Parameter choice and radiation properties

(Optimization of XFEL operating in Angstrom wavelength range)

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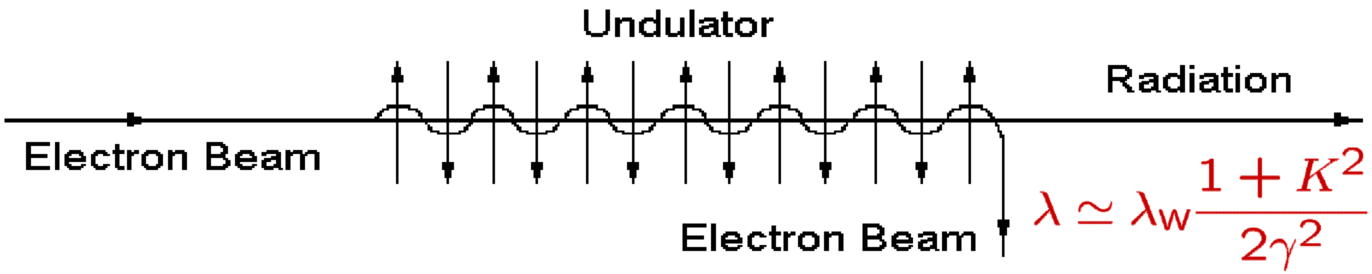
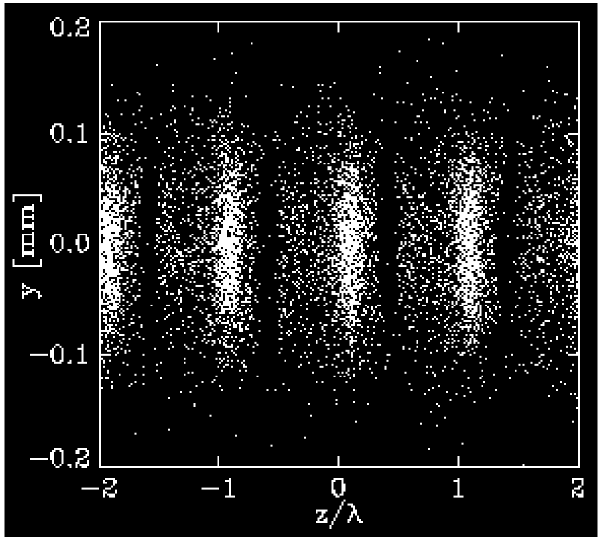
ESFRI XFEL Workshop, October 30-31, 2003

- An approach to global optimization of XFEL parameters
- Analysis of parameter space
- Preliminary conclusions

Principle of SASE FEL operation



$$\lambda \simeq \lambda_{\mathrm{w}} \frac{1 + K^2}{2\gamma^2}$$



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Ya.S. Derbenev
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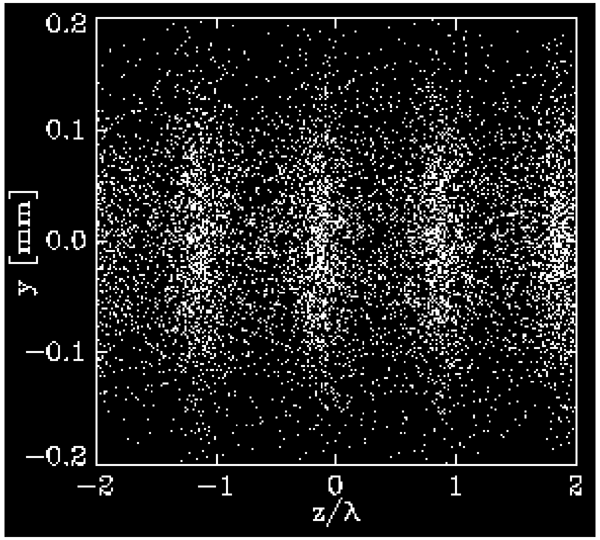
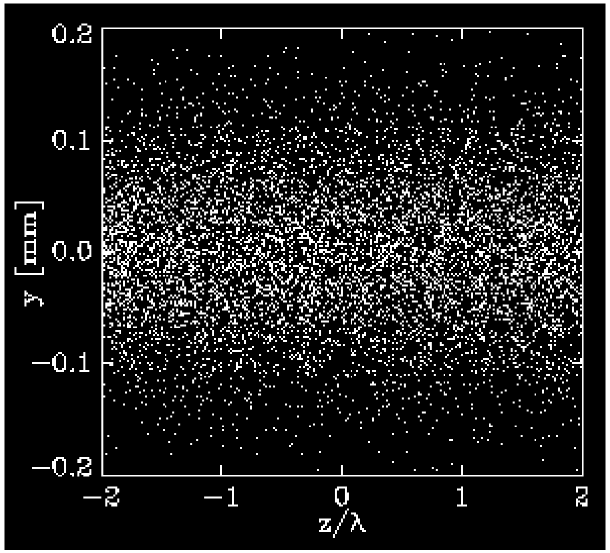
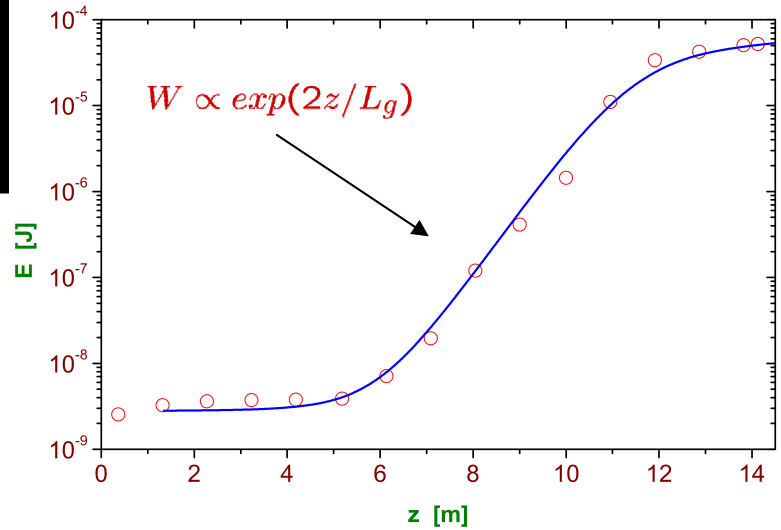






Undulator length is about 10 L_g for X-ray SASE FEL

Main characteristics of the SASE FEL can be estimated in terms of the FEL parameter ρ and number of cooperating electrons N_c:

- Number of cooperating electrons $N_c = N_\lambda/(2\pi\rho)$, where $N_\lambda = 2\pi I_0/(e\omega_0)$ is number of electrons per radiation wavelength
- The field gain length is $L_g \sim \lambda_w/(4\pi\rho)$
- Saturation length is about ten field gain lengths, $L_{sat} \sim 10 \times L_g$
- Effective power of shot noise

$$\frac{W_{sh}}{\rho W_b} \simeq \frac{3}{N_c\sqrt{\pi \ln N_c}}$$

- Saturation efficiency is about ρ
- The power gain at saturation:

$$G \simeq \frac{1}{3} N_c \sqrt{\pi \ln N_c} \ .$$

- Spectrum bandwidth is about 2ρ
- Coherence time at saturation:

$$(\tau_c)_{max} \simeq \frac{1}{\rho\omega_0}\sqrt{\frac{\pi \ln N_c}{18}}$$

$$\rho = \left[\frac{I}{I_A}\frac{A_{JJ}^2 K^2 \lambda_w^2}{32\pi^2\gamma^2\epsilon_n\beta_f}\right]^{1/3}$$

see poster for more details

- Gain length is function of beam and undulator parameters:

$$L_{\rm g} = f(I,\ \gamma,\ \epsilon_n,\ <(\delta\gamma)^2>,\ \lambda_{\rm w},\ K,\ \beta_{\rm f})$$

$$\lambda = \frac{\lambda_{\rm w}}{2\gamma^2}(1+K^2/2)\ , \qquad K = \frac{eH_{\rm w}}{\kappa_{\rm w} m_{\rm e} c^2}\ , \qquad \kappa_{\rm w} = 2\pi/\lambda_{\rm w}$$

- Gap limitation imposes a constrain on value of K:

$$H_{\rm w} = a_1 exp\left[a_2 \frac{g}{\lambda_{\rm w}} + a_3 \frac{g^2}{\lambda_{\rm w}^2}\right]\ , \qquad \text{NdFeB}: a_1 = 3.694,\ a_2 = -5.068,\ a_3 = 1.52$$

- Quantum fluctuations of incoherent radiation cause diffusion of the energy spread:

$$\frac{d<(\delta\gamma)^2>}{dz} = \frac{7}{15}\lambdabar_{\rm c} r_{\rm e} \gamma^4 \kappa_{\rm w}^3 K^2 F(K)$$

$$F(K) \simeq 1.20K + \frac{1}{1+1.33K+0.40K^2}$$

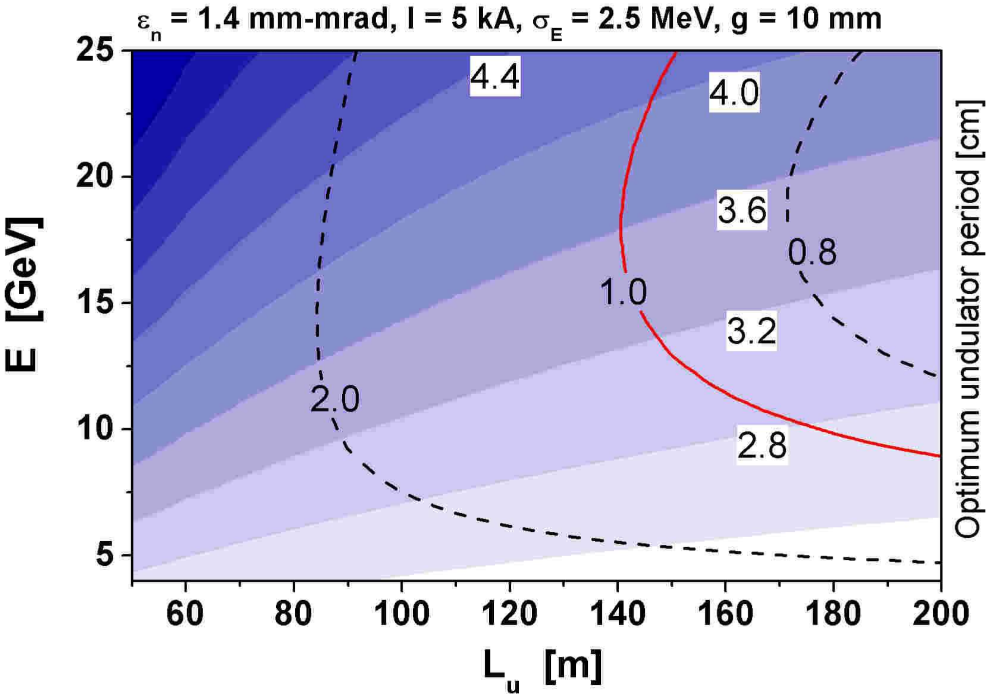
Energy spread becomes to be dependent on the value of the gain length $L_{\rm g}$.

Questions to be answered:

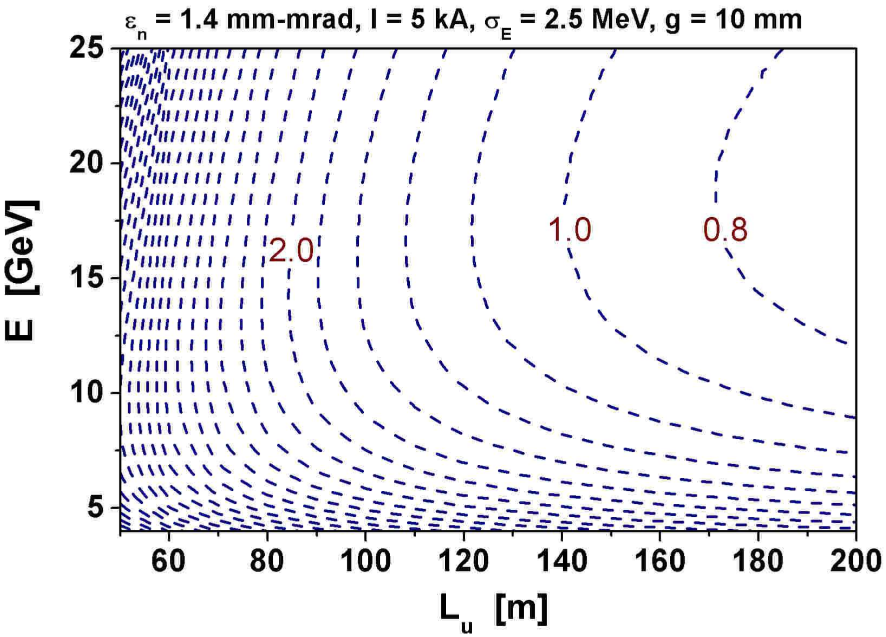
- Which minimum wavelength can be achieved at given beam parameters (local energy spread and emittance), and limitations on the undulator length and gap?
- Which electron energy corresponds to minimum wavelength?
- What are optimum undulator period and optimum focusing beta-function?
- What is target goal for optimization strategy of the electron beam parameters?

An approach to global optimization of X-ray FEL:

- We fix peak current, emittance, in and undulator gap. Then we searc which allows to reach saturation. U minimum which gives us optimum period, and external focusing beta

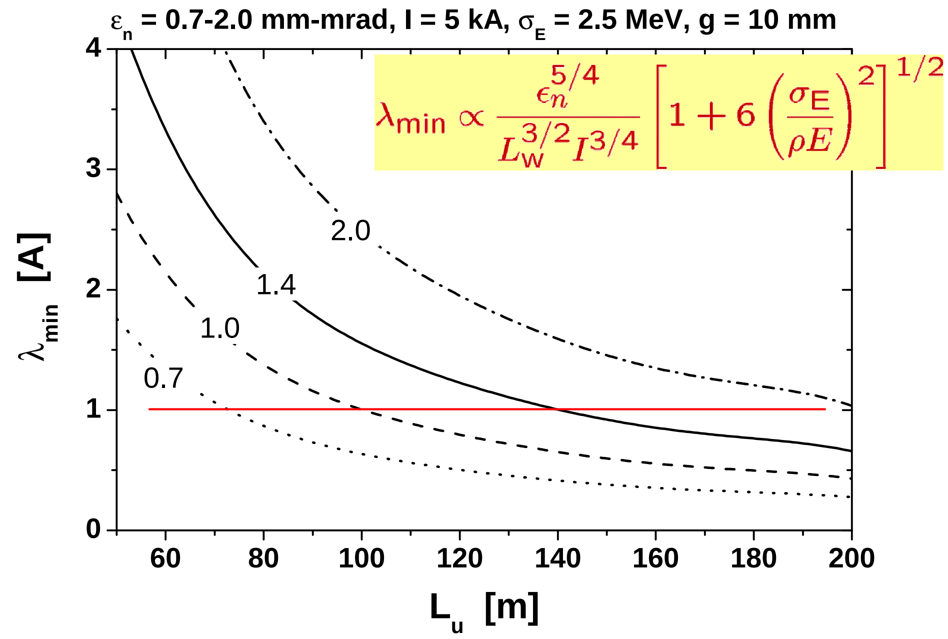


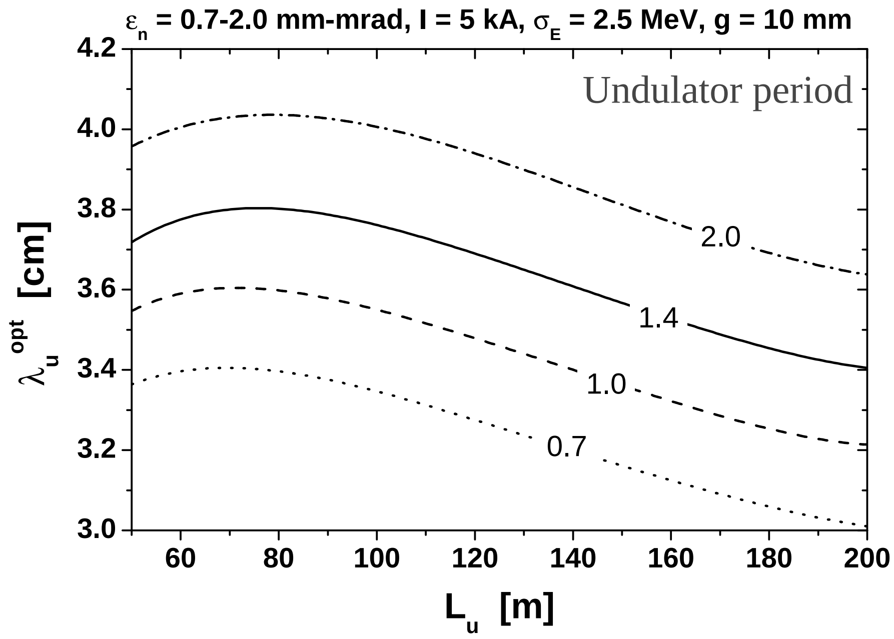
- The rest is simple scan over remaini emittance, initial energy spread, u
- Note that at all steps of calculat the eigenvalue problem (no fitting region).
- Final results are p … for choice of optimal parameters.

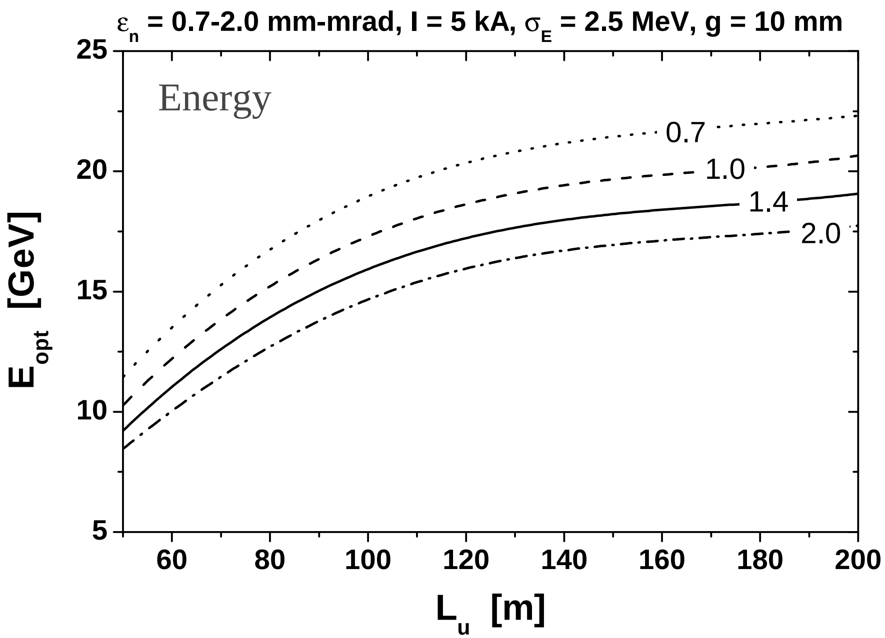


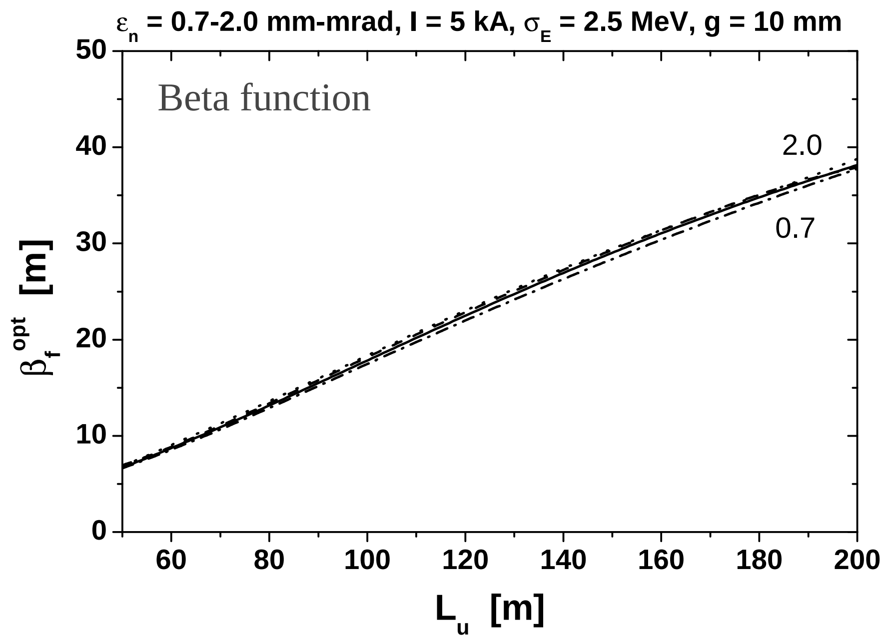
- Typically, depend … her smooth and can be clearly interpr
- Presented approa … omplete overview of parameter space

Overview of parameter space: emittance

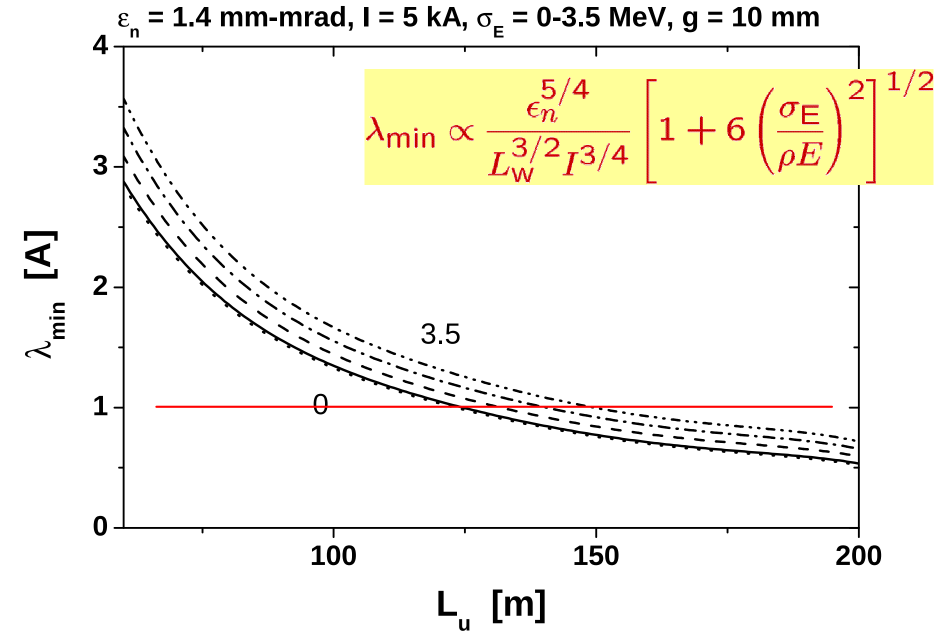


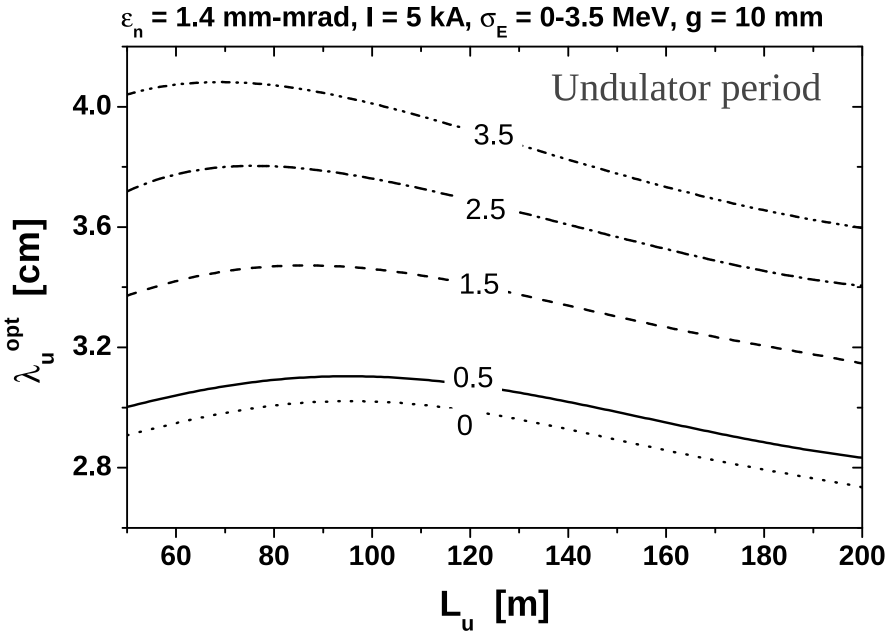


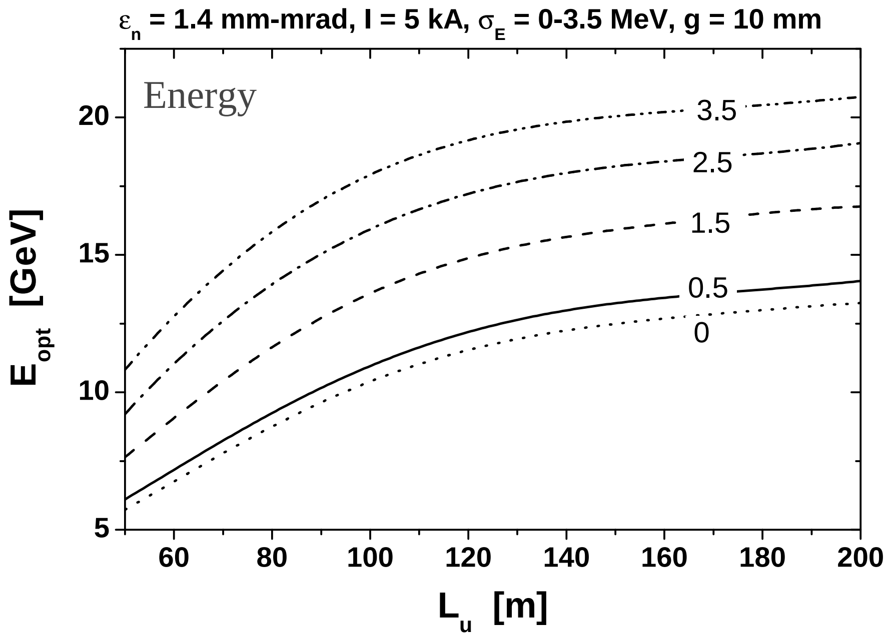


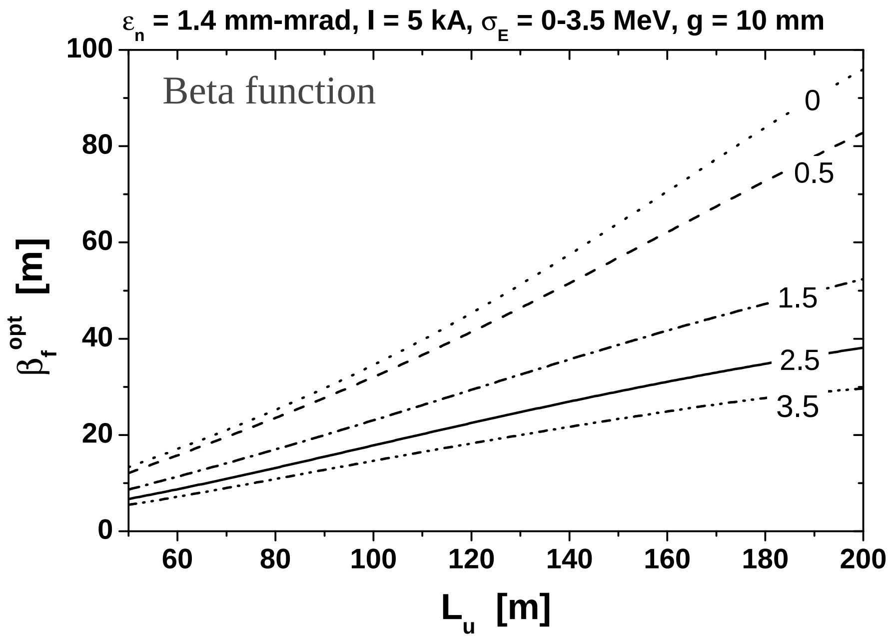


Overview of parameter space: energy spread

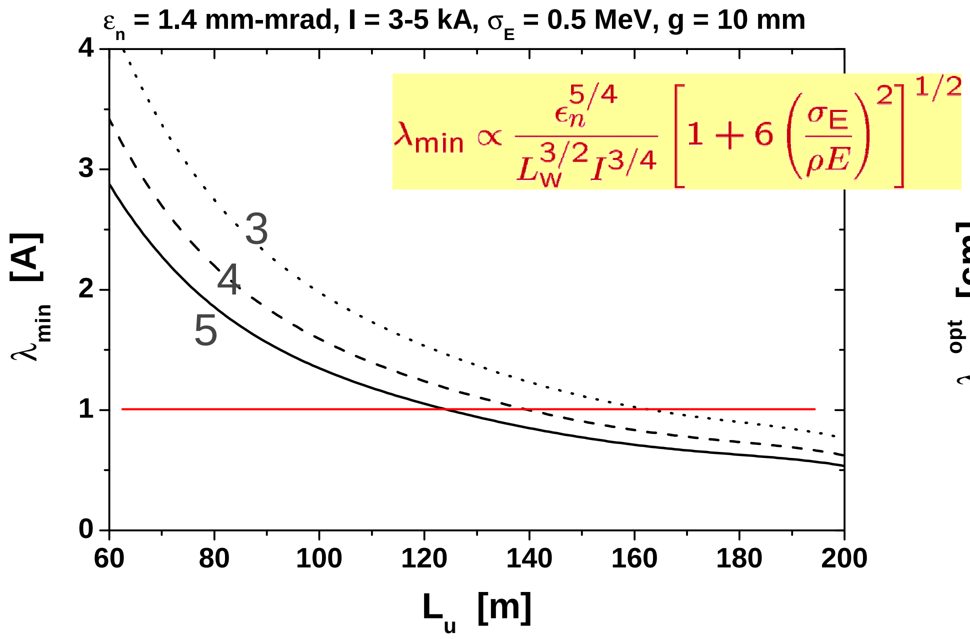


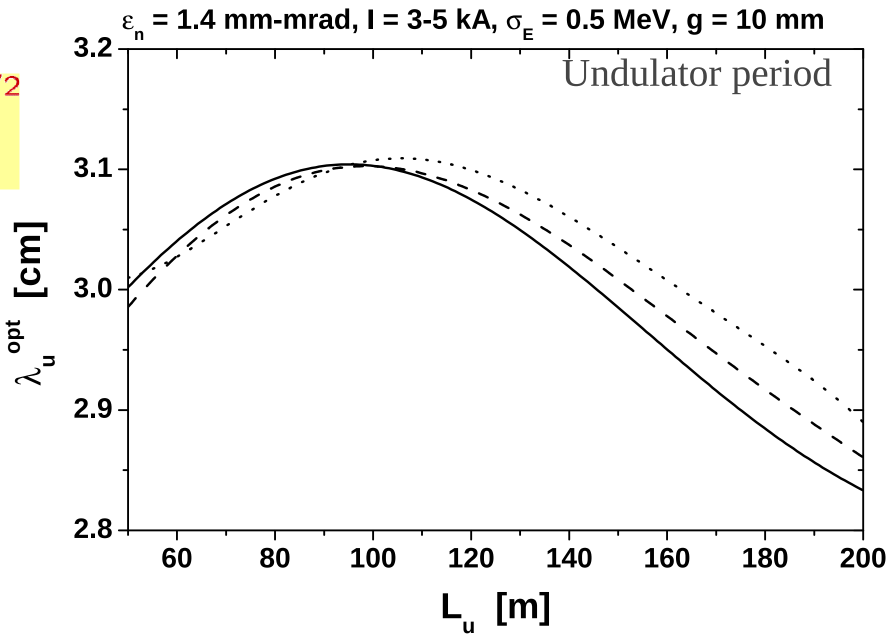


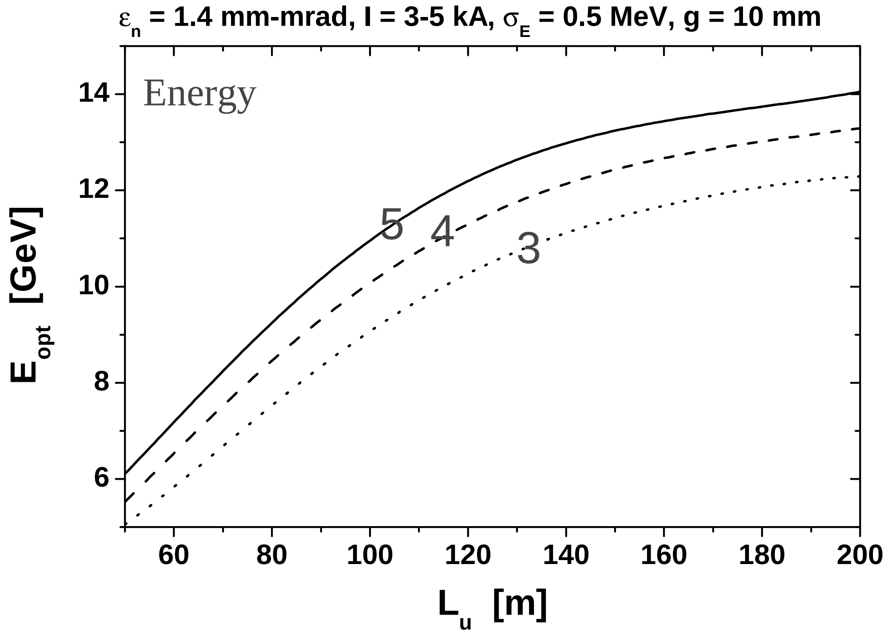


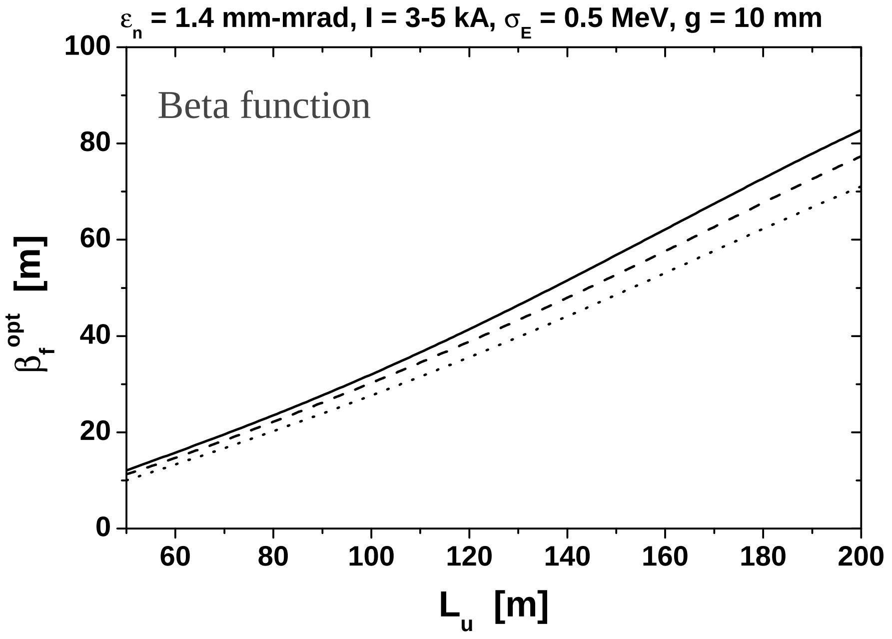


Overview of parameter space: peak current

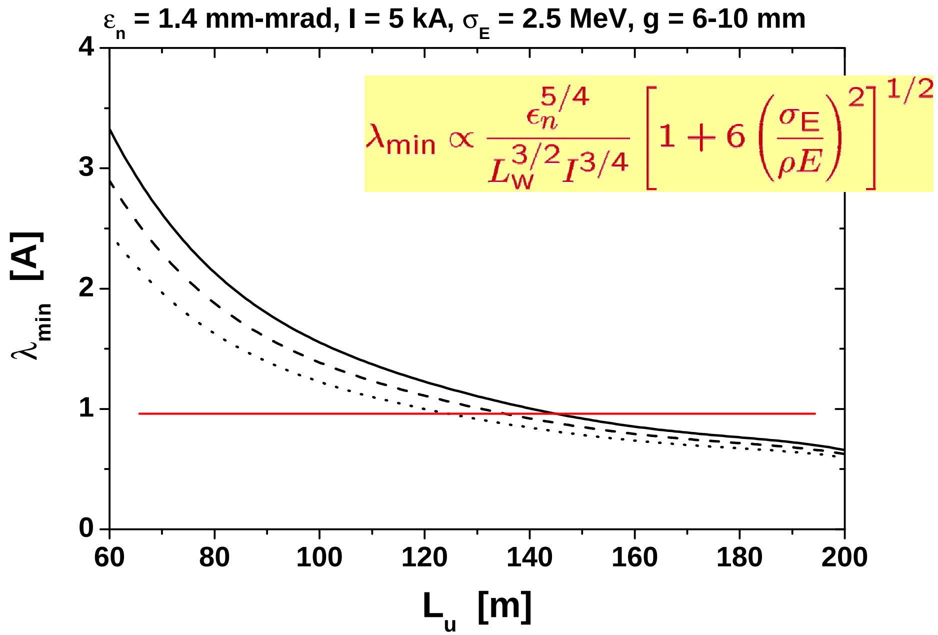


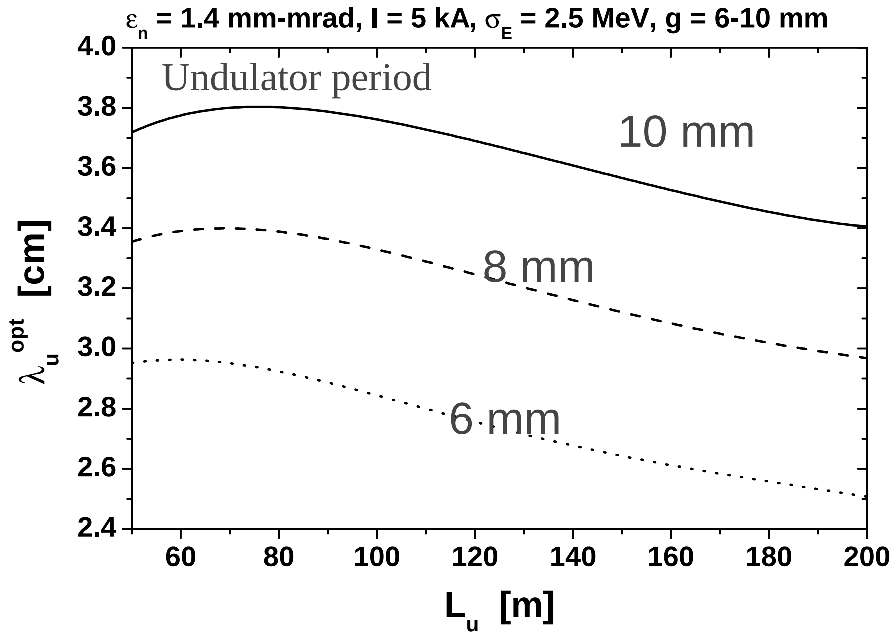


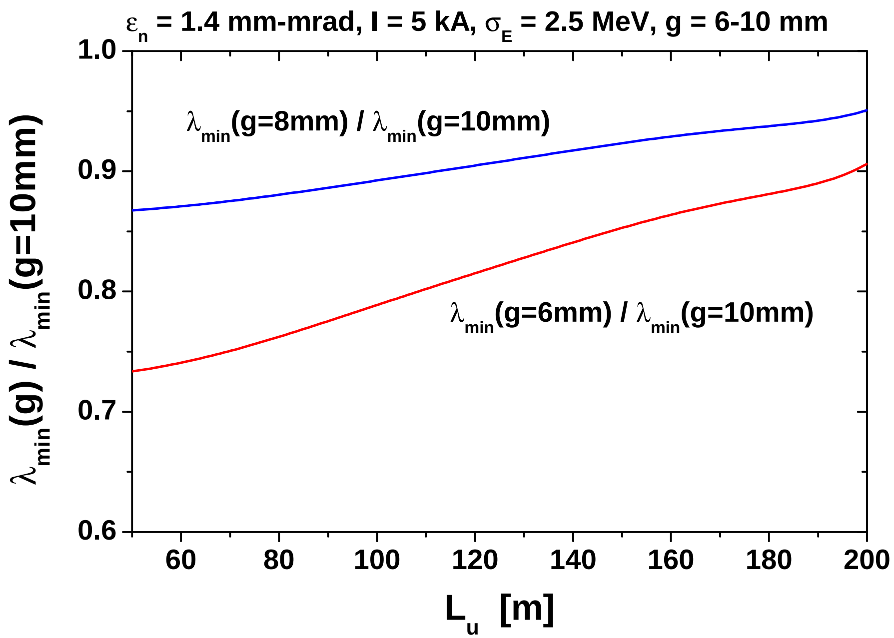


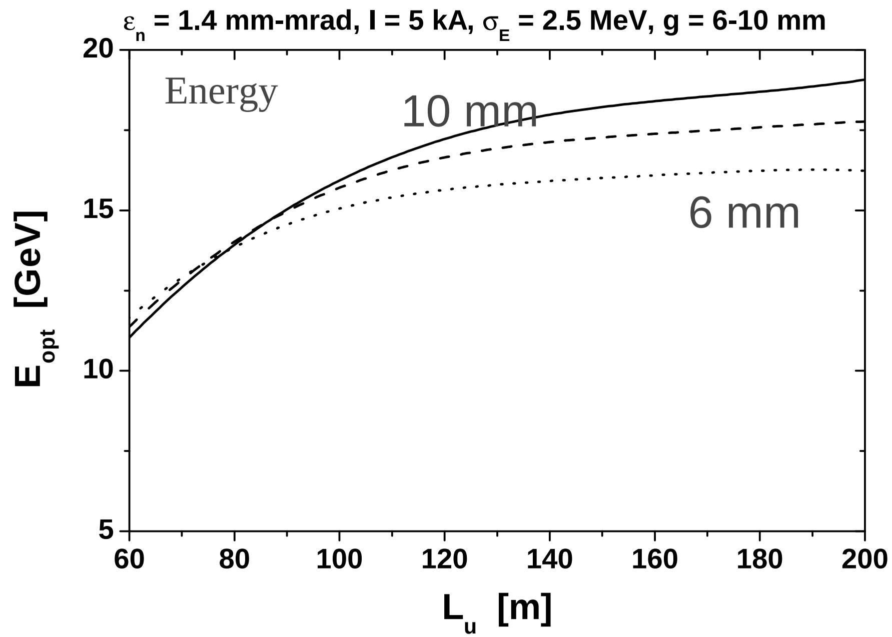


Overview of parameter space: undulator gap

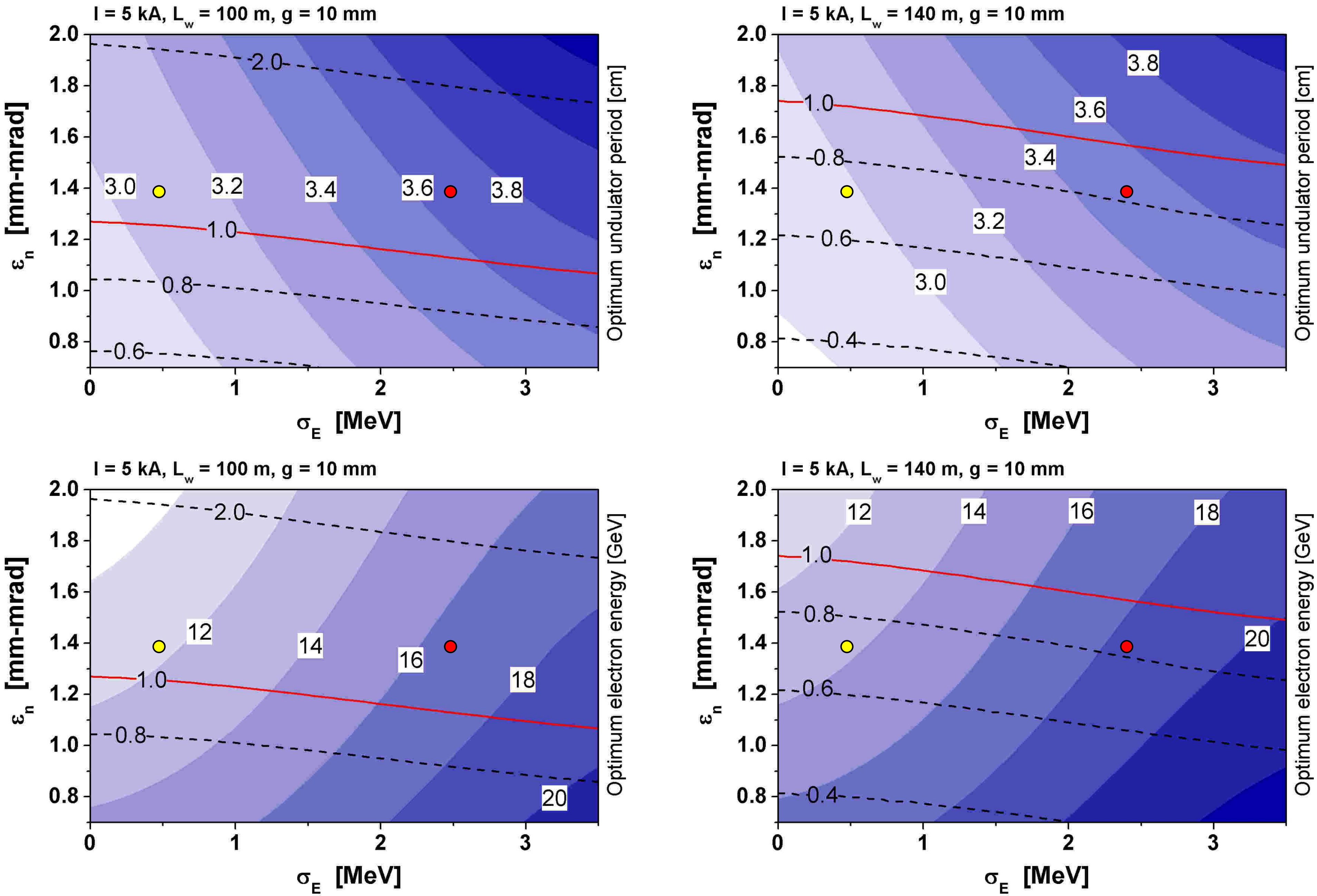








Global overview for parameter space



Discussion

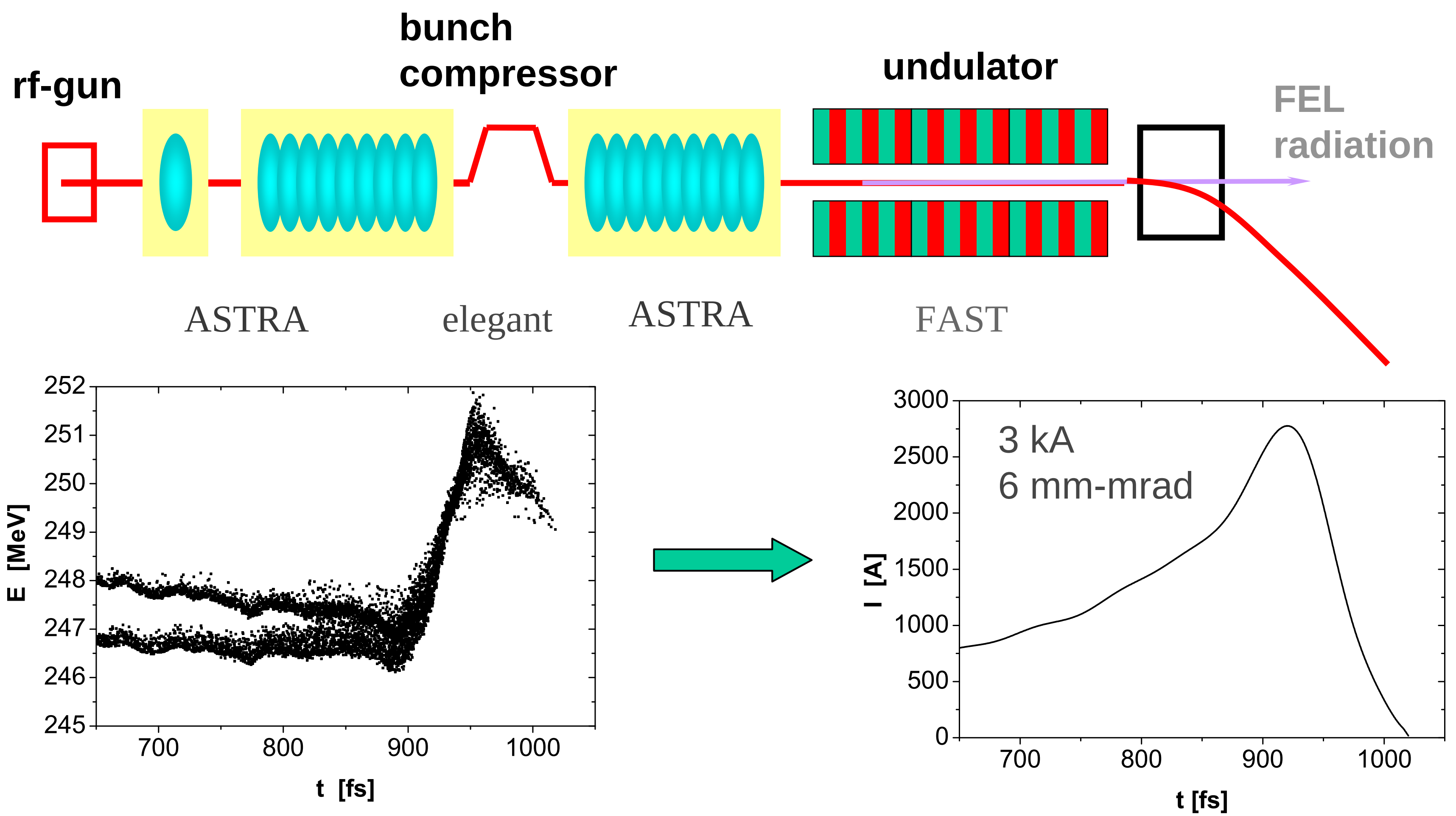
- **Maximum energy of 20 GeV seems to be sufficient for target goal of 0.85-1 Å with project parameters of electron beam and reasonable undulator length.**
- **Main targets for optimization of the electron beam slice parameters are the ratio $\epsilon_n^{5/4}/I^{3/4}$ (approximately, the beam brightness in the transverse phase space), and local energy spread below 1 MeV:**

$$\lambda_{\mathrm{min}} \propto \frac{\epsilon_n^{5/4}}{L_{\mathrm{w}}^{3/2} I^{3/4}} \left[1 + 6 \left(\frac{\sigma_{\mathrm{E}}}{\rho E} \right)^2 \right]^{1/2}$$

- **Reducing of the undulator gap does not provide significant improvement of the FEL performance while the effect of resistive wall wakefields is increased.**
- **Choice of optimum undulator parameters visibly depends on electron beam parameters. Possible gates for uncertainty should be fixed as soon as possible.**

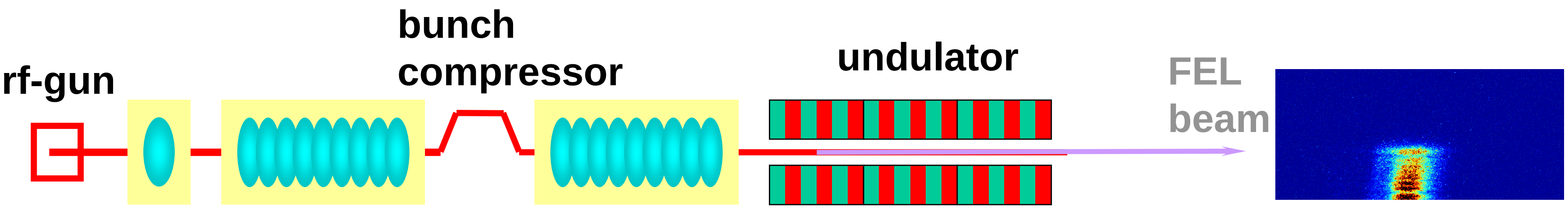
„Full physics“ start-to-end simulations of TTF1:

Reliable base for extrapolation of experience to XFEL design

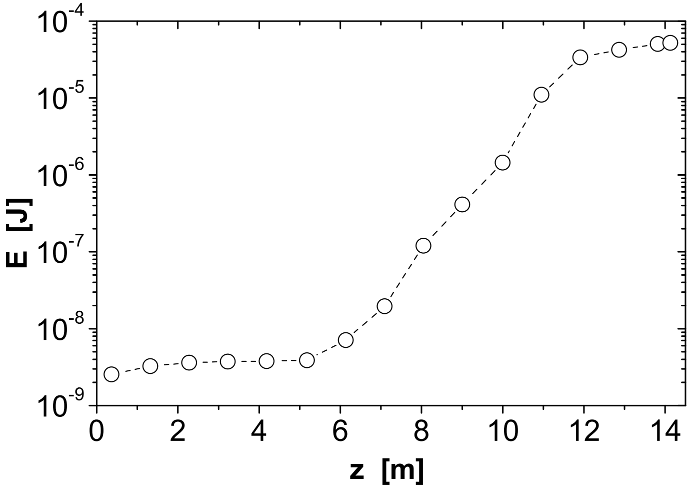


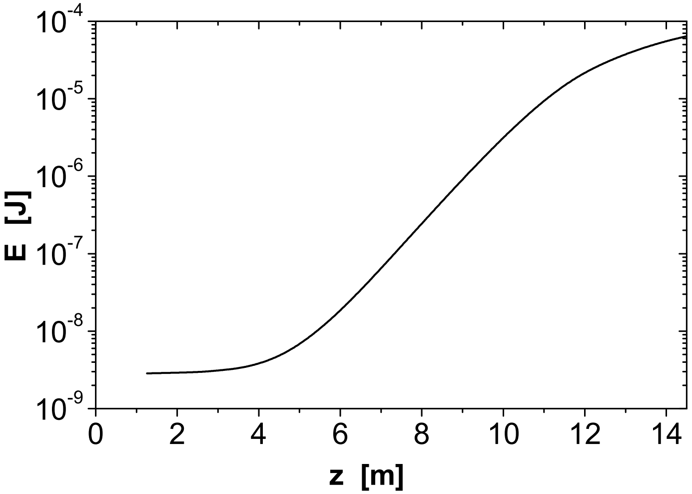
ASTRA (DESY)	- space charge dominated electron beams
elegant (Argonne Natl. Lab.)	- electron beam tracking in BC (including CSR)
FAST (DESY/JINR)	- simulation of SASE FEL

„Full physics“ start-to-end simulations of TTF1:

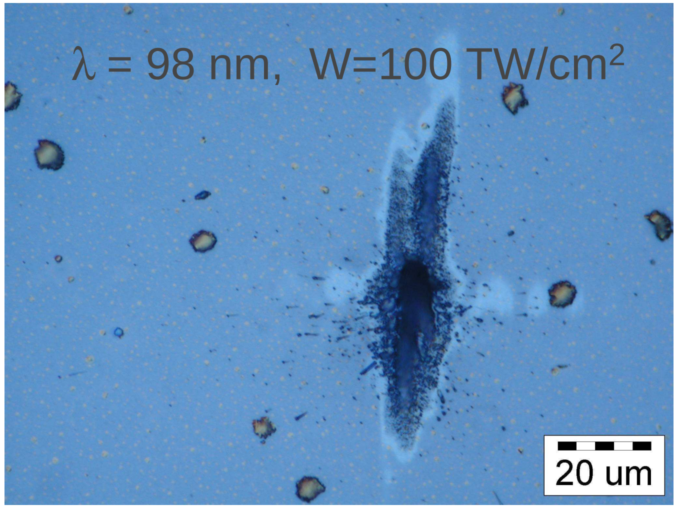


Energy in the radiation pulse





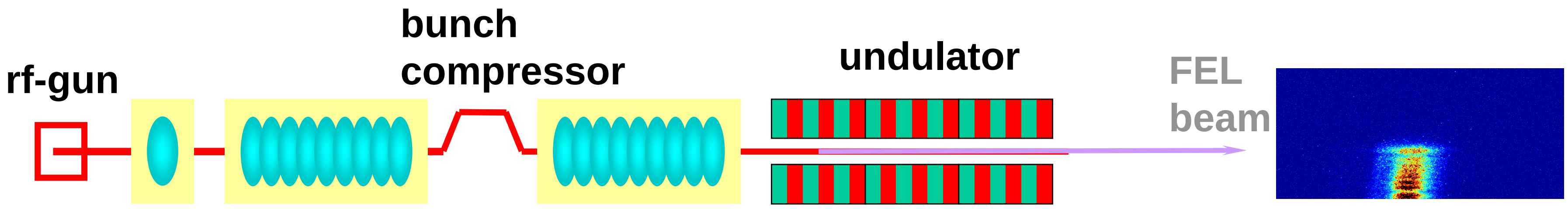
Au film (15 nm) on Si substrate irradiated by a single SASE pulse



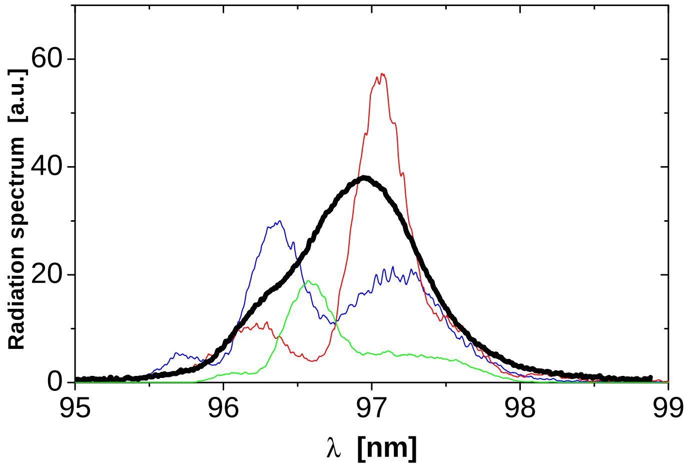
Courtesy to Jacek Krzywinski

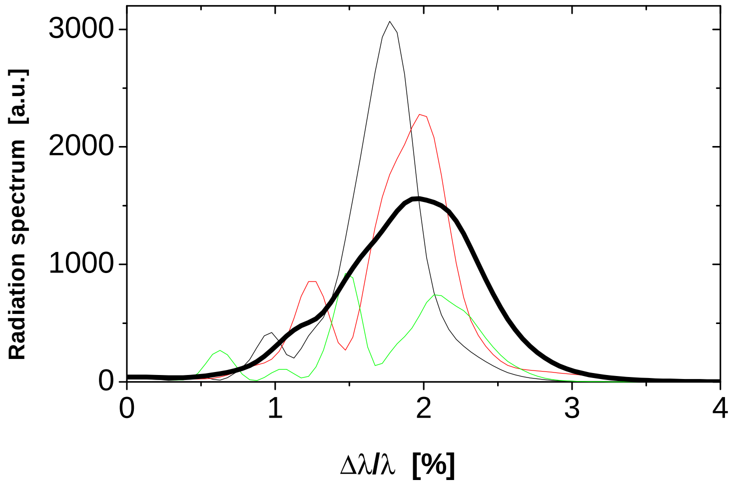
GW-level of output power
in ultra-short (40 fs) radiation pulses

„Full physics“ start-to-end simulations of TTF1:

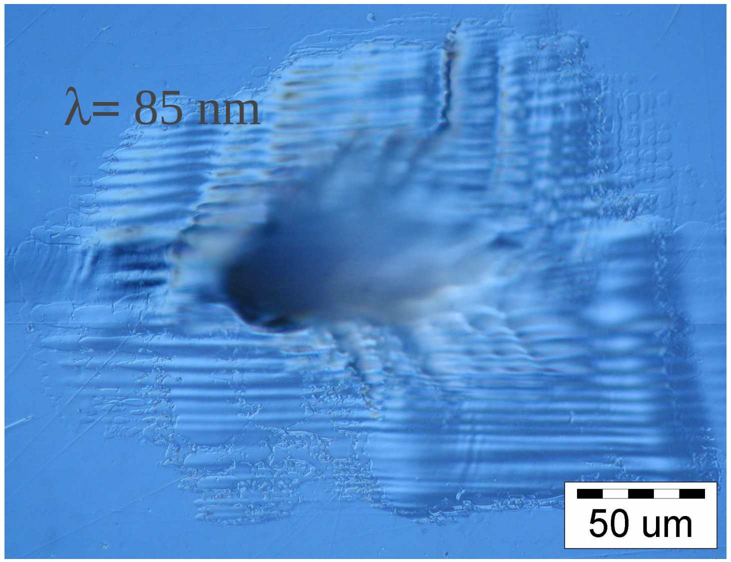


Spectra at saturation





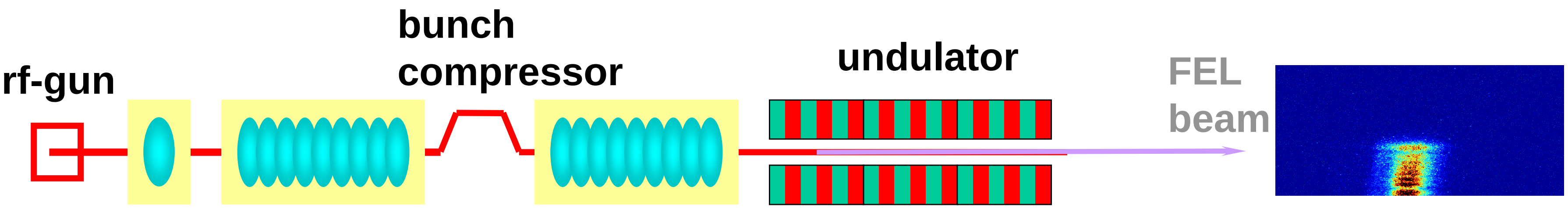
Surface of photoresist PMMA after multiple irradiation by SASE FEL pulses



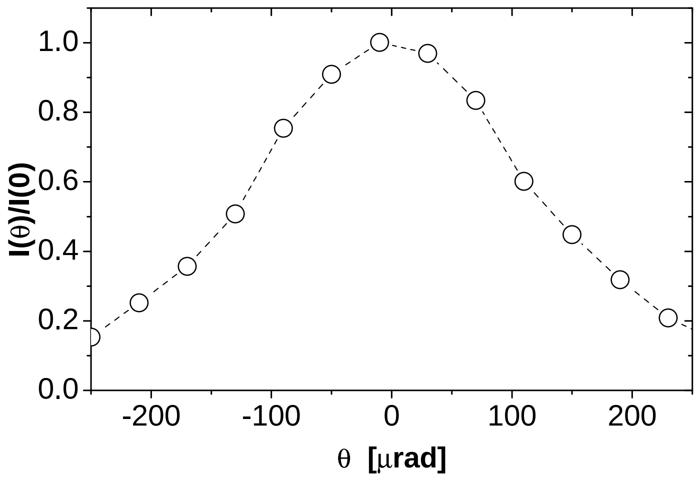
Courtesy to Jacek Krzywinski

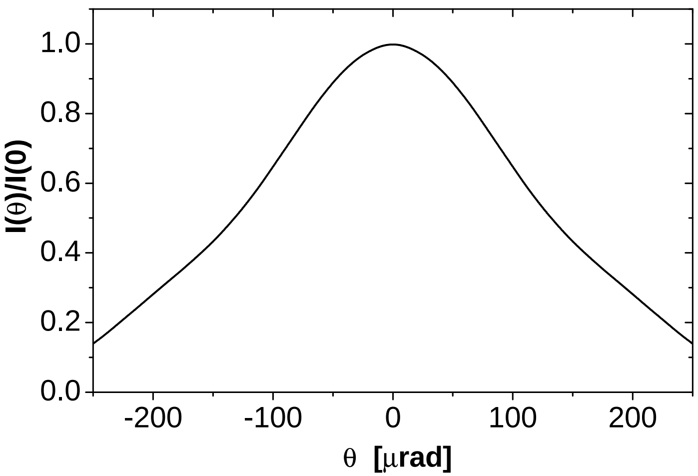
Nearly complete longitudinal coherence

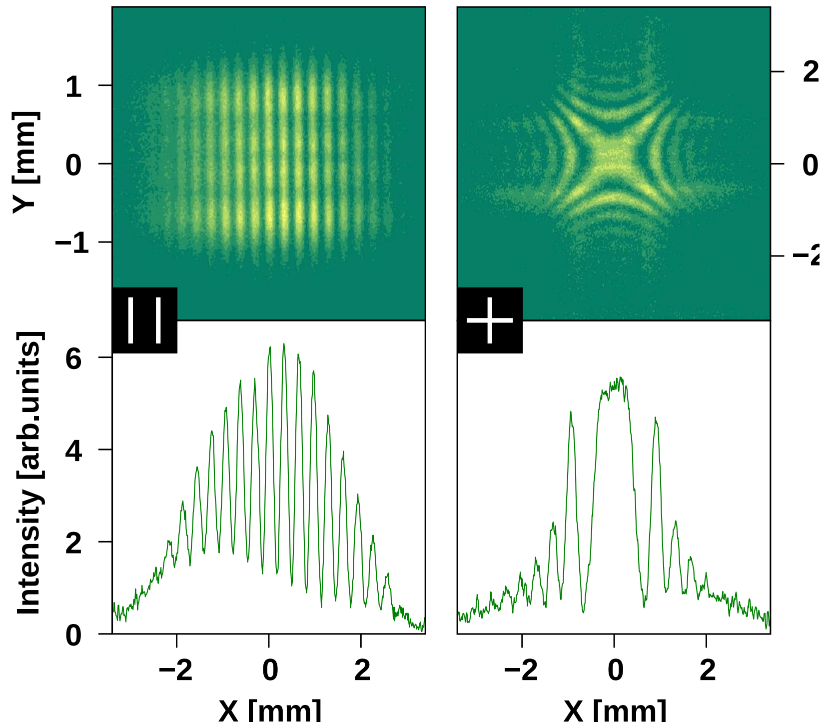
„Full physics“ start-to-end simulations of TTF1:



Angular divergence



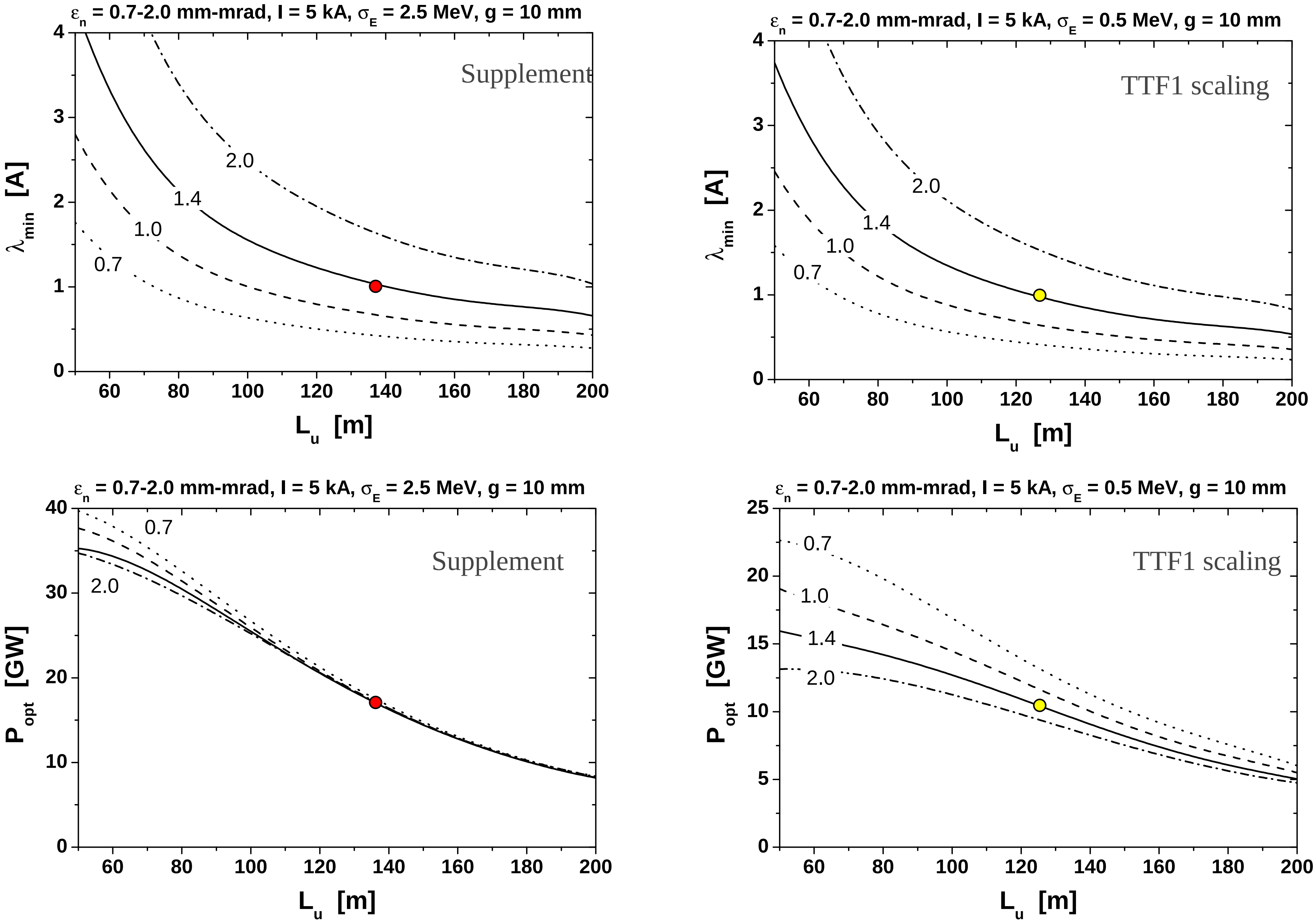




Nearly complete transverse coherence

The end

Overview for peak output power



Overview for project parameters of the electron beam