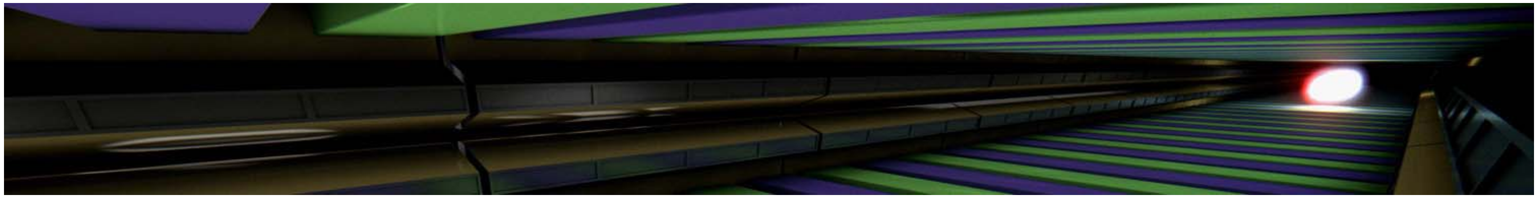


Microbunching instability and lessons from laser heater operation at LCLS

E. Schneidmiller and M. Yurkov

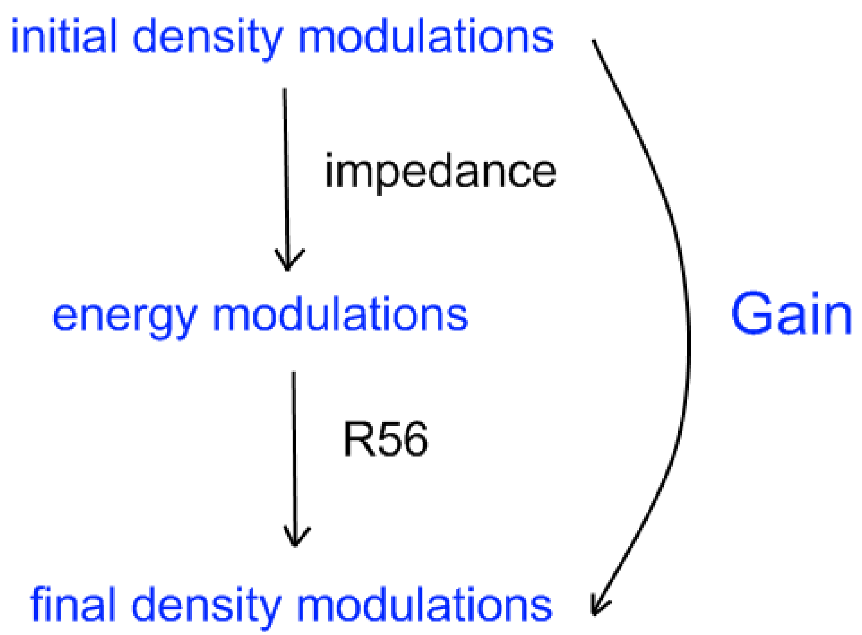
Beam Dynamics Meeting, 8 March 2010

Outline

- Introduction
- Laser heater operation at LCLS
- Microbunching instability in FLASH?
- Laser heater concept for FLASH
- Brief discussion on LH for the European XFEL
- Conclusions

Mechanism of microbunching instability

High-gain klystron-like amplifier



E. Saldin, E. Schneidmiller and M. Yurkov, NIM A483(2002)516

Theory and simulations

CSR (Coherent Synchrotron Radiation) instability

M. Borland et al., NIM A483(2002)268

E. Saldin, E. Schneidmiller and M. Yurkov, NIM A490(2002)1

S. Heifets, G. Stupakov and S. Krinsky, PRST-AB 5(2002)064401

Z. Huang and K.-J. Kim, PRST-AB 5(2002)074401

…

not so dangerous

LSC (Longitudinal Space Charge) instability

E. Saldin, E. Schneidmiller and M. Yurkov, NIM A483(2002)516

E. Saldin, E. Schneidmiller and M. Yurkov, TESLA-FEL-2003-2, NIM A528(2004)355

Z. Huang et al. , PRST-AB 7(2004)074401

…

much stronger than CSR, can be dangerous

Experimental observations

Enhanced radiation in infrared and visible range

H. Loos et al., Proc. of FEL’08 (Gyengju, Korea), p. 485

B. Schmidt et al., Proc. of EPAC’08 (Genoa, Italy), p. 132

A. Lumpkin et al., Phys. Rev. ST-AB 12(2009)080702

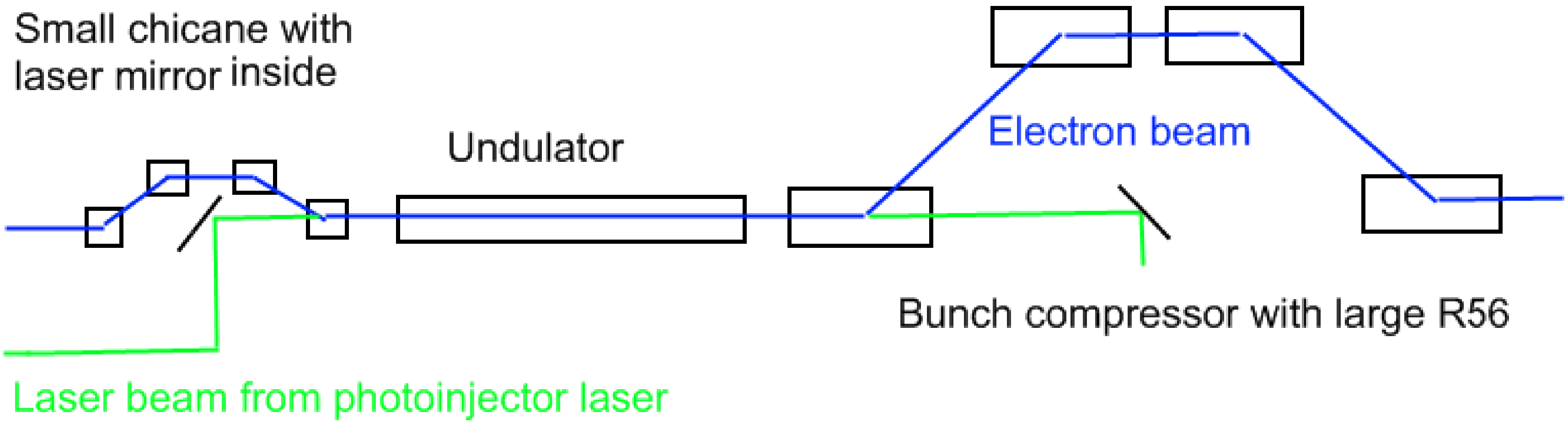
S. Wesch et al., Proc. of FEL’09 (Liverpool, UK), p. 619

…

Effect on x-ray FEL performance; laser heater operation

Z. Huang et al., PRST-AB 13(2010)020703

Original concept of a laser heater



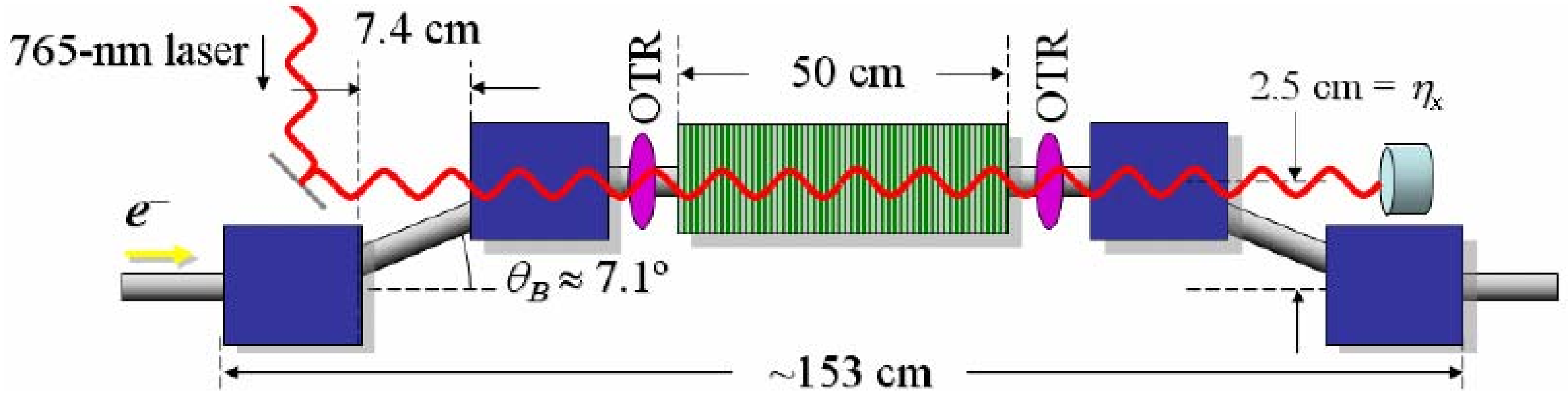
Smearing due to a large R_{56} of BC and natural energy spread:

$$\frac{\sigma_\gamma}{\gamma} \frac{2\pi R_{56}}{\lambda} \geq 1$$

(similar to a storage ring FEL)

Saldin, Schneidmiller and Yurkov, TESLA-FEL 2003-02, also NIM A528(2004)355

Laser heater design for LCLS



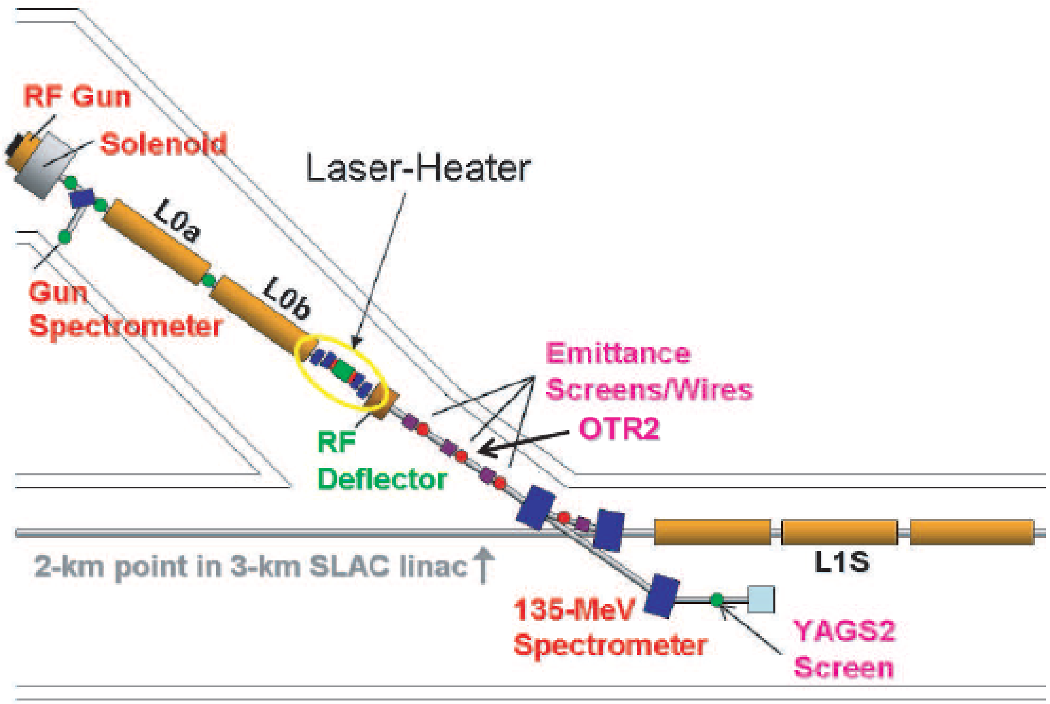
Matched laser beam (no energy chirp - beam is not tilted);

Smearing due to R_{52} (through half chicane) and angular spread:

$$\sigma_{x'} \frac{2\pi R_{52}}{\lambda} \geq 1$$

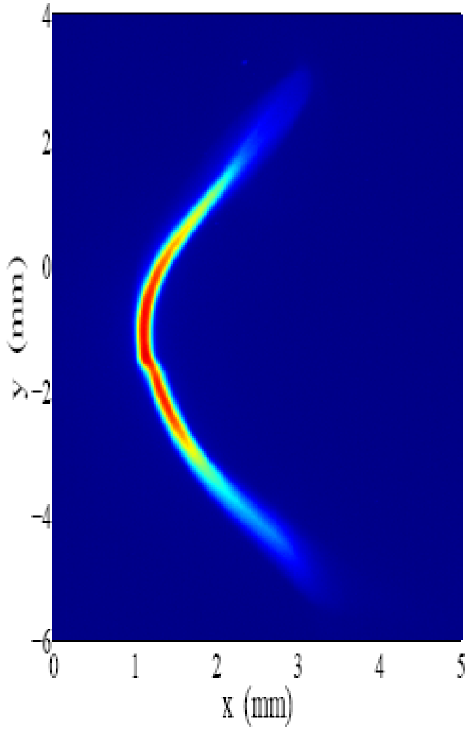
Z. Huang et al. , PRST-AB 7(2004)074401

LCLS injector layout

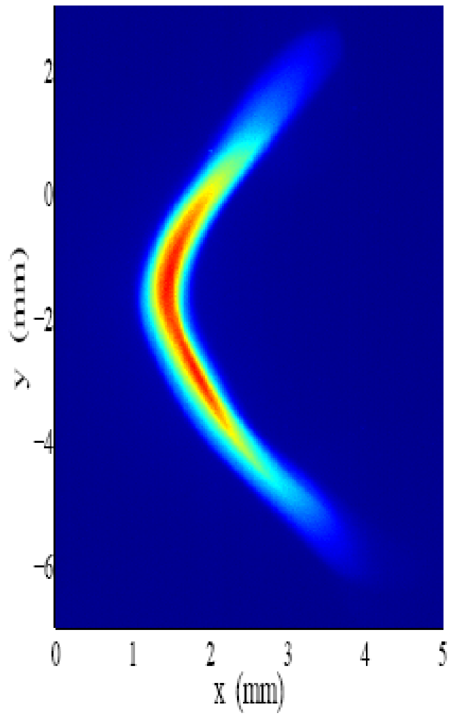


Longitudinal phase space can be measured with the help of transverse RF deflector and spectrometer

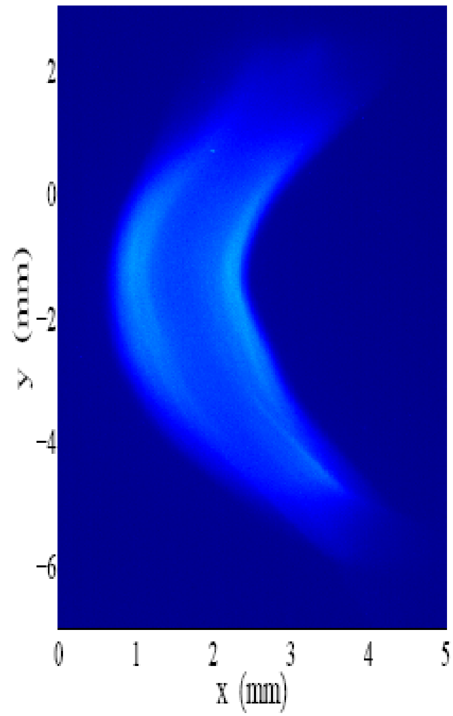
Longitudinal phase space



(a)no heating



(b)nominal heating

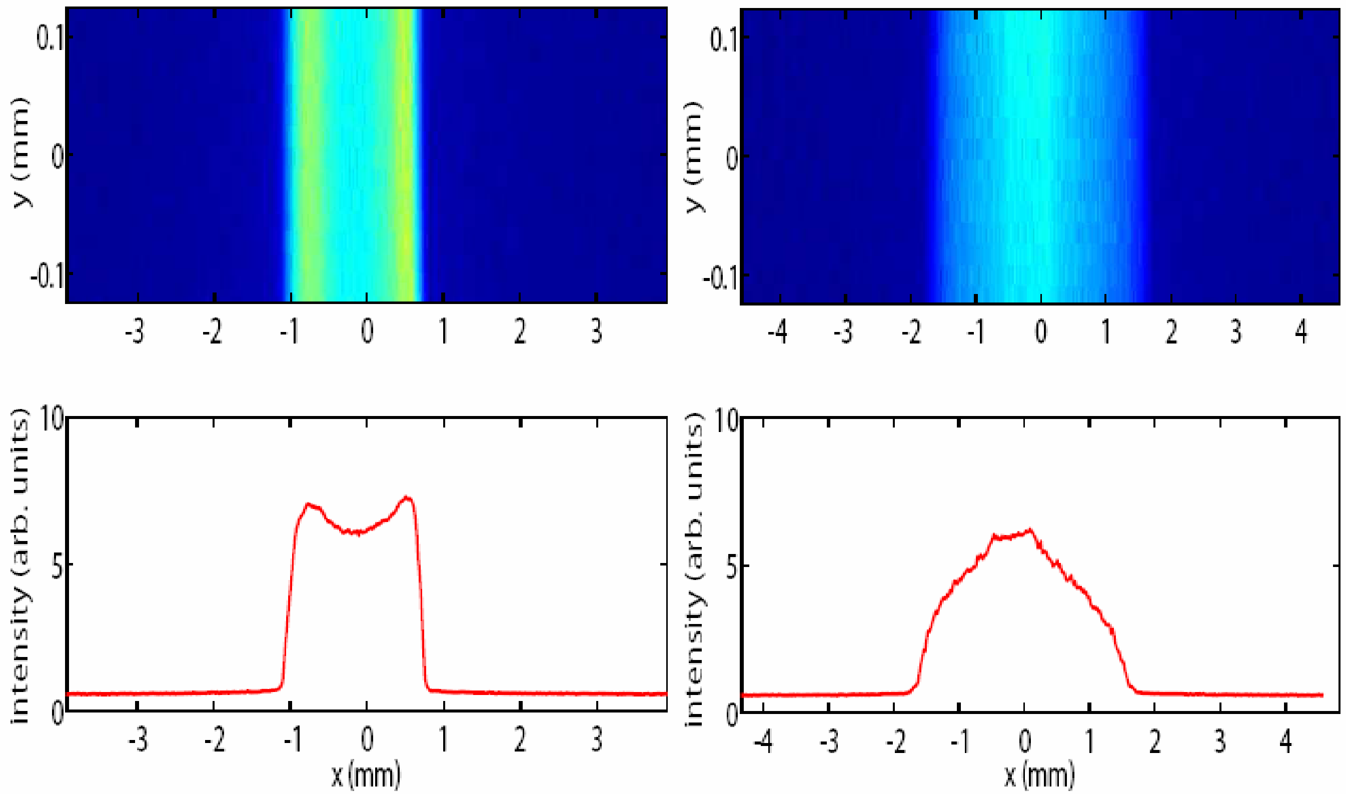


(c)maximum heating

FIG. 6: Measured longitudinal phase space on "YAGS2" screen at 135 MeV with (a) laser heater off, (b) IR laser energy at 10 μJ, and (c) at 220 μJ.

Z. Huang et al., PRST-AB 13(2010)020703

Central slice energy distribution

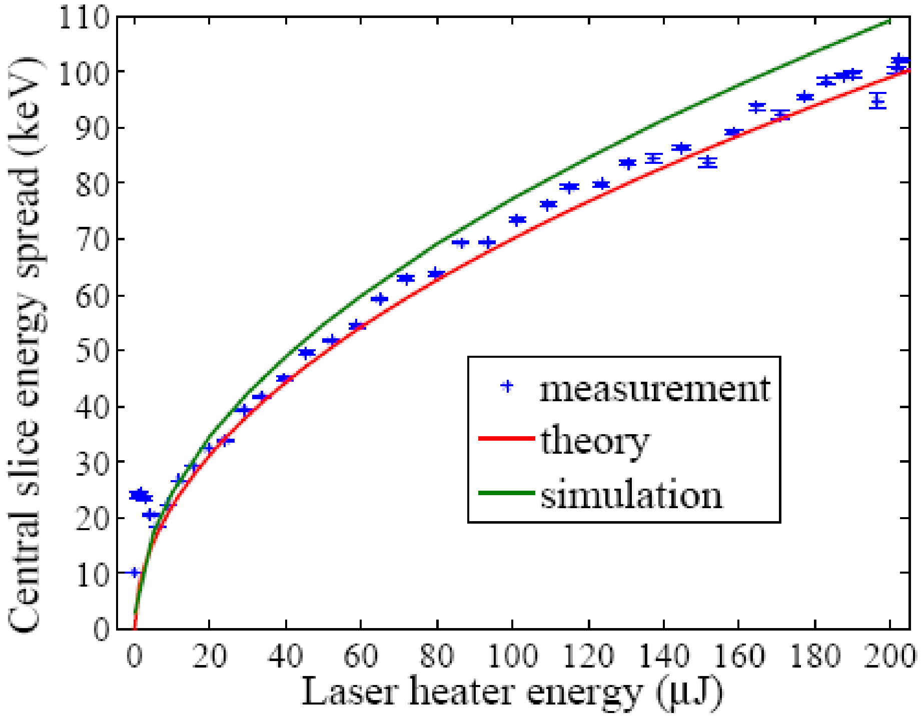


(a)Larger laser spot (b)Matched laser spot

FIG. 7: Central slice images (upper plots) and horizontal profiles (lower plots) showing both the double horn (a) and more Gaussian-like (b) energy distributions.

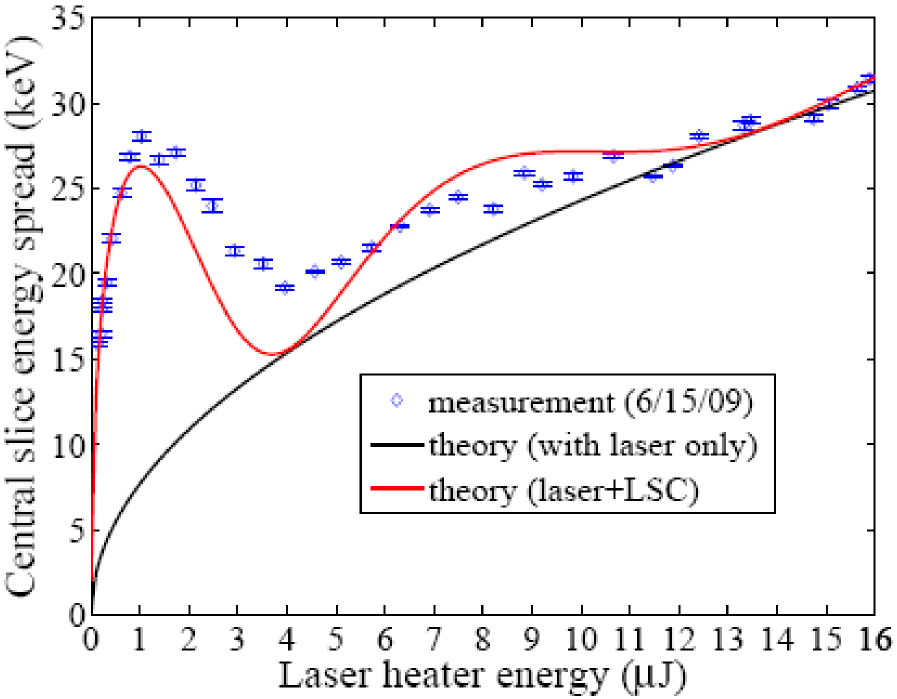
Z. Huang et al., PRST-AB 13(2010)020703

Central slice energy spread



Z. Huang et al., PRST-AB 13(2010)020703

Trickle* heating

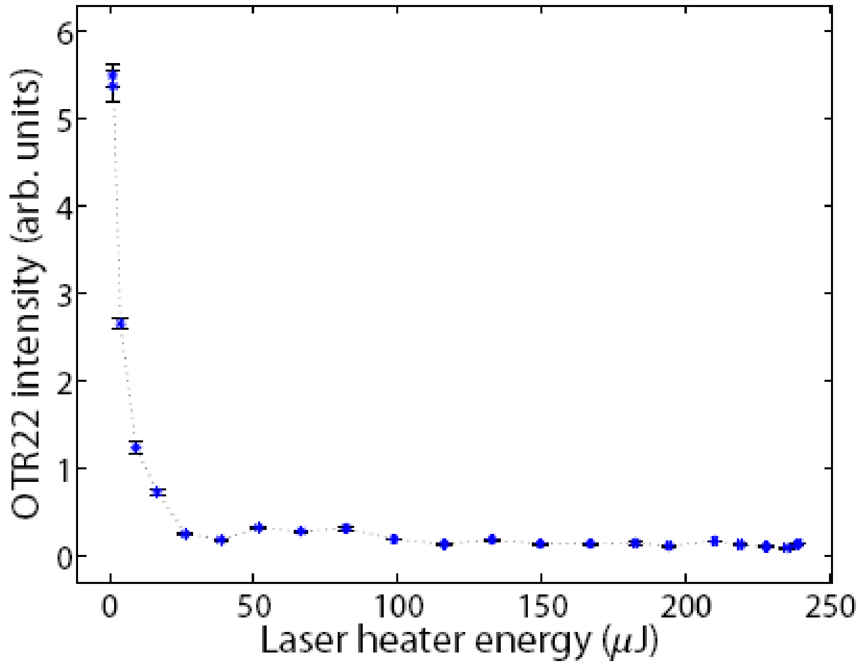


Anomalous increase of slice energy spread at very low laser energies

Z. Huang et al., PRST-AB 13(2010)020703

*to flow or fall by drops, or in a small, gentle stream

Suppression of instability: effect on COTR



The laser heater suppresses these coherent signals by orders of magnitude in many cases but does not appear to completely remove a small level of COTR after compression

Z. Huang et al., PRST-AB 13(2010)020703

Suppression of instability: effects on FEL

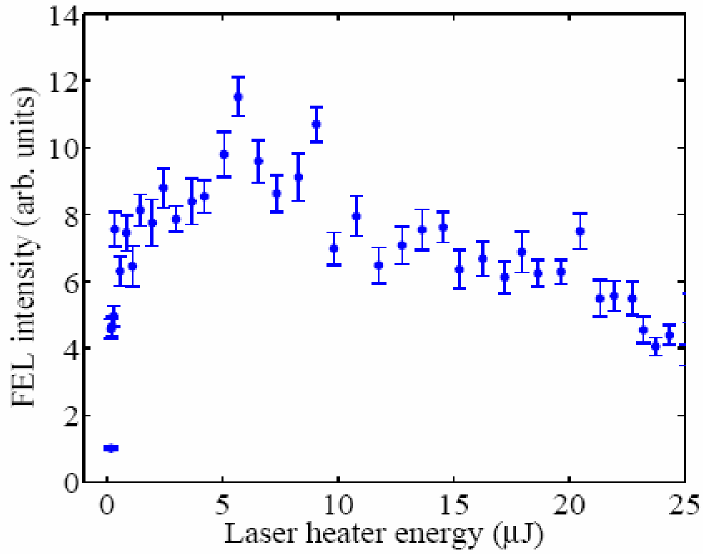


FIG. 15: FEL intensity at 1.5 Å measured on a downstream YAG screen vs. LH energy when 12 undulator sections are inserted.

Strong effect in exponential gain regime (improvement by an order of magnitude). In a deep saturation it is about a factor of 2.

Z. Huang et al., PRST-AB 13(2010)020703

Suppression of instability: effects on FEL (cont'd)

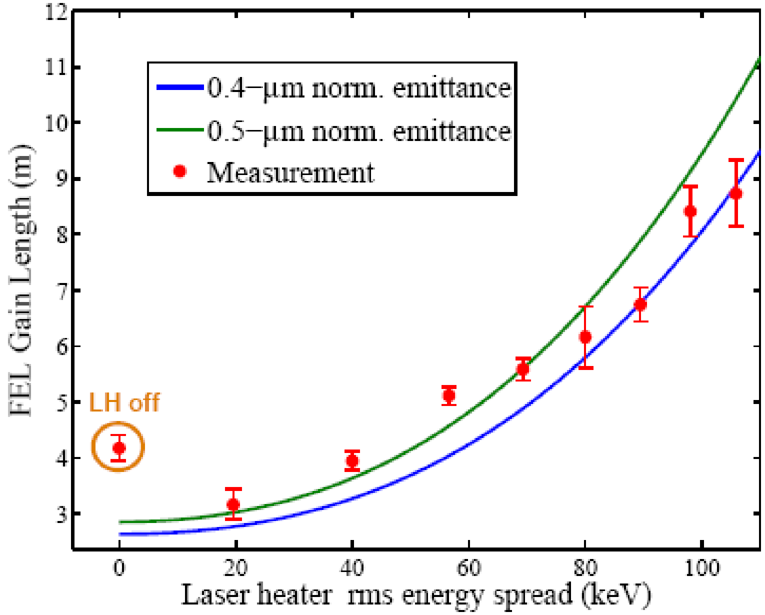


FIG. 16: FEL gain length at 1.5 Å vs. LH-induced energy spread.

FEL gain length for no heating case is about 30% larger than for optimal heating.

Z. Huang et al., PRST-AB 13(2010)020703

Trickle heating: explanation

- Due to a finite R56 of the half chicane a density modulation at laser wavelength is created: $J_1(kR_{56}\frac{\Delta\gamma_L}{\gamma})$
- It is supposed to be smeared by angular spread and R52 of the half chicane. But it is not a true smearing:
- The modulation is hidden in x'-z plane, but downstream in the beamline the x'-z correlation develops into x-z correlation (next slide)
- Although modulation planes are tilted, LSC can still be significant. It leads to a parasitic heating that can be stronger than the heating by the laser
- Effect depends on optics as well as on beam parameters

Z. Huang et al., PRST-AB 13(2010)020703

Trickle heating: explanation (cont'd)

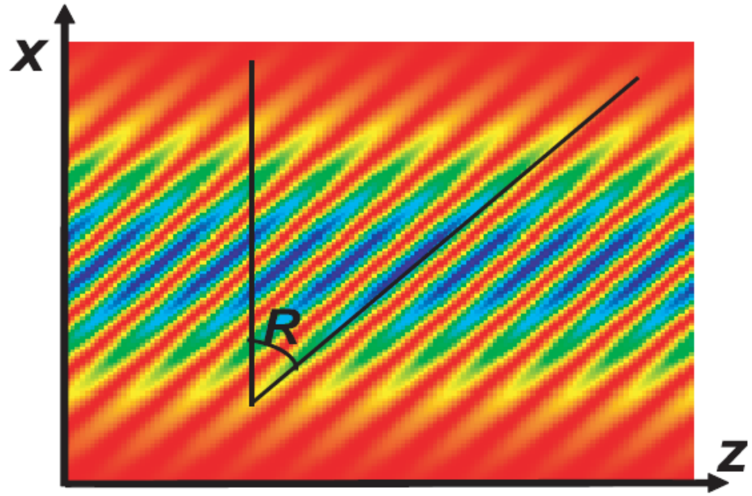


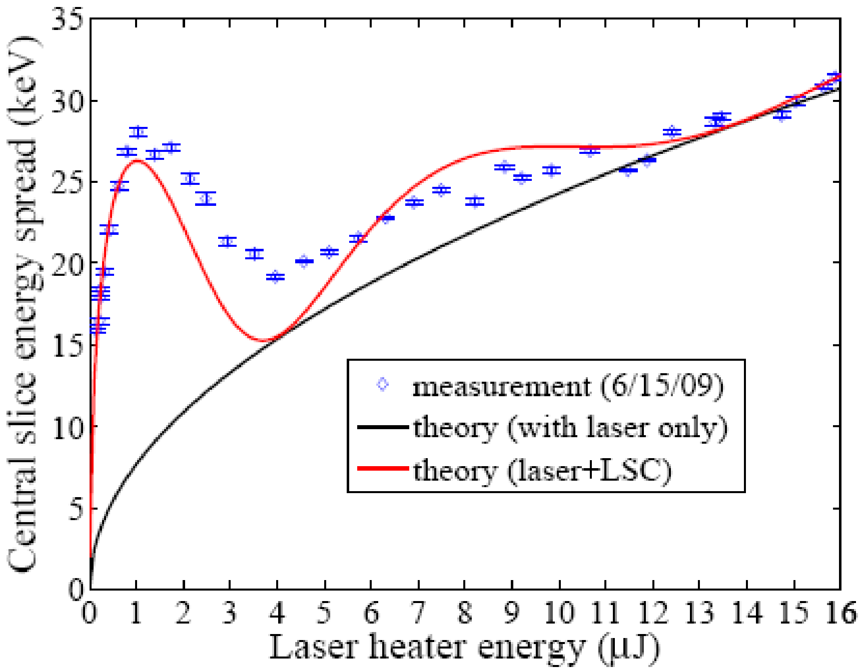
FIG. 13: A bunch with its density modulation tilted in $x-z$ plane. The tilt angle is denoted as R, and the bunch head is to the right. Blue represents higher density region and red represents lower density region.

$$E_z(k_0) \approx \frac{-iI_0 Z_0}{2\pi k_0 \sigma_x^2} \frac{a_0}{1+\gamma^2 R^2} .$$

$$\gamma R \approx 2$$

Z. Huang et al., PRST-AB 13(2010)020703

Trickle heating: explanation (cont'd)



For laser energy about 1 keV the expected energy modulation is 7.5 keV but in reality it is 28 keV. For R56 = 4 mm the energy modulation from the laser corresponds to the maximum of Bessel function J1.

In LCLS the trickle heating may be minimized by changing the optics downstream of LH.

Trickle heating should be avoided in other machines!

Z. Huang et al., PRST-AB 13(2010)020703

Microbunching instability in FLASH?

- uBI was observed (B. Schmidt et al.) in IR and visible range, especially for uncompressed bunches (small energy spread)
- In case of roll-over compression one should not expect sub-structures within the spike because it is formed at local FULL compression in BC3; energy spread smears any sub-structures (if existed); the shortest possible scale is the spike width
- Some amplification of short wavelengths (within the spike) through the dogleg is possible, but not expected to be strong
- In case of linearized compression we use UNDER-compressed regime, sub-structures can be amplified (and not smeared) through both bunch compressors, and – if the instability develops to saturation – can hamper FEL operation.

Microbunching instability in FLASH? (cont'd)

•Spike is made of a short slice in initial distribution; by changing compression phases we choose the slice

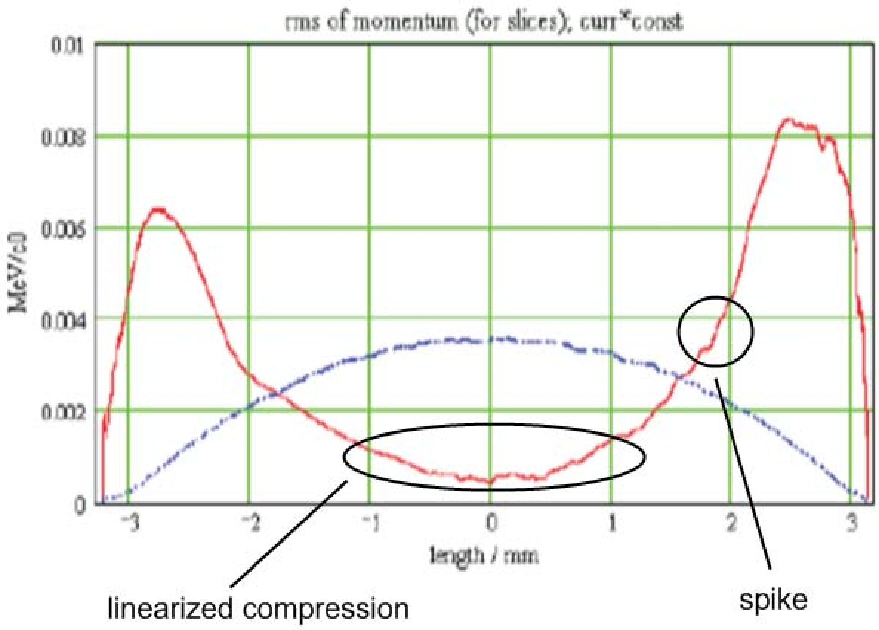
•Spike width and peak current are defined by slice energy spread and current in initial distribution; we work on the slope where slice energy spread is not too small; we have knobs to optimize spike parameters

•In case of linearized compression the relevant energy spread is much smaller, no way to control it

•If uBI develops to saturation, the sub-structures can be much sharper than the spike from roll-over compression

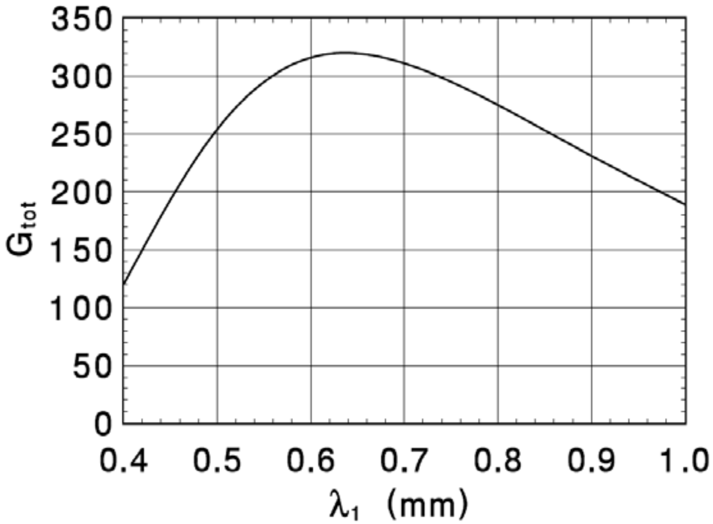
•Energy chirps due to LSC after BC3 would be much larger with all related problems: strong effect of the dogleg on longitudinal dynamics (it can even mix up different spikes resulting in strong increase of local energy spread), transverse dispersion etc.

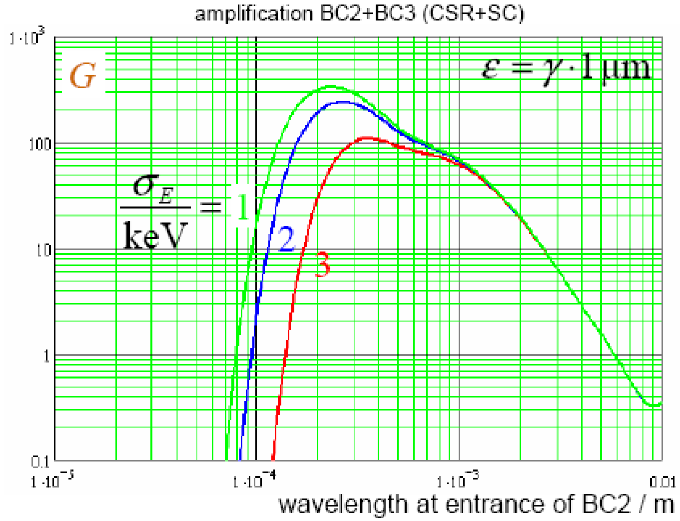
•Significant degradation of the FEL gain length is possible; stability, reproducibility?



Microbunching instability in FLASH? (cont'd)

Amplitude gain





Saldin,Schneidmiller,Yurkov, TESLA-FEL 2003-02

M. Dohlus, presentation at BDM, 30.11.2009

Gain in the range of few hundred: still too small for amplification of shot noise (~10^{-4}) to saturation (~1)

But: it can be dangerous if ripples on laser pulse are converted into beam density modulations, and the latter survive (get frozen in ACC1) at a few per mille level

Do we have to worry?

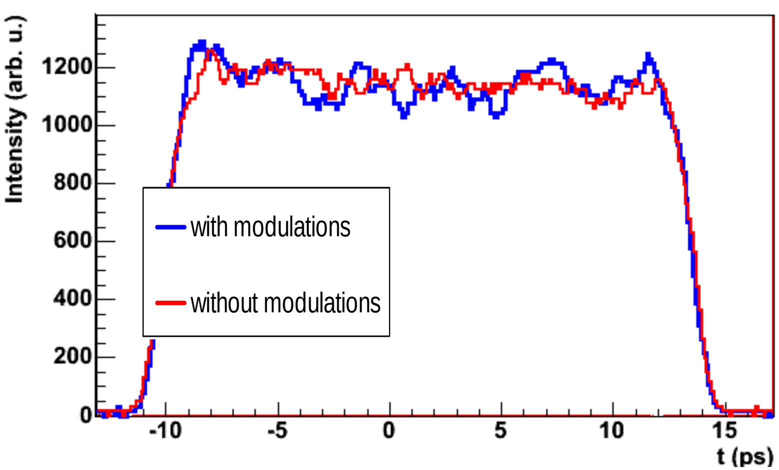
• PITZ results (next slide): phase space modulations show up behind the booster (in qualitative agreement with Astra simulations by Juliane Roensch)
• No guarantee that density modulations will be below per mille level (and no significant energy modulations)

• We have to be prepared for the worst-case scenario: with linearized compression the FEL performance is worse than with roll-over compression
• Plan B: continue working for users with roll-over compression, urgently prepare for installation of laser heater
• Now we can start discussing the choice of LH scheme, checking (numerically) trickle heating etc.

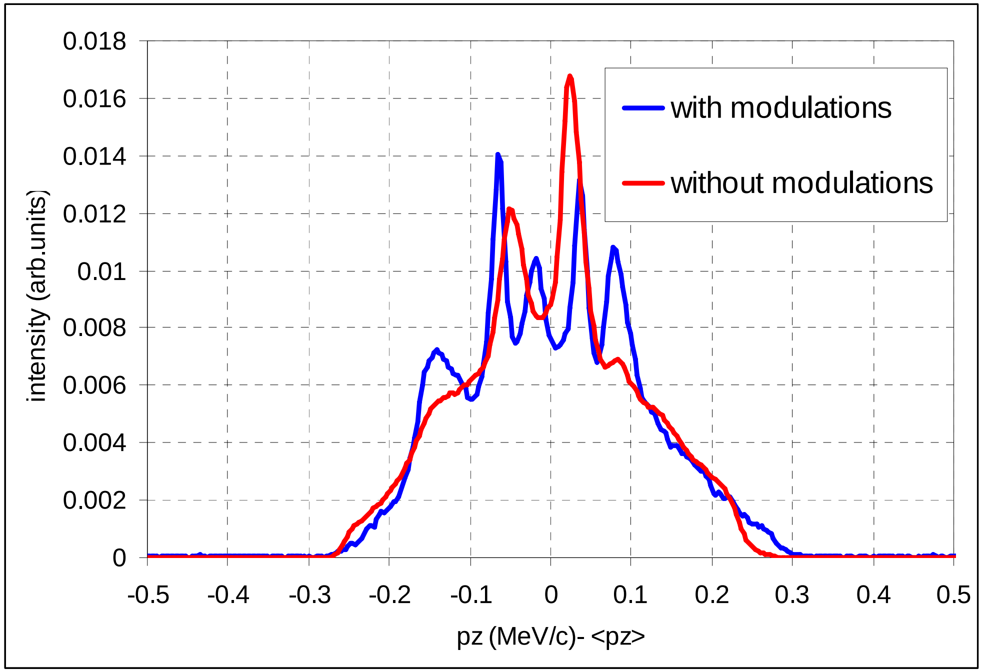
Results from PITZ (courtesy M. Krassilnikov)

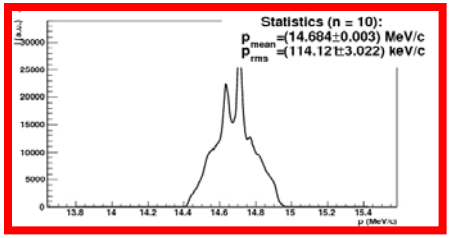
Measurements with and without modulations on the temporal laser distribution (using the medium Lyot filter)

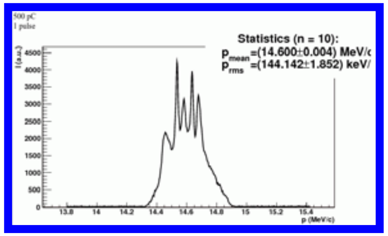
Laser temporal profiles



Electron beam longitudinal momentum distribution

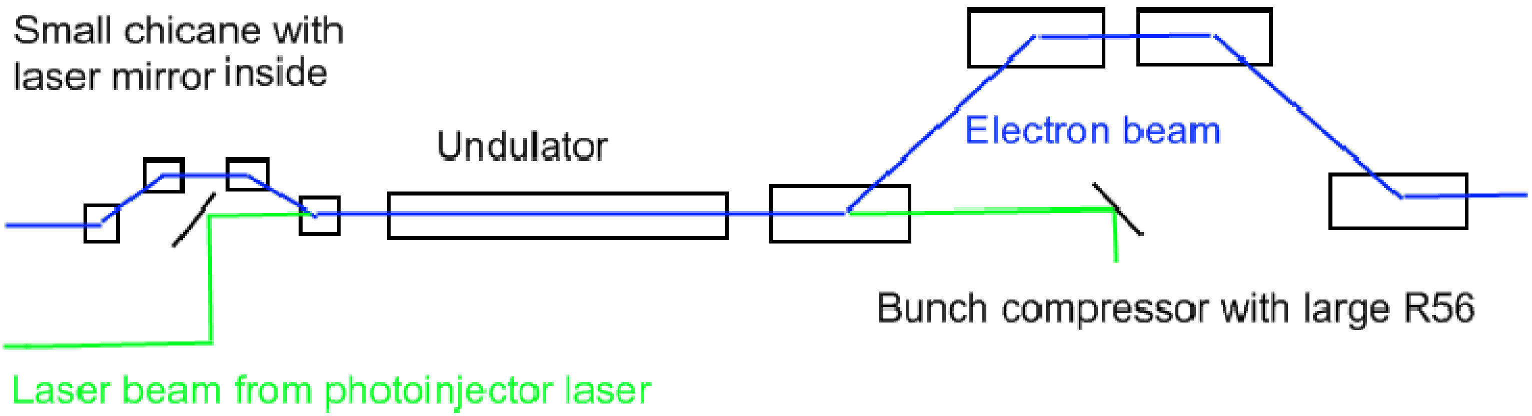






Machine conditions:
- gun – on-crest
- booster -10deg off-crest
- bunch charge 500pC
- 1 (5) laser pulse used

Laser heater for FLASH?



No dispersion in the undulator: no tilt of energy-chirped beam

Does this scheme avoid trickle heating? Safe smearing through BC2 - but what happens inside?

In the first dipole of BC2:

$$R_{51} = \theta \qquad R_{52} = \frac{R\theta^2}{2} \qquad R_{56} = \frac{R\theta^3}{6}$$

Laser heater for FLASH? (cont'd)

In the first dipole of BC2: coherent density modulations may appear due to R_{56}. For laser induced energy modulations about 10 keV the required R_{56} (for strong density modulations) is on the order of 1 mm. For R = 1.6 m this corresponds to the bending angle 0.15 (middle of the dipole). At this position R_{51}= 0.15, R_{52}= 2 cm. For emittance 1 mm mrad and beta about 10 m:

$$\sigma_x R_{51} \approx 30\mu m \qquad \sigma_{x'} R_{52} \approx 0.4\mu m$$

to be compared with $\lambda/(2\pi) \approx 0.08\mu m$ for green light.

The tilt parameter $(\gamma\theta)^2 = (\gamma R_{51})^2 \approx 10^3$ for "tilted LSC" (not applicable in bends)

CSR is strongly suppressed due to transverse size $\sigma_x \;>>\; (\lambda/2\pi)^{2/3} R^{1/3}$

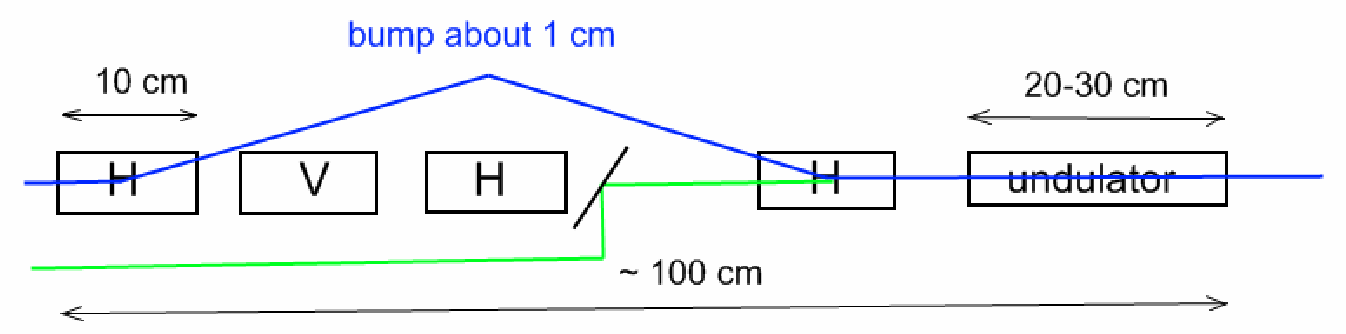
and large tilt $\theta >> (\lambda/2\pi R)^{1/3}$

R_{51} and R_{52} quickly increase along the compressor and smear modulations through the whole compressor, except very end – but there we have strong (and irreversible!) smearing due to R_{56} = 20 cm.

No self-heating is expected - to be checked with codes like CSRtrack

LH without moving BC2 downstream?

- Sacrifice some diagnostics (BPM, BAM, toroid)
- There is about 107 cm between Q1.3UBC2 and the bellow
- Install short (20-30 cm) undulator: 5-10 periods, period length 3-5 cm (depending on chosen laser wavelength – better green than IR)
- Install two additional horizontal steerers, rearrange steerer positions
- OTR screen in front of the undulator? – might fit (downstream we can use the OTR in the straight section of BC2)



- Alternative compact (but not optimal) solution: send laser beam with an angle of a few mrad w.r.t. undulator axis, adjust resonance. Might be difficult to commission and operate. Size not matched (elliptical laser beam to match at least vertical size?).

Laser heater for European XFEL

Issues in the present design:

• Energy chirp might be too large for 10 periods of the undulator: bunch edges not sufficiently heated (noticed by P. Emma)
• Tilted beam in the undulator due to energy chirp and dispersion: double horn in energy distribution within a slice due to non-matched laser beam size
• Trickle heating (being investigated by M.Dohlus)

Design might have to be re-considered!

Conclusions

- Microbunching instability may have a significant impact on x-ray FEL operation (proven at LCLS)
- LCLS laser heater is successfully used to optimize FEL performance
- Trickle heating has to be avoided in other LH designs
- First principle codes for calculations of EM fields (like CSRtrack) should be used to check if trickle heating is possible in a given setup
- Alternative schemes of laser heater might be considered
- Harmful microbunching instability in FLASH is not excluded, we must be prepared
- Design of laser heater for the European XFEL might have to be re-considered (tilted beam, trickle heating)

Acknowledgements

We would like to thank M. Dohlus, P. Emma, Z. Huang, M. Krassilnikov, T. Limberg, and J. Roensch for useful discussions.