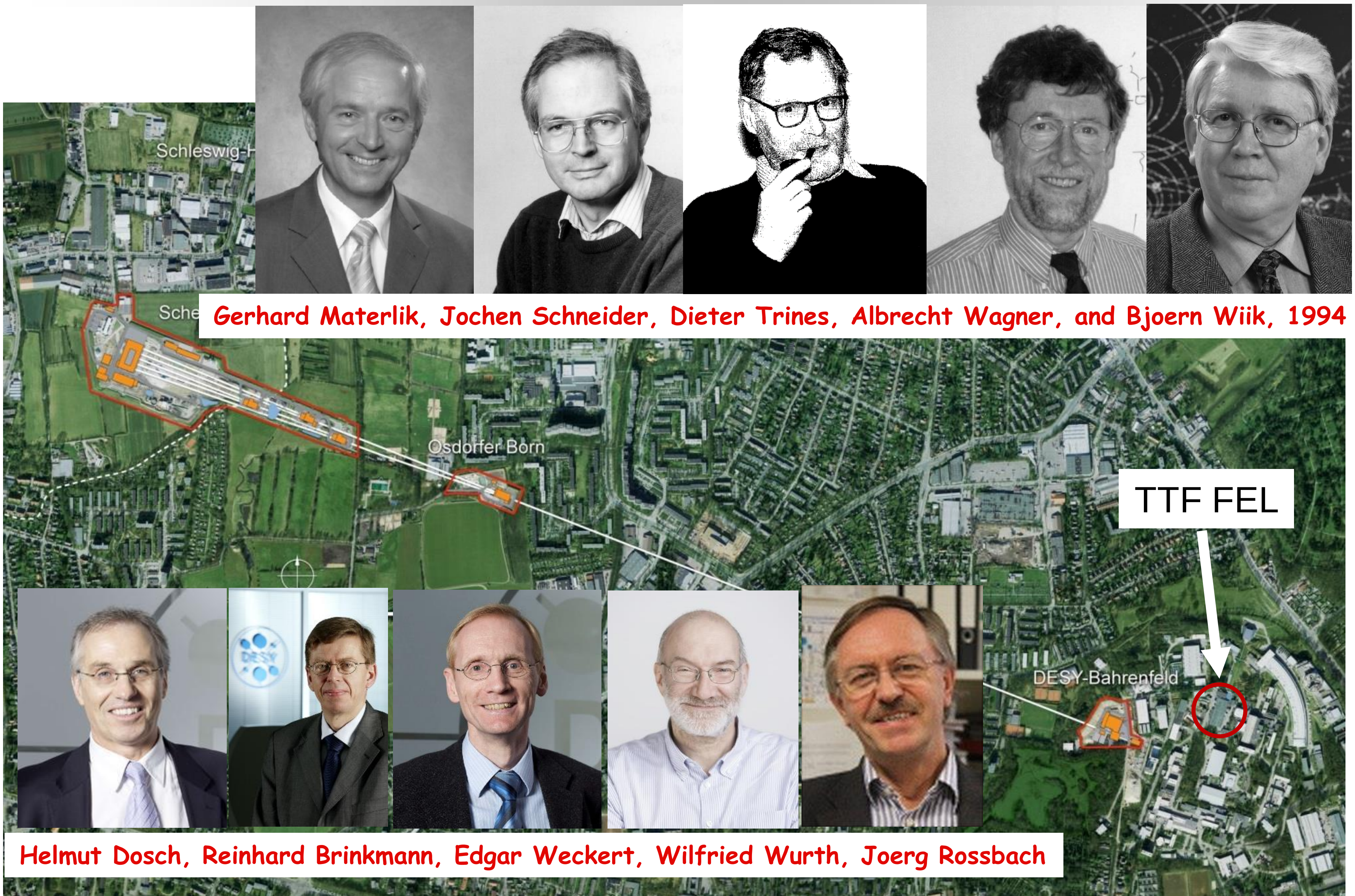
TTF FEL: Lessons learned from the first lasing to saturation

Mikhail Yurkov on behalf of TTF FEL Team

Many thanks to Rasmus Ischebeck for collecting our faces, https://www.ischebeck.net/posters/ttf-team_2004.pdf

Ground of success: Strong leaders with great intuition



Selected references related to TTF FEL /project, experiment, theory/

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J. Andruszkow et al., First observation of self-amplified spontaneous emission in a free-electron laser at 109 nm wavelength, Phys. Rev. Lett. 85(2000)3825.

V. Ayvazyan et al. A new powerful source for coherent VUV radiation: Demonstration of exponential growth and saturation at the TTF free-electron laser, Eur. Phys. J. D 20(2002)149.

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M. Huening and H. Schlarb, Measurements of the beam energy spread in the TTF photoinjector, Proc. of PAC2003 (2003) 2074.

M. Dohlus et al, Start-to-end simulations of SASE FEL at the TESLA Test Facility, phase 1, Nucl. Instrum. and Methods A 530(2004)217.

E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Numerical simulations of the UCLA experiments on a high gain SASE FEL, AIP Conf. Proc. 468(1999)321.

B. Faatz et al., Regenerative FEL Amplifier at the TESLA Test Facility at DESY, Nucl. Instrum. and Methods A429}(1999)424.

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B. Faatz et al., Development of a pump-probe facility combining a far-infrared source with laser-like characteristics and a VUV free electron laser, Nucl. Instrum. and Meth. A 475(2001)363.

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.

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J. Feldhaus et al., Possible application of X-ray optical elements for reducing the spectral bandwidth of an X-ray SASE FEL

Opt. Commun. 140, 341 (1997).

C.Pagani et al., Design considerations of 10 KW-scale extreme ultraviolet SASE FEL for lithography, Nucl. Instrum. and Methods A 463(2001)9.

Validity of pioneer SASE publications

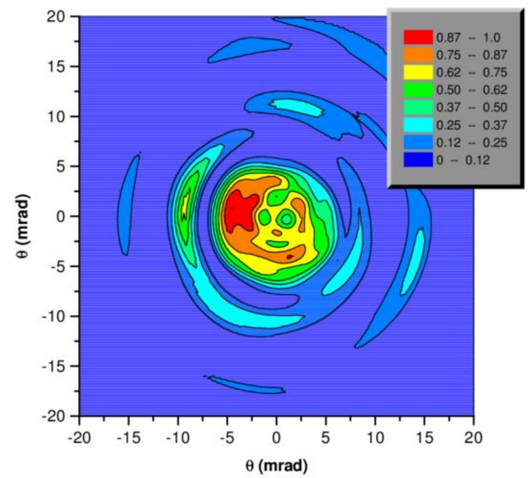
Basic question in 1994: Can we use theory based on pioneer SASE publications?

- A.M. Kondratenko, E.L. Saldin, Generation of coherent radiation by a relativistic electron beam in an undulator, Part. Accelerators 10, 207-216 (1980).
- Ya.S. Derbenev, A.M. Kondratenko, E.L. Saldin, On the possibility of using a free-electron laser for polarization of electrons in storage rings, Nucl. Instrum. and Methods 193, 415-421 (1982).
- R. Bonifacio, C. Pellegrini, L.M. Narducci, Collective instabilities and high-gain regime in a free-electron laser. Opt. Commun. 50, 373 (1984).
- J.B. Murphy, C. Pellegrini, Free electron lasers for the XUV spectral region, Nucl. Instrum. and Methods A 237, 159-167 (1985).

Answer: Yes, we can.

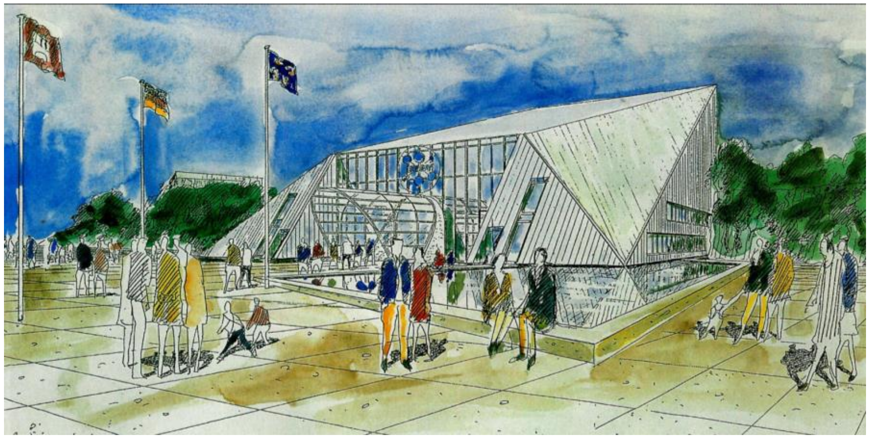
In 1998 we had an opportunity to benchmark UCLA/LANL SASE FEL operating in a 10 um wavelength range. Claudio Pellegrini and colleagues (Swen Reiche, Alexander Varfolomeev) kindly provided us with a full set of experimental data of their experiment, and we found excellent agreement with theory and numerical codes. Partially we included this analysis in our book (The Physics of Free Electron Lasers).

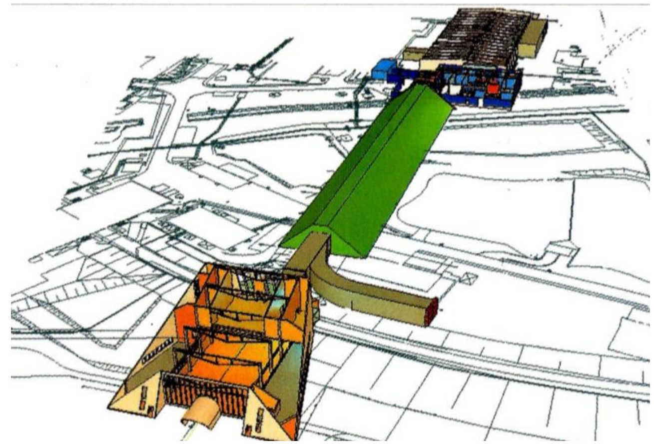
Later on, LEUTL FEL operated in visible and UV, and our US colleagues demonstrated good agreement between theory and experiment.



1998, code FAST: 3D, time-dependent simulations of UCLA/LANL SASE FEL

Time constraints and physical requirements





From June to October 2000, the hall will house the 1200 square-metre Light for the New Millennium exhibition, DESY's contribution to the EXPO 2000 World Exhibition (*CERN Courier, May, 1999*)

June 1st, 2000: TTF FEL should be presented at EXPO 2000 as first world's FEL operating in VUV

It should be sufficient that TTF FEL produces powerful VUV radiation in a high gain exponential regime

2001: Pioneer user experiments should be performed using unique features of FEL radiation. Two experiments has been selected: by Thomas Moeller and Jacek Krzywinski groups.

For success of user experiments TTF FEL should produce radiation with ultimate intensity corresponding to saturation characteristics.

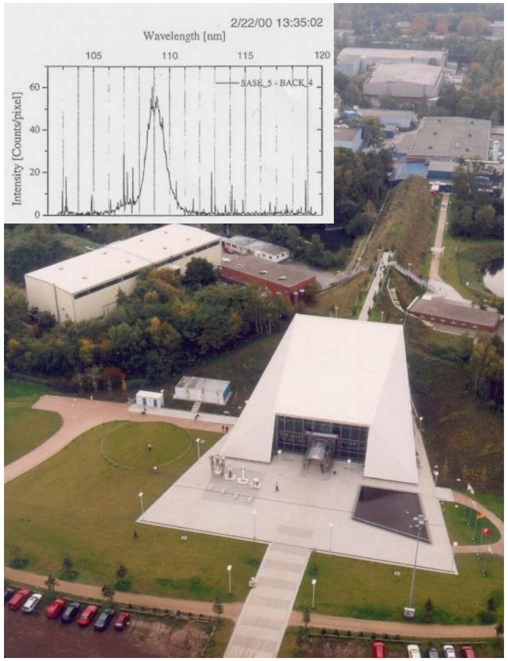
TTF FEL: Expectations and experimental results

Undulator: Period λ_u = 27.3 mm   Peak field: 0.46 T   Length: 3 modules of 4.5 m

Parameter	Units	Project value	Experiment Feb. 2000	Experiment Sep. 2000-2002
rms energy spread at gun	keV	25	22.1± 2.7	<5 (slice)
rms electron pulse length at gun	mm	2	3	3
peak electron current	A	60	40	40
beam energy at undulator	MeV	up to 270	233 ± 5	180-270
rms energy spread	MeV	0.3-0.5	0.3 ± 0.2	0.1 (slice)
rms transverse beam size	μm	60	100 ± 30	100 ± 30
normalized emittance in the undulator	π mm mrad	2	6 ± 3	6 ± 3
electron bunch charge	nC	1	1	1-3.5
peak electron current	A	500	400 ± 200	1-2 kA
FEL gain	#	~3000	~3000	10^5➔10^7
FEL radiation pulse length	ps	0.3 - 1	0.3 – 1 (?)	0.05

- With expected project parameters TTF FEL should work in the high gain exponential regime with FEL power gain about 10^3 – 10^4. This is sufficient for the EXPO 2000 constraint – demonstration of lasing in VUV.
- User experiments require ultimate saturation characteristics. Hoping on wonders of tuning and possible improvements, we, however, launched the project of Regenerative FEL amplifier (RAFEL).

TTF FEL: First lasing on February 22, 2000



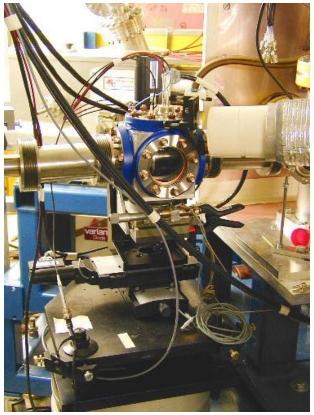
Light for the New Millennium exhibition: DESY's contribution to the EXPO 2000 World Exhibition.

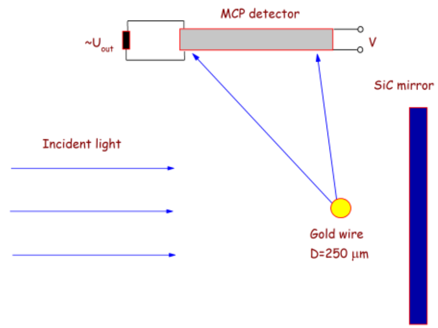
Nowadays it accomodates FLASH tunnel and experimental hall.

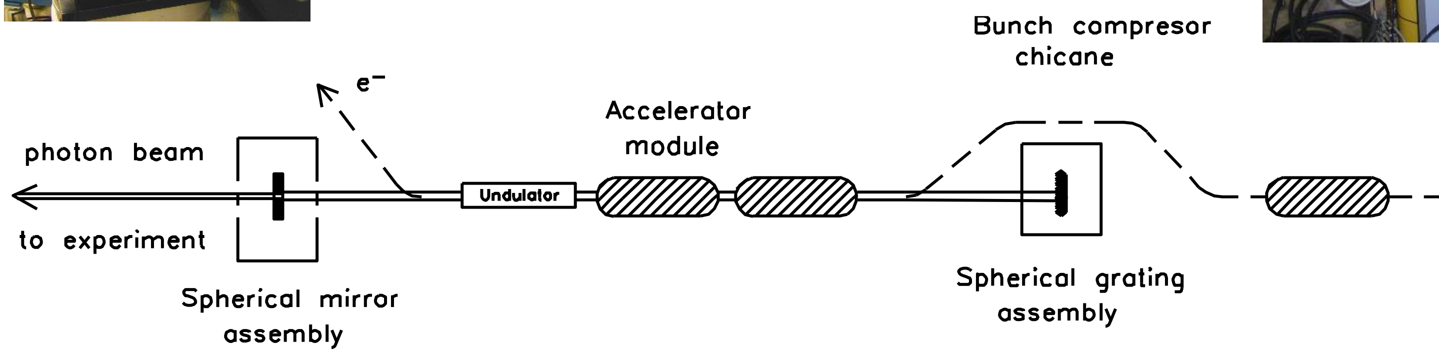
- First lasing at 109 nm happened on February 22, 2000, just in time for the EXPO 2000 event.
- Analysis of the photon beam and electron beam measurements available at that time (J. Andruszkov et al., Phys. Rev. Lett. 85(2000)3825) was in agreement with project parameters.

- There was a puzzle of the first lasing: for a few months we did not see any signature of lasing.
- When the first lasing has been detected, we found that horizontal orbit seen by BPMs exhibited a strong bump. Its value exceeded significantly electron beam size in the undulator (100 um).
- Correction of the orbit to “zero” BPM readings killed SASE.
- That was the subject for intensive debates which are not finished up to now.
- However, we were almost happy, but remembered that pioneer user experiments were planned after EXPO 2000 which required ultimate FEL performance.

Regenerative FEL Amplifier at TTF FEL

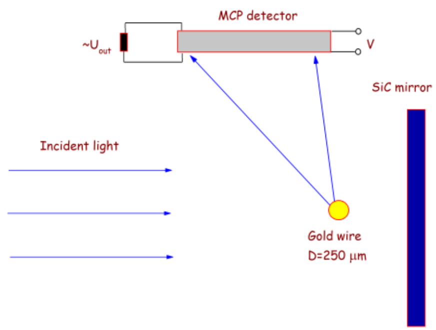


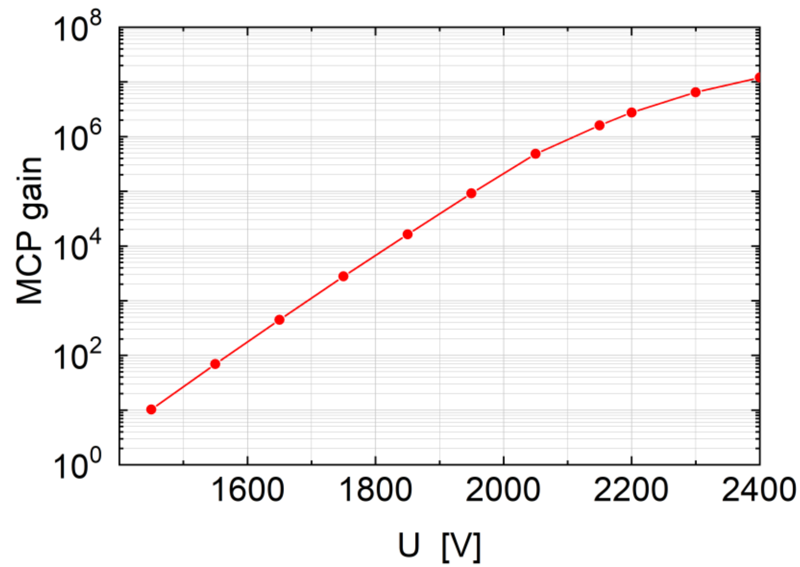




- RAFEL was joint venture of three side collaboration: DESY, Joint Institute for Nuclear Research (JINR, Dubna), and Polish Academy of Sciences.
- Two vacuum chambers (spherical mirror assembly and spherical grating assembly) have been installed in the bunch compressor area and in the end of the photon beamline.
- Lack of space and requirements for a large dynamic range of radiation intensities 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.

Saturation of PtSi detector on September 19, 2000





- After first lasing we gradually improved skill of machine tuning, and got saturation of PtSi detector even at smallest possible aperture of 0.5 mm. Electron bunch charge was 3.5 nC. Question was if this is FEL saturation, or saturation of the photon detector.
- At that time we already installed MCP detector into RAFEL setup which demonstrated significant reserve in improving FEL gain.
- In close contact with Hamamatsu experts we carefully calibrated gain curve of MCP detector, and derived FEL gain to be in the range of 10^5, significantly higher than project value.

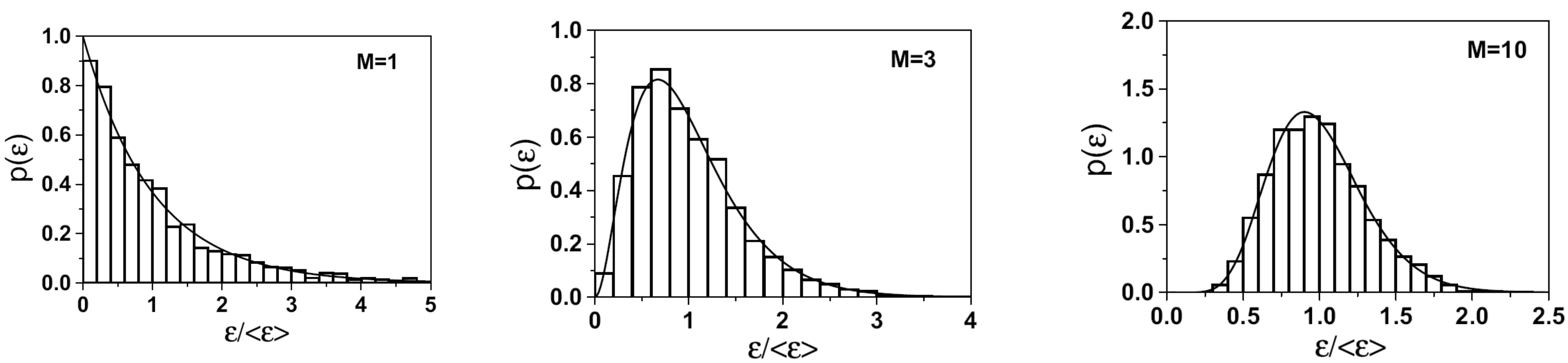
Use of statistical measurements for determination of pulse duration

- 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:

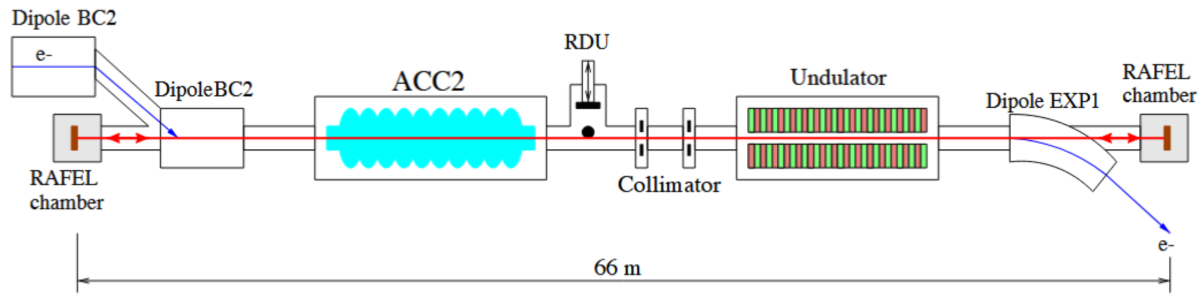
$$p(E) = \frac{M^M}{\Gamma(M)} \left(\frac{E}{\langle E \rangle} \right)^{M-1} \frac{1}{\langle E \rangle} \exp\left(-M \frac{E}{\langle E \rangle} \right) , \qquad M = \frac{1}{\sigma^2} , \qquad \sigma^2 = \frac{\langle (E - \langle E \rangle)^2 \rangle}{\langle E \rangle^2} .$$

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

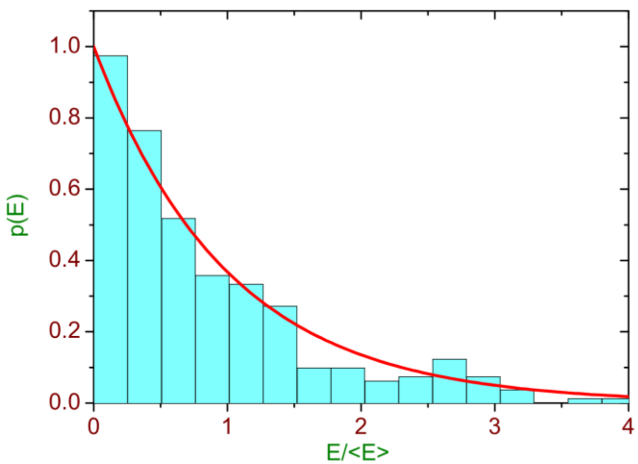
- Total number of modes is product of the number of longitudinal modes by the number of transverse modes.
- Measurements of the fluctuations of the total pulse energy and of the radiaiton energy after a pinhole gives us the number of longitudinal modes, and the total number of modes.

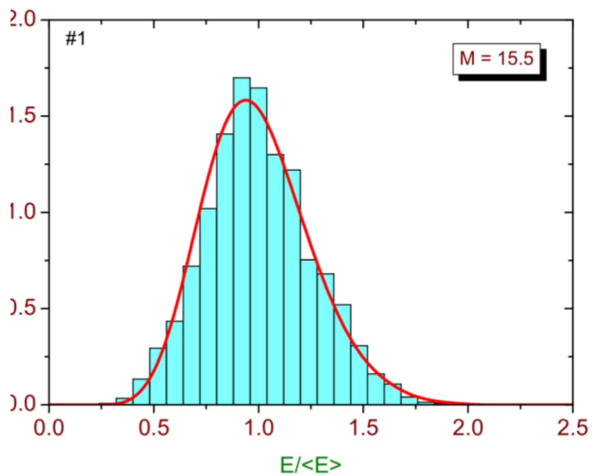


Use of statistical measurements for determination of pulse duration
Spring 2001: pulse duration is in agreement with project value



Two MCP detectors provide measurements of the total pulse energy in the end RAFEL chamber, and measurements of the radiation pulse energy after narrow band monochromator (RAFEL grating installed in the BC area) by the radiation detector unit (RDU).





- Measurements of full radiation energy gave the number of modes M about 15, in agreement with project range for pulse durations of 0.3-1 ps. Average radiation pulse energy was in 10 uJ range.
- Fluctuations after narrow band monochromator exhibited negative exponential distribution - indication on linear mode of operation.
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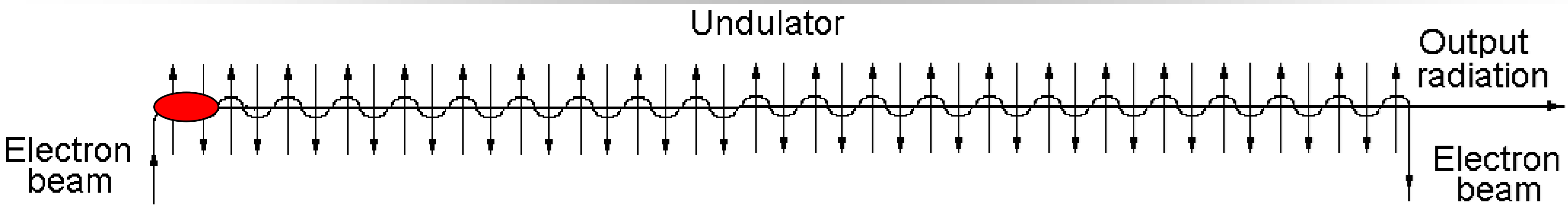
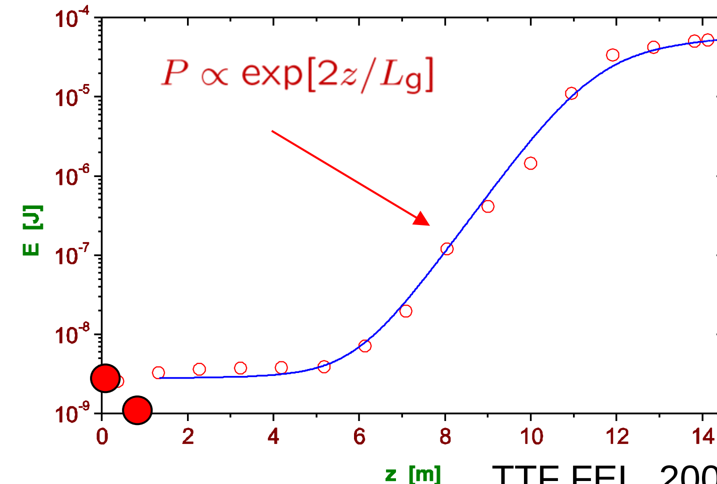
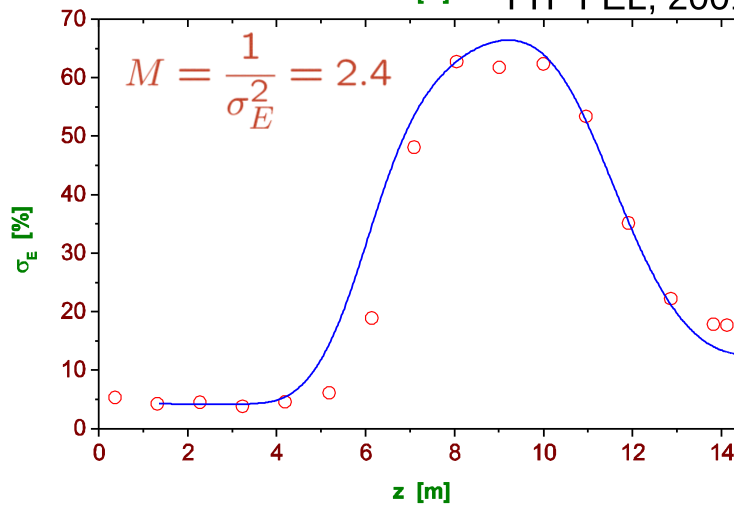
September, 2001: Discovery of femtosecond mode of operation



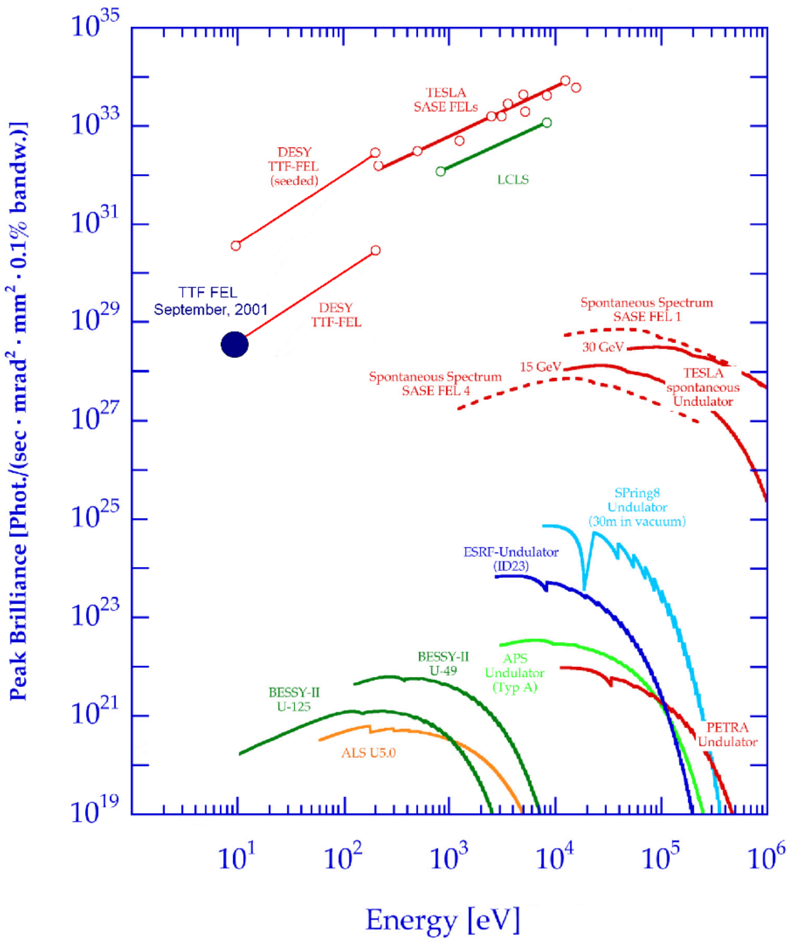
- In the middle of 2001 the date for user experiment approached, and we got full freedom for empirical tuning of machine parameters (bunch charge, BC1, BC2, gun solenoid, rf phases, optics, etc) having a target for highest radiation intensity.
- Finally, we tuned radiation intensity on the level of the order of a hundred uJ.
- Surprizing feature of opeartion at low intensities was very high fluctuations of the radiation pulse energy - indication on ultra short pulse duration.
- Physical behavior of both curves (saturation of power growth and drop of fluctuations) at higher intensities indicated on operation of TTF FEL in the saturation regime. Further analysis have shown that indeed, we demonstrated for the first time operation of the VUV FEL in saturation with 50 fs pulse duration and GW level of peak power.

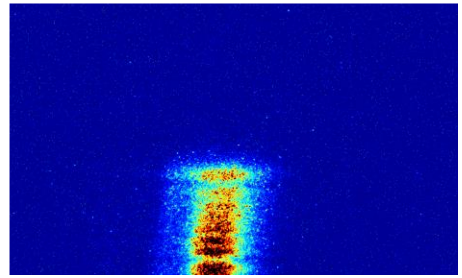


TTF FEL, 2001



September 10,2001: Saturation of TTF FEL





"Compared to the best synchrotron light sources where we presently carry out our research, our free electron laser is a million times better."

DESY director of research, Prof. Jochen Schneider

☻ Radiation wavelength	80-120 nm
☻ Radiation pulse energy at saturation	30-100 μJ
☻ Radiation pulse duration (FWHM)	30-100 fs
☻ Radiation peak power	1-1.5 GW
☻ Radiation average power up to	5 mW
☻ Spectrum width (FWHM)	1%
☻ Divergence	diff. limited
☻ Radiation peak brilliance up to	10^{29}
☻ Radiation average brilliance up to	10^{18}

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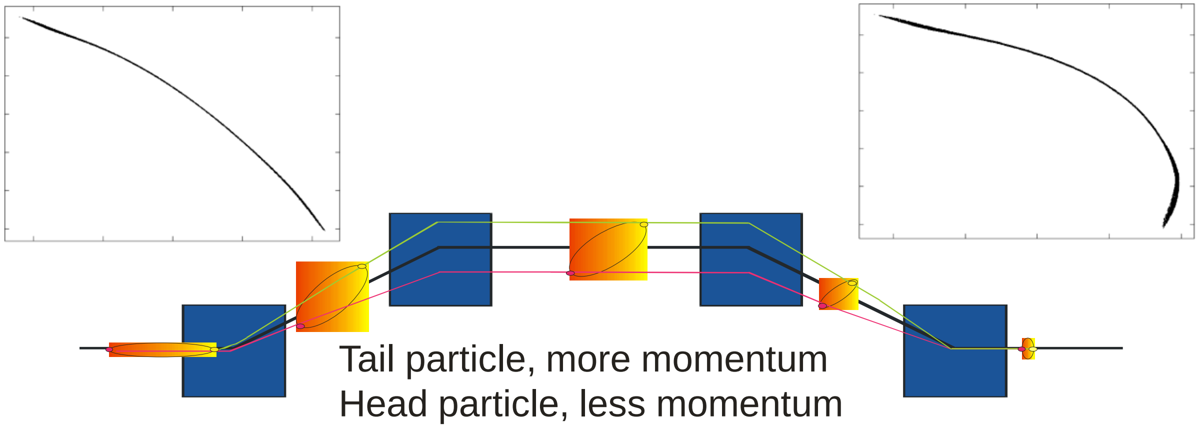
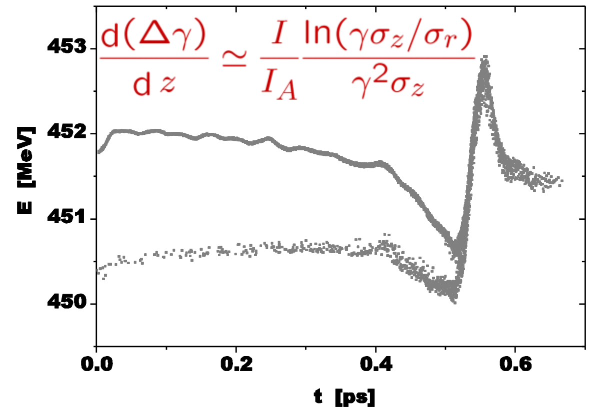
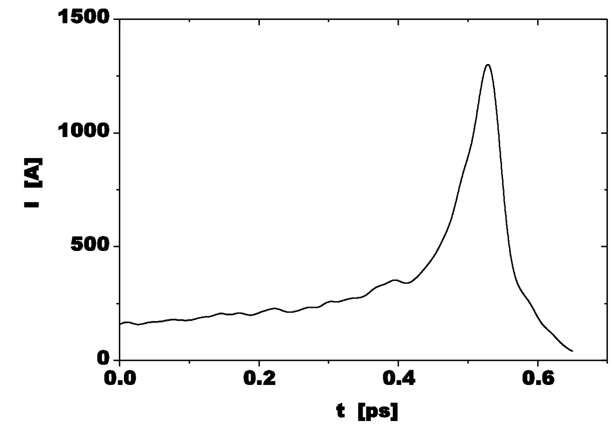
rms transverse beam size	μm	60	100 ± 30	100 ± 30
normalized emittance in the undulator	π mm mrad	2	6 ± 3 (sim)	6 ± 3
electron bunch charge	nC	1	1	1-3.5
peak electron current	A	500	400 ± 200	**1-2 kA**
FEL gain	#	~3x10^3-10^4	~3000	**10^5➔10^7**
FEL radiation pulse length	ps	0.3 - 1	0.3 – 1 (sim)	**0.05**

- Experimental results (saturation, high radiation pulse energy, short pulse duration), can be explained only assuming that slice energy spread in the injector is below 5 keV.
- Relevant studies of the electron gun characteristics have been undertaken (Holger Schlarb and Markus Huening). Diagnostic setup has been improved, and it has been confirmed that indeed, the value of slice energy spread in the gun is close and below 5 keV.

Formation of electron bunches with ultra-short lasing spike (femtosecond mode of operation)







- Bunch compressors form bunches with strongly non-gaussian shape
- Short spike in the head of electron bunch, (containing 10 to 20% of electrons), produces SASE FEL radiation

Bunch formation process is strongly influenced by collective effects:

$$I_{\mathrm{peak}} \simeq \frac{\lambda_{\mathrm{rf}} I_0}{R_{56}\pi\sqrt{2}\sigma_{\mathrm{E}}}$$

$$\sigma_z \simeq 5 R_{56}\sigma_{\mathrm{E}}$$

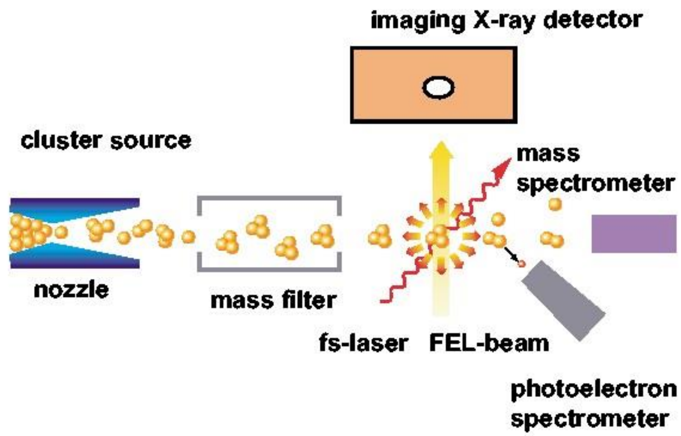
$$\mathrm{CSR}: \quad \propto \; I/\sigma_z^{1/3} \propto 1/\sigma_{\mathrm{E}}^{5/6}$$

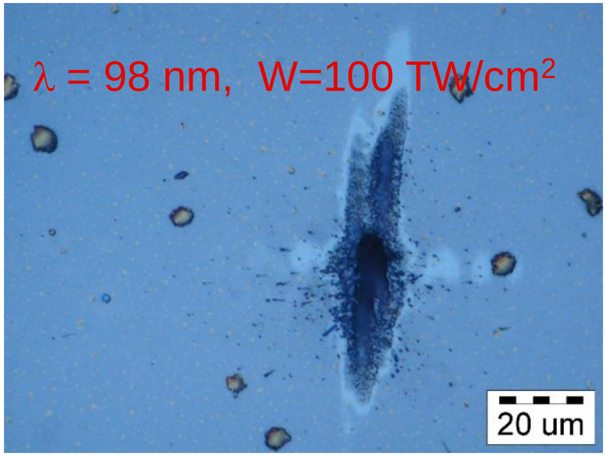
$$\mathrm{LSC}: \quad \propto \; I/(\sigma_z\gamma^2) \propto 1/(\sigma_{\mathrm{E}}^{3/2}\gamma^2)$$

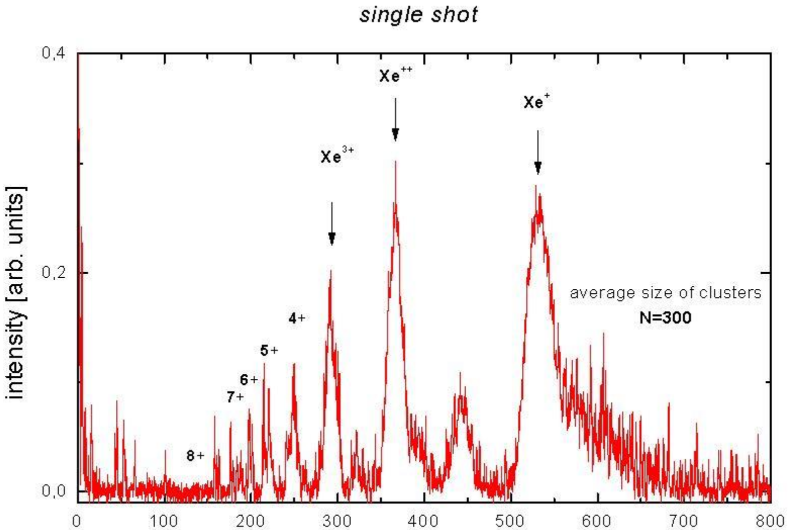
Femtosecond mode of operation: success of user program

Thomas Moeller group: Coulomb explosion of clusters, Nature, 420 (2002)482

Jacek Krzywinski group: Ablation experiment, J. Alloys and Compounds, 382(2004)264







- Femtosecond mode of operation defined not only success of pilot user experiments at TTF FEL, but also the next decade of user operation at FLASH.
- Its realization became possible due to very low slice energy spread (~ 3 keV) in the injector which was not foreseen at the project stage.

Interaction with solids and spontaneous surface patterning (FELIPSS – Free-Electron Laser-Induced Surface Structures):

R. Sobierajski et al.: Experimental station to study the interaction of intense femtosecond vacuum ultraviolet pulses with matter at TTF1 free electron laser, *Rev. Sci. Instrum.* 76, 013909 (2005)

L. Juha et al.: Ablation of various materials with intense XUV radiation, *Nucl. Instrum. Meth. Phys. Res.* A507, 577 (2003)

J. Krzywinski et al.: Conductors, semiconductors and insulators irradiated with short-wavelength free-electron laser, *J. Appl. Phys.* 101, 043107 (2007)

L. Juha et al.: Short-wavelength ablation of molecular solids: pulse duration and wavelength effects, *J. Microlith. Microfab. Microsyst.* 4, 033007 (2005)

J. Pelka et al., Structure modifications in silicon irradiated by ultra-short pulses of XUV free electron laser, Journal of Alloys and Cmpounds, 382 (2004) 264.

Radiation damage to optical elements and their performance:

B. Steeg et al.: Total reflection amorphous carbon mirrors for VUV Free Electron Laser, *Appl. Phys. Lett.* 84, 657 (2004).

Radioluminescence of solids:

M. Kirm et al.: Influence of excitation density on luminescence decay in $Y_3Al_5O_{12}$:Ce and BaF_2 crystals excited by free electron laser radiation in VUV, *phys. stat. solidi* (c) 2, 649 (2005)

J. Krzywinski et al.: Saturation of a Ce:$Y_3Al_5O_{12}$ scintillator response to ultra-short pulses of extreme ultraviolet, soft x-ray and x-ray laser radiation, *Opt. Mater. Express* 7, 665 (2017)

Coulomb explosion of clusters:

H. Wabnitz, Multiple ionization of atom clusters by intense soft X-rays from a free-electron laser,

Nature, 420 (2002)482.

Courtesy to Libor Juha for generating user’s list of references

Impact of TTF FEL success on X-ray FEL development

The Cambrian explosion is an interval of time beginning approximately 538.8 million years ago in the Cambrian period of the early Paleozoic, when a sudden radiation of complex life occurred and practically all major animal phyla started appearing in the fossil record.

//Wiki//

LCLS

TTF FEL, FLASH, FLASH2, FLASH 2020+

TESLA FEL / European XFEL

SACLA

PAL XFEL

FERMI

SHINE

Recent trends: (X-ray) FELs driven by a plasma-based electron accelerator

- 30+ years ago we observed an origin of similar explosion in X-ray FEL development. On a decade+ time scale several mega projects have been discussed, and their funding was granted after TTF FEL success. All these billion scale projects were realized in a short term.
- TTF FEL project was the main milestone on the way to X-ray FELs operating in Angstrom regime. It has been proceeded by earlier developments, Paladin FEL (IR,1986), UCLA FEL (IR, 1998) and LEUTL FEL (visible, 2000).

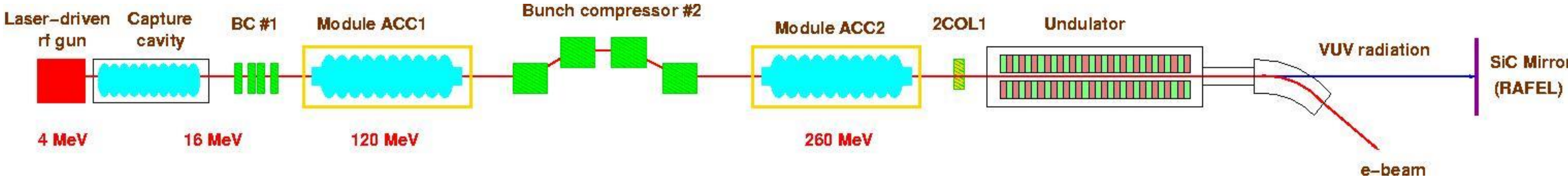
Summary: “Cambrian” explosion caused by TTF FEL

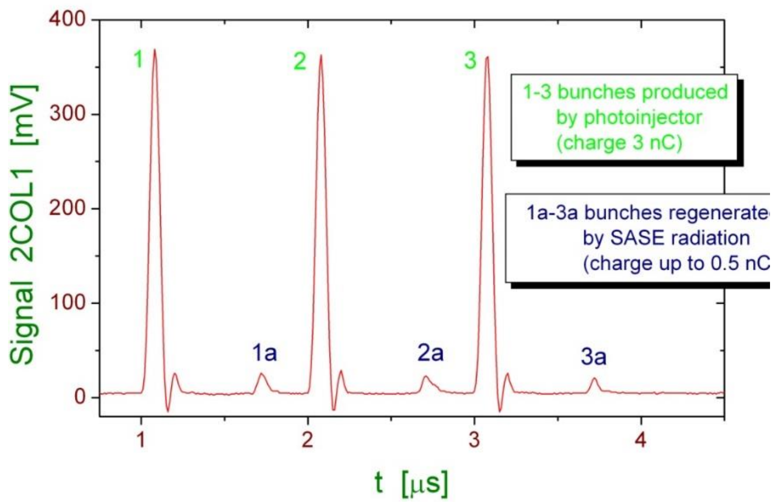
TESLA and TTF FEL project combined a great number of experts in the field in a one place which gave significant boost to perspective developments in accelerator and FEL physics and techniques:

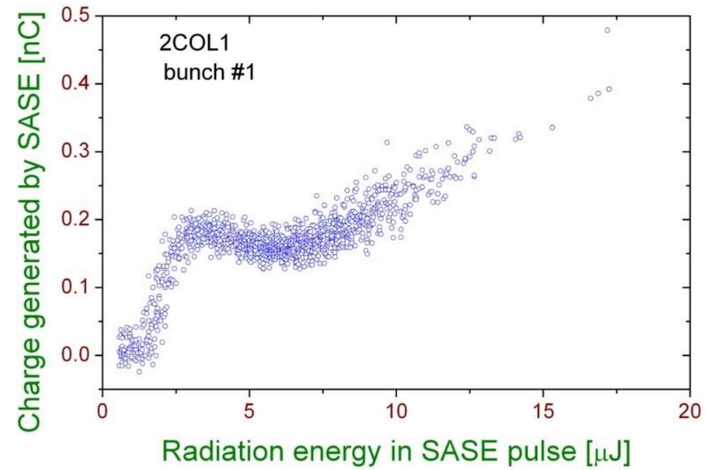
- TTF FEL, Phase 2 (now it is FLASH)
- European XFEL
- The physics and techniques of intense, ultrashort electron beams
- Ultrabright injectors for x-ray FELs
- Pump probe facility combining coherent FIR undulator radiation and X-ray/VUV radiation
- Self-seeding option
- Relativistic Electron Gun for Atomic Exploration (REGAE) for Ultrafast Electron Diffraction experiments (UED).
- Application of FELs for lithography
- Single shot imaging of molecules
- Generation of attosecond x-ray pulses
- … and many others

Extra slides

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.