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Mitigation of Microbunching Instability for Improved FEL Spectral Brightness

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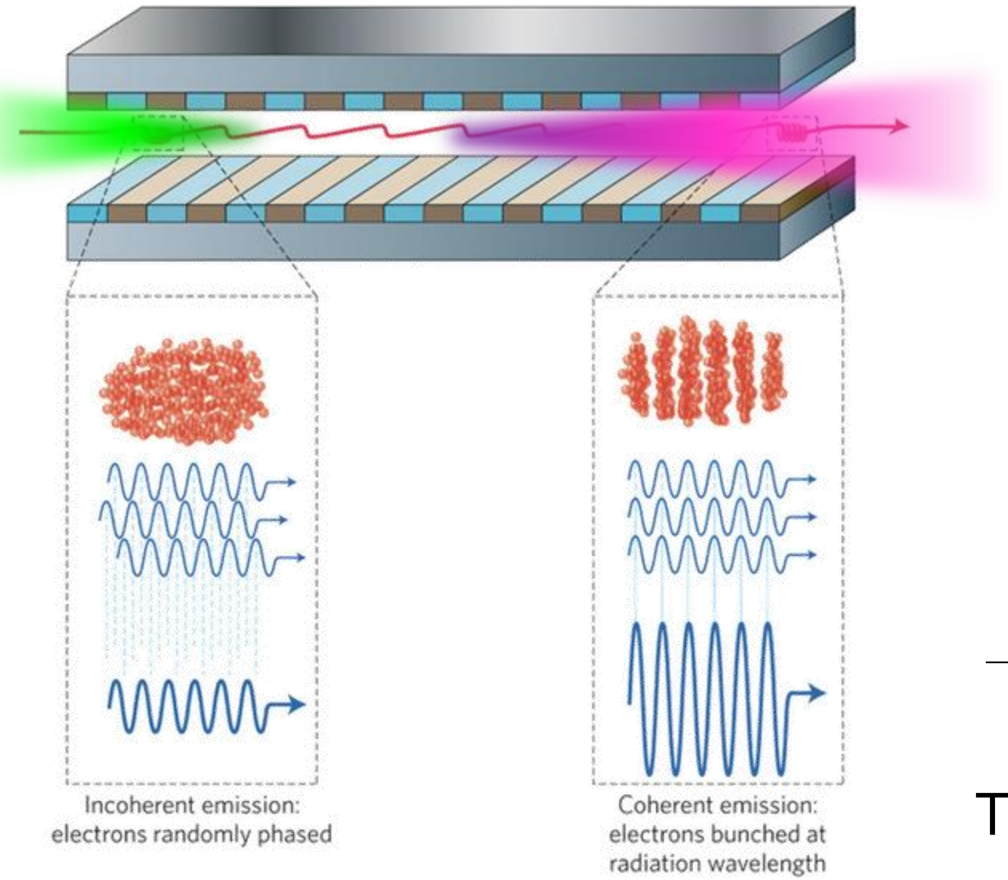
Prologue & Acknowledgment

- Focused on experimental tests, conducted at/in collaboration with: LCLS (SLAC), ATF (BNL), SwissFEL (PSI), SXFEL (SINAP), ASTeC (STFC), ASML, FERMI (Elettra),…
- Instability control through e-beam optics – an open path of research.

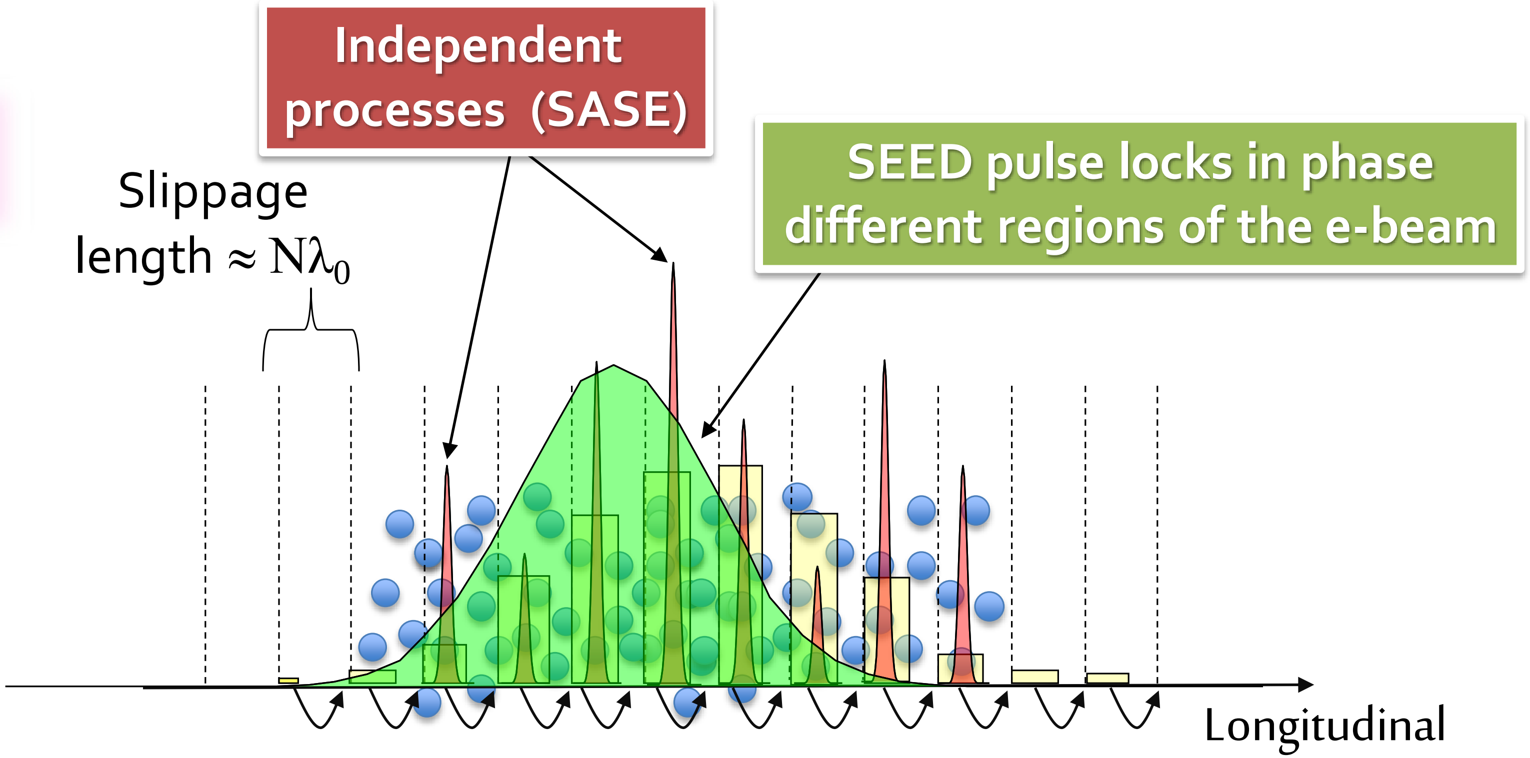
Contributions, guidance and support from: D. Ratner, G. Marcus, S. Bettoni, C. Feng, A. Gover, W. Fawley, M. Venturini, R. Li, P. H. Williams, A. Wolski, I. Setija, E. Roussel, L. Giannessi, S. Spampinati, and the FERMI team.

Special thanks to: C.-Y. Tsai (JLAB/HUST), A. Brynes (STFC, Univ. Liverpool), G. Perosa (Univ. Trieste)

Longitudinal coherence in FELs



B. McNeil, N. Thompson, Nat. Phot. 4 (2010)



The radiation "slips" over the electrons of a distance $N\lambda_0$

Motivations

❑ Femtosecond-resolved RIXS:

probe the evolution of low energy electronic excitations in **correlated materials.**

❑ Nonlinear X-ray optics:

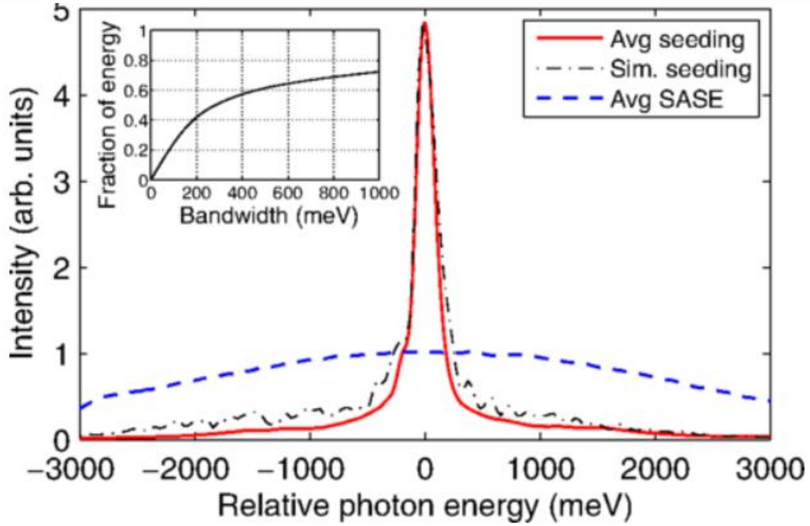
measuring **disordered systems** with higher **sensitivity** than conventional linear spectroscopy

❑ X-ray attosecond science:

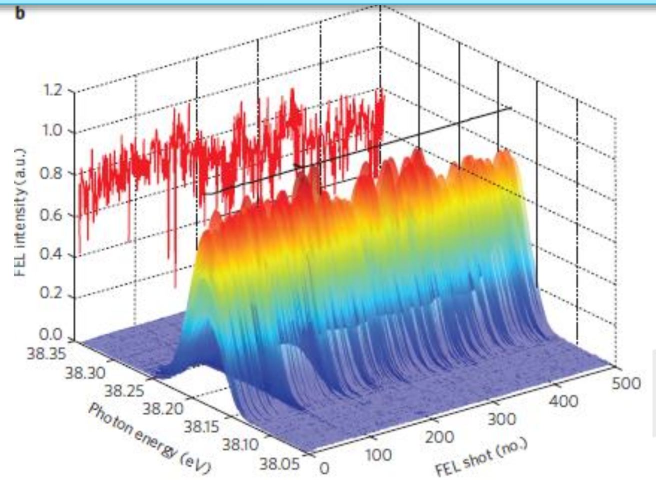
coherent phase control to build attosecond pulse trains

D. Ratner et al., PRL 114 (2015)

GW's peak power at the Fourier limit



Stable single spectral line



E. Allaria et al., Nat. Phot. 6 (2012)

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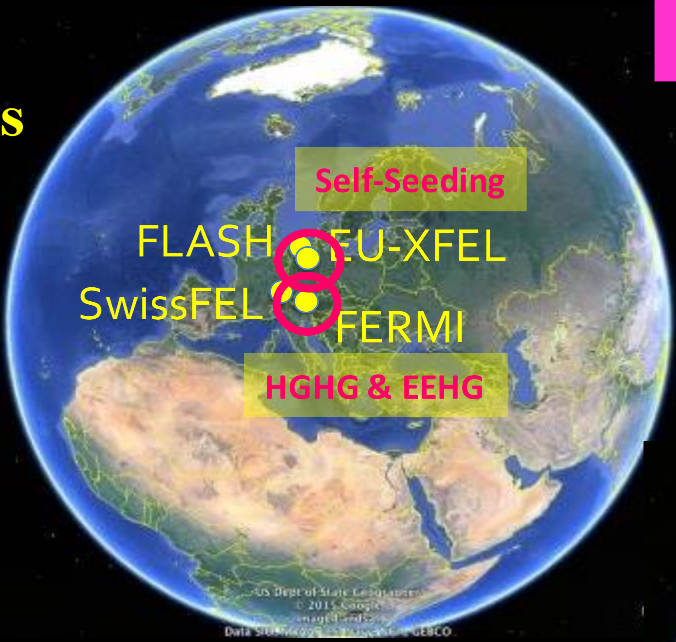
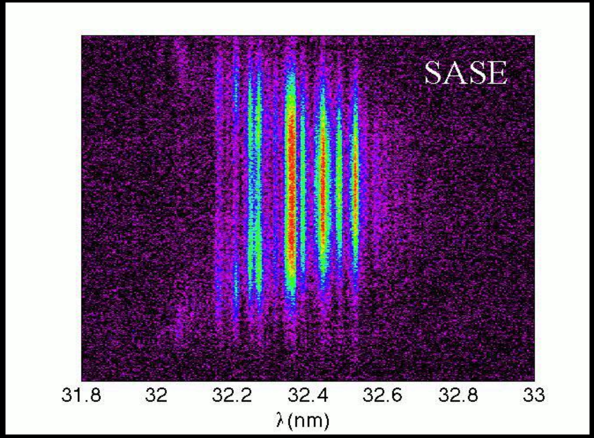
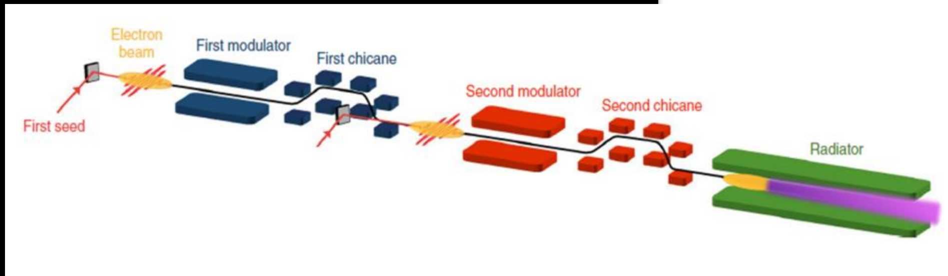
Facilities

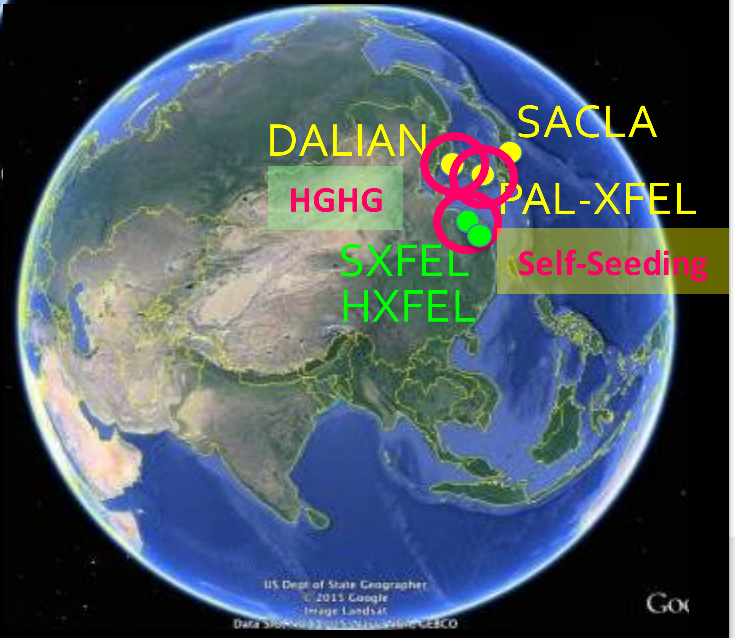
Existing and planned UV & X FEL user facilities





Longitudinal coherence





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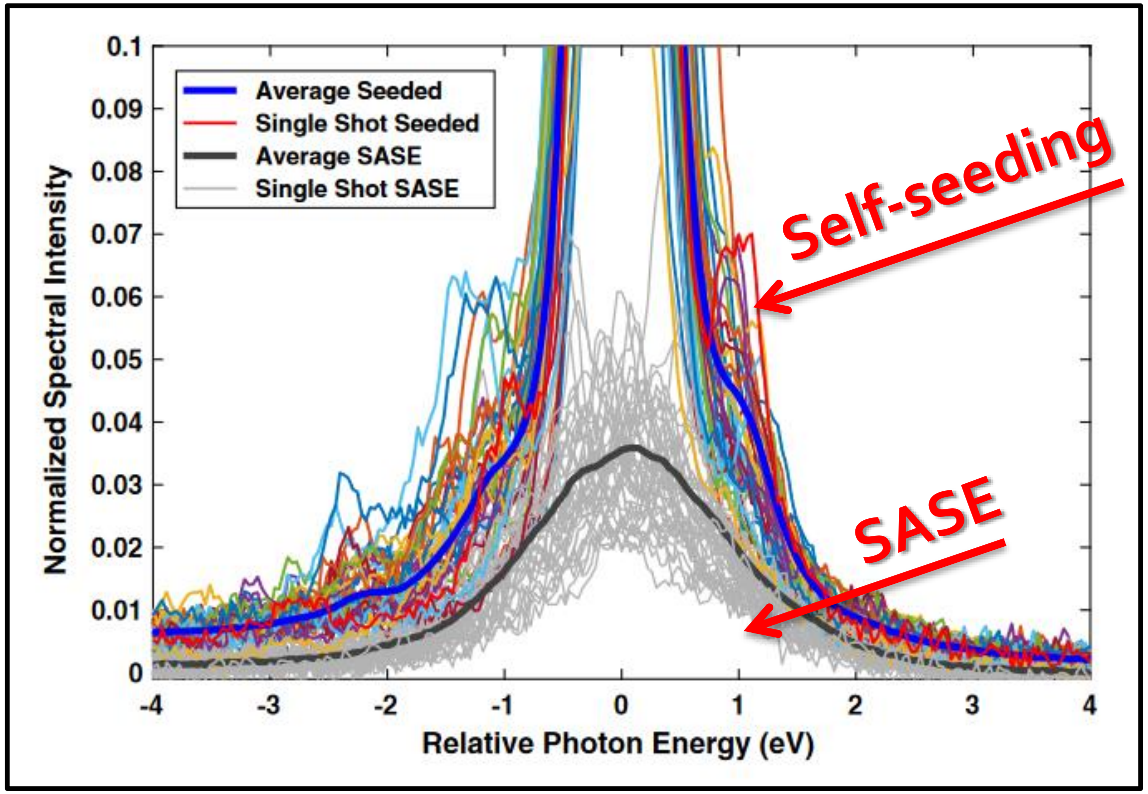
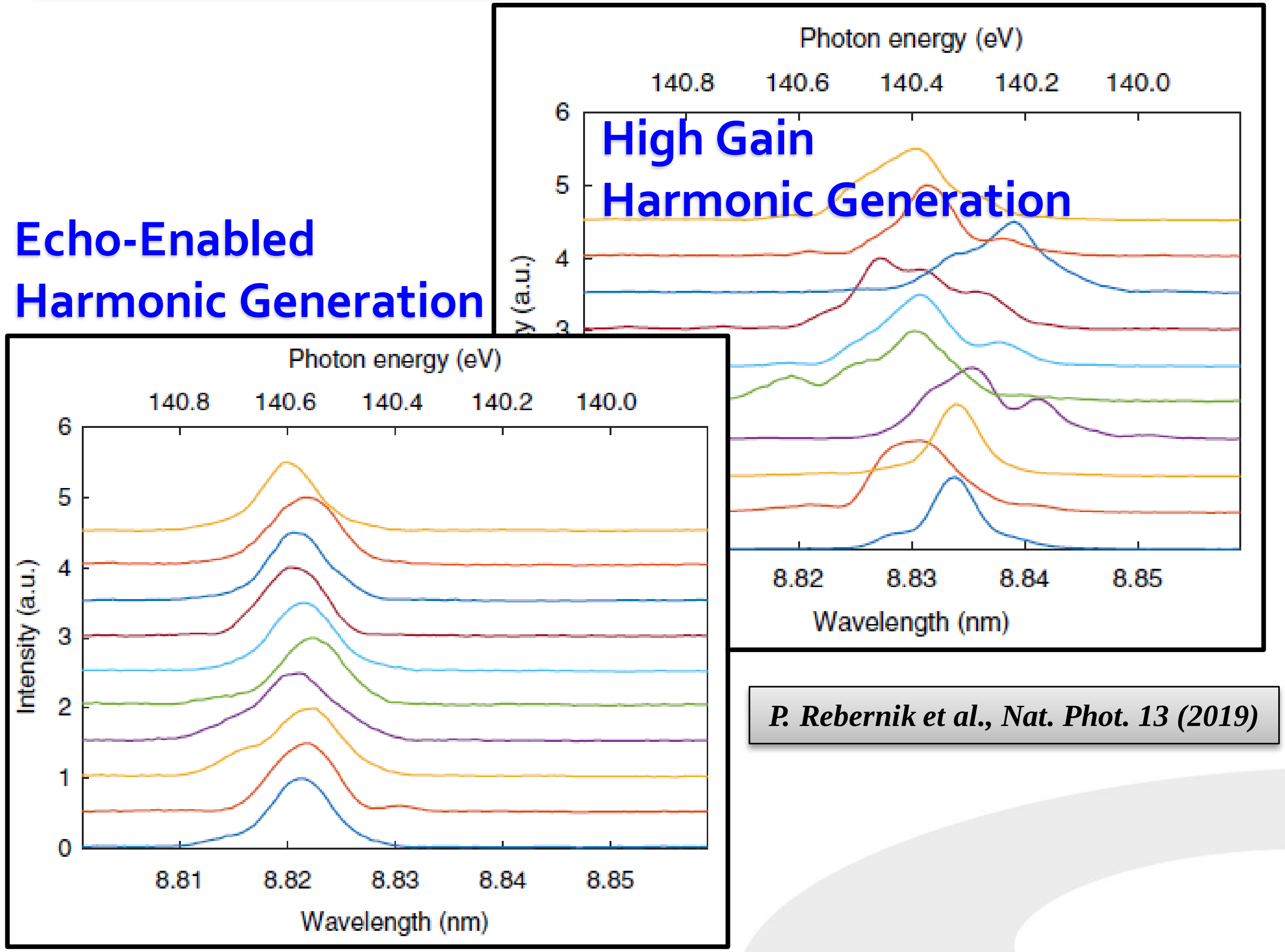
Spectral broadening in seeded FELs

FEL spectrum at LCLS: *SX-SS*



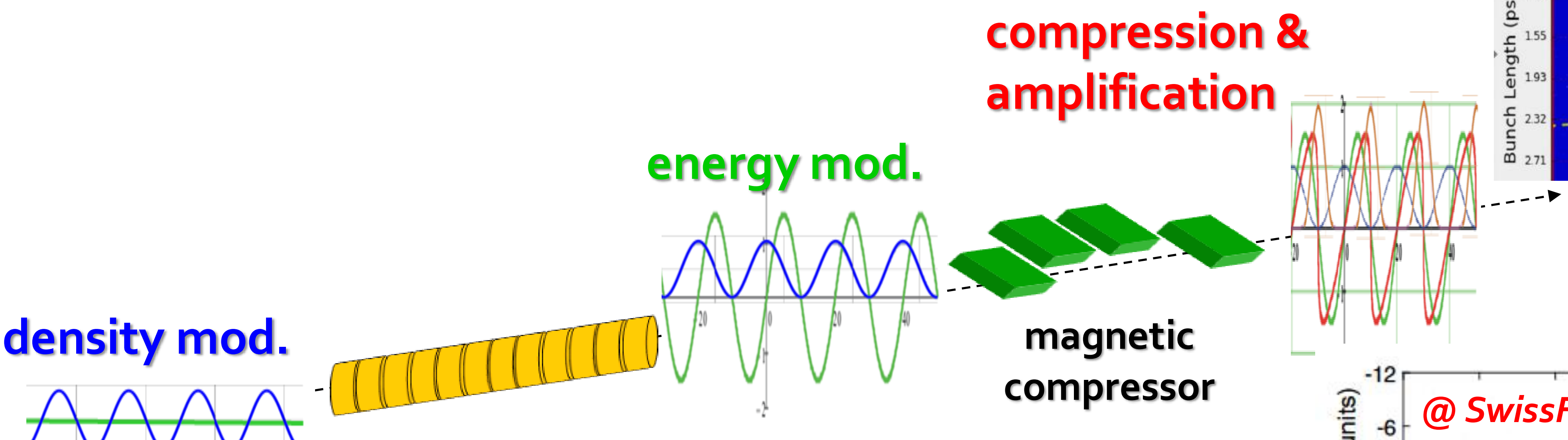
G. Marcus et al., PRAB 22 (2019)

FEL spectrum at FERMI: *HGHG, EEHG*

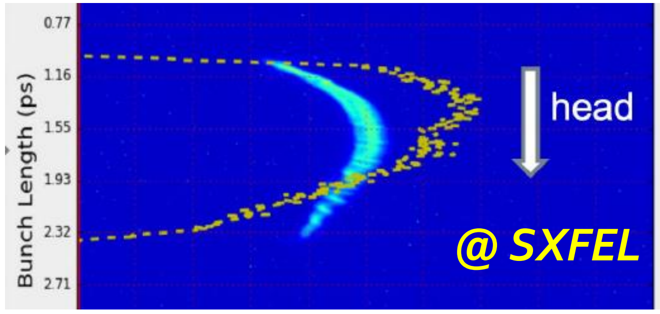


P. Rebernik et al., Nat. Phot. 13 (2019)

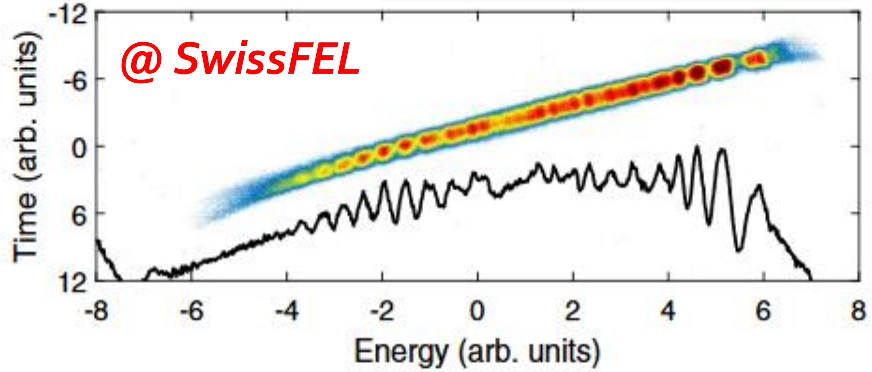
Microbunching instability



Courtesy C. Feng



S. Bettoni et al., PRAB 23 (2020)

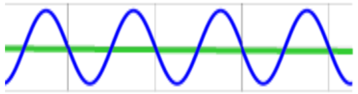


Microbunching instability

Peak at $\frac{r_b k}{\gamma} \simeq 1$

$\lambda \sim 1 - 10\ \mu m$

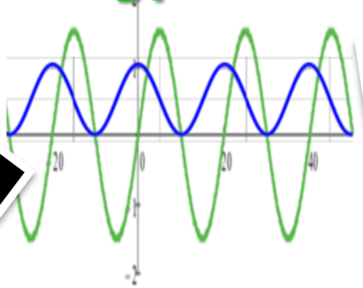
density mod.



LSC

linac

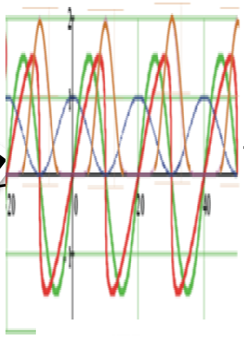
energy mod.



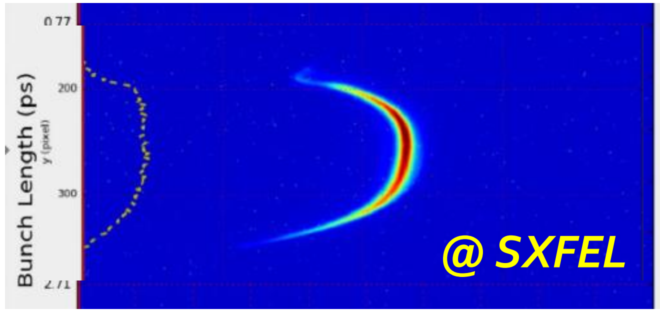
R_{56}, CSR

magnetic compressor

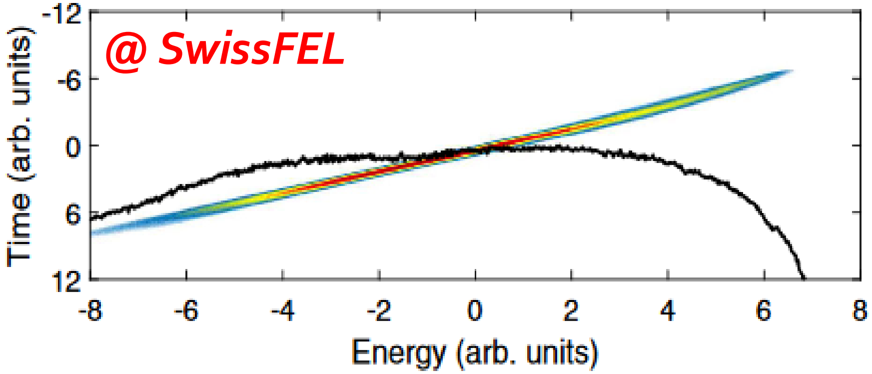
compression & amplification

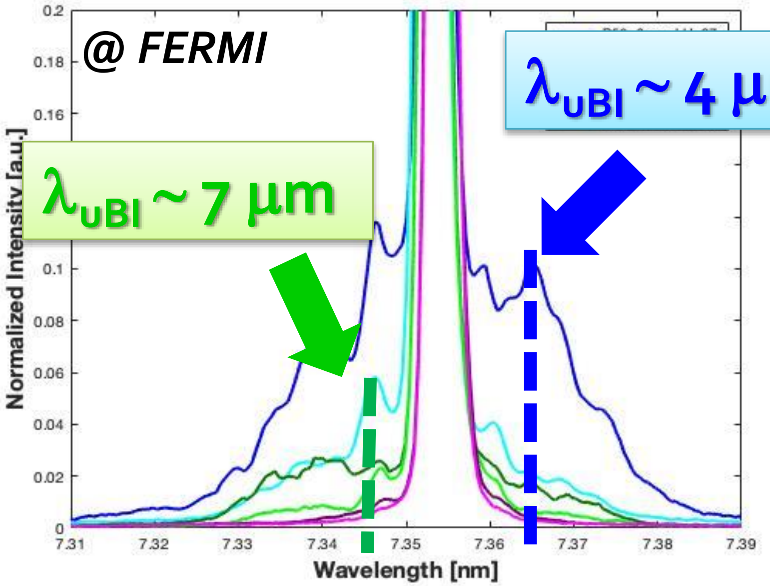


Courtesy C. Feng



S. Bettoni et al., PRAB 23 (2020)





$k_{FEL} = h k_{seed} \pm m k_{ubi}$

- ✓ Slow-response photo-cathode
- ✓ Pulse stretcher *vs.* stacking

Laser heater

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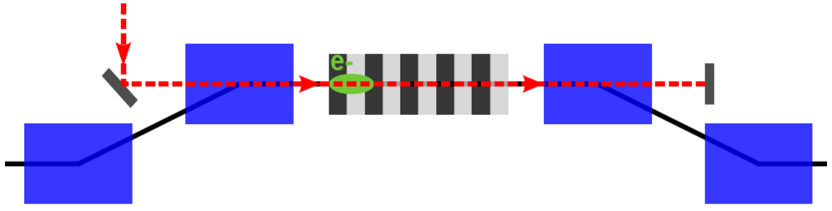
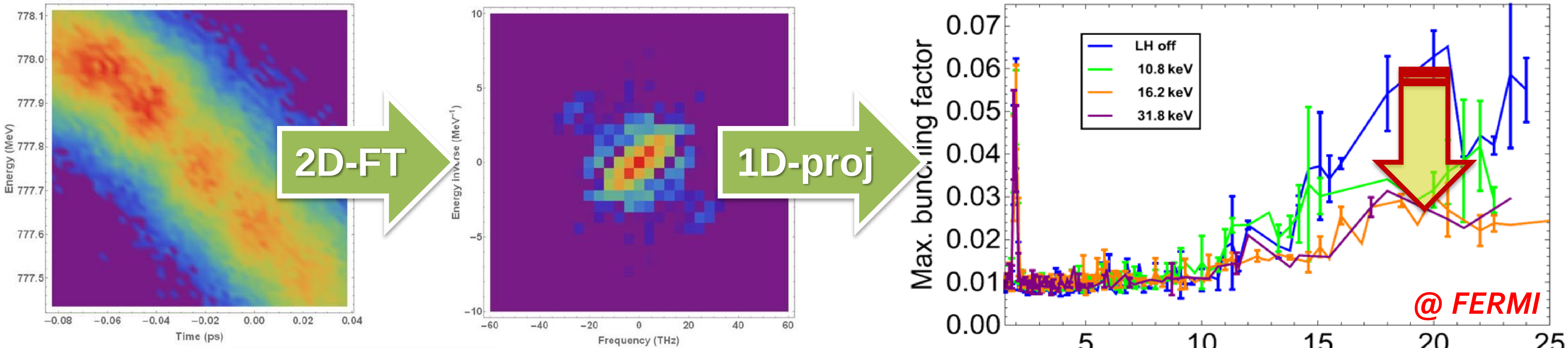


Instability gain = amplification of bunching

$$G(k) \cong \frac{4\pi I_0}{Z_0 I_A} Ck|R_{56}| \left| \int d\,s \frac{Z_{LSC}(k;s)}{\gamma(s)} \right| exp\left[-\frac{1}{2}(CkR_{56}\sigma_\delta)^2 \right]$$

amplification **damping**

A tool to increase the (initial) beam uncorrelated energy spread, σ_δ



A. Brynes et al., Sci. Rep. 10 (2020)

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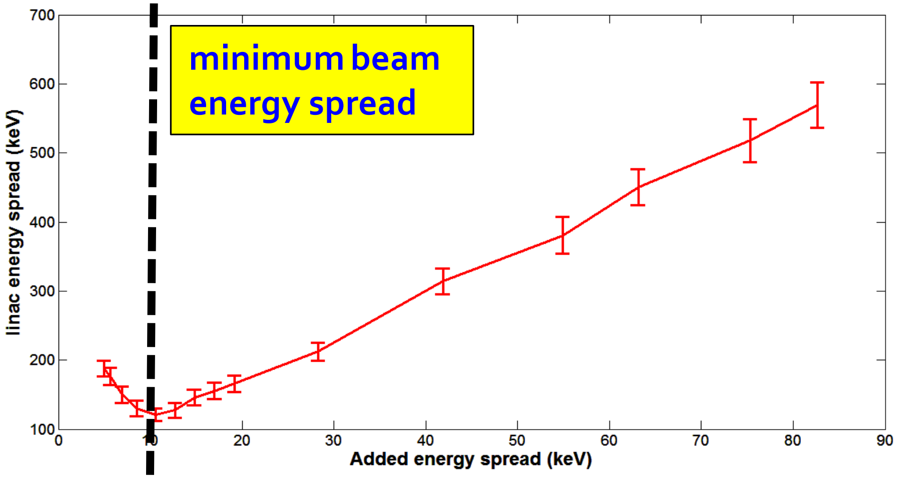
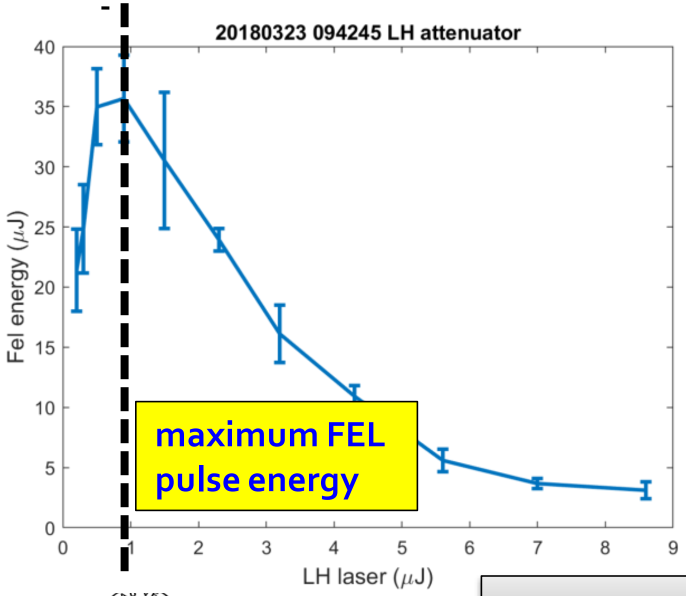
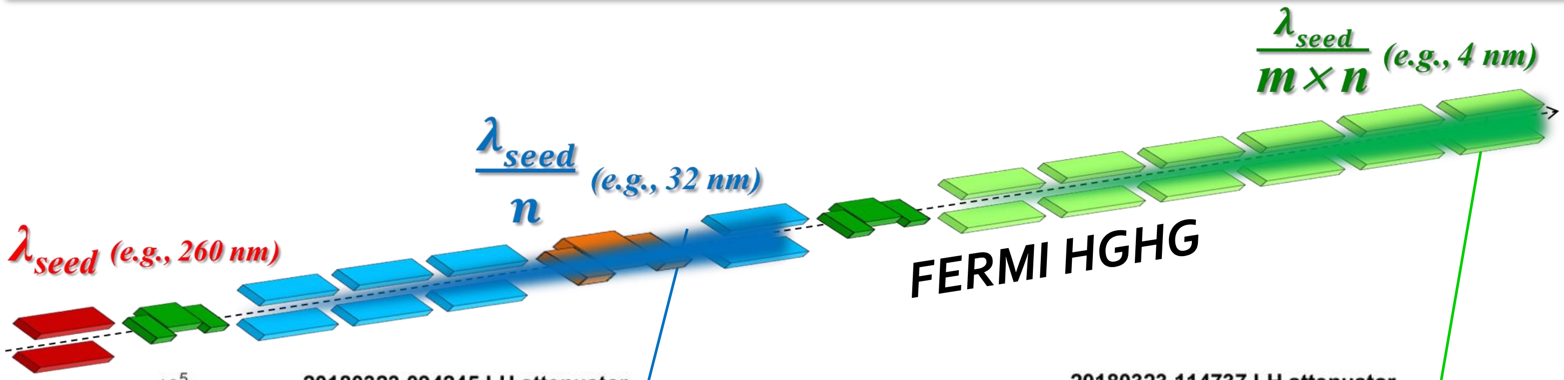
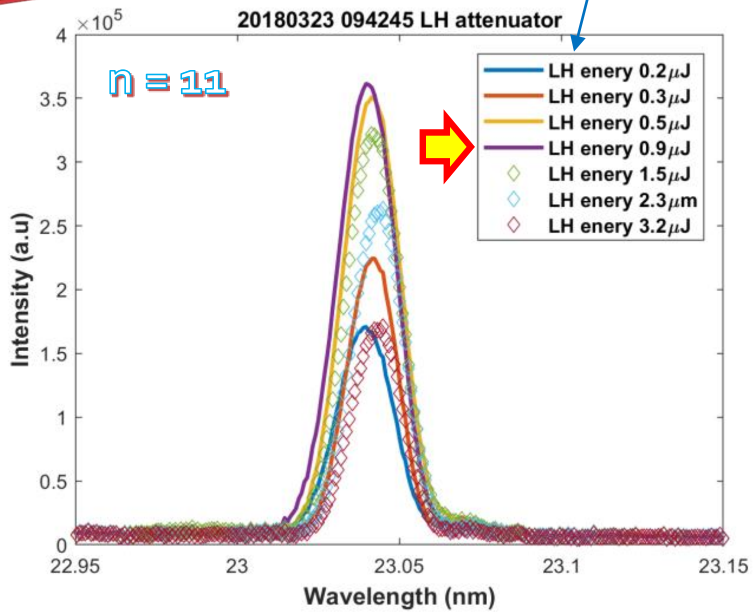
FEL optimization

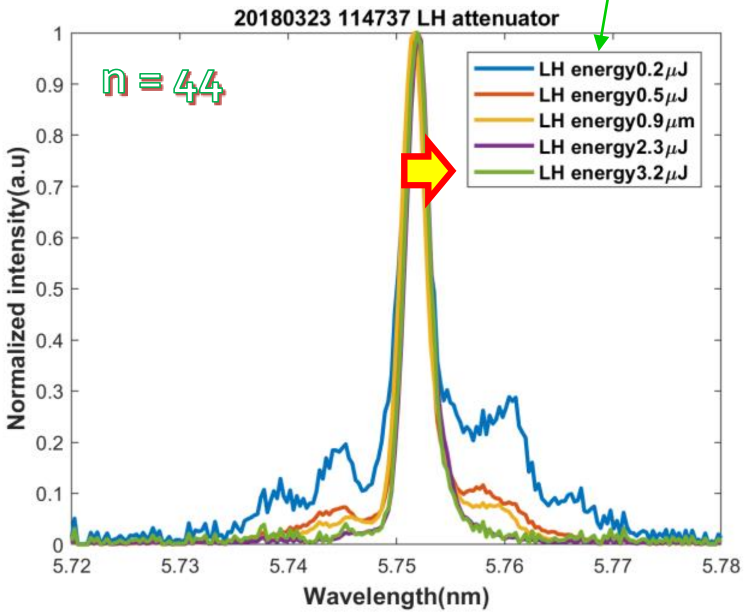
- The laser heater maximizes the spectral brightness
- Compromise intensity *vs.* bandwidth at shorter λ











Courtesy S. Spampinati

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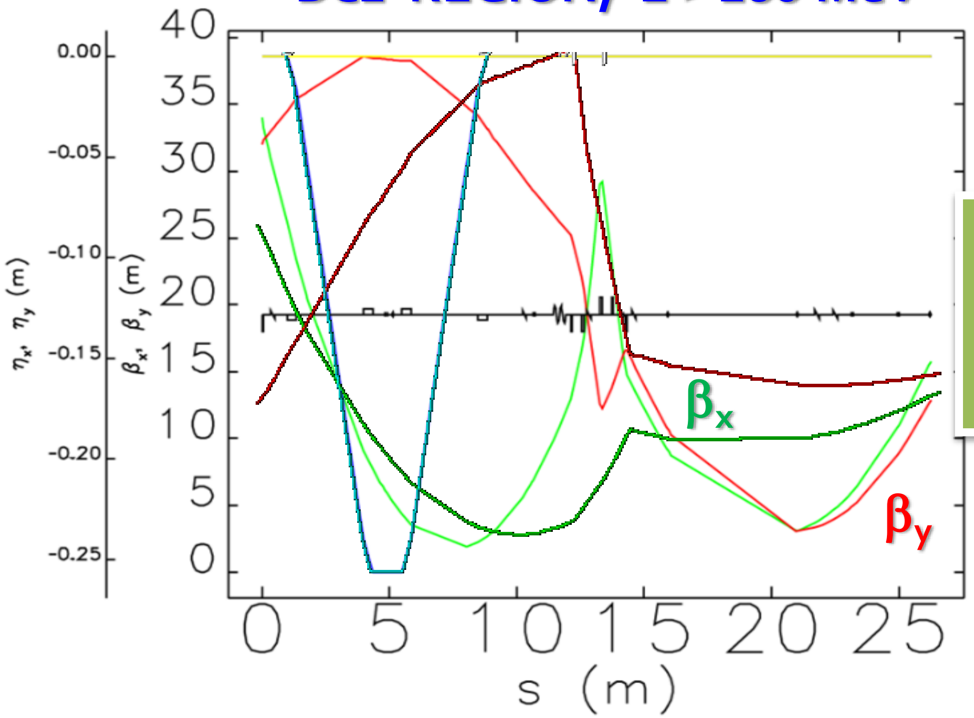
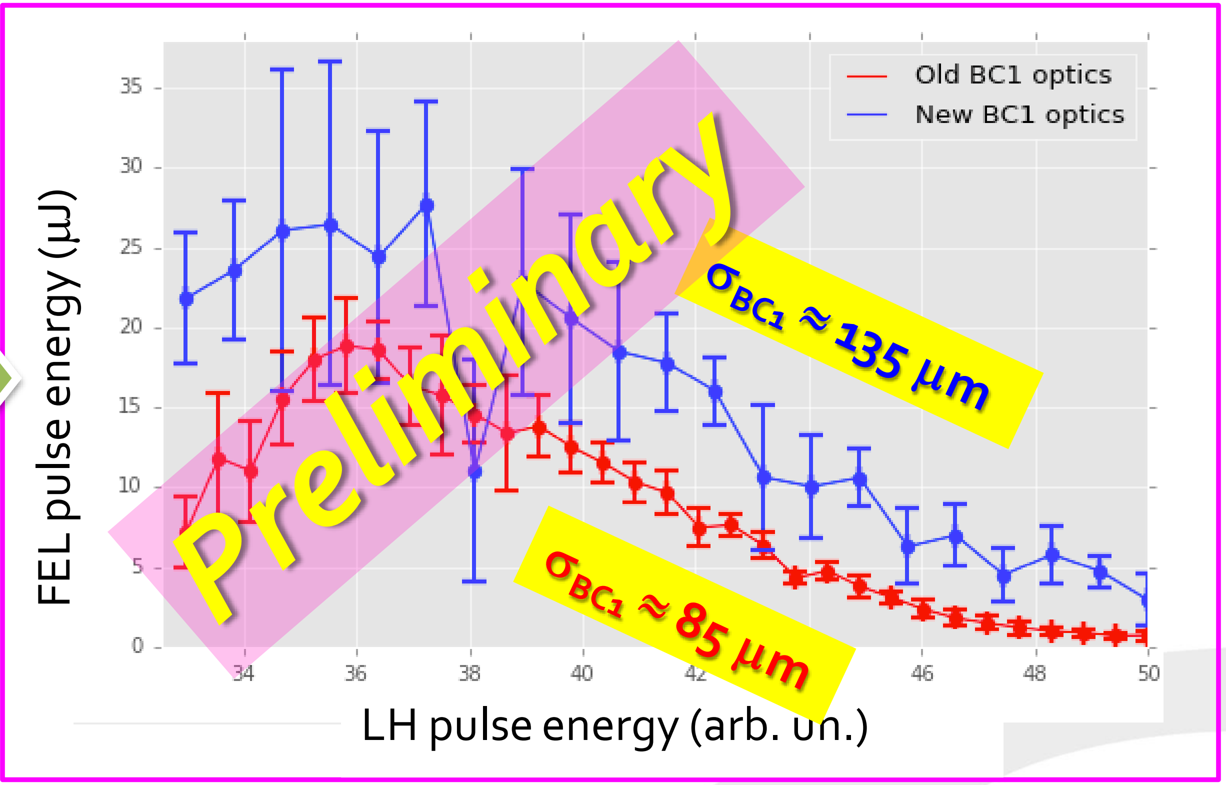
Large beam envelope

- ☐ **3-D effects** are expected at $\lambda \leq 4\pi r_b/\gamma \approx 2\ \mu m \Rightarrow$ ***within gain bandwidth !***
- ☐ **LSC effects** are reduced at $r_b \geq \lambda\gamma/4\pi \approx 150\ \mu m \Rightarrow$ ***effective at E ≤ 1 GeV !***

BC1 REGION, E > 280 MeV



from Linac to FEL



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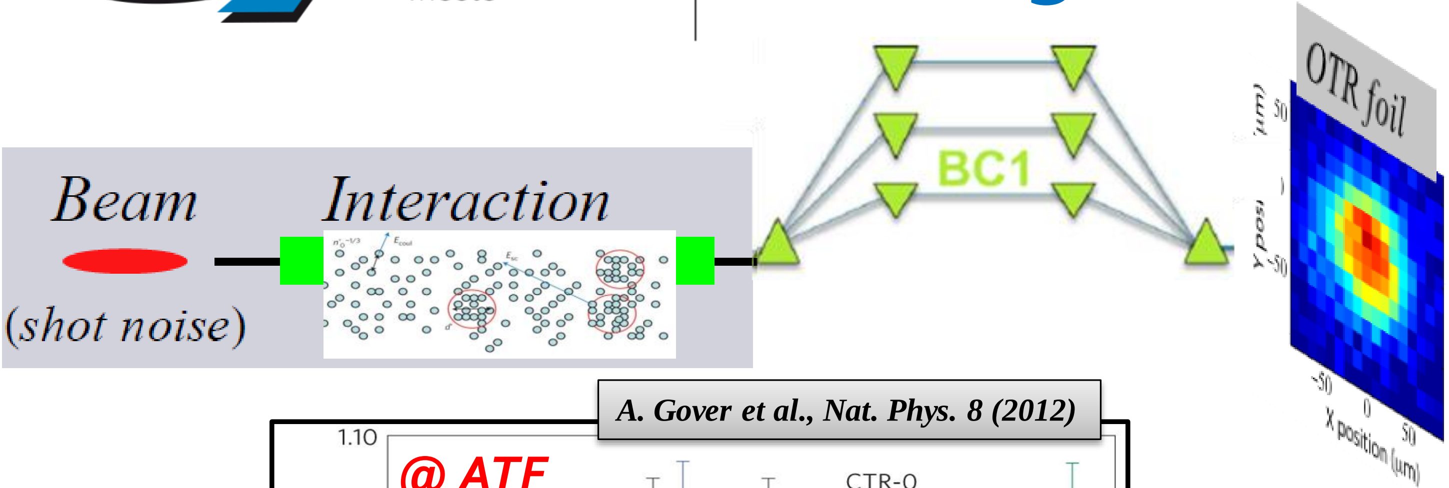
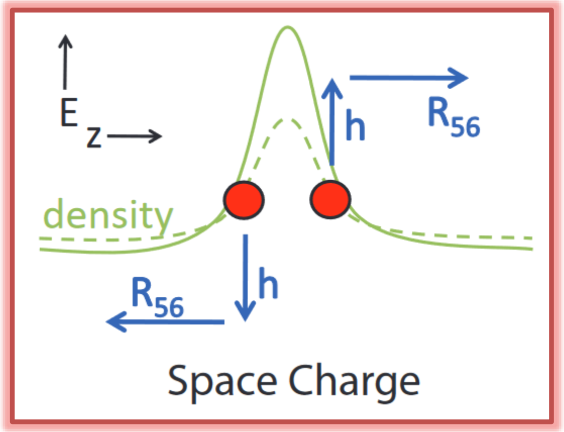
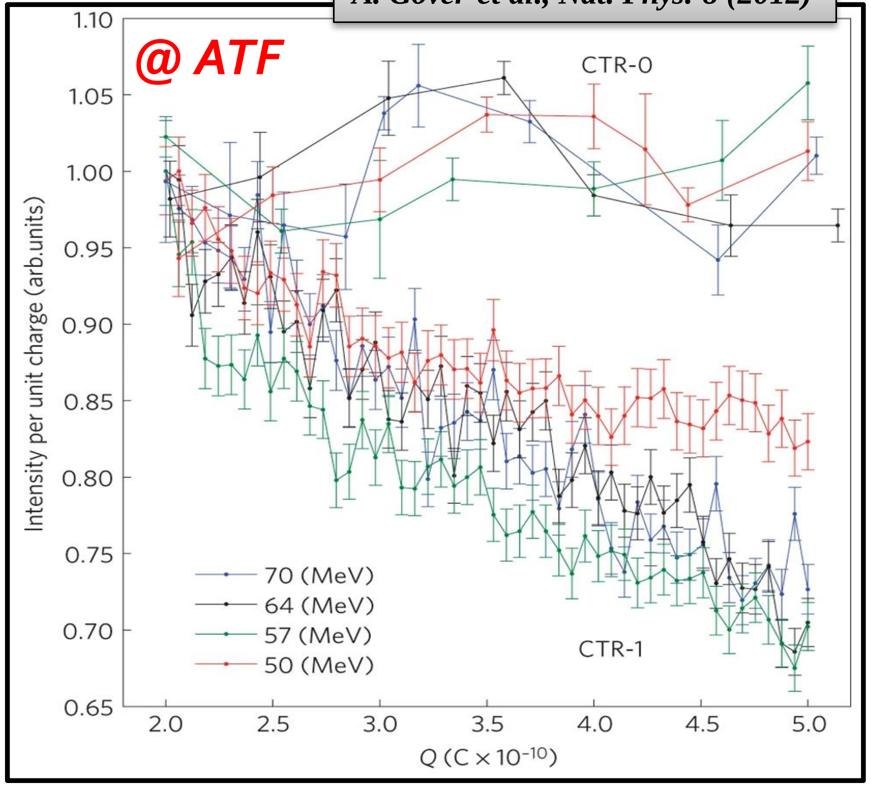
Beating the shot-noise limit

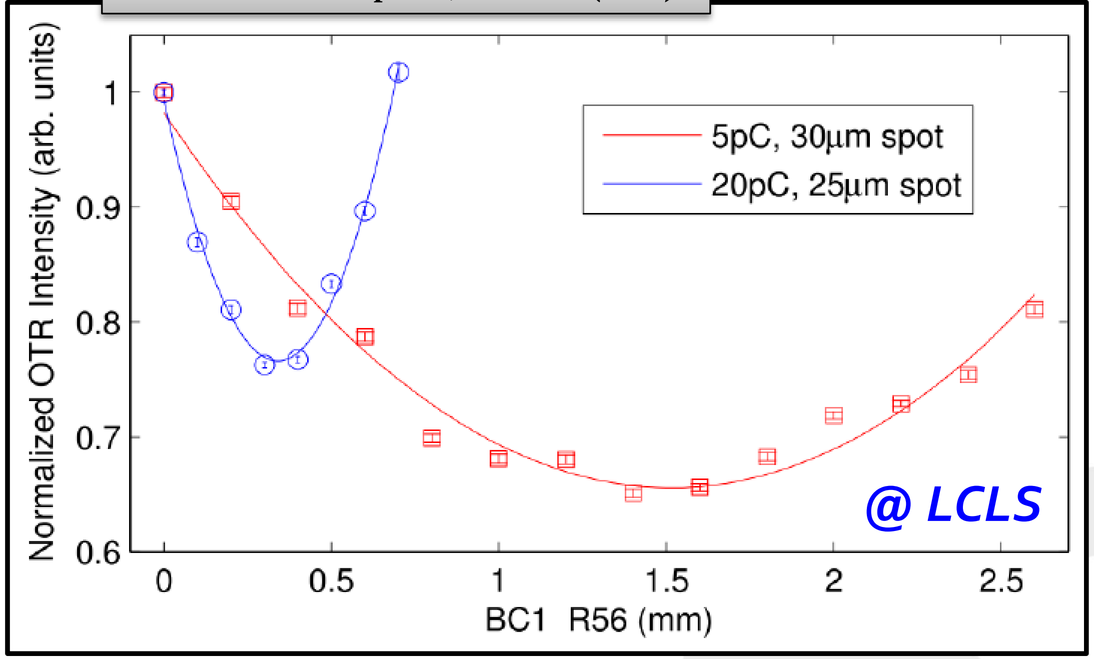




A. Gover et al., Nat. Phys. 8 (2012)



D. Ratner & G. Stupakov, PRL 109 (2012)



Phase mixing

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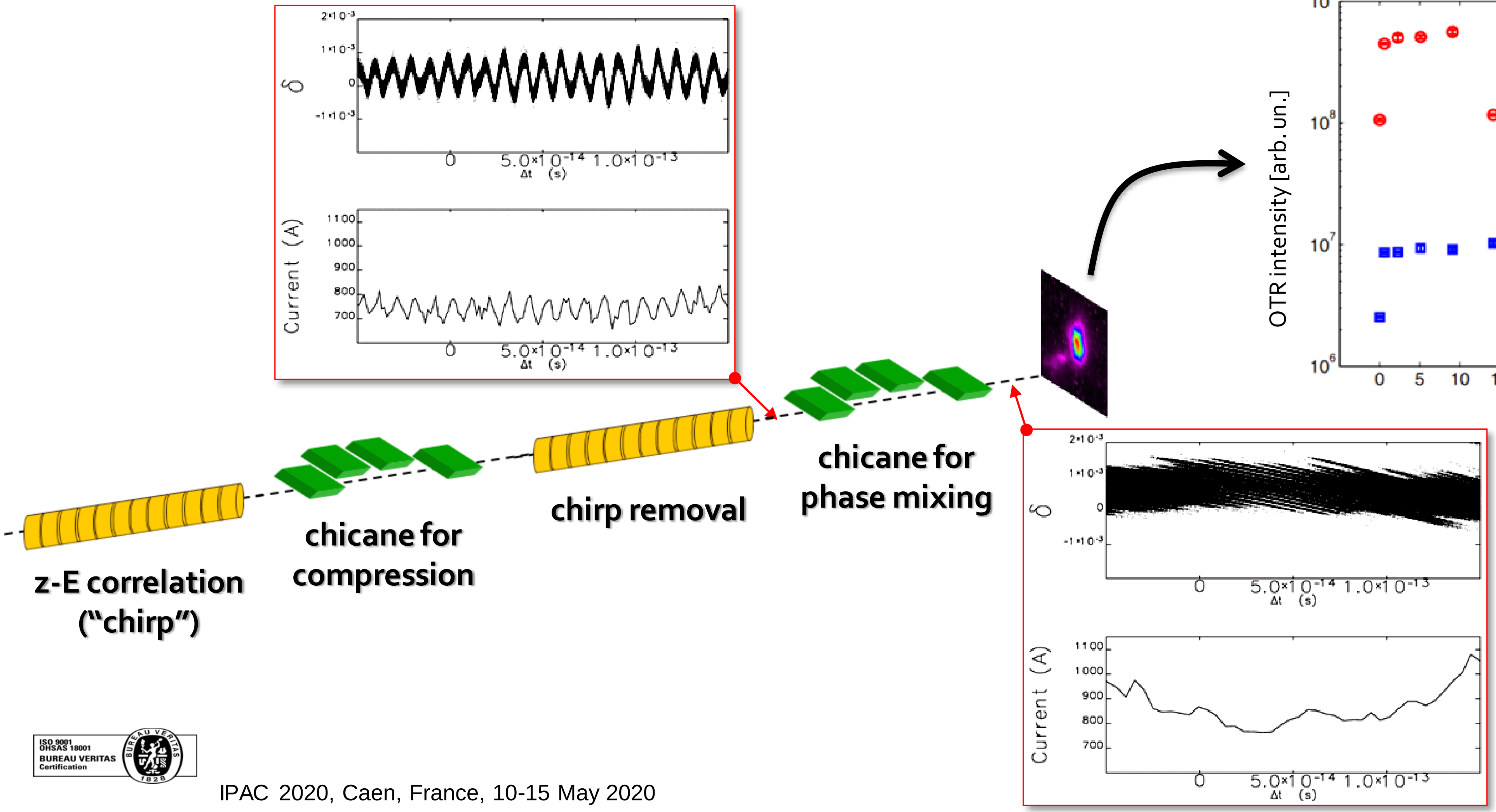
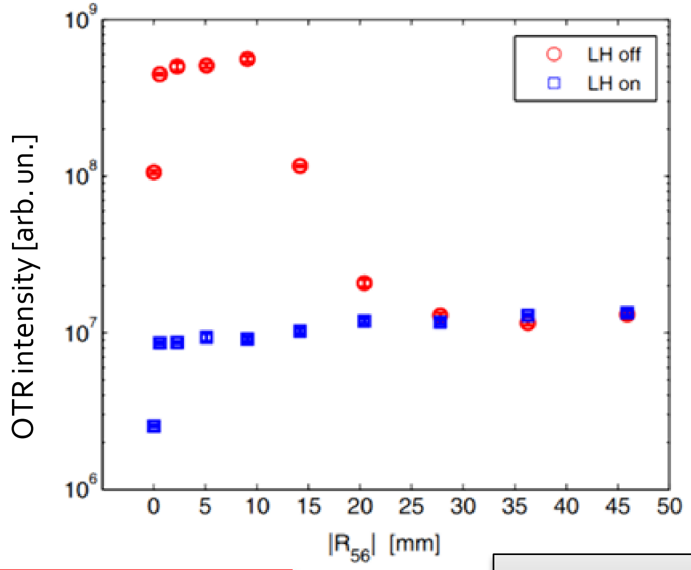
✓ Large R_{56} washes the phase space out, without addition of energy spread





S. Di Mitri S. Spampinati, PRL 112 (2014)

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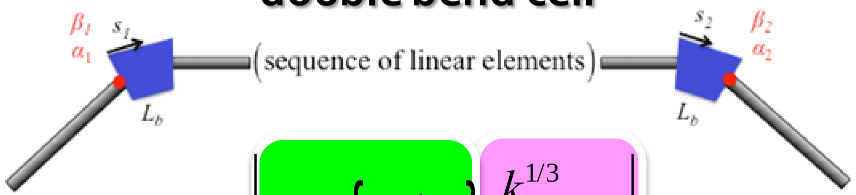
Isochronous optics

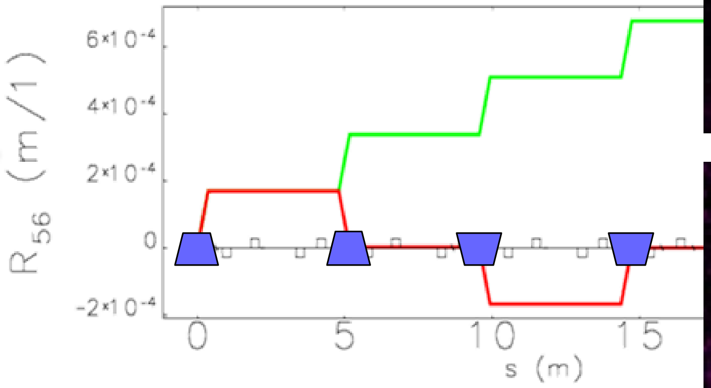
double bend cell

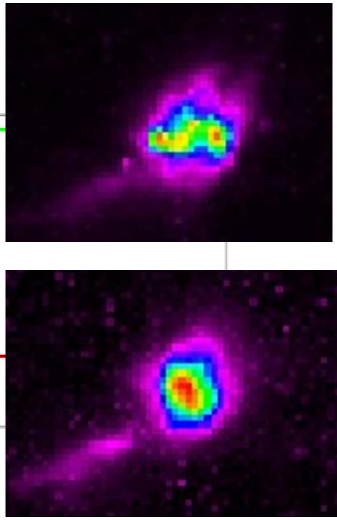


$$x = \left| \max\left\{ R_{56}^{s'\to s} \right\} \frac{k^{1/3}}{r^{2/3}} \Delta L \right|$$

~ ***local*** **momentum compaction** ~ **CSR field**

- *Low betas*
- *π-phase adv.*
- *Isochronicity*

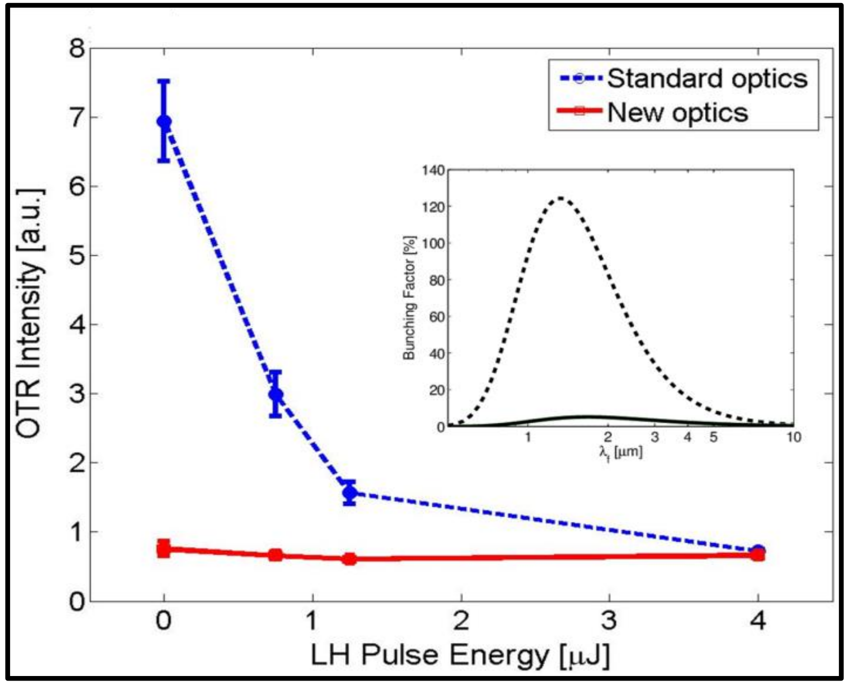




OTR signal from an Al screen is ∝ sub- μm modulations

- ✓ **An isochronous optics "freezes" the electrons, so lowering the local gain to 1**

C.-Y. Tsai et al., PRAB 20 (2017)



S. Di Mitri S. Spampinati, PRAB 20 (2017)

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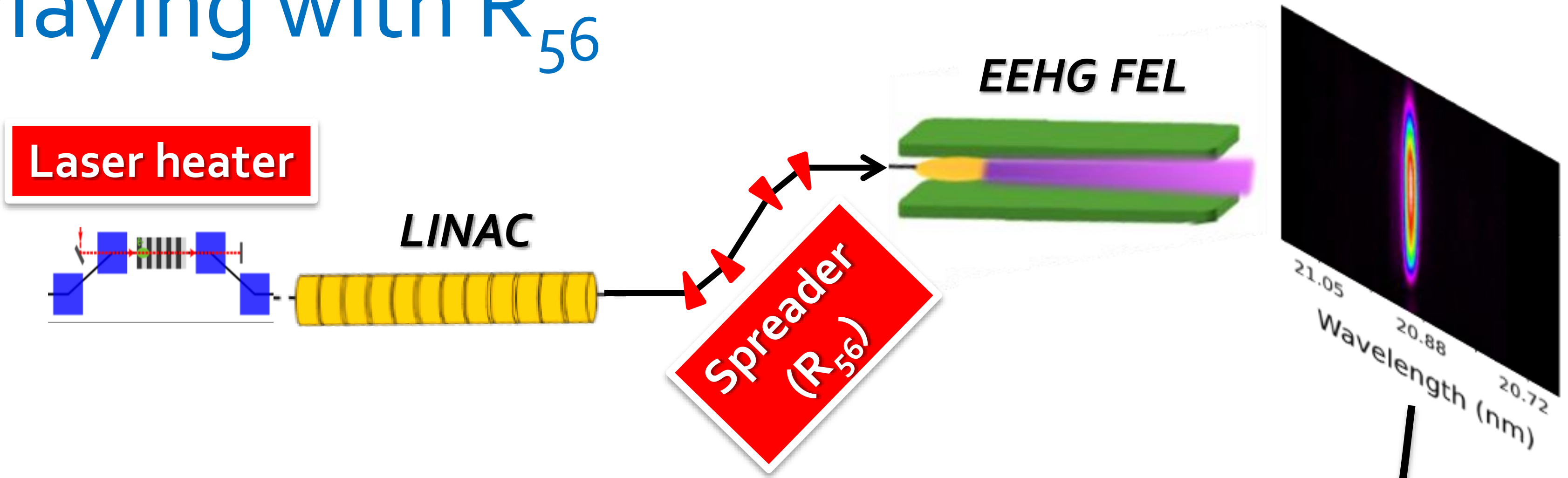
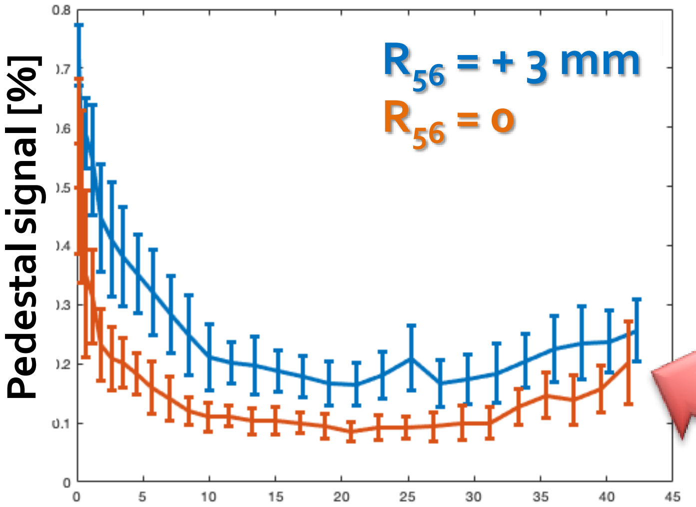
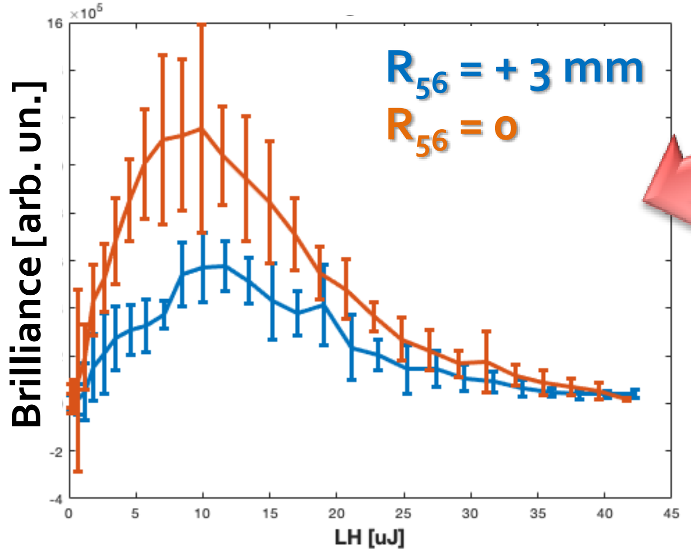
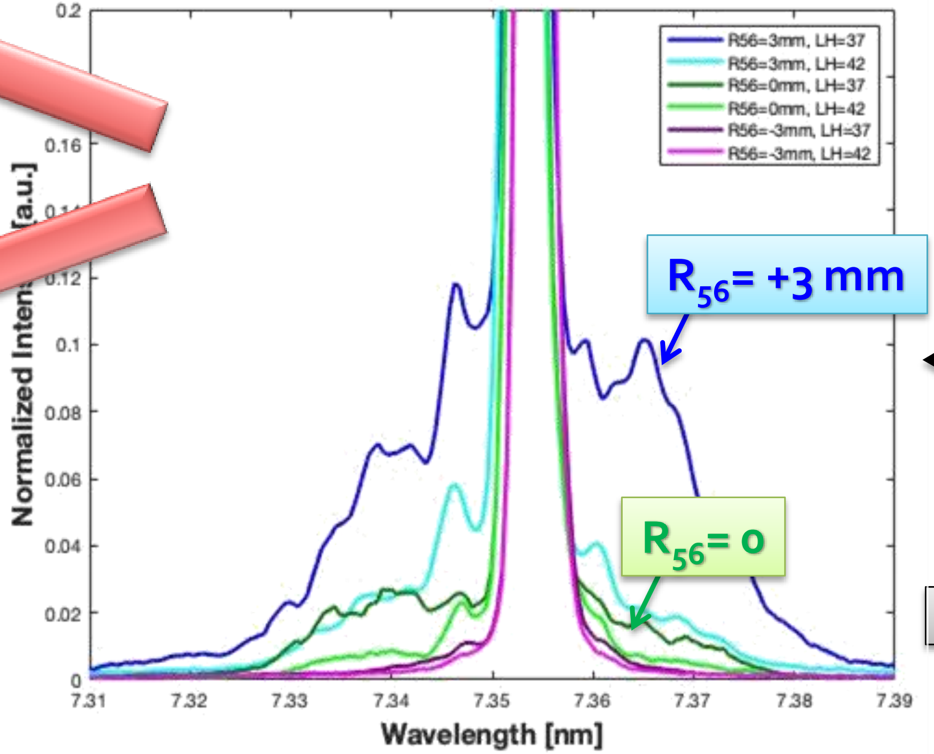
Playing with R_{56}



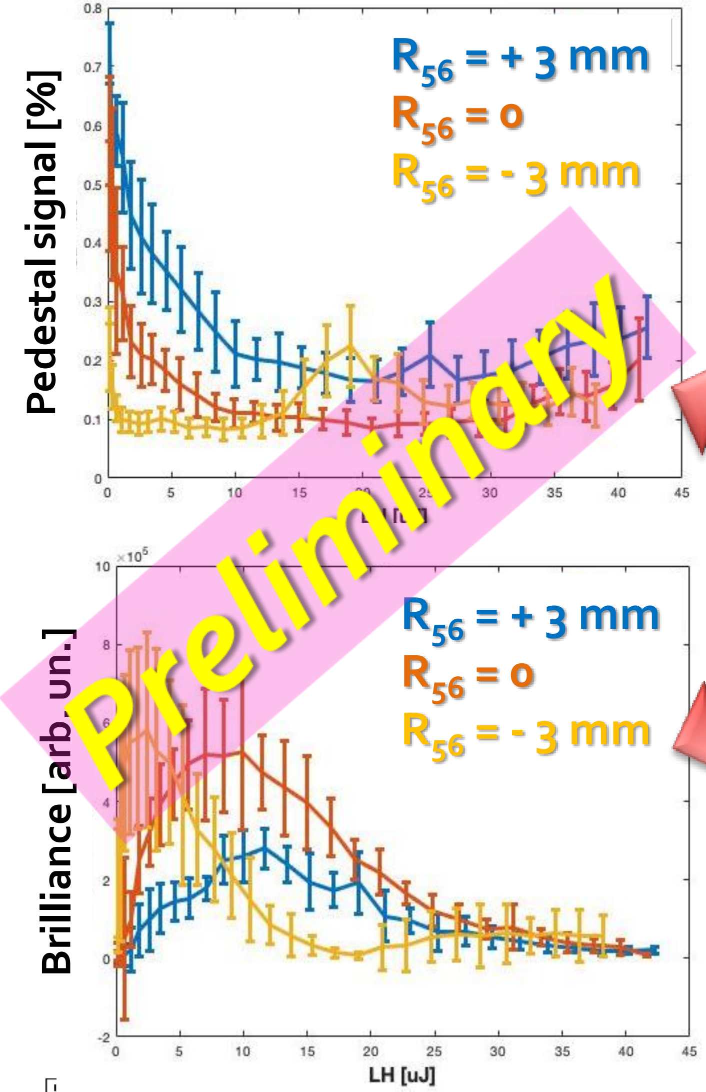


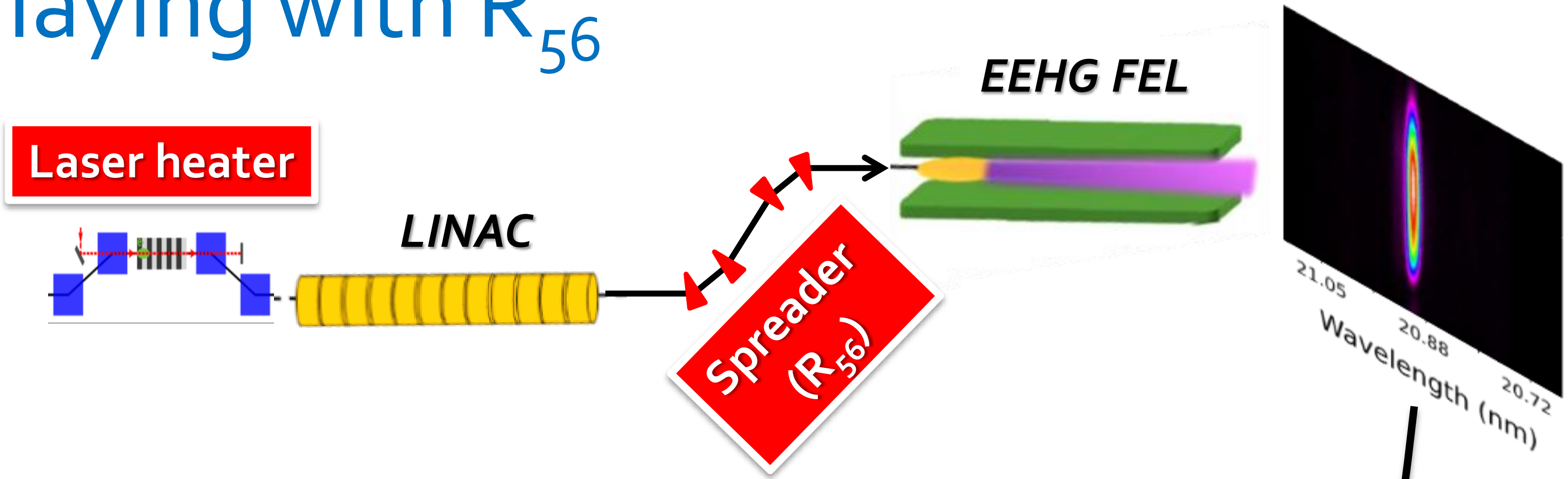


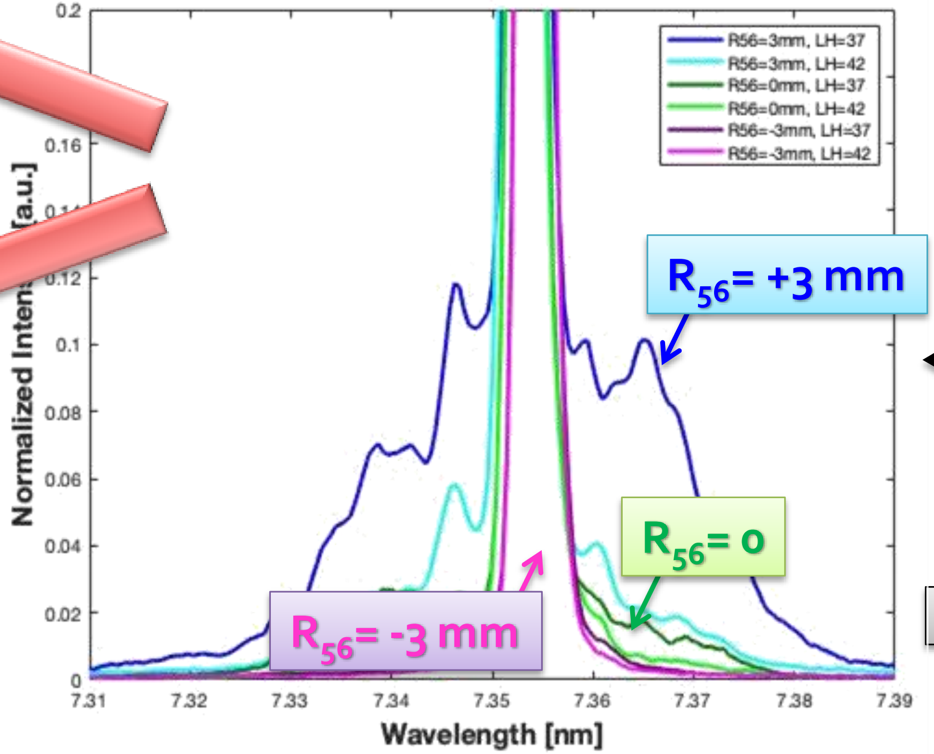


Courtesy G. Perosa

Playing with R_{56}







Courtesy G. Perosa

Conclusions & outlook

1. Now 20 years of instability studies. **Show-stopper** to stable, full longitudinal coherence – ***few μm's*** modulations harmful to **soft x-rays.**

2. **Laser heater** – most powerful tool for damping. However, not a conclusive solution for soft x-rays / high harmonic jumps: $\sigma_\delta \leq \rho_{FEL}/h$.

3. **Smooth and quiet** electron beams from photo-injectors get (almost) rid of the LH, but shot-noise driven modulations survive.

4. **Linear optics** control of the sideband instability (large beam envelope, isochronicity, phase mixing) needs additional validation.
→ **complementary** knob to the LH, with ***no addition of energy spread.***

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