The challenges of seeded FELs

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What a FEL user is dreaming of...

- Much higher peak brilliance than standard synchrotron radiation sources and full tuneability in the VUV/X-ray spectral region

- Possibility of controlling pulse duration vs energy resolution

- Full transverse and longitudinal coherence of radiation pulse

- High shot-to-shot reproducibility, i.e. :
    - power stability (especially needed for nonlinear experiments)
    - spectral stability (especially needed for energy resolved experiments)
    - point source and pointing stability (especially needed for experiment design)
    - low temporal jitter (especially needed for pump-probe experiments)

Outline

- Introduce **seeded schemes**

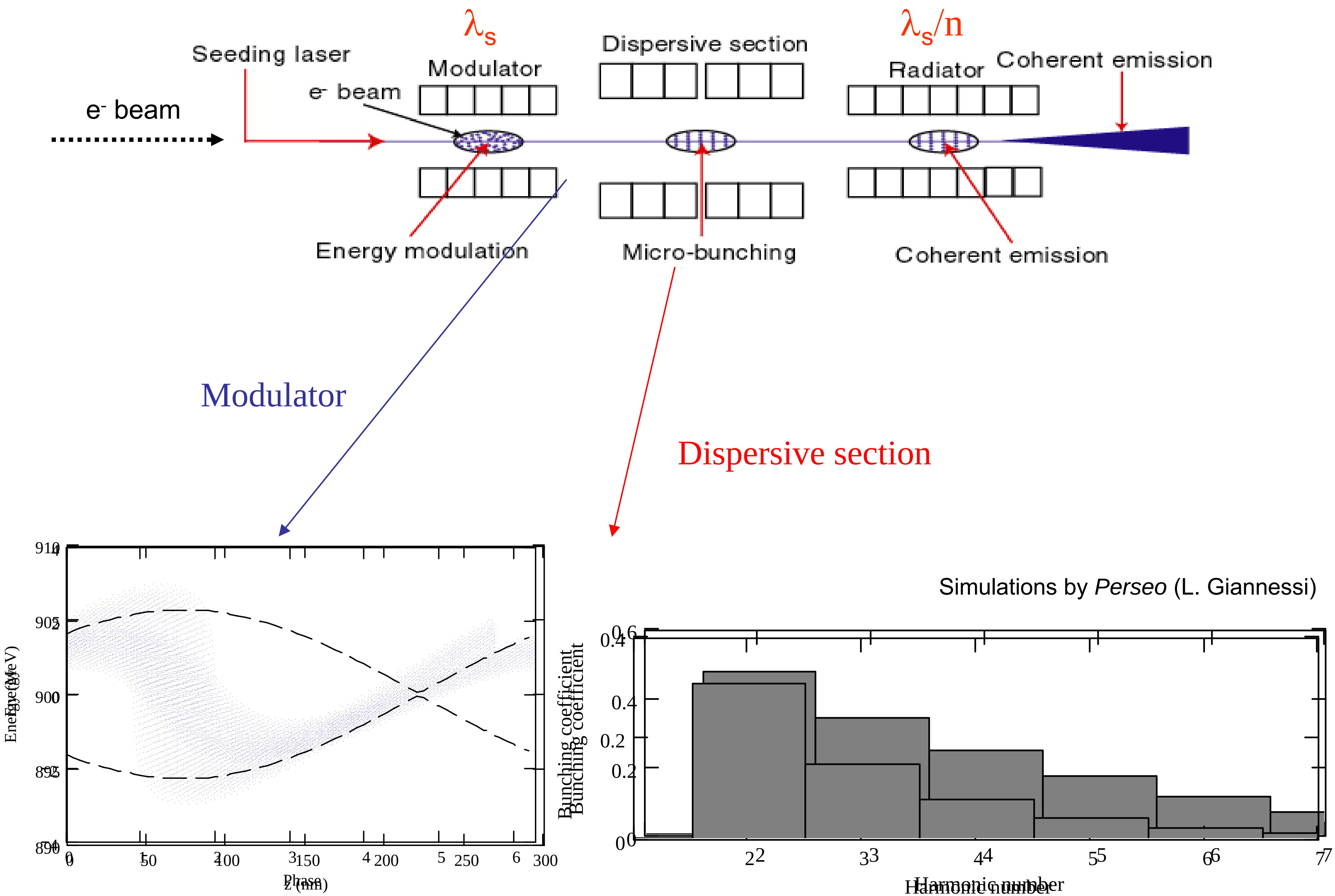
*A major advantage of the High Gain Harmonic Generation FEL is that the output properties at the harmonic wavelength are **a map** of the characteristics of the high-quality fundamental seed laser (L.H. Yu et al., Science 289, 932 (2000))*

- Review of **"basic" requirements** for fourth generation light sources

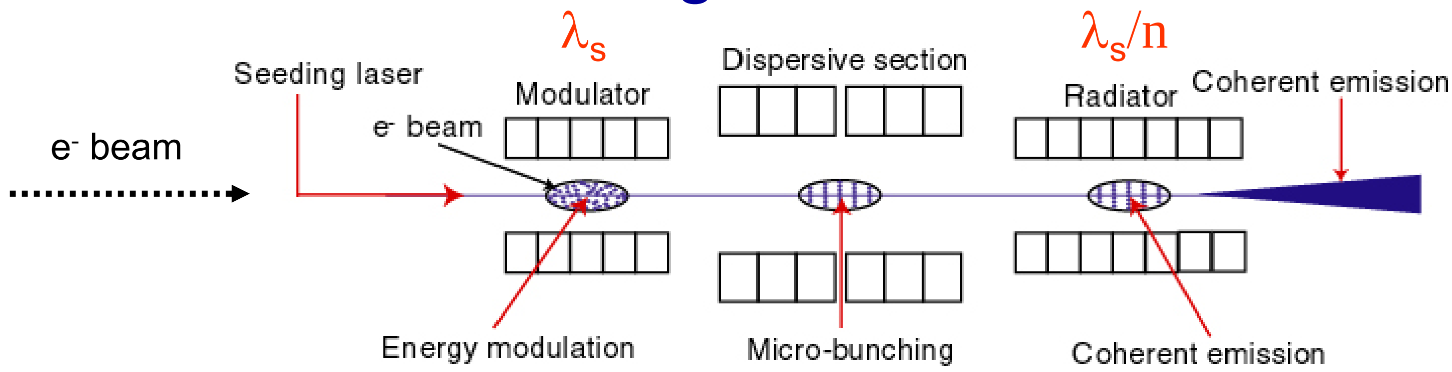
- Review **"advanced" requirements** : <u>control of longitudinal e-beam phase space</u>, <u>minimization of jitter in input parameters and seed-bunch synchronism</u> at undulator entrance

- Conclusion

Seeded harmonic generation: the cascade

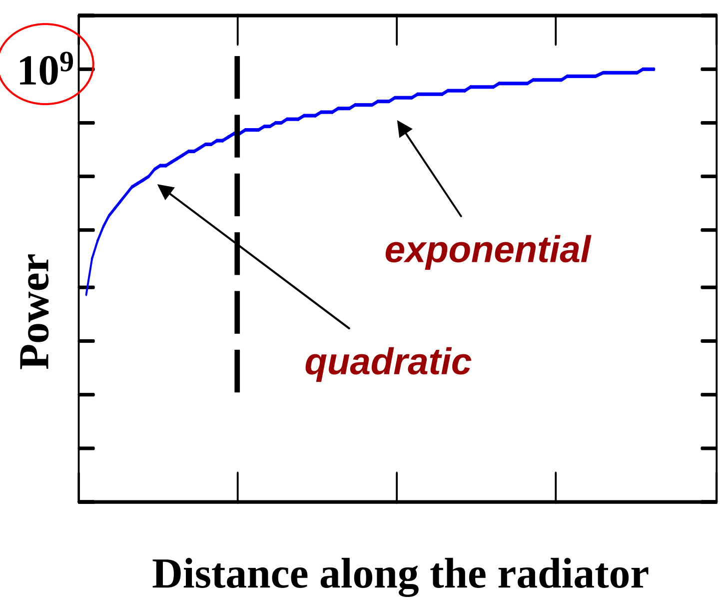


Seeded harmonic generation: the cascade

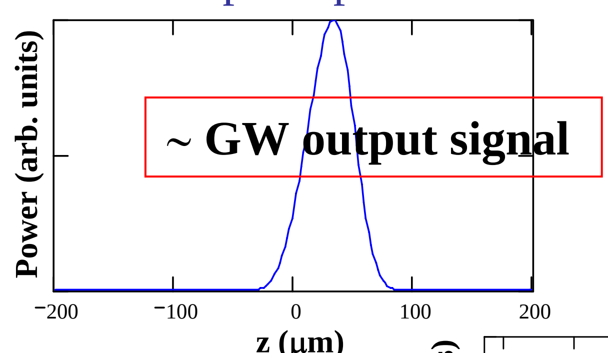


Radiator

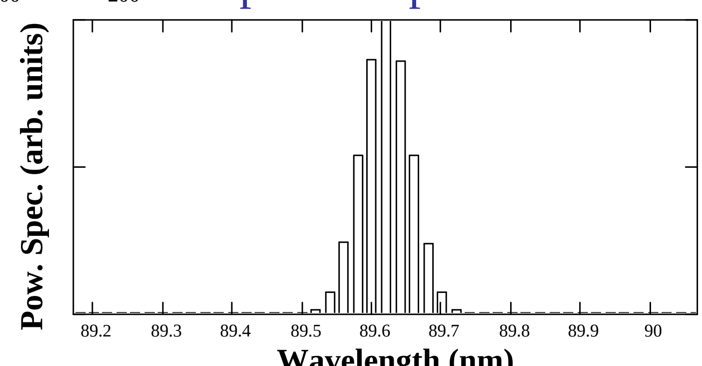
Evolution of the harmonic signal



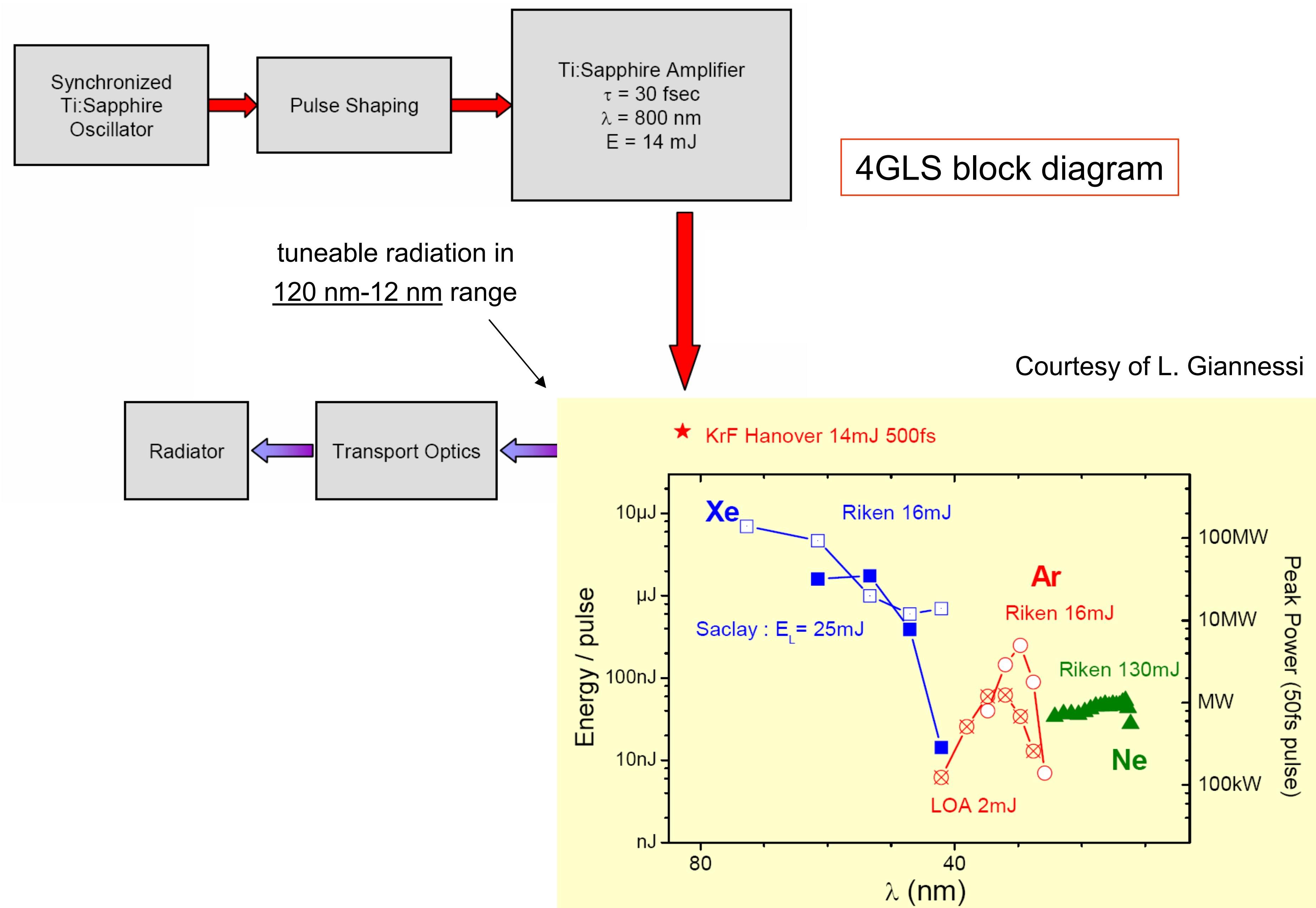
Temporal profile



Spectrum profile

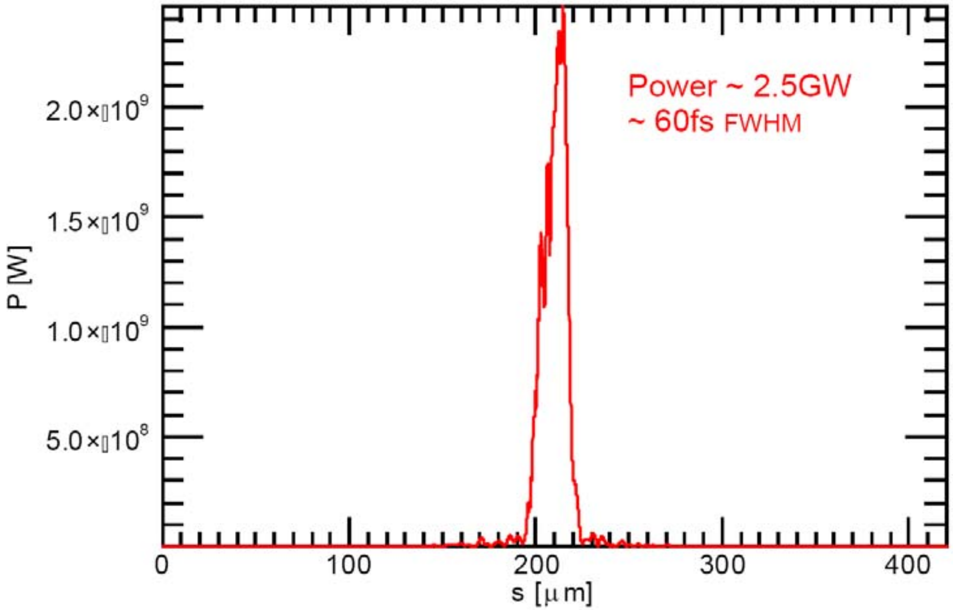


Seeding with high order harmonics generated in gas



Seeding with high order harmonics generated in gas

4GLS output pulse at 12.4 nm



See, B. Mc Neil's talk (this session)

- High harmonic generation in gas is presently limited to short pulses. It is therefore complementary to cascade approach

- Most of the following considerations hold for both configurations

1D "ideal" scaling laws

For an ideal <u>uniform</u> electron beam with zero energy spread and zero emittance linear analysis shows that (*on resonance*) the power grows exponentially along the undulator coordinate. In this case:

$$\begin{cases} P_{sat} = \rho P_{beam} \\ L_g = \dfrac{\lambda_u}{4\sqrt{3}\pi\rho} \end{cases}$$

where

P_{sat}: saturation power

L_g: gain length

P_{beam}: e-beam power

λ_u: undulator period

and

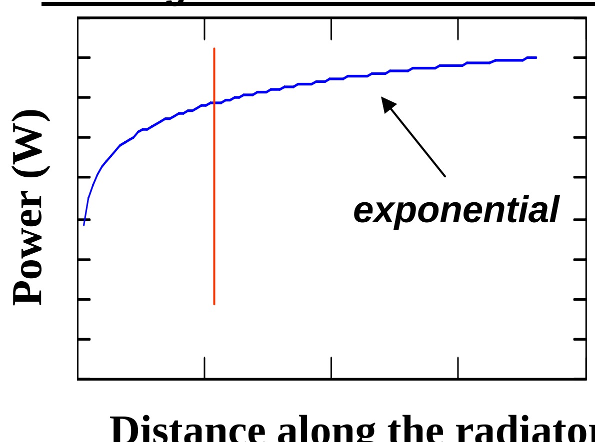
$$\rho \approx \frac{\left(n_{peak}\right)^{\frac{1}{3}}}{\gamma_r}$$

<u>Pierce parameter</u>

This provides the best performance for given n_{peak} and γ_r

The same analysis is approximately valid when the electron beam is initially <u>bunched</u>, as in the case of seeded schemes, and one considers the (later) exponential part of the process.

<u>Power growth in a seeded scheme</u>



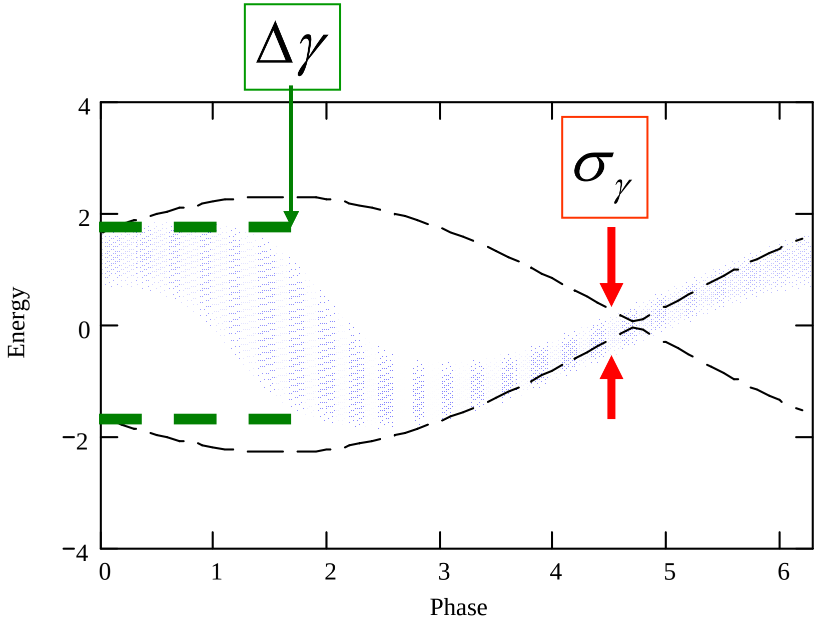
“Basic” electron beam requirement: energy spread

To stay within gain line-width

$$\sigma_{\gamma,tot} < \frac{1}{N_u}$$ low-gain regime

$$\sigma_{\gamma,tot} < \rho$$ high-gain regime

where $$\boxed{\sigma_{\gamma,tot} = \sqrt{\sigma_\gamma^2 + \frac{(\Delta\gamma)^2}{2}}}$$



For effective harmonic generation:

$$\boxed{\Delta\gamma > N\sigma_\gamma}$$

but too small σ_γ leads to SASE growth

$\longrightarrow$ need a compromise

“Basic” electron beam requirement: transverse dimension

Radius of an electron beam
matched to a linear transverse focusing:

$$r_b = \sqrt{\frac{\varepsilon_n \beta}{\gamma_r}}$$

$$\boxed{\rho \approx \frac{\left(n_{peak}\right)^{\frac{1}{3}}}{\gamma_r}} \longrightarrow \boxed{\rho \approx \left(\frac{I_{peak}}{\gamma_r^2 \varepsilon_n \beta}\right)^{\frac{1}{3}}}$$

Emittance

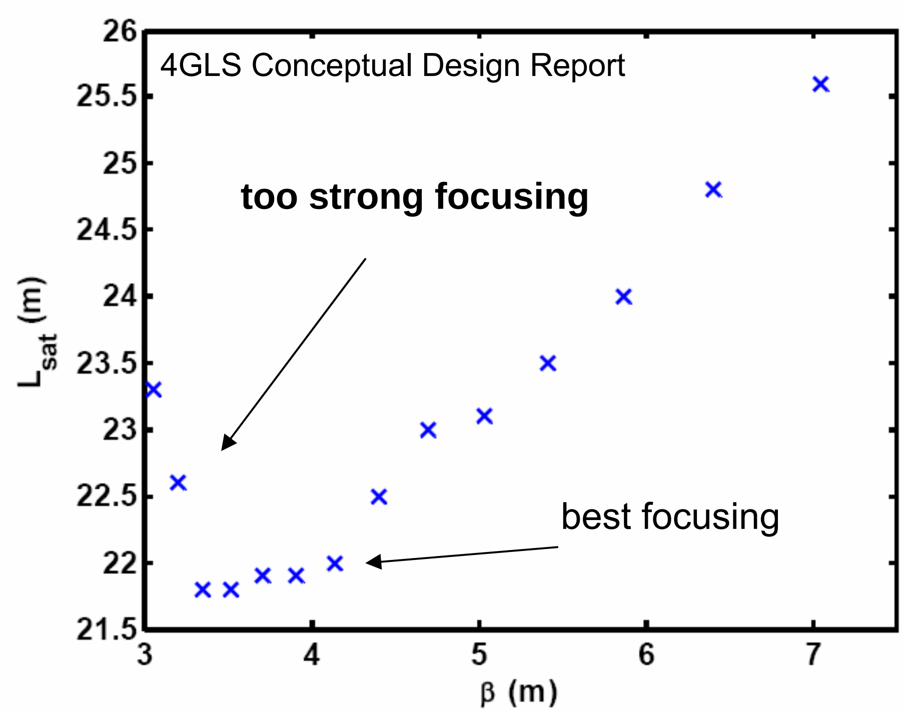
Affects interaction coupling.

Good transverse overlap requires

$$\boxed{\varepsilon_n \leq \lambda}$$

critical at short wavelengths

Focusing



“Advanced” requirements

Requirements on energy spread and e-beam transverse dimensions are not enough for insuring that *the output properties at the harmonic wavelength are* ***a map*** *of the characteristics of the seeding signal.*

The fundamental features the FEL output pulse is supposed to inherit from the seeding signal are longitudinal coherence and shot-to-shot reproducibility. **They rely on**

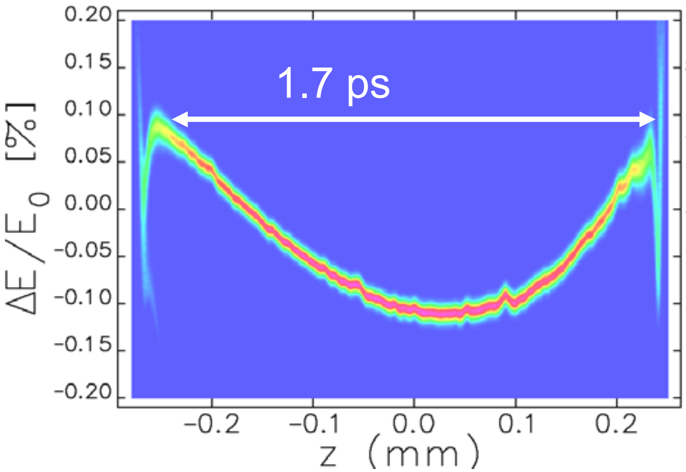
- Control on longitudinal e-beam distributions (i.e., flat phase space, uniform current and energy spread distributions at the undulator entrance)

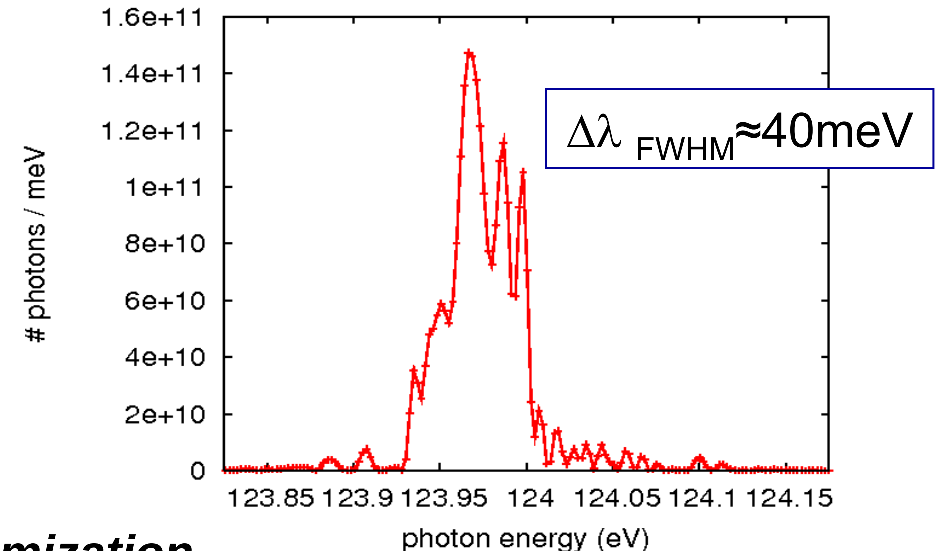
- low jitter of input parameters (e.g., energy, current, energy spread, emittance, seed power, …)

- low seed-bunch temporal jitter

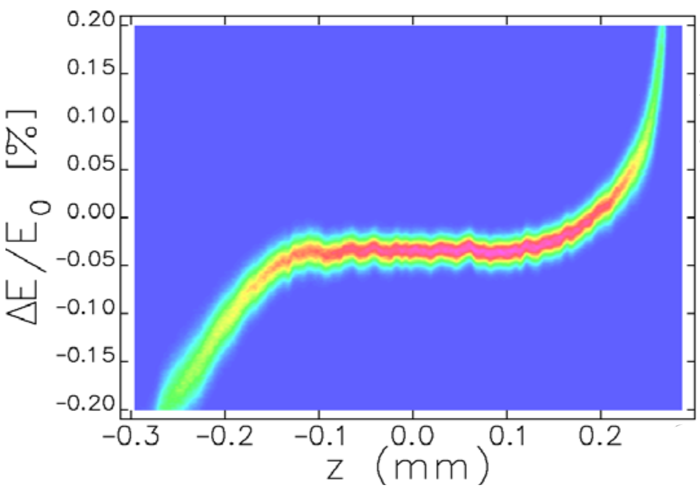
Phase-space homogeneity (FERMI)

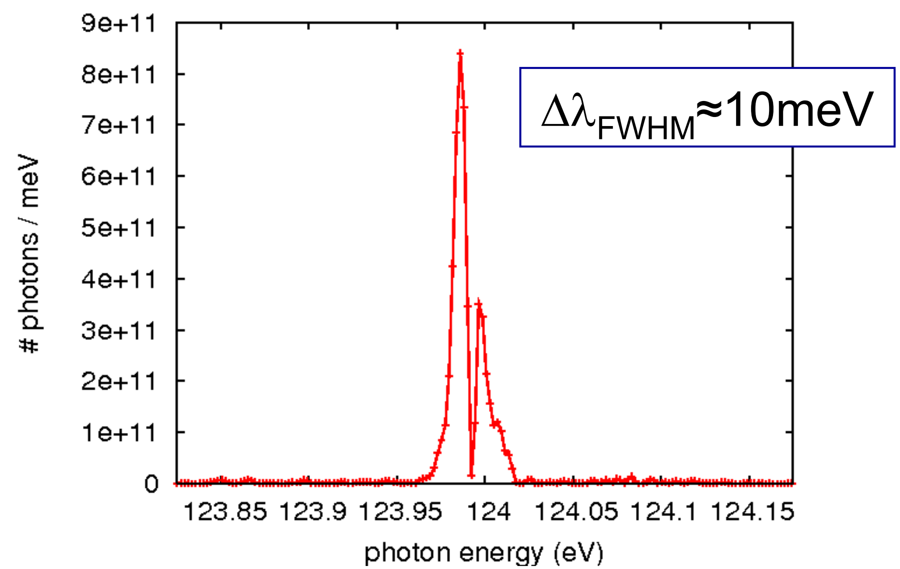
Before optimization



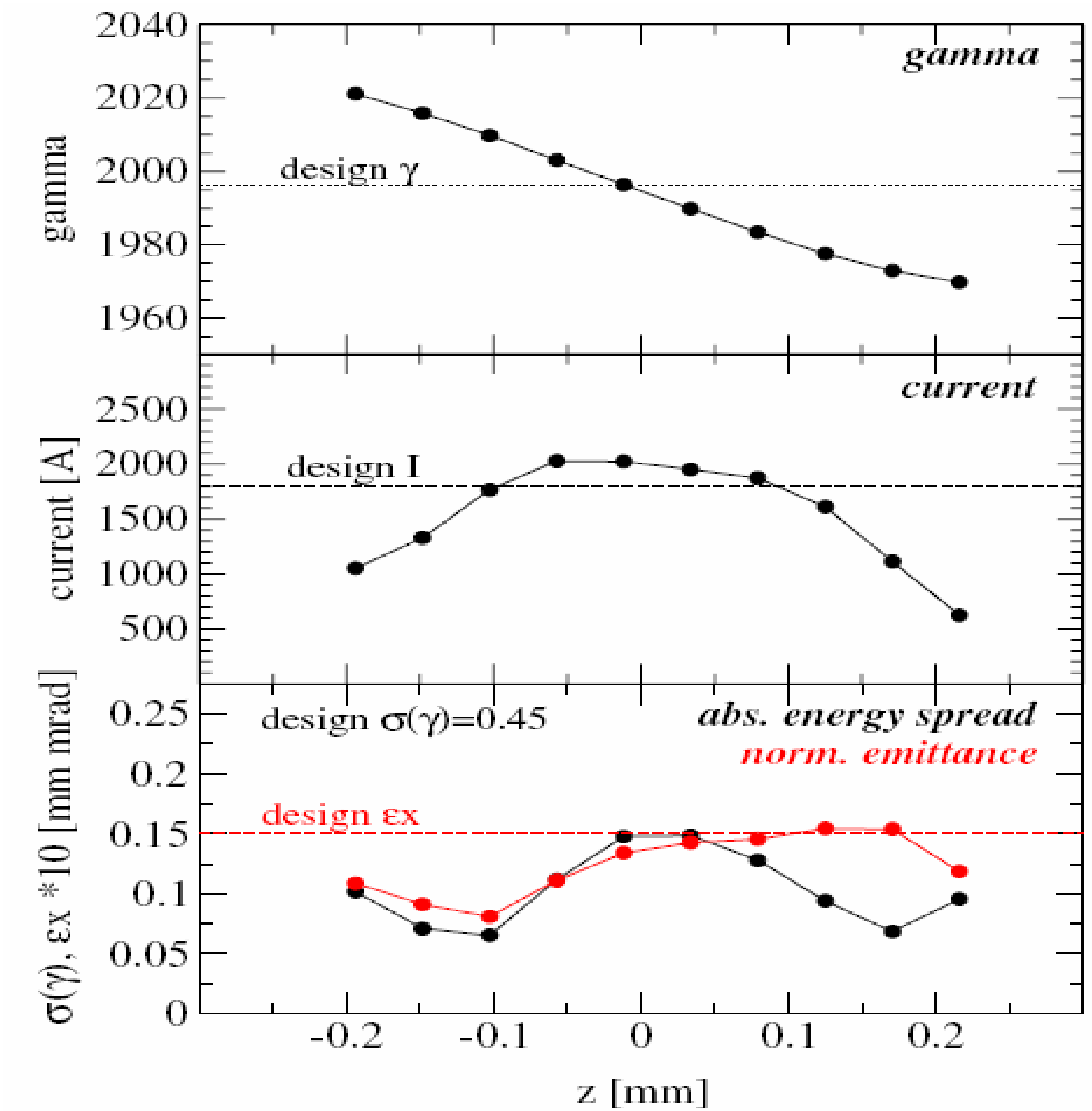


After optimization





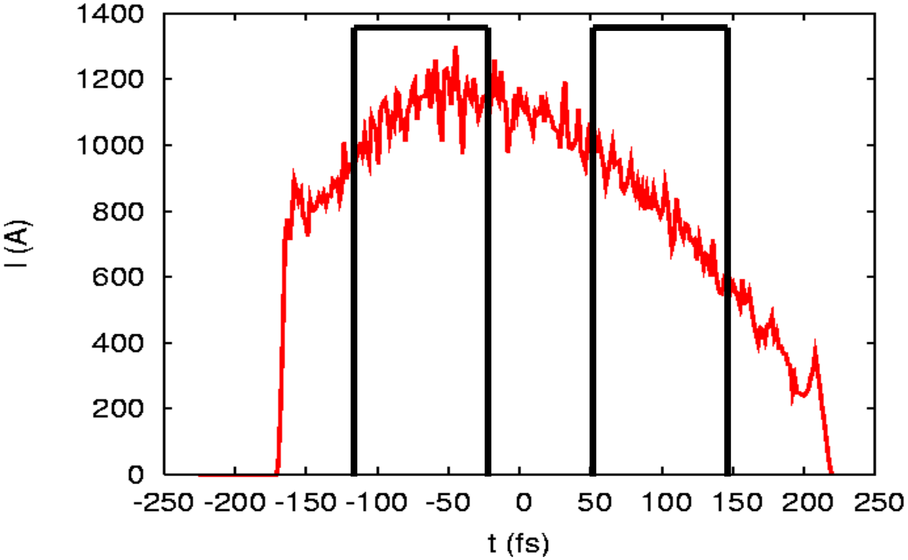
Phase-space homogeneity (Bessy)



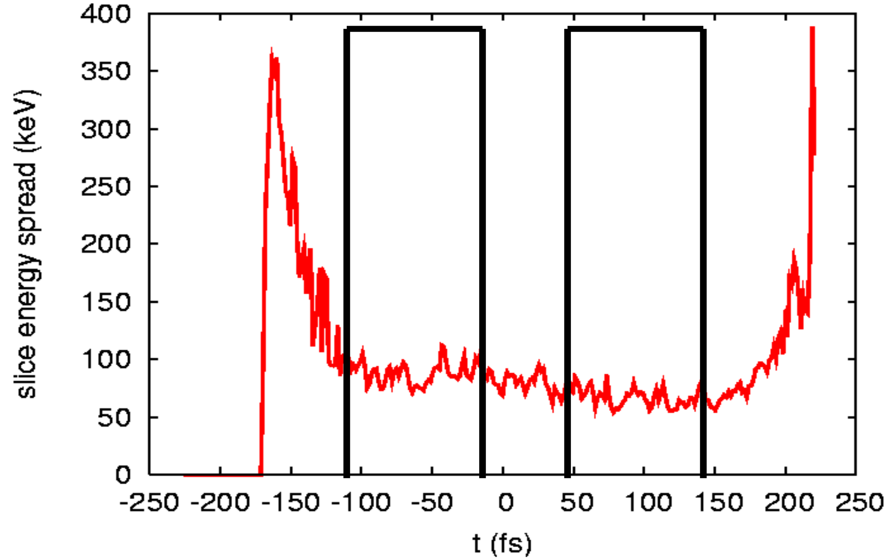
B. Kuske et al.
Proceeding FEL06

Uniformity of current and energy spread profiles (FERMI)

Current

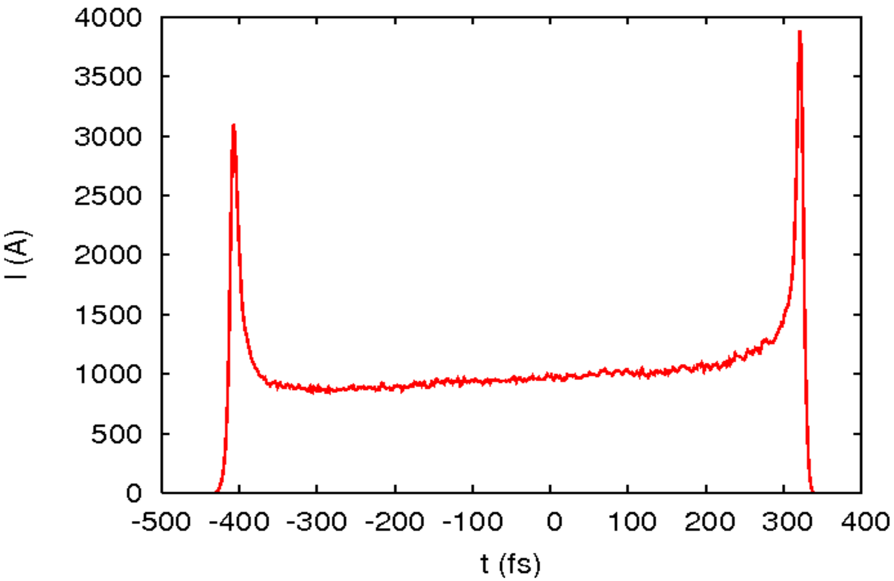


Energy spread

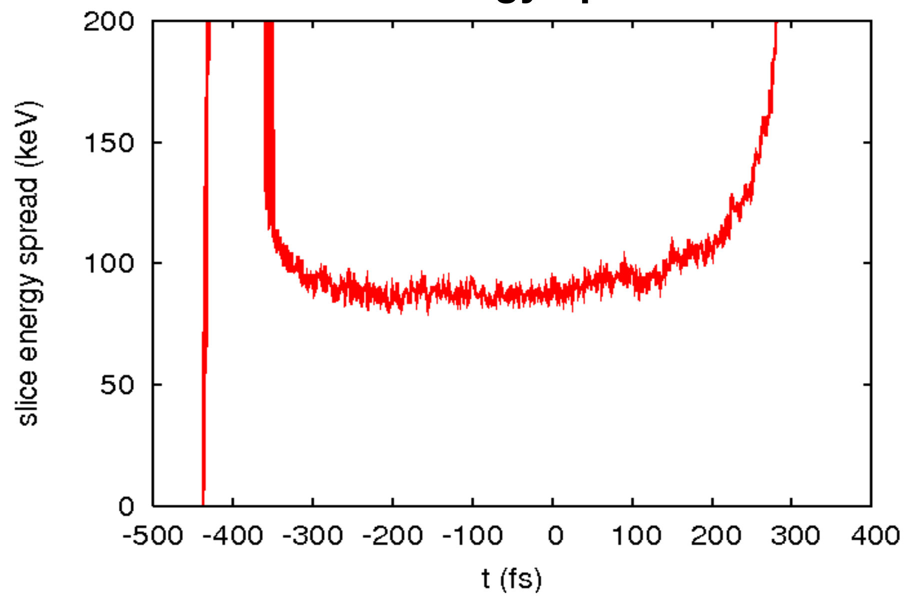


After optimization

Current



Energy spread



Jitter of input parameters

Expected bunch parameter RMS variations at the end of linac extracted from start-to-end time-dependent simulations for **FERMI** and **Bessy-FEL** case

Shot-to-shot variation

Parameter	**FERMI**	**Bessy**	**Bessy** (only time jitter)
Mean energy	**0.1 %**	0.02%	**0.25%**
Peak current	4 %	6%	6%
Emittance	10%	4.5%	9%
Energy spread	10 %	20%	6%
Time offset	**130 fs**	**75 fs**	

- The Bessy-FEL is dominated by variations induced by seed-bunch time jitter (due to non-homogeneous phase space)

- Fluctuation of mean energy and time offset is the most limiting factor for achieving good output stability (see next slides)

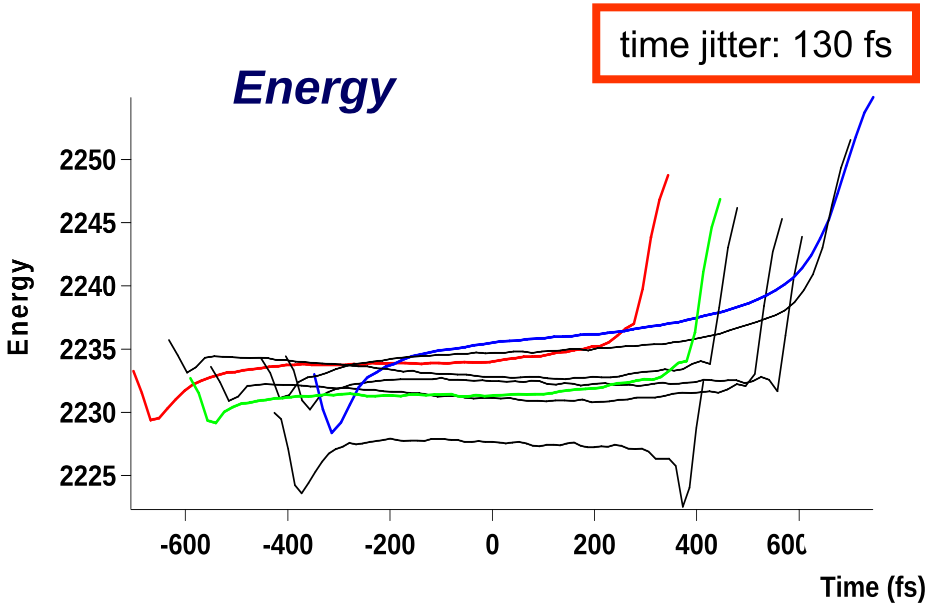
Stability study: the FERMI case

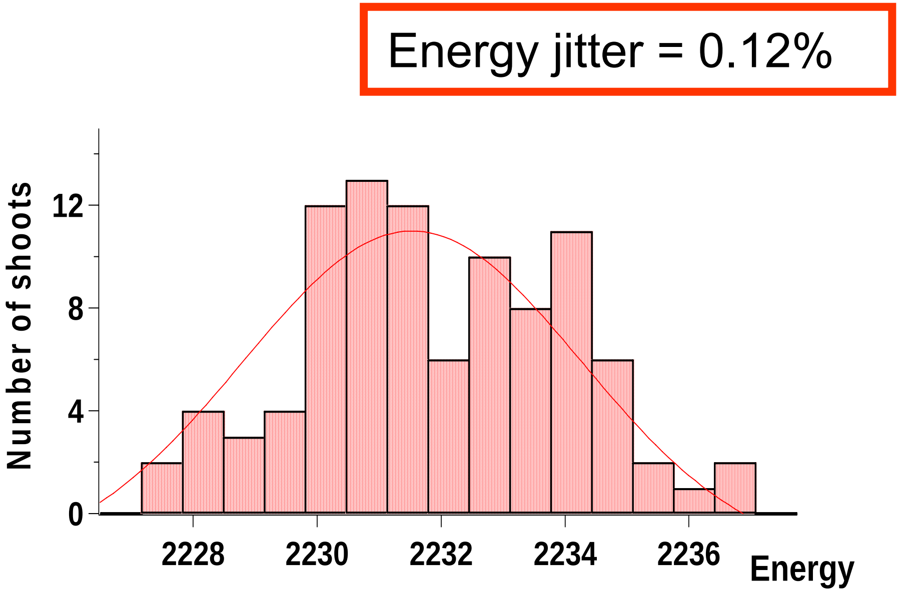
A set of 100 start-to-end time dependent simulations have been performed including errors in the gun and in the linac for the case of FERMI tuned at 40 nm. Nominal values are the following.

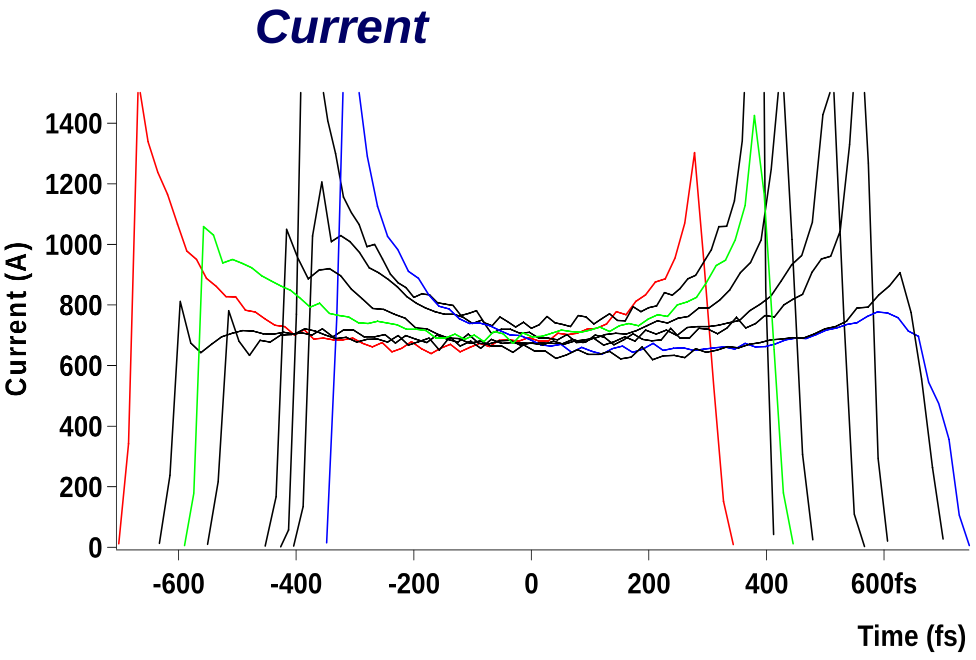
Nominal values

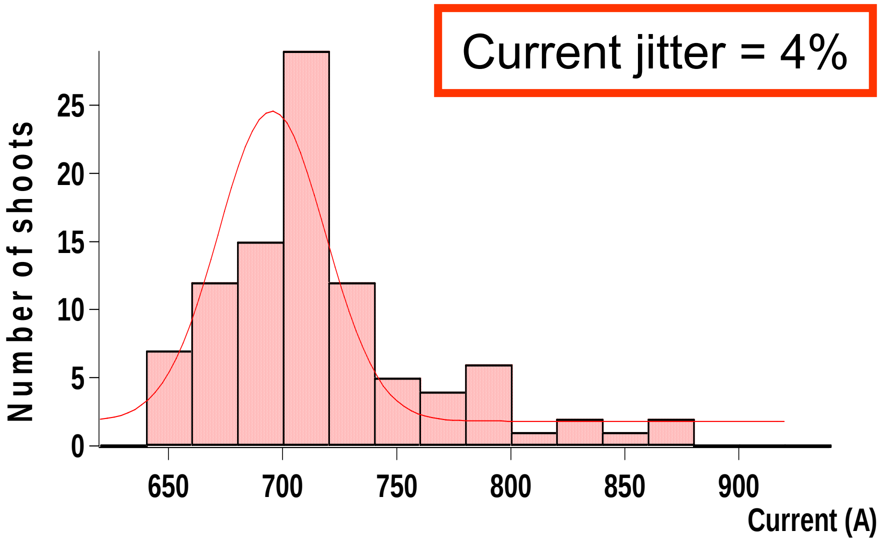
Parameter	*Value*	*Units*
Input Seed power	100	MW
Electron Beam Energy	1.2	GeV
Peak current	800	A
Uncorrelated energy spread (“slice” value)	150	KeV
Norm. Transverse Emittance (“slice” value)	1.5	mm-mrad
Electron Bunch Length (flat portion)	0.6	ps

Energy and current fluctuations

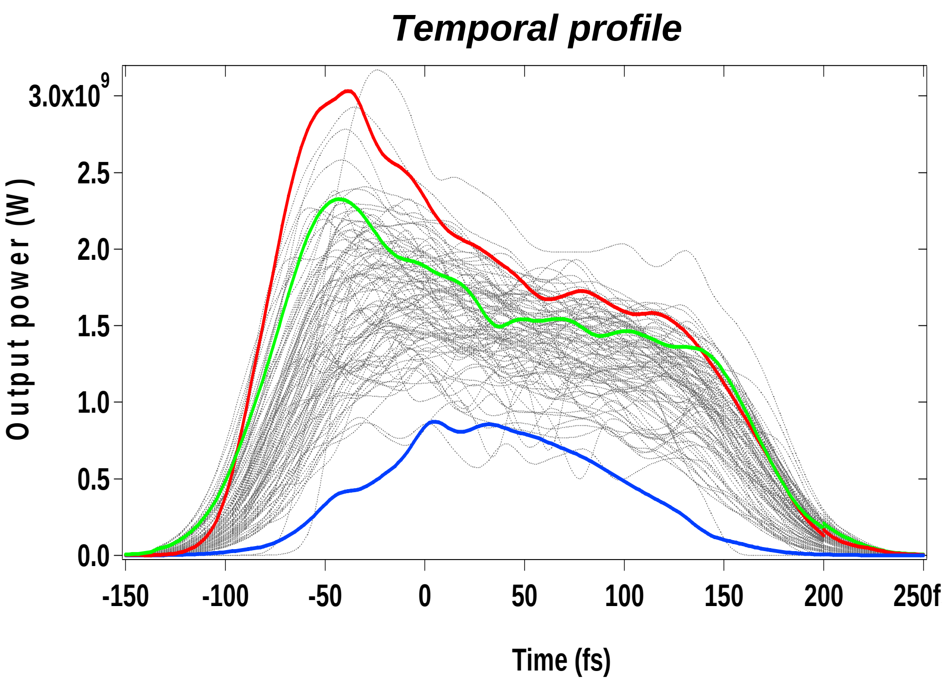


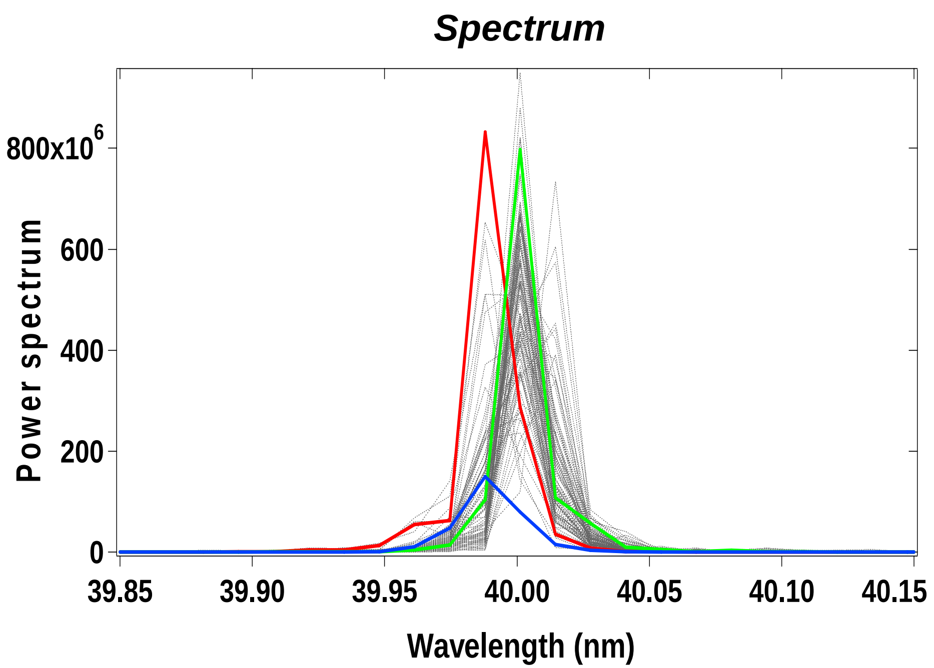






FEL output fluctuations





Average photon number : $4.5 \cdot 10^{13}$

Jitter output photon number **23%**

Average pulse width: 54 fs

Average central wavelength: 40 nm

Jitter output central wavelength: 0.01%

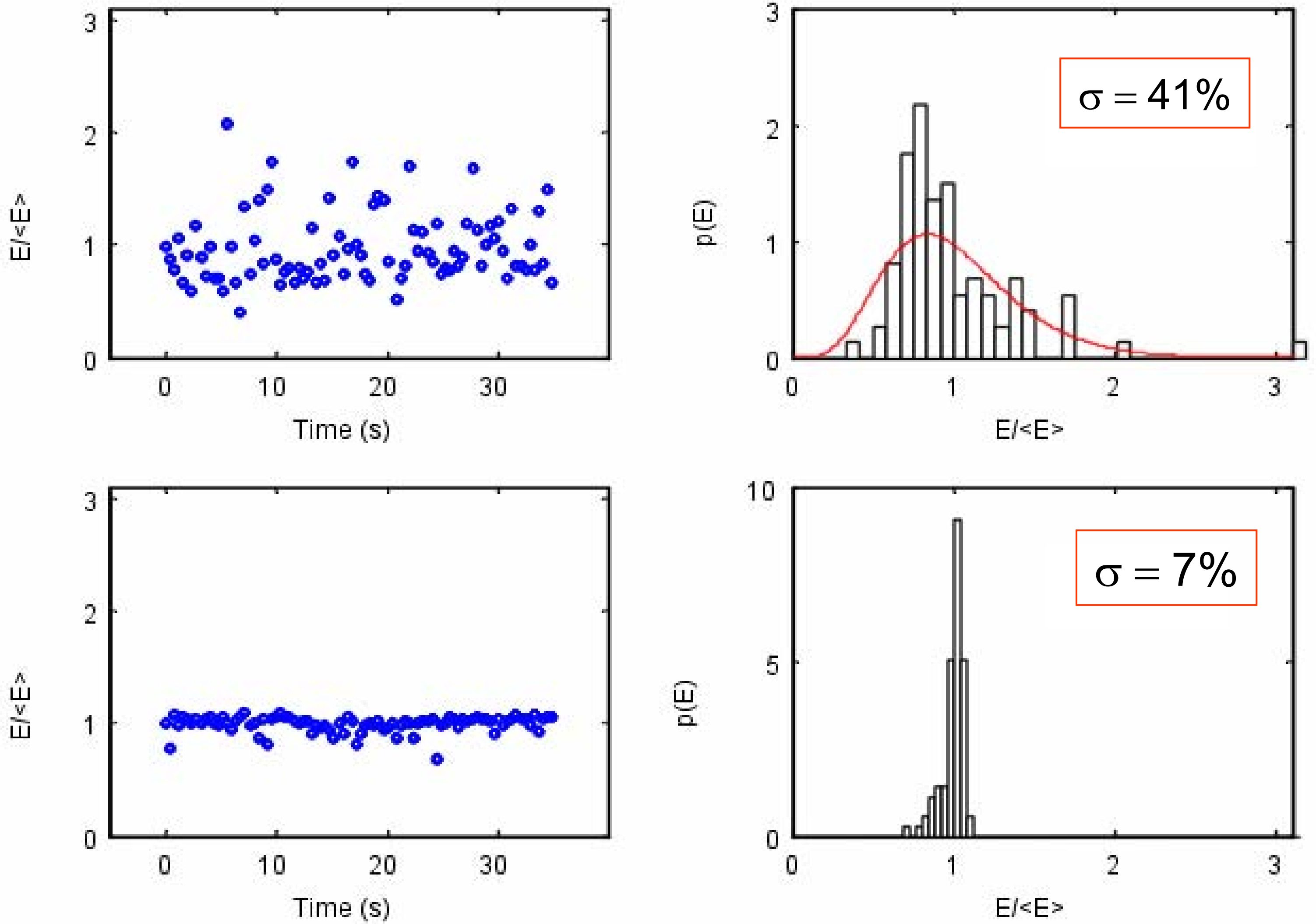
Average bandwidth: 0.03 %

factor ~ 2.2 above transform limit

Shot-to-shot fluctuations at Brookhaven

SASE

Harmonic generation



Conclusions

- High-quality characteristics of the seeding signal are transferred to output FEL pulse only if stringent physical and technological requirements are satisfied. This includes:

- Small normalized (slice) emittance
- Trade-off for incoherent energy spread and transverse focusing
- Good transverse light-electron overlapping over propagation length

- Control on longitudinal e-beam distributions
- Shot-to-shot e-beam reproducibility
- Small seed-bunch jitter

Impact on:

Longitudinal coherence

Shot-to-shot FEL fluctuations