Modeling the fluctuations of FEL radiation and their effect on the interaction with atoms

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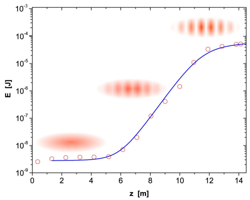
Self-Amplified Spontaneous Emission

Summary of FEL mechanism

1. oscillating e^- inside the undulator radiate spontaneously
2. radiation acts back on the e^- and bunches them
3. bunched e^- radiate coherently and amplify the co-propagating EM wave (stimulated emission)
   - for λ determined by resonance (synchronism) condition

Amplification of noisy spontaneous radiation at the entrance of the undulator (seeding)



http://hasylab.desy.de

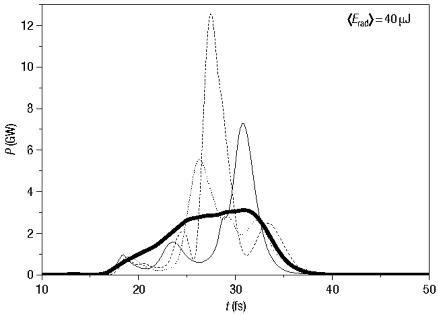
Radiation power ($N_e \sim 10^9$):

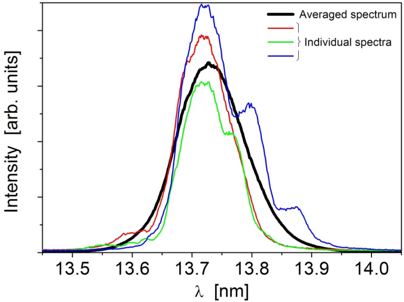
- $\propto N_e$ for individual e^-
- $\propto N_e^2$ for e^- confined in λ
- $I(z) = I_0 e^{z/L_g}$

Properties of FEL Radiation

FEL pulses in the time and frequency domain

Spiky behavior, with the width of the main peaks determined by the coherence time T_c.





Ackermann *et al.*, Nature **1**, 336 (2007).

Properties of FEL Radiation

Fluctuations in intensity

Probability distribution of the instantaneous intensity follows the negative exponential distribution

$$P[\tilde{I}(t)] = e^{-\tilde{I}(t)}$$

- $\tilde{I}(t) = I(t)/\langle I(t)\rangle$
- $\langle I(t)\rangle$: average intensity at a given time and position

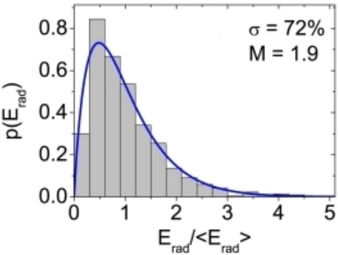
Properties of FEL Radiation

Fluctuations in energy

Prob. distribution of energy W, follows a Gamma distribution

$$P(\tilde{W}) = \frac{M^M}{\Gamma(M)} \tilde{W}^{M-1} \exp(-M\tilde{W})$$

- $\tilde{W} = W/\langle W \rangle$
- M: av. number of modes
  $M \approx (T_u - T_l)/T_c$
- $(T_u - T_l) \gg T_c$
  $P(\tilde{W}) \rightarrow$ Gaussian
- $(T_u - T_l) \ll T_c$
  $P(\tilde{W}) \rightarrow$ neg. exponential

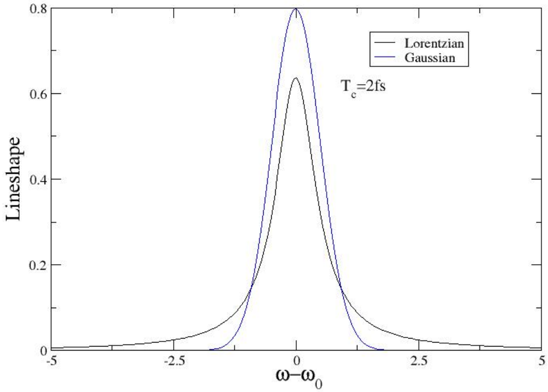


W. Ackermann *et al.*, Nature **1**, 336 (2007).

Simulation Algorithms

Gallery of results

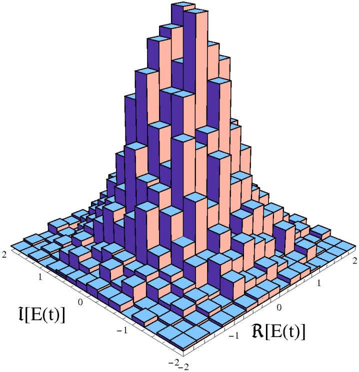
Two different lineshapes

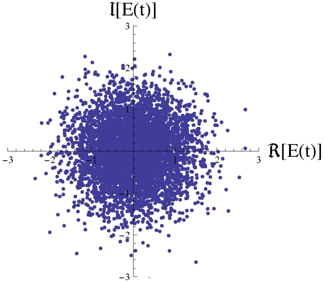


Simulation Algorithms
Gallery of results

Electric field at a given time

Complex Gaussian random variable

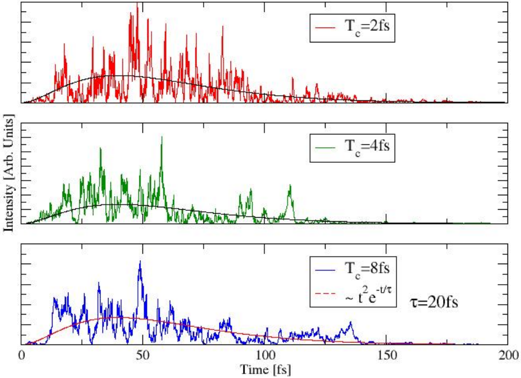




Simulation Algorithms

Gallery of results

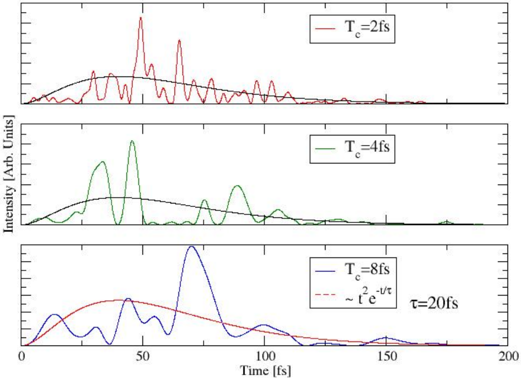
Lorentzian spectral linewidth: Typical random pulses



Simulation Algorithms

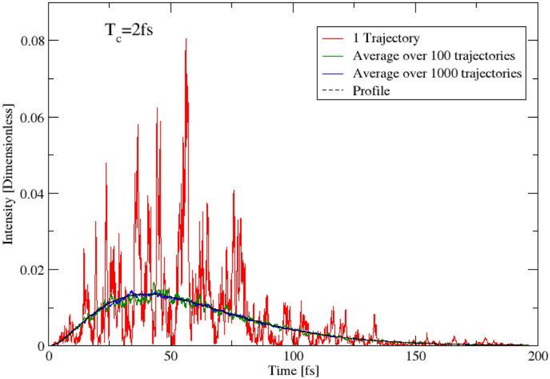
Gallery of results

Gaussian spectral linewidth: Typical random pulses



Simulation Algorithms
Gallery of results

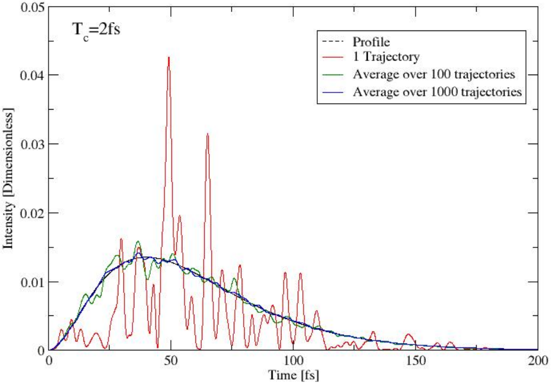
Lorentzian spectral linewidth: Averaging over random pulses



Simulation Algorithms

Gallery of results

Gaussian spectral linewidth: Averaging over random pulses

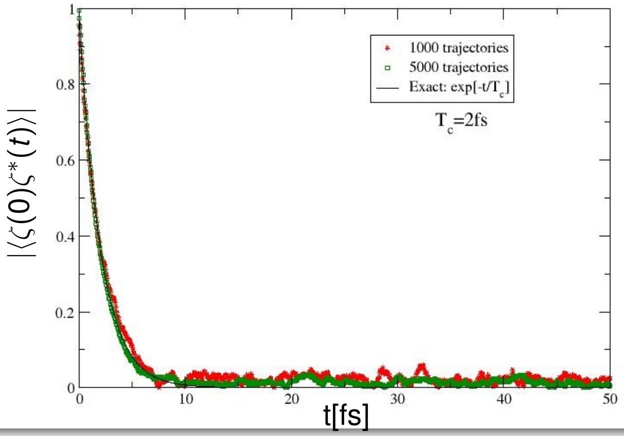


Simulation Algorithms

Gallery of results

Lorentzian spectral linewidth: First-order correlation function

$$g^{(1)}(t_1, t_2) \sim \langle E(t_1)E^*(t_2)\rangle \sim \langle \zeta(t_1)\zeta^*(t_2)\rangle$$



Simulation Algorithms

Gallery of results

Gaussian spectral linewidth: First-order correlation function

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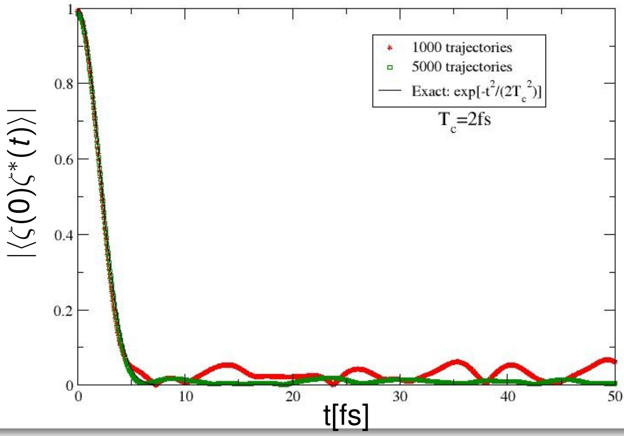


Simulation Algorithms

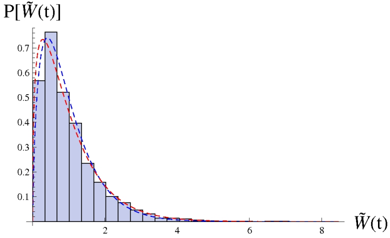
Gallery of results

Gaussian spectral linewidth: Fluctuations in energy

Prob. distribution of energy follows a Gamma distribution

$$W = \int_{T_l}^{T_u} I(t)dt; \quad P(\tilde{W}) = \frac{M^M}{\Gamma(M)} \tilde{W}^{M-1} \exp(-M\tilde{W})$$

- $\tilde{W} = W/\langle W \rangle$
- M: av. number of modes $M \approx (T_u - T_l)/T_c$
- $(T_u - T_l) \gg T_c$ $P(\tilde{W}) \to$ Gaussian
- $(T_u - T_l) \ll T_c$ $P(\tilde{W}) \to$ neg. exponential



$T_u - T_l = 2T_c$; Estimated $M \approx 1.4$

Simulation Algorithms

Gallery of results

Gaussian spectral linewidth: Fluctuations in energy

Prob. distribution of energy follows a Gamma distribution

$$W = \int_{T_\mathrm{l}}^{T_\mathrm{u}} I(t)dt; \quad P(\tilde{W}) = \frac{M^M}{\Gamma(M)} \tilde{W}^{M-1} \exp(-M\tilde{W})$$

- $\tilde{W} = W / \langle W \rangle$
- M: av. number of modes
  $M \approx (T_\mathrm{u} - T_\mathrm{l}) / T_\mathrm{c}$
- $(T_\mathrm{u} - T_\mathrm{l}) \gg T_\mathrm{c}$
  $P(\tilde{W}) \to$ Gaussian
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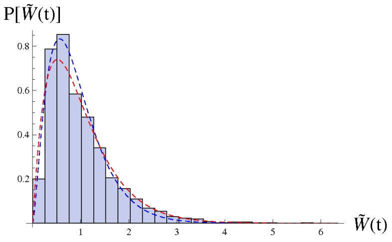


$T_u - T_l = 4T_c$; Estimated $M \approx 2.1$

Simulation Algorithms

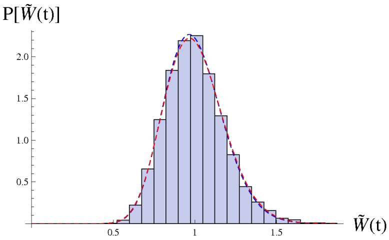
Gallery of results

Gaussian spectral linewidth: Fluctuations in energy

Prob. distribution of energy follows a Gamma distribution

$$W = \int_{T_l}^{T_u} I(t)dt; \quad P(\tilde{W}) = \frac{M^M}{\Gamma(M)} \tilde{W}^{M-1} \exp(-M\tilde{W})$$

- $\tilde{W} = W/\langle W \rangle$
- M: av. number of modes $M \approx (T_u - T_l)/T_c$
- $(T_u - T_l) \gg T_c$ $P(\tilde{W}) \to$ Gaussian
- $(T_u - T_l) \ll T_c$ $P(\tilde{W}) \to$ neg. exponential



$T_u - T_l = 100T_c$; Estimated $M \approx 30.1$

Simulation Algorithms

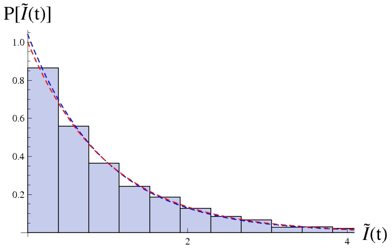
Gallery of results

Gaussian spectral linewidth: Fluctuations in intensity

Prob. distribution of instantaneous intensity

$$P[\tilde{I}(t)] = \exp(-\tilde{I}(t))$$

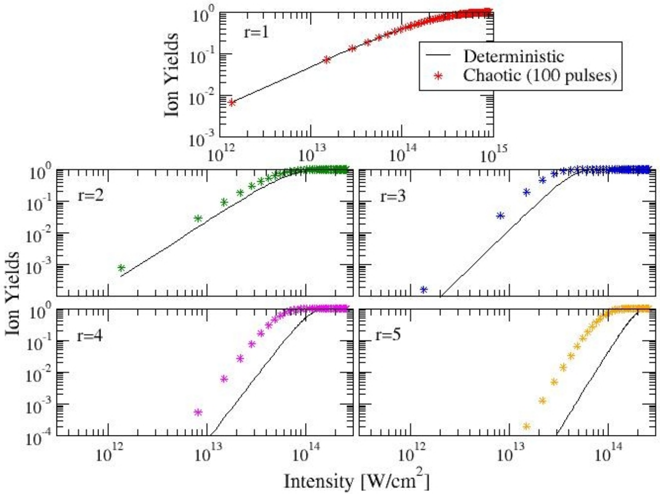
- $\tilde{I}(t) = I(t)/\langle I(t)\rangle$
- $\langle I(t)\rangle$: average intensity at given time and position



5000 trajectories

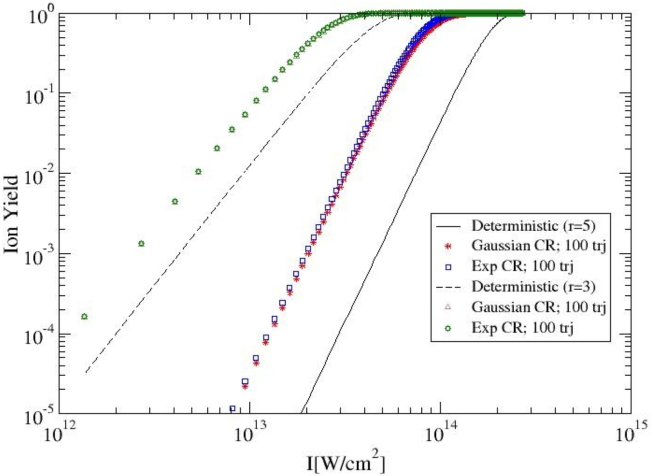
Enhancement of Non-Linear Processes

r-photon absorption



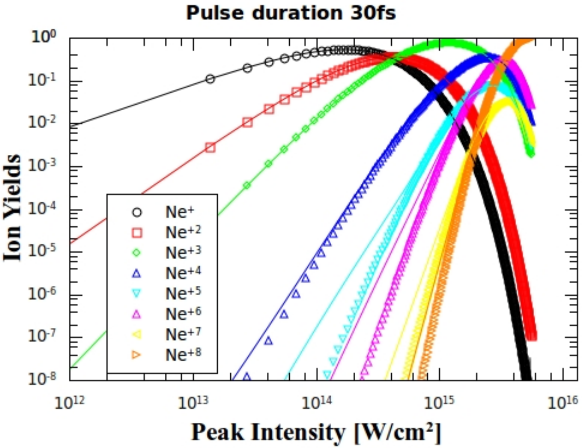
Enhancement of Non-Linear Processes

r-photon absorption: Gaussian vs Exponential correlation



Ionization of Ne @ 93 eV

Effects of the pulse duration: Sequential vs Direct channels



- Symbols: Yields when only sequential is present
- Lines: Yields when both sequential and direct are present

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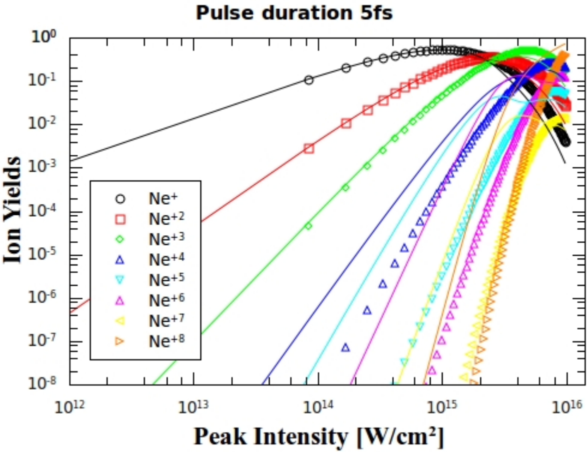

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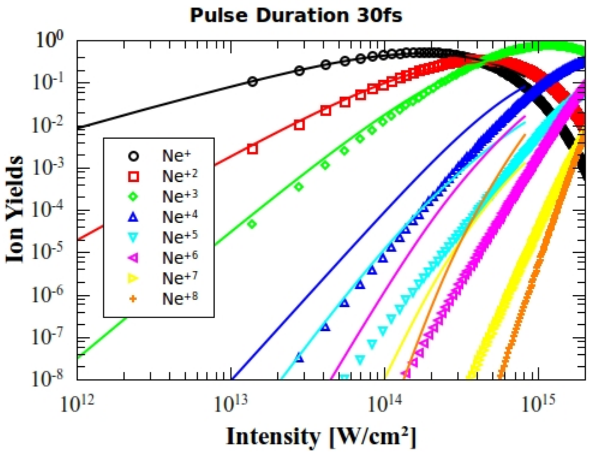
Effects of chaotic pulses



- Symbols: Yields for deterministic pulse
- Lines: Average yields for 10^4 chaotic pulses

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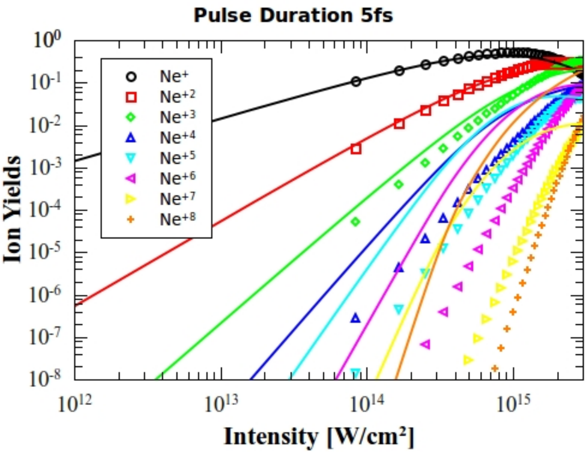

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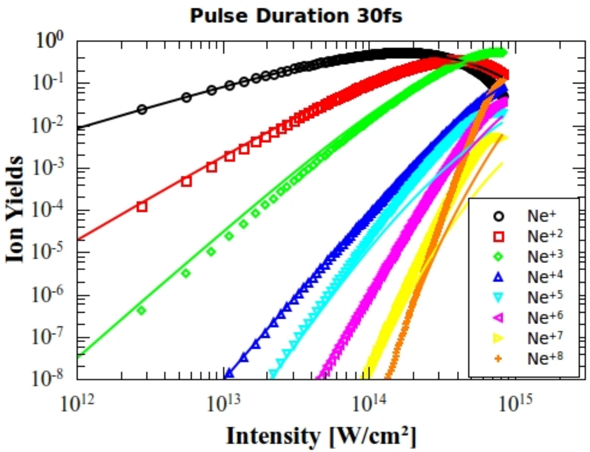
Ionization of Ne @ 93 eV

Can we obtain average stochastic yields deterministically?



- Symbols: Yields for deterministic pulse & $(n!)\times$CS
- Lines: Average yields for 10^4 chaotic pulses

Ionization of Ne @ 93 eV

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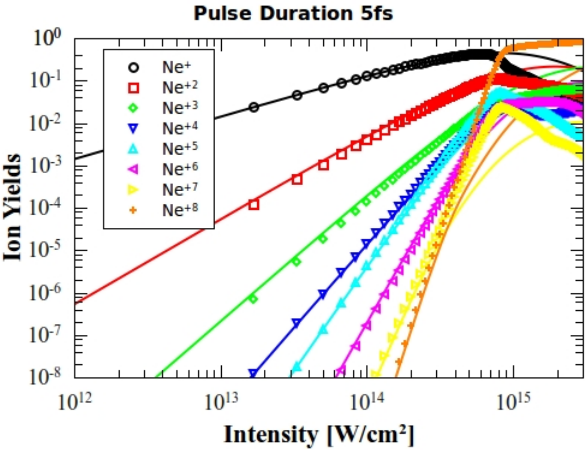

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