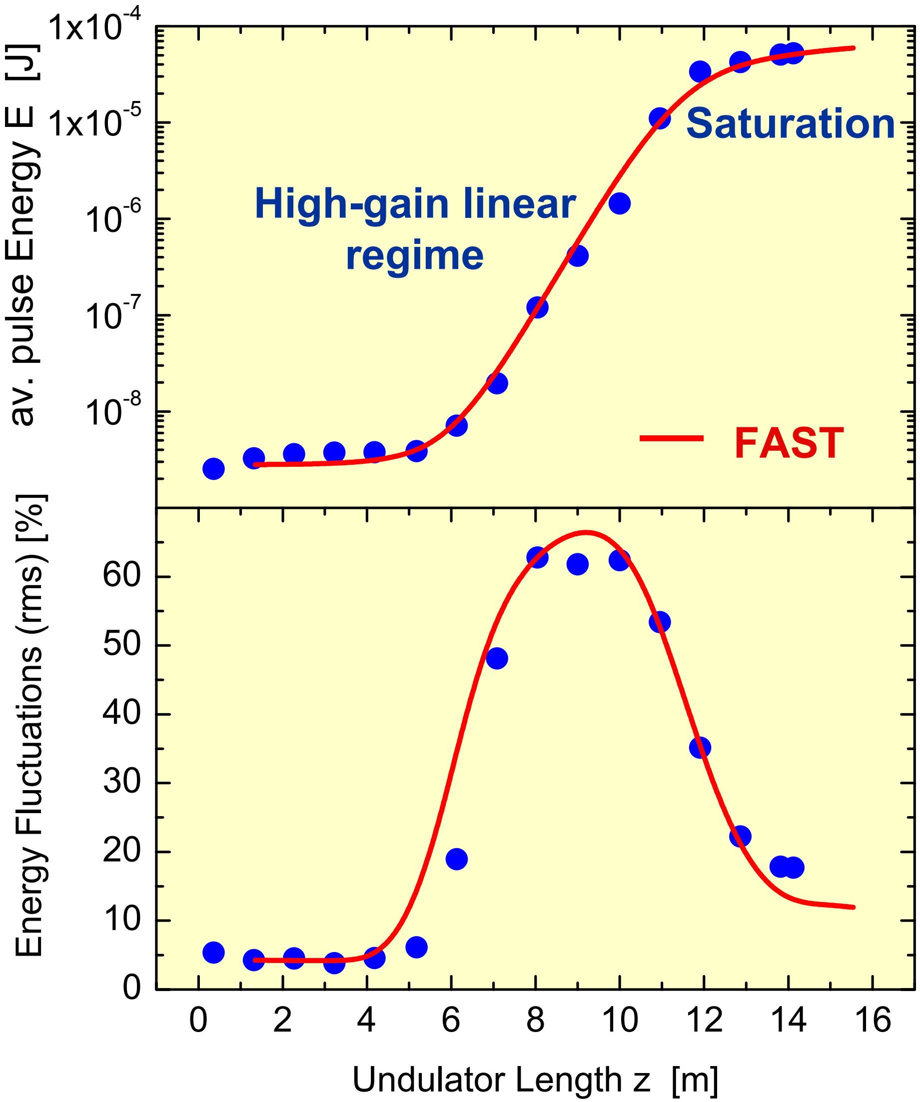
Statistical Properties of a VUV FEL

Christopher Gerth

Main contributions to the understanding of the SASE statistics:
Evgeni Saldin
Evgeni Schneidmiller
Michael Yurkov

VUV Free-Electron Laser at the TESLA Test Facility at DESY
⇨ FR-O-03 J. Roßbach: General Overview

Amplification process vs. undulator length



Exponential growth:
$P(z) = P_0 * \exp(z/L_g)$

Gain length: $L_g = 0.68$ m

Photon beam	Design values	Status 9/01
Pulse energy	330 -700 μJ	50 -100 μJ
Pulse duration	1.3 ps	?

No direct measurement of the pulse duration

(Power) Gain length L_g :

$$P(z) \approx P_0 * \exp(z/L_g)$$

$$L_g \approx \frac{\lambda_u}{4\pi \cdot \rho}$$

$\rho \approx 3 \cdot 10^{-3}$ FEL Parameter

Information about electron beam parameters, e.g. I

with $\lambda_u = 27.3$ mm

$L_g = 68$ cm

Coherence length l_c :

$$l_c \approx \tau_c \cdot c$$

with $\tau_c = 1/\omega\rho$ and $c = \lambda \cdot \omega/2\pi$

$$l_c \approx \frac{\lambda \cdot \omega}{\omega\rho \cdot 2\pi}$$

$$l_c \approx \frac{2L_g \cdot \lambda}{\lambda_u} = 5\ \mu m$$

If the pulse is longer than l_c:
Several longitudinal modes

Coherence time τ_c :

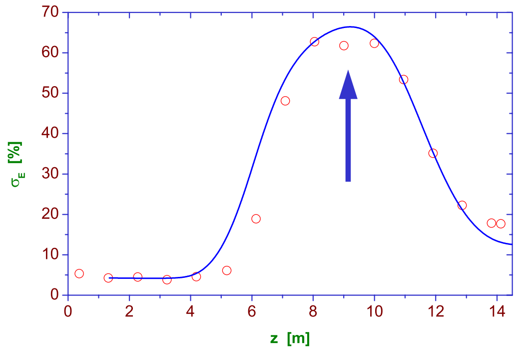
$$\tau_c \approx \frac{l_c}{c} \approx \frac{T}{\omega\rho T} \approx \frac{T}{M} \approx 20 \text{ fs}$$

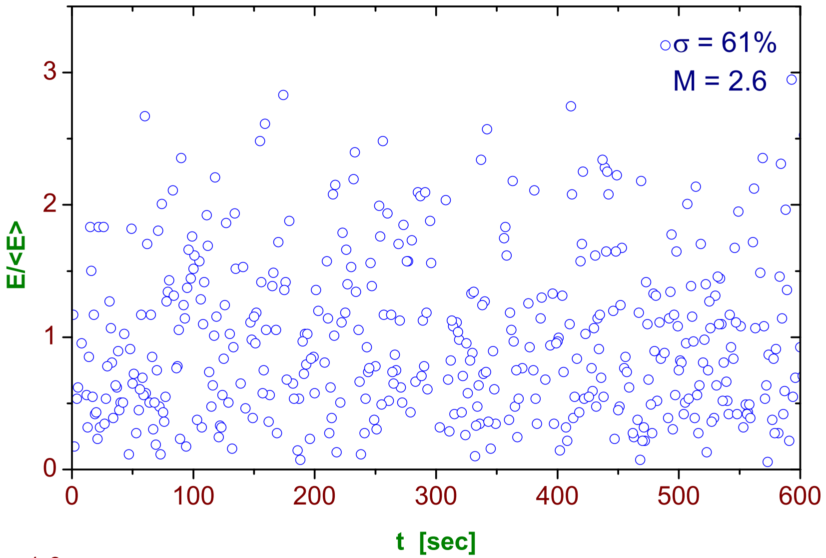
Pulse duration: $T \approx M \cdot \tau_c$

with M: No. of Modes

Linear regime

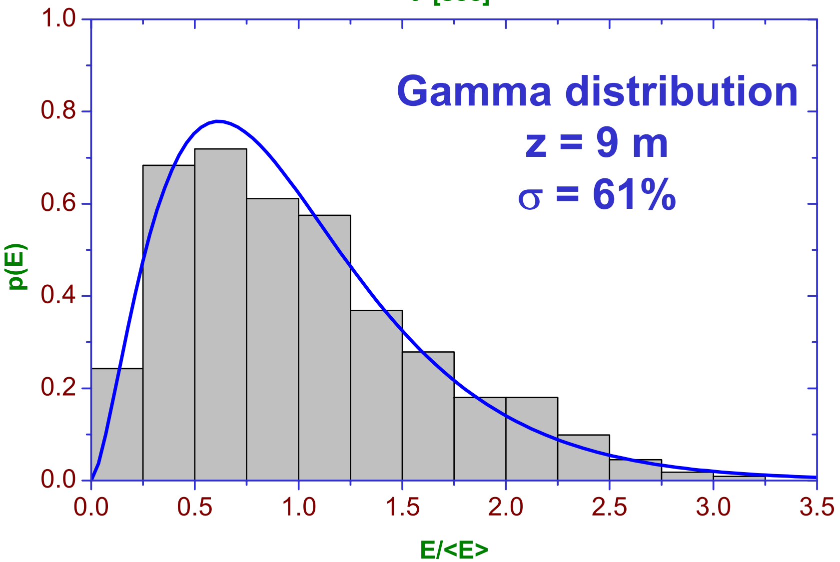
Probability distribution of the pulse energy





In the linear regime:
Pulse energy of chaotic polarized light fluctuates according to Gamma-distribution

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

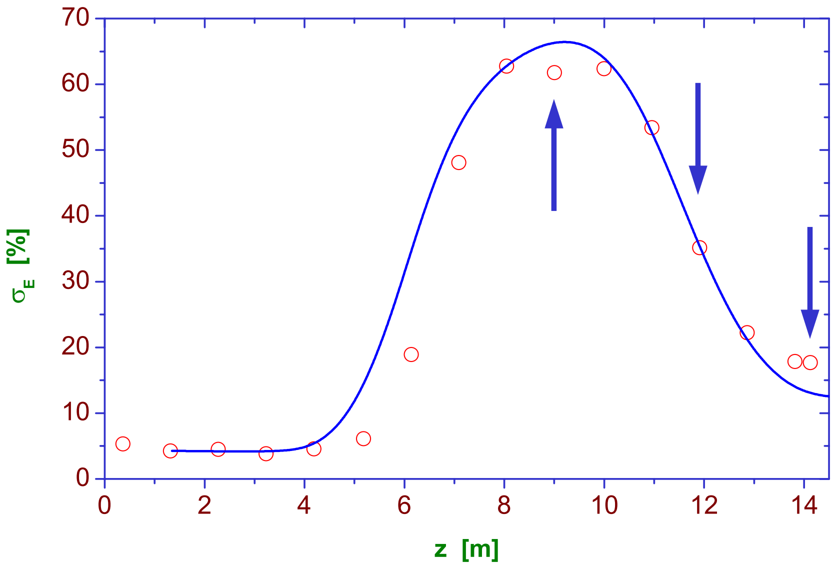


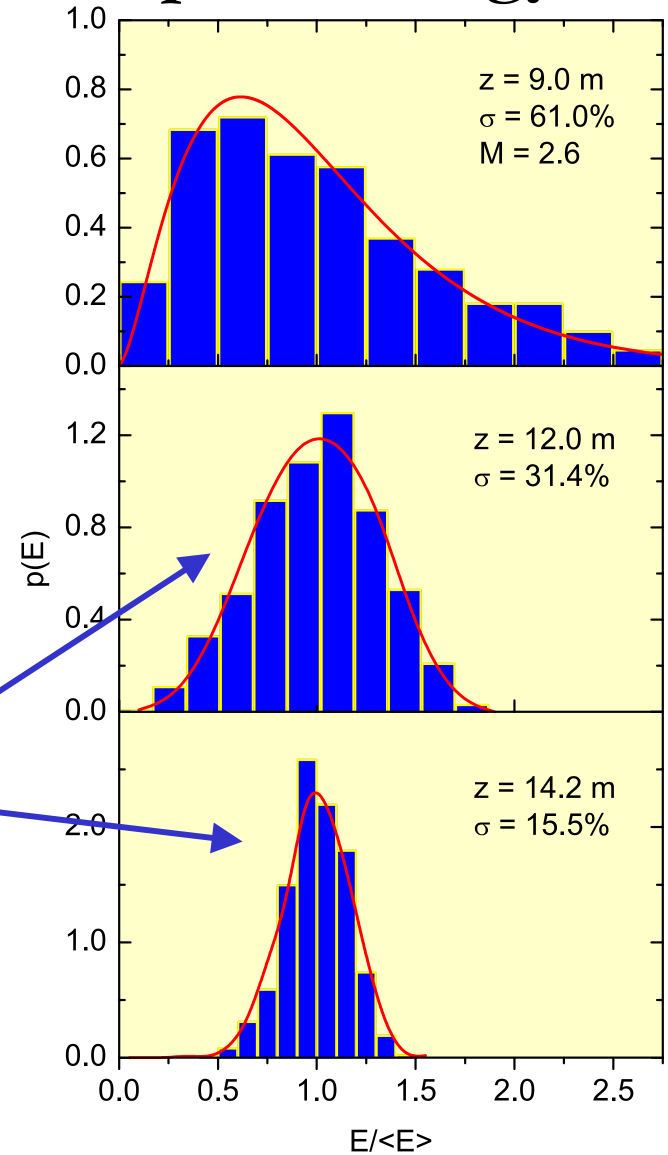
Energy Fluctuations: $\sigma = 61\%$
No. of Modes: $M = 1/\sigma^2 = 2.6$

Pulse duration **T**
$T \cong M * 20$ fs $\cong 50$ fs

Nonlinear regime

Probability distribution of the pulse energy

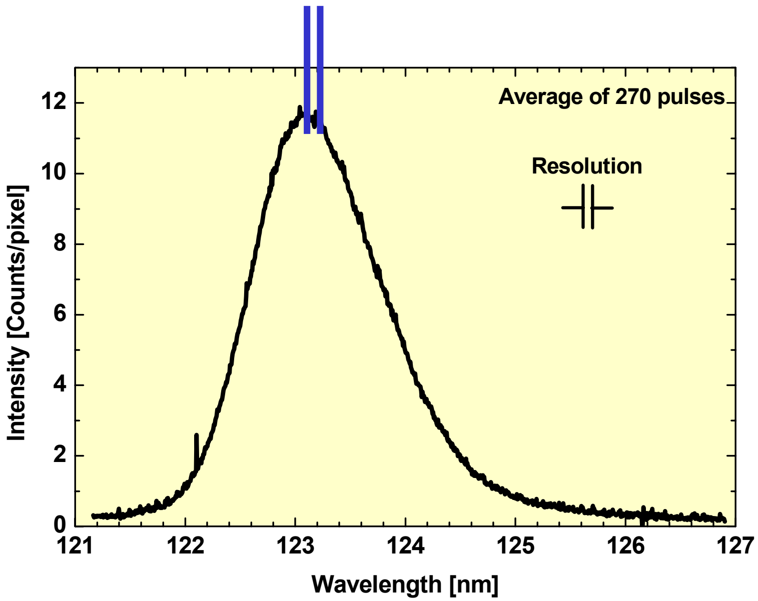


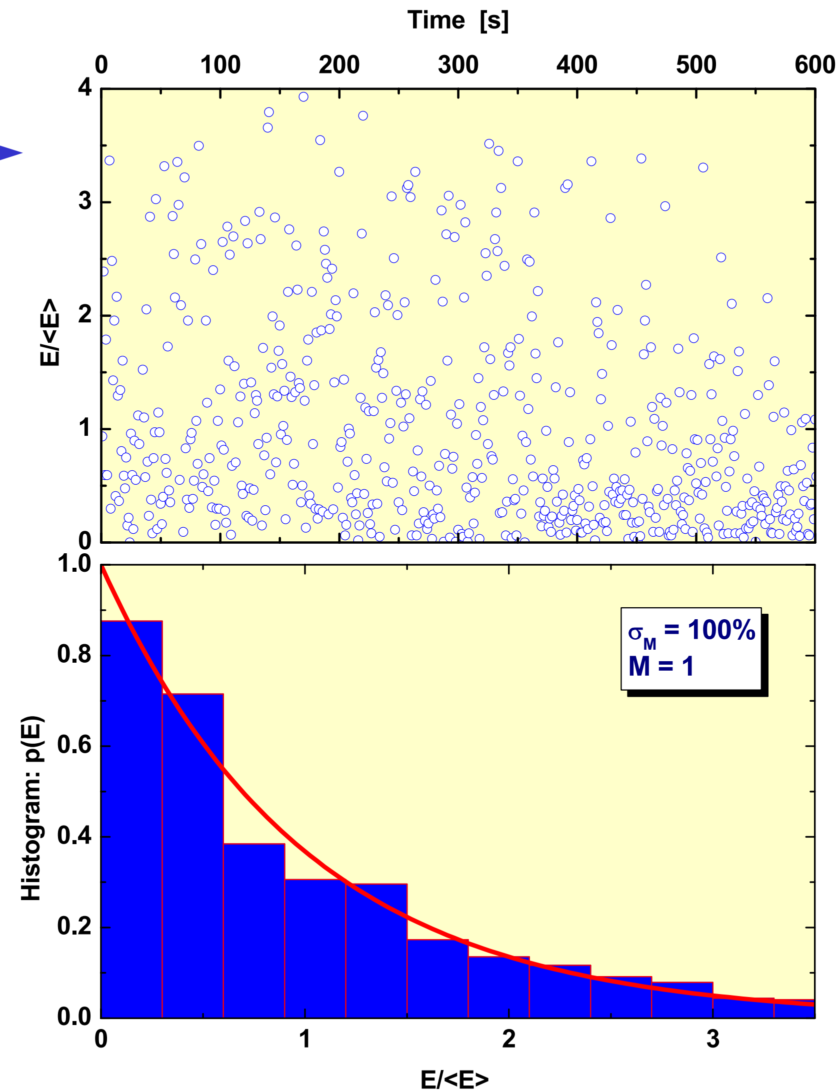


In the saturation regime:
Fluctuations of the pulse energy cannot be described by a Gamma-distribution
σ not connected to M anymore

Energy fluctuations behind a narrow-band monochromator

Linear regime

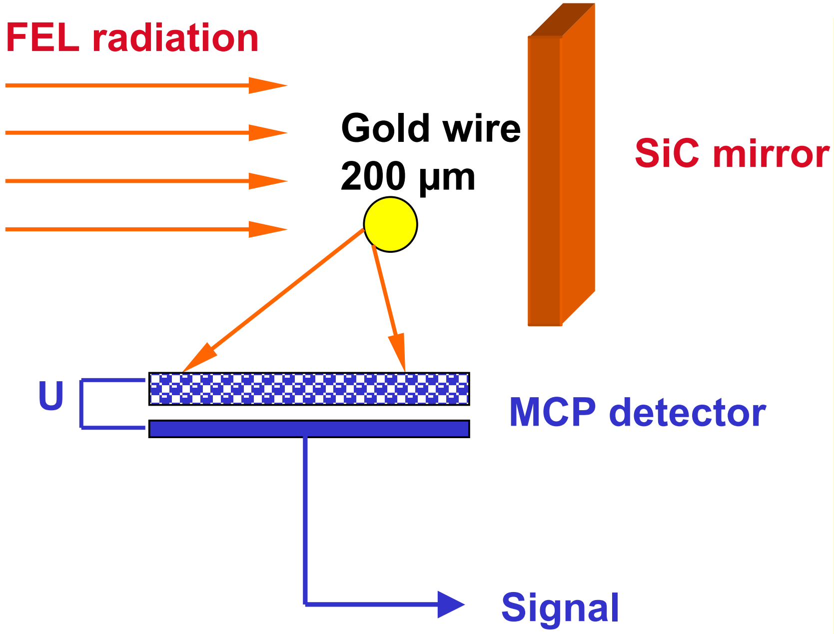




Negative exponential distribution
Intensity fluctuations: σ = 100 %

Pulse energy

Wire + Micro Channel Plate Detector



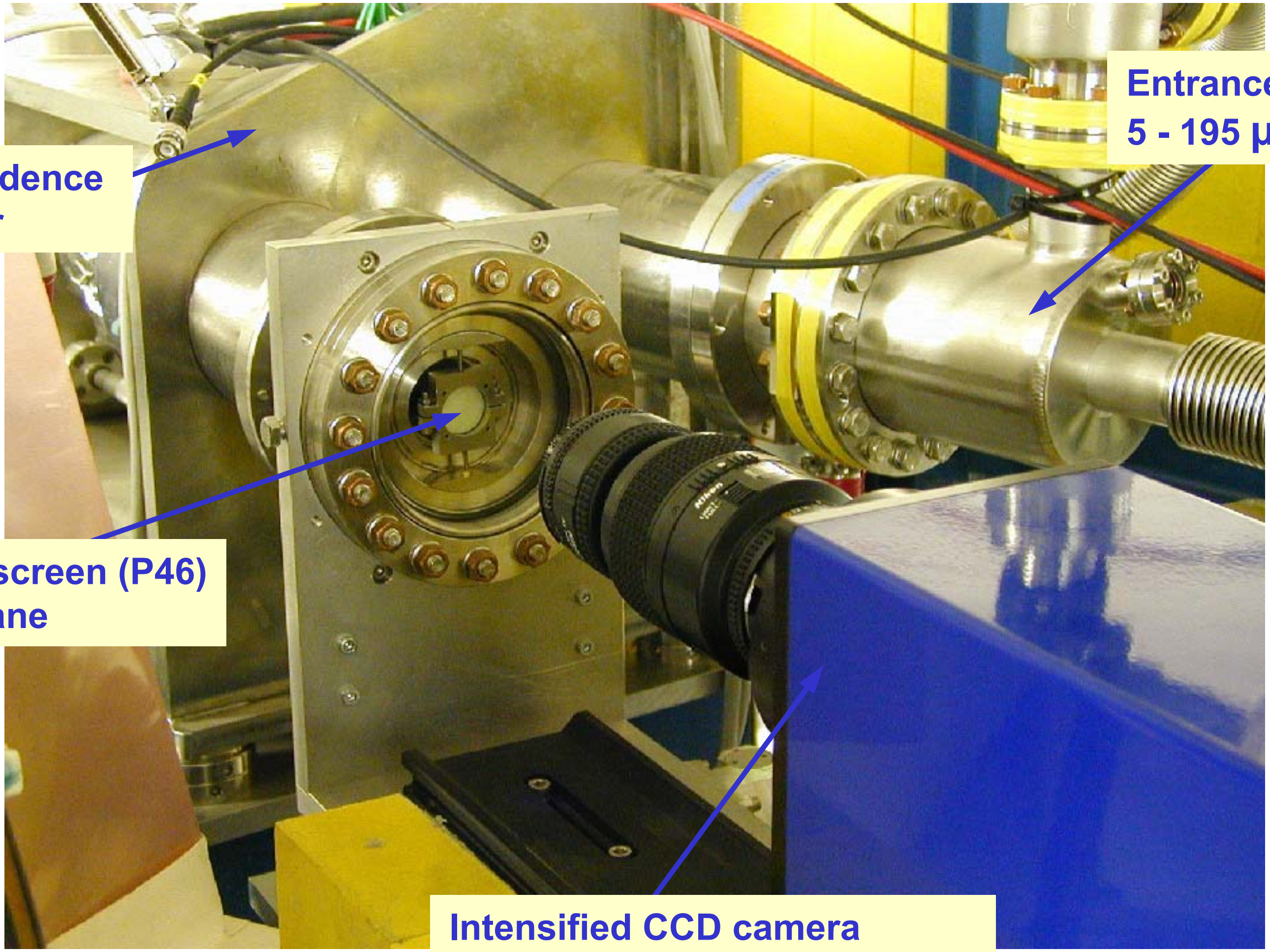
The determination of absolute pulse energies in the VUV is a challenging task.

- Large dynamic range: 10^7
  (The MCP has been calibrated for different voltage settings U)
- Spont. Emission: gain = 1
  $E = gain \cdot Q \cdot f(\lambda)$
  (f can be calculated precisely)
- Corroborated by independent detectors

Data selection:
Charge fluctuations < 1% (rms)
Orbit deviation < 50 µm

Spectral distribution

Measurement of the Spectral Distribution

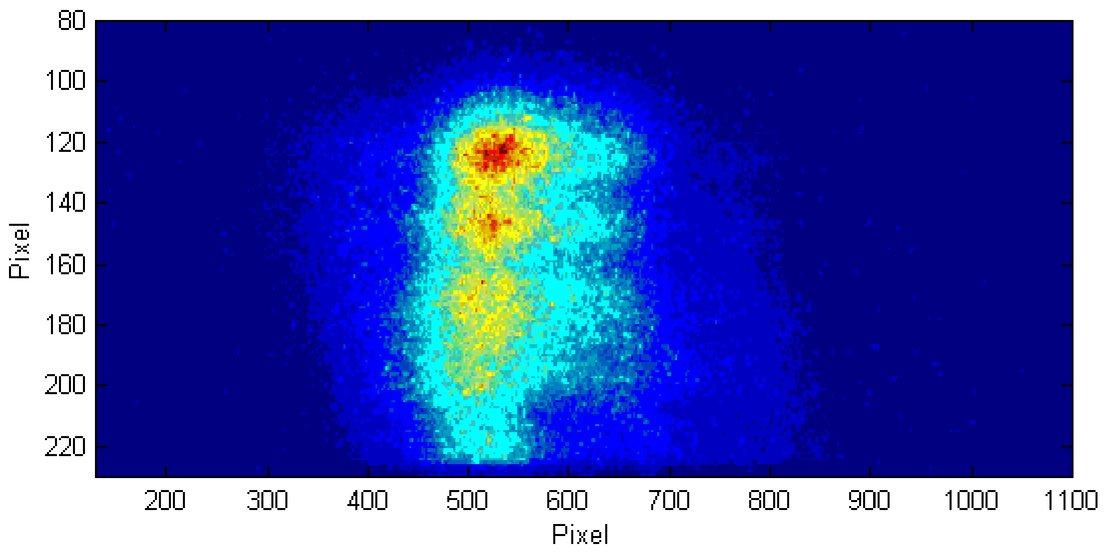


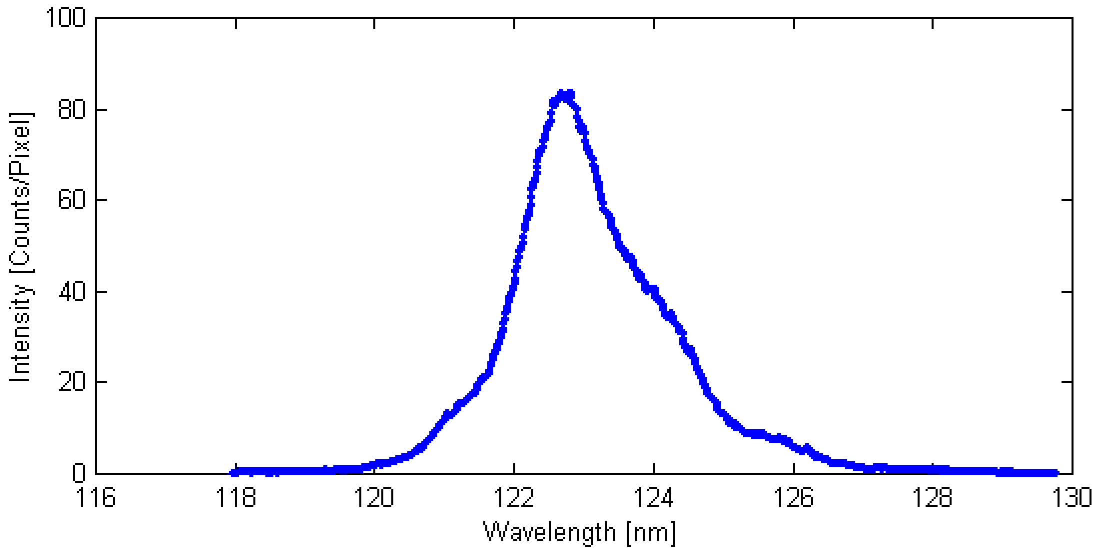
1 m Normal Incidence Monochromator

Entrance slit
5 - 195 µm

Fluorescent screen (P46)
in the exit plane

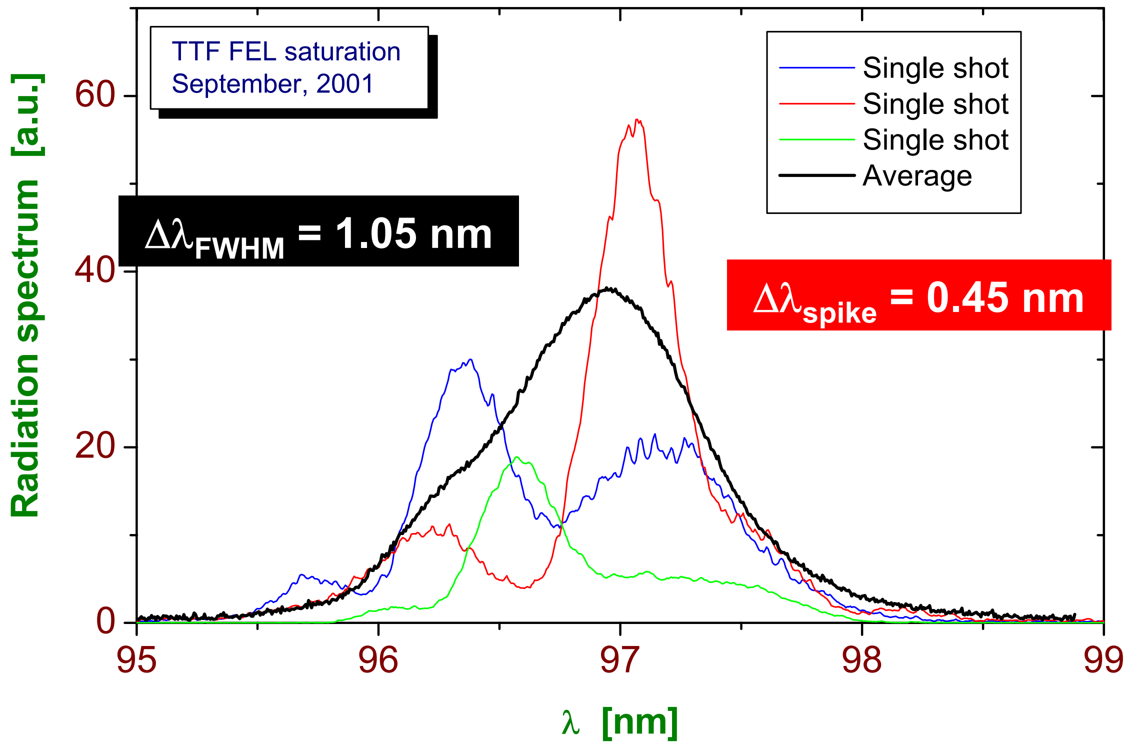
Intensified CCD camera
⇨ MCP as a fast shutter (5 ns)
⇨ single pulse spectra


80
100
120
140
160
180
200
220
Pixel
200
300
400
500
600
700
800
900
1000
1100
Pixel


100
80
60
40
20
0
Intensity [Counts/Pixel]
116
118
120
122
124
126
128
130
Wavelength [nm]

Spectral distribution

Determination of the pulse duration



Spike: $T \cong 2\pi^{1/2}(\Delta\omega)_{spike}$ = 37 fs

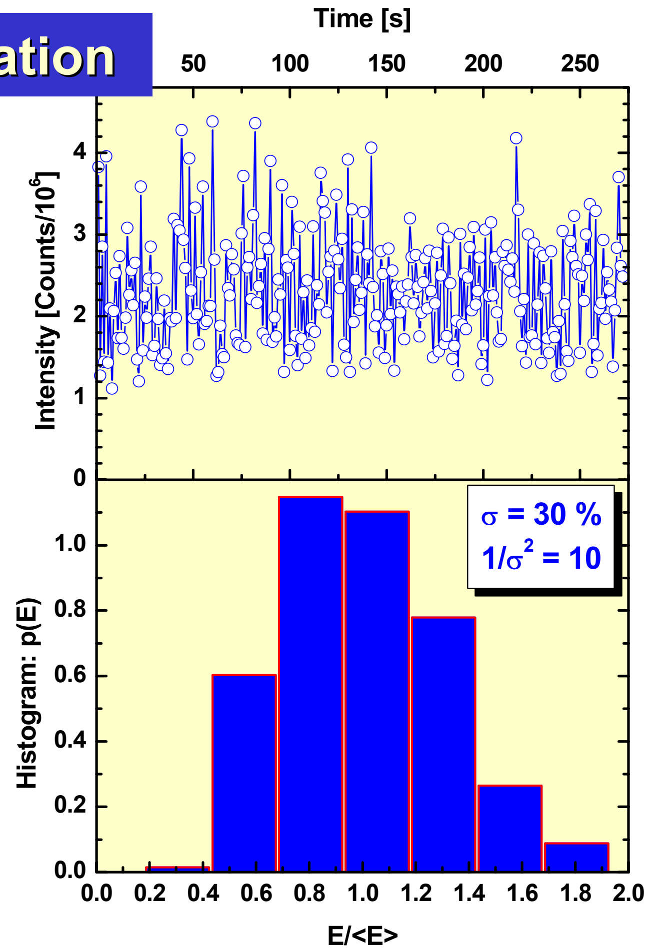
Average: $2\pi^{1/2}(\Delta\omega)_{FWHM}$ = 16 fs

$T \cong M * 2\pi^{1/2}/(\Delta\omega)_{FWHM} \cong$ 41 fs

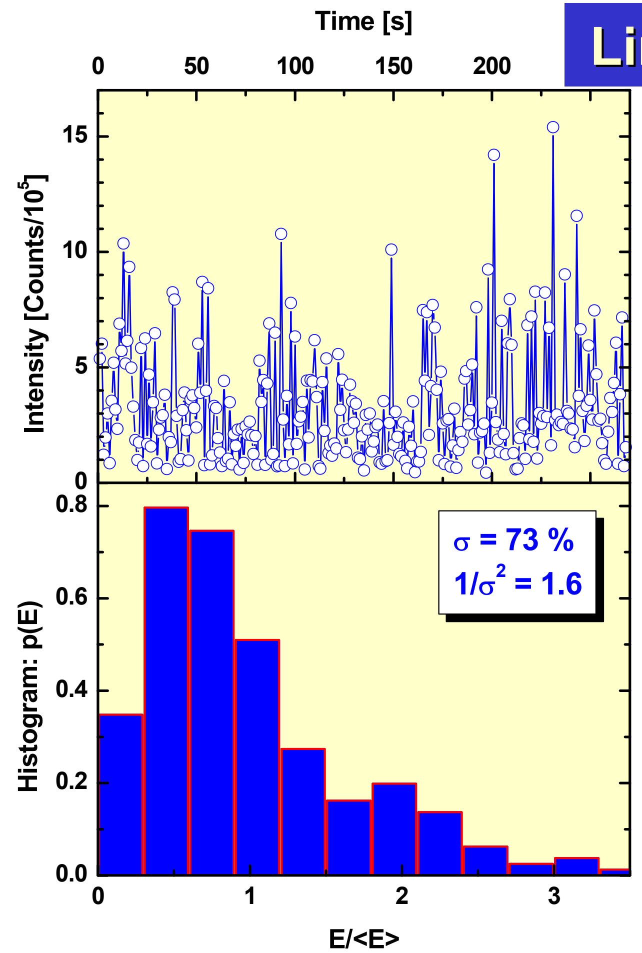
Spectral distribution

Fluctuations of integral intensity in the spectra

Saturation



Linear regime



M = 1.6

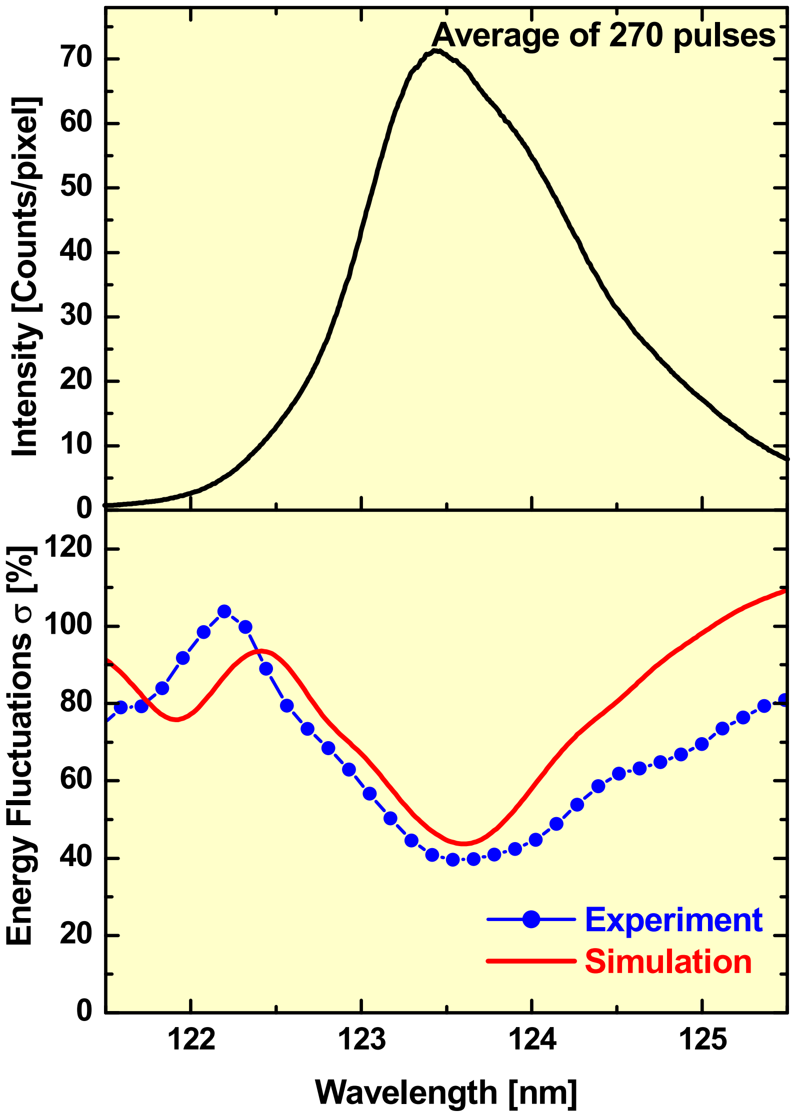
Estimation of the radiation pulse length τ_{rad} :

Modes: $M = 1/\sigma^2 = 1.6$

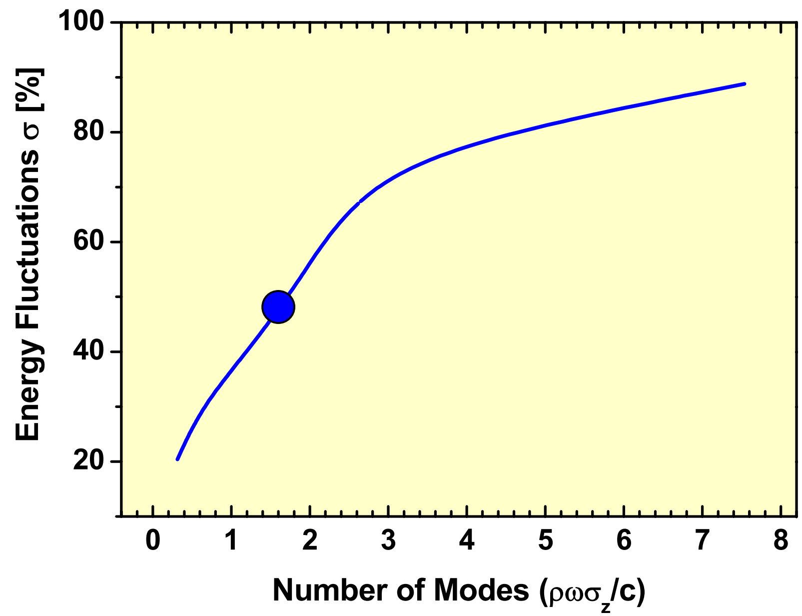
$\tau_{rad} \cong 2M\pi^{1/2}/\Delta\omega \cong 40$ fs

Spectral distribution

Fluctuations at saturation (spectrally resolved)



Energy fluctuations for a narrow bandwidth in the centre of the spectral distribution

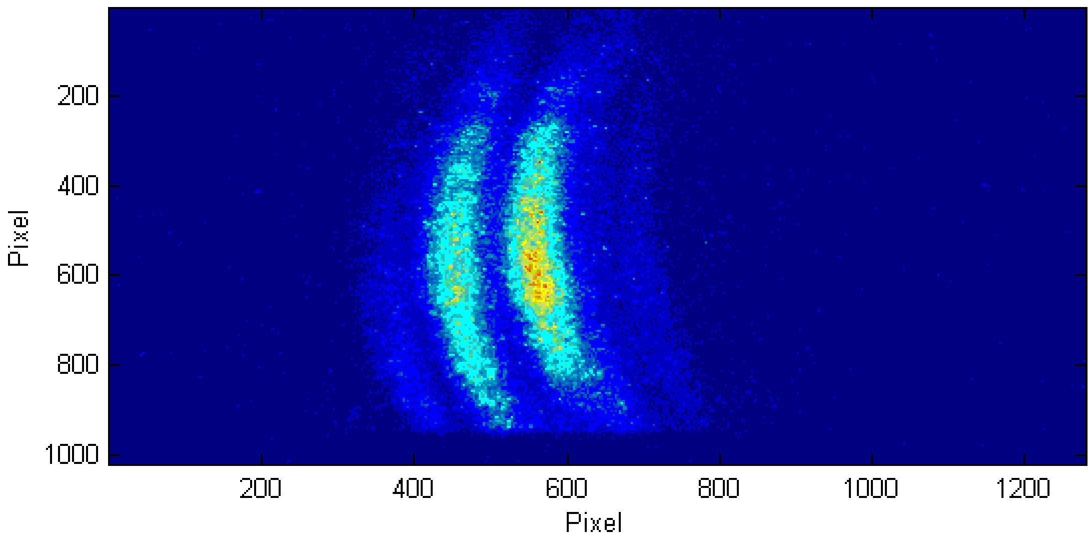


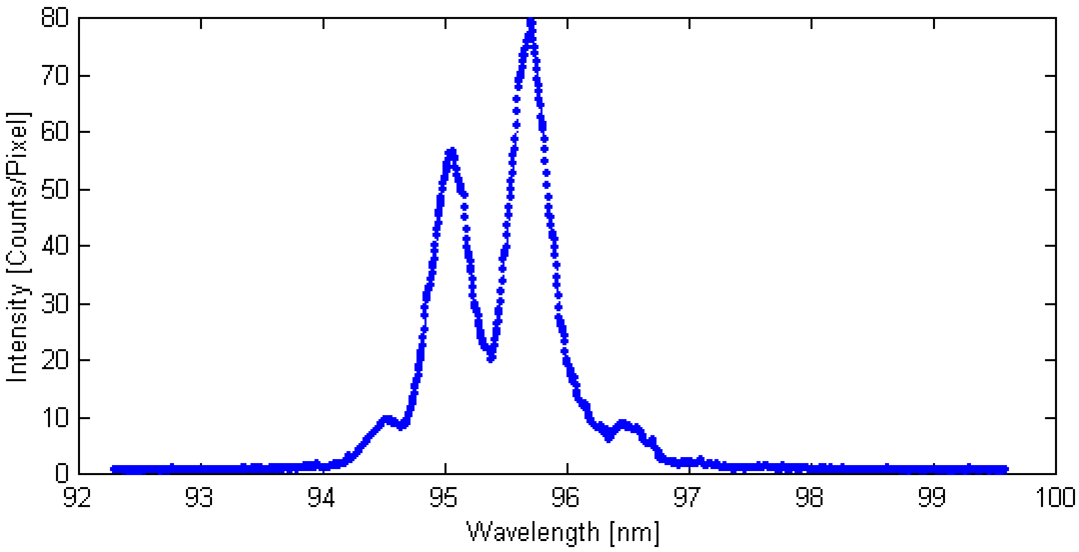
- **Few modes M ⇨ fluctuations decrease**
- **Many modes M ⇨ 100 % fluctuations!**

Design value: M ≈ 20

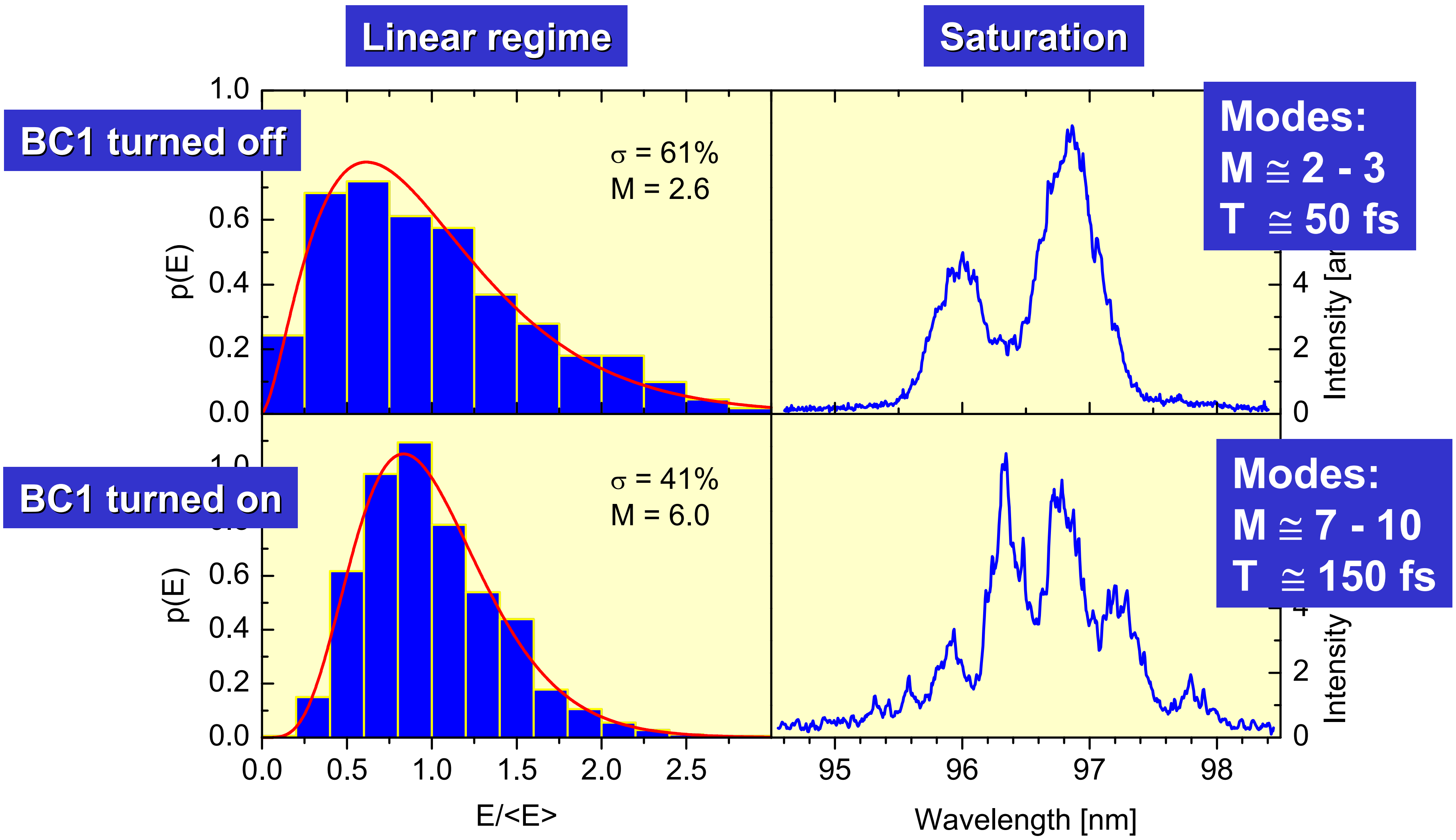
M = 1.6 ⇨ σ = 46 %

BC1 on


200
400
600
800
1000
Pixel
200
400
600
800
1000
1200
Pixel


80
70
60
50
40
30
20
10
0
Intensity [Counts/Pixel]
92
93
94
95
96
97
98
99
100
Wavelength [nm]

Pulse duration tailoring with Bunch Compressors



Summary

- Statistical properties of the SASE FEL are helpful for the determination of electron and photon beam properties.

- FEL parameters

Photon beam properties	Design values	Status
Pulse energy at saturation	330 -700 μJ	50 -100 μJ
Pulse duration (FWHM)	1.3 ps	30 -100 fs
Peak power	0.23-0.5 GW	1 GW
Energy fluctuations behind narrow-band mono at saturation	100%	40%

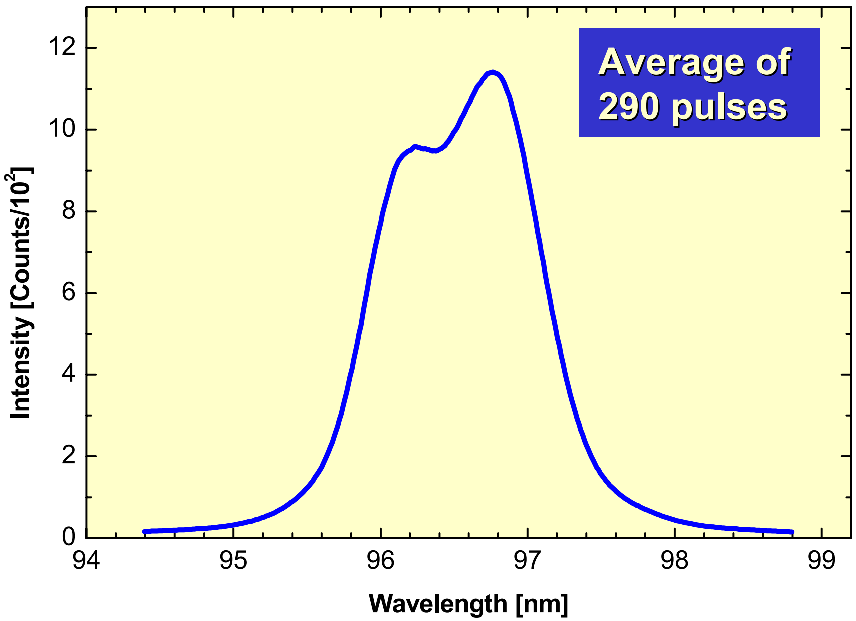
- Energy fluctuations behind a narrow-band monochromator decrease for short bunches.

THE END

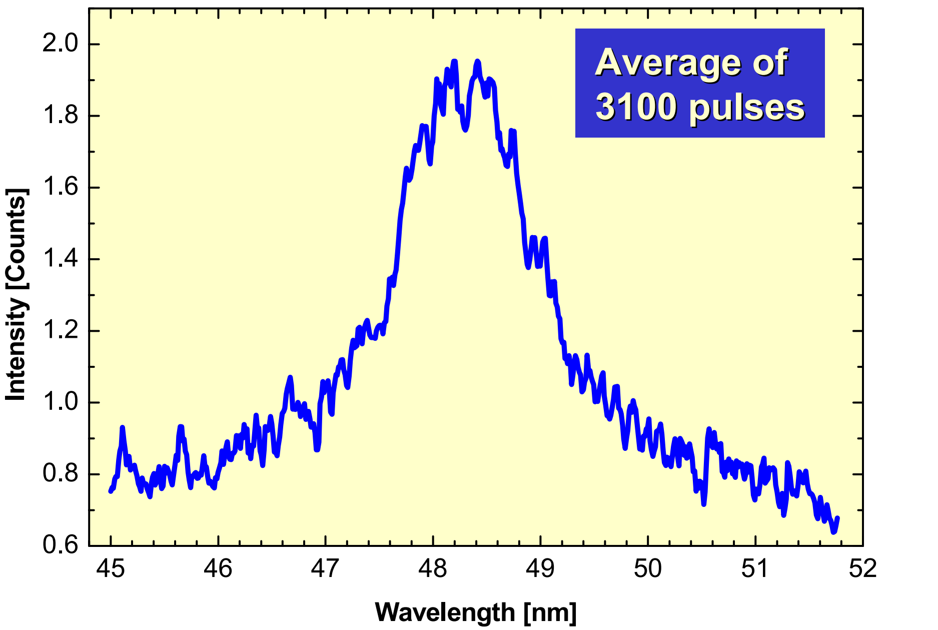
Spectral distribution

Higher Harmonics

Fundamental



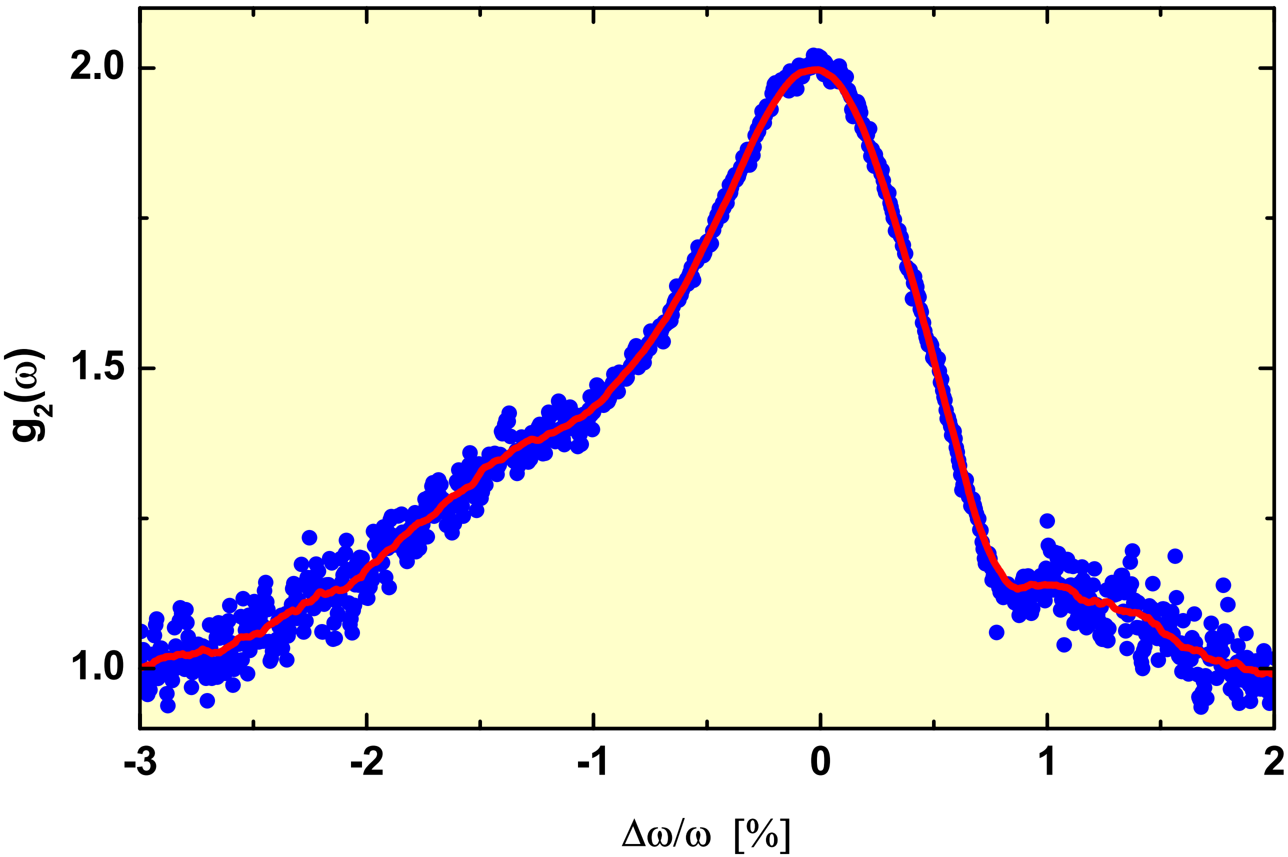
2nd Harmonic



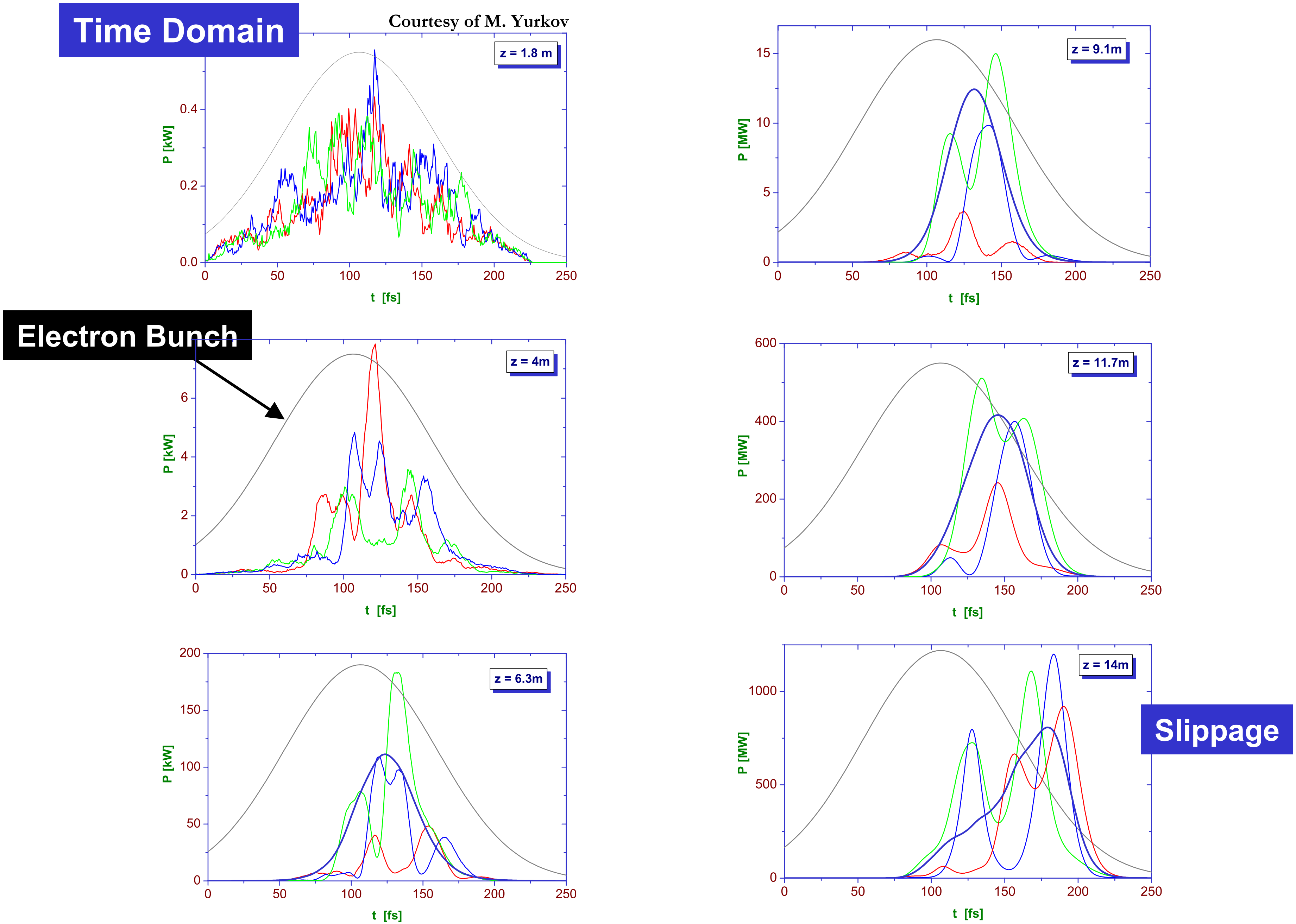
⇨ **Intensity of 2nd harmonic is about 1.0 - 0.1 % of the fundamental**

Second Order Spectral Correlation

$$g_2(\omega, \omega') = \frac{\langle \bar{E}(\omega) \cdot E(\omega') \rangle}{\langle \bar{E}(\omega) \rangle \cdot \langle E(\omega') \rangle} = 1 + \frac{\sin^2((\omega - \omega')T/2)}{((\omega - \omega')T/2)^2}$$



⇨ Method for the determination of the radiation pulse length T

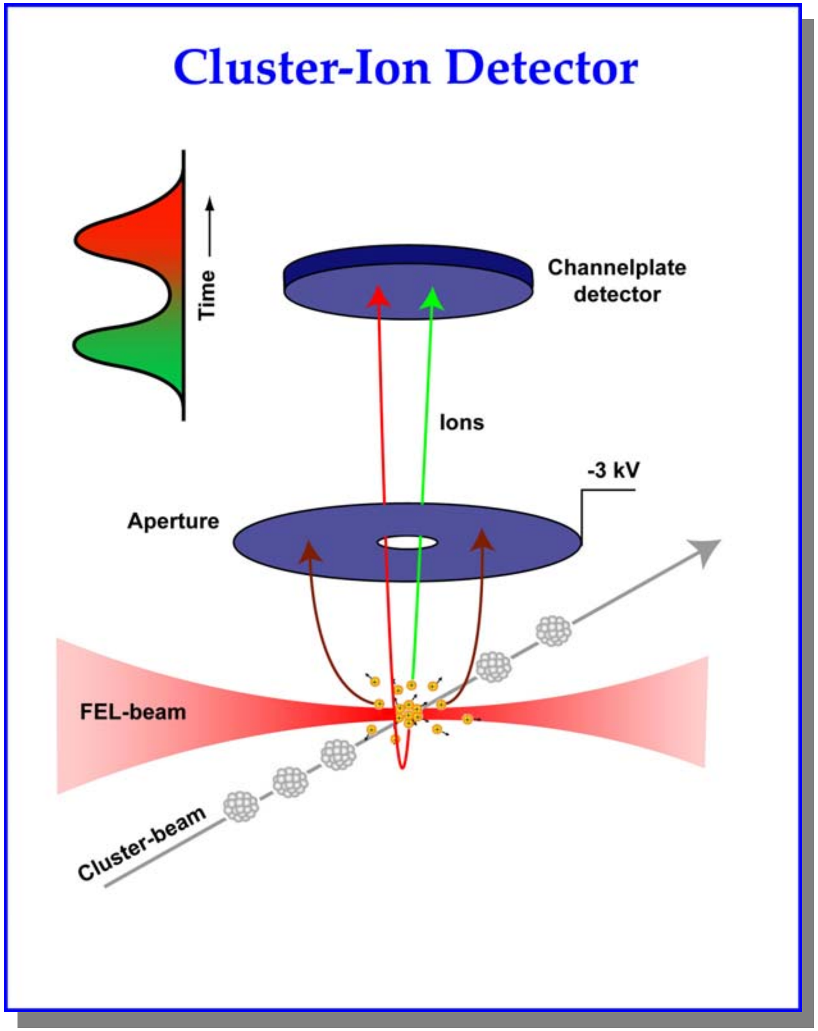


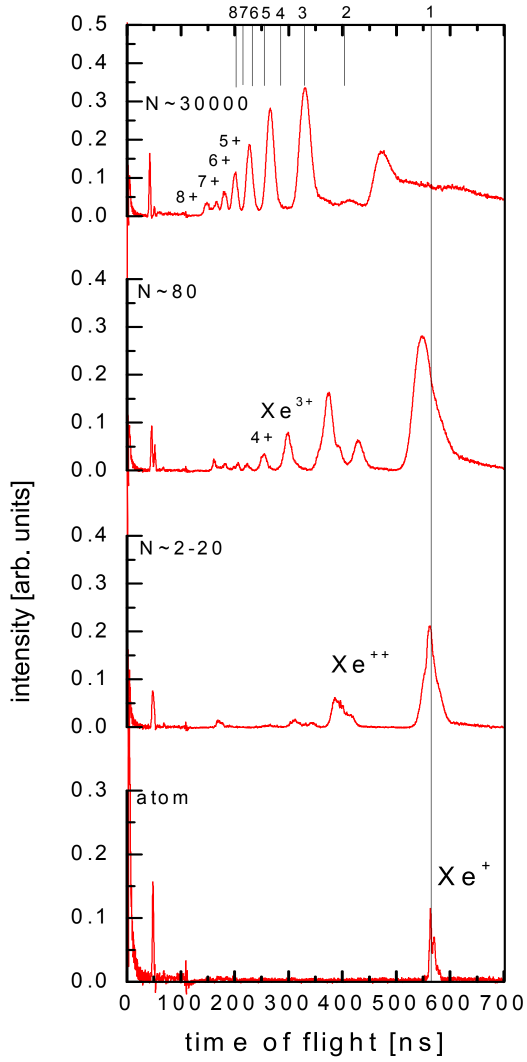
Time Domain
Courtesy of M. Yurkov
Electron Bunch
Slippage
z = 1.8 m
z = 4m
z = 6.3m
z = 9.1m
z = 11.7m
z = 14m
P [kW]
P [MW]
t [fs]

Applications

Cluster Experiment

Hubertus Wabnitz, Thomas Möller *et al.*

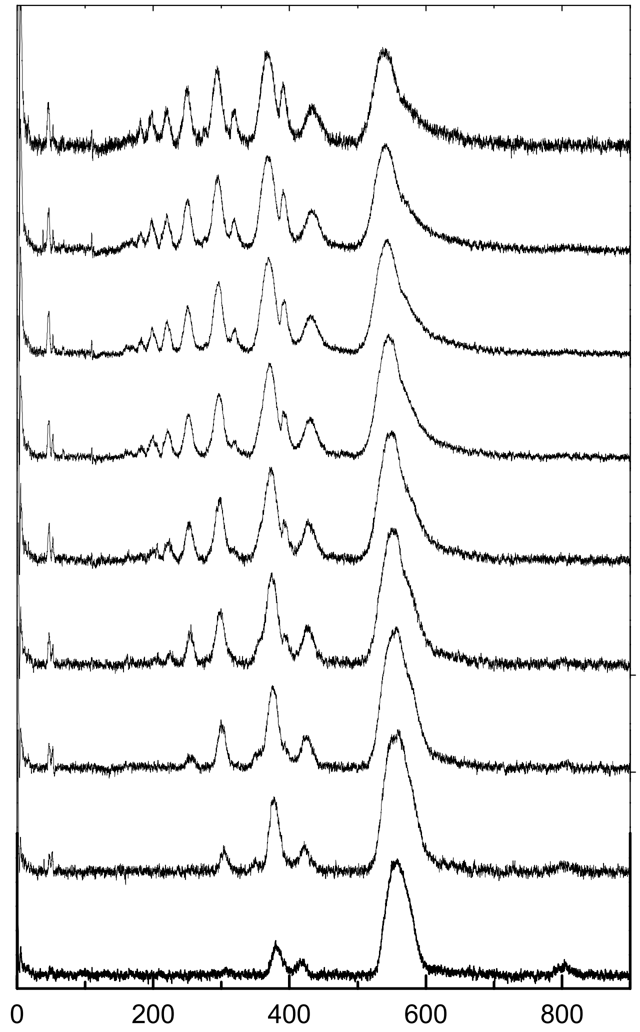




- **emission of highly charged ions from clusters**
- **ions have high kinetic energies**

Applications

Dependence on Cluster Size



Xenon clusters, 50 atoms

10^{13} Watt/cm^2

$5*10^{11}$ Watt/cm^2

Applications

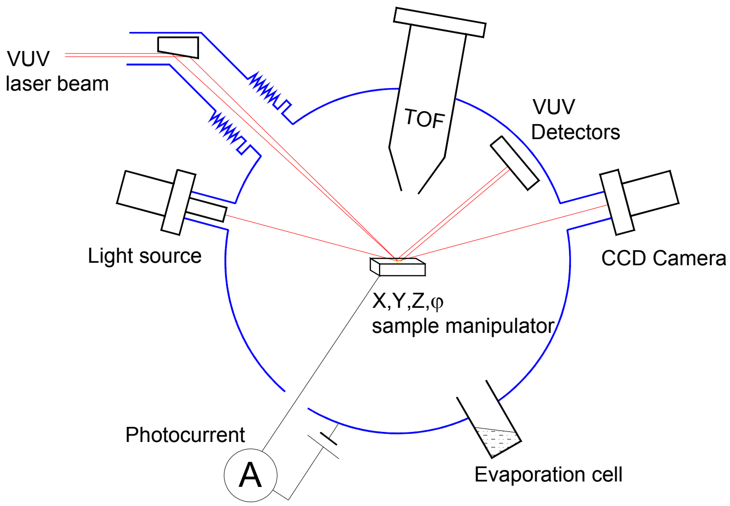
Radiation Stability

FELIS Experiment:

(R. Sobierajski, J. Krzywinski, *et al.*)

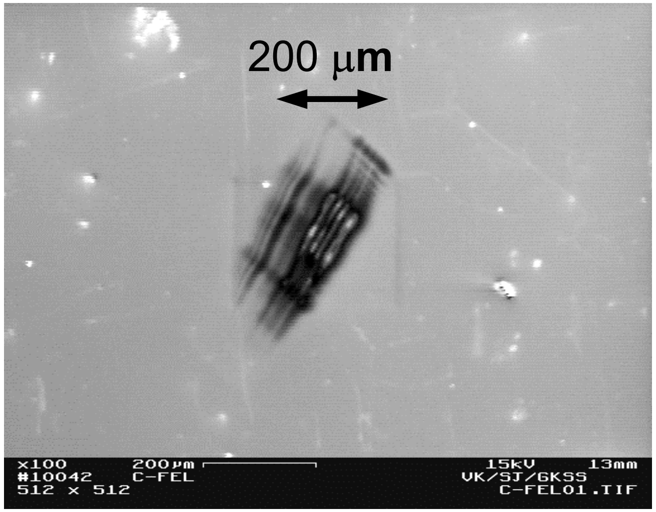
wavelength: 98 nm
pulse length: 100 fs
pulse energy : 40 μJ

damage threshold: 0.06 J/cm²



Sample:
carbon mirror with 39 nm thickness

diffraction at intensity monitor
(gold wire)

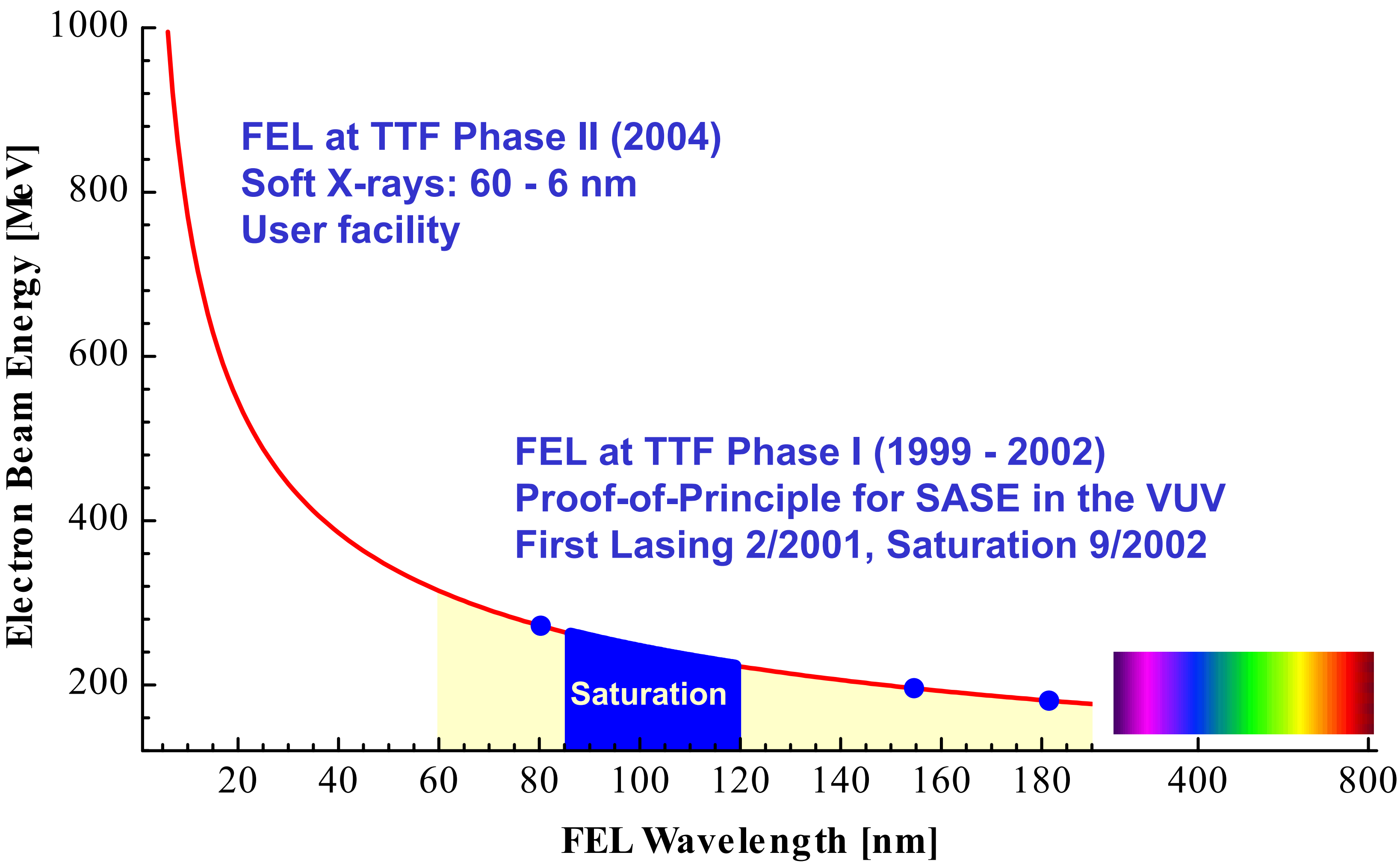


Summary

- Free-Electron Laser at the TTF produces Gigawatt, femtosecond, laser-like radiation in the VUV
- Multiple Ionisation of Clusters
- Determination of Damage Thresholds

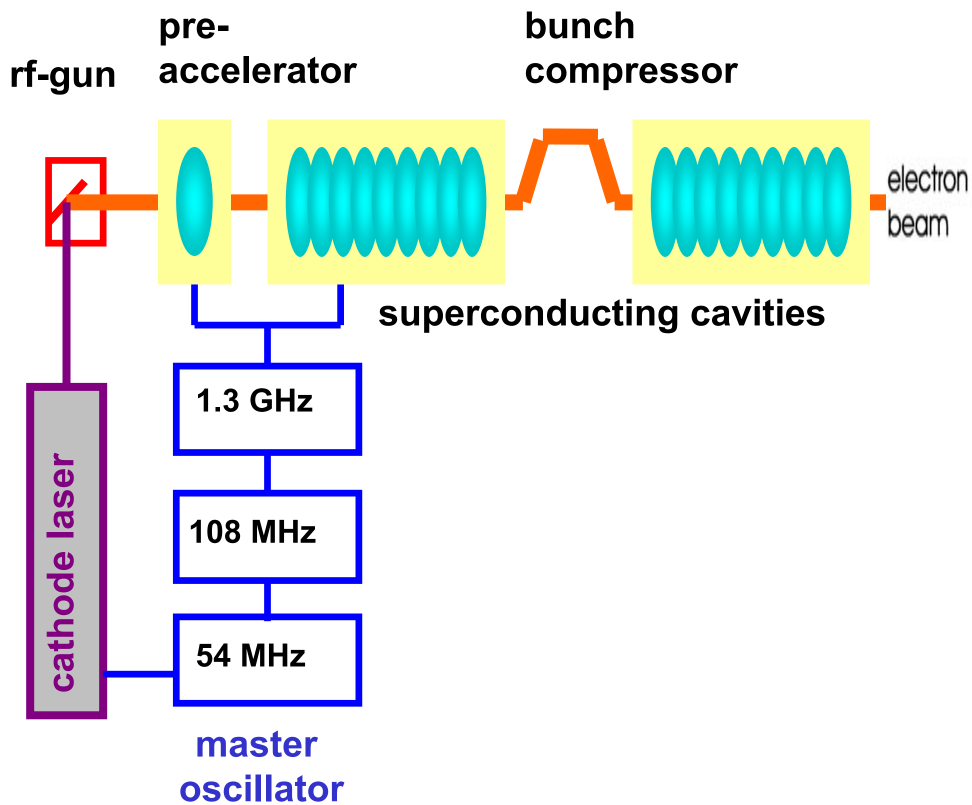
Experimental Setup

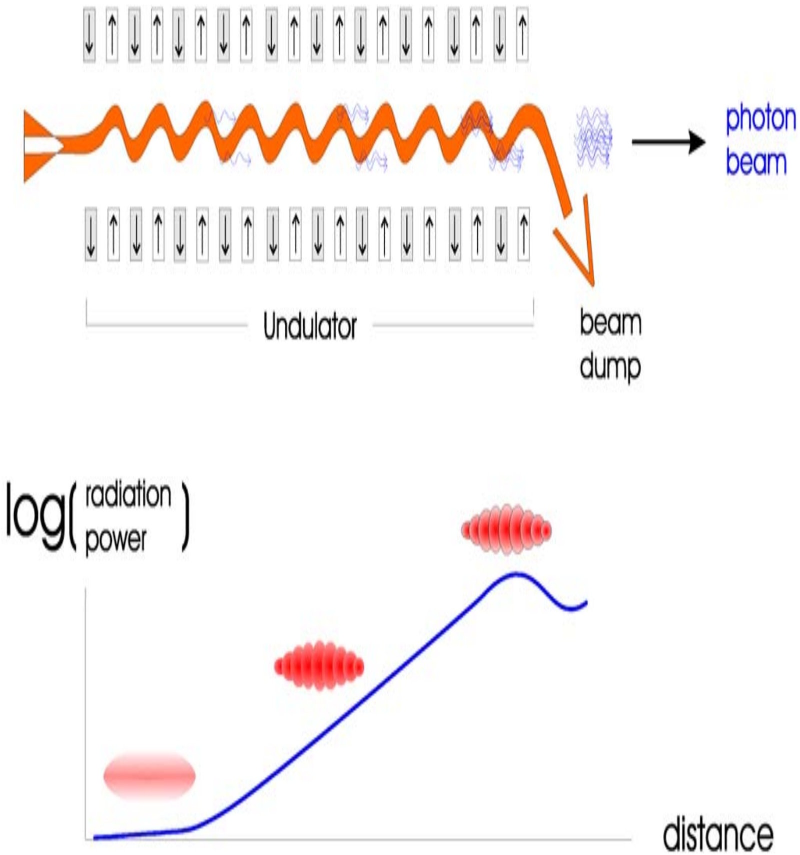
SASE in the Saturation Regime



Experimental Setup

The Free-Electron Laser at TTF: Phase I



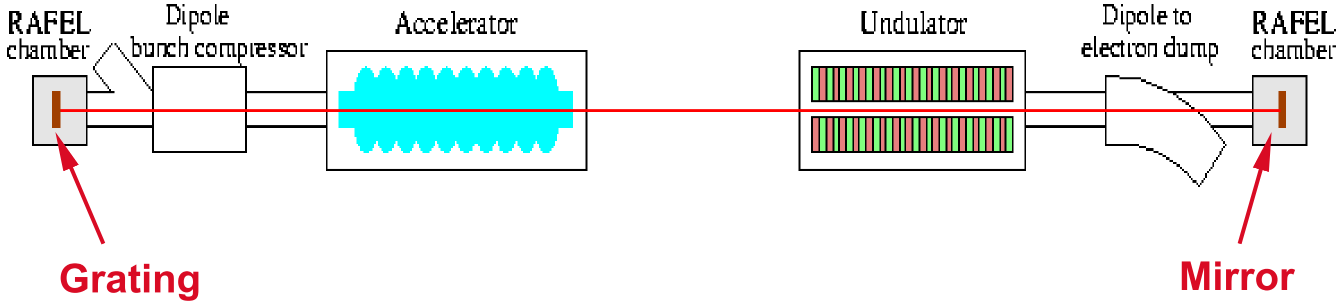


Idea: high gain ⇨ single pass ⇨ no mirrors !

Toroid reading

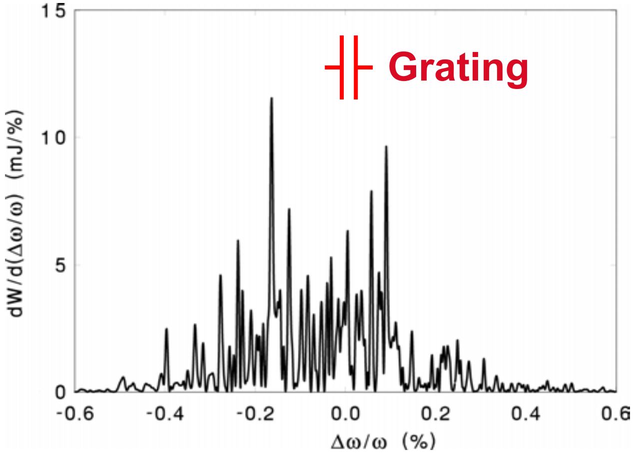
Second peak ??

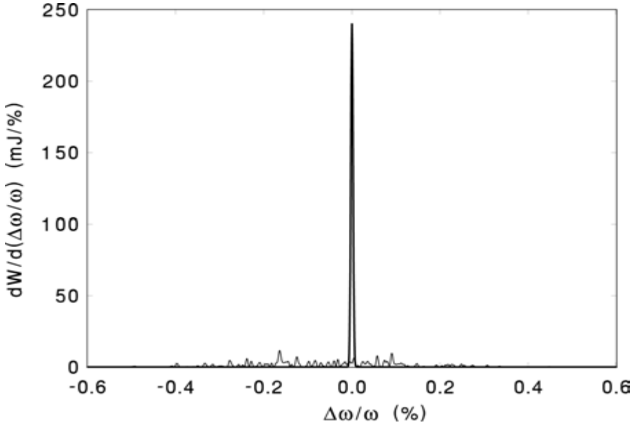
Regenerative FEL Amplifier (RAFEL)



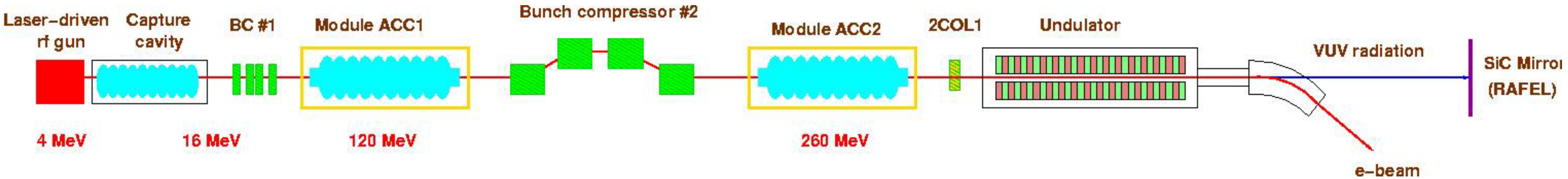
Idea:

to seed the SASE process of an electron bunch with a small bandwidth of the radiation emitted by the preceding electron bunch





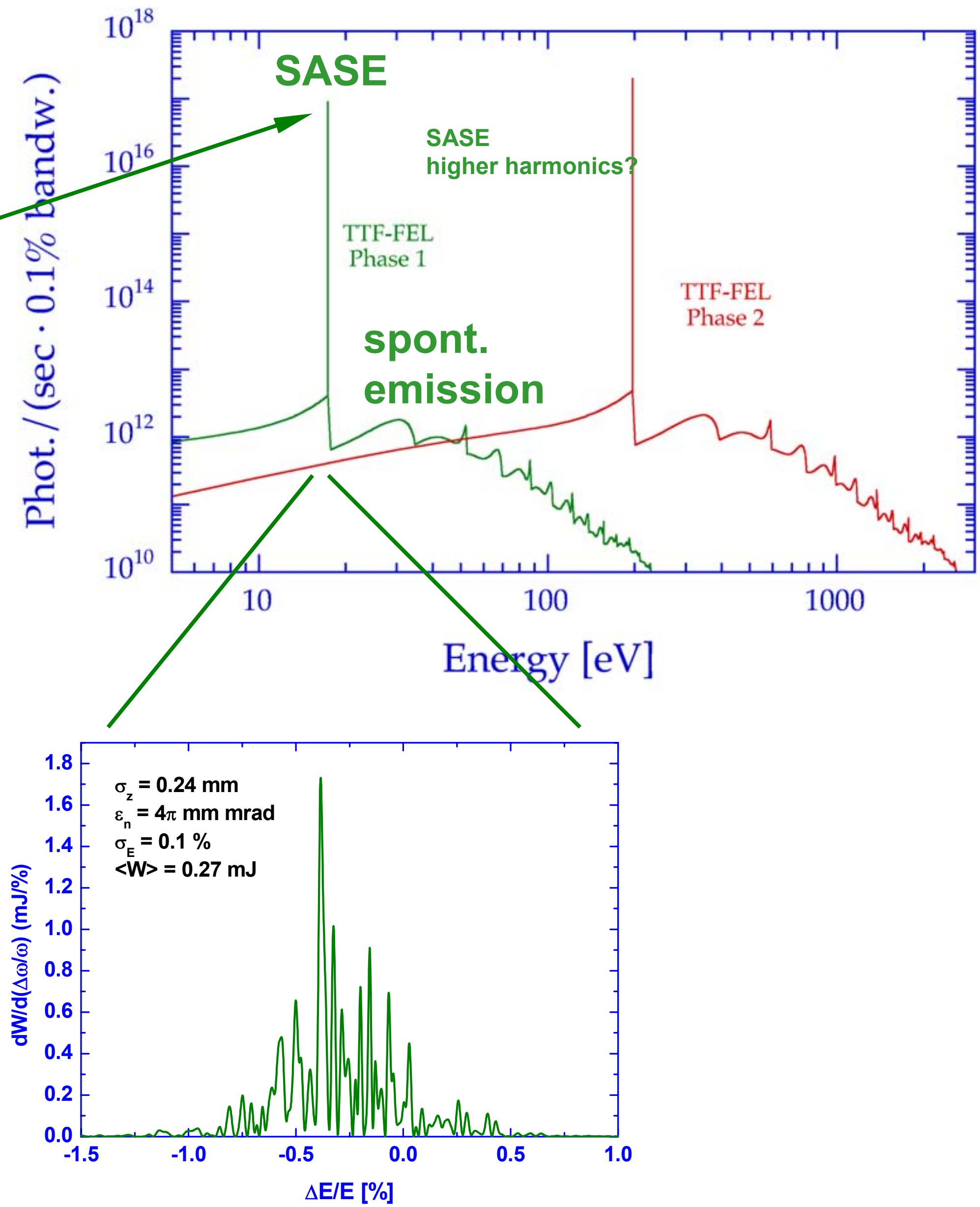
- ⇨ small bandwidth
- ⇨ full longitudinal coherence
- ⇨ Seeding Option in Phase II



Courtesy of E. Schneidmiller

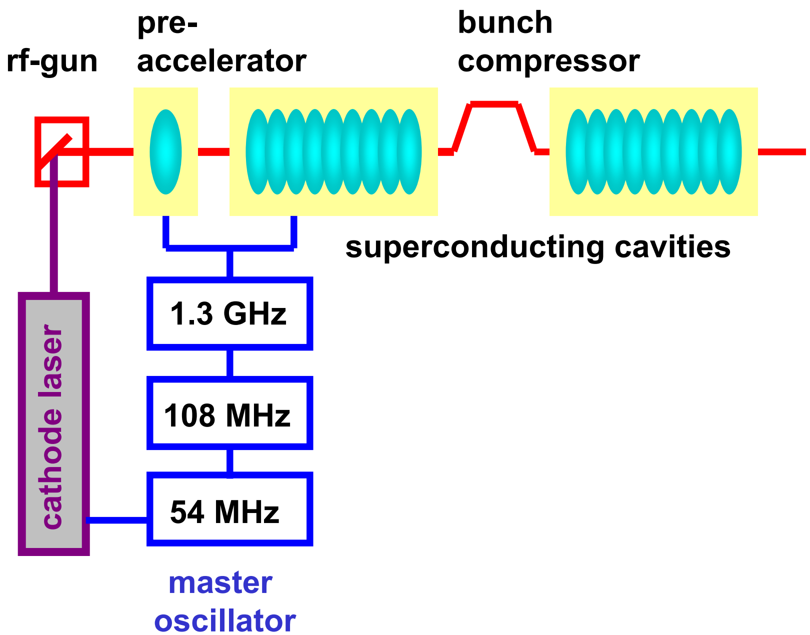
Full wavelength tunability by electron energy variation

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

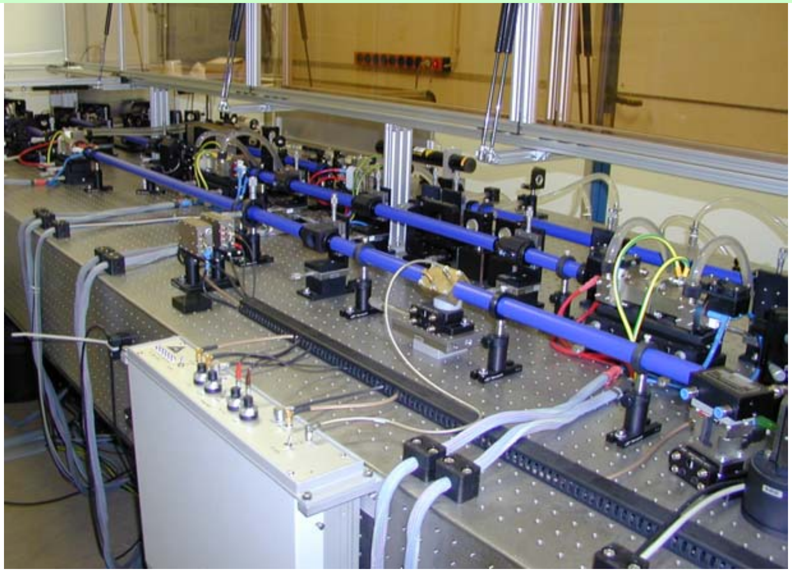


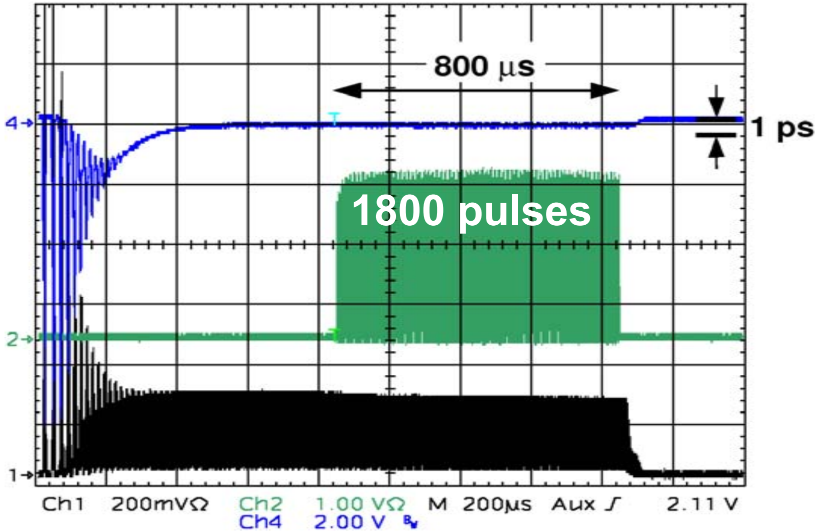
Full transverse coherence

BUT
not longitudinally coherent



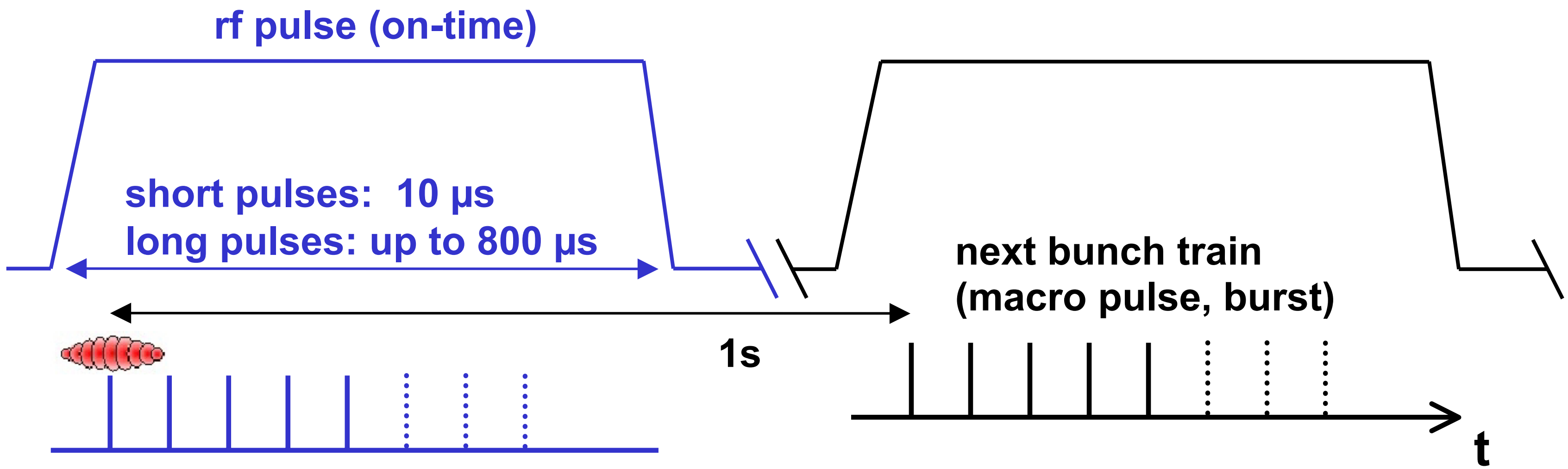
Frequency-quadrupled ND:YLF laser 1047 nm ⇒ 262 nm





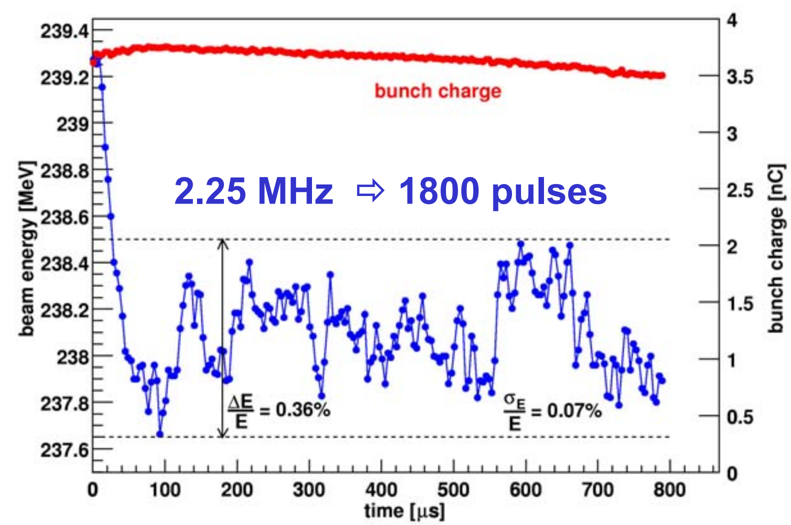
Pulse train	800 µs
Pulse energy	50 µJ
Pulse duration (rms)	7 ps
Energy variation:	
pulse to pulse	< 5%
Variable shape	

Time structure of electron bunches



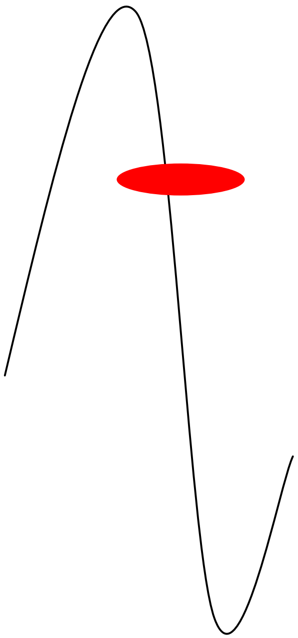
10 µs = 100 kHz
1 µs = 1 MHz
444 ns = 2.25 MHz

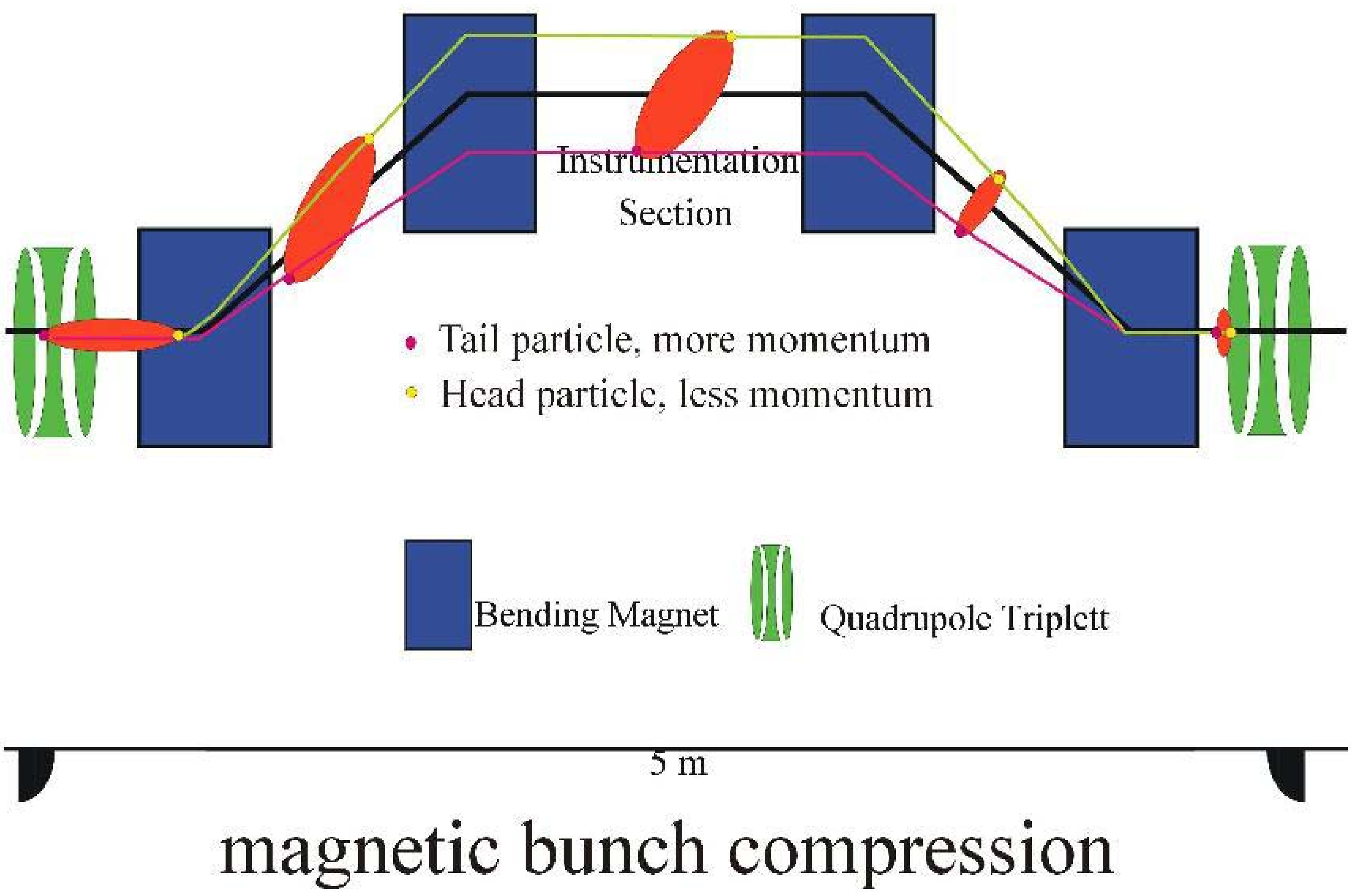
Number of pulses can be selected via control system



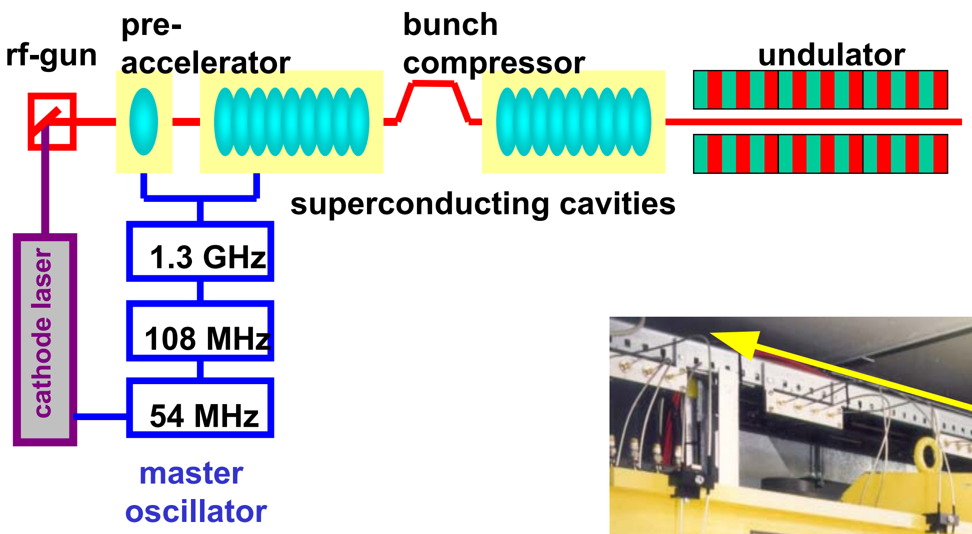
Bunch Compressor Scheme

Module 1





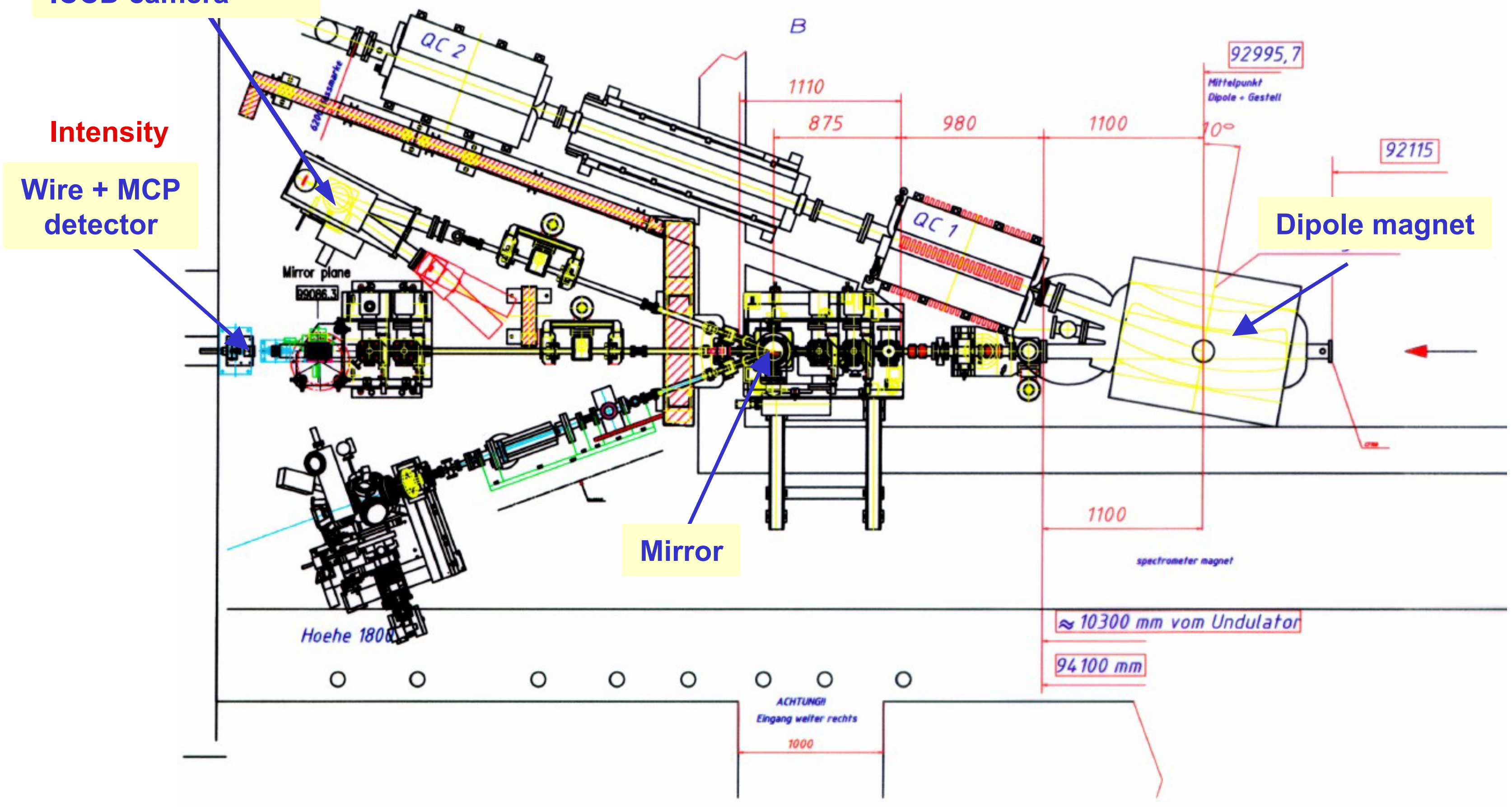
Phase of rf:
off crest ⇨ energy chirp



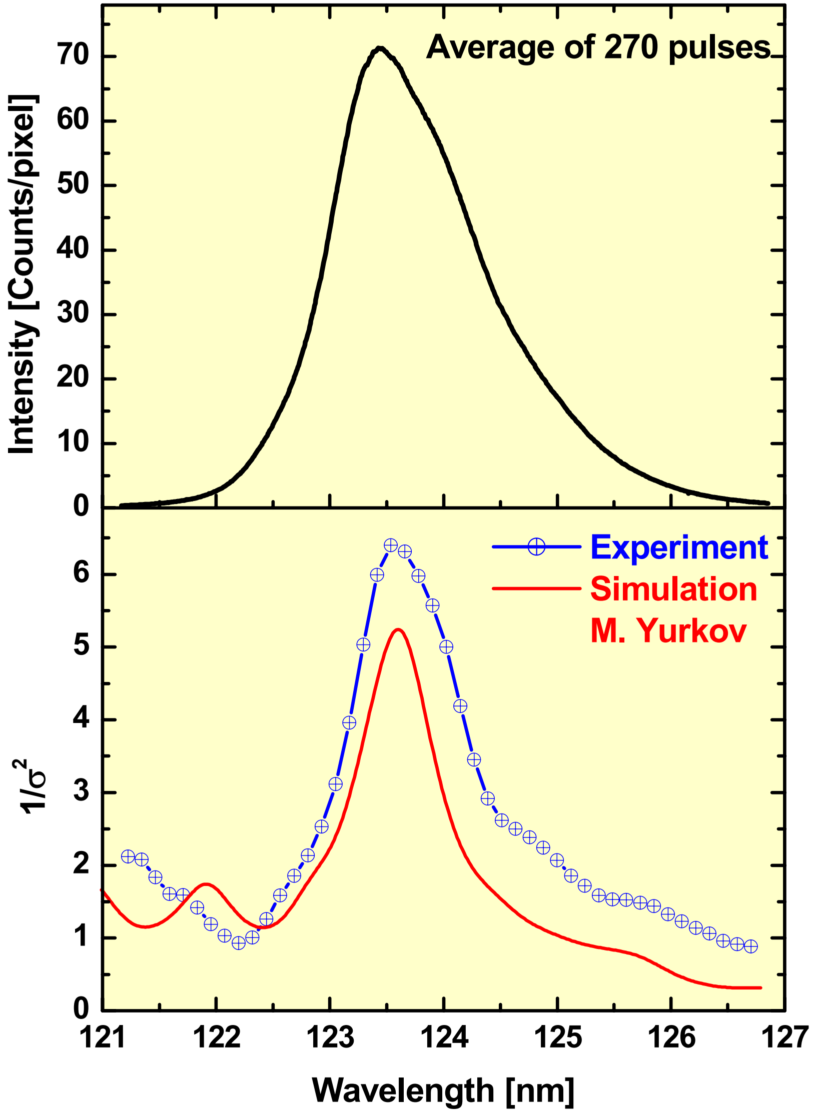
Period length: λ_u = 27.3 mm
Magnetic peak field: B = 0.46 T
Undulator parameter: K = 1.17

- Long undulator
  3 modules of 4.5 m
- fixed gap
- Integrated focusing
- Corrector coils (steerers)

Photon Diagnostics Area



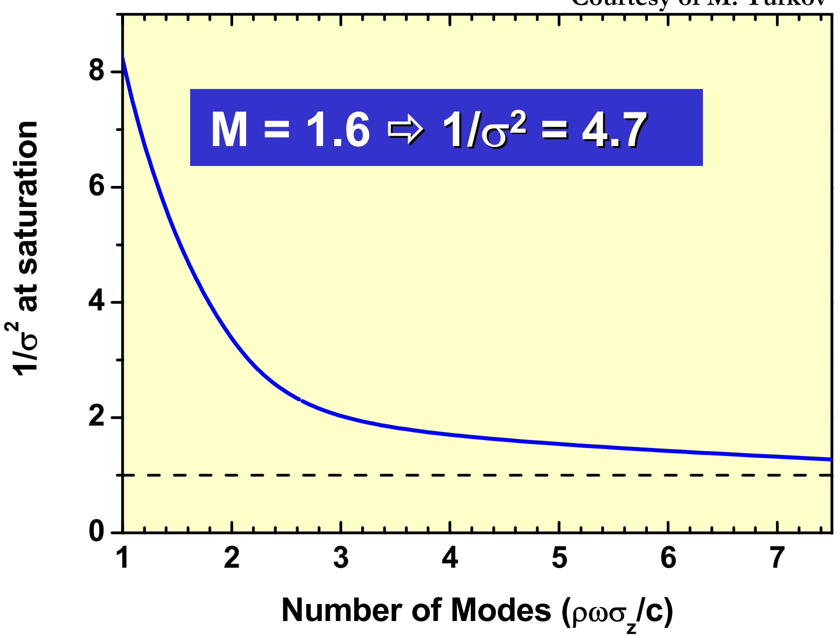
Probability Distribution behind a narrow-band monochromator



At saturation:

- Probability distribution changes within the spectral distribution
- Asymmetric shape
- Many modes ⇨ 100 % fluctuations!

Courtesy of M. Yurkov



Cathode Laser

Wavelength	262 nm
Pulse energy	≈ 50 μJ
No. of Photons	$\approx 5 \cdot 10^{13}$
Pulse duration	10 ps

Energy variation:
pulse to pulse < 5%

LINAC

Energy	245 MeV
No. of electrons	$\approx 10^{10}$
Pulse duration	10 ps

Energy variation:
pulse to pulse < 0.1%

FEL

Wavelength	90 nm
Pulse energy	≈ 90 μJ
No. of Photons	$\approx 5 \cdot 10^{13}$
Pulse duration	50 fs

Energy variation: ≈ 25%

Electrons Conversion Photons

Current in the flashlamps

Lasing in Nd:YLF oscillator
Frequency doubling

Photocathode
Acceleration
Undulator

spont. emission/SASE
Mirror
Monochromator
Ce:YAG fluorescence screen
Tandem optics

Photocathode
MCP

P46 fluorescence screen
Tandem optics

CCD
ADC
Computer
Monitor

Eye ...