

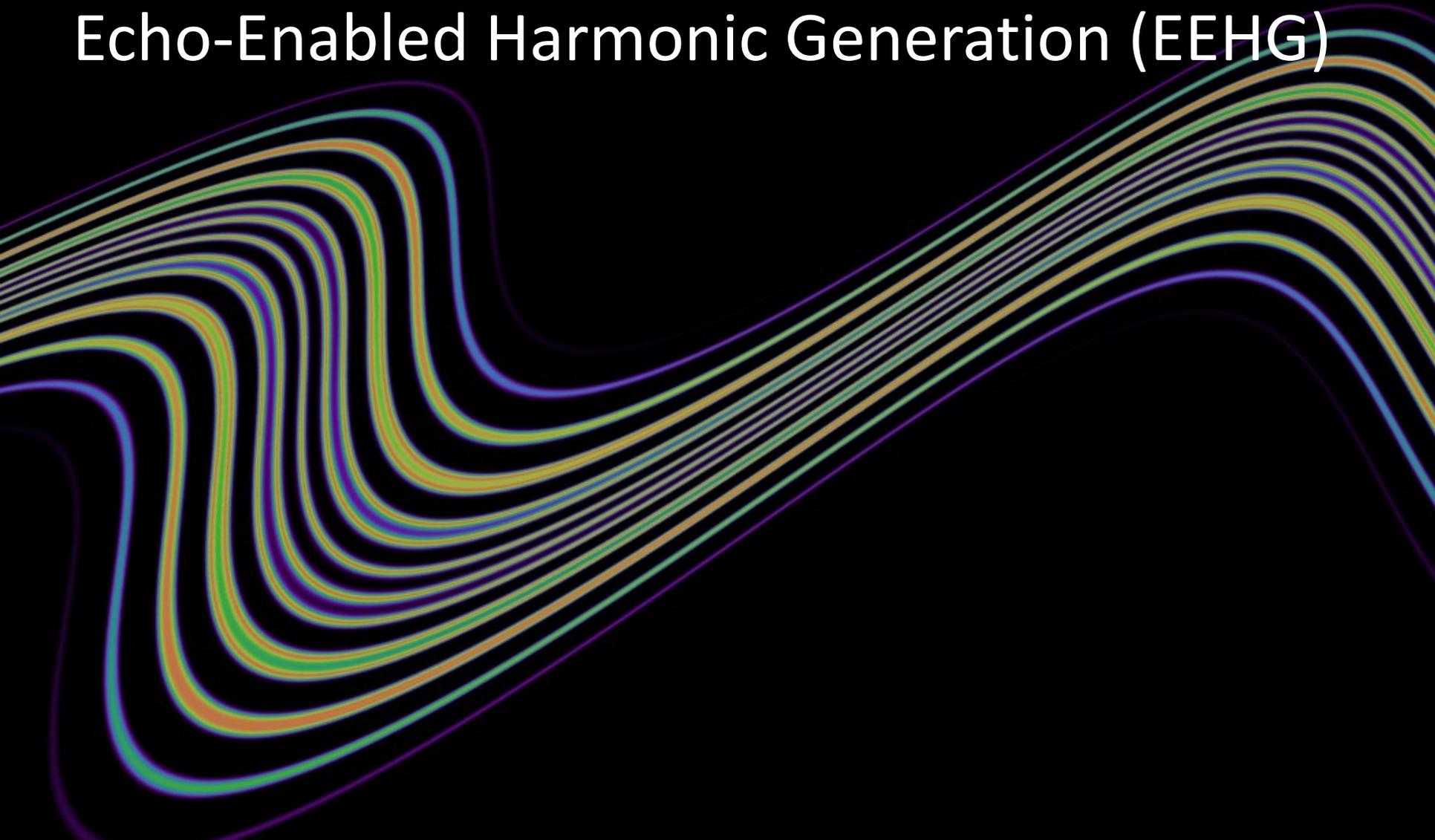
EEHG Seeding Development

Christoph Lechner, MPY

FEL Seminar

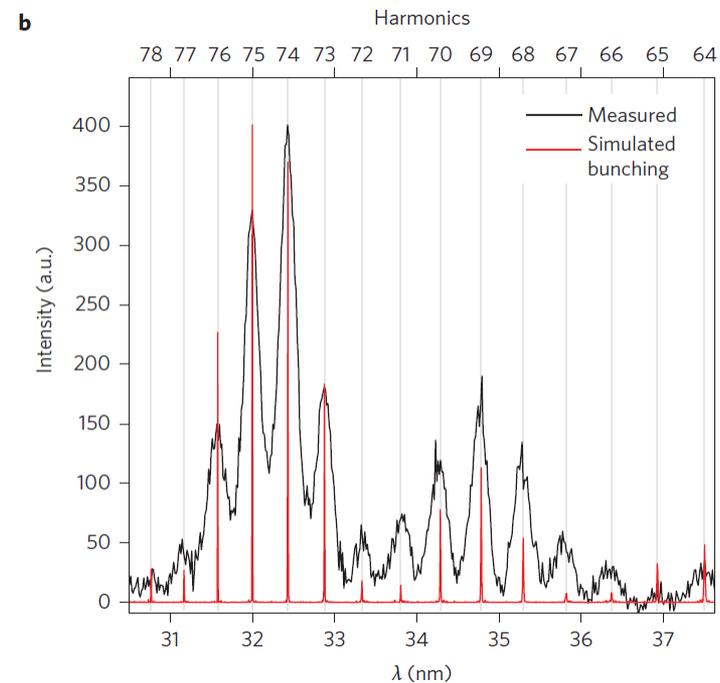
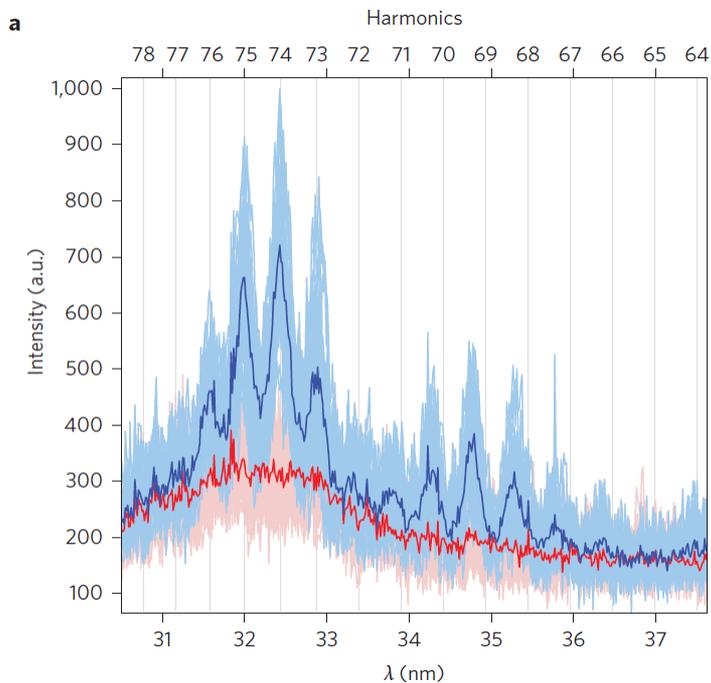
April 18, 2017

Echo-Enabled Harmonic Generation (EEHG)



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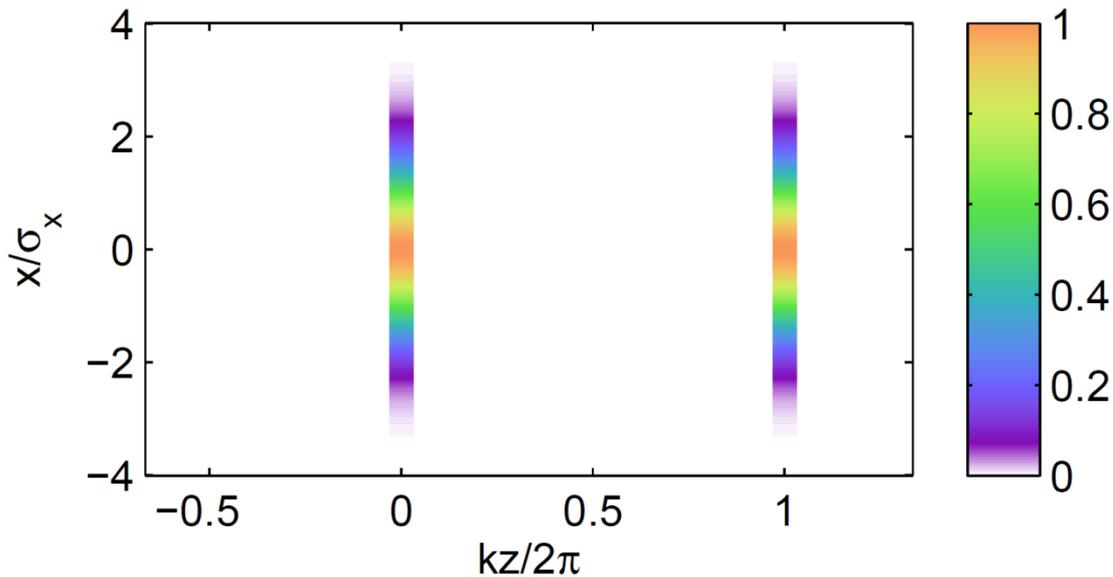
- Proposed in 2009 by G. Stupakov
- More experimental effort:
two modulators, two chicanes, two laser pulses
- But: EEHG enables seeding at higher harmonics



Bunching Factor

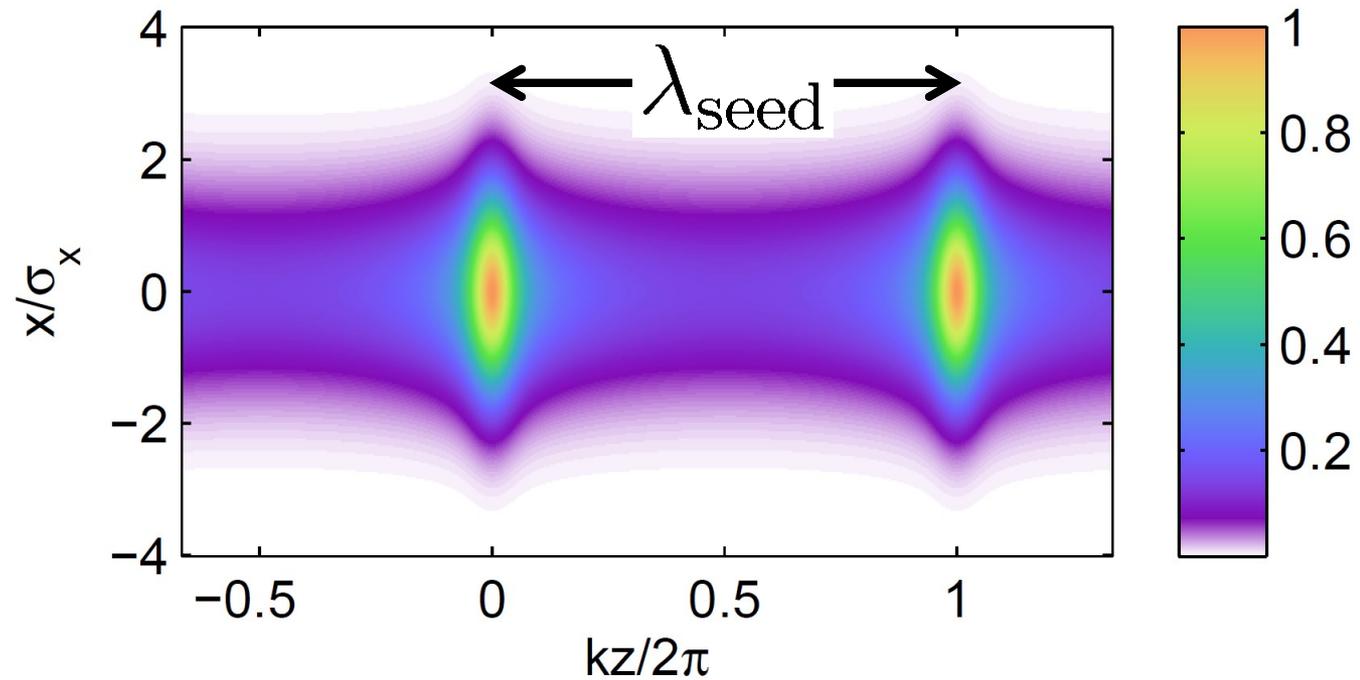
The “bunching factor” quantifies the longitudinal, periodic density modulation of the electron beam

$$b = |\langle \exp(ikz) \rangle|$$

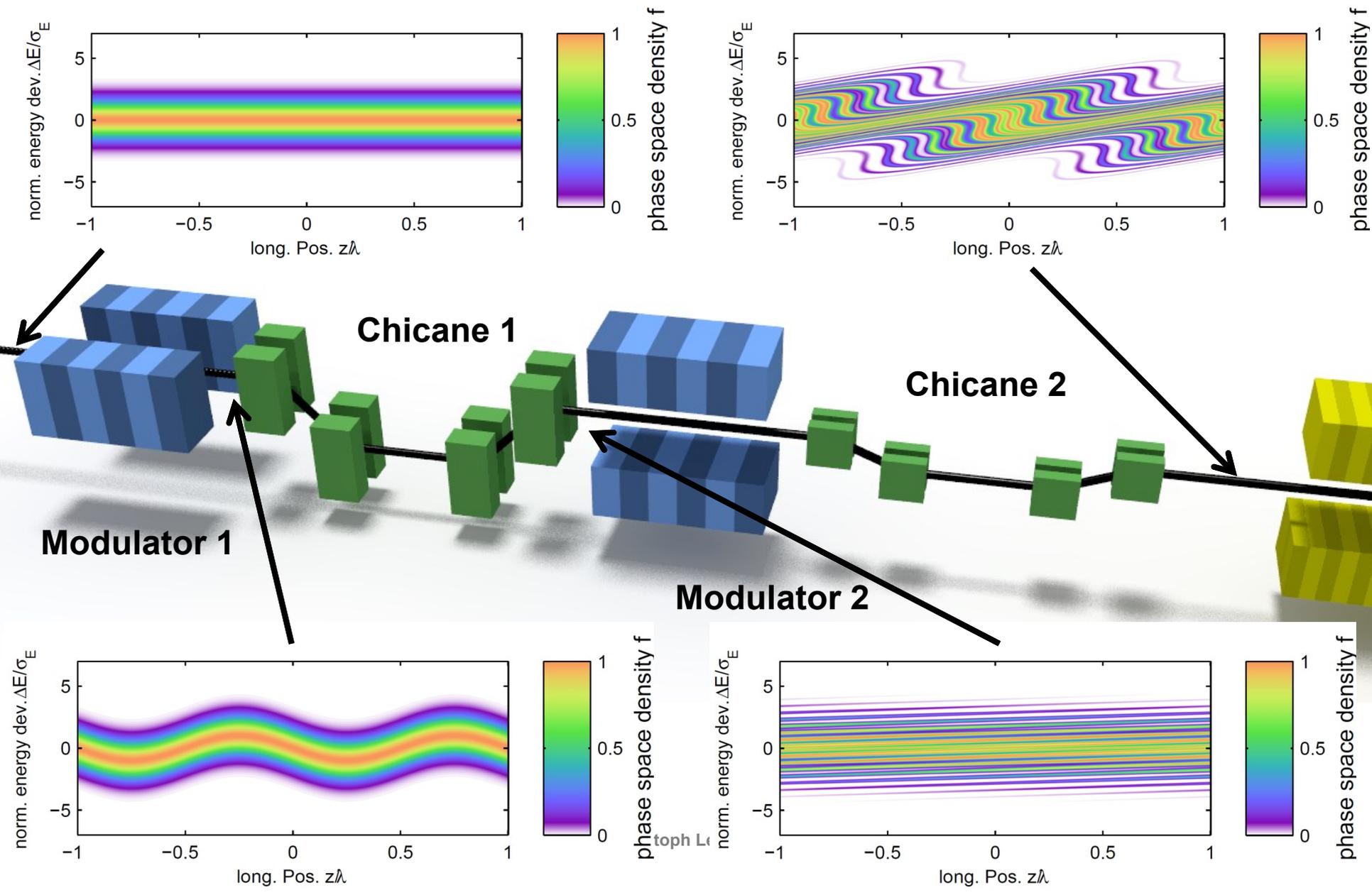


$$b \approx 1$$

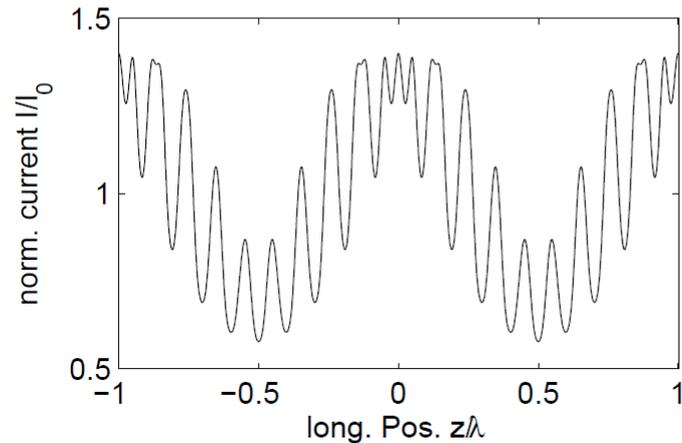
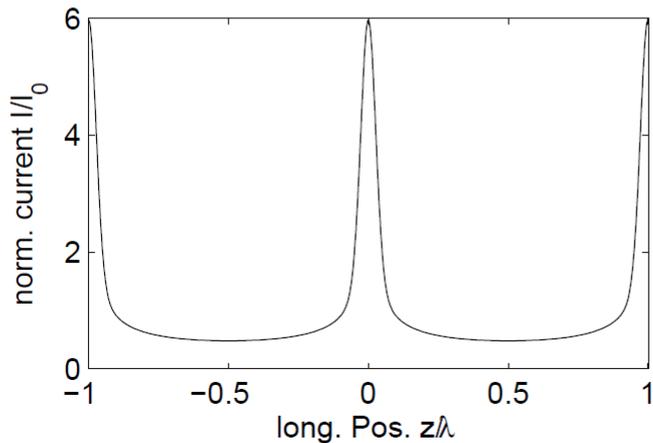
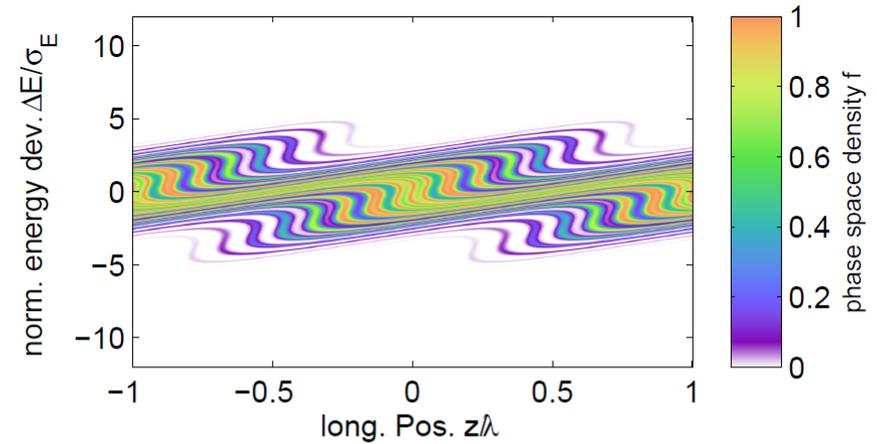
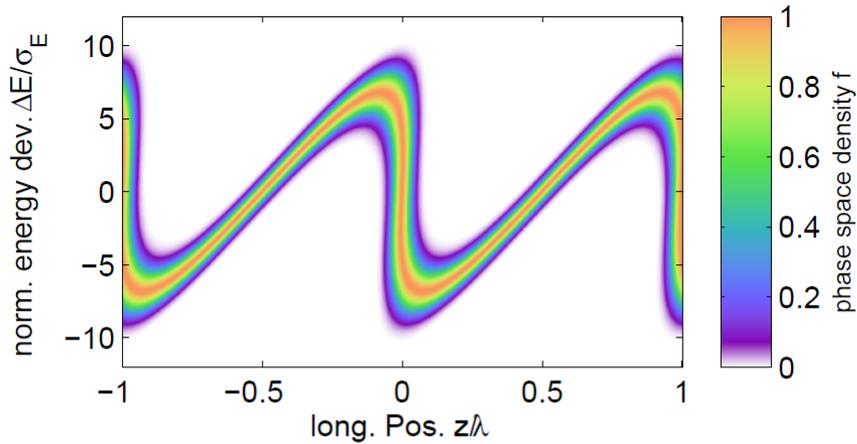
Realistic Phase-Space Distribution



EEHG: Manipulation of Phase Space



Comparison of HGHG and EEHG Seeding



Both distributions have identical bunching on $h=10$

$$\sigma_E = 4.9\sigma_{E,0}$$

$$\sigma_E = 1.4\sigma_{E,0}$$

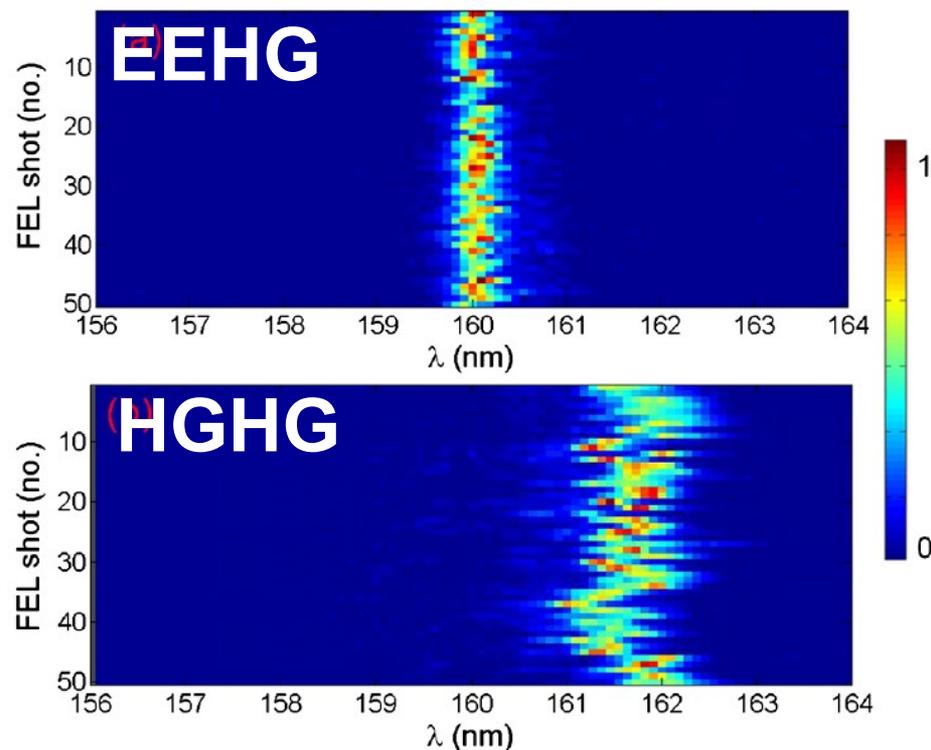


Comparison of HGHG and EEHG Seeding

- Significantly smaller contribution to slice energy spread than for HGHG
 - Enables seeding at significantly higher harmonics
- Electron beam imperfections have smaller impact on generated photons
- Superior FEL performance expected
- Higher bunching efficiency

Spectra of seeded
undulator radiation

NLCTA @SLAC



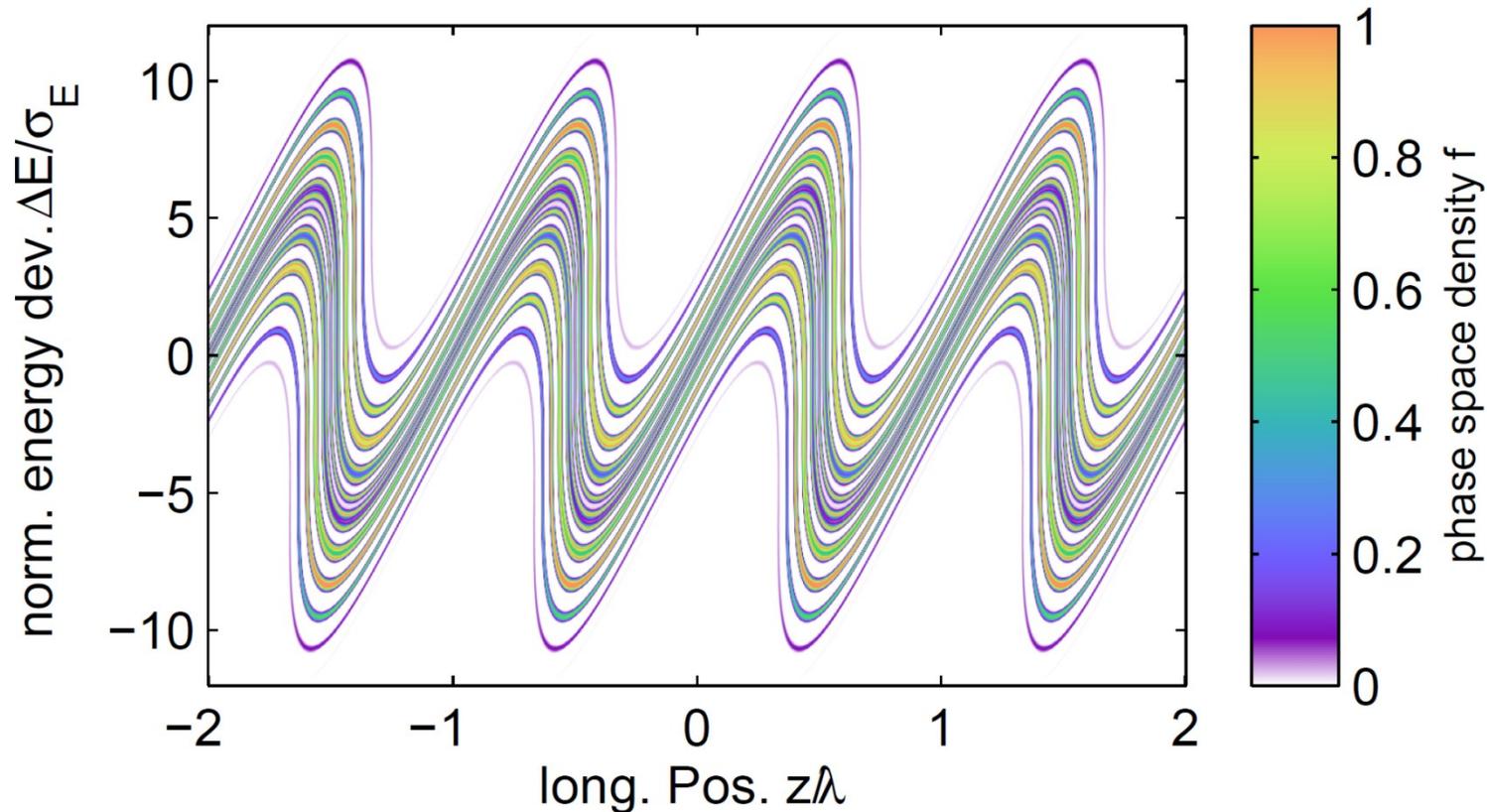
What makes EEHG “Energy-Spread Efficient”?

Example:

final rms slice energy spread
951 keV

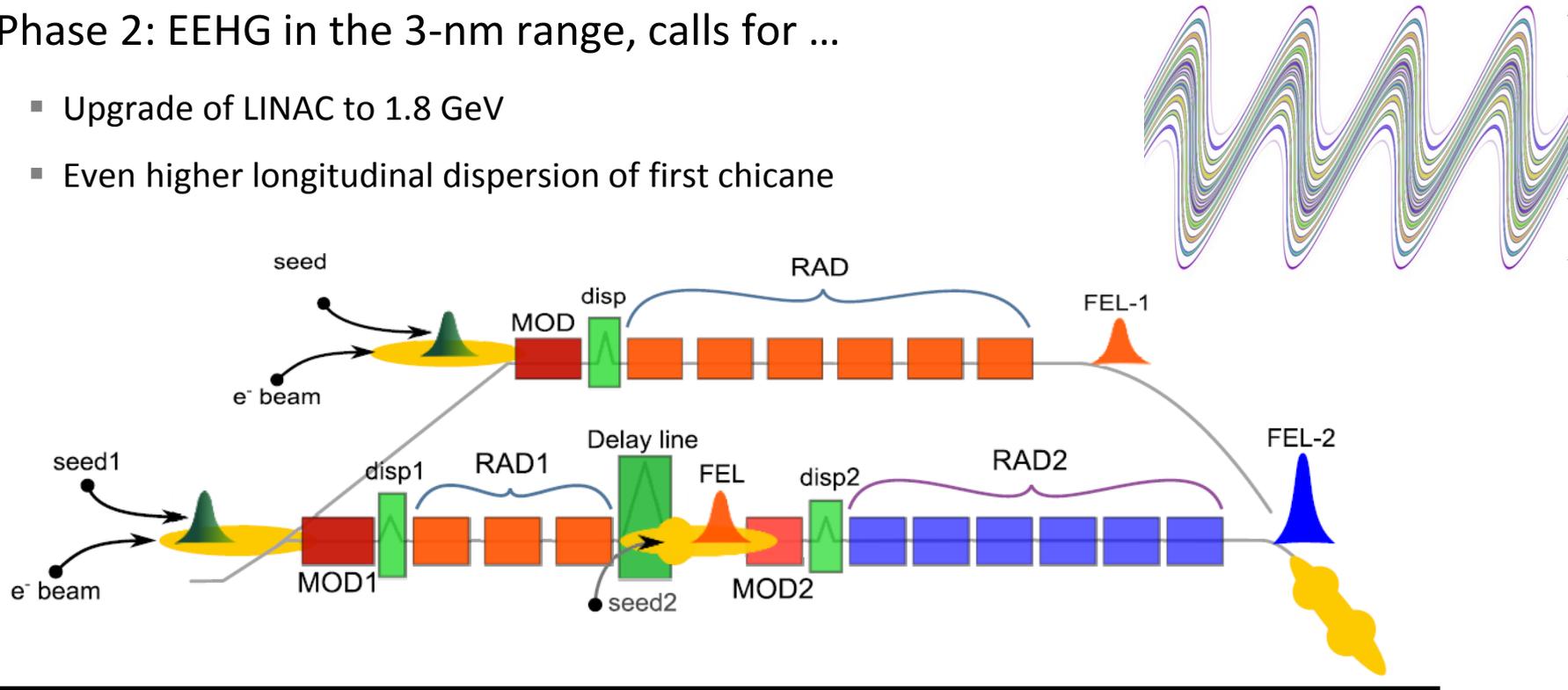
➤ $E_0=1400$ MeV, $\sigma_E=150$ keV

➤ 260-nm seed laser, $\Delta E_1=450$ keV, $\Delta E_2=824$ keV, $R_{56,1}=2.1$ mm, $R_{56,2}=74$ μm

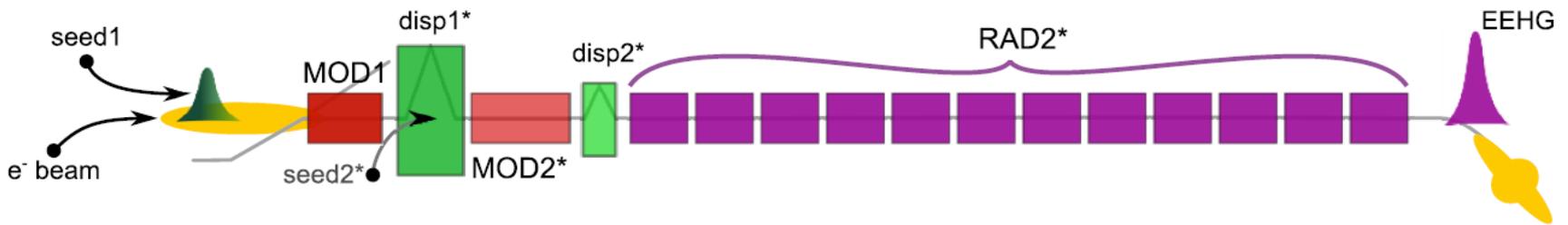


EEHG Plans at FERMI@Elettra

- > Phase 1: EEHG at $\lambda=5.2$ nm (50th harmonic of 260-nm seed laser)
- > Phase 2: EEHG in the 3-nm range, calls for ...
 - Upgrade of LINAC to 1.8 GeV
 - Even higher longitudinal dispersion of first chicane



Upgrade under consideration



b)

EEHG Window of Opportunity

LETTERS

PUBLISHED ONLINE 13 MAY 2012 | DOI: 10.1038/NPHOTON.2012.105

nature
photonics

First lasing of an echo-enabled harmonic generation free-electron laser

Z. T. Zhao^{1*}, D. Wang¹, J. H. Chen¹, Z. H. Chen¹, H. X. Deng¹, J. G. Ding¹, C. Feng¹, Q. Gu¹, M. M. Huang¹, T. H. Lan¹, Y. B. Leng¹, D. G. Li¹, G. Q. Lin¹, B. Liu¹, E. Prat², X. T. Wang¹, Z. S. Wang¹, K. R. Ye¹, L. Y. Yu¹, H. O. Zhang¹, J. Q. Zhang¹, Me. Zhang¹, Mi. Zhang¹, T. Zhang¹, S. P. Zhong¹ and Q. G. Zhou¹

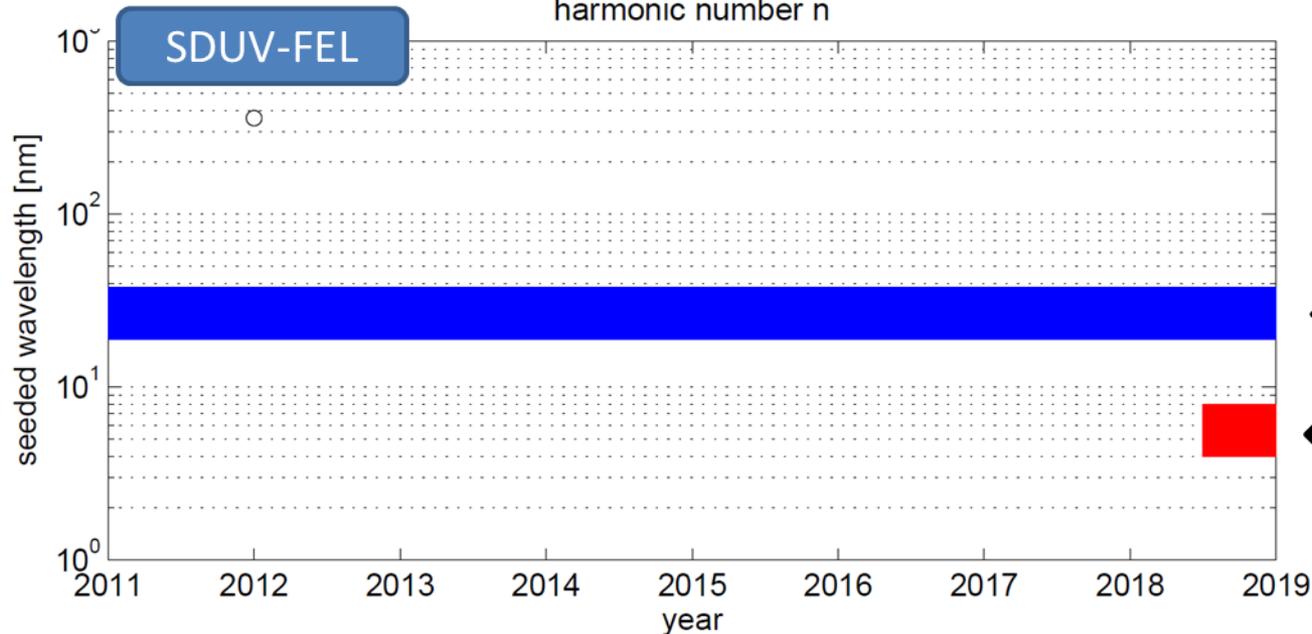
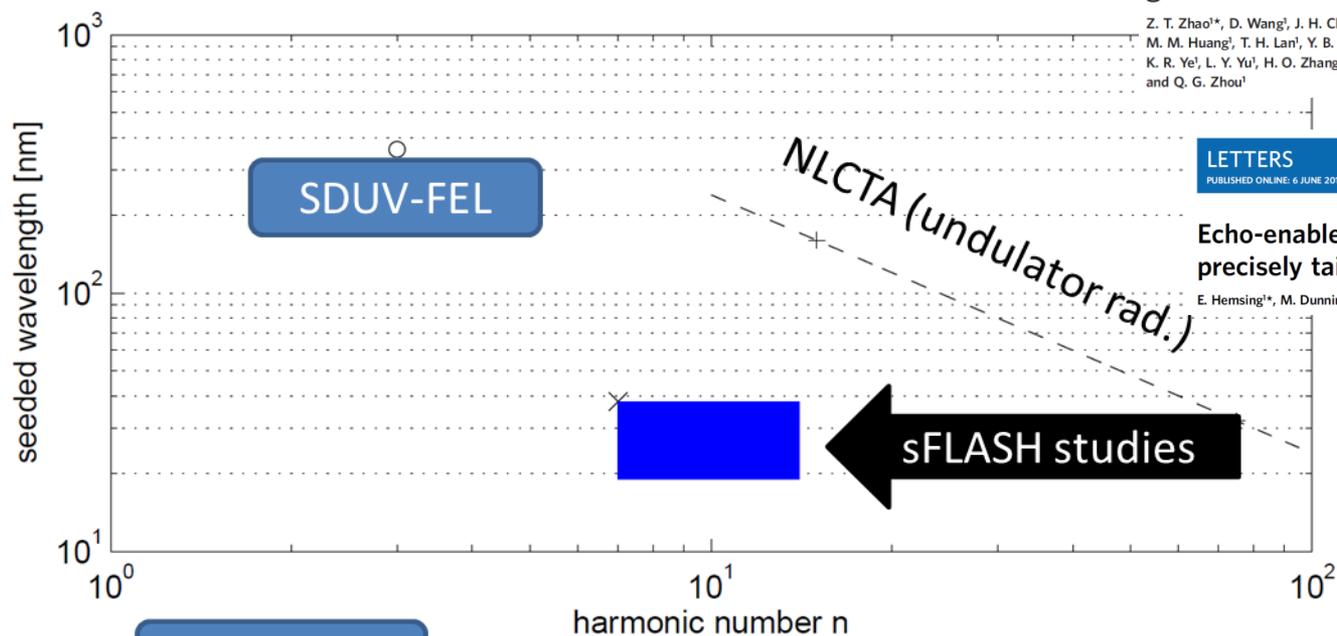
LETTERS

PUBLISHED ONLINE 6 JUNE 2016 | DOI: 10.1038/NPHOTON.2016.101

nature
photonics

Echo-enabled harmonics up to the 75th order from precisely tailored electron beams

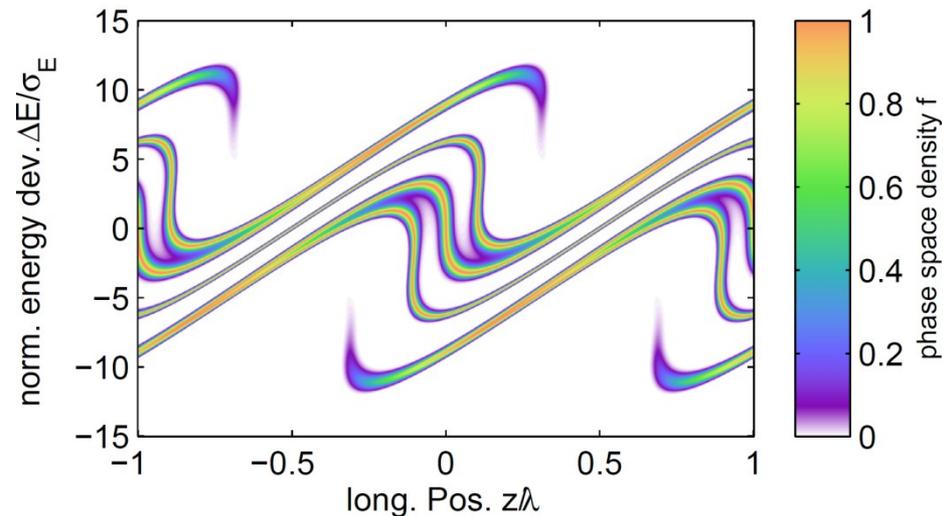
E. Hemsing^{1*}, M. Dunning¹, B. Garcia¹, C. Hast¹, T. Raubenheimer¹, G. Stupakov¹ and D. Xiang^{2,3*}



Choice of Parameters

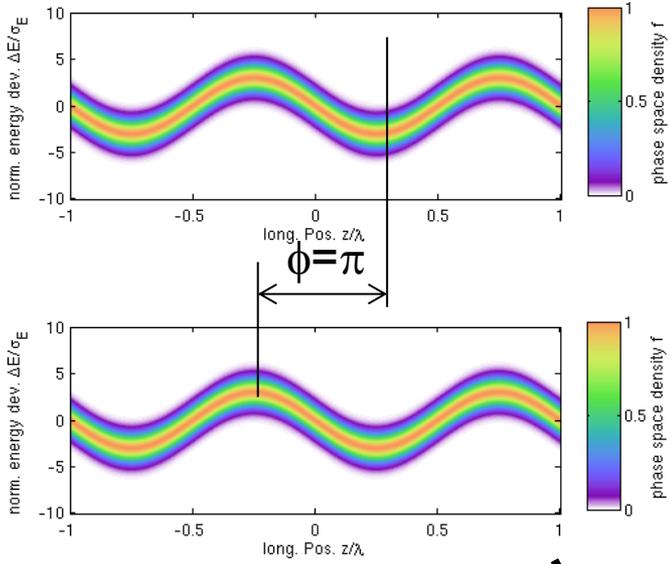
Parameters based on demonstrated HGHG seeding:

- Electron beam parameters: $\sigma_E=70$ keV, $E_0=700$ MeV
- Seed laser modulation amplitudes $\Delta E_1=\Delta E_2=350$ keV
- Maximum R_{56} of chicanes: $R_{56,1}=600$ μm , $R_{56,2}=150$ μm
- Example: 10th harmonic (26.7 nm)
- Possible parameter set: $R_{56,1}=430$ μm , $R_{56,2}=110$ μm

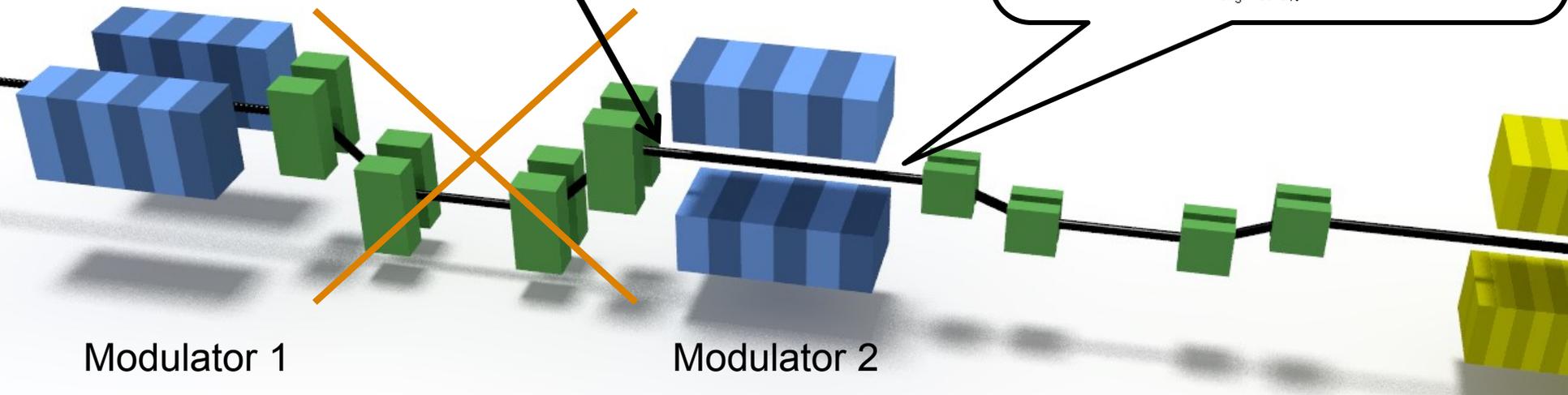
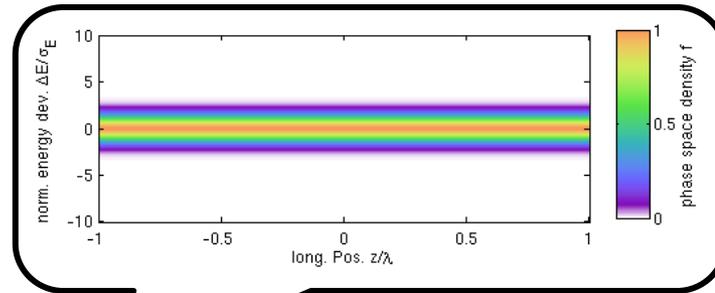


Definition of ϕ

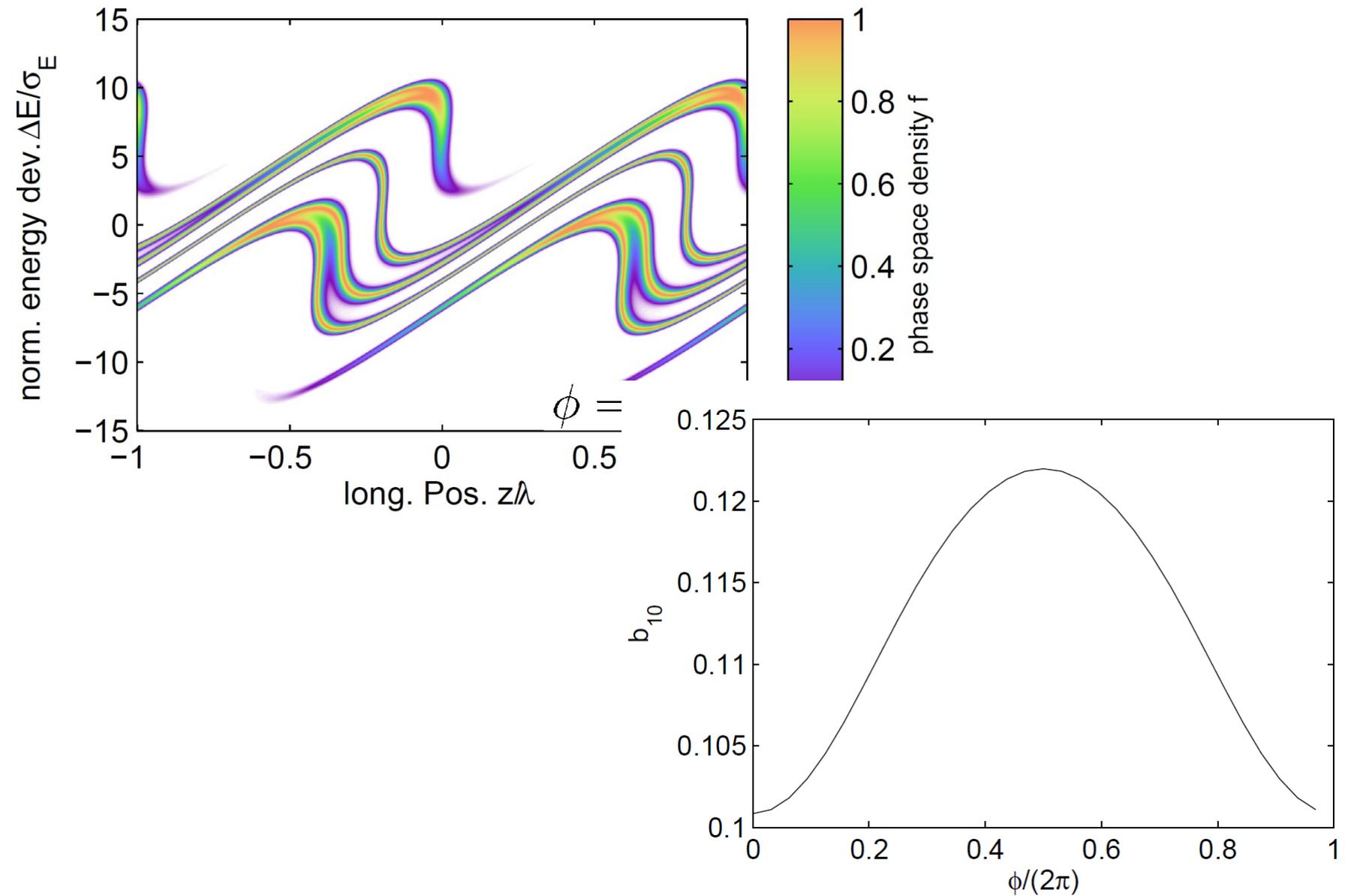
Modulation going to be added in Modulator 2



Modulation from Modulator 1

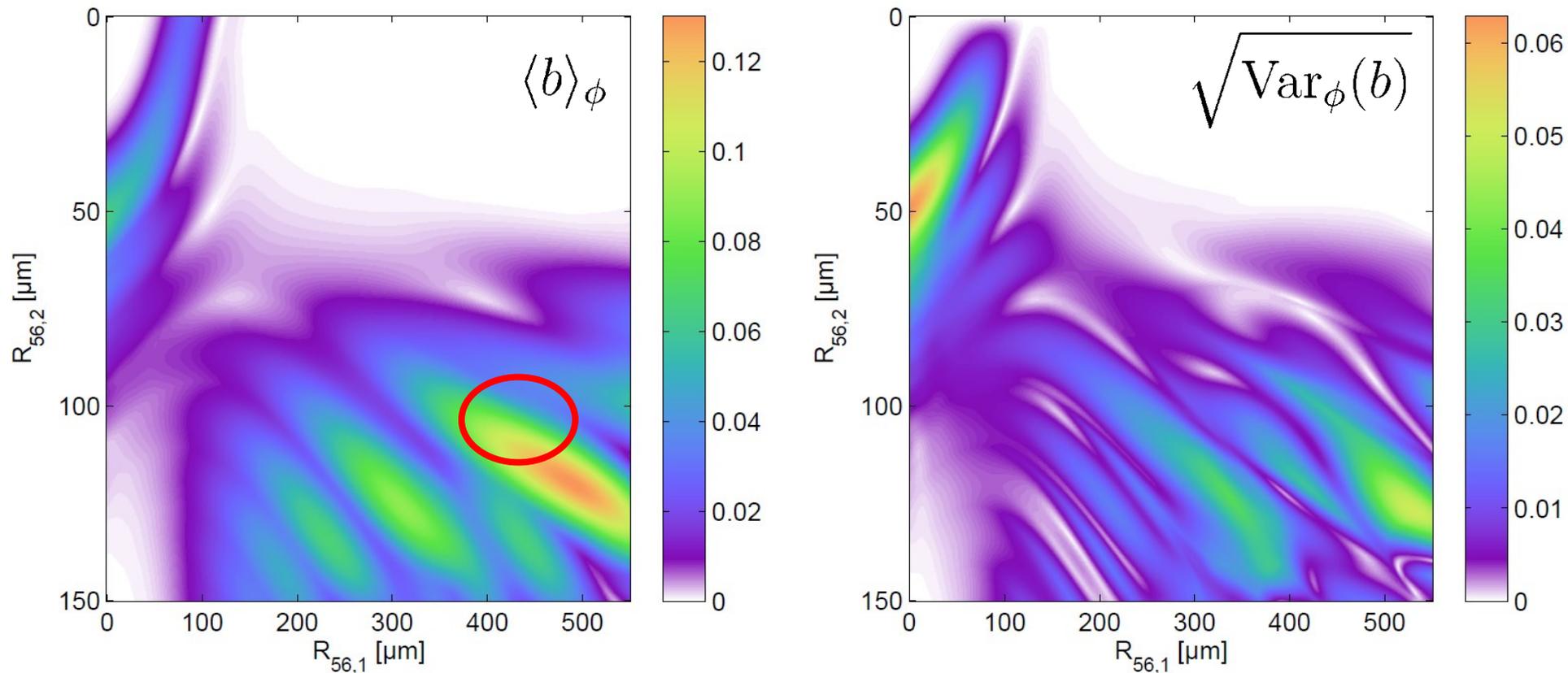


Impact of Phase ϕ

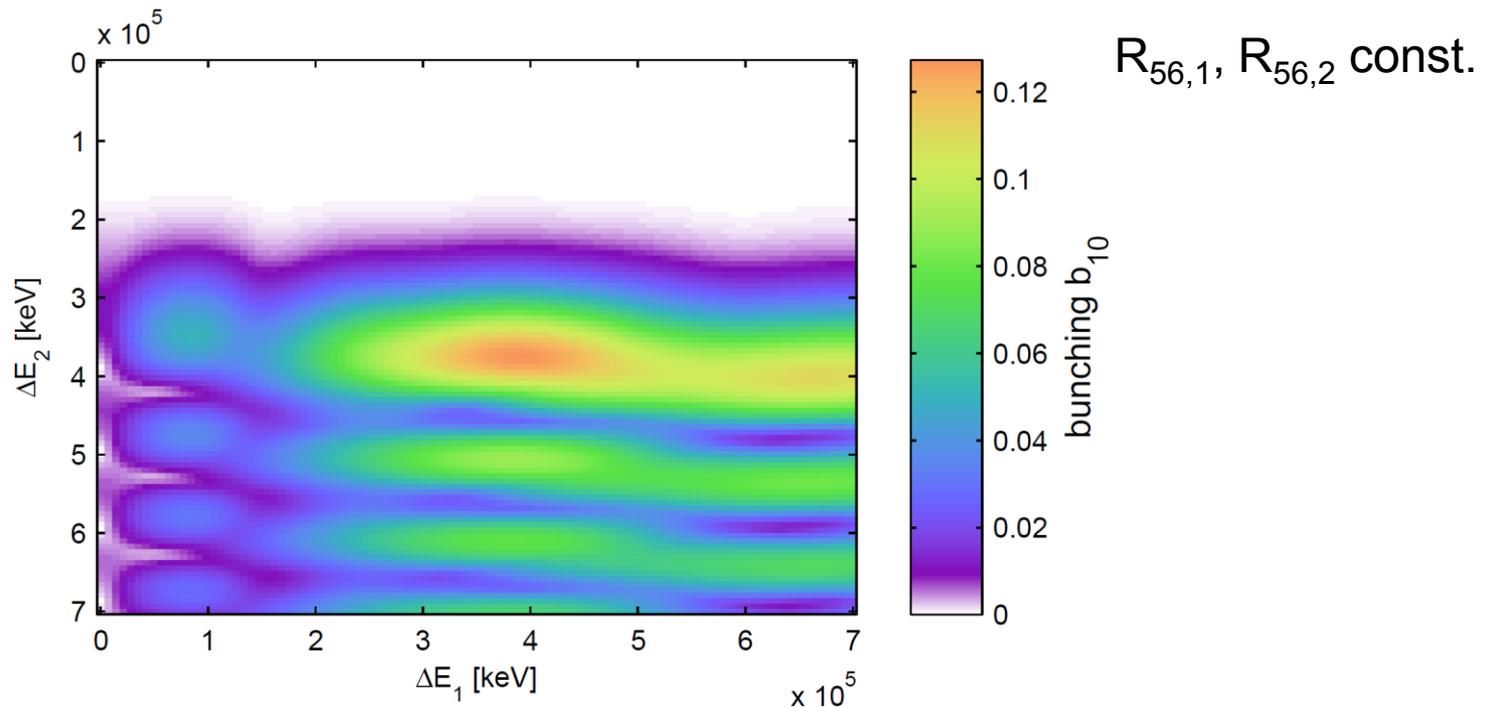


Bunching Map (10th Harmonic)

- Phase ϕ relevant for low-dispersion chicanes (as in sFLASH experiment)
- Perform statistics over ϕ ... (see also: TESLA-FEL 2011-05)



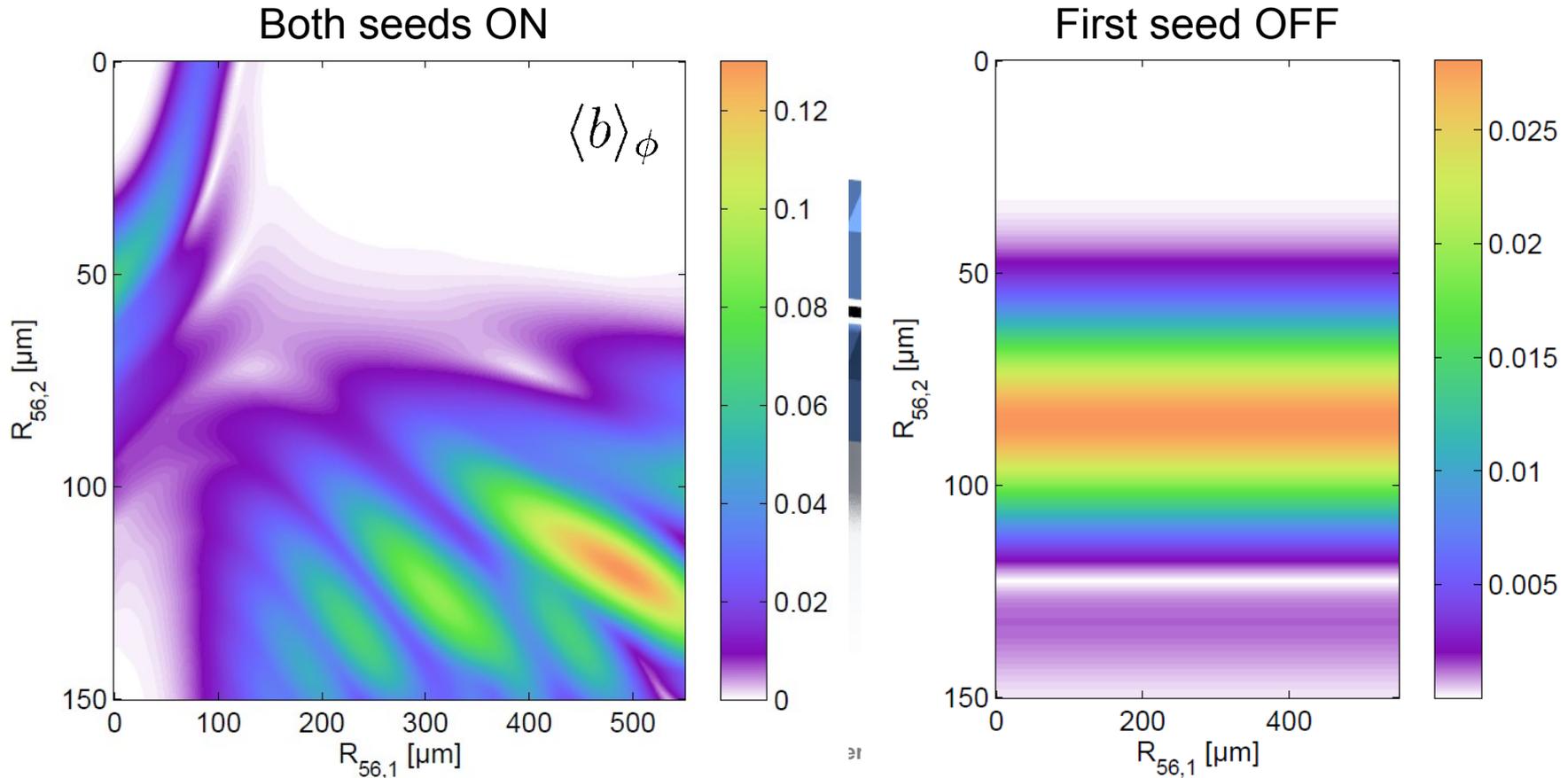
Tolerance Analysis



- Acceptable deviations in ΔE_2 comparable to HGHG at $h=10$ (307 keV ... 425 keV for 50% bunching drop)
- Relaxed tolerances in ΔE_1 (210 keV ...)
- ΔE_1 and ΔE_2 expected to be dominant source of shot-to-shot deviations
 - Still, combined tolerance analysis in all parameters required (modulation amplitudes, chicanes)

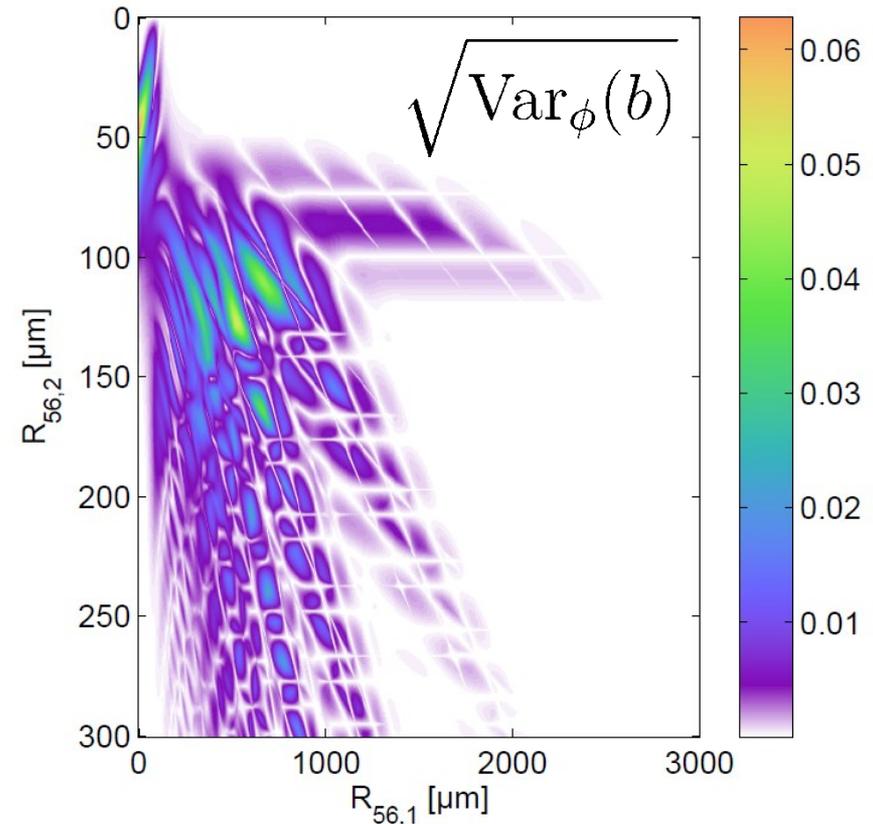
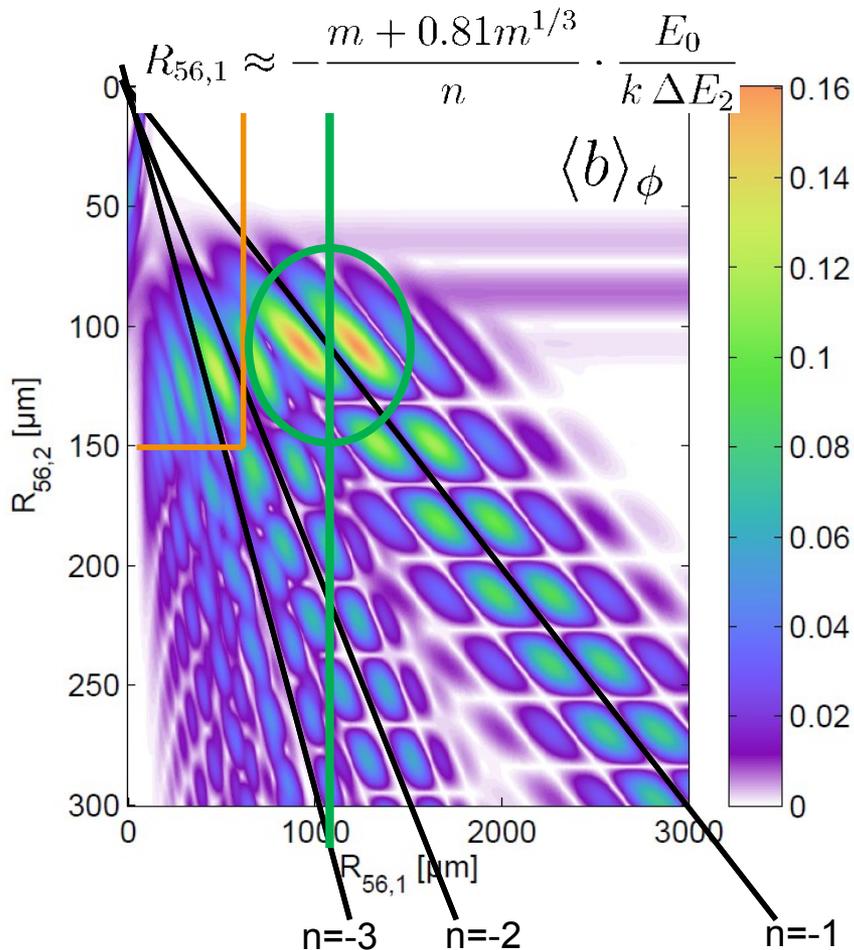
Discrimination of EEHG and HGHG (h=10)

- HGHG from first modulator is suppressed by the strong first chicane
- HGHG from second modulator: not fully suppressed
 - HGHG suppressed for $h \gg 10$



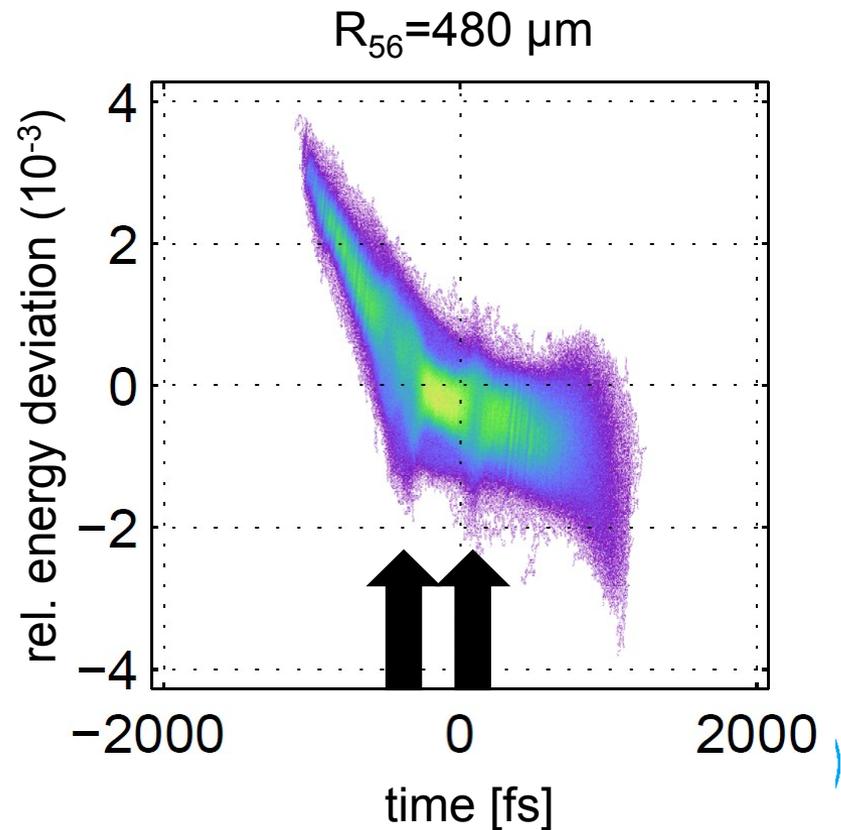
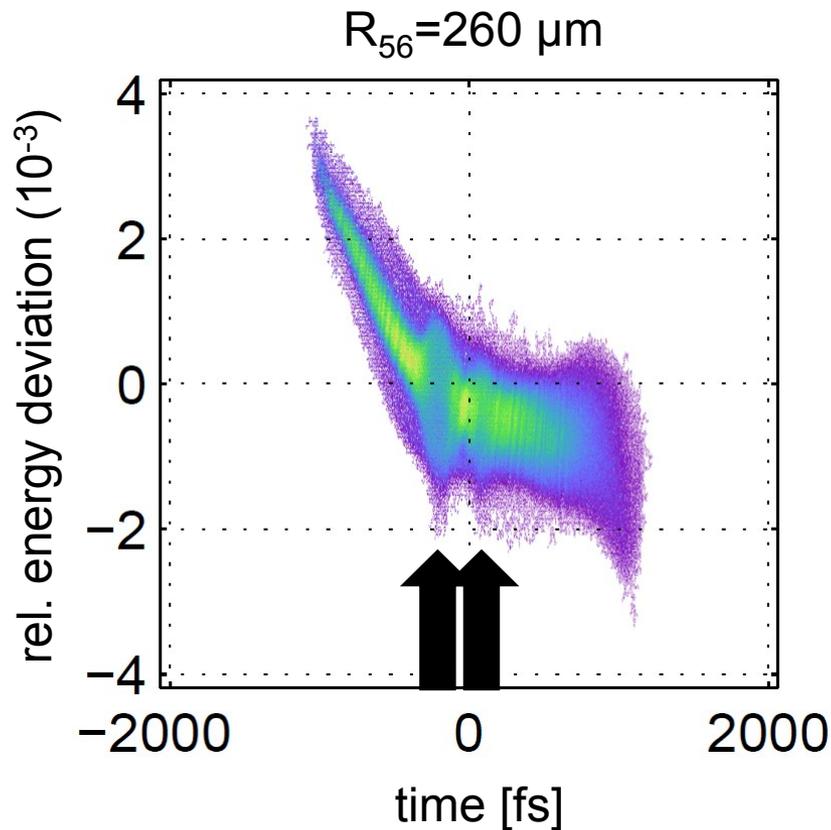
If we had a stronger chicane ...

- Efficient bunching at high harmonics (with present chicane: need higher energy modulation amplitude)
- ϕ effects become negligible



First Steps

- Overlap of electron beam and single laser pulse in both modulators
- Longitudinal dispersion of first chicane delays electron beam w.r.t. to laser pulse
- Data analysis ongoing ...



EEHG at sFLASH

- Upgrade of seed laser system with second, independent UV seed source
- Injection of both seed pulses through same beam line
- Beam combiner element (thin film polarizer, TFP) successfully tested



Experimental Procedure

- > Challenge: find the 'island' in multi-dimensional parameter space
- > Match electron beam into ORS and SFUND
 - Only quads are Q1ORS and Q2ORS
 - All other magnets are cycled to exclude detrimental effects from kicks
- > Define reference positions on screens using seed laser beam
 - Used to align electron beam
- > Setup CHG (with 266-nm seed) at desired harmonic (use second chicane)
 - Determine correct undulator gap and orbit
 - Estimates energy modulation amplitude in both modulators
- > Set the chicanes to chosen operating point
- > Scan the energies of the seed laser pulses to find the island
- > Optimize EEHG-driven emission from undulators



- > Echo-Enabled Harmonic Generation seeding scheme
- > EEHG results
- > EEHG at sFLASH
 - Specific issues at sFLASH
 - Experimental program



- > Tolerance studies (bunching generation mechanism)
- > Beam dynamics considerations
 - Effect of incoherent synchrotron radiation
 - Chicane imperfections (R_{51} , R_{52} effects)
 - Collective effects: coherent synchrotron radiation (CSR), longitudinal space-charge effects (LSC)
- > Simulations of EEHG-seeded FEL process
 - Complex structures in longitudinal phase-space



Thank you for your attention

