technische universität
dortmund

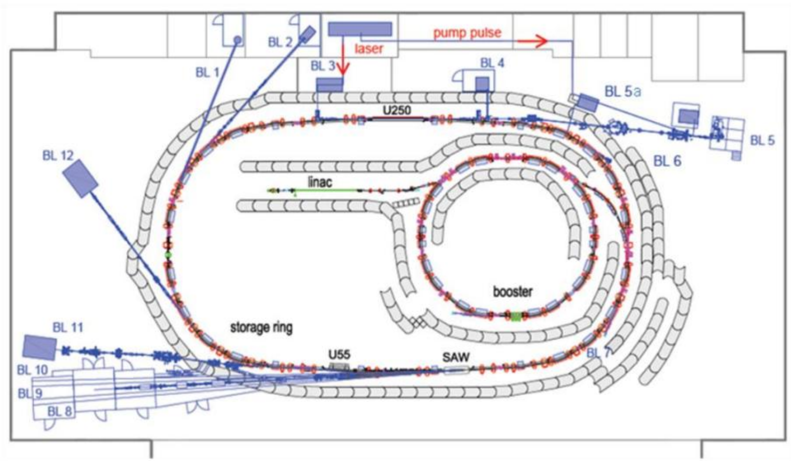
# Seeding of Electron Bunches at the DELTA Storage Ring

*Carsten Mai*
on behalf of the
DELTA seeding group

# Contents

- DELTA electron storage ring
- seeding activities
    - coherent harmonic generation (CHG)
    - precursor experiments: echo-enabled harmonic generation (EEHG)
- THz pulse shaping
    - interferometric approach / phase modulation
- applications for beam diagnostics

# DELTA – the light source at TU Dortmund University



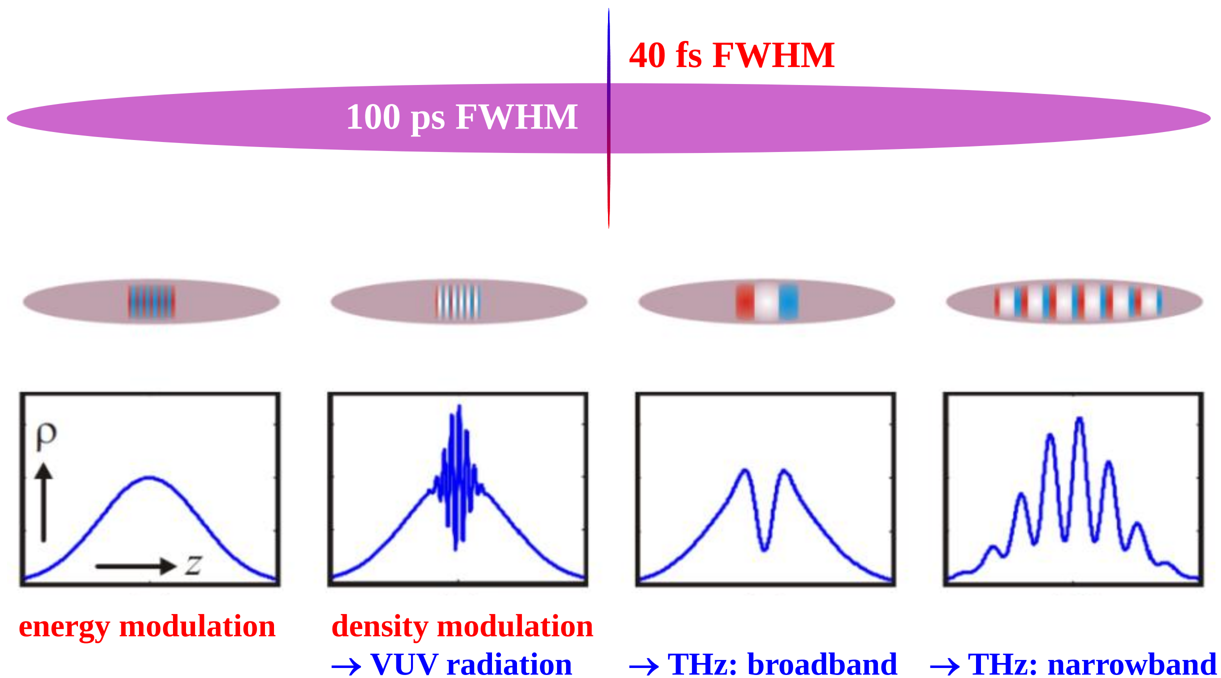

**Parameters**

| | |
|---|---|
| circumference: | 115.2 m |
| beam energy: | 1.5 GeV |
| beam current: | 130 mA multi-bunch |
| | 20 mA single bunch |
| beam lifetime: | ~15 h @ 100 mA |
| emittance: | ~16 nm rad (horiz.) |
| bunch length: | 100 ps (FWHM) |

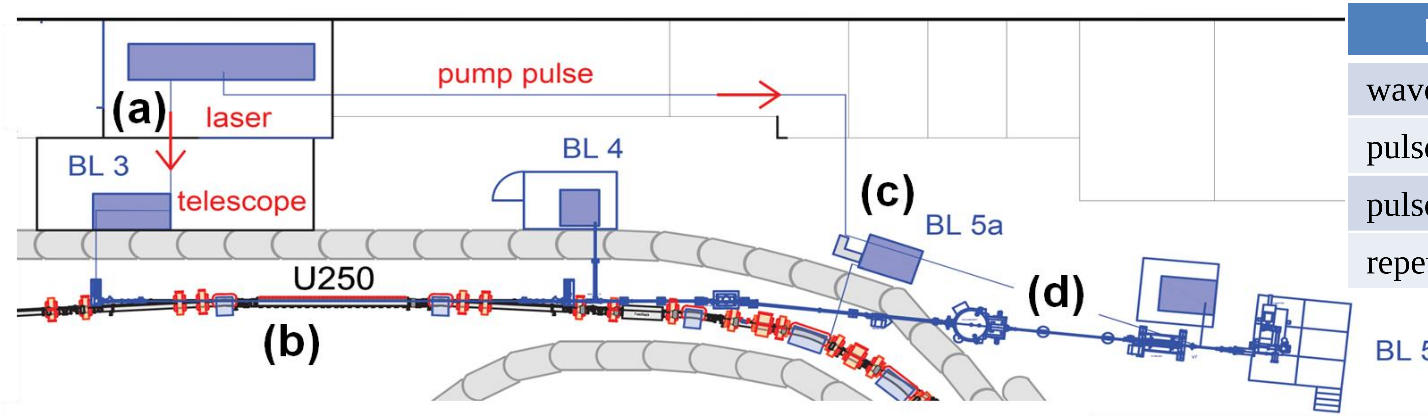
**Operation times**

| | |
|---|---|
| user experiments: | 2000 h / year |
| machine studies: | 1000+ h / year |

# Seeding schemes at DELTA



# The DELTA short-pulse facility

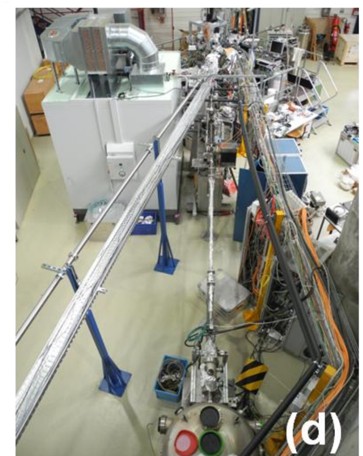



| laser parameters | |
|---|---|
| wavelength | 800 nm |
| pulse length | 40 fs |
| pulse energy | 8 mJ |
| repetition rate | 1 kHz |


fs laser system

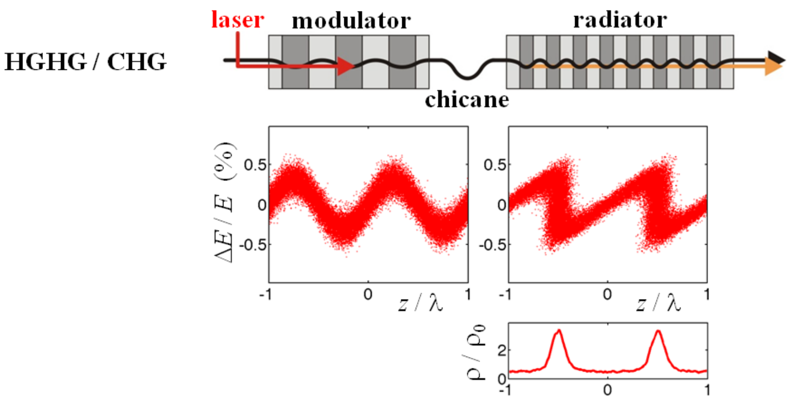

undulator U250


THz beamline

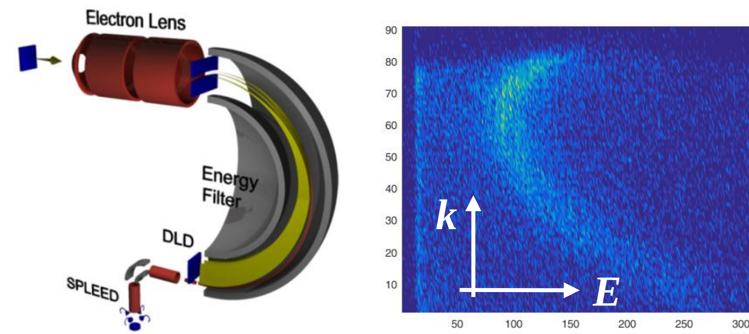



VUV beamline for pump-probe experiments

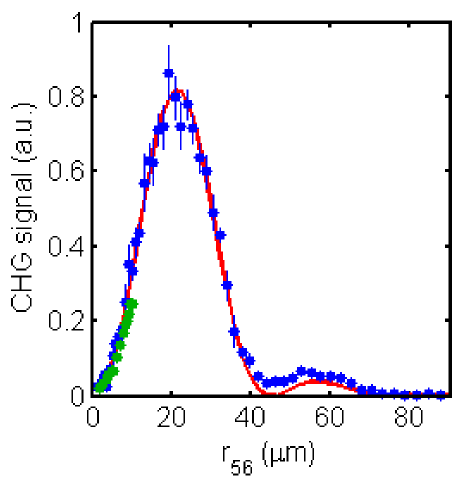
# Coherent harmonic generation (CHG)

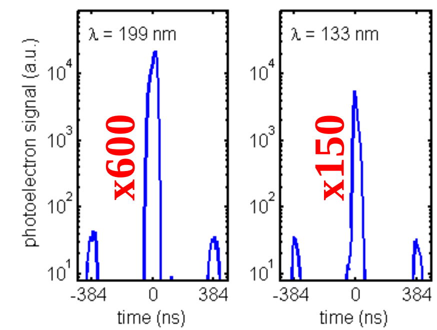



## delay line detector



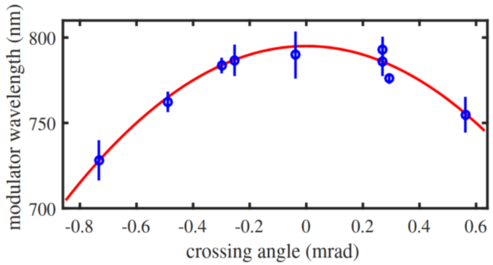

## variation of chicane strength



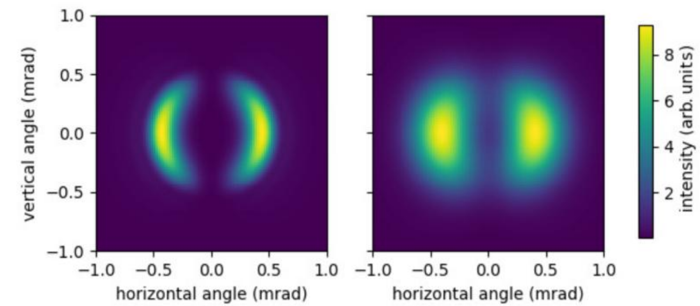
# Characterization of CHG radiation: Off-axis seeding

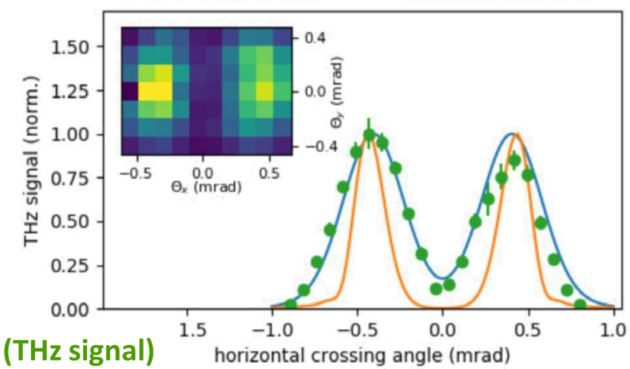
**study: seeding with crossing angle**




**study: seeding at the second undulator harmonic**
**(laser 400 nm, undulator: < 800 nm)**

SPECTRA simulations: spontaneous radiation
without / with laser spot size



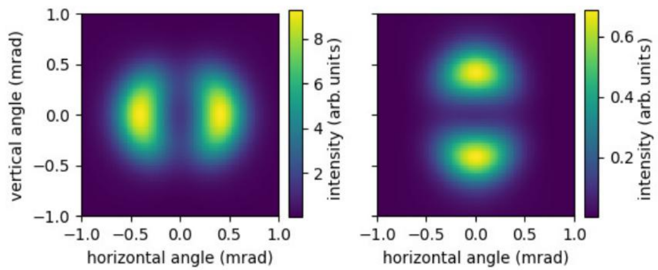

energy modulation (THz signal)
SPECTRA simulation (laser PSF)
SPECTRA simulation

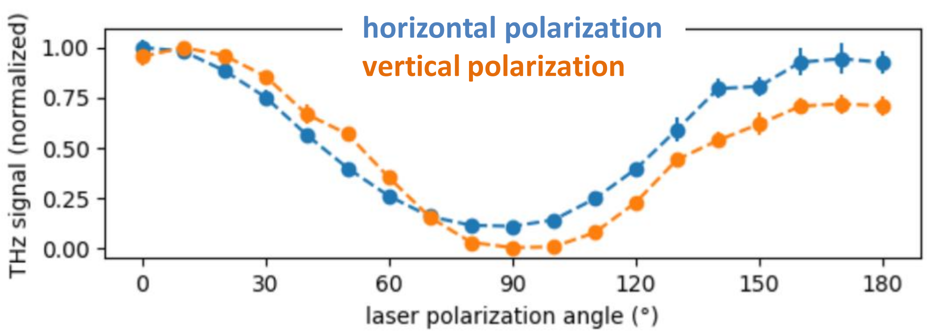
**Proc. of FEL 2019, TUP080**

# Characterization of CHG radiation: Off-axis seeding

**study: seeding with vertical laser polarization**

SPECTRA simulations:
horizontal / vertical polarization



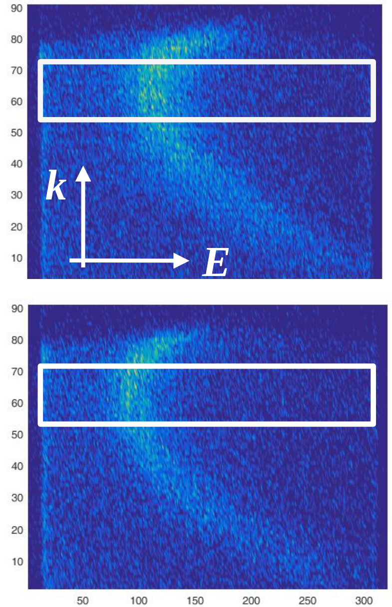

**Proc. of FEL 2019, TUP080**

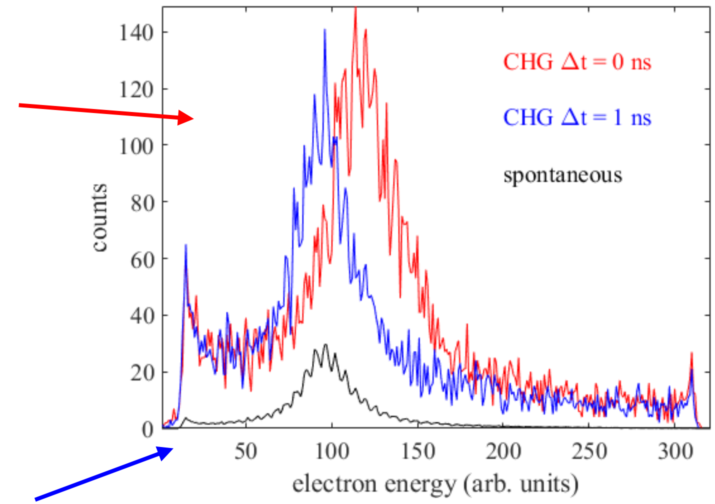
# First CHG pump-probe demo experiment

Cu(111), 1.5 eV pump, 9 eV probe

delay: 0 ns

delay: 1 ns



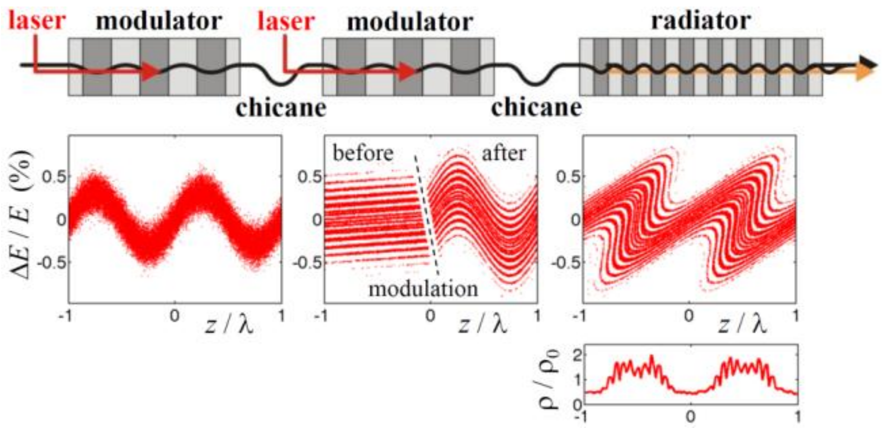





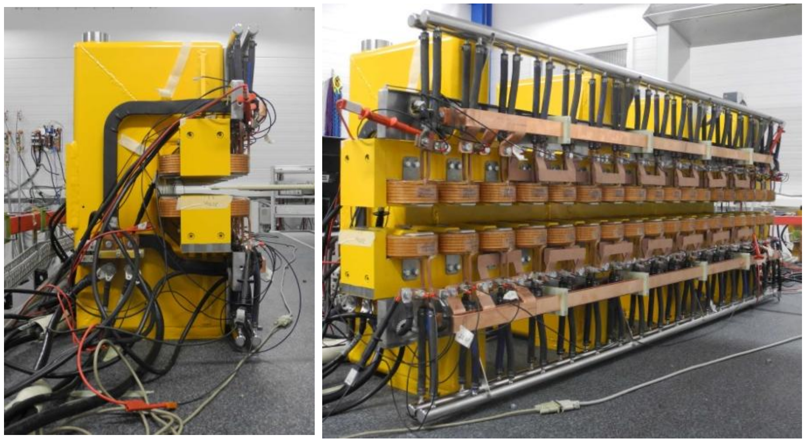
negative delay (probe before pump)

positive delay (probe after pump )

# Echo-enabled harmonic generation (EEHG)




- delivered and tested:
  - new undulators
  - power supplies
- chicane design studied
- new storage ring optics



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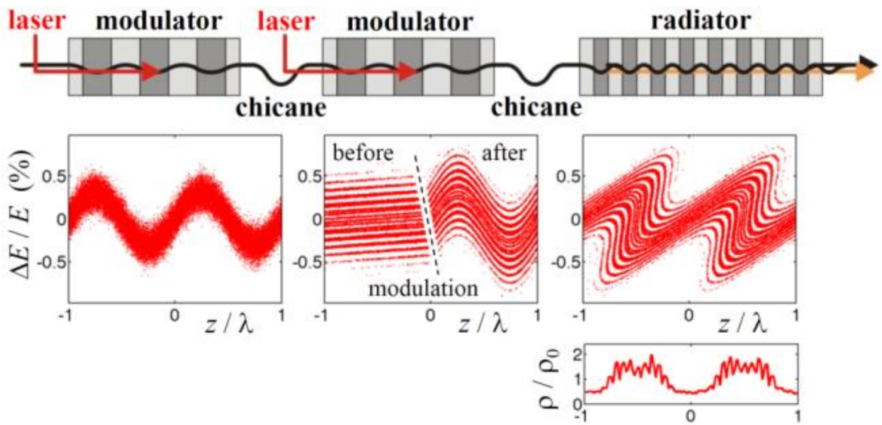


- delivered and tested:
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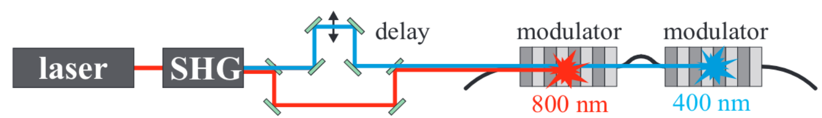
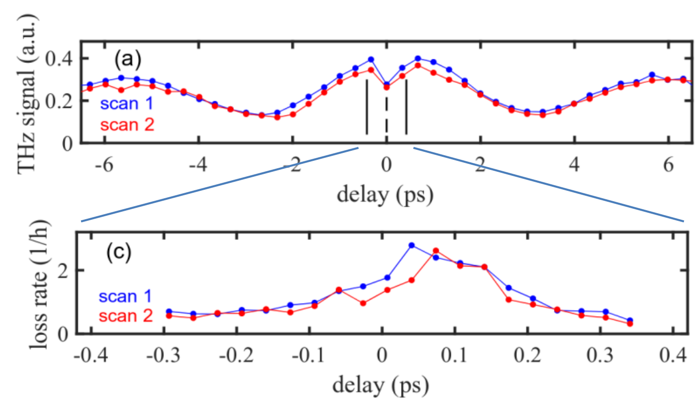
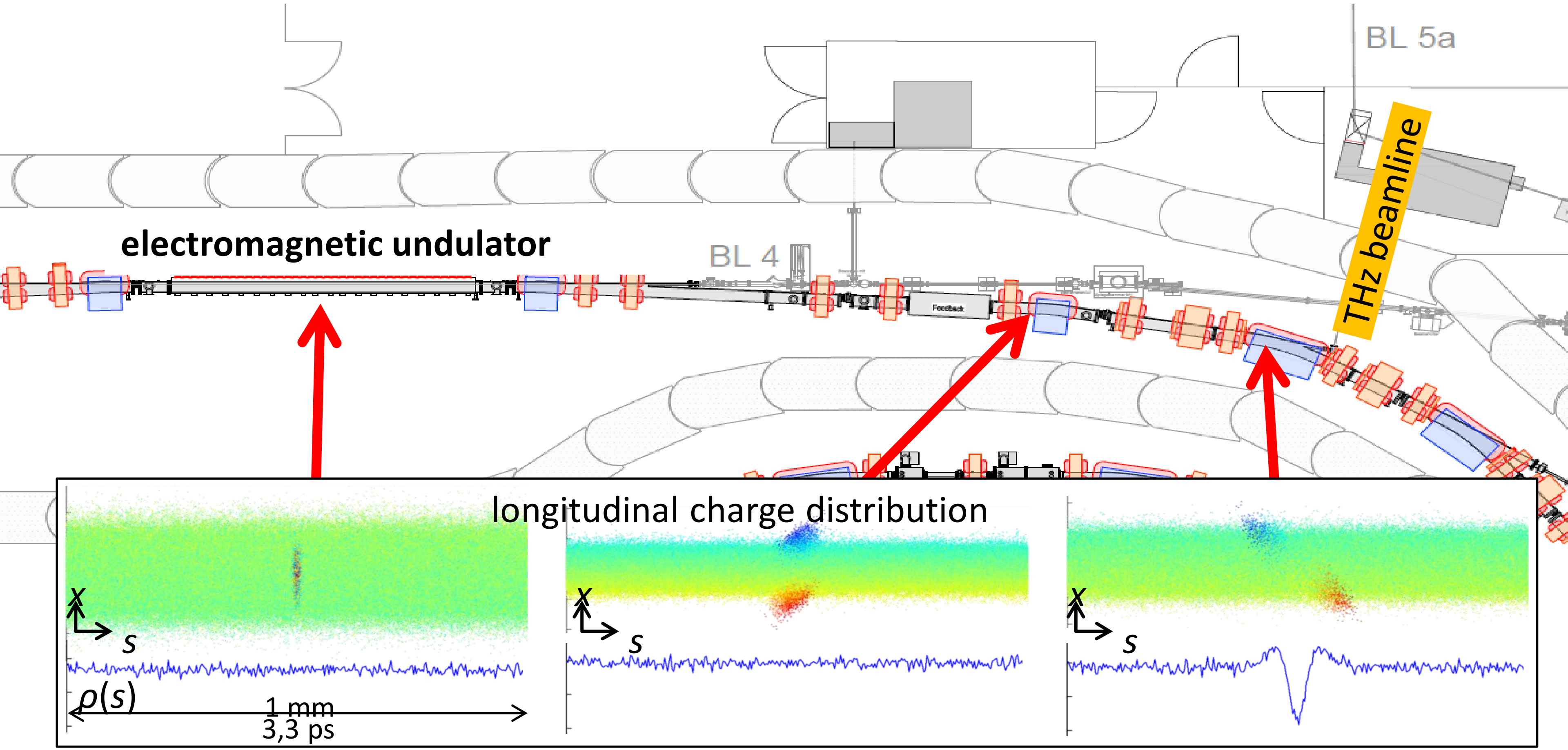
precursor experiment:



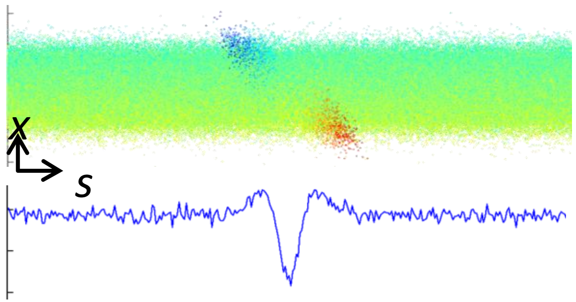



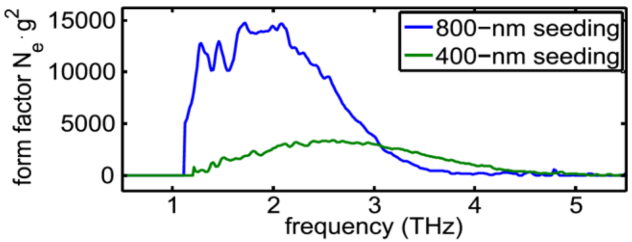
# Coherent emission of THz radiation



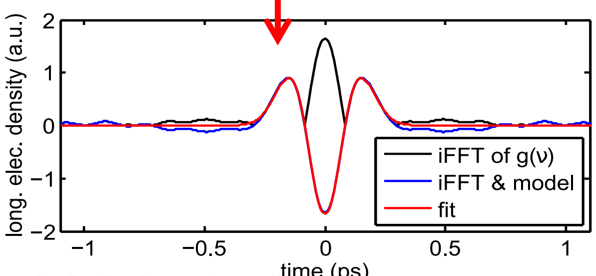
# Broadband THz generation: spectrotemporal evolution

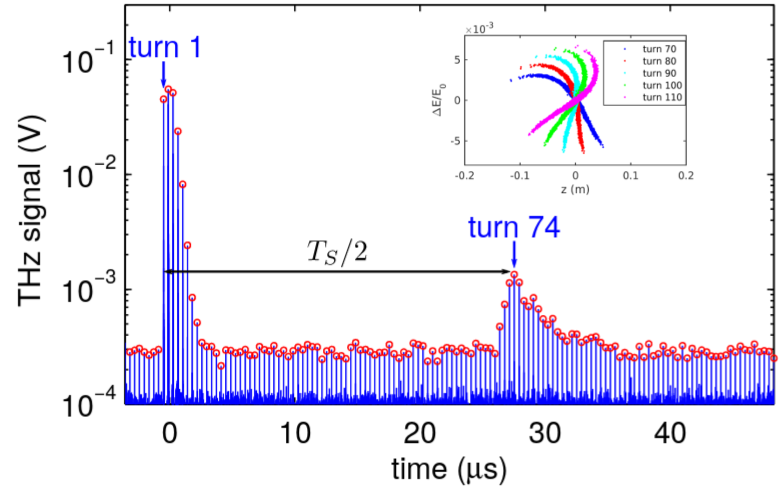
simulation

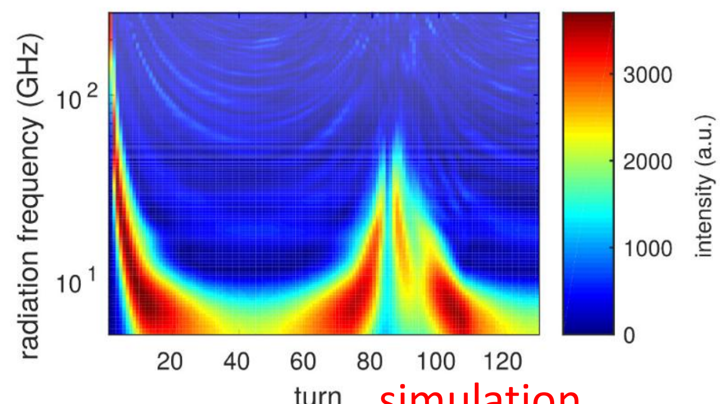



Fourier transform

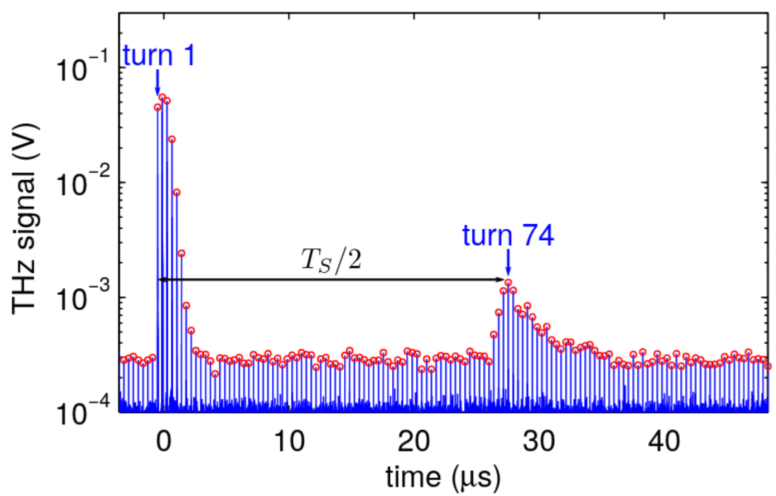


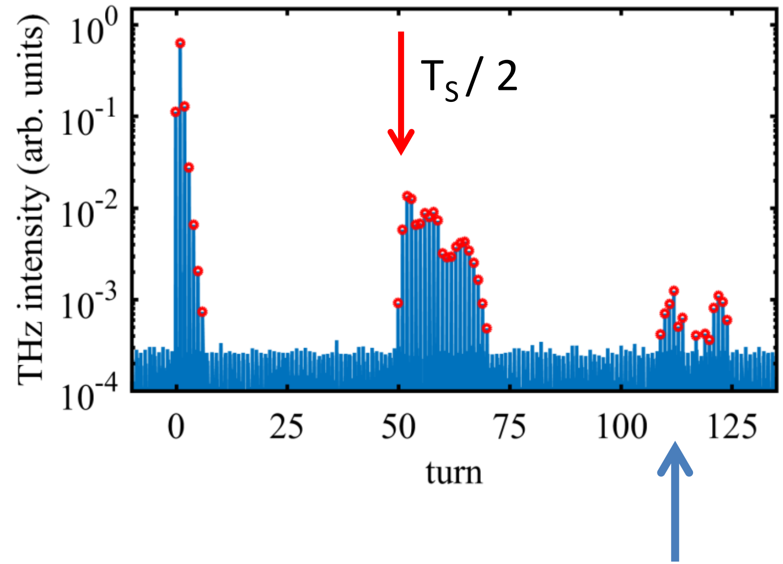




simulation

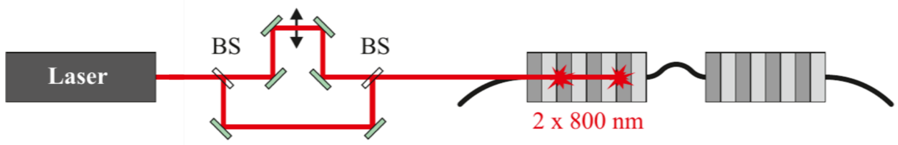
# Temporal evolution after storage ring RF upgrade

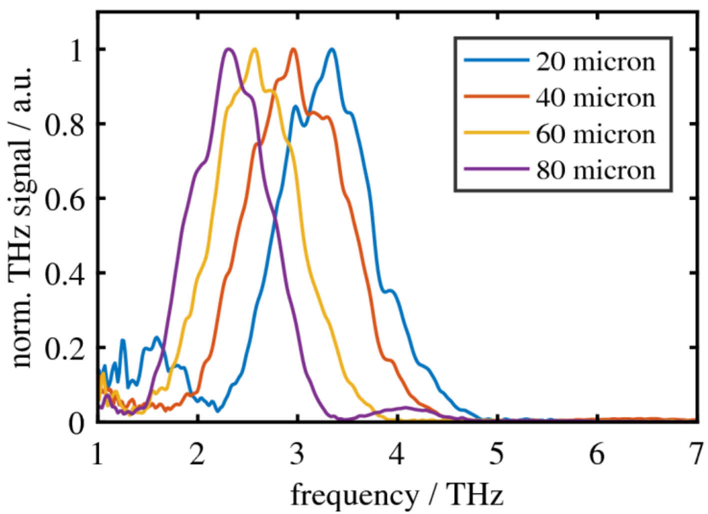


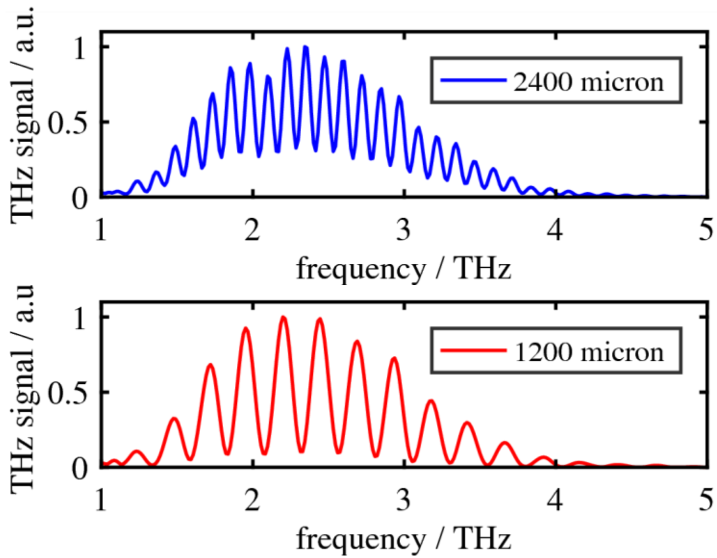

RF power x2



# Increasing spectral control of THz generation

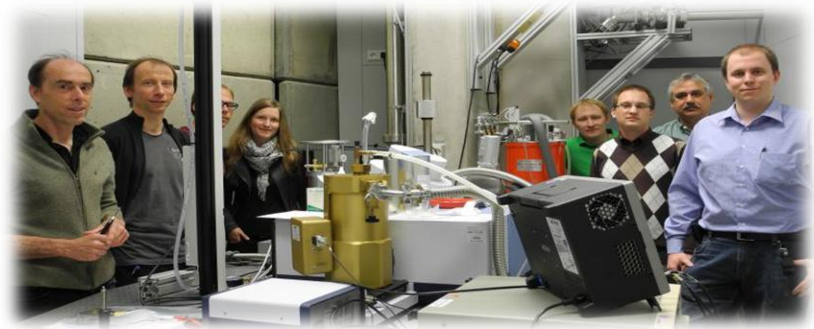


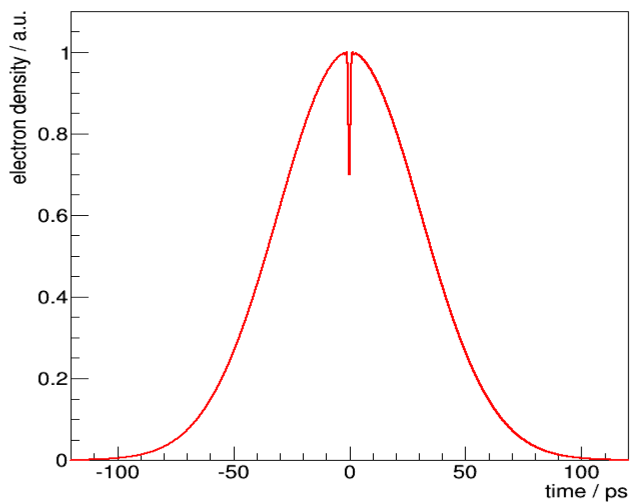
# Towards tunable narrowband radiation

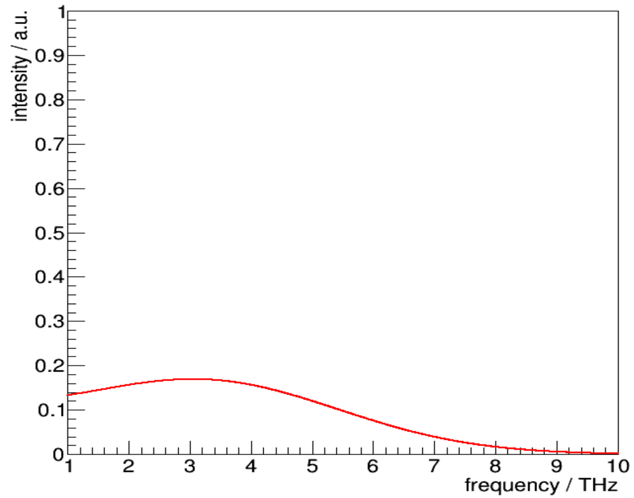
cooperation with PhLAM, Lille



- multi-dip modulation of the electron bunch leads to narrow THz spectrum
- idea: modulate long, chirped laser pulse with Michelson interferometer
- first realized at UVSOR

simple model:



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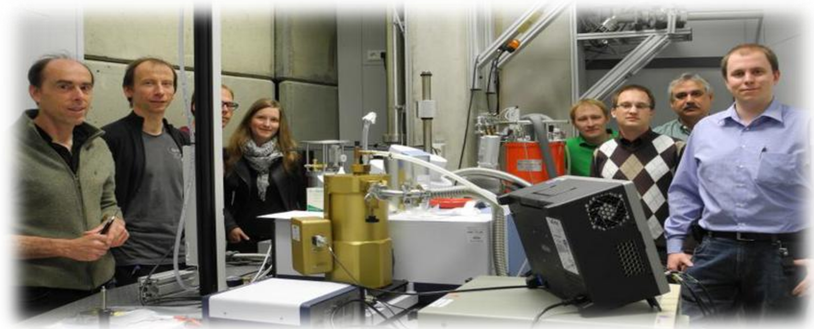

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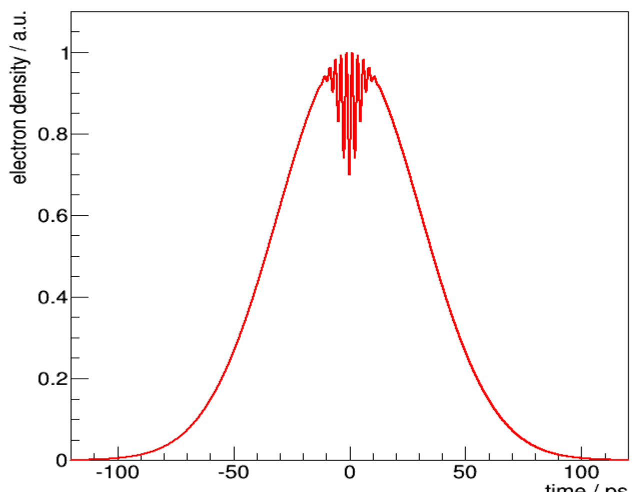


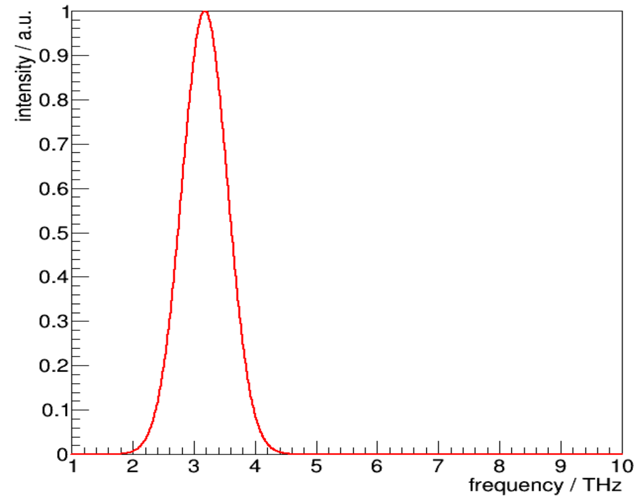

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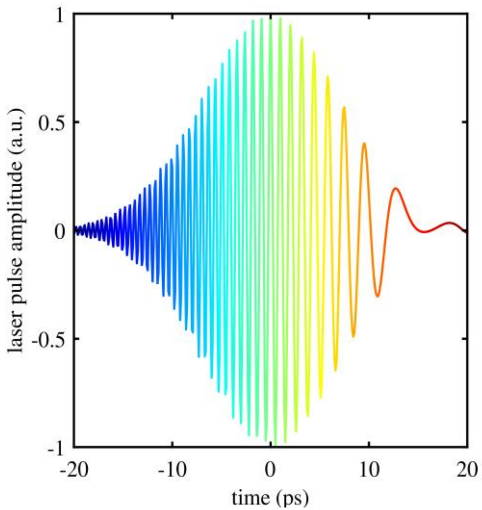
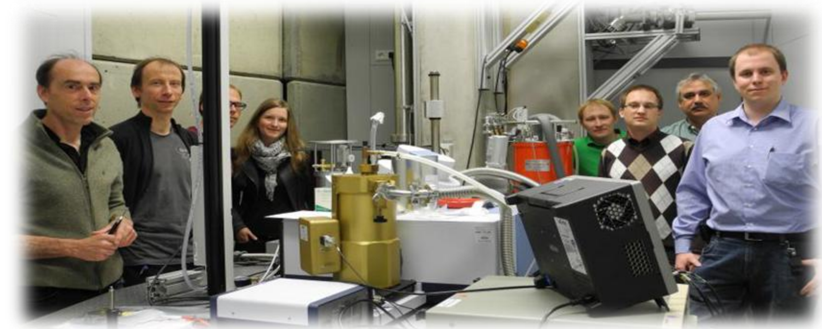
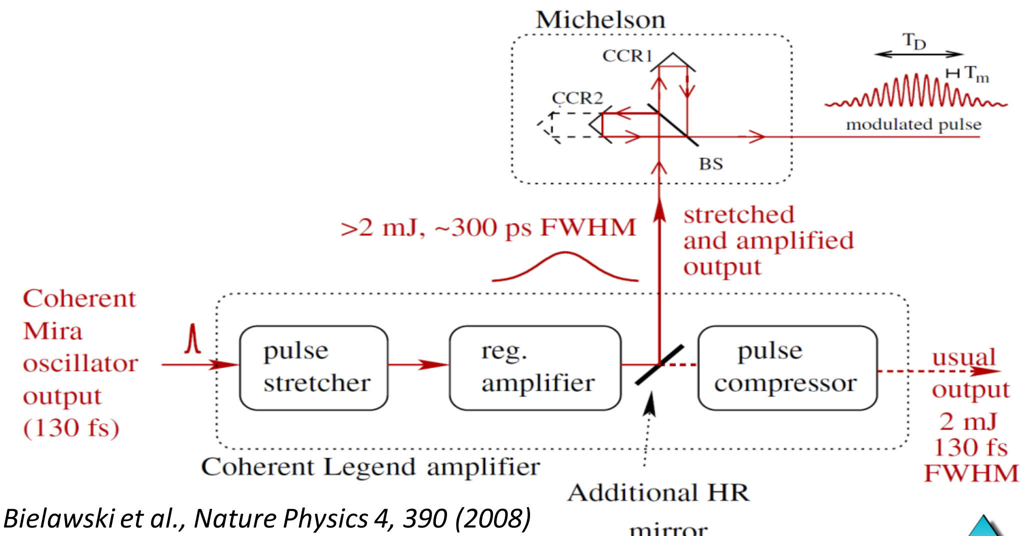



cooperation with PhLAM, Lille






*S. Bielawski et al., Nature Physics 4, 390 (2008)*
*C. Evain et al., PRST-AB 13, 090703 (2010)*

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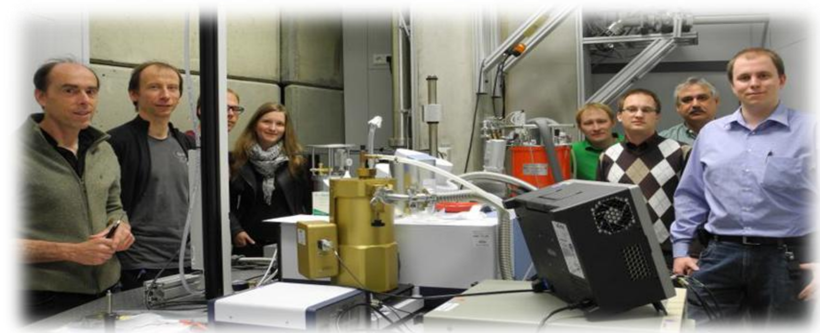

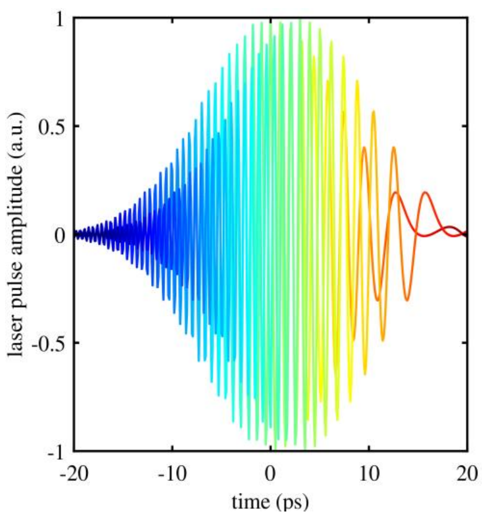


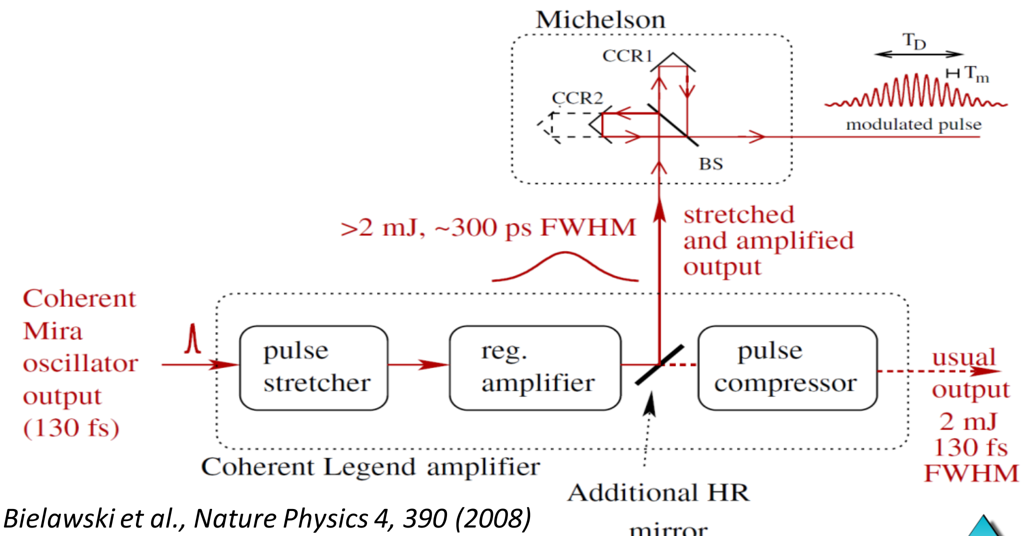


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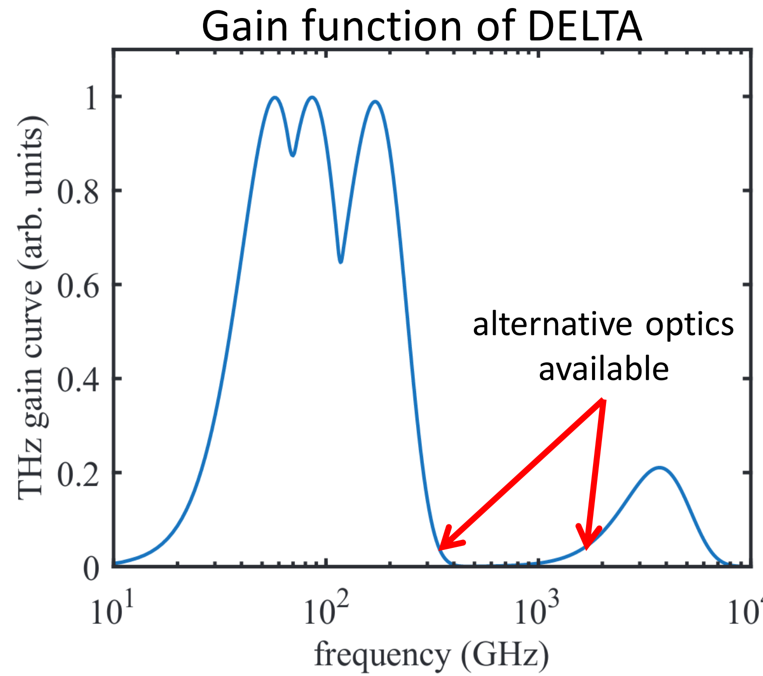
# Which spectral range is accessible?

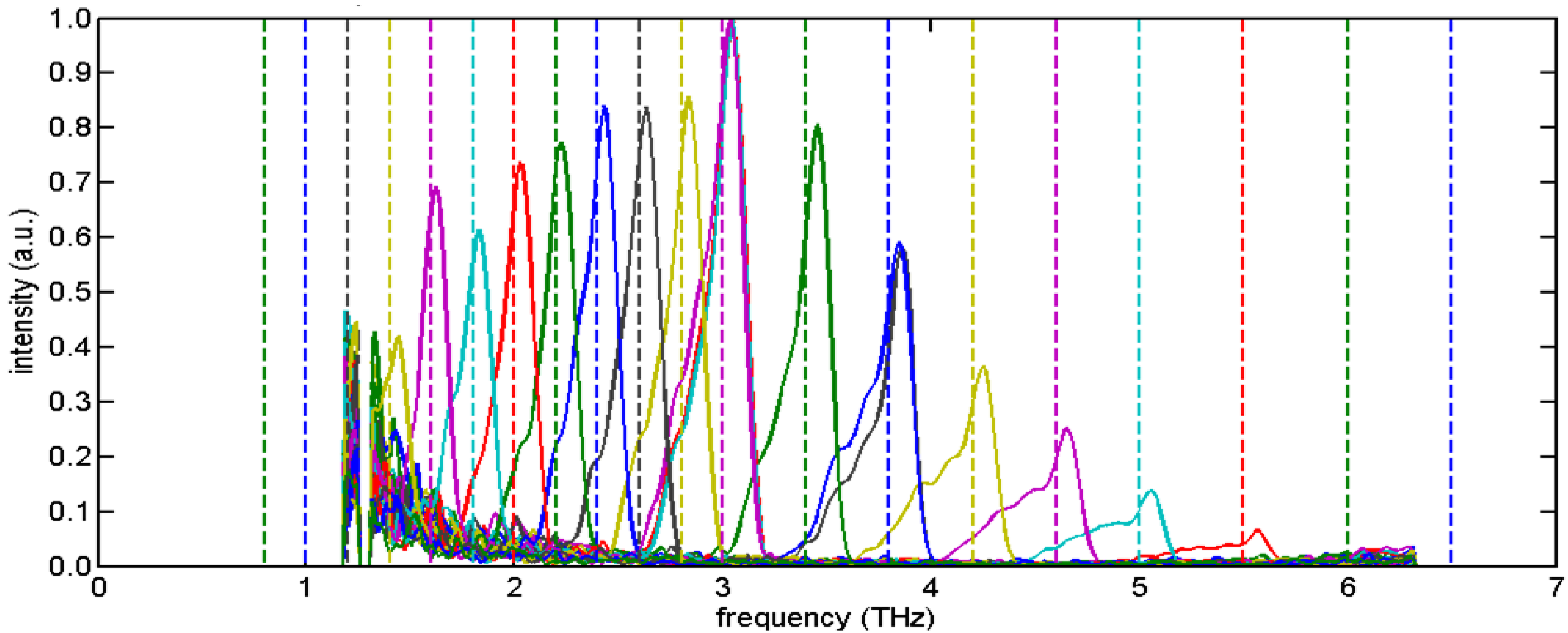
$$g^2(f) = \left| \int \rho(t) e^{i\omega t} \mathrm{d}t \right|^2$$
$$\propto \left( r_{56} \frac{\sigma_E}{E} \frac{2\pi f}{c} \right)^4$$
$$\cdot \exp\left[ -\left( \frac{2\pi f}{c} \right) \left( r_{51}^2 \sigma_x^2 + r_{52}^2 \sigma_{x'}^2 + r_{56}^2 \frac{\sigma_E^2}{E^2} \right) \right].$$

Phys. Rev. ST Accel. Beams **13**, 090703 (2010)

- storage ring optics: $\mathbf{r_{51}}$, $\mathbf{r_{52}}$, $\mathbf{r_{56}}$ (accumulated turn-wise)
- energy spread

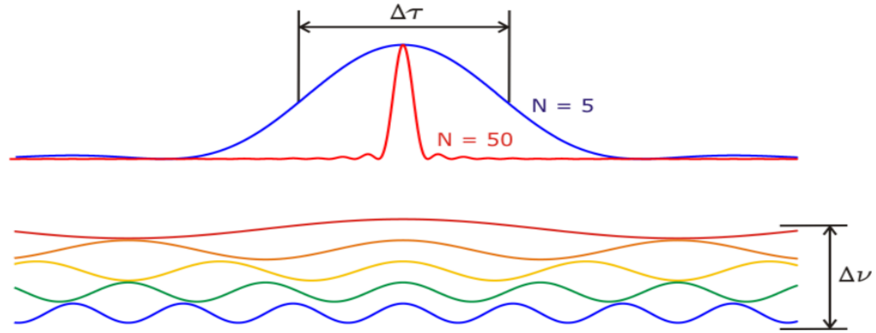


# Tunable THz radiation

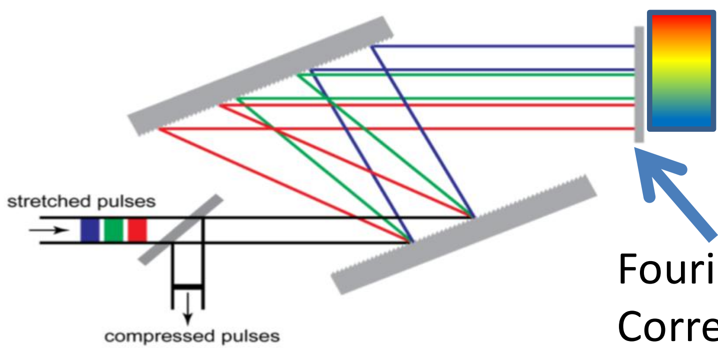



- asymmetric shape
- higher order chirp introduces spectral broadening

# Ultrashort Laser Pulses / Grating Compressors



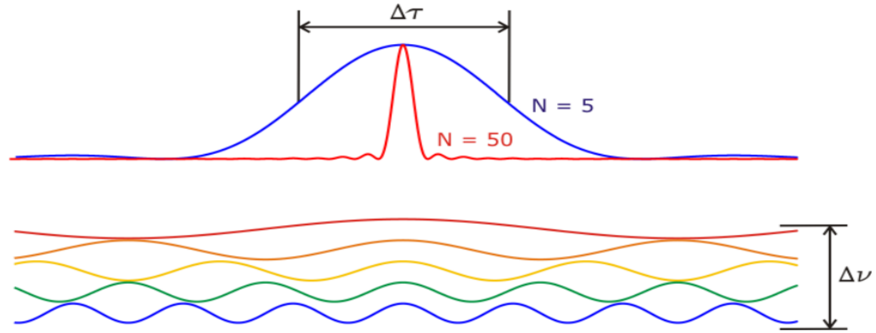

- chirped-pulse amplification (CPA):
  amplify laser pulse, compress afterwards




ideal:
linear relation of path length and distance

Fourier plane:
Correlation of spatial coordinate and laser wavelength

# Ultrashort Laser Pulses / Grating Compressors

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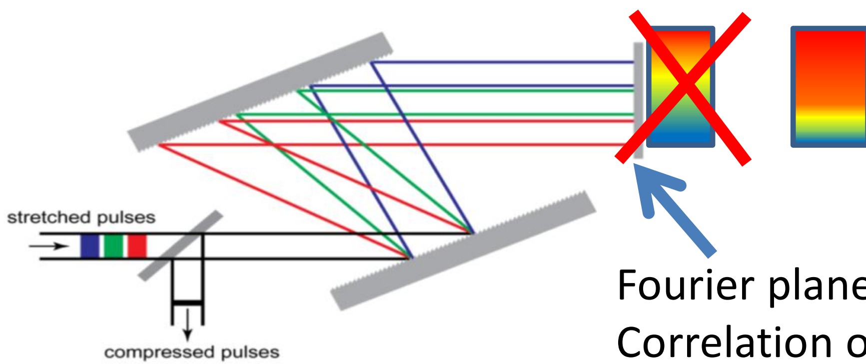



reality:
grating compressor
introduces non-linear chirp

$$D_2 = -2 \cdot \frac{4\pi^2 c d}{\omega_0^3 g^2} \left\{ 1 - \left[ \frac{2\pi c}{\omega_0 g} - \sin\gamma \right]^2 \right\}^{-\frac{3}{2}}$$

Fourier plane:
Correlation of spatial coordinate and laser wavelength

# Higher Order Dispersion

- Taylor expansion of the optical phase:

$$\phi(\omega) = D_0 + D_1 \cdot (\omega - \omega_0) + D_2 \cdot (\omega - \omega_0)^2 + D_3 \cdot (\omega - \omega_0)^3 + \ldots$$

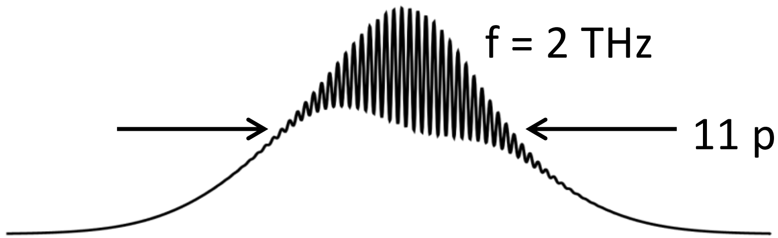
**$D_2$ : linear chirp of the pulse**

instantaneous laser frequency:

$$\nu(t) = \frac{1}{2\pi}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- intensity autocorrelation:

$$I(t) \sim \cos\left(\frac{\tau}{D_2}t + 3D_3\tau t^2\right)$$




**intensity beating is linearly chirped by third order term of the phase**

**→ difference frequency generation reduces each term by one order**

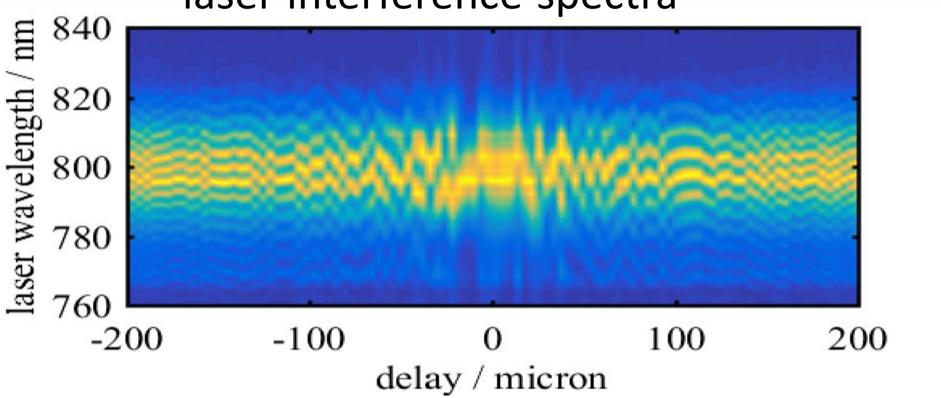
# Pulse characterization

- intensity autocorrelation

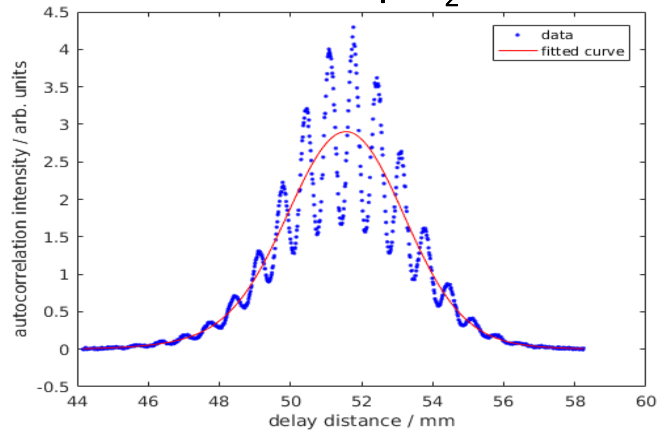
$$I(t) \sim \cos\left(\frac{\tau}{D_2}t + 3D_3\tau t^2\right)$$

- parameter derivation:

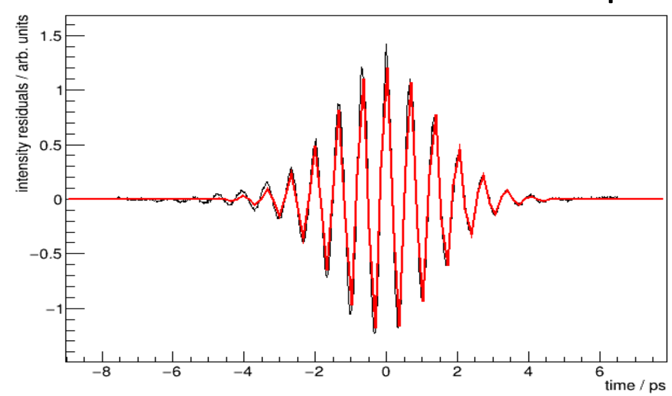
laser interference spectra




linear chirp $D_2$:

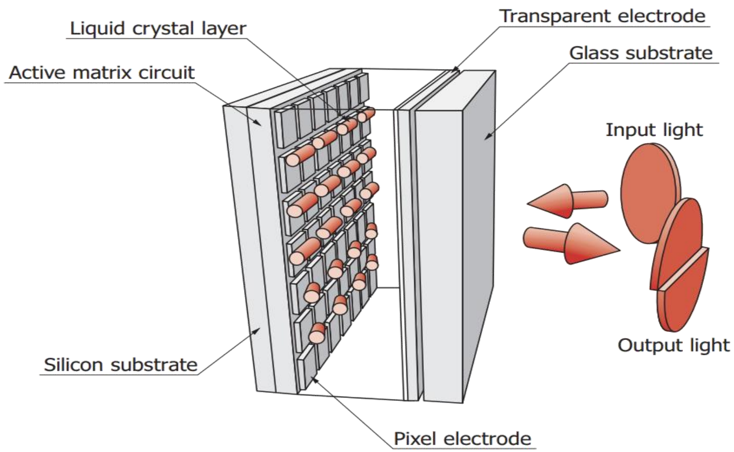



non-linear chirp $D_3$:
determine correlation chirp

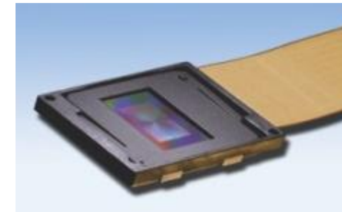


# Adaptive Optical Elements for Spatial Light Modulation

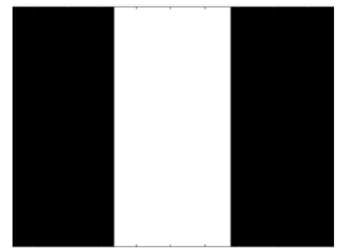
## liquid-crystal modulators



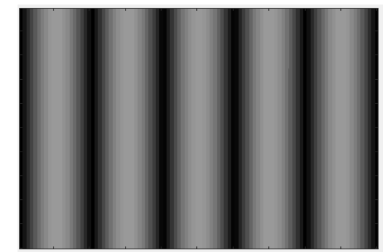

from: Hamamatsu Photonics,
LCOS-SLM manual



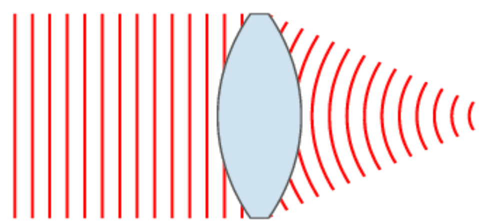
slit



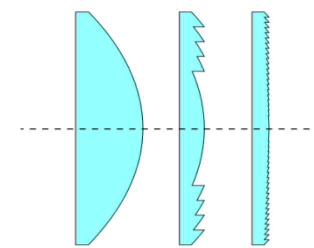
grating



lens

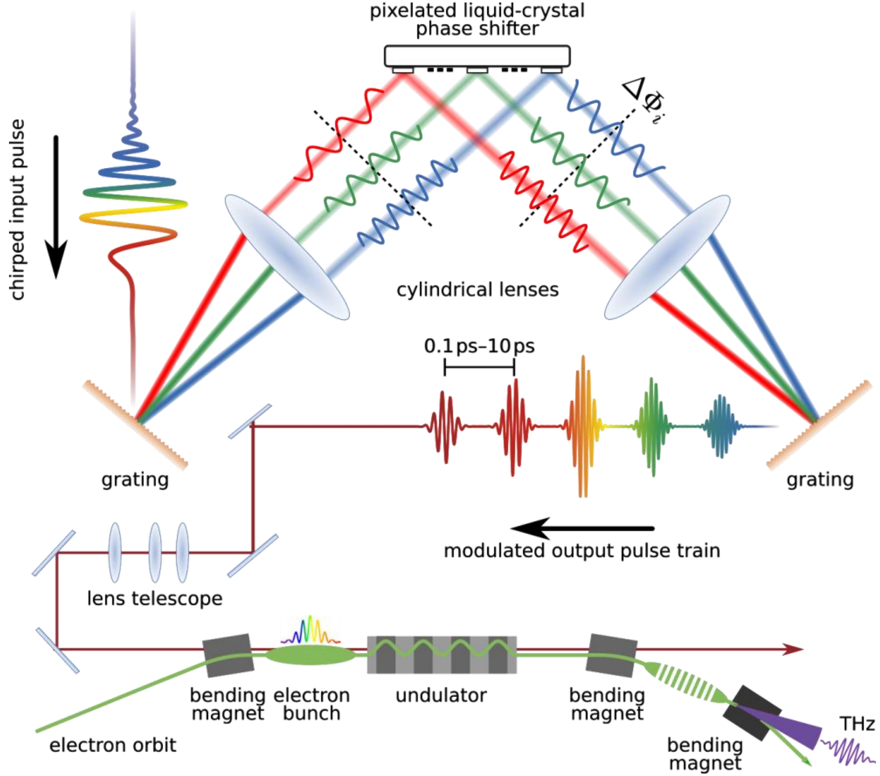


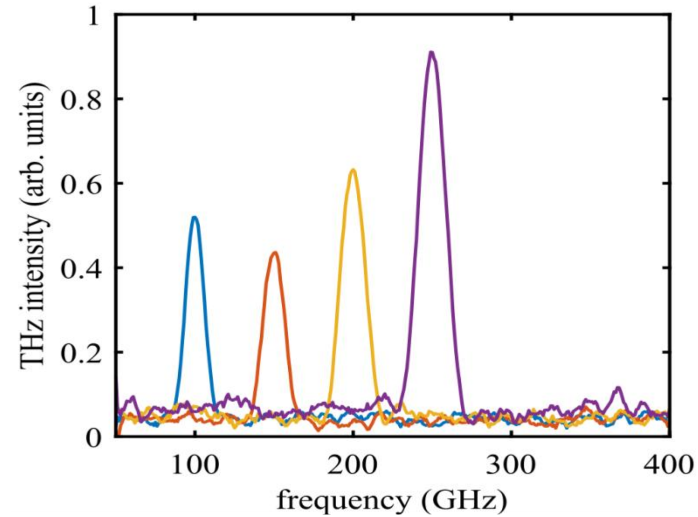
Fresnel lens

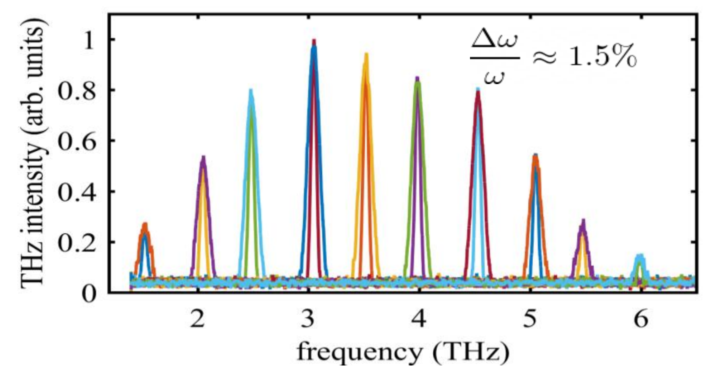


- reflective spatial modulator
- phase shift: 0 – 2π
- 1920x1080 pixels
- 15.3 x 8.6 mm$^2$
- pixel pitch: 8µm
- refresh rate: 60 Hz

# Spectral shaping of THz radiation

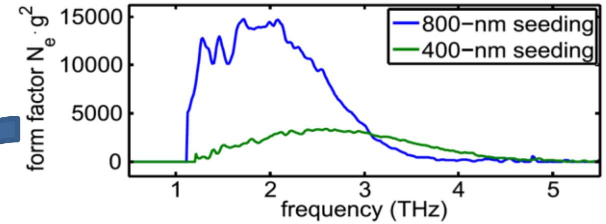


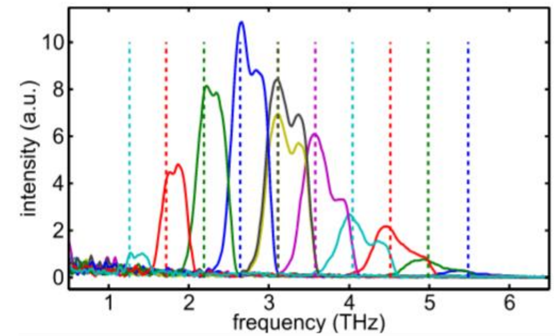




C. Mai et al., "Pulse shaping methods for laser-induced Generation of THz radiation at the DELTA storage ring", IPAC 2019.

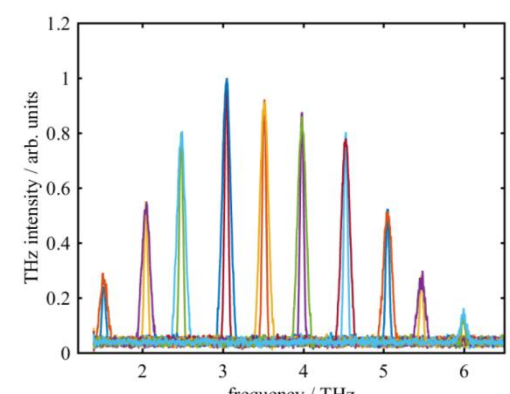
broadband generation



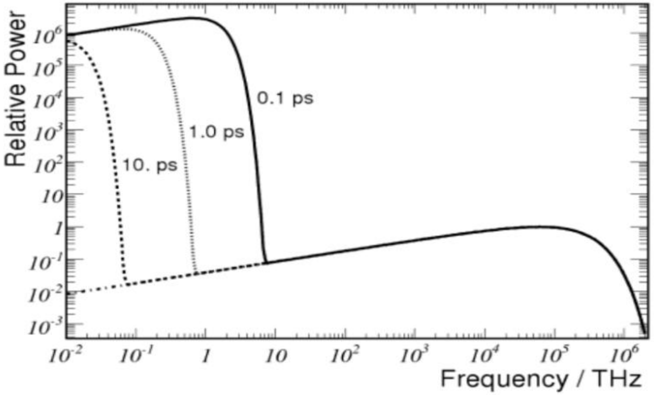

chirped-pulse beating




pulse shaping by phase modulation

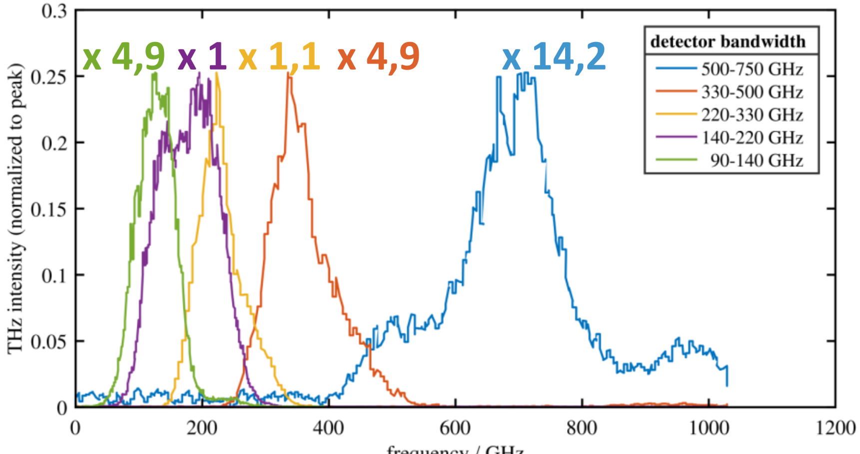


# Applications for beam diagnostics




- *best* detector for bunch length diagnostics?
- spectral response?
- pulse response?
- comparison under same conditions

direct detector comparison

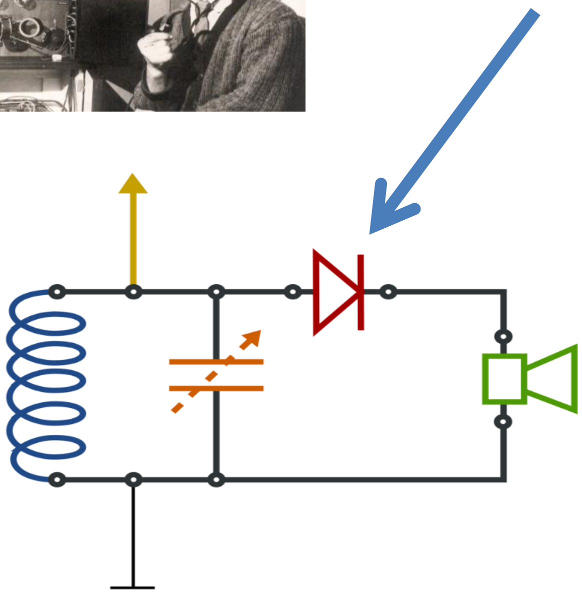



# Modern THz detectors

**crystal radio (1920):**
**Schottky contact: lead glance + metal spring**

**benefits of schottky detectors:**

- **low forward voltage (0.1 V – 0.4 V)**
- **electrons follow electric field**
  **→ fast switching**



**antenna**

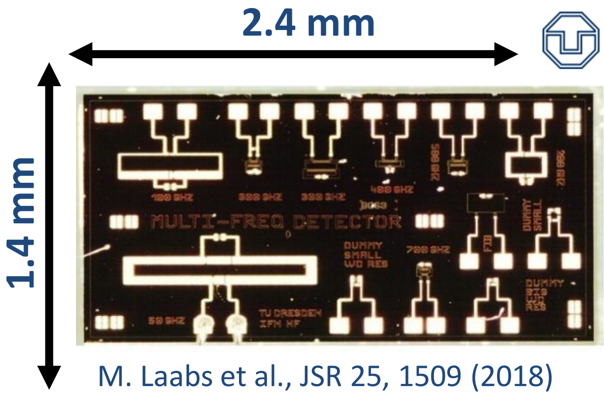
**diode**

**capacitor**

**speaker**

**inductivity**

# Modern THz detectors



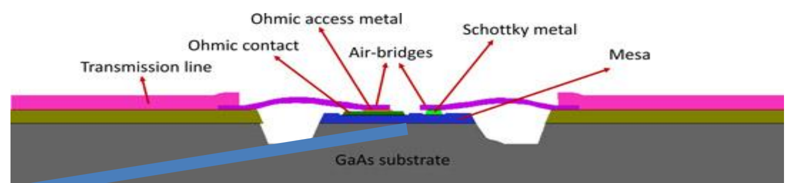

TECHNISCHE UNIVERSITÄT DRESDEN

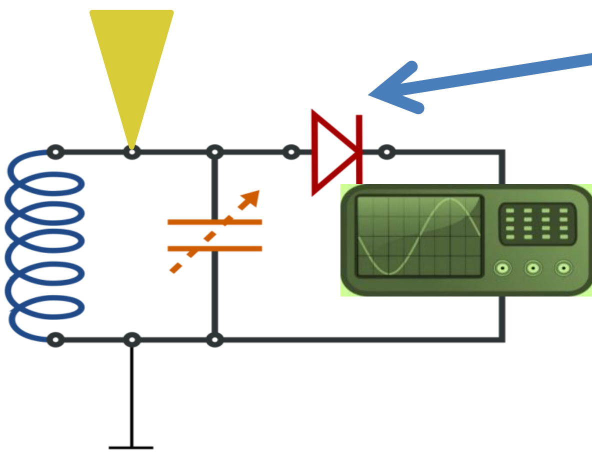
M. Laabs et al., JSR 25, 1509 (2018)

## THz Detector (2020): GaAs Schottky contact

**benefits of schottky detectors:**

- low forward voltage (0.1 V – 0.4 V)
- electrons follow electric field
  → fast switching



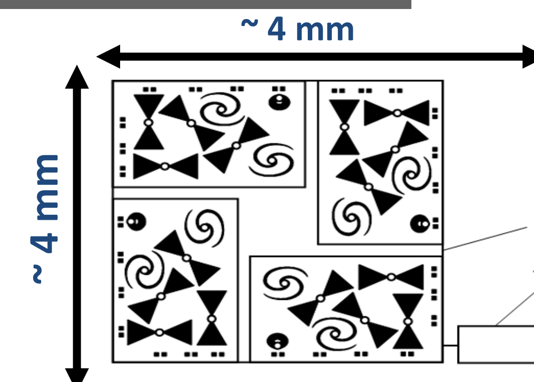
antenna

diode

capacitor

oscilloscope

inductivity




N. Neumann, C. Mai dt. Patent DE1020192083587

# Summary

- short-pulse facility is in operation
  - detailed studies of CHG radiation
  - different seeding modes
    - flexible wavelength / angle / polarization

- preparations towards EEHG operation
  - successful two-fold energy modulation

- flexible THz pulse-shaping schemes
  - phase modulation implemented
  - applications for beam diagnostics
  - user experiments: two-color THz?

- DELTA is back in operation from 6 July on

# Thank you for your attention!

**Thanks for the support of:**

KIT Karlsruhe Institute of Technology

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PTB

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National Institutes of Natural Sciences 分子科学研究所 Institute for Molecular Science

TU berlin

DESY

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DFG Deutsche Forschungsgemeinschaft

HOLOEYE