Application of statistical techniques for characterization of the radiation from SASE FEL

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- Physics of SASE FEL related to statistical techniques.
- Hardware: MCP detectors at FLASH.
- Photon beam characterization with statistical techniques: TTF FEL and FLASH.
- Studies of sporadic jitters at FLASH2.

Background

Selected references to theory and experimental results:

E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, The Physics of Free Electron Lasers (Springer-Verlag, Berlin, 1999).

E.A. Schneidmiller, and M.V. Yurkov, Coherence Properties of the Radiation from X-ray Free Electron Lasers, CERN Yellow Reports: School Proceedings, Vol. 1, 2018, 539-596; DOI: http://dx.doi.org/10.23730/CYRSP-2018-001.539.

E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Statistical properties of radiation from VUV and X-ray free electron lasers, Optics Communications 148(1998)383.

E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Statistical properties of radiation from SASE FEL driven by short electron bunches, Nucl. Instrum. and Methods A507 (2003) 101-105.

V. Ayvazyan et al., Study of the statistical properties of the radiation from a VUV SASE FEL operating in the femtosecond regime, Nucl. Instrum. and Methods A507(2003)368.

C. Behrens et al., Constraints on photon pulse duration from longitudinal electron beam diagnostics at a soft x-ray free-electron laser, Phys. Rev. ST Accel. Beams 15 (2012) 030707.

S. Duesterer et al., Development of experimental techniques for the characterization of ultrashort photon pulses of extreme ultraviolet free-electron lasers, Phys. Rev. ST Accel. Beams 17 (2014) 120702.

Ivette J. Bermúdez Macias et al., Study of temporal, spectral, arrival time and energy fluctuations of SASE FEL pulses, Optics Express, vol. 29 (2021) 10491-10508.

E.A. Schneidmiller, and M.V. Yurkov, Application of Statistical Methods for Measurements of the Coherence Properties of the Radiation from SASE FEL, Proc. IPAC2016, MOPOW013.

E.A. Schneidmiller, and M.V. Yurkov, Studies of harmonic lasing self-seeded FEL at FLASH2, Proc. IPAC2016, MOPOW009.

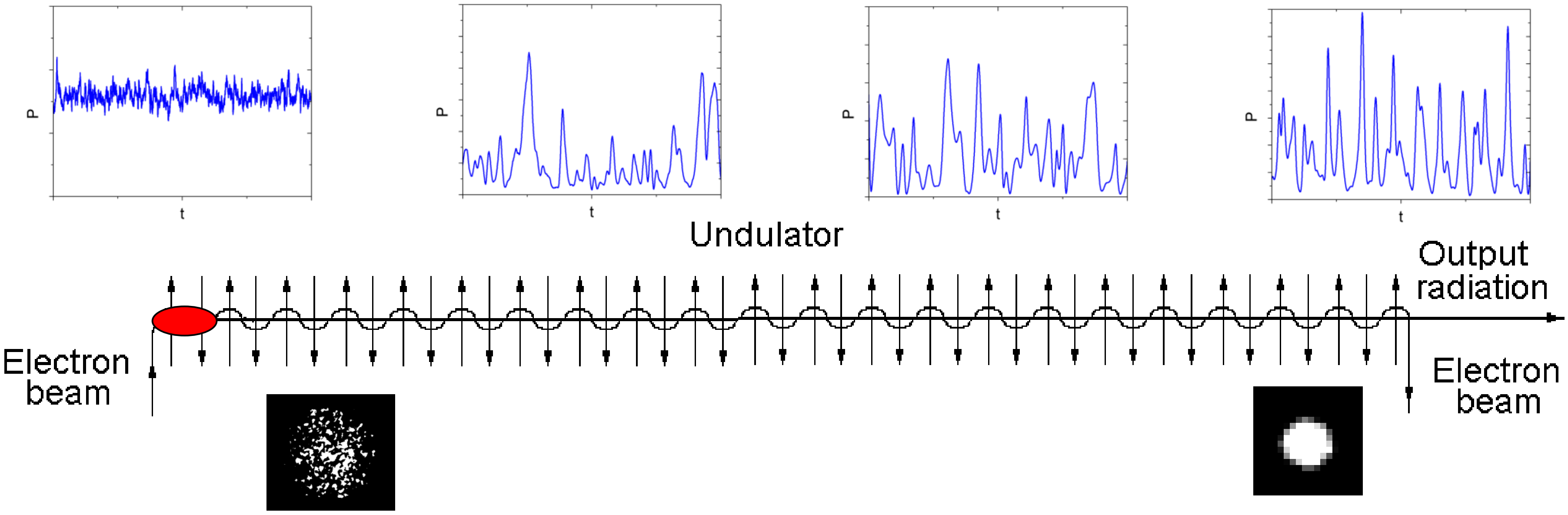
S. Grunewald et al., Experience with MCP-based photon detector at FLASH2, Proc. FEL2019, WEP073,

J. Wu et al., LCLS X-ray pulse duration measurement using the statistical fluctuation method, Proc. FEL2010, MOPC14.

Outline

- **Physics of SASE FEL related to statistical techniques.**
- Hardware: MCP detectors at FLASH.
- Photon beam characterization with statistical techniques: TTF FEL and FLASH.
- Studies of sporadic jitters at FLASH2.

SASE FEL



- When the electron beam enters the undulator, the presence of the beam modulation at frequencies close to the resonance frequency initiates the process of amplification.
- Fluctuations of current density in the electron beam are uncorrelated not only in time but in space, too. Thus, a large number of transverse radiation modes are excited when the electron beam enters the undulator.
- These radiation modes have different gain. As undulator length progresses, the high gain modes will predominate more and more and we can regard the XFEL as filter, in the sense that it filters from arbitrary radiation field those components corresponding to the high gain modes.

Definition of statistical characteristics

- The first order time correlation function and coherence time:

$$g_1(\vec{r}, t-t') = \frac{\langle \tilde{E}(\vec{r},t)\tilde{E}^*(\vec{r},t')\rangle}{\left[\langle \mid \tilde{E}(\vec{r},t) \mid^2\rangle\langle \mid \tilde{E}(\vec{r},t') \mid^2\rangle\right]^{1/2}} \, , \qquad \boxed{\tau_c = \int\limits_{-\infty}^{\infty} |g_1(\tau)|^2 \, \mathrm{d}\,\tau \, .}$$

- The first-order transverse correlation function and degree of transverse coherence:

$$\gamma_1(\vec{r}_\perp, \vec{r\prime}_\perp, z, t) = \frac{\langle \tilde{E}(\vec{r}_\perp, z, t)\tilde{E}^*(\vec{r\prime}_\perp, z, t)\rangle}{\left[\langle|\tilde{E}(\vec{r}_\perp, z, t)|^2\rangle\langle|\tilde{E}(\vec{r\prime}_\perp, z, t)|^2\rangle\right]^{1/2}} \, .$$

$$\boxed{\zeta = \frac{\int\int |\gamma_1(\vec{r}_\perp, \vec{r\prime}_\perp)|^2 \langle I(\vec{r}_\perp)\rangle\langle I(\vec{r\prime}_\perp)\rangle \, \mathrm{d}\,\vec{r}_\perp \, \mathrm{d}\,\vec{r\prime}_\perp}{[\int \langle I(\vec{r}_\perp)\rangle \, \mathrm{d}\,\vec{r}_\perp]^2} \, .}$$

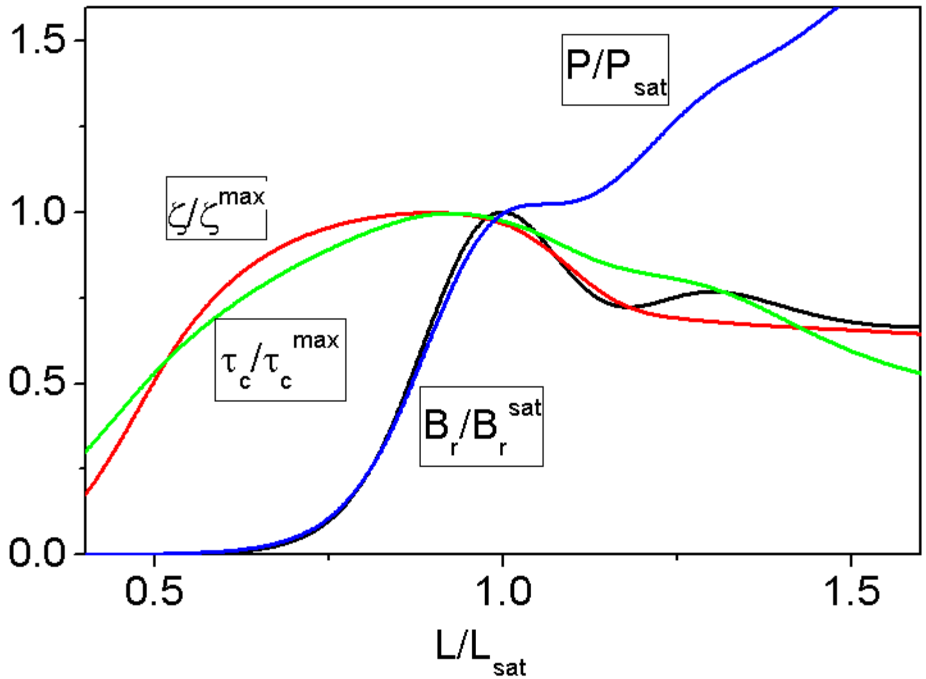
- Degeneracy parameter – the number of photons per mode (coherent state):

$$\delta = \dot{N}_{ph}\tau_c\zeta \, .$$

- Peak brilliance is defined as a transversely coherent spectral flux:

$$\boxed{B_r = \frac{\omega \, \mathrm{d}\,\dot{N}_{ph}}{\mathrm{d}\,\omega} \frac{\zeta}{\left(\frac{\lambda}{2}\right)^2} = \frac{4\sqrt{2}c}{\lambda^3}\,\delta \, .}$$

General overview of SASE FEL



Radiation power

Brilliance

Degree of transverse coherence

Coherence time

- Amplification process develops from the shot noise in the electron beam, passes exponential stage, and enters nonlinear stage.
- Radiation power grows continuously along the undulator length.
- Brilliance of the radiation reaches maximum value at the saturation point.
- Degree of transverse coherence and coherence time reach their maximum values in the end of exponential gain regime.

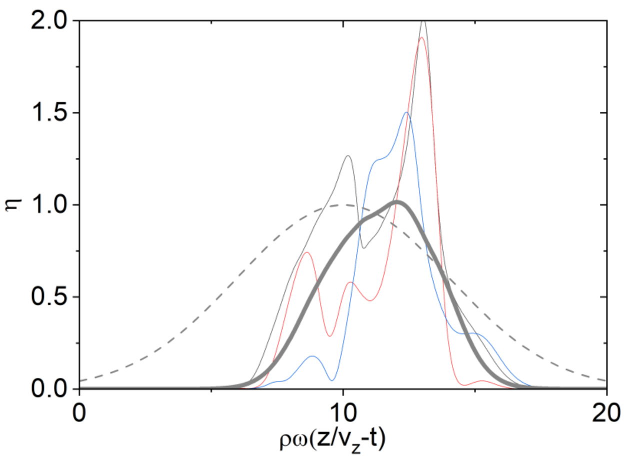
Statistical fluctuation method: Number of modes in the radiation pulse

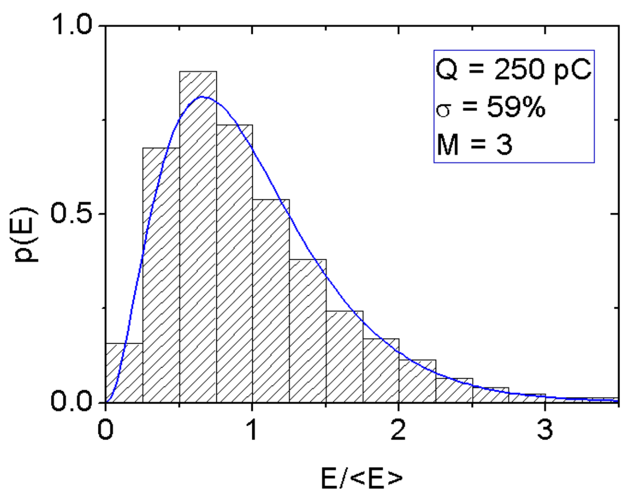
- SASE FEL operating in the linear regime holds features of completely chaotic polarized light - fundamenatl statistical object described by gaussian statistics.
- The probability density function of the radiation pulse energy, $p(E)$, follows the gamma distribution:

$$p(E) = \frac{M^M}{\Gamma(M)} \left(\frac{E}{\langle E \rangle} \right)^{M-1} \frac{1}{\langle E \rangle} \exp \left(-M \frac{E}{\langle E \rangle} \right) , \qquad M = \frac{1}{\sigma^2} , \qquad \sigma^2 = \frac{\langle (E - \langle E \rangle)^2 \rangle}{\langle E \rangle^2} .$$

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.



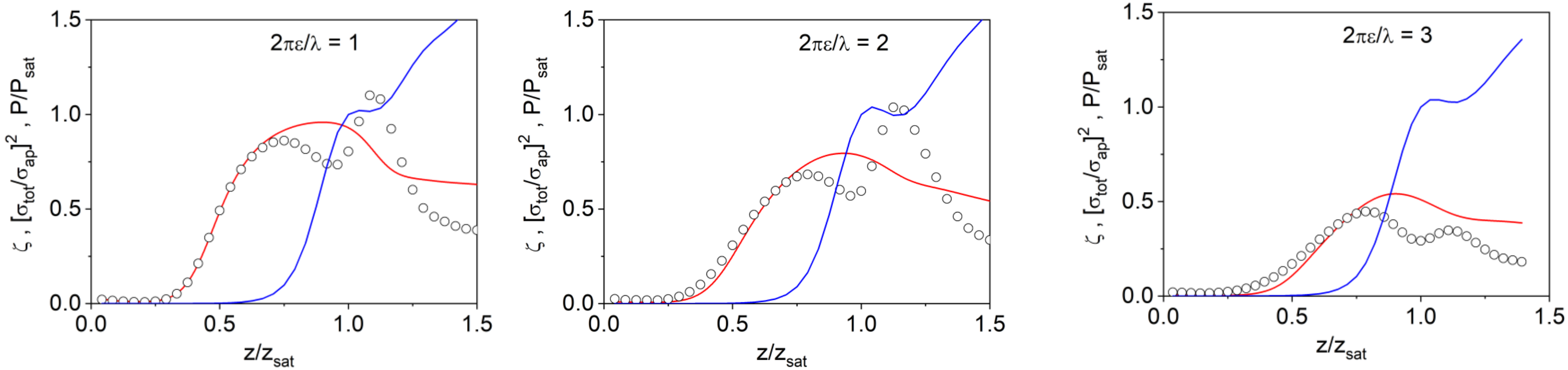


E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Opti. Comm. 148(1998)383.

Statistical fluctuation method: transverse coherence

- Measurements of the fluctuations in the high gain exponential regime of the total pulse energy and of the radiaiton energy after a pinhole gives us the total number of modes $M_{tot} = 1/\sigma^2_{E,tot}$ and the number of longitudinal modes $M_l = 1/\sigma^2_{E,ap}$.
- Total number of modes is the product of the number of longitudinal modes by the number of transverse modes.
- Their ratio gives the number for the degree of transverse coherence:

$$\zeta = \frac{M_l}{M_{tot}} = \frac{\sigma^2_{E,tot}}{\sigma^2_{E,ap}} .$$

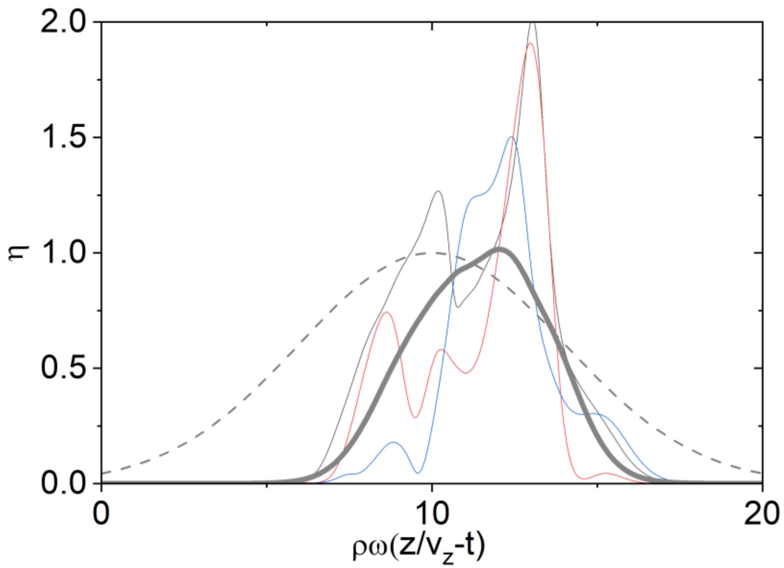


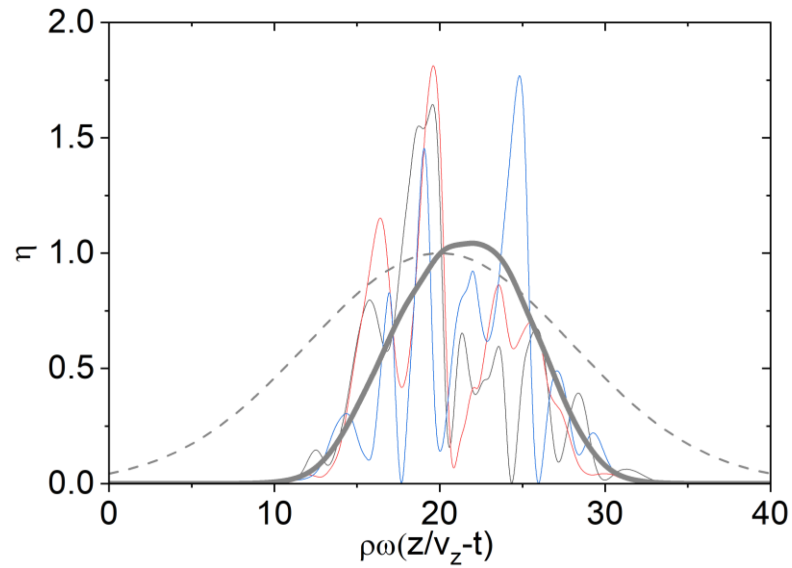
Degree of transverse coherence (red curve); FEL power (blue curve);

Circles: the ratio $\sigma^2_{E,ap}/\sigma^2_{E,tot}$ of fluctuations of the total radiation energy to the fluctuations of the radiation energy in a pinhole.

E.A. Schneidmiller and M.V. Yurkov, Proc. IPAC2016, MOPOW013.

Short pulses: raw results





- Photon pulse energy E_r, center of mass of the photon pulse (photon pulse arrival time) τ_{ar}), and its rms duration τ_{ph}:

$$E_{\mathrm{r}} = \int P(t)\mathrm{d}t \,, \qquad \tau_{\mathrm{ar}} = \frac{\int tP(t)\mathrm{d}t}{E_{\mathrm{r}}} \,, \qquad \tau_{ph}^2 = \frac{\int (t-\tau_{\mathrm{ar}})^2 P(t)\mathrm{d}t}{E_{\mathrm{r}}} \,.$$

- Energy, duration, and arrival time of radiation pulses fluctuate from shot to shot which is described with relevant standard deviations:

$$\sigma_{\mathrm{E}}^2 = \langle (E_{\mathrm{r}} - \langle E_{\mathrm{r}} \rangle)^2 \rangle / \langle E_{\mathrm{r}} \rangle^2 \,, \qquad \sigma_{ar}^2 = \langle (\tau_{\mathrm{ar}} - \langle \tau_{\mathrm{ar}} \rangle)^2 \rangle \,, \qquad \sigma_{\mathrm{ph}}^2 = \langle (\tau_{\mathrm{ph}} - \langle \tau_{\mathrm{ph}} \rangle)^2 \rangle \,,$$

Short pulses: application of similarity techniques

- Photon pulse energy E_r, center of mass of the photon pulse (arrival time) τ_{ar}), rms duration τ_{ph}, and their standard deviations:

$$E_{\mathrm{r}} = \int P(t)\mathrm{d}t \ , \qquad \tau_{\mathrm{ar}} = \frac{\int tP(t)\mathrm{d}t}{E_{\mathrm{r}}} \ , \qquad \tau_{ph}^2 = \frac{\int (t-\tau_{\mathrm{ar}})^2 P(t)\mathrm{d}t}{E_{\mathrm{r}}} \ .$$

$$\sigma_{\mathrm{E}}^2 = \langle (E_{\mathrm{r}} - \langle E_{\mathrm{r}} \rangle)^2 \rangle / \langle E_{\mathrm{r}} \rangle^2 \ , \qquad \sigma_{ar}^2 = \langle (\tau_{\mathrm{ar}} - \langle \tau_{\mathrm{ar}} \rangle)^2 \rangle \ , \qquad \sigma_{\mathrm{ph}}^2 = \langle (\tau_{\mathrm{ph}} - \langle \tau_{\mathrm{ph}} \rangle)^2 \rangle \ ,$$

- To be specific, we consider model of electron bunch with gaussian longitudinal profile with rms pulse duration τ_{el}.
- We apply similarity techniques allowing to translate results of specific numerical simulations on a map of physical parameters. Typical temporal scale of the FEL physics is coherence time, and relevant scaling parameter for variables having dimension of time is $\rho\omega$:

$$\hat{\tau}_{\mathrm{el}} = \rho\omega\tau_{\mathrm{el}} \ , \qquad \hat{\tau}_{\mathrm{ph}} = \rho\omega\tau_{\mathrm{ph}} \ , \qquad \hat{\sigma}_{\mathrm{ar}} = \rho\omega\sigma_{\mathrm{ar}} \ , \qquad \hat{\sigma}_{\mathrm{ph}} = \rho\omega\sigma_{\mathrm{ph}} \ .$$

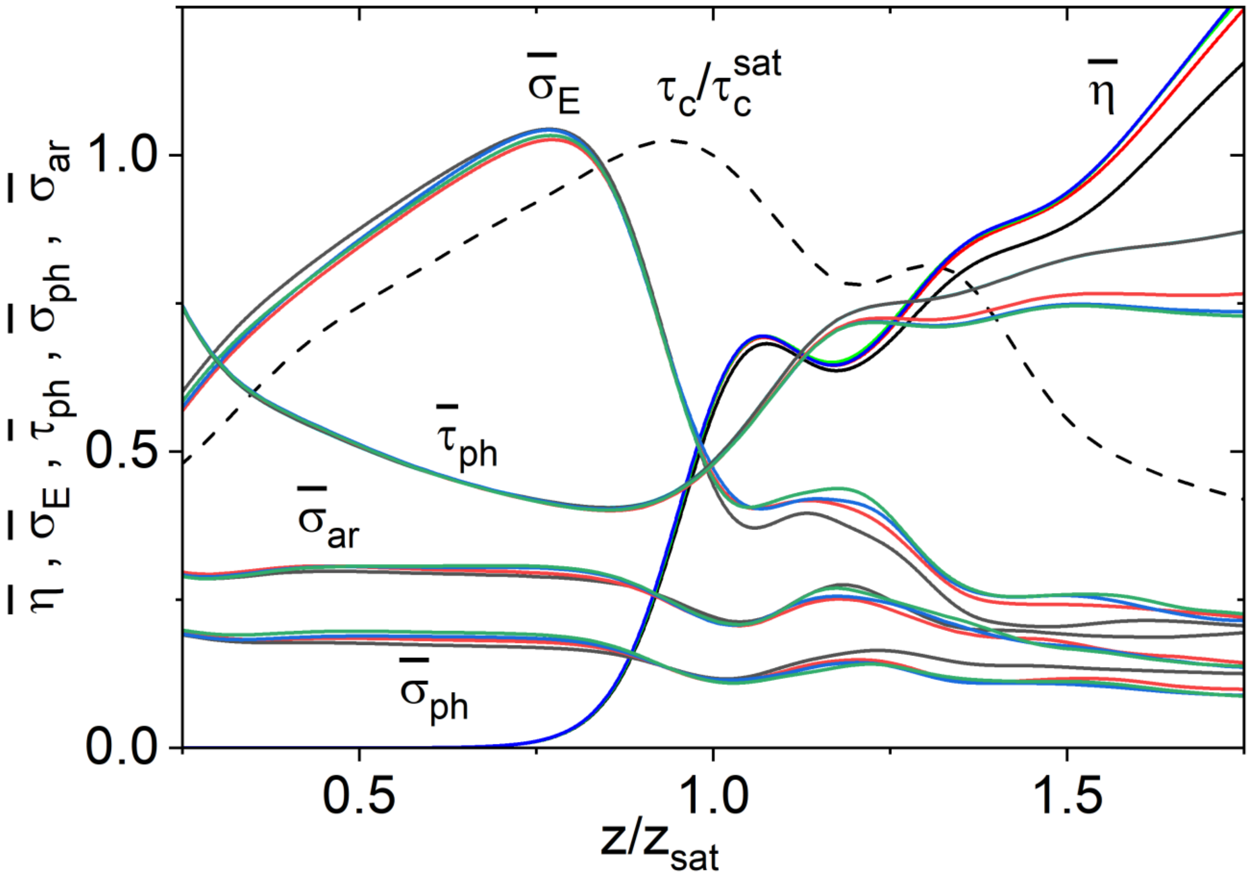
- Then we apply scaling of parameters with electron pulse duration:

$$\bar{\tau}_{\mathrm{ph}} = \tau_{\mathrm{ph}}/\tau_{el} \ , \qquad \bar{\sigma}_{\mathrm{ph}} = \hat{\sigma}_{\mathrm{ph}}/\hat{\tau}_{el}^{1/2} \ , \qquad \bar{\sigma}_{\mathrm{ar}} = \hat{\sigma}_{\mathrm{ar}}/\hat{\tau}_{el}^{1/2} \ , \qquad \bar{\sigma}_{\mathrm{E}} = \sigma_{\mathrm{E}}\hat{\tau}_{\mathrm{el}}^{1/2} \ .$$

- Normalized FEL efficiency is defined as $\bar{\eta} = E_{\mathrm{r}}/(\rho E_{\mathrm{eb}})$, and E_{eb} is kinetic energy of the electron bunch.

Ivette J. Bermúdez Macias et al., Optics Express, vol. 29 (2021) 10491-10508.

Short pulses: application of similarity techniques



- Evolution along the undulator of the scaled FEL efficiency, $\bar{\eta}$, scaled rms fluctuations of the radiation pulse energy $\bar{\sigma}_E$, scaled rms photon pulse duration and its scaled rms deviation, $\bar{\sigma}_{ph}$ and $\bar{\sigma}_{\sigma_{ph}}$, and scaled rms deviation of the photon pulse arrival time, $\bar{\sigma}_{ar}$.
- Four different colors of the curves correspond to different scaled electron pulse durations $\bar{\sigma}_{\sigma_{el}} = 4, 8, 16$, and 32. Dashed line shows coherence time scaled to coherence time at the saturation.

Ivette J. Bermúdez Macias et al., Optics Express, vol. 29 (2021) 10491-10508.

Statistical fluctuation method: Gain length. Saturation length. Coherence time. Pulse duration

- Saturation length and coherence time at saturation:

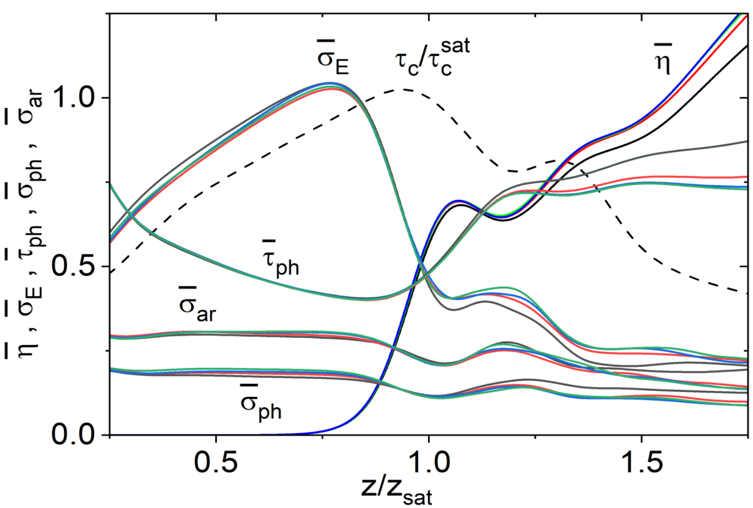
$$L_{\mathrm{sat}} \simeq \frac{\lambda_{\mathrm{w}}}{4\pi\rho}\left(3 + \frac{\ln N_{\mathrm{c}}}{\sqrt{3}}\right) , \qquad \tau_{\mathrm{c}}^{\mathrm{sat}} \simeq \frac{1}{\rho\omega}\sqrt{\frac{\pi \ln N_{\mathrm{c}}}{18}} .$$

are expressed in terms of the FEL parameter ρ and the number of cooperating electrons $N_{\mathrm{c}} = I/(e\rho\omega)$. 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 τ_{c} relate to the saturation length as:

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

- Minimum number of modes and pulse duration occur in the end of high gain linear regime at $z/z_{\mathrm{sat}} \simeq 0.8$. For the number of modes $M \gtrsim 2$ we have:

$$M \simeq 0.94 \times \hat{\tau}_{\mathrm{el}} , \qquad \tau_{\mathrm{ph}}^{\mathrm{min}} \simeq 0.4\tau_{\mathrm{el}} \simeq \frac{M\lambda L_{\mathrm{sat}}}{15c\lambda_{\mathrm{w}}} \simeq \frac{M\tau_{\mathrm{c}}^{\mathrm{sat}}}{4} .$$

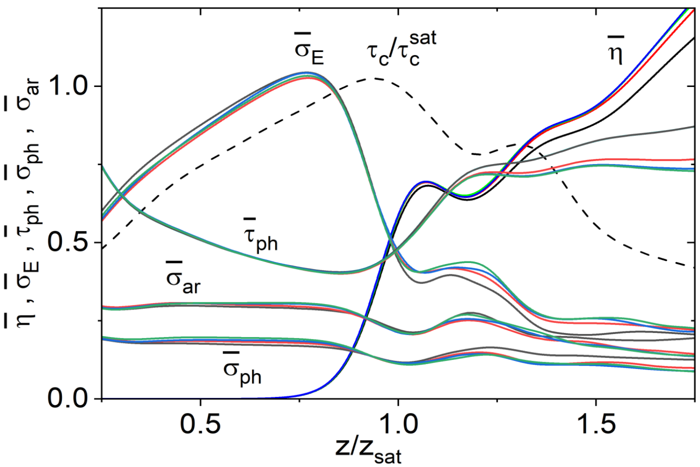


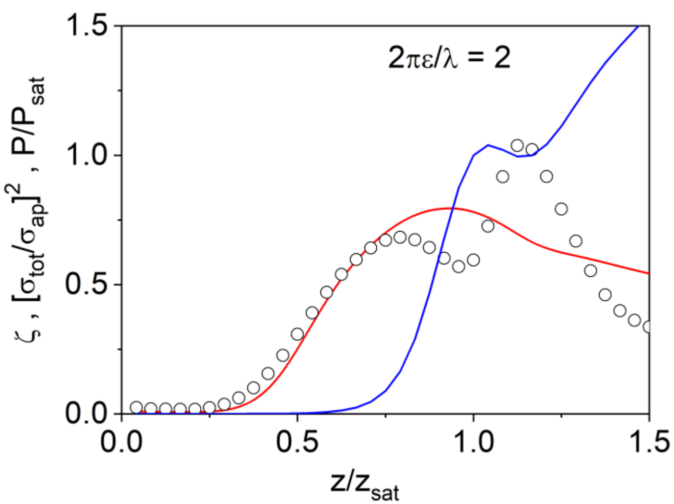
Lengthening of the radiation pulse occurs when amplification process enters nonlinear regime. This happens due to lasing to saturation of the electron bunch tails, and due to slippage effect. The latter effect is more pronouncing for shorter pulses. At the saturation point pulse lengthening is about factor of 1.2 with respect to the minimum pulse length, and it is increased up to a factor of 1.8 in the post-saturation regime.

Ivette J. Bermúdez Macias et al., Optics Express, vol. 29 (2021) 10491-10508.

Statistical fluctuation method: Experimental procedure

Ivette J. Bermúdez Macias et al., Optics Express, vol. 29 (2021) 10491-10508
E.A. Schneidmiller, and M.V. Yurkov, Proc. IPAC2016, MOPOW013





1. Set a pinhole of relevant size.

2. Measure gain curve: average pulse energy and fluctuations.

3. Inverse square of fluctuations in the end of exponential regime gives us the number of lingitudinal modes $M_l = 1/\sigma^2_{E,ap}$.

4. Point on the gain curve corresponding to the drop of fluctuations by a factor of 3 wrt maximum value is saturation point, L_{sat}. Thus, we derive the value for coherence time and rms pulse duration in the end of the high gain exponential regime:

$$\tau_{\mathrm{c}} \simeq \lambda L_{\mathrm{sat}}/(2\sqrt{\pi}c\lambda_{\mathrm{w}}) \ , \qquad \tau_{\mathrm{ph}}^{\mathrm{min}} \simeq \frac{M_l \lambda L_{\mathrm{sat}}}{15 c\lambda_{\mathrm{w}}}$$

Note that photon pulse duartion in the saturation point is lengthened by a factor of 1.2.

5. Remove aperture and measure fluctuations of the full radiation pulse energy, $\sigma_{E,tot}$ in the maximum of fluctuations (end of the high gain linear regime). Ratio, $\sigma^2_{E,ap}/\sigma^2_{E,tot}$, gives the number for the degree of transverse coherence:

$$\zeta = \frac{\sigma^2_{E,tot}}{\sigma^2_{E,ap}} \ .$$

Intermediate summary

- Statistical technique for SASE FEL characterization is essentially based on the following features:
  - Radiation of SASE FEL operating in the linear regime holds properties of completely chaotic polarized light;
  - Application of similarity techniques in the FEL theory.
- Measurements of the gain curve (average radiation pulse energy and fluctuations) allows to derive main characteristics of the SASE FEL radiation:
  - Number of longitudinal and transverse radiation modes;
  - Degree of transverse coherence;
  - Saturation length;
  - Gain length;
  - Coherence time;
  - Radiation pulse duration;
  - FEL parameter ρ.
- What is needed for this technique to work at real machine:
  - Precise measurements of the radiation pulse energies of individual pulses.
  - Stable operation of the hardware.
  - Good electron beam diagnostics and diagnostics of accelerator systems allowing to gate measurements and remove machine jitters.

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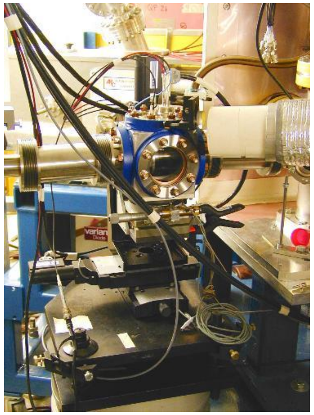
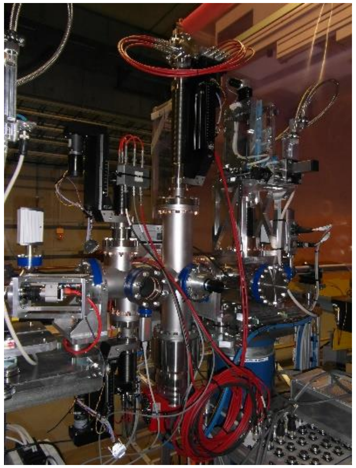
MCP based radiation detector at FLASH

1999 TTF FEL	2004	2007	2012 FLASH2
	FLASH1		

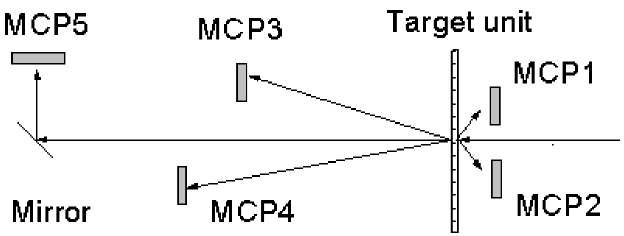




- Several generations of MCP detectors have been developed in the framework of collaboration between DESY and JINR (Dubna), and installed at the TESLA Test Facility, FLASH and FLASH2 in 1999, 2004, 2007, and 2012.

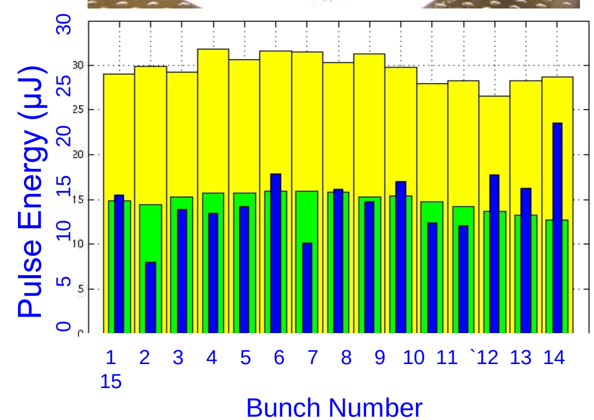
S. Ackermann et al., Nature Photonics 1 (2007) 346.

MCP detector at FLASH1



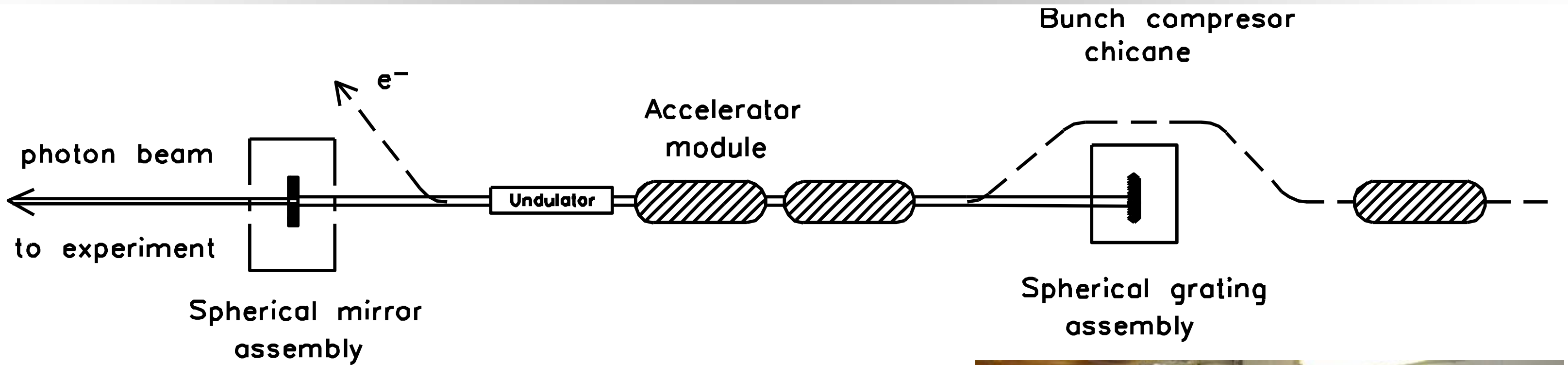
Target

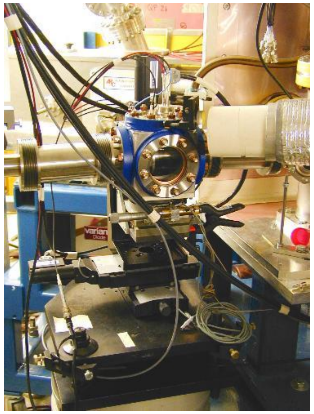
MCP



- Principle of operation: detection with a micro-channel plate of a fraction of the radiation scattered by a highly transparent metallic mesh (target).
- Output signal is proportional to the total photon yield, thus MCP detector serves as a calorimeter of radiation.
- Operating wavelength range of the detector covers the whole range of FLASH, from 2 nm to 200 nm.
- Dynamic range of the detector spans from a pJ to mJ level.
- MCP-detector is the main tool for search, tuning and primary characterization of SASE at FLASH. Use of highly transparent mesh allows parallel operation of other photon diagnostic tools, like visual observations with CeYaG crystal and spectral measurements.

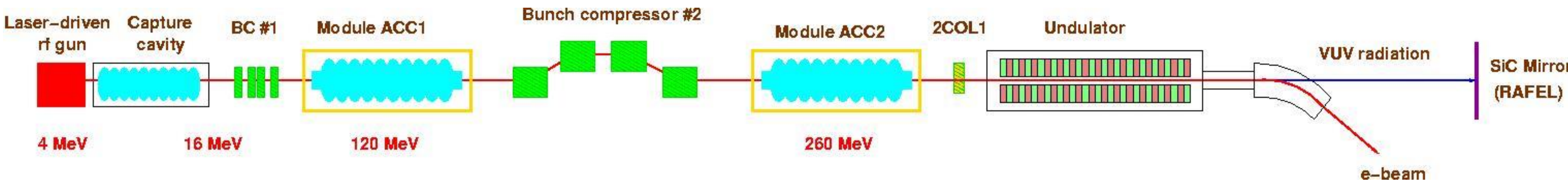
TTF FEL: Regenerative FEL amplifier

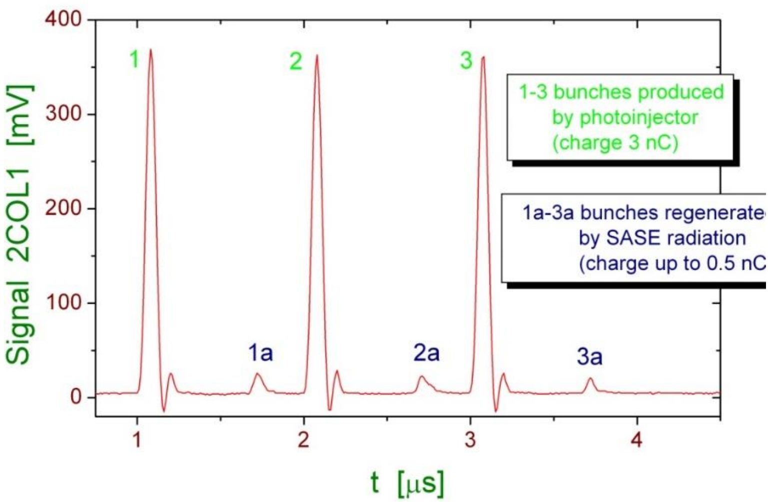


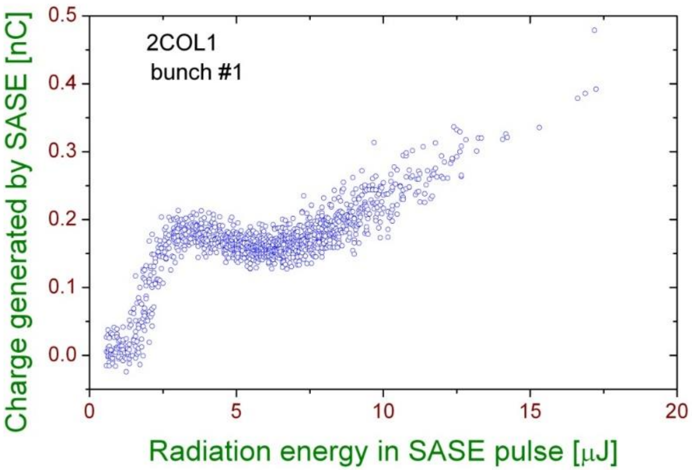


- Original purpose: test of a concept of Regenerative FEL amplifier (RAFEL) – multi-bunch mode of operation with reduced spectrum width. Multi pass operation would allow to reach saturation.
- Lack of space and requirements for a large dynamic range did not allow us to install “standard” photon diagnostics, so we were forced to install compact MCP detector.
- Actual result: experimental discovery of the saturation of TTF FEL operating in a femtosecond regime.

TTF FEL: Regenerative FEL amplifier
SASE driven rf gun







- Primary electron bunches (charge 3nC) are produced by laser-driven rf gun.
- During single pass of the undulator primary bunch produces powerful VUV radiation (λ=95 nm).
- Radiation is reflected by plane SiC mirror and is directed back to the photocathode of rf gun.
- Electron bunch produced by SASE radiation (charge up to 0.5 nC) is accelerated and detected by charge monitor 2COL1 installed at the entrance of the undulator.
- Separation between “parent” and regenerated bunch is 650 ns (or, 195 meters) - round-trip time between photocathode and mirror.

B.Faatz et al., VUV FEL driven RF gun, Nucl. Instrum. and Meth. A 507 (2003) 350.

MCP detector: Measurements of the dark current in FLASH1 undulator

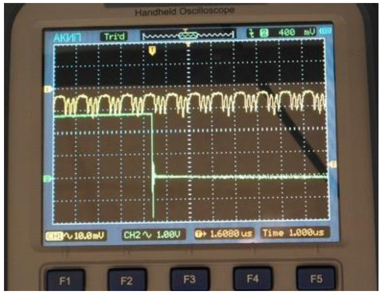
- We measure synchrotron radiation from the electron buches passing through FLASH1 undulator. MCP detector is calibrated at 10 pC bunch charge.
- Measured charge of the dark current in 1.3 GHz buckets is about 1 fC (10^{-15} C). Accuracy of measurements is in the range of a few aC (10^{-18} C).

  Note that the charge of a single electron is 1.6×10^{-19} C.

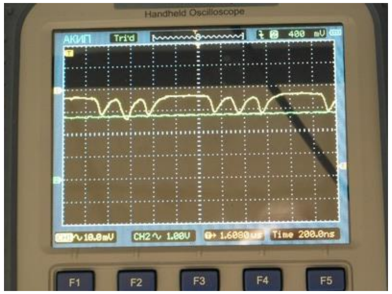
  Thus, we find that that significant fraction of the dark current produced in the gun is transported through the whole accelerator.
- Temporal structure of the dark current is rather complicated with period of 1 microsecond. This feature relates to 1 MHz frequency of the dark current kicker installed in the gun. Dark current is perfectly suppressed at one half cycle, but two dark current emitters make it through the collimator in the other half cycle.
- We have also been able to measure a high contrast of radiation produced by the photoinjector laser pulses switched on and off by a 1 MHz repetition rate Pockels cells which gives an estimate for suppression of bunches closed by the laser 2 Pockels cell to be much less than 10^{-6} (most probably 10^{-8}).

Dark current seen by MCP detector

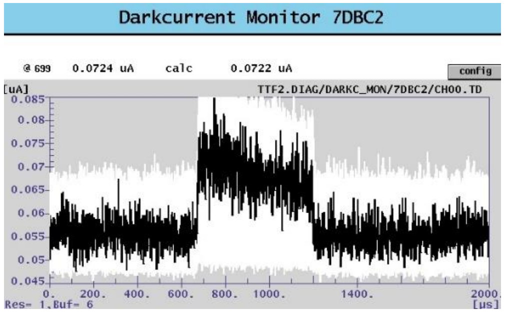
50 μs/div



1 μs/div



200 ns/div



Dark current measurements with DaMon

O. Brovko et al., Proc. IPAC2016, MOPOW014.

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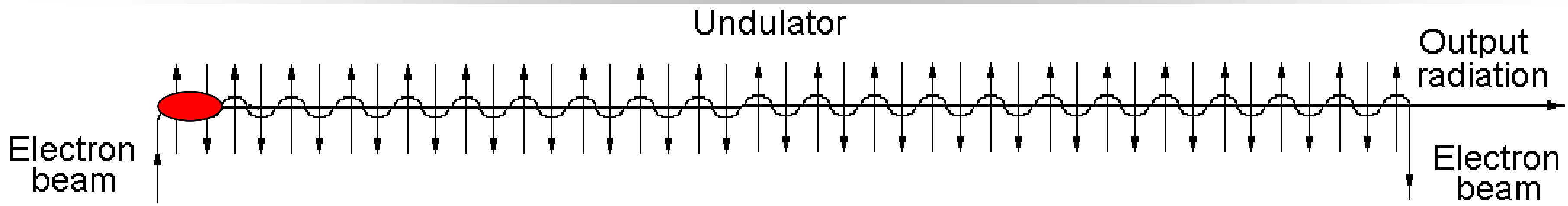
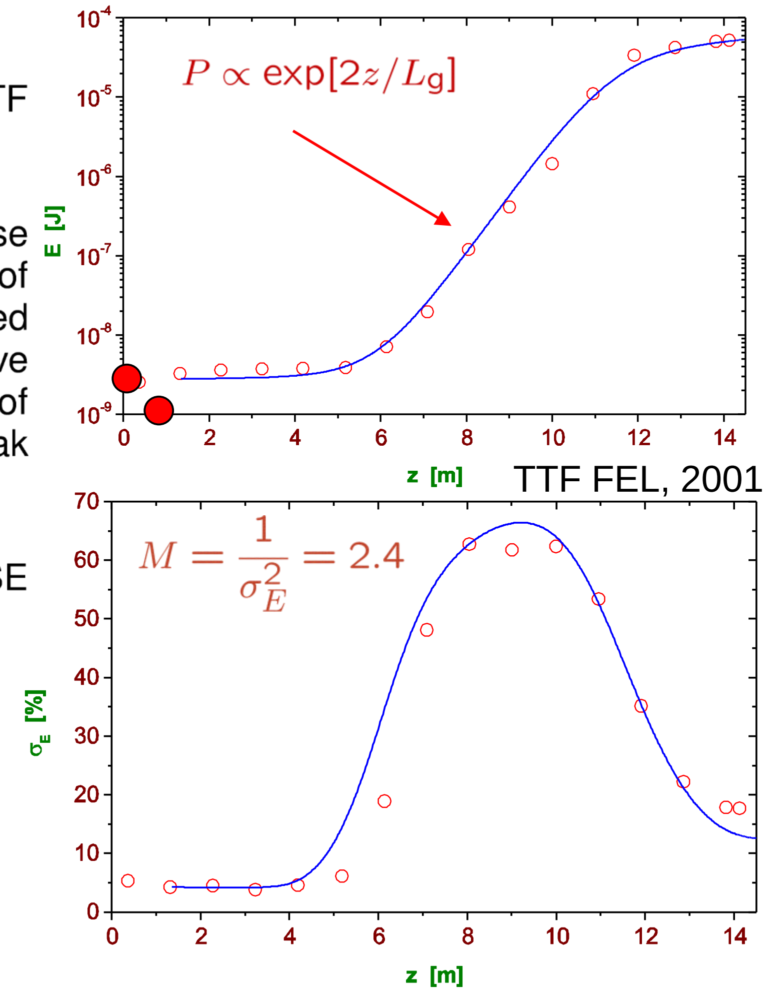
Statistical techniques of SASE FEL characterization: TTF FEL, 2000-2002



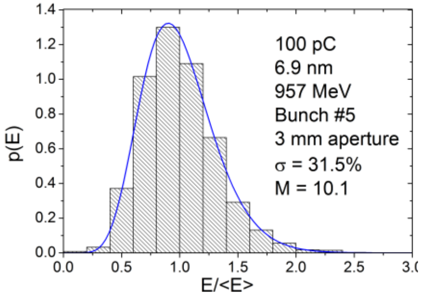
- First full gain curve with MCP detector has been measured at TTF FEL on September 10, 2001.
- Surprizing feature was very high fluctuations of the radiation pulse energy indicating on ultra short pulse duration. Physical behavior of both curves (power gain saturation and drop of fluctuations) indicated on operation of TTF FEL in saturation regime. Further analysis have shown that indeed, we demonstrated for the first time operation of VUV FEL in saturation with 50 fs pulse duration and GW level of peak power.
- Femtosecond mode of operation became the main mode of SASE FEL operation at FLASH for almost ten years.

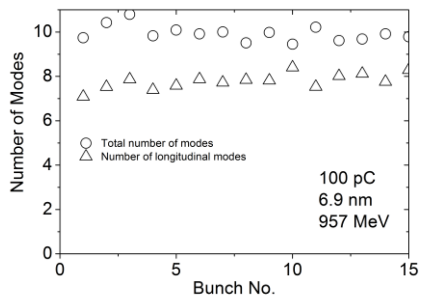
V. Ayvazyan et al., Phys. Rev. Lett. 88 (2002) 10482

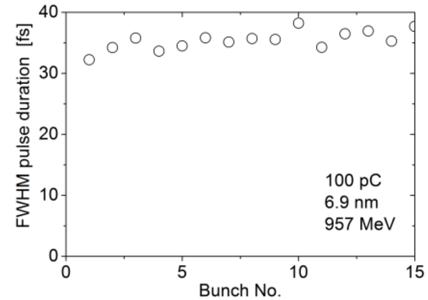


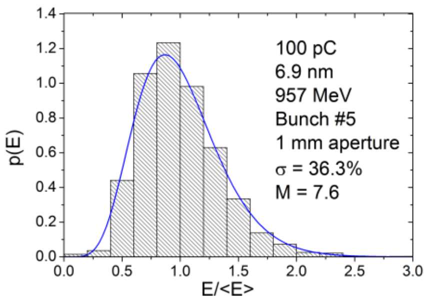
Statistical fluctuation method
Degree of transverse coherence

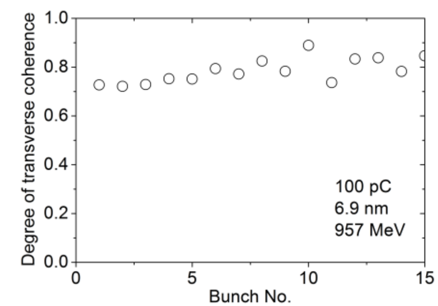
Experimental results from FLASH1, 01.05.2016









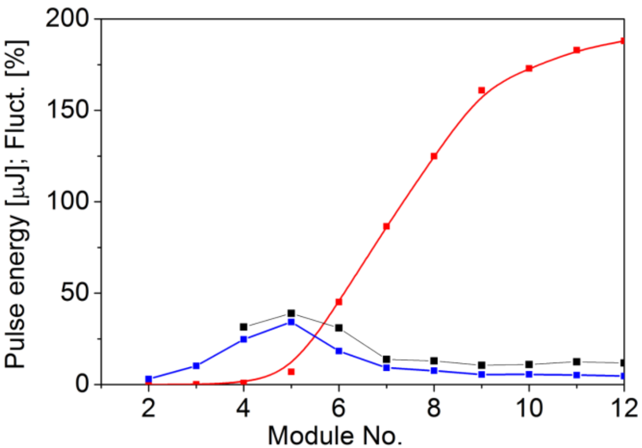


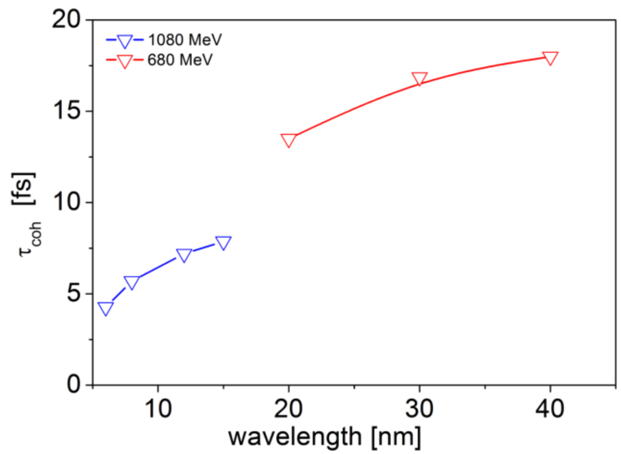
- Fast MCP detector is being used for radiation energy measurements. The electronics of MCP-detector has low noise, about 1 mV at the level of signal of 100 mV (1% relative measurement accuracy).
- Two measurements: full radiation energy, and the energy after pinhole give us total number of modes, and 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.

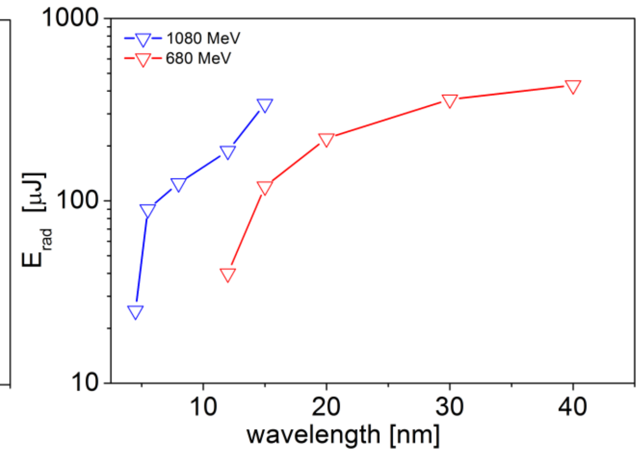
Statistical fluctuation method

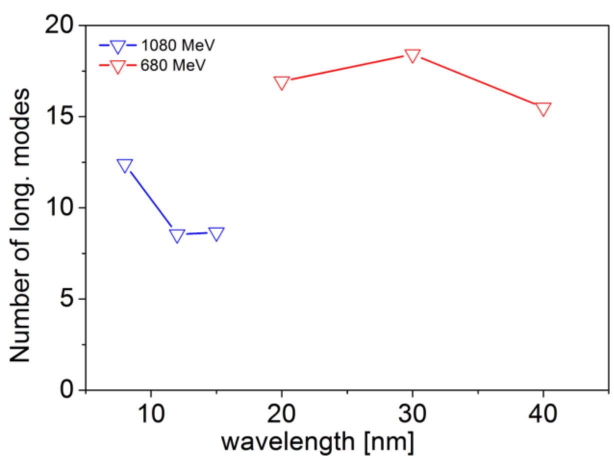
Complete radiation pulse characterization at FLASH2, September 2016:

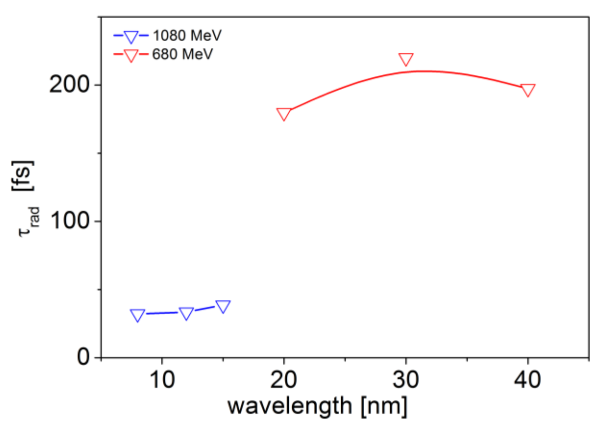
Gain, number of modes, coherence time, degree of transverse coherence, pulse duration.

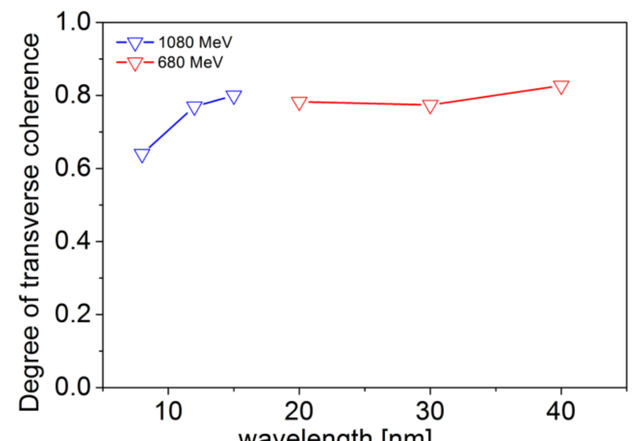










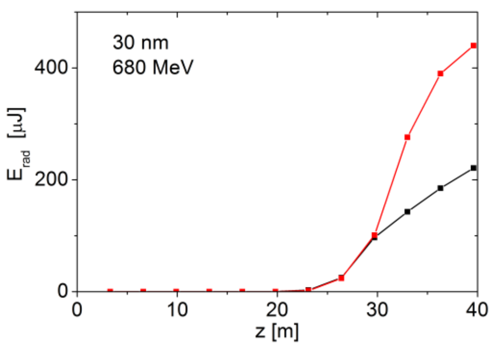


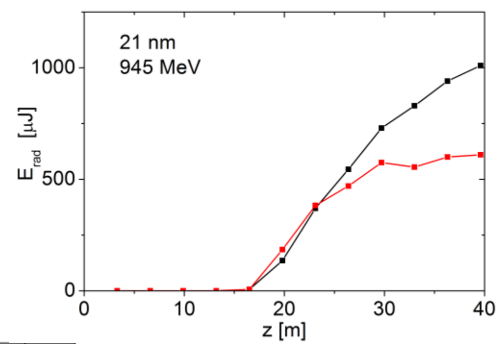
Post-saturation undulator tapering for efficiency increase

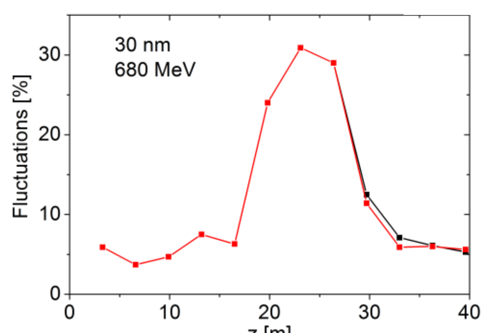
Use of statistical measurements for tuning optimum undulator tapering:

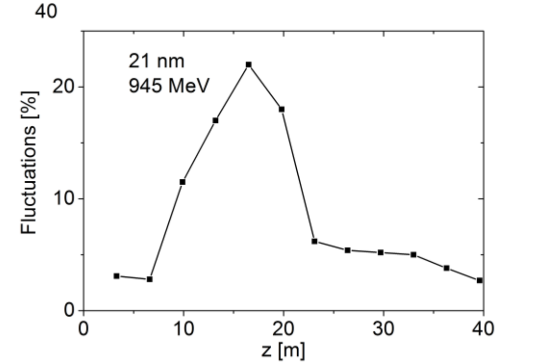
- Optimum conditions of the undulator tapering assume the starting point to be by two field gain lengths before the saturation point (Phys. Rev. ST AB 18, 030705 (2015)) corresponding to the maximum brilliance of the SASE FEL radiation.
- Saturation point on the gain curve is defined by the condition 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



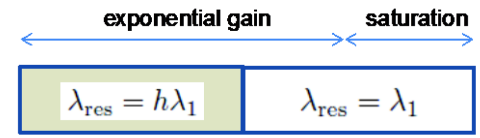






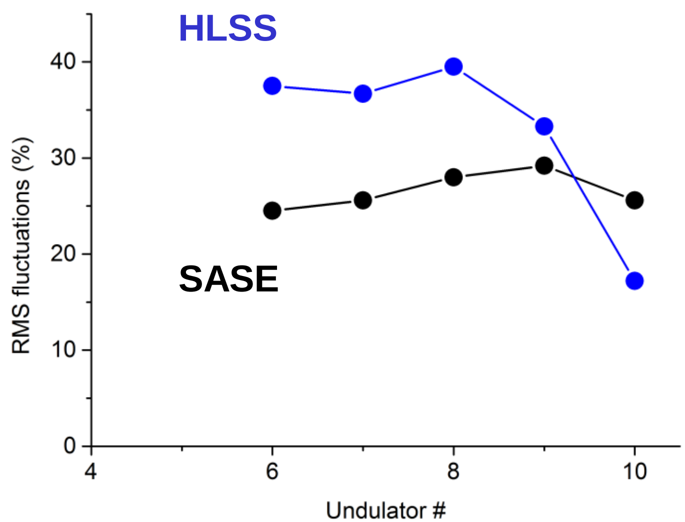
Harmonic lasing self-seeding (HLSS)

Experiment at FLASH2 on June 6-7, 2016 at 11 nm: demonstration of spectrum width reduction, increase of spectral brightness, and increase of coherence time.



4u x 33 nm   6u x 11 nm

Statistical determination of an increase of the coherence time



- Number of longitudinal modes:

$$M_l = 1/\sigma_E^2 \propto 1/\tau_c$$

at fixed pulse length.

- Measured increase of the coherence time is

$$\frac{\tau_{\mathrm{c,HLSS}}}{\tau_{\mathrm{c,SASE}}} = \frac{\sigma^2_{\mathrm{E,HLSS}}}{\sigma^2_{\mathrm{E,SASE}}} = 1.8$$

Measured increase of the coherence length is in agreement with theory:

$$R = h\frac{\sqrt{L_{\mathrm{w}}^{(1)} L_{\mathrm{sat,h}}}}{L_{\mathrm{sat,1}}} = 0.57h = 1.7$$

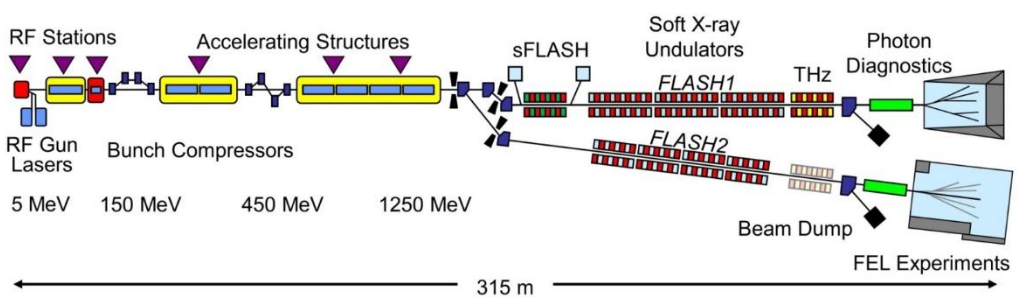
E. A. Schneidmiller et al., Phys. Rev. Accel. Beams 20 (2017) 020705

Outline

- Physics of SASE FEL related to statistical techniques.
- Hardware: MCP detectors.
- Photon beam characterization with statistical techniques: TTF FEL and FLASH.
- **Studies of sporadic jitters at FLASH2.**

Studies of sporadic jitters at FLASH2

- In February, 2019 we recorded status of FLASH2 operation corresponding to typical conditions of user run during last months.
- One of the features during user run was sporadic appearance of machine jitters affecting stability of the SASE FEL output.
- Data of photon diagnostics accelerator diagnostics have been recorded in DAQ during measurements of FEL gain curves.
- At the final step we performed correlation analysis of SASE data with essential parameters of the electron beam (jitters of orbit and beam formation system).



List of BPMs at FLASH2

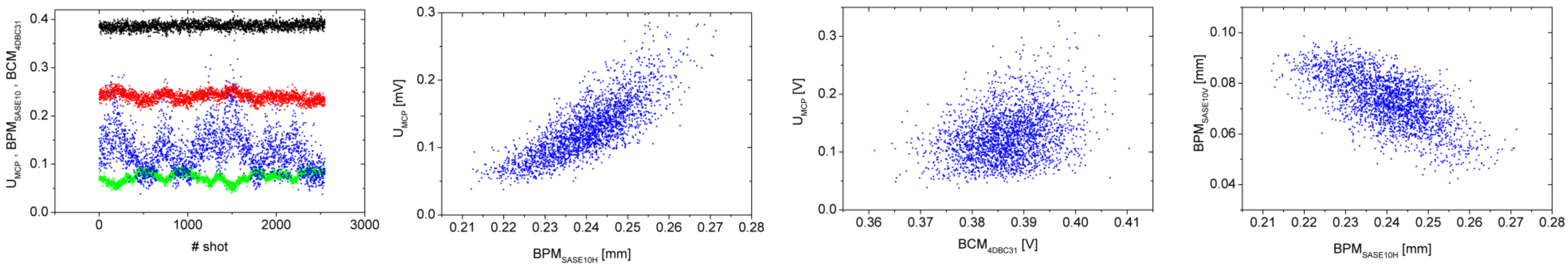
1	1GUN	11	3DBC3	21	3FL2SASE3
2	3GUN	12	11ACC7	22	3FL2SASE4
3	2UBC2	13	15ACC7	23	3FL2SASE5
4	1DBC2	14	19ACC7	24	3FL2SASE6
5	3DBC2	15	4FL2EXTR	25	3FL2SASE7
6	5DBC2	16	5FL2EXTR	26	3FL2SASE8
7	7DBC2	17	8FL2EXTR	27	3FL2SASE9
8	11DBC2	18	3FL2SEED1	28	3FL2SASE10
9	1UBC3	19	3FL2SEED4	29	3FL2SASE11
10	2UBC3	20	3FL2SEED7	30	3FL2SASE12
		31	3FL2SASE13	32	3FL2SASE14

Ivette J. Bermúdez Macias e al., Optics Express, vol. 29 (2021) 10491-10508.

Studies of sporadic jitters at FLASH2
Raw data

- Influence of machine jitters on SASE FEL output depends on the stage of amplification process. Maximum contribution of the machine jitters is obtained in the end of the high gain linear regime, and becomes less pronouncing in the saturation regime.

- Correlation signals of MCP-BPM (related to orbit jitters) are clean, but correlation signals MCP-BCMs (reflecting jitters of the beam formation system) are not co clean due to larger noise in BCM devices.



Left: raw signal of MCP detector (blue), BPM 3FL2SASE10 (x - red, y - green), and BCM 4DBC31 (black). Right correlation plots of MCP signal versus BPM3FL2SASE10H and BCM, and x and y positions of BPM 3FL2SASE10 (right).Measurements are performed after 7 undulator modules. Radiation wavelength is 10 nm.

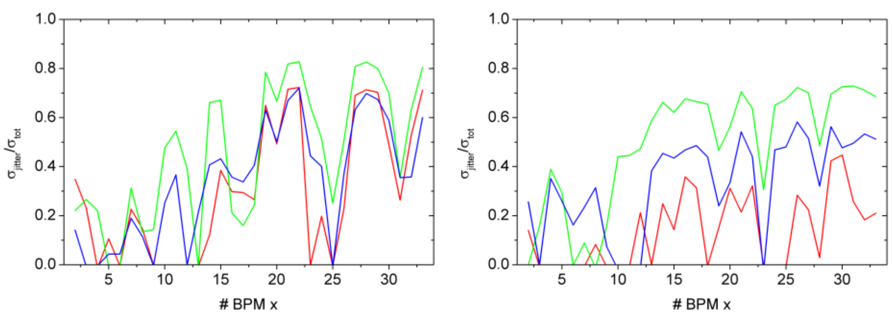
S. Grunewald et al., Proc. FEL2019, WEP073

Studies of sporadic jitters at FLASH2
Analysis of machine jitters

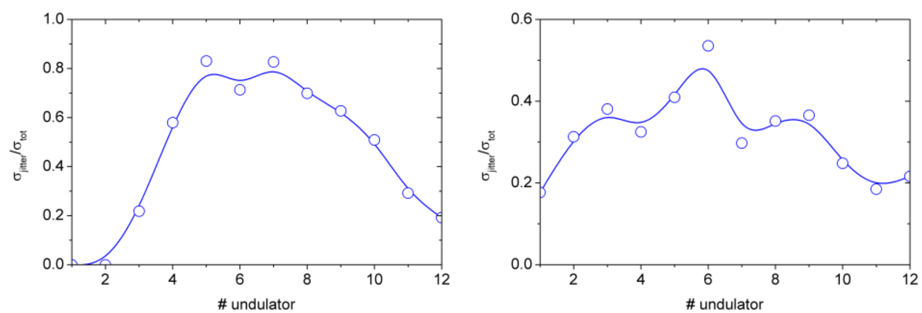
- Fundamental SASE fluctuations and machine jitters are statistically independent, so total fluctuations are: $\sigma^2_{tot} = \sigma^2_{SASE} + \sigma^2_{jitter}$, and required figure of merit is ratio of machine induced fluctuations to total fluctuations, $\sigma_{jitter}/\sigma_{tot}$.

- The value of σ_{jitter} is calculated after gating of the experimental results. Application of gating procedure sequentially for each measured machine parameter allows to trace evolution of the jitter along accelerator.

- We note that some machine jitters are already detected with BPMs in the gun area, then they become pronouncing after the first accelerating module ACC1, and gradually increase along the accelerator.



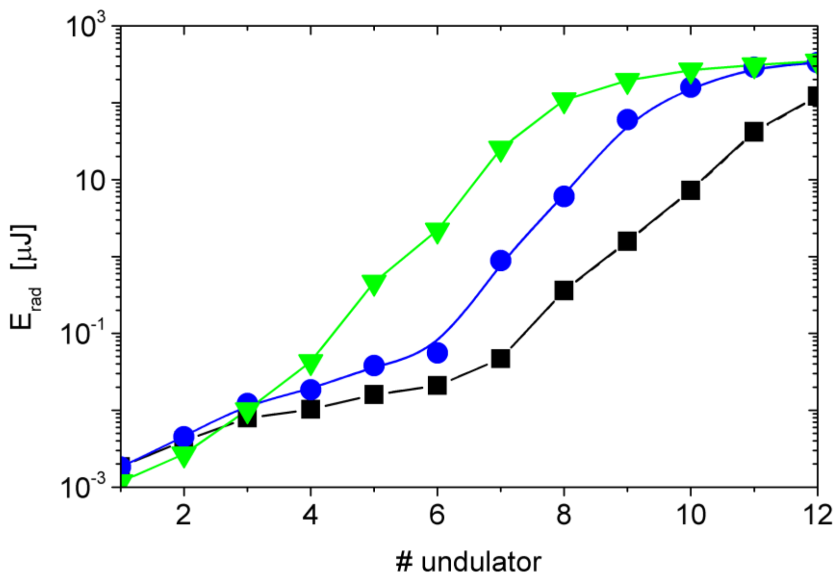
Contribution of the machine jitters seen by BPMs to total fluctuations of the radiation pulse energy. Left: horizontal BPMs, right: vertical BPMs. Red, green, and blue curves refer to measurements after 6, 7, and 8 undulator modules, respectively.

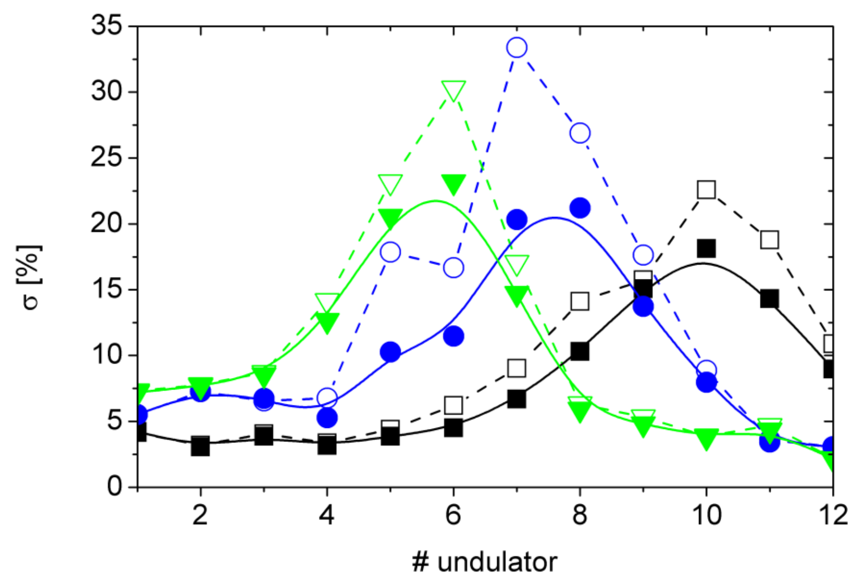


Contribution of machine jitters to total fluctuations of the radiation energy seen by BPM 3FL2SASE10H (left) and BCM 4DBC31 (right) along the undulator.

Studies of sporadic jitters at FLASH2 FEL characterization

- Sporadic machine jitters contribute significantly to fluctuations.
- Sensitivity analysis of machine jitters tells us that the most sensitive diagnostics elements are BPM 3FL2SASE10H (orbit) and BCM 4DBC31 (beam compression).
- Using double discrimination with these parameters we reject 80% of the shots subjected to jitters, and get a good quality of the gain curve governed mainly by fundamental SASE FEL fluctuations.
- A strong argument in favor of this statement is that values of the rms electron pulse duration σ_z agree with good accuracy for all measurements.

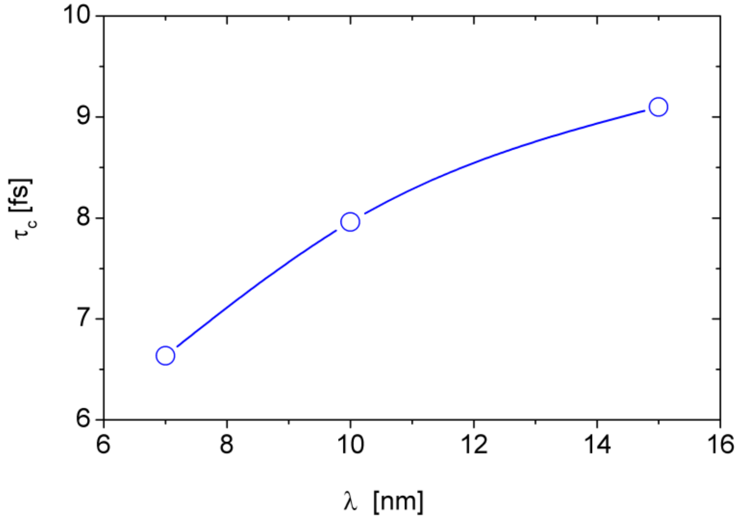


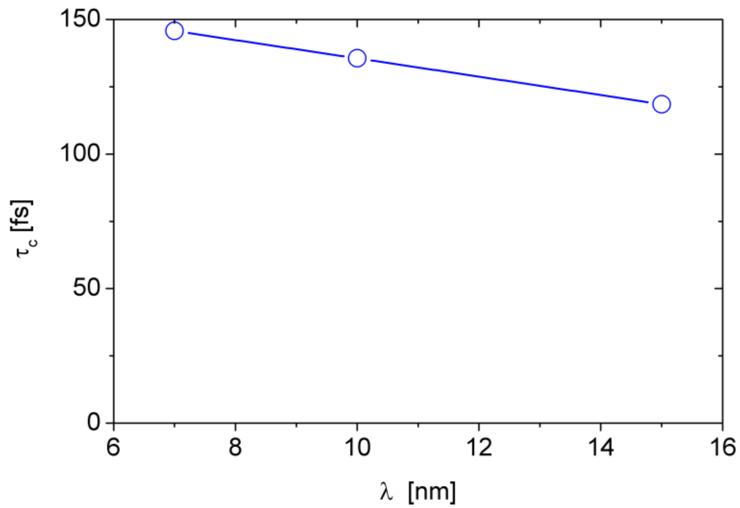


Gain curve of SASE FEL at FLASH2: average energy in the radiation pulse (top) and its fluctuations (bottom). Dashed and solid curves correspond to raw and gated data. Black, blue and green colors correspond to the radiation wavelength 7 nm, 10 nm, and 15 nm.

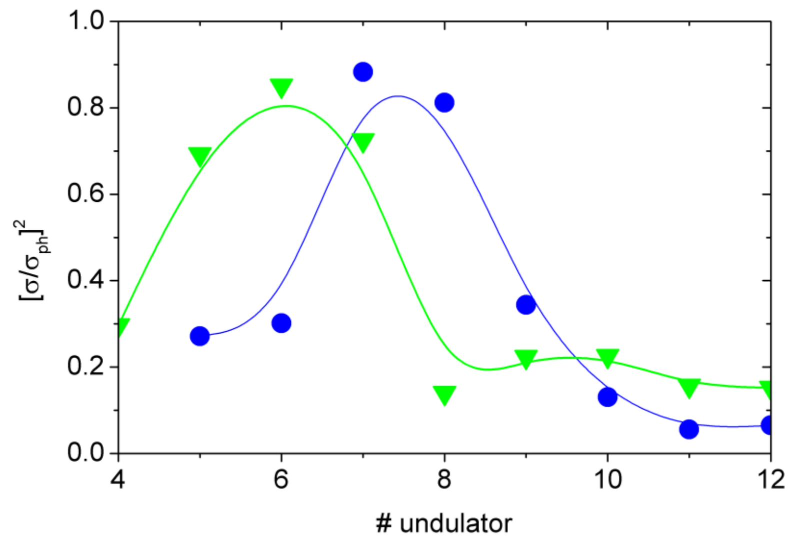
Studies of sporadic jitters at FLASH2
FEL characterization

Coherence time, pulse duration, degree of transverse coherence





Coherence time(top) and pulse duration (bottom) versus wavelength.



Ratio of dispersions of the full radiation pulse energy to that filtered by a pinhole. Blue and green colors correspond to the radiation wavelength 10 nm and 15 nm. Maximum degree of transverse coherence is 80%.

Summary

- Statistical techniques is extremely powerful tool for characterization of the main SASE FEL parameters: saturation length, FEL gain length, coherence time, photon pulse duration, number of longitudinal and transverse radiation modes, and the degree of transverse coherence.
- Method is based on the fundamental principles, and measured values have strict physical meaning.
- Statistical measurements are used at FLASH since start of its operation in 1999. There was also trial experiment at LCLS in 2010. However, 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: (1) availability of fast and precise radiation detector capable to measure radiation energy of individual pulses in a wide range of the radiation intensities and (2) small jitter of the machine parameters. At FLASH we use MCP detector with relative accuracy of measurements better than 1%. We believe also that good phase stability of the superconducting accelerator FLASH helps as well. In addition, success of the technique depends on the quality of accelerator diagnostics allowing to detect jitters of the electron beam and machine parameters.
- Next task for the development statistical technique at FLASH, its implementation for every day use in the control room, is in the progress.

We thank FLASH team for useful collaboration and support of our studies. Special thanks to Juliane Roensch-Schulenburg, Sigfried Schreiber, and Markus Tischer for their help in running FLASH2 systems and with resolving technical problems.