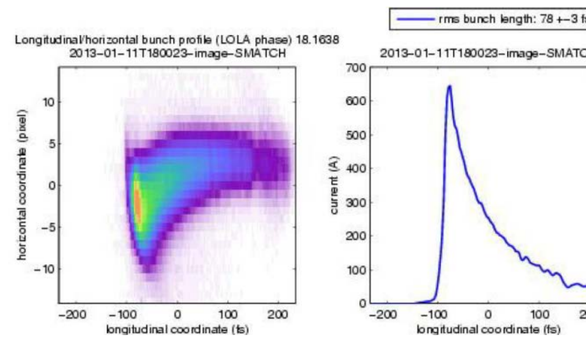
Good agreement between simulation and experimental results is observed.

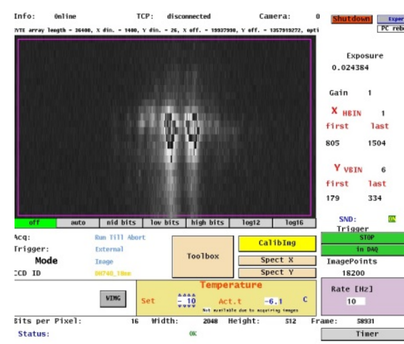
Measured parameters of FLASH FEL

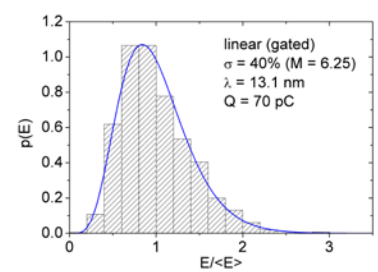
Transverse laser shape	Flat-top
Longitudinal laser shape	Gaussian
Injector laser pulse duration (FWHM)	2.4 ps
Electron energy	689 MeV
Bunch charge	70 pC
rms norm. emittance	0.8-1 mm-mrad
rms electron bunch length	78 fs
Radiation wavelength	13.1 nm
<u>Linear regime (18 m):</u>	
Radiation pulse energy	2 μJ
Fluctuations of pulse energy	40%
Number of modes	6.2
FWHM radiation pulse duration	40 fs
FWHM spectrum width	0.35%
<u>Full length (27 m):</u>	
Radiation pulse energy	25 μJ
Fluctuations of pulse energy	12.5%
FWHM radiation pulse duration	60 fs
FWHM spectrum width	0.42%











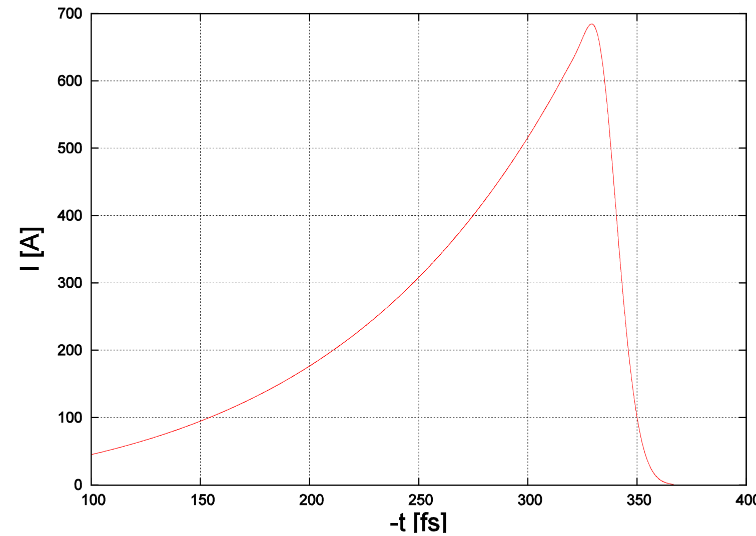
Production of ultra-short radiation pulses
Parameters of the electron bunch for simulations

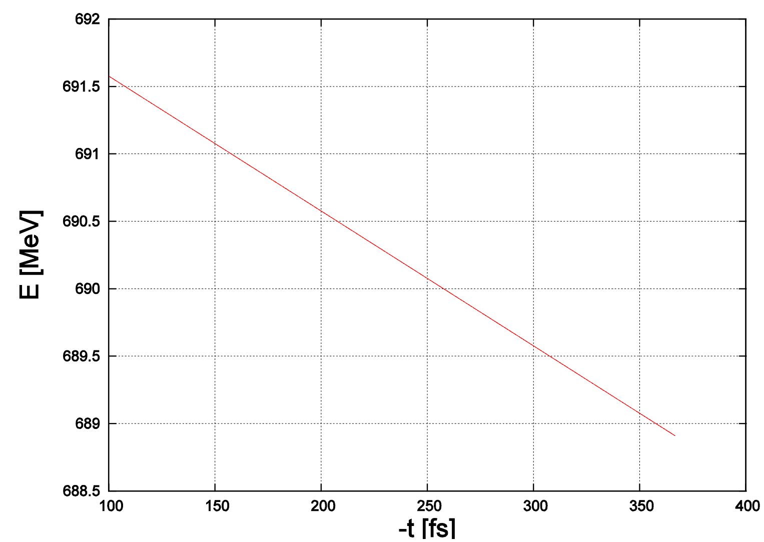
Measured parameters of the electron bunch were used as input for SASE FEL simulation:

Reference electron energy: 689 MeV
Reference peak beam current: 685 A
Bunch charge: 70 pC
Bunch profile: LOLA measurements
rms normalized emittance: 0.8 mm-mrad – 1 mm-mrad
Energy chirp: 10 keV / fs along lasing fraction
Bunch head is on the right-hand side

Optics in the undulator:

- Assumption for an ideal tuning (periodic solution)



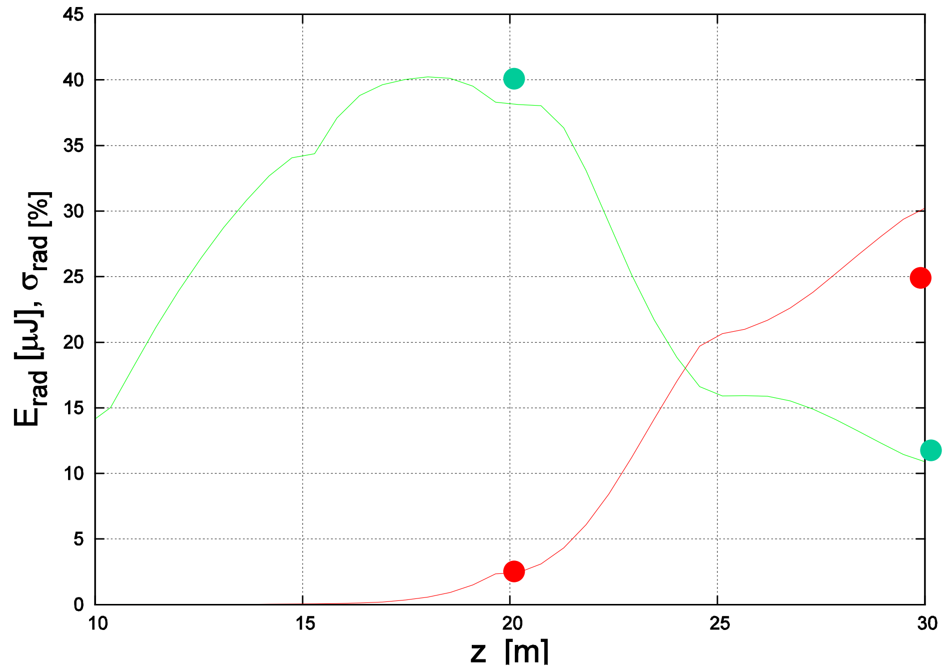


Production of ultra-short radiation pulses
FAST: Average radiation energy and fluctuations

FAST: curves derived from 120 shots

Average energy in the radiation pulse

Deviation of energy fluctuations



Experimental data:

After 4th module (20 m): 2.1 uJ and 40%

After 6th module (30 m): 25 uJ and 12.5%

FAST:

After 4th module (20 m): 2.3 uJ and 39.6% (800 sh.)

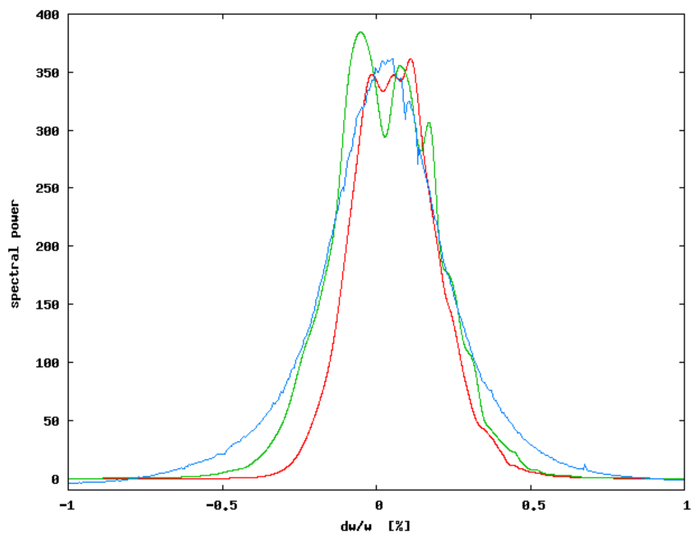
After 6th module (30 m): 30 uJ and 10.5% (120sh.)

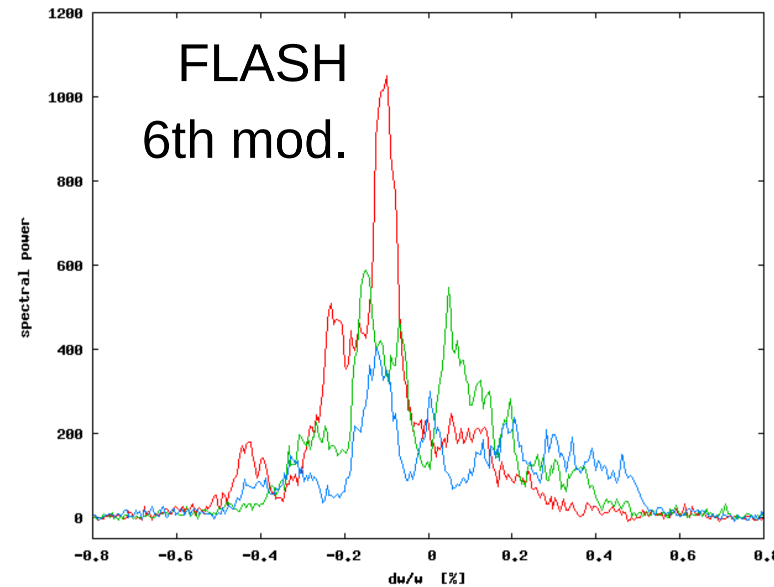
Production of ultra-short radiation pulses
FAST: Radiation spectra

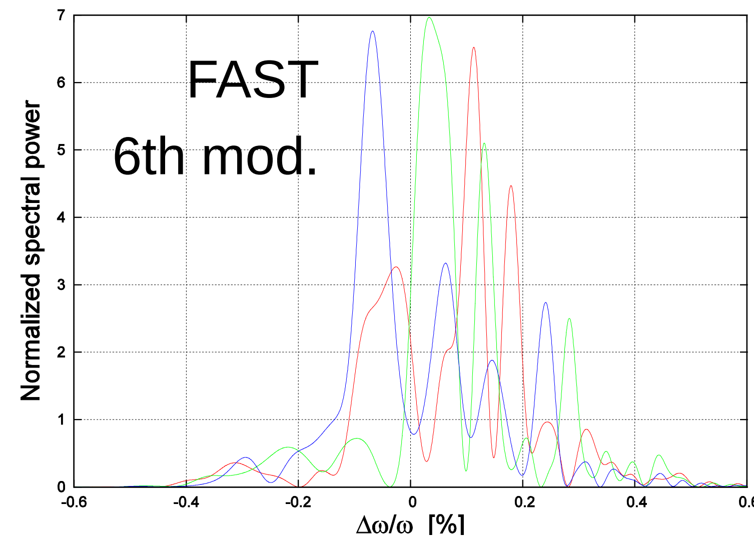
Red: FAST, 4^{th} module

Green: FAST, 6^{th} module

Blue: FLASH, 6^{th} module







Averaged and single shot spectra

Points of output: 4^{th} mod. (z = 20 m) and 6^{th} mod (z = 30 m)

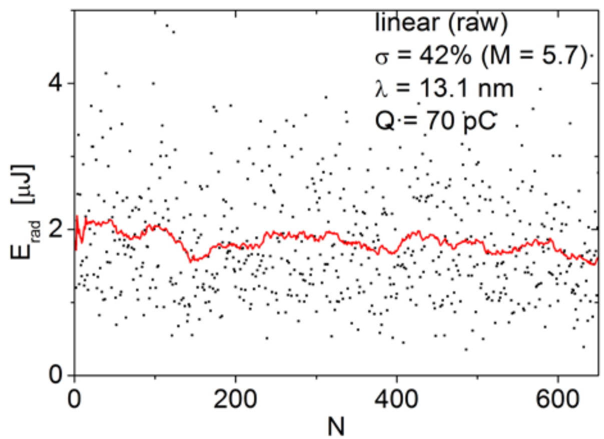
Experimental data for FWHM specrum width:

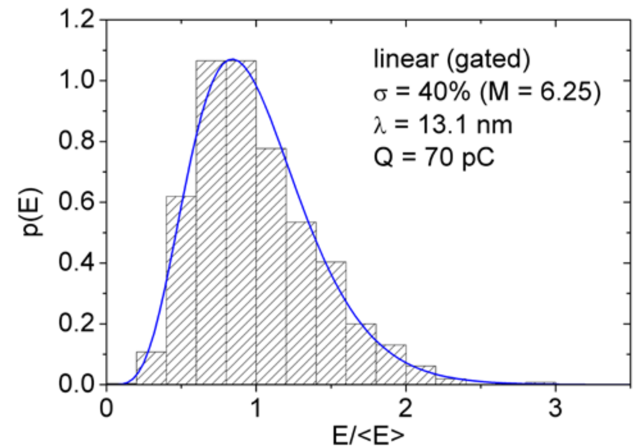
After 4^{th} module (20 m): 0.32%

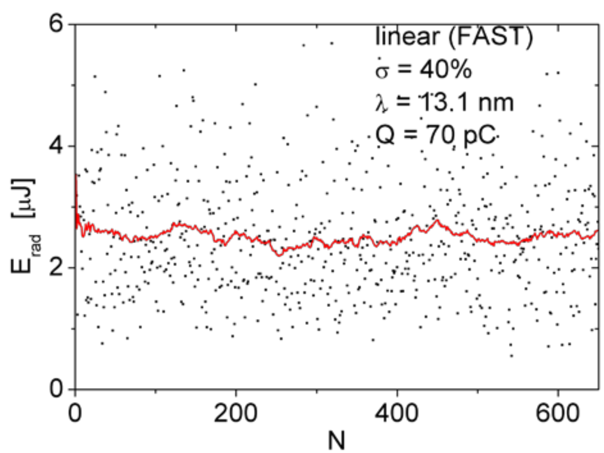
After 6^{th} module (30 m): 0.46%

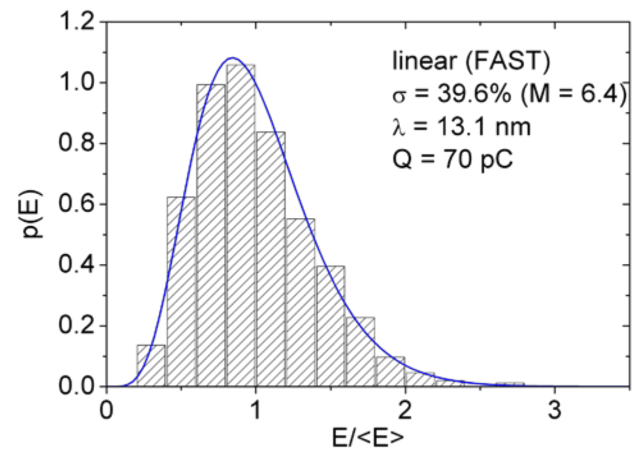
Production of ultra-short radiation pulses

Single-shot pulse energies in the linear regime (after 4 modules)









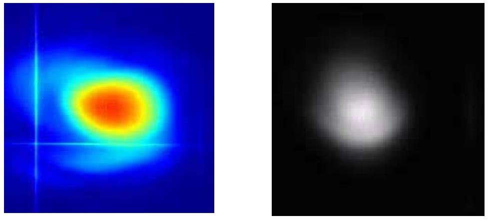
Red curve is averaging over 50 shots.

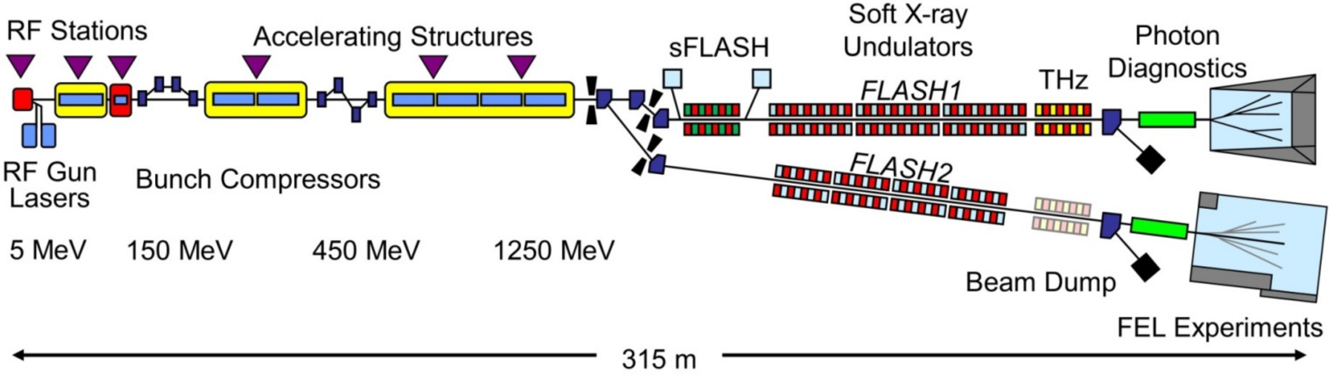
Blue curves present gamma distribution.

FLASH: Transverse coherence and pointing stability

Energy	[GeV]	0.5-1.25	
Wavelength	[nm]	4.1-55 (FLASH1)	
		3.x-8.x (FLASH2)	
Pulse energy	[uJ]	up to 1000	
Rep. rate	[Hz]	5000	
Undulators			
	Period	Length	
FLASH1:	2.73 cm	27 m (6 x 4.5 m modules)	fixed gap
FLASH2:	3.14 cm	30 m (12 x 2 m modules)	variable gap

FLASH experiment : 2006 2015

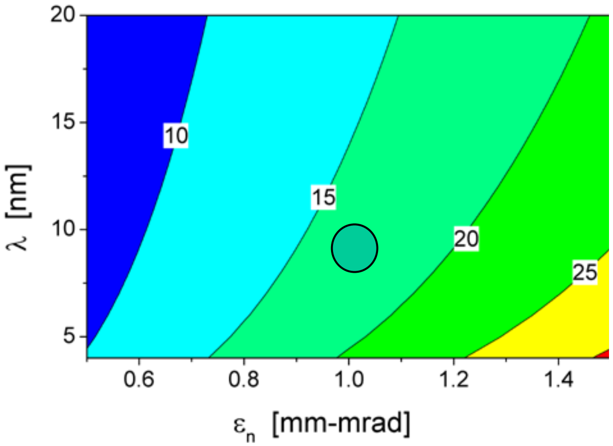


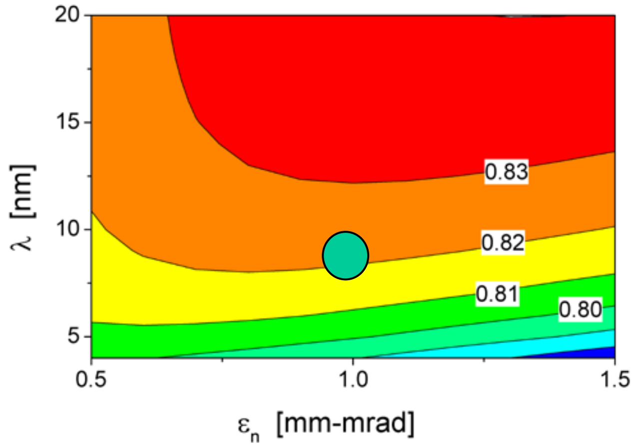


Observation at FLASH:

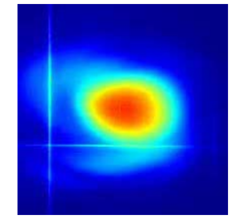
- The degree of transverse coherence is visibly less than unity in the post-saturation regime
- Transverse shape of the photon pulse is not stable.
- Pointing stability is not perfect.
- Pointing stability degrades for shorter photon pulses.

FLASH: Transverse coherence and pointing stability

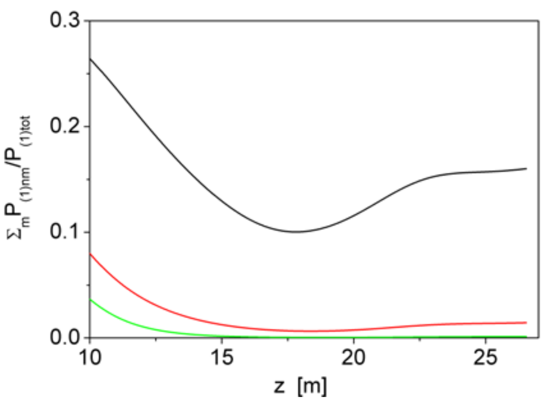


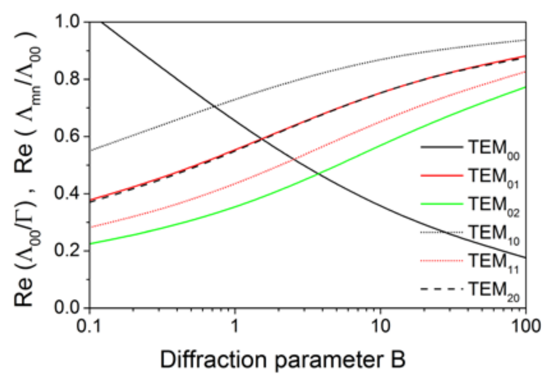


FLASH: experiment



FLASH: FAST simulations





Parameter space of FLASH:

Large values of diffraction parameter (B = 10 - 25) and “cold” electron beam.

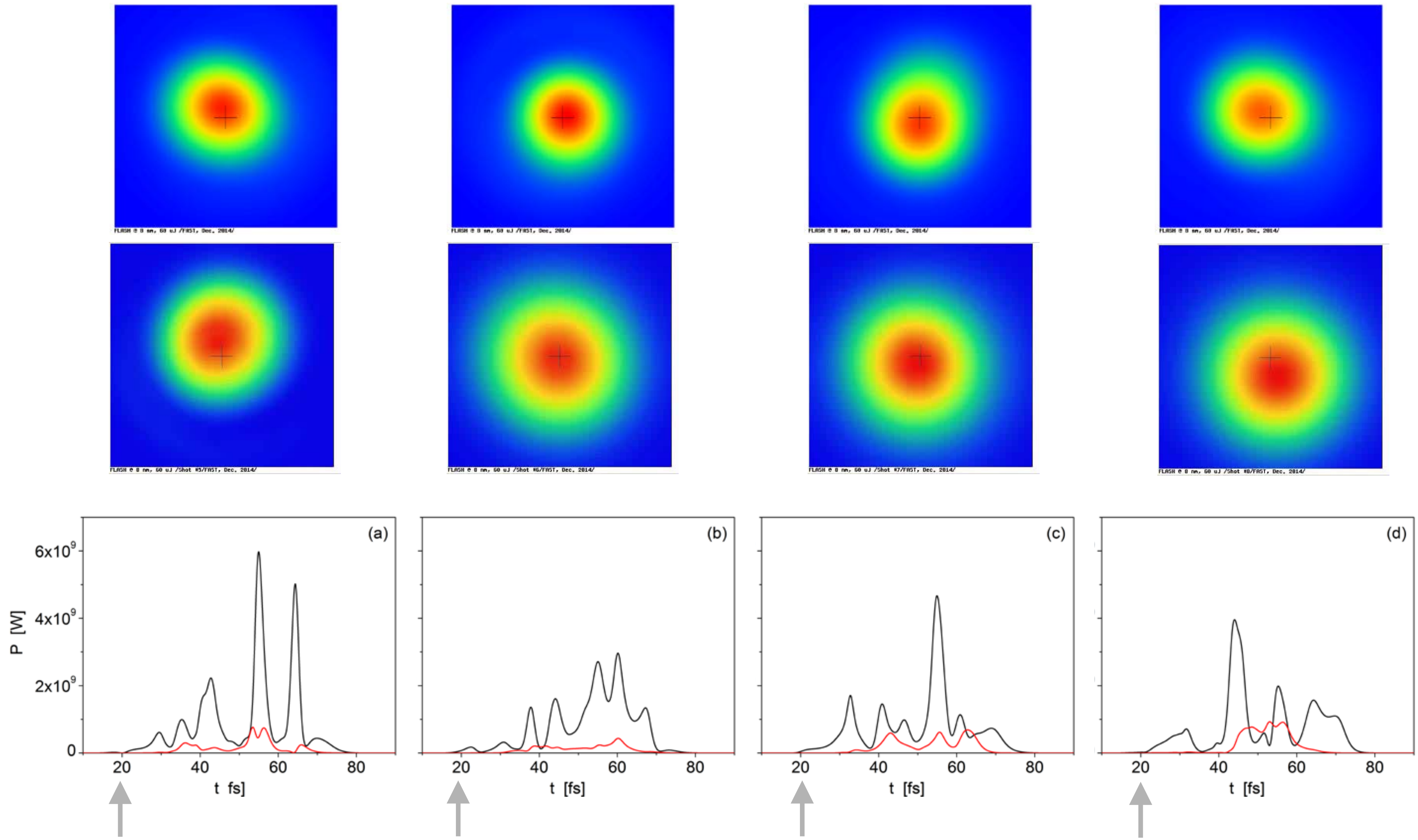
Mode degeneration effect is strong (gain of TEM_{10} mode is 0.8 – 0.83 of the fundamental TEM_{00}).

Contribution of the first azimuthal mode to the total power is 10 to 15%.

Result: unstable shape and pointing of the photon pulse.

FLASH: Transverse coherence and pointing stability

FLASH: FAST simulations



Evolution of the intensity distribution in the far zone along radiation pulse.

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Photon and electron beam diagnostics at FLASH

Electron beam:

Electron beam energy.

Measurements of the bunch charge with toroids and rf techniques.

Measurements of orbit.

Longitudinal phase space tomography with transverse deflecting cavity.

Transverse phase space tomography with screens.

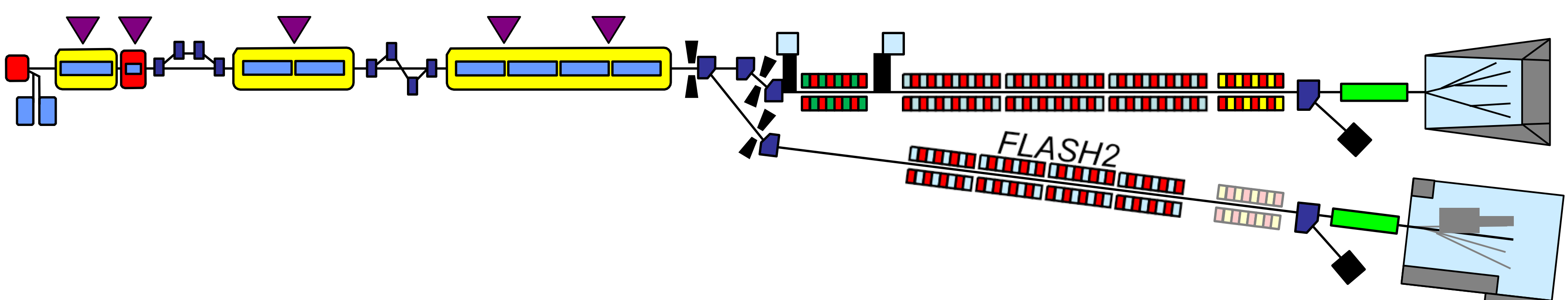
Photon beam:

Average radiation pulse energy with gas monitor detector (GMD).

Single pulse energy and statistical measurements with MCP based detector.

Single shot spectra with plane grating monochromator (PGM).

Single shot radiation pulse profile with CeYaG screen (qualitative data).



Statistical fluctuation method

- SASE FEL operating in linear regime holds features of completely chaotic polarized light - fundamenatl statistical object described by gaussian statistics.

- The probability density function of the radiation pulse energy, $p(E)$, follows the gamma distribution:

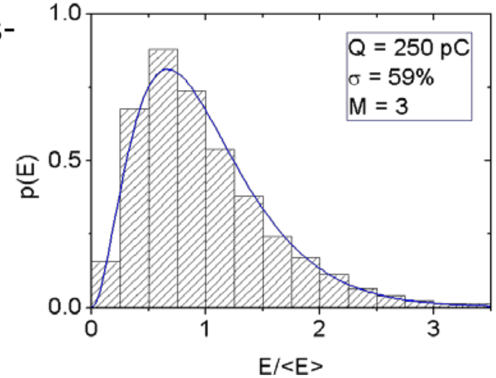
$$p(E) = \frac{M^M}{\Gamma(M)} \left(\frac{E}{<E>}\right)^{M-1} \frac{1}{<E>} \exp\left(-M\frac{E}{<E>}\right) \ ,$$
$$M^{-1} = \sigma^2 = < (E - < E >)^2 > / < E >^2$$

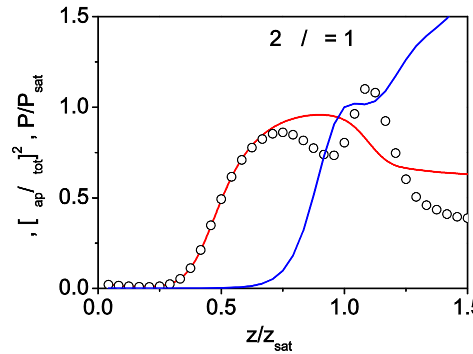
  Parameter M has physical sence of the number of modes in the radiation pulse.

- Total number of modes is product of the number of longitudinal modes by the number of transverse modes.

- Measurements of the fluctuations of the total pulse energy and of the radiaiton energy after a pinhole gives us the number of longitudinal modes, and the total number of modes.

- Their ratio gives the number for the degree of transverse coherence.



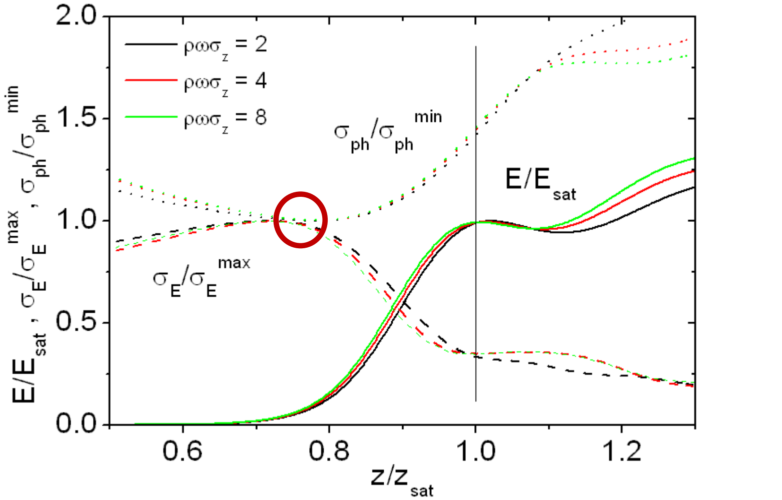


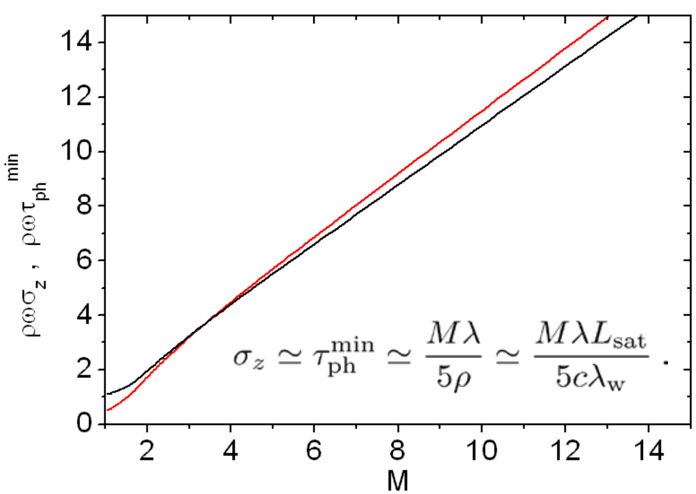
Degree of transverse coherence (red)
FEL power (blue).
Circles: the ratio of fluctuations of the total radiation energy to the fluctuations of the radiation energy in a pinhole.

V. Ayvazyan et al., Pys. Rev. Lett. 2002
S. Ackermann et al., Nature Photonics 1 (2007) 346.
C. Behrens et al., Phys. Rev. ST Accel. Beams 15, 030707 (2012)
E.A. Schneidmiller and M.V. Yurkov, Proc. IPAC2016, MOPOW013.

Statistical fluctuation method
Coherence time. Pulse duration

C. Behrens et al., Phys. Rev. ST Accel. Beams 15, 030707 (2012)





Maximum value of the coherence time and saturation length

$$(\tau_{\rm c})_{\rm max} \simeq \frac{1}{\rho\omega}\sqrt{\frac{\pi \ln N_{\rm c}}{18}}\,, \qquad L_{\rm sat} \simeq \frac{\lambda_{\rm w}}{4\pi\rho}\left(3 + \frac{\ln N_{\rm c}}{\sqrt{3}}\right)\,,$$

are expressed in terms of the FEL parameter ρ and the number of cooperating electrons $N_{\rm c} = I/(e\rho\omega)$. Practical estimate for parameter ρ comes from the observation that in the parameter range of SASE FELs operating in the VUV and x-ray wavelength range, the number of field gain lengths to saturation is about 10. Thus, the parameter ρ and coherence time $\tau_{\rm c}$ relate to the saturation length as:

$$\rho \simeq \lambda_{\rm w}/L_{\rm sat}\,, \qquad \tau_{\rm c} \simeq \lambda L_{\rm sat}/(2\sqrt{\pi}c\lambda_{\rm w})\,.$$

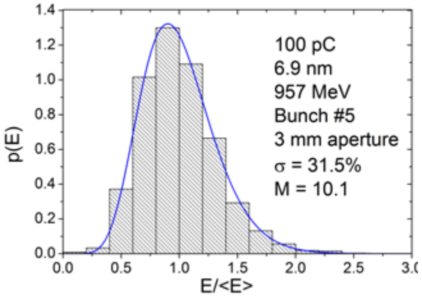
For the number of modes $M \gtrsim$ 2m the rms electron pulse length and minimum FWHM radiation pulse length $\tau_{\rm ph}^{\rm min}$ in the end of the linear regime are given by:

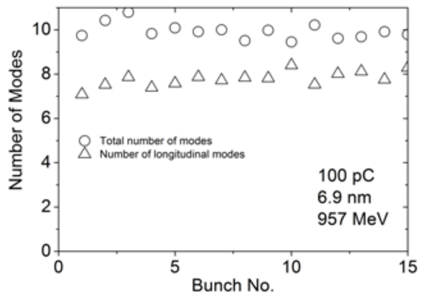
$$\tau_{\rm ph}^{\rm min} \simeq \sigma_z \simeq \frac{M\lambda}{5\rho} \simeq \frac{M\lambda L_{\rm sat}}{5c\lambda_{\rm w}}\,.$$

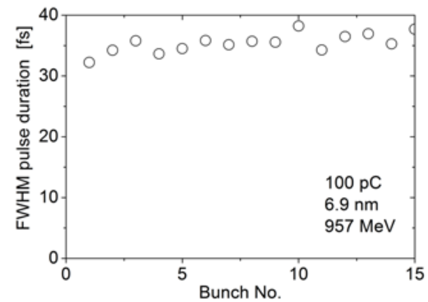
Minimum radiation pulse duration expressed in terms of coherence time is $\tau_{\rm ph}^{\rm min} \simeq 0.7 \times M \times \tau_{\rm c}$.

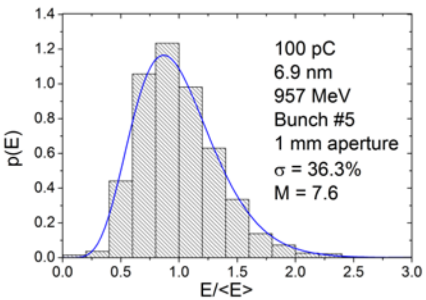
Statistical fluctuation method
Degree of transverse coherence

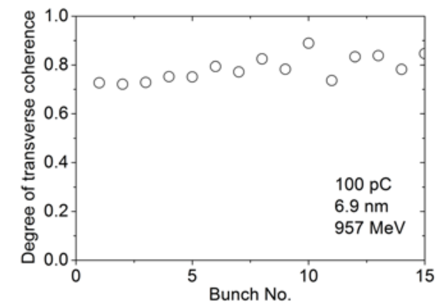
Experimental results from FLASH1, 01.05.2016







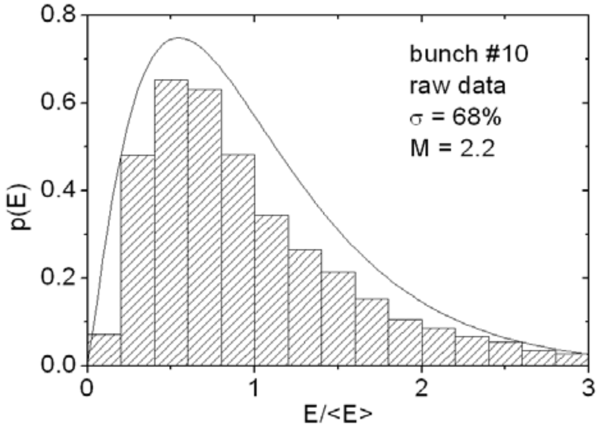


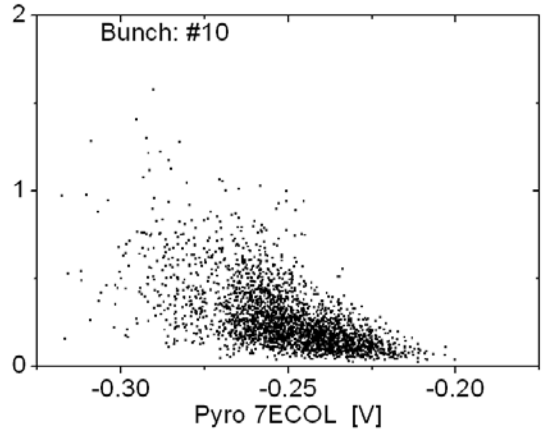


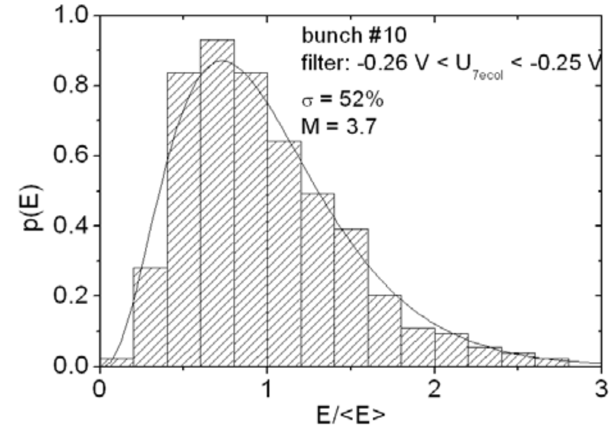
- Fast MCP detector is been used for radiation energy measurements. The electronics of MCP-detector has low noise, about 1 mV at the level of signal of 100 mV (1% relative measurement accuracy).
- Two measurements: full radiation energy, and the energy after pinhole give us total number of modes, and number of longitudinal modes.
- The degree of transverse coherence is given by $\zeta = M_{ap}/M_{tot}$.
- Knowledge of the number of longitudinal modes gives us the radiation pulse duration.

Statistical fluctuation method
Gaiting of machine fluctuations

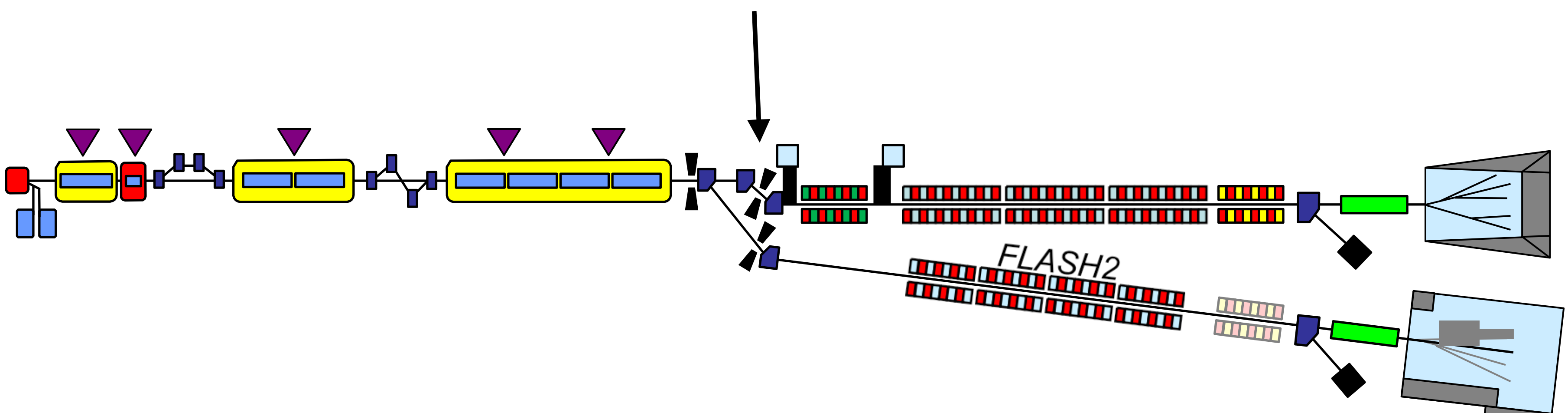
Example from: C. Behrens et al., Phys. Rev. ST Accel. Beams 15, 030707 (2012)







Pyrodetector



Statistical fluctuation method

- Statistical measurements of the radiation pulse energy is extremely powerful technique for characterization of the main SASE FEL parameters: FEL parameter ρ, coherence time, photon pulse duration, and the degree of transverse coherence.

- It is based on fundamental principles, and measured values have strict physical meaning.

- By now FLASH is the only facility where statistical measurements are routinely used for SASE FEL characterization.

- Statistical measurements are conceptually simple, but rely on two important technical requirements. The first requirement is availability of fast and precise radiation detector capable to measure radiation energy of every pulse with high relative accuracy in a wide range of radiation intensities. At FLASH we use MCP detector with relative accuracy of measurements better than 1%.

- The second requirement is small jitter of the machine parameters, much less than the fundamental SASE FEL fluctuations. Good phase stability of the superconducting accelerator FLASH helps a lot. In addition, success of the technique depends on the quality of diagnostics allowing to detect jitters of the electron beam and machine parameters.

Outline

I. Introduction to FLASH facility.

II. Practical guide on analysis of SASE FEL operation.

III. TESLA Test Facility FEL, Phase I: nonlinear compression and production of ultra-short radiation pulses.

IV. Present day performance of FLASH: (i) Example from the program for production of ultra-short radiation pulses; (ii) Transverse coherence and pointing stability.

V. Development of statistical methods for measurements of the main parameters of SASE FEL radiation.

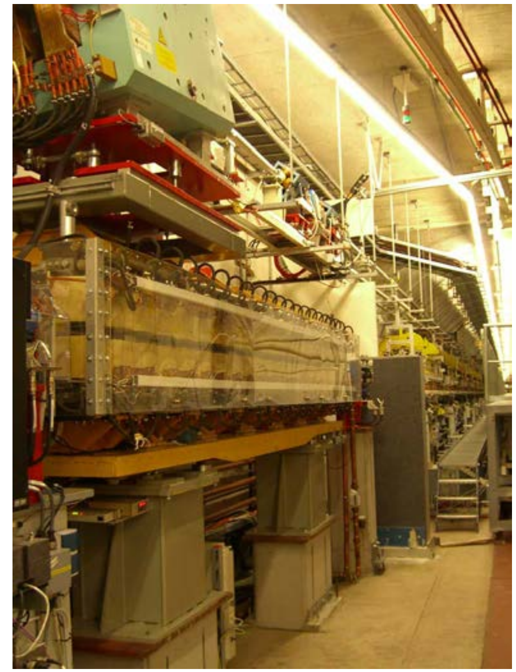
VI. Advanced developments: FIR undulator, optical afterburner for SASE FEL, optical replica synthesizer, undulator tapering for efficiency increase, reverse undulator tapering, harmonic lasing and harmonic lasing self-seeding, external seeding developments.

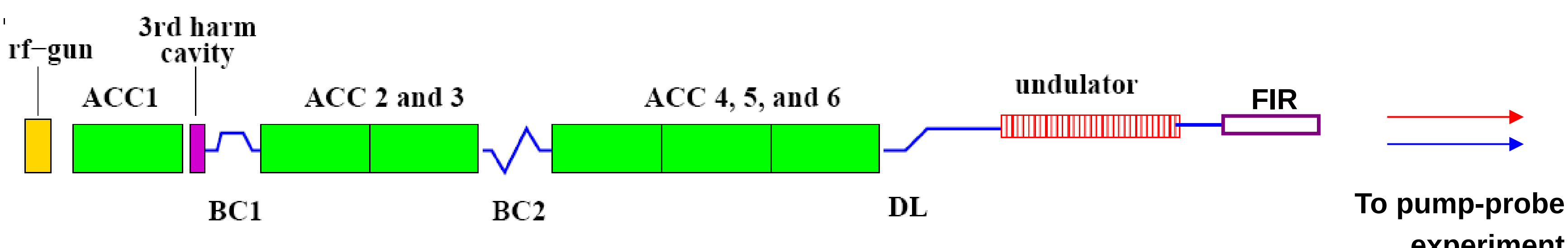
FIR undulator at FLASH: tool for femtosecond resolution pump-probe experiments

Electron beam	
Energy	500-1250 MeV
Number of electrons per bunch	6×10^9
rms bunch length	10-50 μm
Undulator	
Type	Planar, EM
Period	40 cm
Peak magnetic field	0–1.8 T
Number of periods	9
Output radiation (into central cone)	
Wavelength	a few to $\sim$ 200 μm
Bandwidth	Transform-limited
Peak power	up to 50 MW
Micropulse energy	fraction of mJ

$$\langle P(\omega)\rangle = p(\omega)[N + N(N-1)|\bar{F}(\omega)|^2] \ ,$$

$$F(t) = \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left(-\frac{c^2t^2}{2\sigma_z^2}\right) \quad , \quad \bar{F}(\omega) = \exp\left(-\frac{\omega^2\sigma_z^2}{2c^2}\right) \ .$$





FIR undulator at FLASH: tool for femtosecond resolution pump-probe experiments

nature photonics

ARTICLES

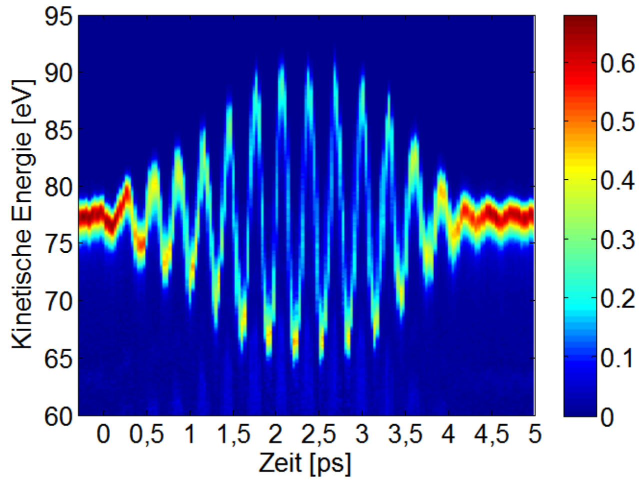
PUBLISHED ONLINE: 23 AUGUST 2009 | DOI: 10.1038/NPHOTON.2009.160

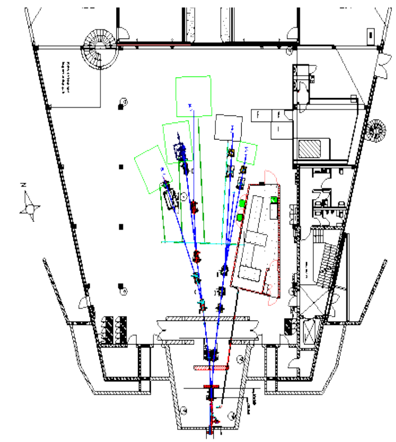
Single-shot terahertz-field-driven X-ray streak camera

Ulrike Frühling[1], Marek Wieland[2], Michael Gensch[1,3], Thomas Gebert[2], Bernd Schütte[2], Maria Krikunova[2], Roland Kalms[2], Filip Budzyn[2], Oliver Grimm[2,4], Jörg Rossbach[2], Elke Plönjes[1] and Markus Drescher[2*]

Courtesy of Ulrike Frühling

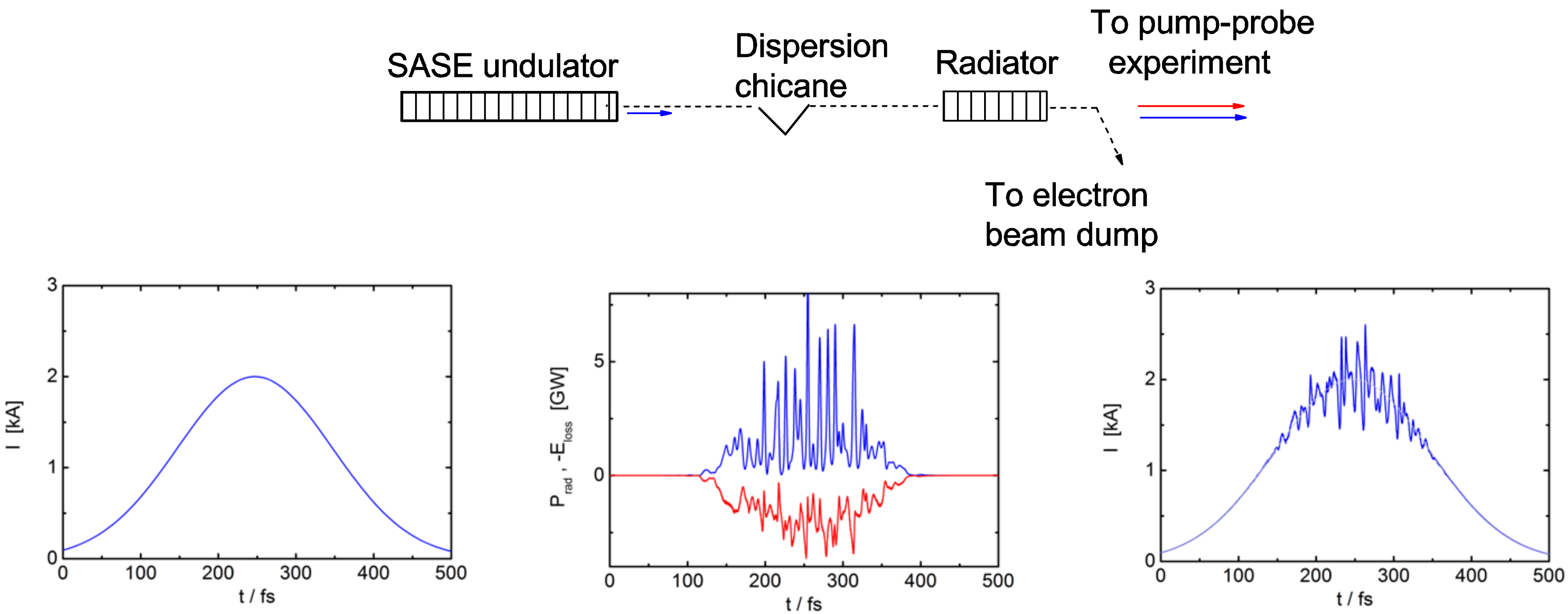
FLASH: 13.5 nm
FIR: 85 μm
Gas: Krypton (4p)





- Two beams (FIR and soft X-ray) were transported about 100 m via separate beam lines and combined in time and space. Measured timing jitter was less than 5 fs rms.
- Currently dedicated beamline and user station at FLASH serve pump-probe user experiments using precisely synchronized FIR and x-ray pulses.

Optical afterburner for SASE FEL at FLASH



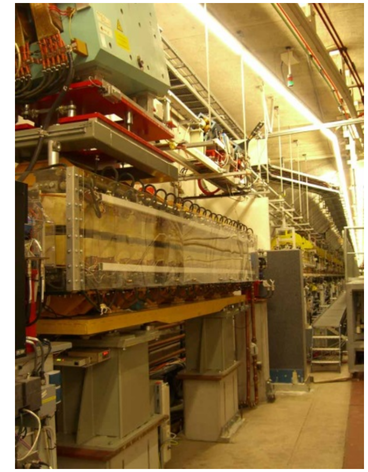
- Electron beam produces x-ray modulation in main undulator and gains mean spiky energy loss on a scale of coherence length.
- This energy loss is converted to the current modulation in the dispersion section.
- Optical replica of X-ray pulses is produced in the radiator.
- X-ray pulse and optical replica are naturally synchronized.

E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Phys. Rev. ST Accel. Beams 13 (2010) 030701.

Optical afterburner for SASE FEL at FLASH

<u>Undulator</u>

Type	Planar, EM
Period	40 cm
Peak magnetic field	0–1.8 T
Number of periods	9

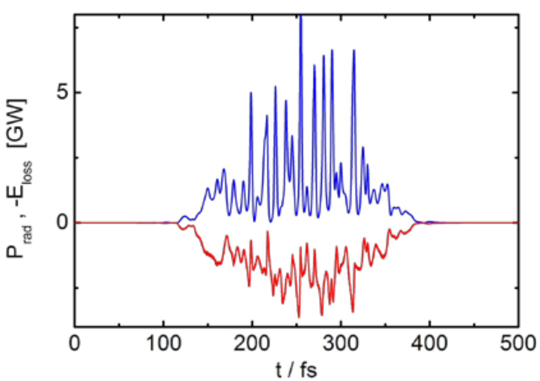


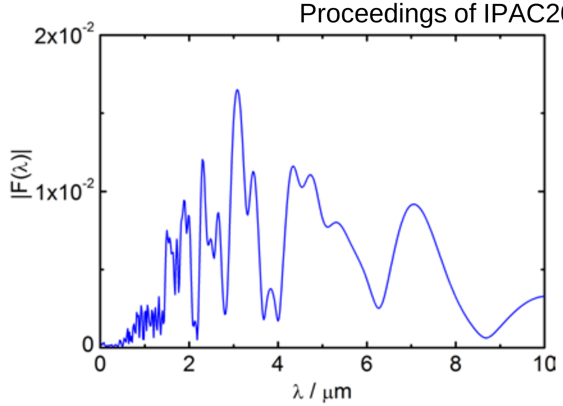
$$\langle P(\omega)\rangle = p(\omega)[N + N(N-1)|\bar{F}(\omega)|^2]\ ,$$

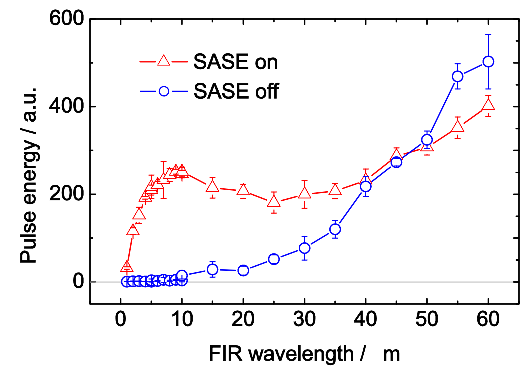
$$F(t) = \frac{1}{\sqrt{2\pi}\sigma_z}\exp\left(-\frac{c^2t^2}{2\sigma_z^2}\right)\quad ,\quad \bar{F}(\omega) = \exp\left(-\frac{\omega^2\sigma_z^2}{2c^2}\right)\ .$$

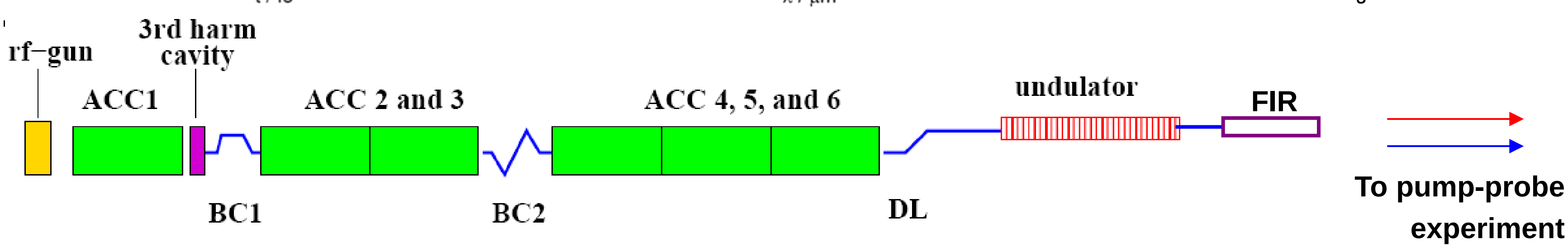
FIR undulator simultaneously serves as dispersion section and radiatior.

M. Foerst et al., Optical Afterburner for a SASE FEL: First Results from FLASH, Proceedings of IPAC2011, San Sebastian, Spain, 2011, THPC084, p. 3089.



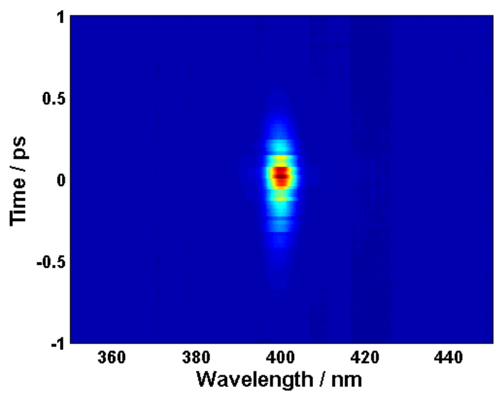


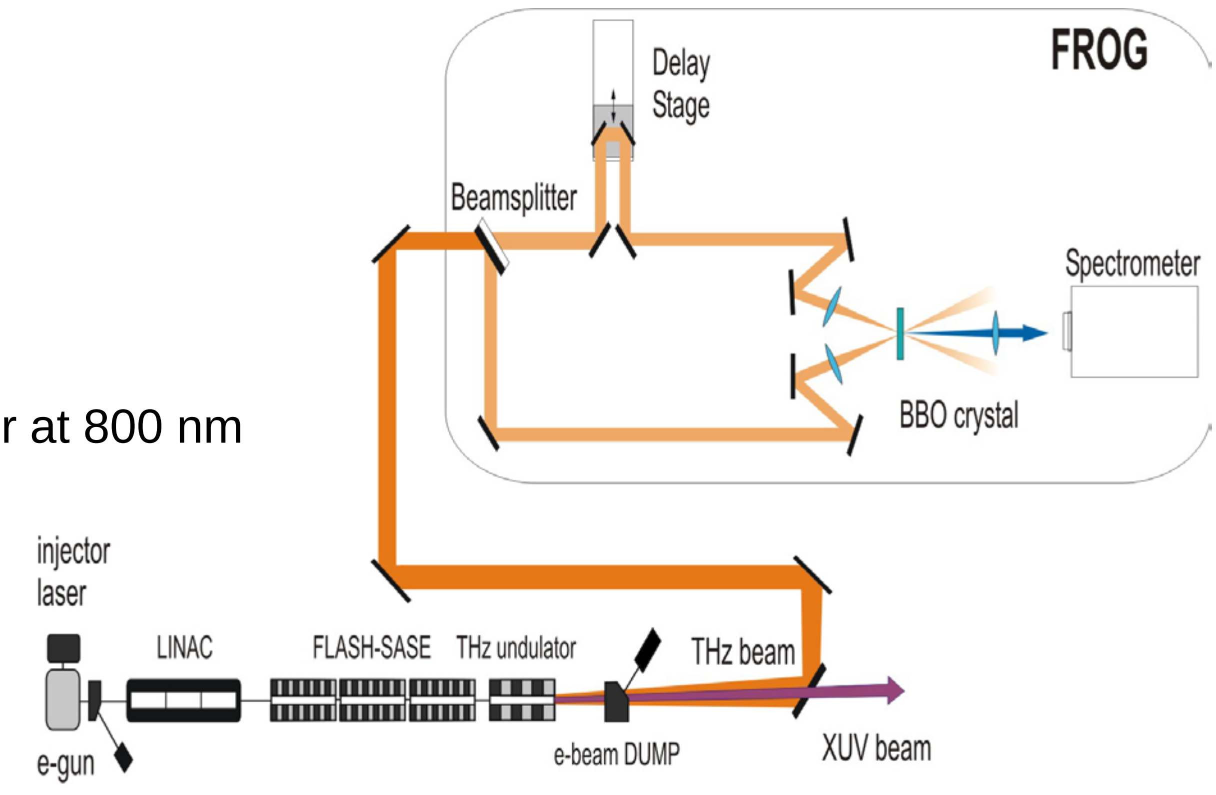




Optical afterburner for SASE FEL at FLASH
On-line monitoring of x-ray pulse duration

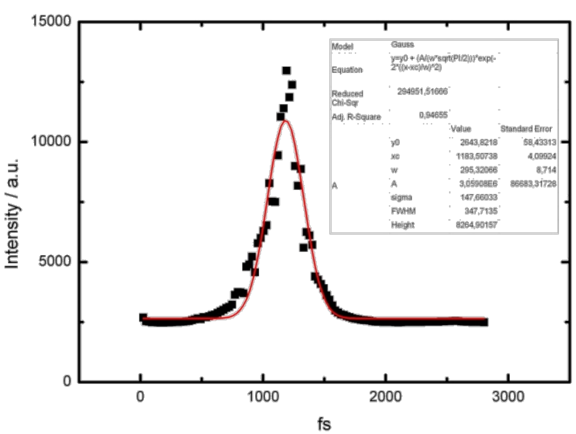
- “Visualization” of X-ray pulse, i.e. translating its width and shape into optical range (making “optical replica”).
- On-line measurement with FROG or similar devices of optical replica.





This work is supported by the BMBF grant nr. 05K10CHC and a collaboration of DESY, HZDR, TUB, FUB.

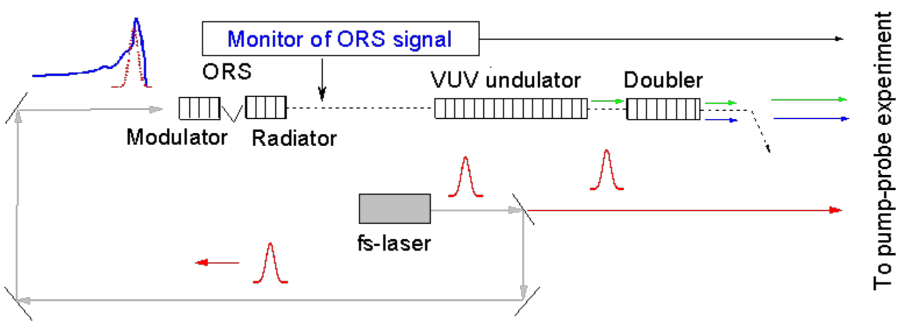
SASE at 8 nm, FIR undulator at 800 nm



Optical replica synthesizer (ORS)
Slice diagnostics of electron beam parameters

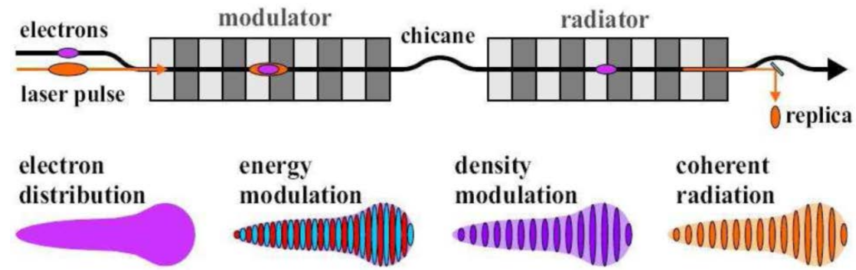
- Main purpose: measurements of electron bunch profile with a few femtosecond resolution. Envelope of optical pulse produced ORS repeats envelope of the electron pulse, and is analysed with standard optical techniques like frequency resolved optical gating (FROG).

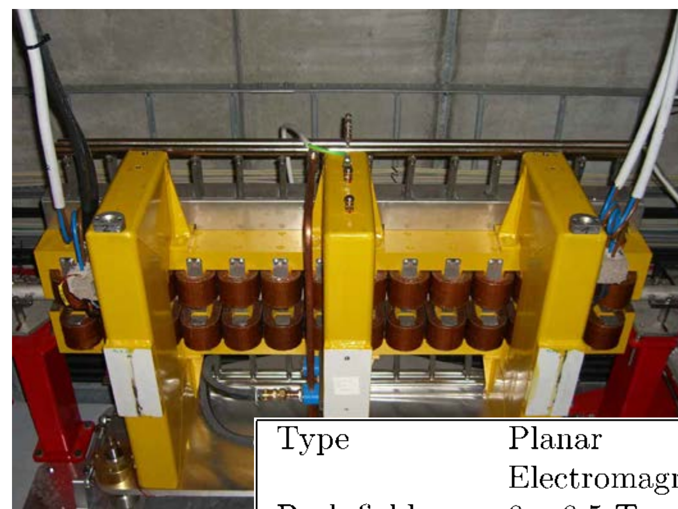
- Future potential: organization of pump-probe experiments with 10 fs temporal resolution.



- Pump-probe experiments involving VUV radiation and external fs laser. Optical replica is used for selection of synchronized pulses.

Optical replica synthesizer





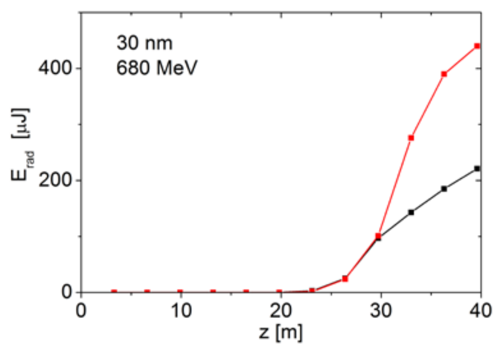
Type	Planar Electromagnetic
Peak field	0 – 0.5 T
Period length	20 cm
# of periods	5

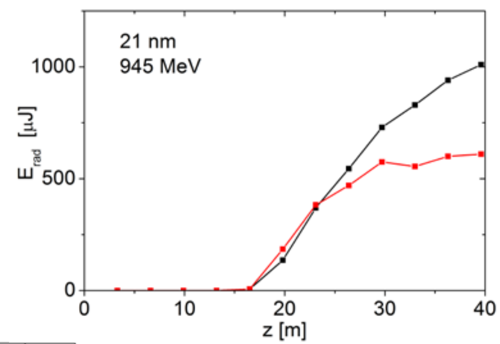
Advanced developments
Undulator tapering for efficiency increase

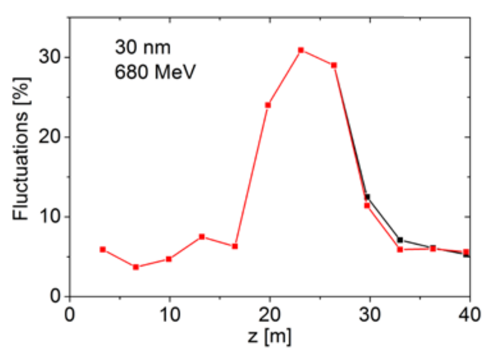
Use of statistical measurements for tuning optimum undulator tapering:

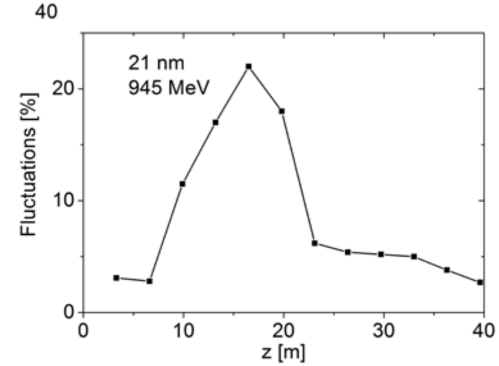
- Optimum conditions of the undulator tapering assume the starting point to be by two field gain lengths before the saturation point (corresponding to the maximum brilliance of the SASE FEL radiation).
- Saturation point on the gain curve is defined by the condition for fluctuations to fall down by a factor of 3 with respect to their maximum value in the end of exponential regime.
- Then quadratic law of tapering is applied (optimal for moderate increase of the extraction efficiency at the initial stage of tapering).

Experimental results from FLASH 2, January-May 2016









Advanced developments
Reverse undulator tapering

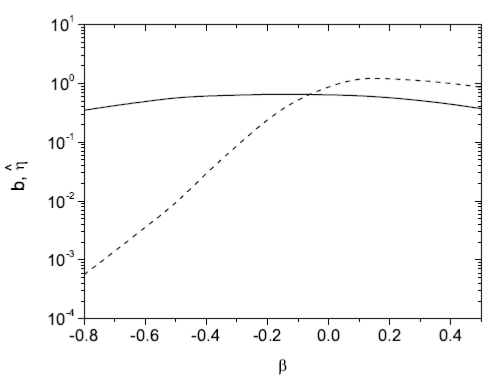
reverse-tapered planar undulator (saturation)

helical afterburner

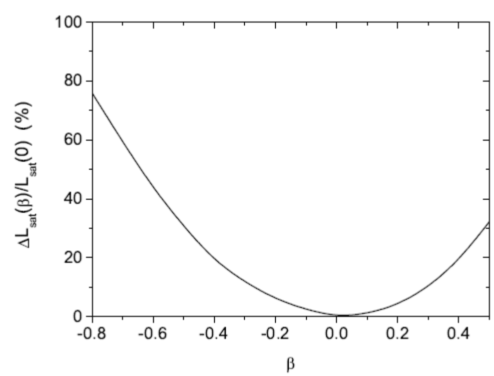
- Fully microbunched electron beam but strongly suppressed radiation power at the exit of reverse-tapered planar undulator
- The beam radiates at full power in the helical afterburner tuned to the resonance

b - bunching factor (0<b<1)

$\hat{\eta} = P/(\rho P_{\mathrm{beam}})$ - normalized power (efficiency)



Bunching and power at saturation

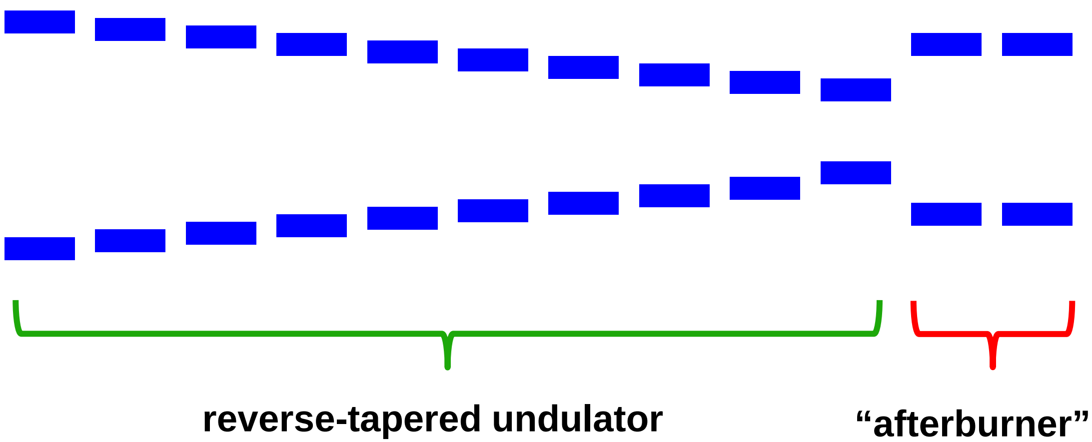


Relative increase of the saturation length

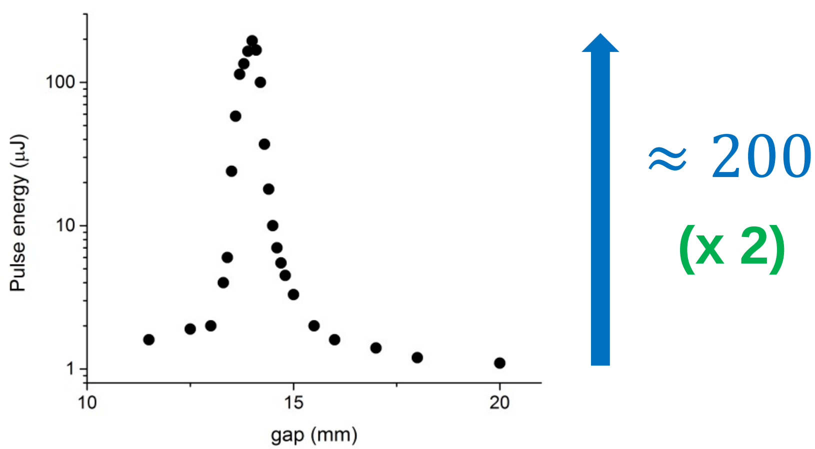
E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 110702(2013)16

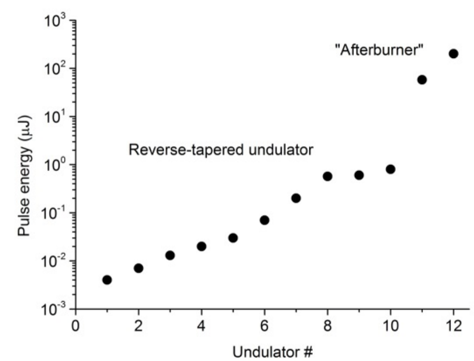
Advanced developments
Reverse undulator tapering

Experiment at FLASH2 on 23.01.2016



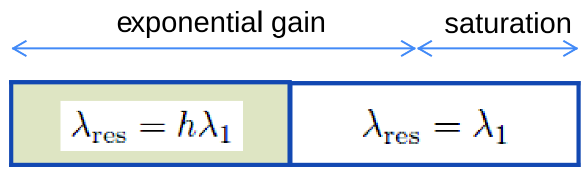
- Beam energy 720 MeV,
- Wavelength 17 nm.
- Reverse taper of 10% along 10 undulator segments;
- The gap of the 11th and 12th segments was scanned.
- Power ratio of 200 was obtained. For a helical afterburner it would be larger by a factor of 2.





E. Schneidmiller and M. Yurkov, Proc. IPAC2016, MOPOW008

Advanced developments
Harmonic lasing self-seeding (HLSS)



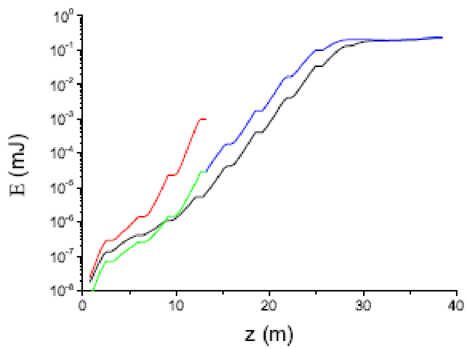


Figure 2: FEL pulse energy versus undulator length. In the first part of the undulator (tuned to the resonance with 39 nm) the first (red) and the third (green) harmonics are shown. The third harmonic continues to get amplified in the second part of the undulator (now as the fundamental) tuned to 13 nm (shown in blue). A reference case of lasing at 13 nm on the fundamental in the whole undulator with constant K-value is shown in black.

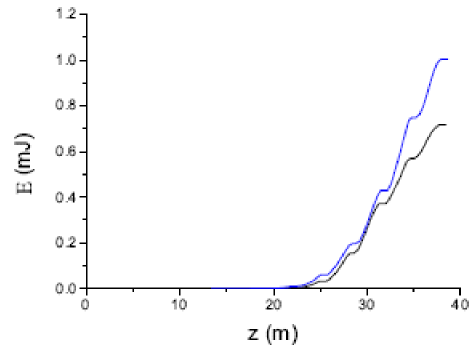


Figure 3: FEL pulse energy versus undulator length when the post-saturation taper is applied. HLSS case is shown in blue, and the SASE case - in black.

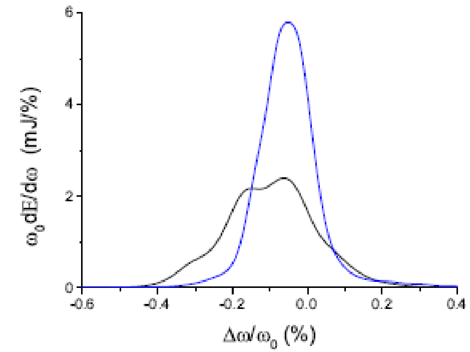


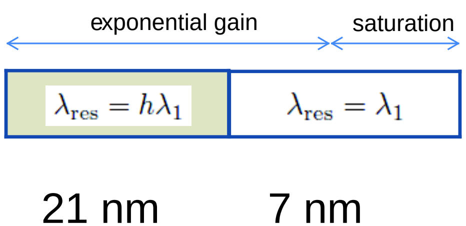
Figure 4: Spectral density of the radiation energy for HLSS FEL configuration (blue) and for SASE FEL (black).

- A gap-tunable planar undulator is divided into two parts such that the first part is tuned to a sub-harmonic of the second part.
- Harmonic lasing occurs in the exponential gain regime in the first part of the undulator,
- In the second part of the undulator the fundamental mode is resonant to the wavelength, previously amplified as the harmonic, and amplification process proceeds to saturation.
- Benefits of HLSS: improvement of the longitudinal coherence, reduction of the spectrum width, and increase of spectral brightness.
- Application of the post-saturation tapering would allow to generate higher peak power than in SASE mode due to an improved longitudinal coherence.

Advanced developments
Harmonic lasing self-seeding (HLSS)

Experiment at FLASH2 on May 1, 2016 (945 MeV, 400 pC, 7 nm):

- Demonstration of harmonic lasing in a high-gain FEL;
- Demonstration of HLSS scheme.



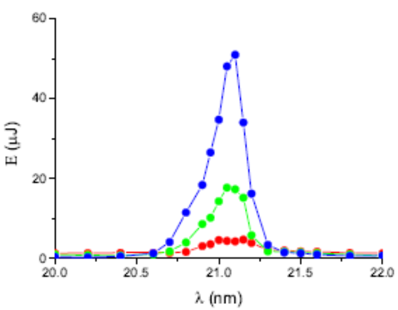
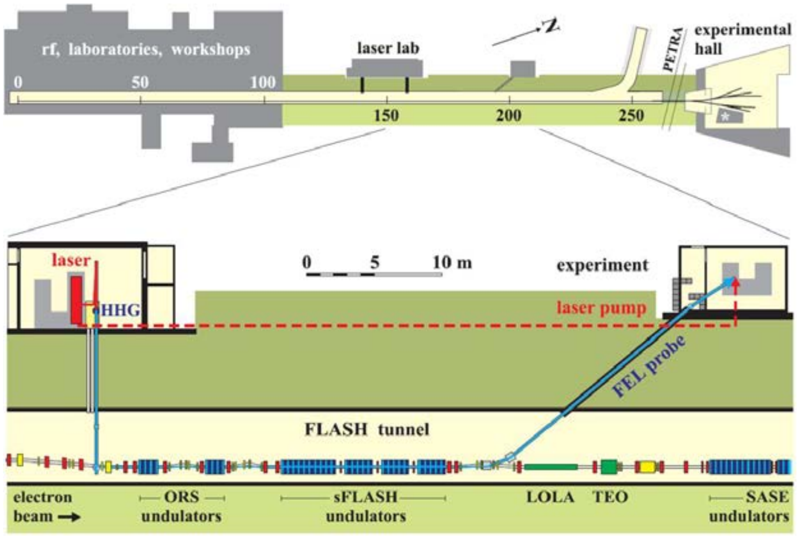


Figure 5: Scan of the resonance wavelength of the first part of the undulator consisting of one undulator section (red), two sections (green), and three sections (blue). Pulse energy is measured after the second part of the undulator tuned to 7 nm.

- Initially 10 undulator sections were tuned to the exponential gain regime at 7 nm; the pulse energy was 12 μJ.
- Then the first section was detuned from 7nm (the pulse energy was reduced to about 1 μJ), tuned to the third subharmonic and scanned around 21 nm (red curve).
- Then measurements were repeated with the first two sections, and then with the first three sections (green and blue curves).
- Pulse energy at 21 nm wavelength from 3 undulator section was 40 nJ, far away from saturation, thus excluding mechanism of the nonlinear harmonic generation in the first part of the undulator.
- The effect is essentially resonant. For example, in the case when 3 undulator sections were scanned, the ratio of pulse energies at the optimal tune, 21.1 nm, and at 20 nm is 51 μJ/0.3 μJ $=$ 170. The actual ratio might have been even larger, because the radiation at 21 nm (even being much weaker than 0.3 μJ) is more efficiently detected.

E. Schneidmiller and M. Yurkov, Proc. IPAC2016, MOPOW009

Seeding developments



The FLASH facility comprises a 260m long tunnel housing the linac and undulators of the SASE FEL, followed by an experimental hall with photon beamlines. A 40m long section preceding the SASE undulators has been remodeled to accommodate additional undulators for sFLASH. Seed pulses from high-harmonic generation (HHG) in a building adjacent to the FLASH tunnel are aligned to the electron beam at a dogleg chicane (left). At the undulator exit, the electron beam will be displaced while FEL radiation is sent by mirrors to an experimental hutch. Delayed laser pulses will be sent directly to the hutch for pump probe applications (dashed line). Also shown are dipole magnets and steerers (yellow), quadrupoles (red) and devices for longitudinal bunch diagnostics (ORS, LOLA and TEO)

http://photon- science.desy.de/research/research_teams/x_ray_femtochemistry_and_cluster_physics/research/research_fields/hhg_seeding_at_flash/index_eng.html

Seeding developments

PRL 111, 114801 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Generation of Coherent 19- and 38-nm Radiation at a Free-Electron Laser Directly Seeded at 38 nm

S. Ackermann,[1,2] A. Azima,[1,5,6] S. Bajt,[2] J. Bödewadt,[1,5,*] F. Curbis,[1,†] H. Dachraoui,[2] H. Delsim-Hashemi,[2] M. Drescher,[1,5,6] S. Düsterer,[2] B. Faatz,[2] M. Felber,[2] J. Feldhaus,[2] E. Hass,[1] U. Hipp,[1] K. Honkavaara,[2] R. Ischebeck,[4] S. Khan,[3] T. Laarmann,[2,6] C. Lechner,[1] Th. Maltezopoulos,[1,5] V. Miltchev,[1] M. Mittenzwey,[1] M. Rehders,[1,5] J. Rönsch-Schulenburg,[1,5] J. Rossbach,[1,5] H. Schlarb,[2] S. Schreiber,[2] L. Schroedter,[2] M. Schulz,[1,2] S. Schulz,[2] R. Tarkeshian,[1,‡] M. Tischer,[2] V. Wacker,[1] and M. Wieland[1,5,6]

[1]*Department of Physics, University of Hamburg, 22761 Hamburg, Germany*
[2]*Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany*
[3]*Technische Universität Dortmund, 44227 Dortmund, Germany*
[4]*Paul Scherrer Institut, 5323 Villigen, Switzerland*
[5]*Center for Free-Electron Laser Science CFEL, DESY, 22607 Hamburg, Germany*
[6]*The Hamburg Centre for Ultrafast Imaging CUI, 22761 Hamburg, Germany*

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Initiating the gain process in a free-electron laser (FEL) from an external highly coherent source of radiation is a promising way to improve the pulse properties such as temporal coherence and synchronization performance in time-resolved pump-probe experiments at FEL facilities, but this so-called "seeding" suffers from the lack of adequate sources at short wavelengths. We report on the first successful seeding at a wavelength as short as 38.2 nm, resulting in GW-level, coherent FEL radiation pulses at this wavelength as well as significant second harmonic emission at 19.1 nm. The external seed pulses are about 1 order of magnitude shorter compared to previous experiments allowing an ultimate time resolution for the investigation of dynamic processes enabling breakthroughs in ultrafast science with FELs. The seeding pulse is the 21st harmonic of an 800-nm, 15-fs (rms) laser pulse generated in an argon medium. Methods for finding the overlap of seed pulses with electron bunches in spatial, longitudinal, and spectral dimensions are discussed and results are presented. The experiment was conducted at FLASH, the FEL user facility at DESY in Hamburg, Germany.

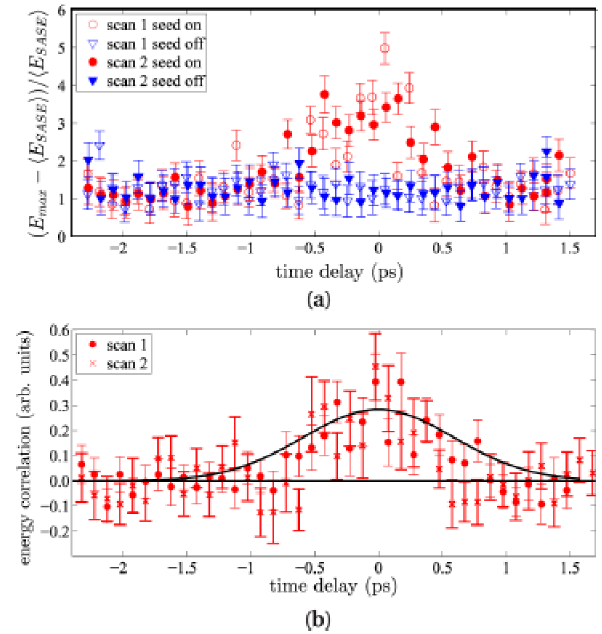

FIG. 3 (color online). Results of time delay scans. (a) Contrast of the maximum pulse energy and the averaged pulse energy of SASE for each time delay as obtained in two independent scans. (b) Correlation data of the EUV seed pulse energy and the output energy for both scans. Error bars indicate 1 standard deviation of statistical fluctuations.

R&D is in progress

Seeding developments

WEP030 Proceedings of FEL2015, Daejeon, Korea

FIRST LASING OF AN HGHG SEEDED FEL AT FLASH

Kirsten Hacker, Shaukat Khan, Robert Molo
DELTA, TU Dortmund, Germany
Sven Ackermann, Ralph Wolfgang Assmann, Jörn Bödewadt, Nagitha Ekanayake,
Bart Faatz, Ingmar Hartl, Rosen Ivanov, Tim Laarmann, Jost Müller, Holger Schlarb
DESY, Hamburg, Germany
Philipp Amstutz, Armin Azima, Markus Drescher, Leslie Lamberto Lazzarino,
Christoph Lechner, Theophilos Maltezopoulos, Tim Plath, Jörg Rossbach
University of Hamburg, Germany

Abstract

The free-electron laser facility FLASH at DESY operates in SASE mode with MHz bunch trains of high-intensity extreme ultraviolet and soft X-ray FEL pulses. A seeded beamline which is designed to be operated parasitically to the main SASE beamline has been used to test different external FEL seeding methods. First lasing at the 7th harmonic of a 266 nm seed laser using high-gain harmonic generation has been demonstrated.

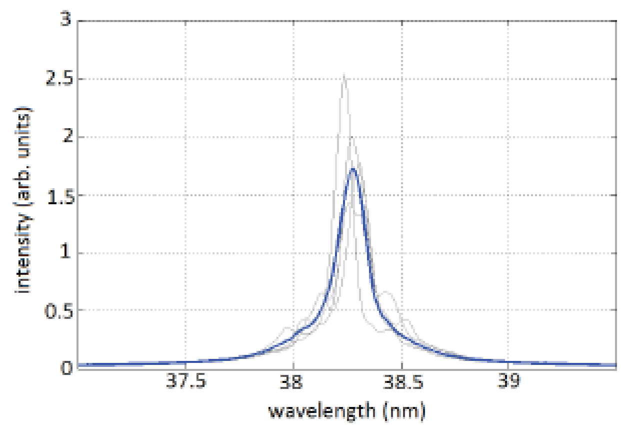

Figure 5: The FEL light is extracted from the beamline and reflected into a spectrometer. The blue curve is the average and the grey curves are individual shots.

R&D is in progress

Summary

- In this lecture we presented methodology of analysis of SASE FEL experimental results together with set of practical formulae for quick calculation of FEL parameters. An overview of perspective developments at FLAH has been presented as well. More deep details can be found in the recommended references.
- Operation of SASE FEL has been illustrated with practical examples from FLASH free electron laser which is in operation since the year 2000. A lot of practical experience has been collected, and all key systems has been upgraded several times for the best performance.
- Electron and photon beam diagnostics have been improved as well. An essential piece of diagnostics – statistical methods - is based on fundamental principles of SASE FEL physics.
- We believe that FEL theory and practical simulation tools are on mature level - with well tuned systems FLASH demonstrate performance which is in good agreement with theoretical understanding of FEL physics, both, qualitative and quantitative.
- Many perspective developments have been implemented at FLASH, but an essential number of them is still on waiting list. The reasons are (i) no space left for new installations; (ii) overbooking of the facility schedule, and strong competition for beam time.

Thank you for your attention!

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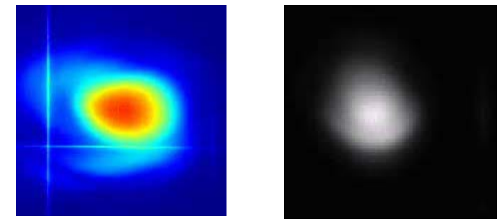
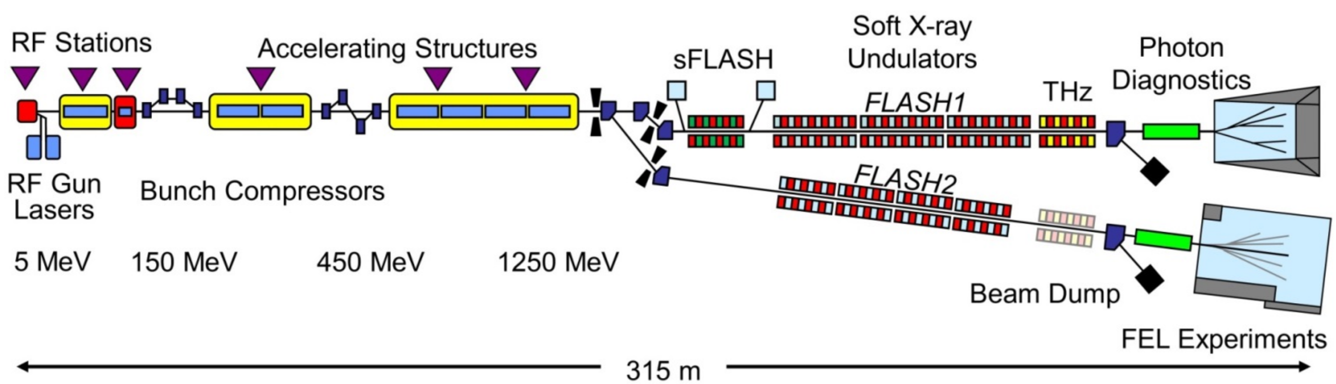
FLASH: Transverse coherence and pointing stability: details

FLASH: Transverse coherence and pointing stability

Energy	[GeV]	0.5-1.25	
Wavelength	[nm]	4.1-55 (FLASH1)	
		3.x-8.x (FLASH2)	
Pulse energy	[uJ]	up to 1000	
Rep. rate	[Hz]	5000	
Undulators			
	Period	Length	
FLASH1:	2.73 cm	27 m (6 x 4.5 m modules)	fixed gap
FLASH2:	3.14 cm	30 m (12 x 2 m modules)	variable gap

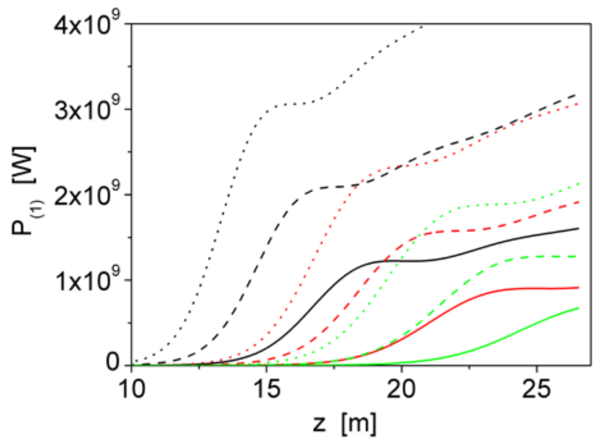
FLASH experiment : 2007 2015

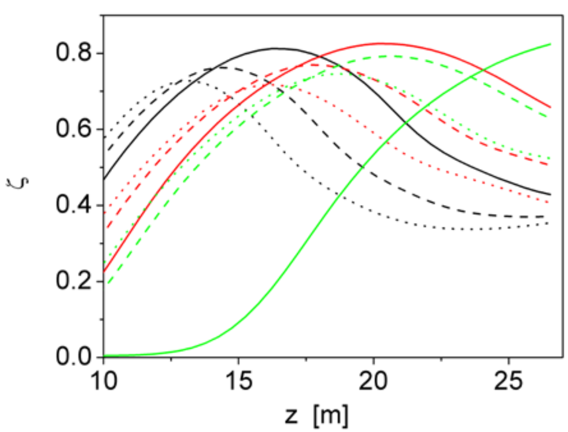




Observation at FLASH:

- The degree of transverse coherence is visibly less than unity in the post-saturation regime
- Transverse shape of the photon pulse is not stable.
- Pointing stability is not perfect.
- Pointing stability degrades for shorter photon pulses.

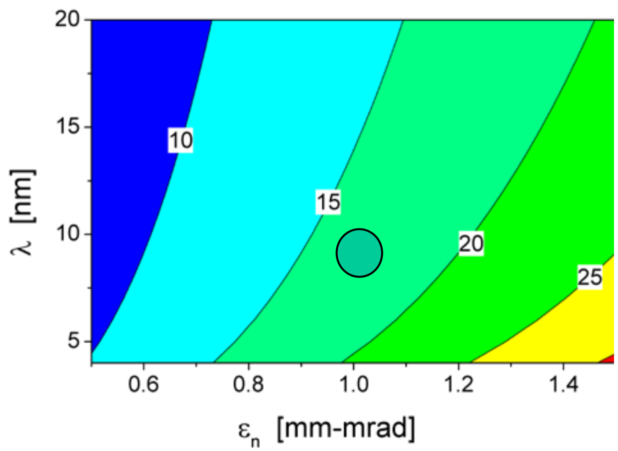


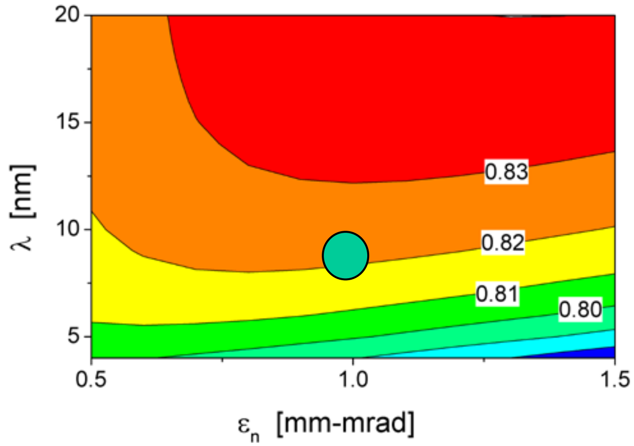


Two effects defines degradation of the transverse coherence at FLASH:

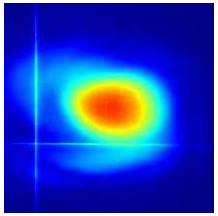
- Mode degeneration.
- Poor longitudinal coherence. The essence of the effect is a superposition of mutually incoherent fields produced by different longitudinally uncorrelated parts of the electron bunch. In the exponential gain regime this effect is relatively weak, but it prevents a SASE FEL from reaching full transverse coherence, even in the case when only one transverse eigenmode survives. In the deep nonlinear regime beyond FEL saturation, this effect can be strong and can lead to a significant degradation of the degree of transverse coherence.

FLASH: Transverse coherence and pointing stability

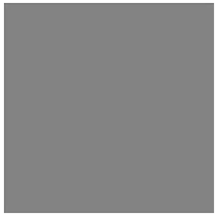


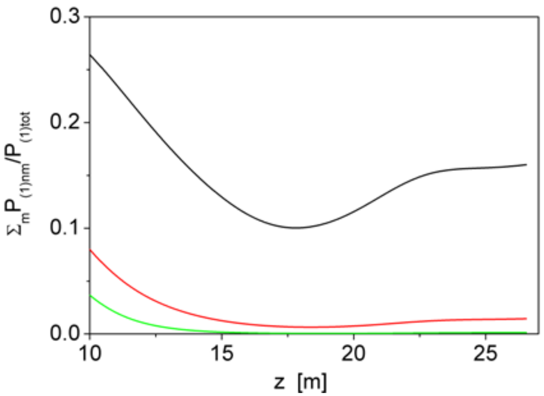


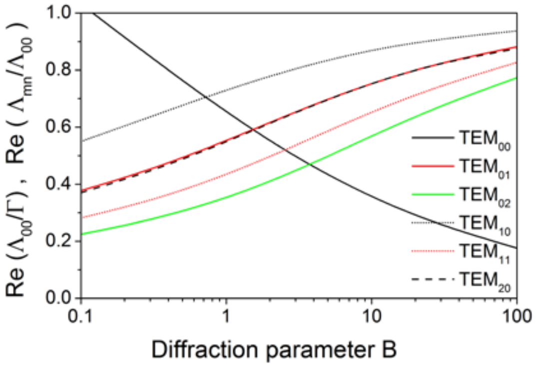
FLASH: experiment



FLASH: FAST simulations







Parameter space of FLASH:

Large values of diffraction parameter (B = 10 - 25) and “cold” electron beam.

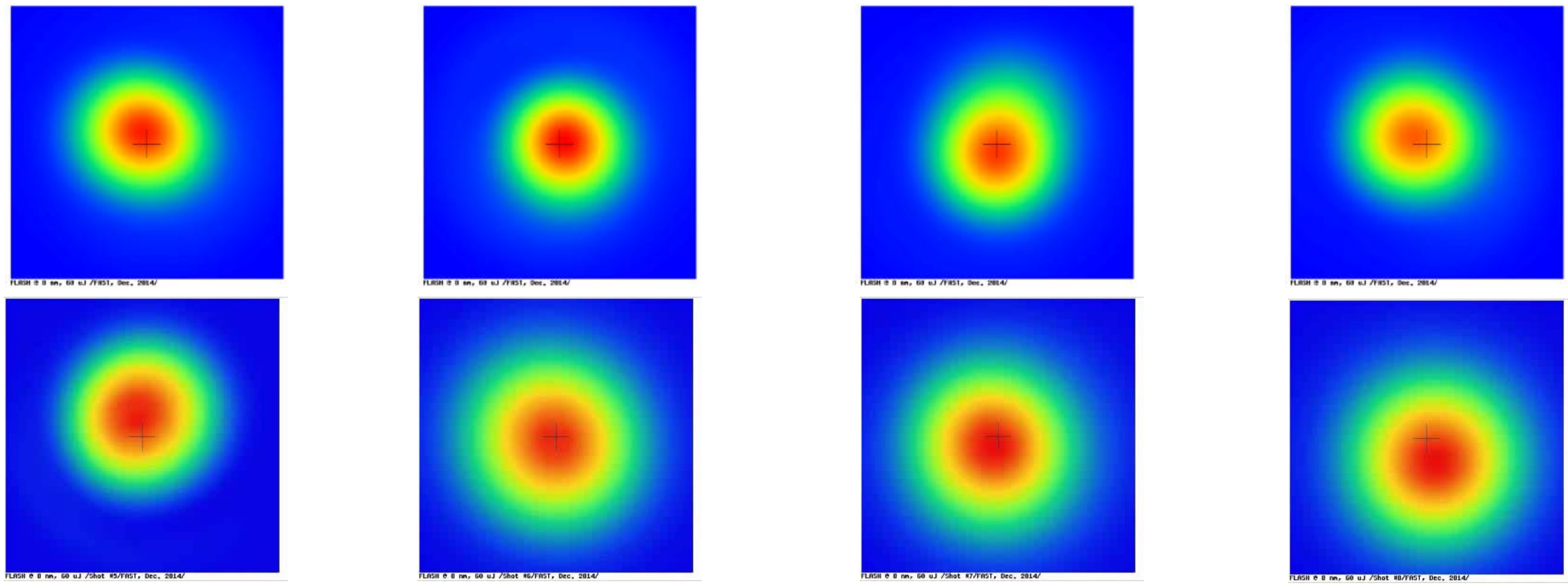
Mode degeneration effect is strong (gain of TEM_{10} mode is 0.8 – 0.83 of the fundamental TEM_{00}).

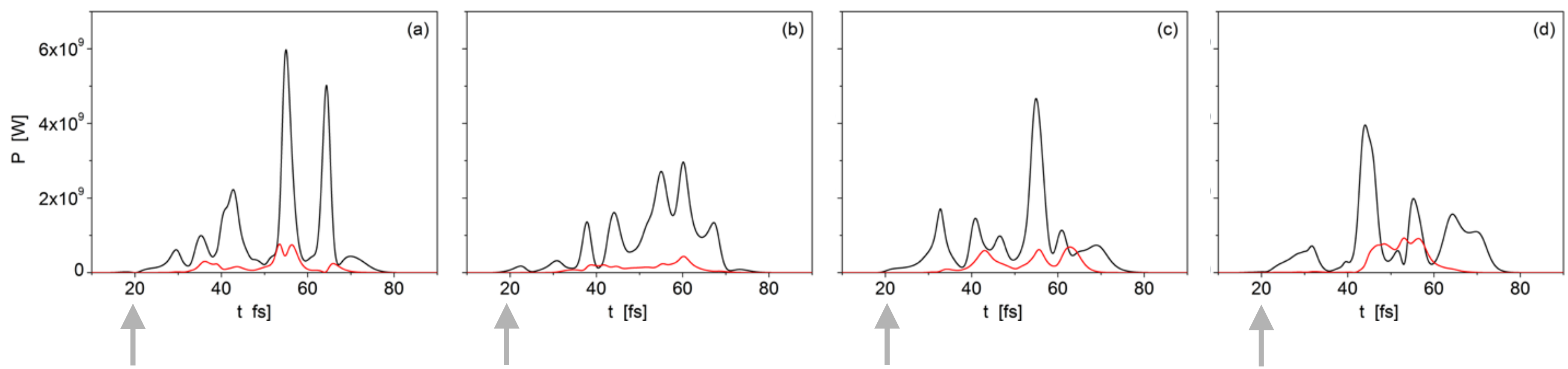
Contribution of the first azimuthal mode to the total power is 10 to 15%.

Result: unstable shape and pointing of the photon pulse.

FLASH: Transverse coherence and pointing stability

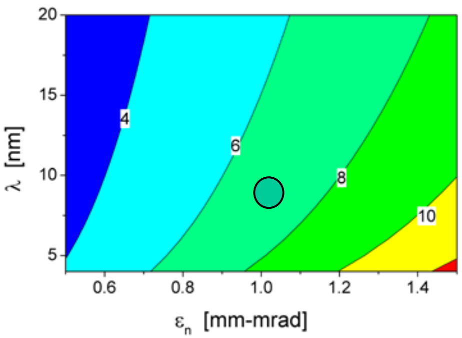
FLASH: FAST simulations

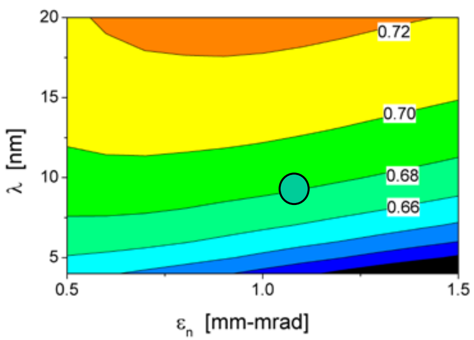


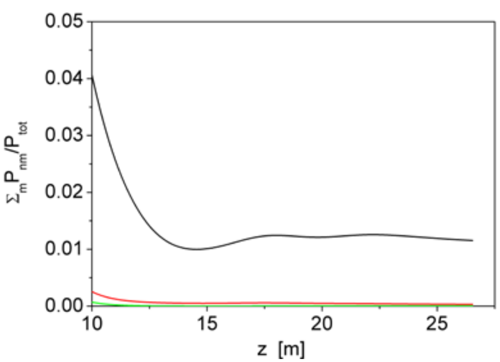


Evolution of the intensity distribution in the far zone along radiation pulse.

Recipes for improving transverse coherence

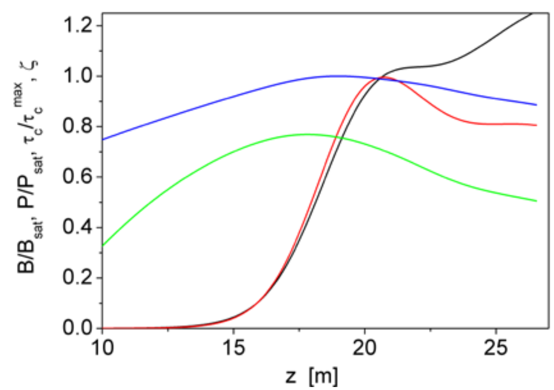






- To decrease the beam current such that saturation is achieved at the very end of the undulator. This would eliminate not only the degradation in the deep nonlinear regime, but would also improve the mode selection process because the diffraction parameter is then reduced while the velocity spread due to emittance is increased. Such a regime was realized at FLASH on user's demand, but it is not typical for the machine operation because the peak power is low due to a low peak current.

- One can also suppress the unwanted effects in the deep nonlinear regime by kicking the electron beam at the saturation point (or, close to it) when the peak current is high. Then one can still have a high power and an improved (about 70-80%) degree of transverse coherence.



- Further improvement could be achieved by the reducing beta-function (thus improving the mode selection due two reduction of the diffraction parameter and increasing of the betatron motion parameter).

FLASH: production of short pulses: details

Production of ultra-short radiation pulses

- The program for production of ultra-short electron pulses at FLASH has been launched several years ago by DESY and Hamburg University.
- Experiment has been performed in January, 2013. Some results are presented at the FEL 2013 Conference:

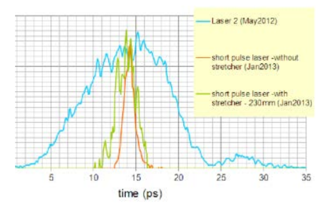
J. Roensch-Schulenburg, E. Hass, A. Kuhl, T. Plath, M. Rehders, J. Rossbach, G. Brenner, C. Gerth, U. Mavric, H. Schlarb, E. Schneidmiller, S. Schreiber, B. Steffen, M. Yan, M.V. Yurkov, Short SASE-FEL Pulses at FLASH, Proc. FEL2013 Conference, New York, USA, 2013, tupso64.
http://accelconf.web.cern.ch/AccelConf/FEL2013/papers/tupso64.pdf

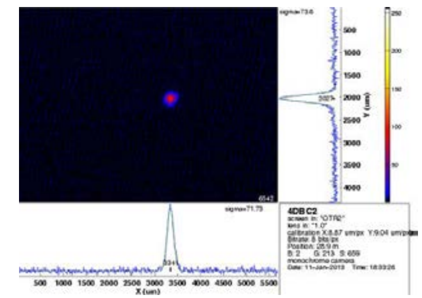
Extended analysis have been presented at the IPAC2016 Conference (report ID: MOPOW013).

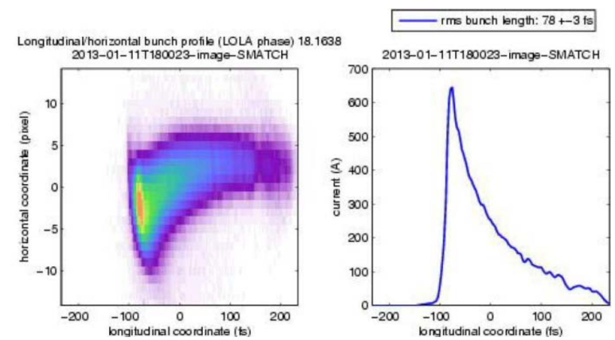
Good agreement between simulation and experimental results is observed.

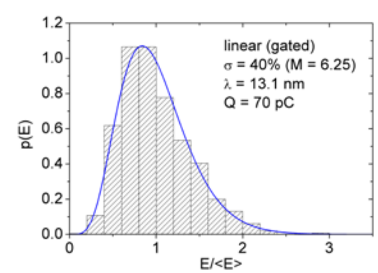
Measured parameters of FLASH FEL

Transverse laser shape	Flat-top
Longitudinal laser shape	Gaussian
Injector laser pulse duration (FWHM)	2.4 ps
Electron energy	689 MeV
Bunch charge	70 pC
rms norm. emittance	0.8-1 mm-mrad
rms electron bunch length	78 fs
Radiation wavelength	13.1 nm
<u>Linear regime (18 m):</u>	
Radiation pulse energy	2 μJ
Fluctuations of pulse energy	40%
Number of modes	6.2
FWHM radiation pulse duration	40 fs
FWHM spectrum width	0.35%
<u>Full length (27 m):</u>	
Radiation pulse energy	25 μJ
Fluctuations of pulse energy	12.5%
FWHM radiation pulse duration	60 fs
FWHM spectrum width	0.42%









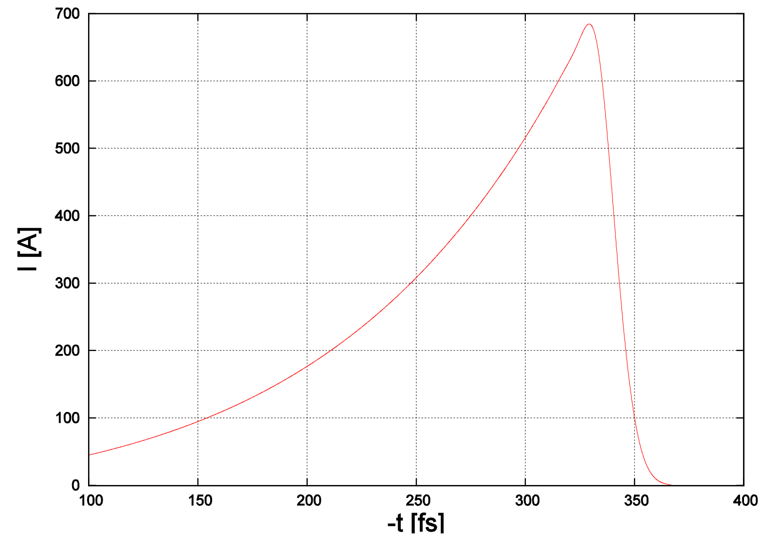
Production of ultra-short radiation pulses
Parameters of the electron bunch for simulations

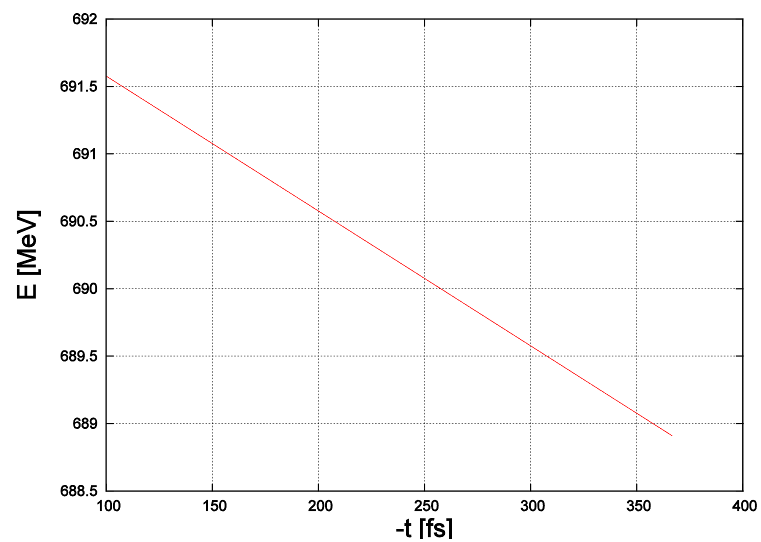
Measured parameters of the electron bunch were used as input for SASE FEL simulation:

Reference electron energy: 689 MeV
Reference peak beam current: 685 A
Bunch charge: 70 pC
Bunch profile: LOLA measurements
rms normalized emittance: 0.8 mm-mrad – 1 mm-mrad
Energy chirp: 10 keV / fs along lasing fraction
Bunch head is on the right-hand side

Optics in the undulator:

- Assumption for an ideal tuning (periodic solution)





Production of ultra-short radiation pulses
Analysis of physical parameters

$E = 690.5$ MeV
$I = 700$ A [570 A]
$\epsilon_n = 1$ mm-mrad
β =7.5 m
λ_{w} =2.73 cm
$\lambda = 13.1$ nm

$$\text{Diffraction parameter} : B = 2\Gamma\sigma^2\omega/c = 7.8 \; [7.04]$$

$$\text{Parameter of betatron oscillations} : \hat{k}_\beta = 1/(\beta\Gamma) = 0.091 \; [0.1]$$

$$\text{Energy spread parameter} : \hat{\Lambda}_{\mathrm{T}}^2 = (\sigma_{\mathrm{E}}/\mathcal{E})^2/\rho^2 = 2.07\times10^{-3} \; [2.5\times10^{-3}]$$

$$\text{FEL parameter} : \rho = \frac{\lambda_{\mathrm{w}}\Gamma}{4\pi} = 3.186\times10^{-3} \; [2.875\times10^{-3}]$$

$$\text{Gain parameter} : \Gamma = \left[\frac{I}{I_{\mathrm{A}}}\frac{8\pi^2K^2A_{\mathrm{JJ}}^2}{\lambda\lambda_{\mathrm{w}}\gamma^3}\right]^{1/2} = (0.682\text{ m})^{-1} \; [(0.756\text{ m})^{-1}]$$

$$\text{rms size of the electron beam} : \sigma = \sqrt{\epsilon\beta} = 74.5\;\mu\text{m}$$

Production of ultra-short radiation pulses
Analysis of physical parameters

$$\left[\frac{\mathrm{d}^2}{\mathrm{d}\hat{r}^2} + \frac{1}{\hat{r}}\frac{\mathrm{d}}{\mathrm{d}\hat{r}} - \frac{n^2}{\hat{r}^2} + 2\mathrm{i}B\hat{\Lambda}\right]\Phi_n(\hat{r})$$

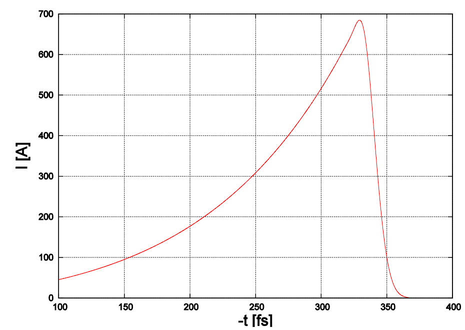
$$= -4\int_0^{\infty} d\hat{r}'\,\hat{r}'\left\{\Phi_n(\hat{r}')\right. \qquad (4)$$

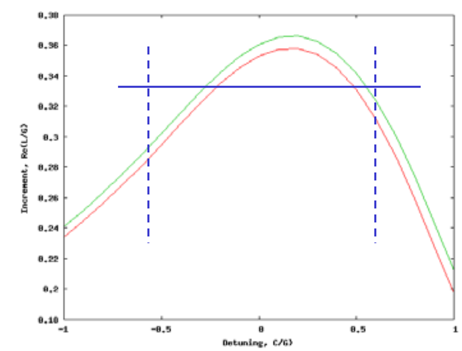
$$\left. + \frac{\hat{\Lambda}_{\mathrm{p}}^2}{2}\left[\frac{\mathrm{d}^2}{\mathrm{d}\hat{r}'^2} + \frac{1}{\hat{r}'}\frac{\mathrm{d}}{\mathrm{d}\hat{r}'} - \frac{n^2}{\hat{r}'^2} + 2\mathrm{i}B\hat{\Lambda}\right]\Phi_n(\hat{r}')\right\}$$

$$\times \int_0^{\infty} \mathrm{d}\zeta \frac{\zeta}{\sin^2(\hat{k}_\beta\zeta)} \exp\left[-\frac{\hat{\Lambda}_T^2\zeta^2}{2} - (\hat{\Lambda} + \mathrm{i}\hat{C})\zeta\right]$$

$$\times \exp\left[-\frac{(1 - \mathrm{i}B\hat{k}_\beta^2/2)(\hat{r}^2 + \hat{r}'^2)}{\sin^2(\hat{k}_\beta\zeta)}\right]$$

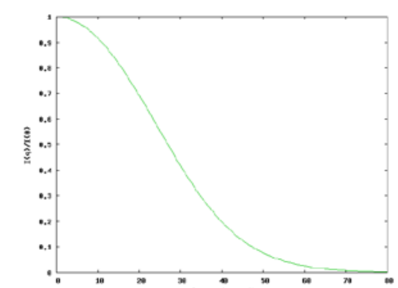
$$\times I_n\left[\frac{2(1 - \mathrm{i}B\hat{k}_\beta^2\zeta/2)\hat{r}\hat{r}'\cos(\hat{k}_\beta\zeta)}{\sin^2(\hat{k}_\beta\zeta)}\right]$$





M. Xie, Nucl. Instrum. and Methods A 445, 59 (2000).

E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Nucl. Instrum. and Methods A 475, 86 (2001).



TEM00: L_max = 0.36 (L_g_min = 190 cm, L_g_av = 200 cm) for I = 700 A

L_max = 0.37 (L_g_min = 210 cm, L_g_av = 230 cm) for I = 570 A

- Fundamental TEM00 mode is expected to be dominant.
- Contribution of the non-symmetric azimuthal modes is 2% in terms of the radiation power at the saturation point.
- Expected FWHM angular divirgence in the linear regime about 60 urad.

Production of ultra-short radiation pulses
Quick estimate of expected parameters with fitting formulae

```
Produced by SASE_Saturation_Table_FAST (E.S. & M.Y.)
Version: August 21, 2011 @ fast01
2015/09/12 12:45
#
Electron beam:
#
Energy of electrons                MeV         690.
Bunch charge                       nC          .700E-01
Peak current                       A           700.
rms normalized emittance           mm-mrad     .100E-03
rms energy spread                  MeV         .100
rms bunch length                   cm          .120E-02
focusing beta function             m           7.50
rms size of electron beam          cm          .745E-02
Repetition rate                    1/sec       .500E+04
Electron beam power                W           241.
#
Undulator:
#
Undulator period                   cm          2.73
Undulator peak field               T           .481
Undulator parameter K (rms)        #           .867
Undulator gap                      cm          1.28
Undulator length                   m           27.0
```

Production of ultra-short radiation pulses
Quick estimate of expected parameters with fitting formulae

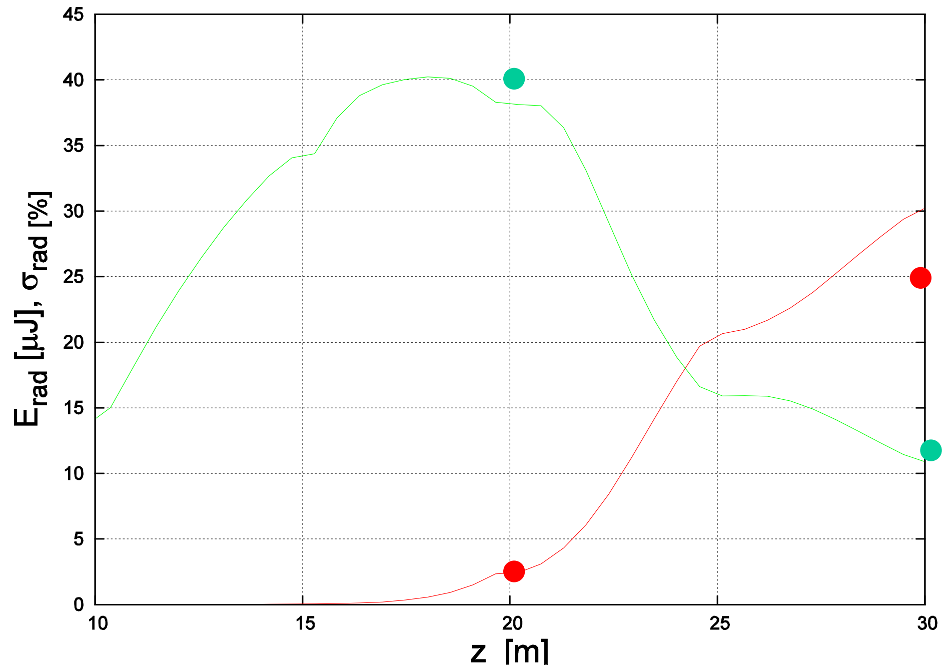
```
Properties of the 1st harmonic in the saturation:
#
Radiation wavelength              nm       13.1
Photon energy                     eV       94.6
Pulse energy                      J        .314E-04
Peak power                        W        .562E+09
Average power                     W        .157
FWHM spot size                    cm       .178E-01
FWHM angular divergence           rad      .399E-04
Coherence time                    sec      .925E-14
FWHM spectrum width               dw/w     .334E-02
Degree of transverse coherence    #        .960
Radiation pulse duration          sec      .559E-13
Number of longitudinal modes      #               6
Fluctuations of the pulse energy  #        .136
Degeneracy parameter              #        .329E+12
Number oh photons per pulse       #        .207E+13
Average flux of photons           ph/sec   .103E+17
Peak brilliance                   #        .248E+30
Average brilliance                #        .693E+20
Saturation length                 m        21.4
# of gain lengths to saturation   #        11.3
#
```

FAST: Average radiation energy and fluctuations

FAST: curves derived from 120 shots

Average energy in the radiation pulse

Deviation of energy fluctuations



Experimental data:

After 4th module (20 m): 2.1 uJ and 40%

After 6th module (30 m): 25 uJ and 12.5%

FAST:

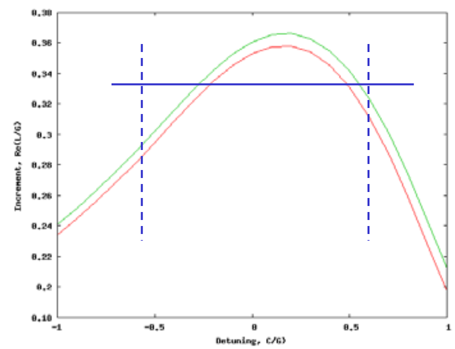
After 4th module (20 m): 2.3 uJ and 39.6% (800 sh.)

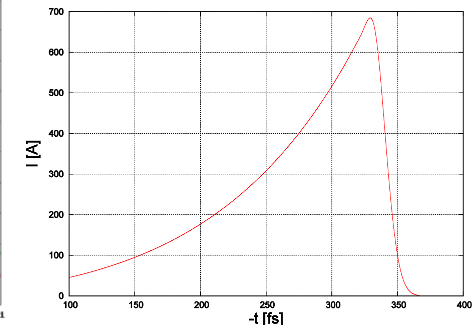
After 6th module (30 m): 30 uJ and 10.5% (120sh.)

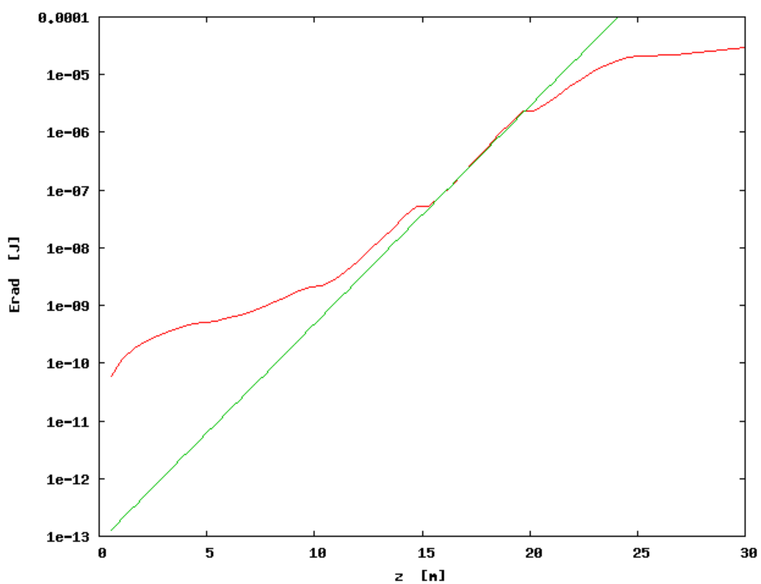
Production of ultra-short radiation pulses

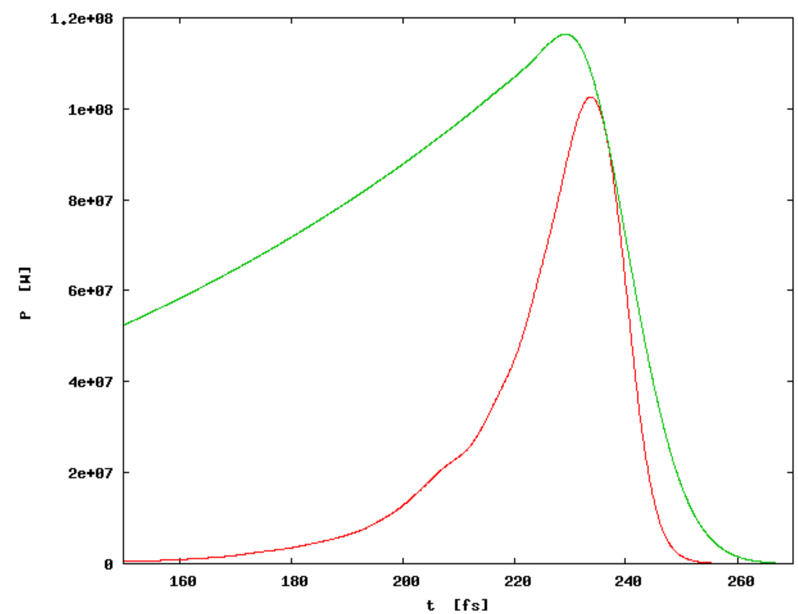
FAST: Effective power of shot noise and gain

- Average gain is defined by the shape of the lasing fraction of the electron beam and bandwidth of SASE FEL of 1.3 x FEL parameter. Power gain length is 1.15 cm (green curve on the left bottom plot).
- Effective power of shot noise of 14 W (SSY, The Physics of Free Electron Lasers) gives pulse energy of 3.5E-13 J for the pulse duration of 25 fs (bottom right plot). This value is consistent with simulation results.

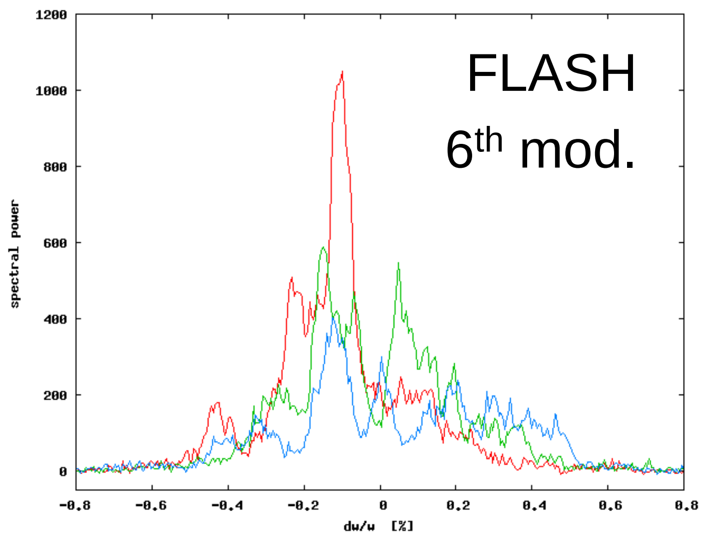


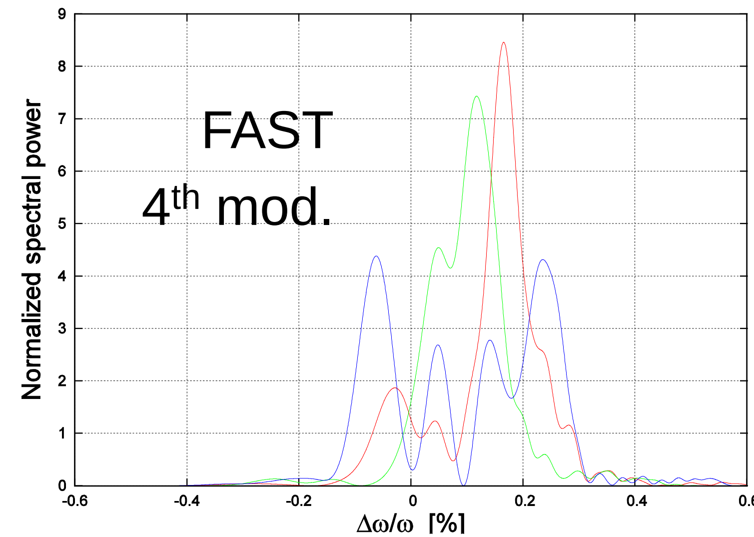


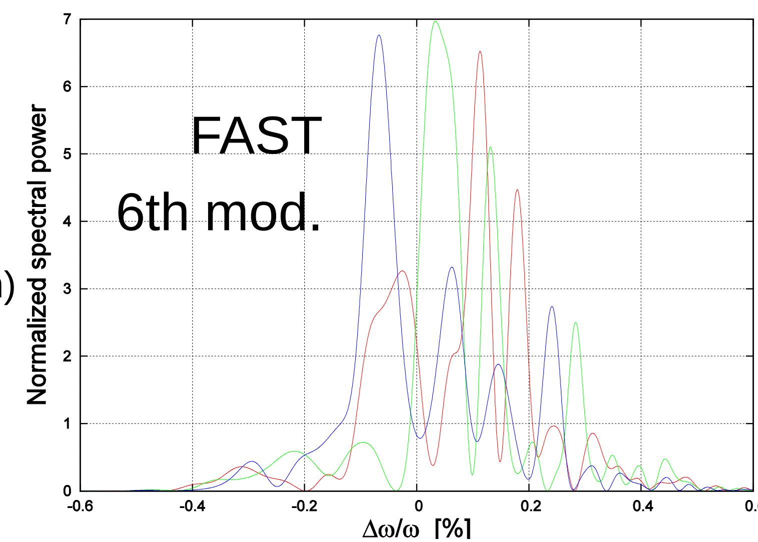




Production of ultra-short radiation pulses
FAST: Radiation spectra







Single shot spectra

FAST: points of output: 4th mod. (z = 20 m) and 6th mod (z = 30 m)

FLASH: 6th module

Experimental data for FWHM specrum width:

After 4th module (20 m): 0.32%

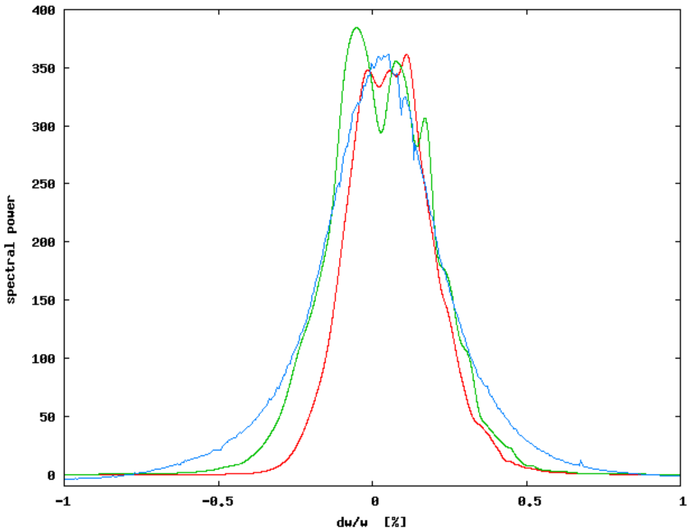
After 6th module (30 m): 0.46%

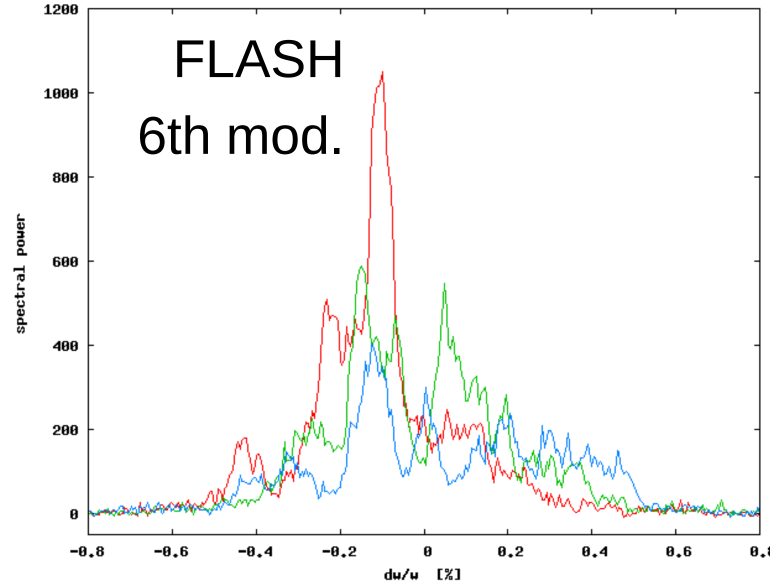
Production of ultra-short radiation pulses
FAST: Radiation spectra

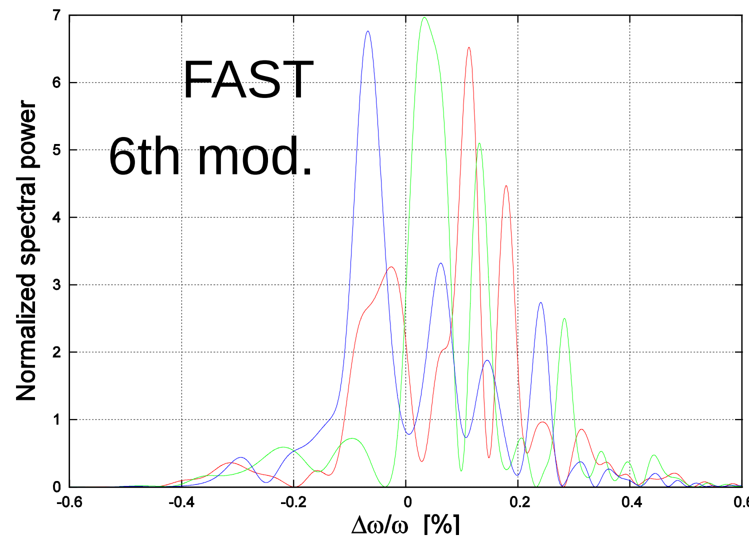
Red: FAST, 4th module

Green: FAST, 6th module

Blue: FLASH, 6th module







Averaged and single shot spectra

Points of output: 4th mod. (z = 20 m) and 6th mod (z = 30 m)

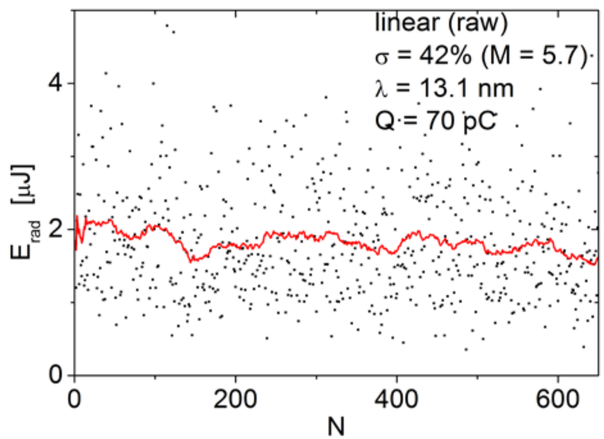
Experimental data for FWHM specrum width:

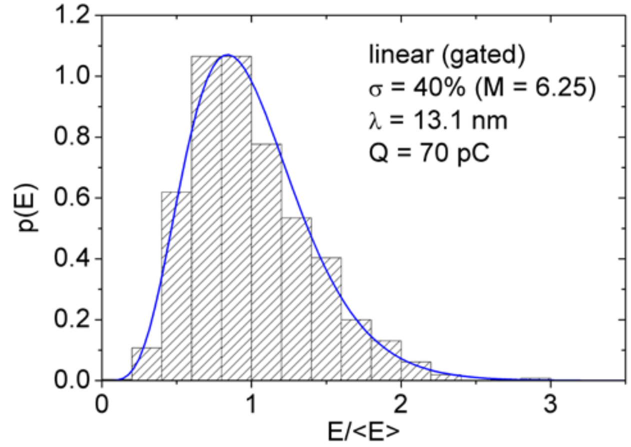
After 4th module (20 m): 0.32%

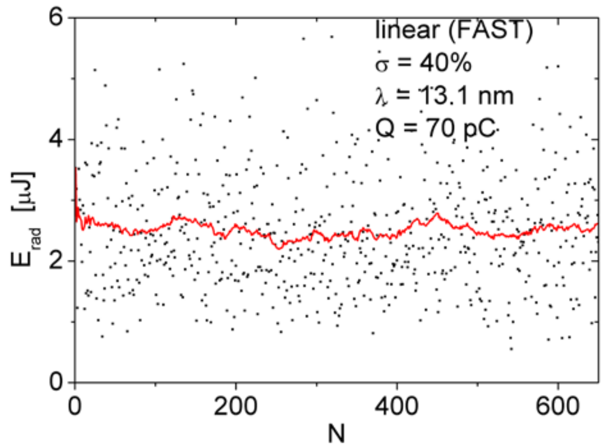
After 6th module (30 m): 0.46%

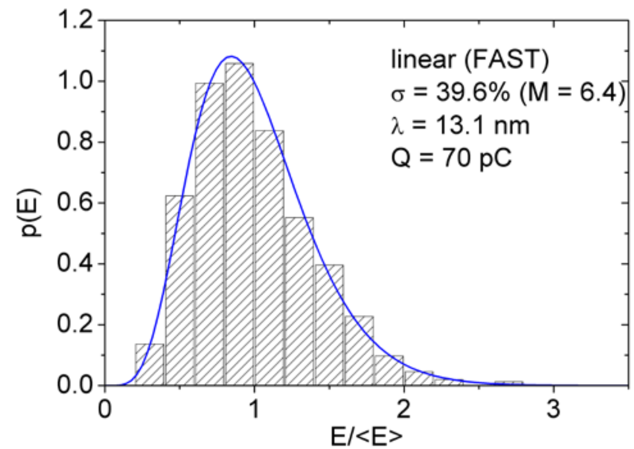
Production of ultra-short radiation pulses

Single-shot pulse energies in the linear regime (after 4 modules)







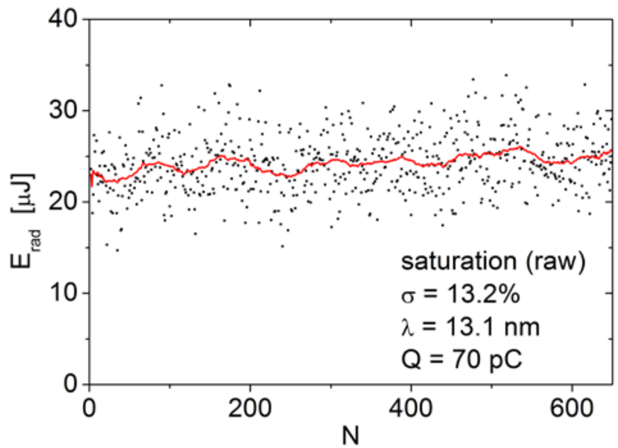


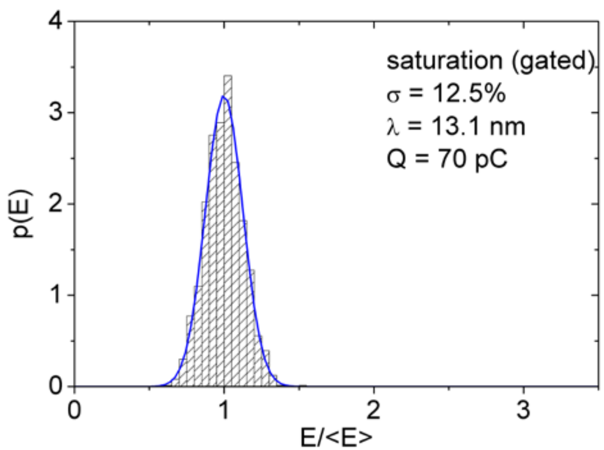
Red curve is averaging over 50 shots.

Blue curves present gamma distribution.

Production of ultra-short radiation pulses

Single-shot pulse energies in saturation (after 6 modules)





Red curve is averaging over 50 shots.

Blue curves present gaussian distribution.