Laser seeding of electron bunches for future ring-based light sources

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TU Dortmund University, Germany

Introduction

Ring-based synchrotron light sources

+ large number of facilities (~50)
+ multiple beamlines
+ high repetition rate
+ high stability
– incoherent emission (low brightness)
– long bunches (long radiation pulses)

MAX IV, Sweden (Wikipedia, image by D. Castor)

Linac-based high-gain FELs

– only 8 user facilities worldwide
– single(few)-user facilities
– low repetition rate
– larger shot-to-shot variations
+ extremely high brightness
+ short bunches (short pulses)

SACLA, Japan

Radiation power

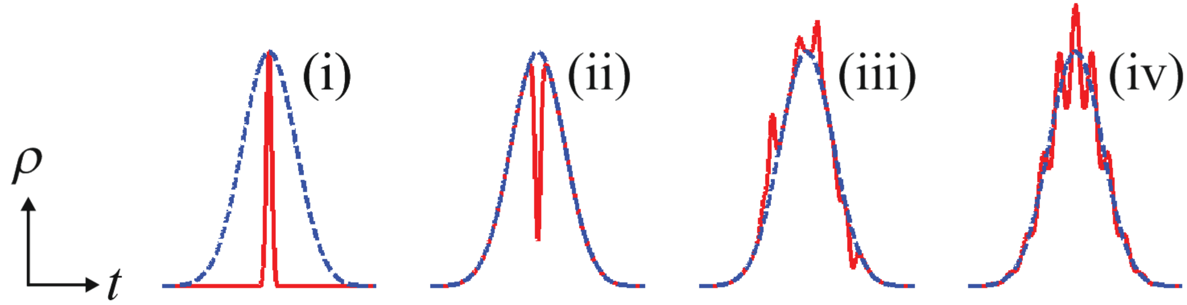
$$P(\omega) = n_e \cdot P_e(\omega) + n_e(n_e - 1) \cdot g^2(\omega) \cdot P_e(\omega)$$

incoherent + coherent emission

Introduction

Coherent emission

(i) short bunch
(ii) short dip
(iii) fluctuations
(iv) microbunching



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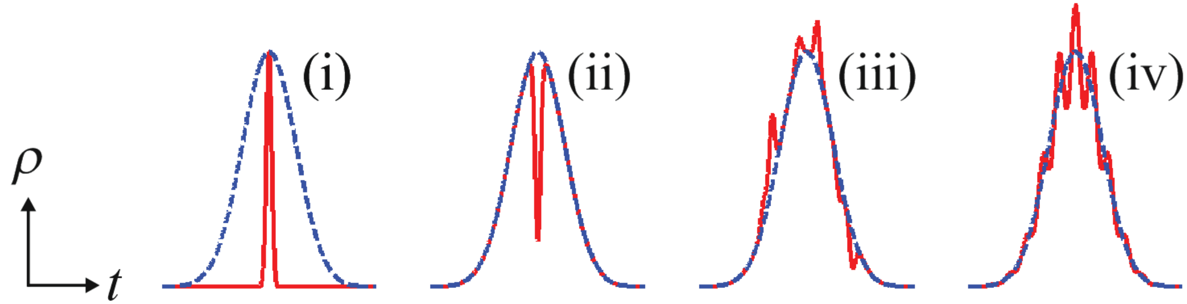
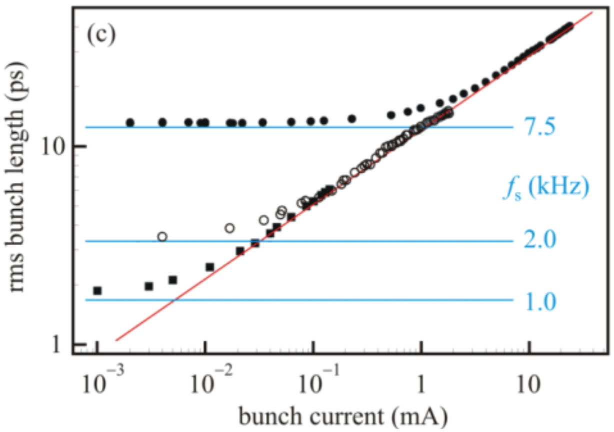


Example:
low-α operation → coherent emission of THz radiation

e.g. M. Abo-Bakr et al., PRL 88, 254801 (2002)



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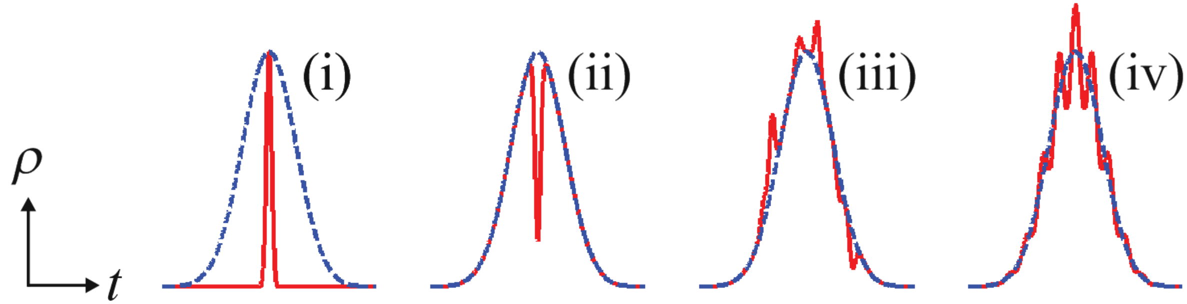

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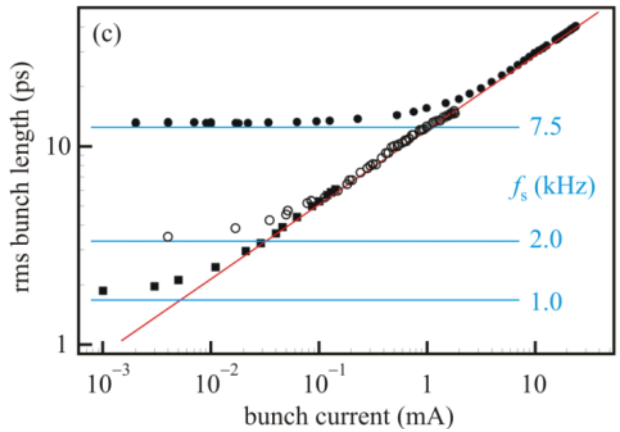

Microbunching in storage rings

– velocity bunching, FEL amplification, wake fields (?)
+ energy modulation + dispersion (similar to FEL seeding)

$$\Delta z = r_{51} \cdot \Delta x + r_{52} \cdot \Delta x' + r_{56} \cdot \Delta E / E$$

Radiation power

$$P(\omega) = n_e \cdot P_e(\omega) + n_e(n_e - 1) \cdot g^2(\omega) \cdot P_e(\omega)$$

incoherent + coherent emission

Short-pulse generation

Starting point:

- laser seeding (energy modulation) of a short "slice" (1/1000 of the bunch length)

Applications:

- femtoslicing (ALS, BESSY, SLS, SOLEIL)
- coherent harmonic generation CHG (ACO, UVSOR, Elettra, DELTA)
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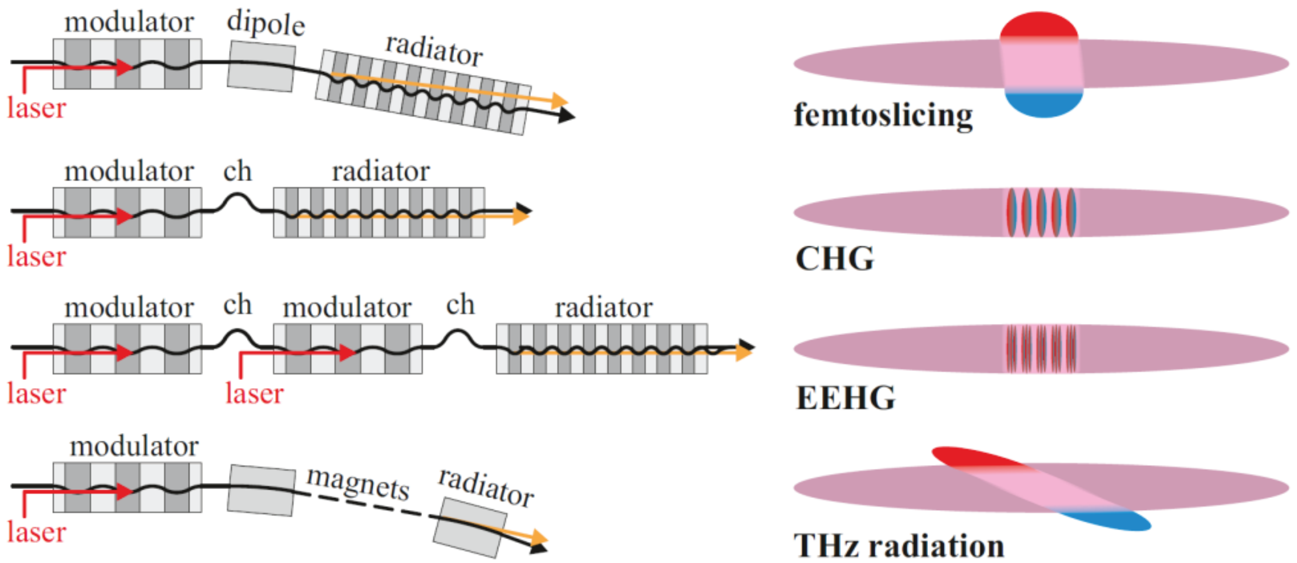

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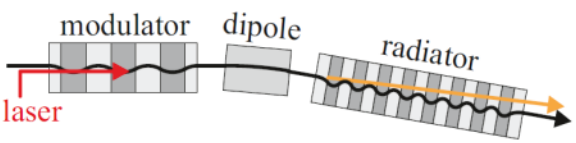

A. Zholents, M. Zolotorev, PRL 76, 912 (1996)
R. W. Schoenlein et al., Science 287, 2237 (2000)
S. Khan et al., PRL 97, 074801 (2006)
P. Beaud et al., PRL 99, 174801
M. Labat et al., J. Sync. Rad. 25, 385 (2018)

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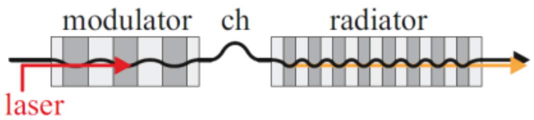
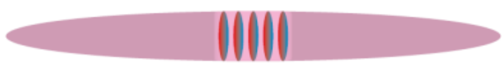


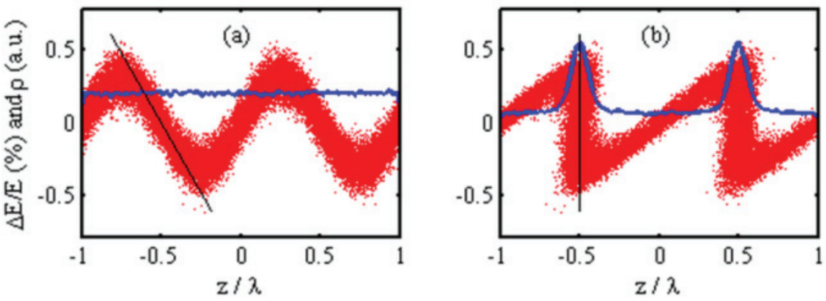


B. Girard et al., PRL 53, 2405 (1984)
M. Labat et al., Eur. Phys. J. D 44, 187 (2007)
G. de Ninno et al., PRL 101, 053902 (2013)

Signal-to-background ratio:

$$\frac{P_{\text{short}}}{P_{\text{long}}} = \frac{n_{\text{short}}^2 \cdot b^2}{n_{\text{long}}} = f^2 \cdot n_{\text{long}} \cdot b^2$$

$$n_{\text{short}} = f \cdot n_{\text{long}} \approx 10^{-3} \cdot n_{\text{long}}$$



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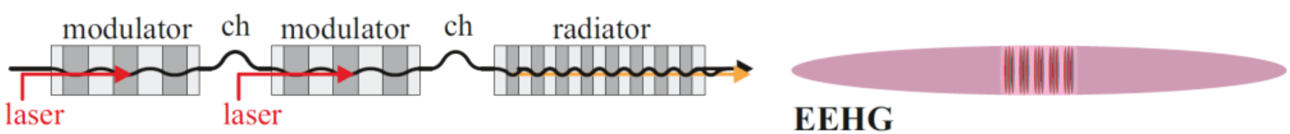
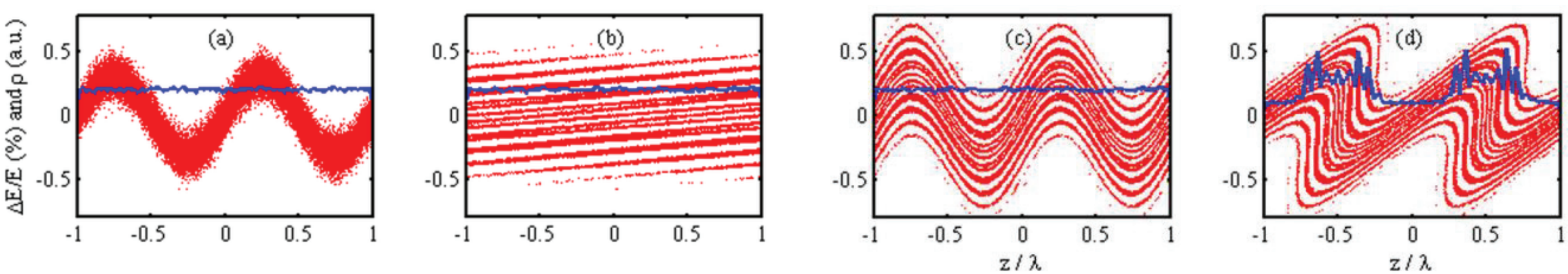


G. Stupakov, PRL 102, 074801 (2009)
Z. T. Zhao et al., Nat. Photonics 6, 360 (2012)
E. Hemsing et al., Nat. Photonics 10, 512 (2016)



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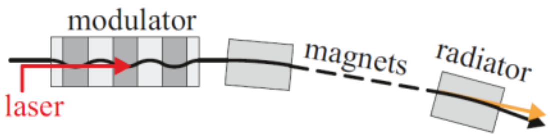
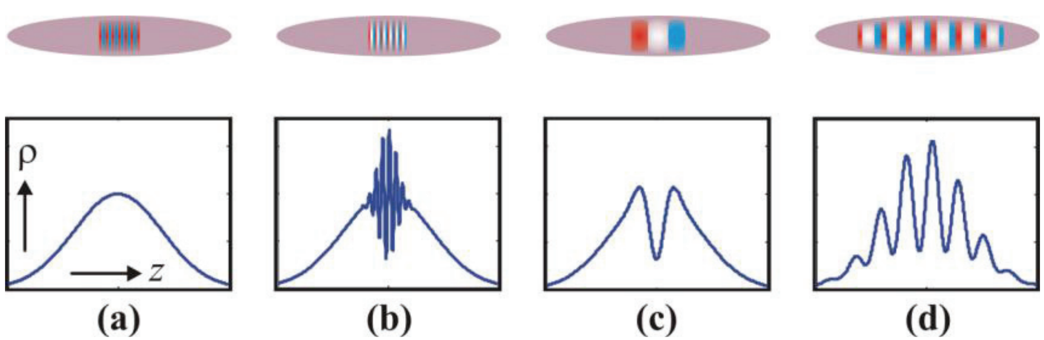
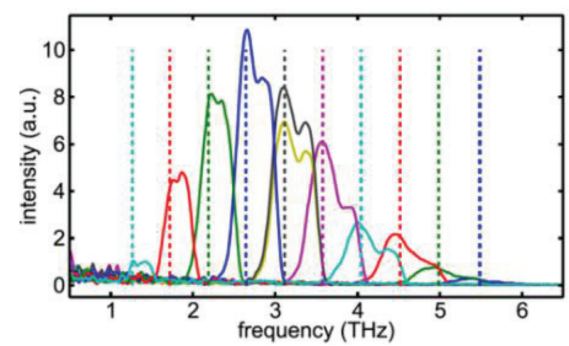


THz radiation

K. Holldack et al., PRL 96, 054801 (2006)
C. Mai et al., IPAC’15, Richmond, USA (2015)





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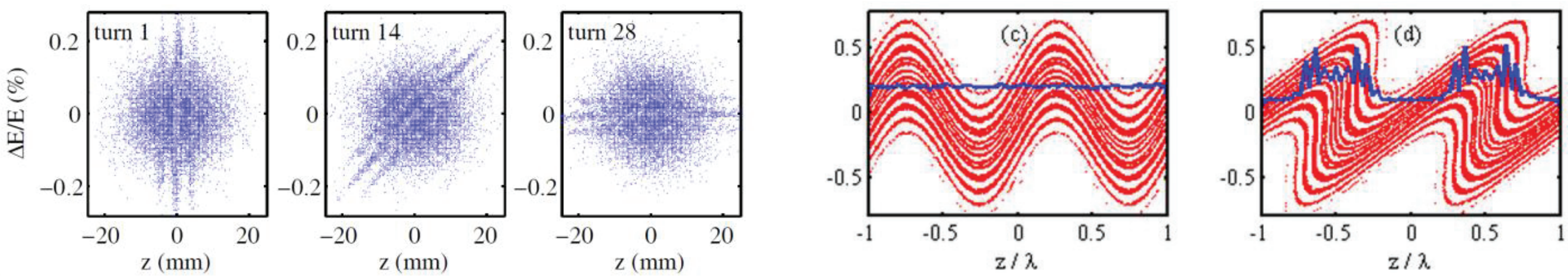
Yet another scheme: discrete-energy CHG

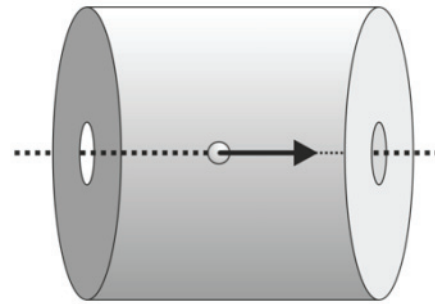
S. Khan, IPAC'15, Richmond, 1448 (2015)



Steady-state microbunching (SSMB)

Coherent emission turn by turn

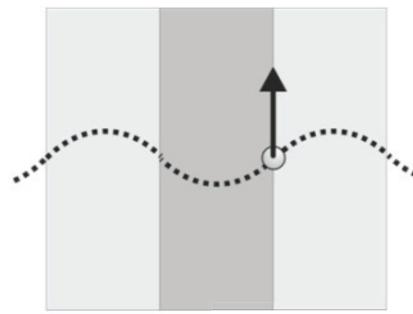
- sustained microbunching
- seeding at every turn



Sustained microbunching

- higher RF frequency, maybe up to X band ($\lambda \approx 25$ mm)

- cw far-infrared FEL ($\lambda \approx 0.3$ mm)
- cw CO_2 laser ($\lambda \approx 0.01$ mm)



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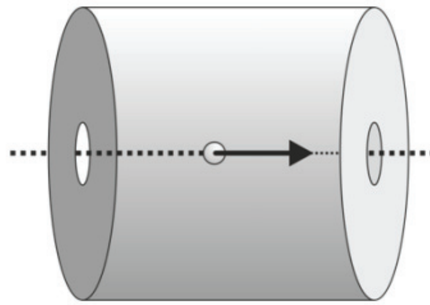

RF cavity

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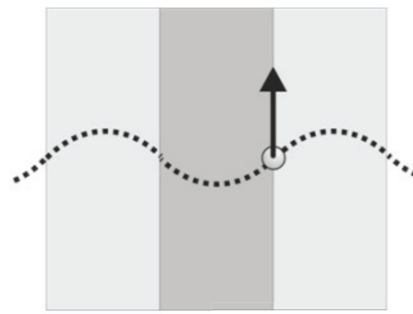
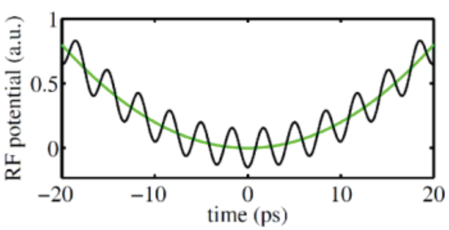
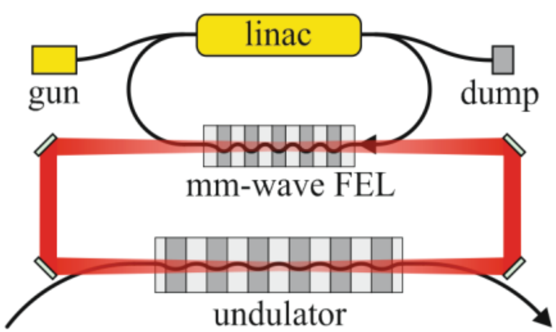


free wave in an undulator

$$\frac{dE}{dt} = -e \cdot \vec{\mathcal{E}} \cdot \vec{v} = -e \cdot |\vec{\varepsilon}| \cdot x' \cdot c$$

V. Litvinenko et al., PAC'01, Chicago, 2614 (2001)





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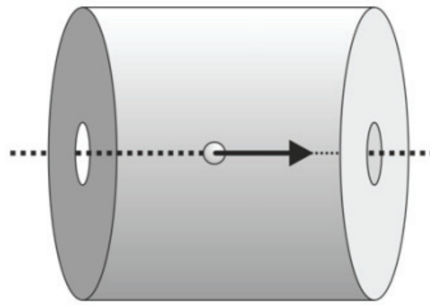

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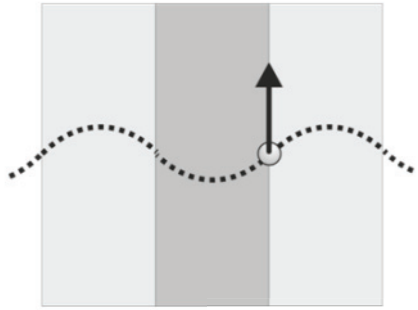

Example: 10 kW cw power

$1\,\mathrm{mm}^2$ spot size $\rightarrow$ 2.7 MV/m

$x' = K/\gamma = 0.01$ $\rightarrow$ 50 keV

S. Khan, NIM A 865, 95 (2017)

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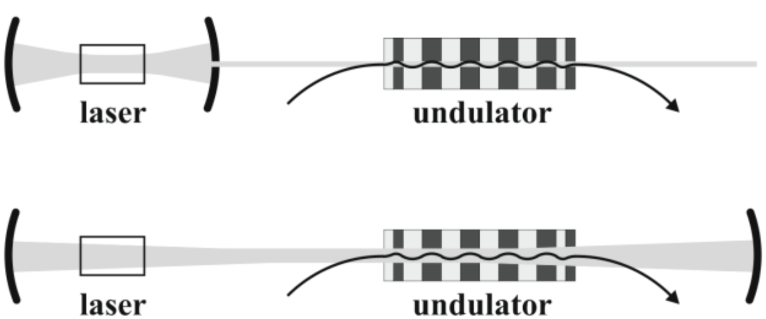

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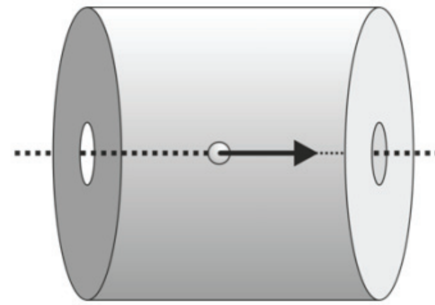

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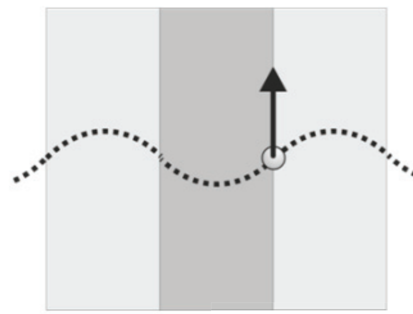

free wave in
an undulator

Isochronicity
- small momentum compaction factor
- betatron motion (r_{51} and r_{52})
- stochastic energy loss along the circumference

$$\frac{dE}{dt} = -e\cdot\vec{\mathcal{E}}\cdot\vec{v} = -e\cdot\left|\vec{\varepsilon}\right|\cdot x'\cdot c$$

Y. Shoji et al., Phys. Rev. E 54, R4556 (1996)
Y. Shoji, PRSTAB 7, 090703 (2004)

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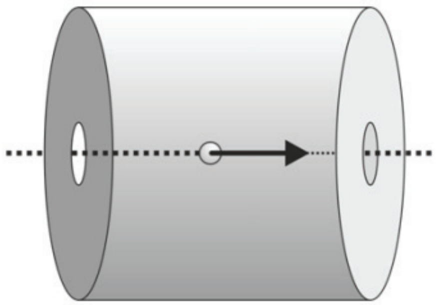

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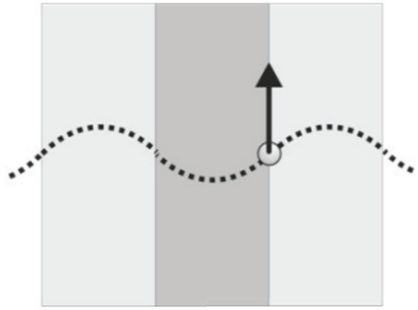

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Seeding at every turn
- user interest?
- how to produce microbunching at VUV or X-ray wavelengths?
- energy modulation must be canceled at each turn

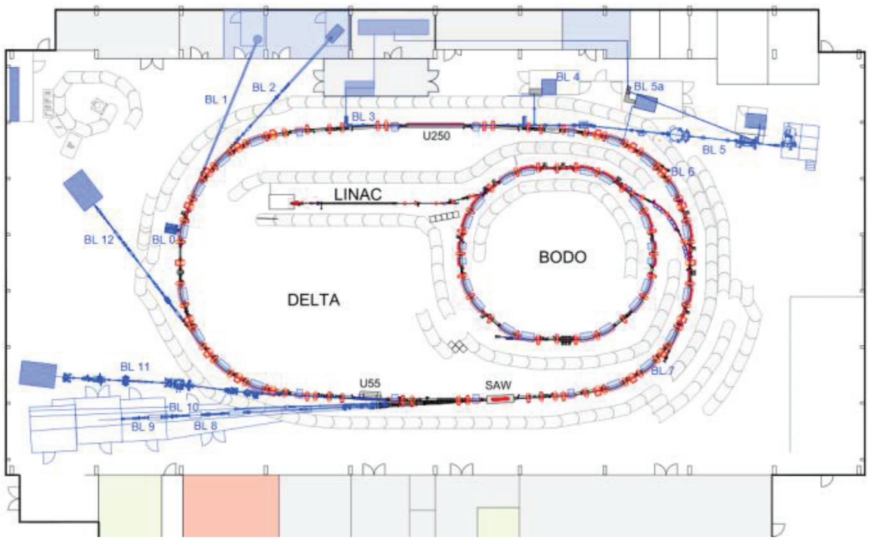
D. Ratner, A. Chao, PRL 105, 154801 (2010)

Short-pulse facility at DELTA

DELTA storage ring at TU Dortmund

- 115.2 m circumference
- 1.5 GeV beam energy
- 130 mA (multi-bunch) 20 mA (single-bunch)
- 2000 hours user operation (20 weeks) 德
- 1000 hours machine studies (10 weeks) 乐

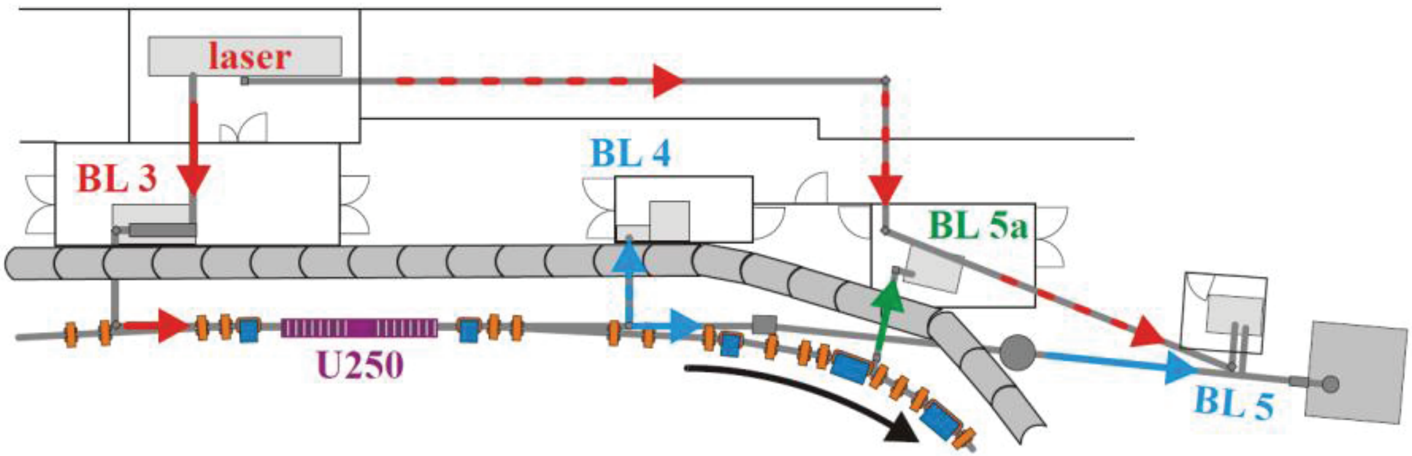
dé lè tă



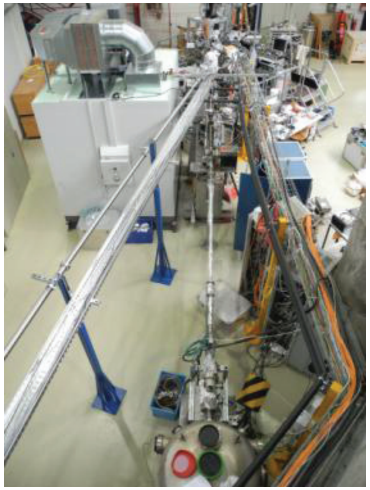
Short-pulse facility at DELTA

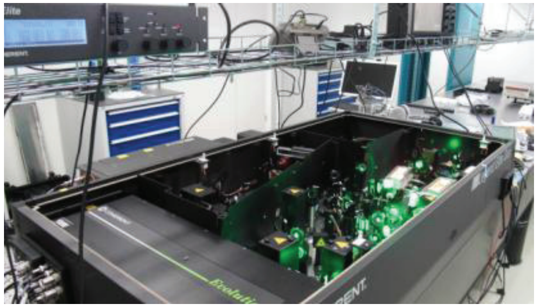
Laser seeding (CHG, THz)
- routinely since 2011
- up to 600 hours/year

S. Khan et. al, Sync. Rad. News 26(3), 25 (2013)



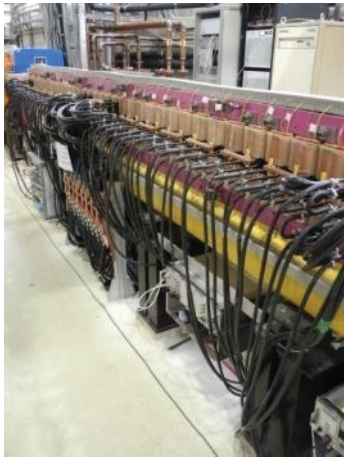
soft X-ray beamline BL 5

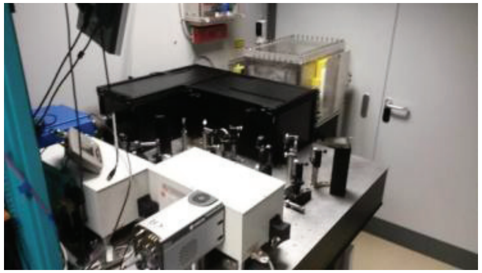




Ti:sapphire laser system

undulator U250





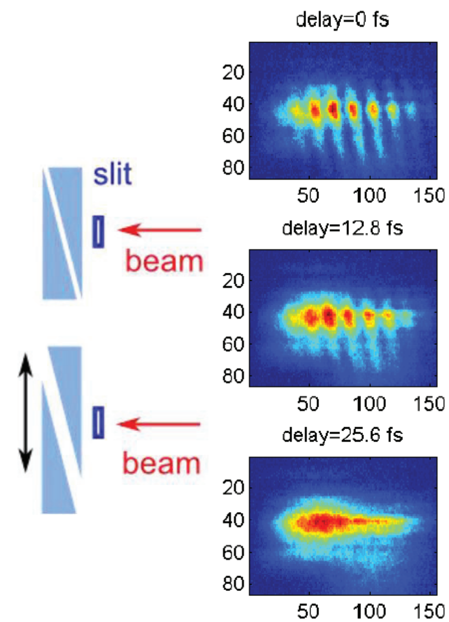
diagnostics beamline BL 4

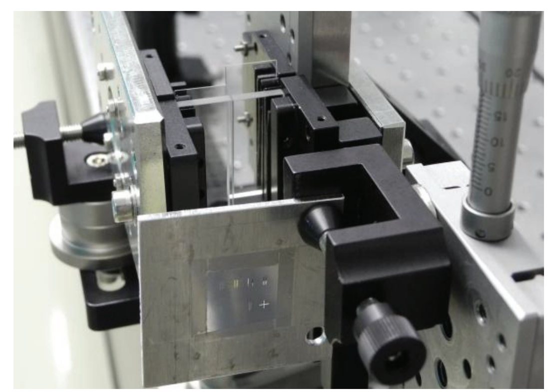
THz beamline BL 5a

Short-pulse facility at DELTA

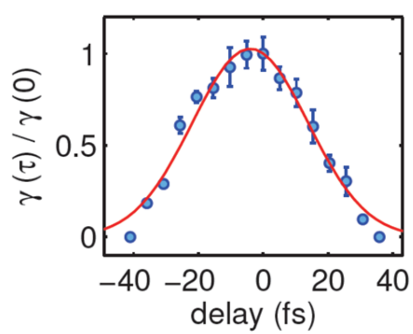
Some results

- coherence of CHG radiation
  - ... Michelson interferometer
  - ... split and delay experiment
  - ... double-slit experiment
  - ... analysis of speckle patterns
- spectrotemporal properties of CHG pulses
  - ... variation of r_{56} $\rightarrow$ longitudinal distribution of microbunching
  - ... variation of laser chirp $\rightarrow$ spacing of microbunching
- seeding with RF phase modulation
  - ... non-equilibrium electron density and energy spread
  - ... increased CHG and THz intensity
- first pump-probe experiments with 133-nm CHG pulses
  - ... Coulomb repulsion of photoelectrons
- broadband THz radiation over many turns
  - ... signal after 1/2 synchrotron period
- narrowband tunable THz radiation
  - ... frequencies from below 1 to 5.5 THz





M. Huck et al.,
IPAC'14, Dresden, 1848 (2014)



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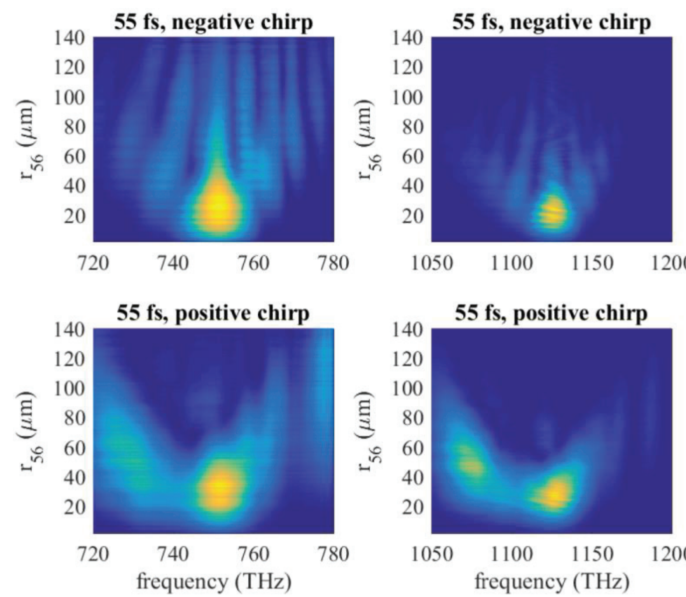

S. Khan et al.,
IPAC'16, Busan, 2851 (2016)

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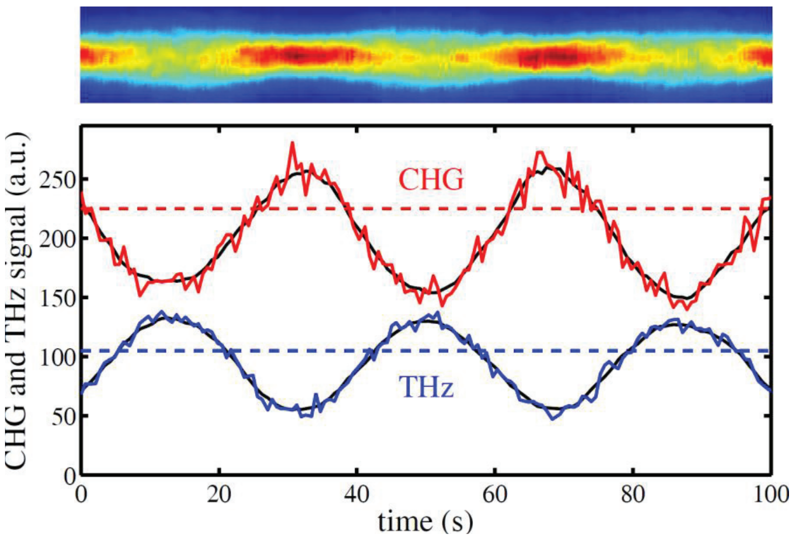

M. Jebramcik et al.,
IPAC'16, Busan, 2847 (2016)

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  ... variation of r_{56} → longitudinal distribution of microbunching
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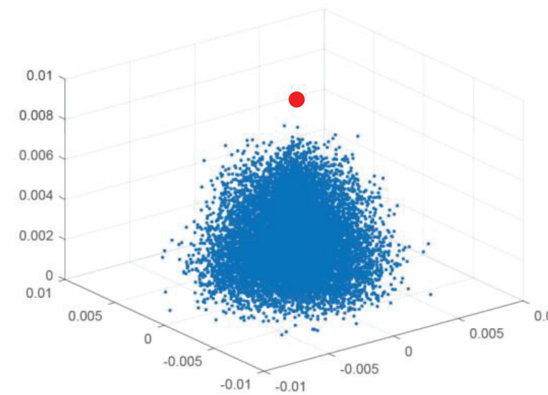
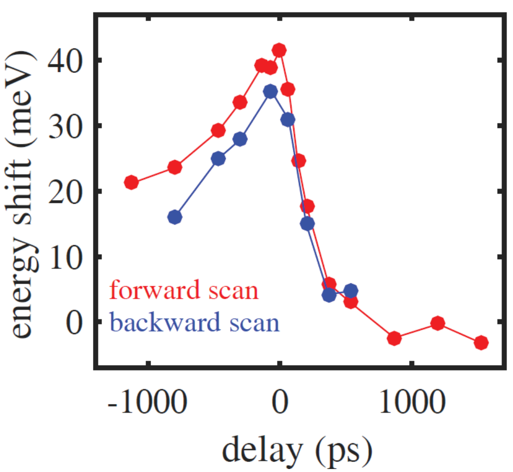
- first pump-probe experiments with 133-nm CHG pulses
  ... Coulomb repulsion of photoelectrons
- broadband THz radiation over many turns
  ... signal after 1/2 synchrotron period
- narrowband tunable THz radiation
  ... frequencies from below 1 to 5.5 THz





S. Khan et al.,
IPAC'17, Kopenhagen, 2578 (2017)

Short-pulse facility at DELTA

Some results

- coherence of CHG radiation
  ... Michelson interferometer
  ... split and delay experiment
  ... double-slit experiment
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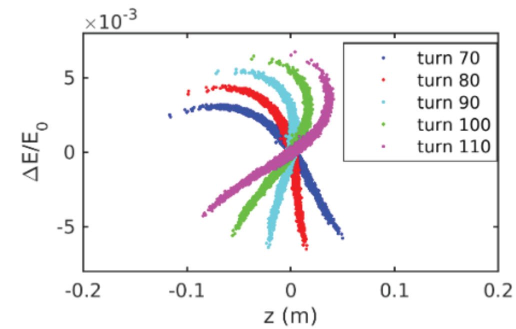
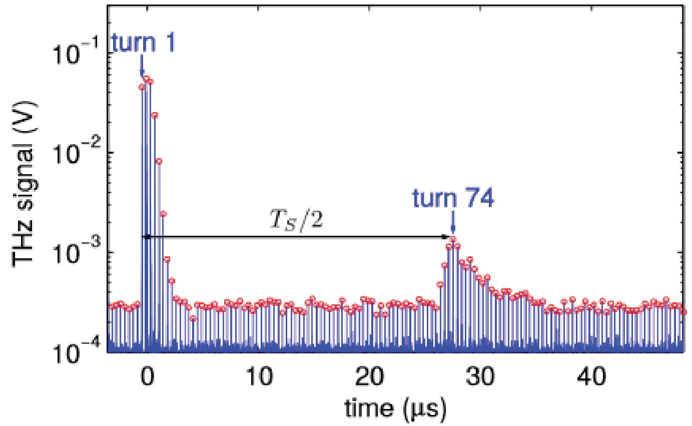


C. Mai et al.,
IPAC'15, Richmond, 823 (2015)



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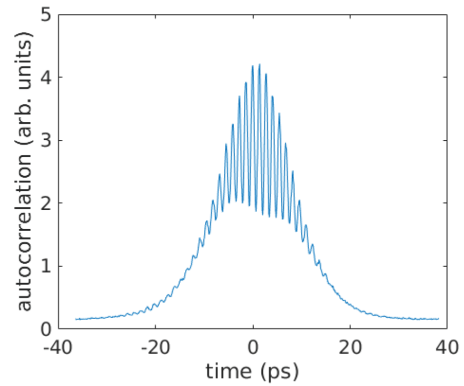
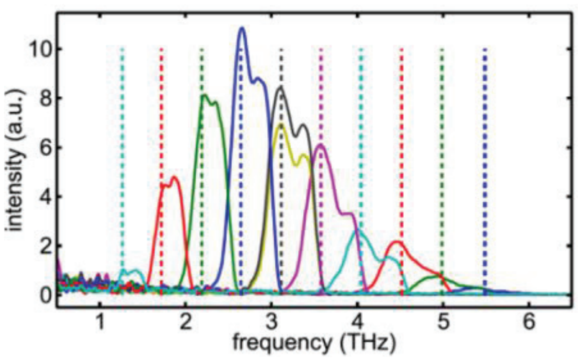


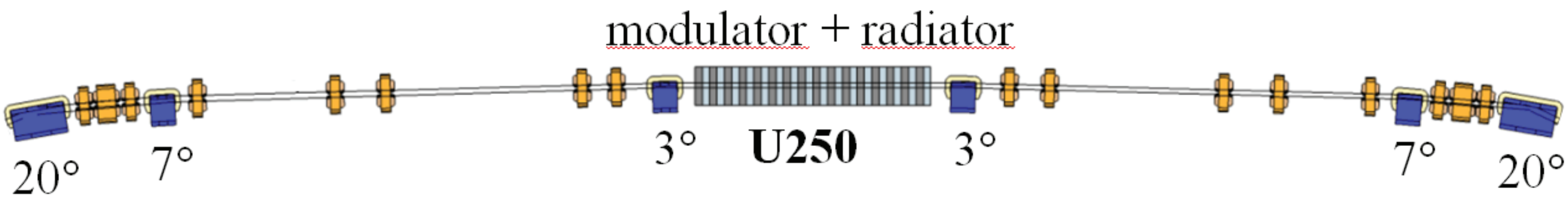
S. Bielawski et al., Nat. Physics 4, 390 (2008)
P. Ungelenk et al., PRAB 20, 020706 (2017)

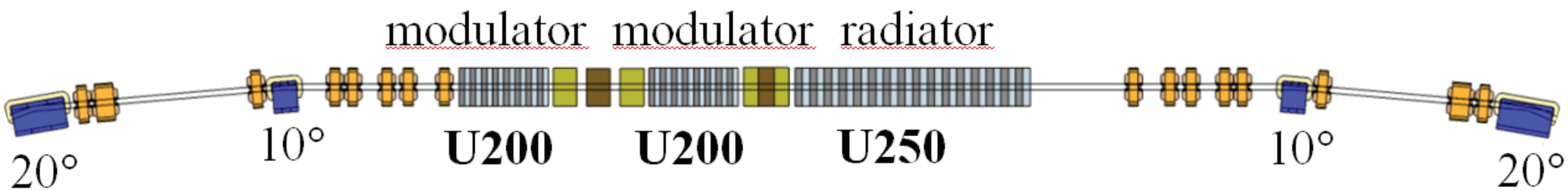


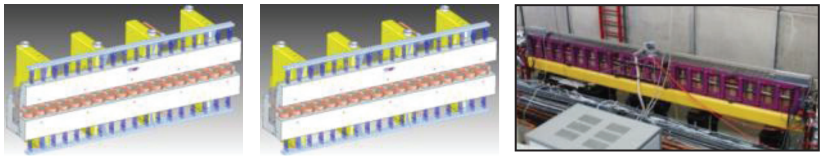
Short-pulse facility at DELTA

Planned implementation of EEHG

- modifying 1/4 of the storage ring
- hardware funded and partly in house
- EEHG-like seeding with 800- and 400-nm pulses







R. Molo et al., FEL'11, Shanghai, 219 (2011)
S. Hilbrich et al., FEL'15, Daejeon, 363 (2015)
B. Büsing, master thesis, TU Dortmund (2017)

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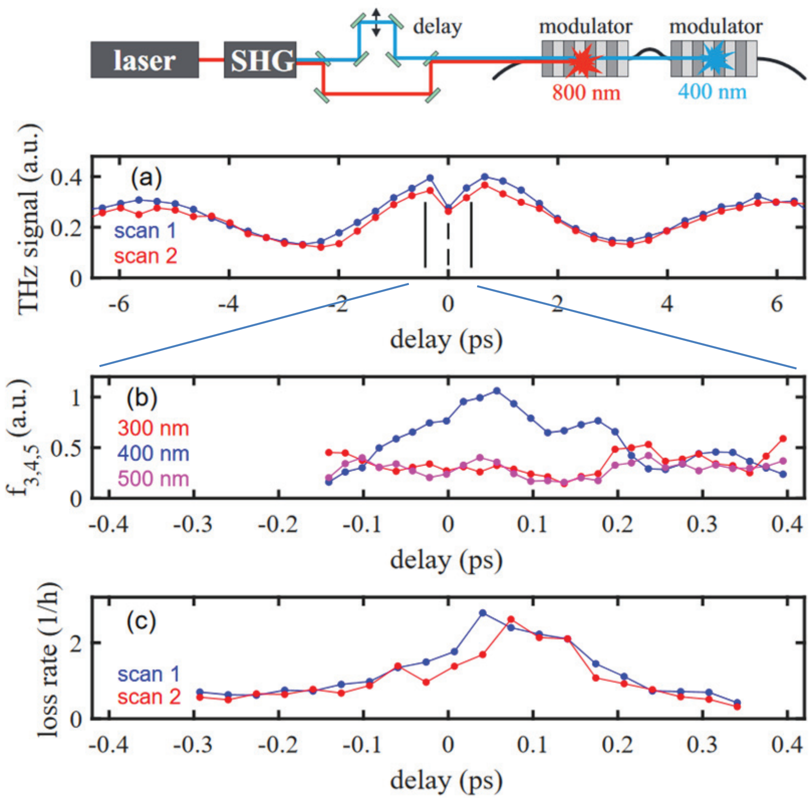

Indications of zero delay (temporal overlap):

(a) THz dip, reduced number of electrons

(b) THz signal sensitive to 400/800-nm phase

(c) increase of loss rate (at low RF power)

S. Khan et al., FEL'17, Santa Fe, MOP027 (2017)

Conclusions

Laser seeding → microbunching → coherent emission
- high intensity
- control of pulse properties

Steady-state microbunching
- sub-mm scale not completely unrealistic (far-IR FEL, CO_2 laser ...)
- nm scale difficult

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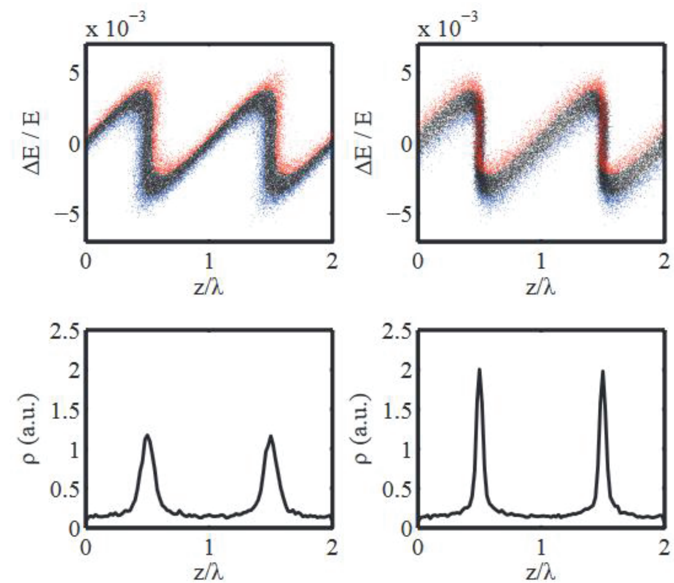
New Ideas
- "cooled CHG"
  correlation between ΔE and transverse coordinates



H. Deng et al., PRL 111, 084801 (2013)
C. Feng et al., PRSTAB 17, 070701 (2014)
S. Khan et al., FEL'14, Basel, 248 (2014)
C. Feng et al., Scient. Reports 7, 4724 (2017)

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DFG Deutsche Forschungsgemeinschaft

Mercator Research Center Ruhr
Eine Initiative der Stiftung Mercator und der Universitätsallianz Ruhr

Bundesministerium für Bildung und Forschung