technische universität dortmund

Generation and Detection of coherently emitted THz radiation at DELTA

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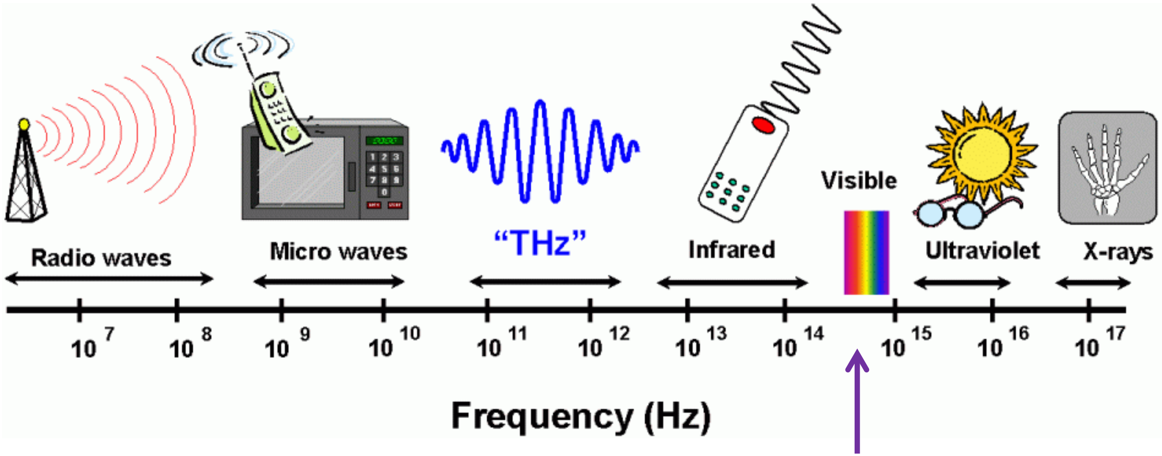
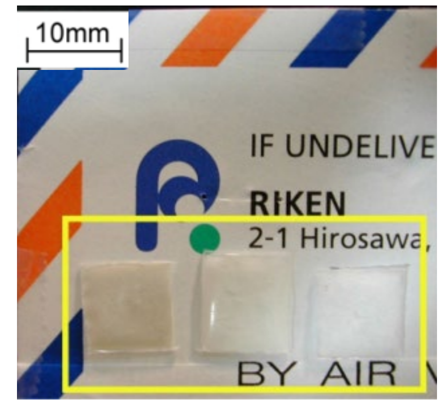
Center for Synchrotron Radiation
TU Dortmund

The Terahertz domain

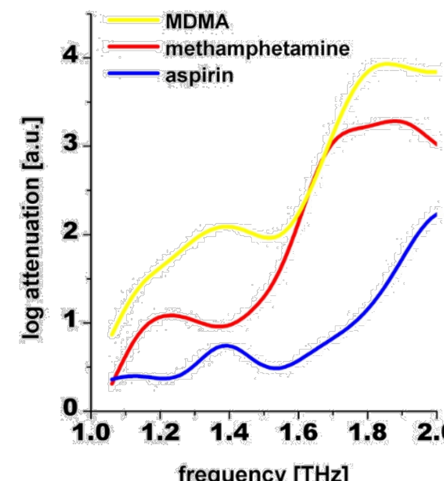


[1]

[2]



1 / 1 THz = 1 ps **c_0 / 1 THz = 0.3 mm** **800 nm ≈ c_0 / 375 THz**



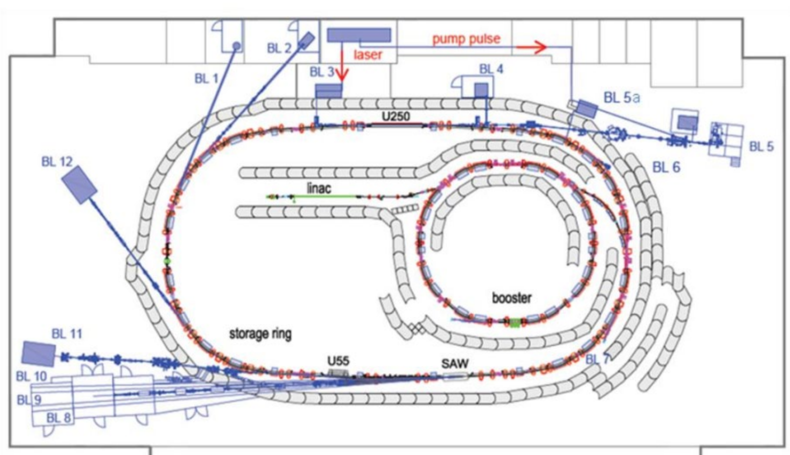
[2]

- *THz gap*
- limited access to sources and detectors

- non-destructive material science
- THz radiation is part of synchrotron radiation spectrum

[1] http://www.terasense.com
[2] K. Kawase et. al, Optics Express 11, 2549 (2003)

DELTA – the light source at TU Dortmund University



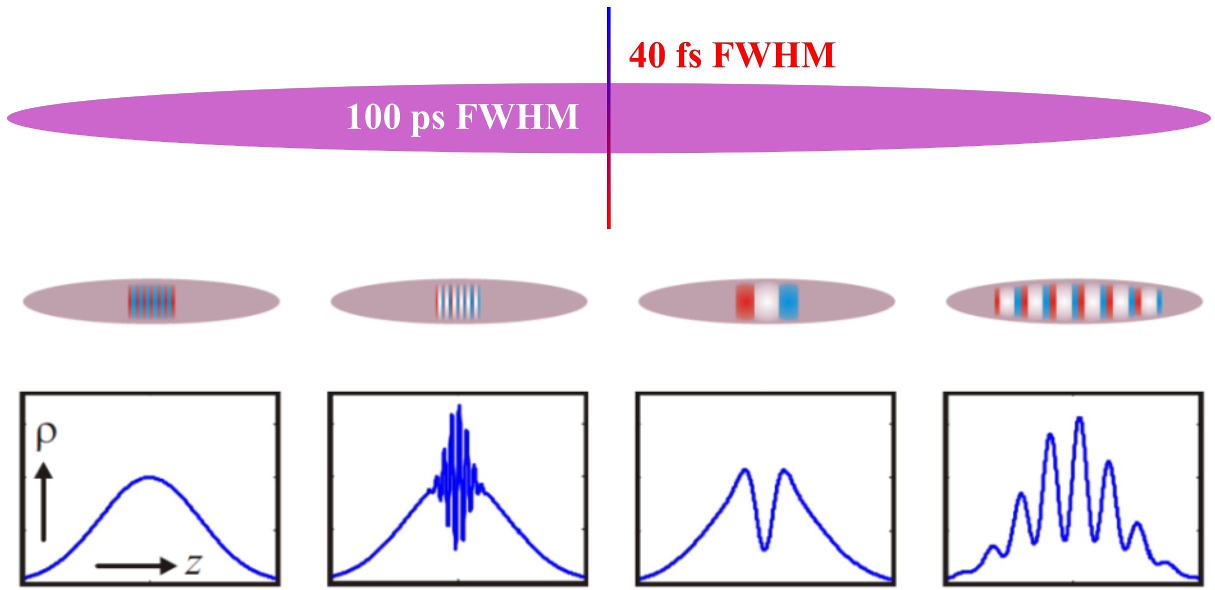
Parameters

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

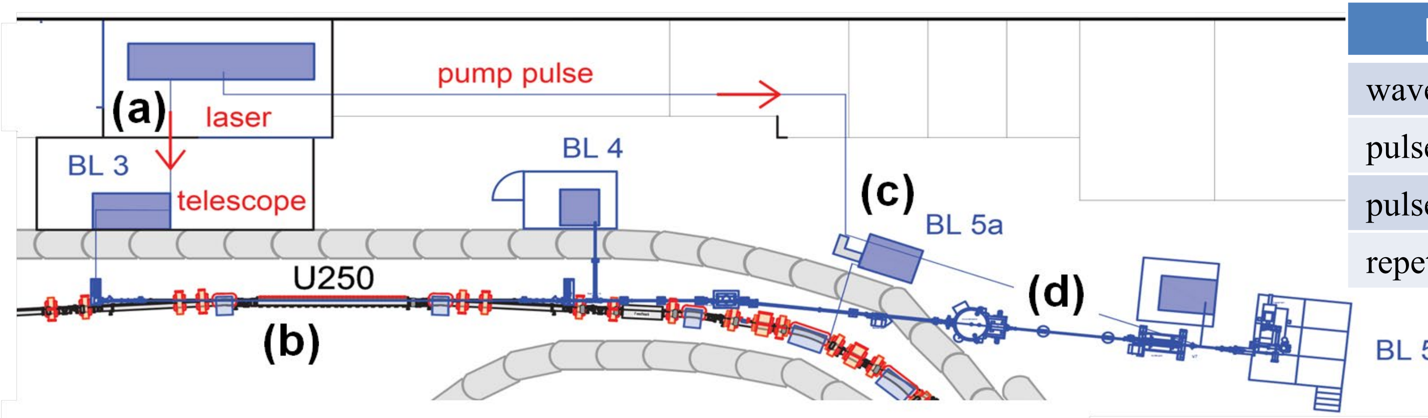


energy modulation

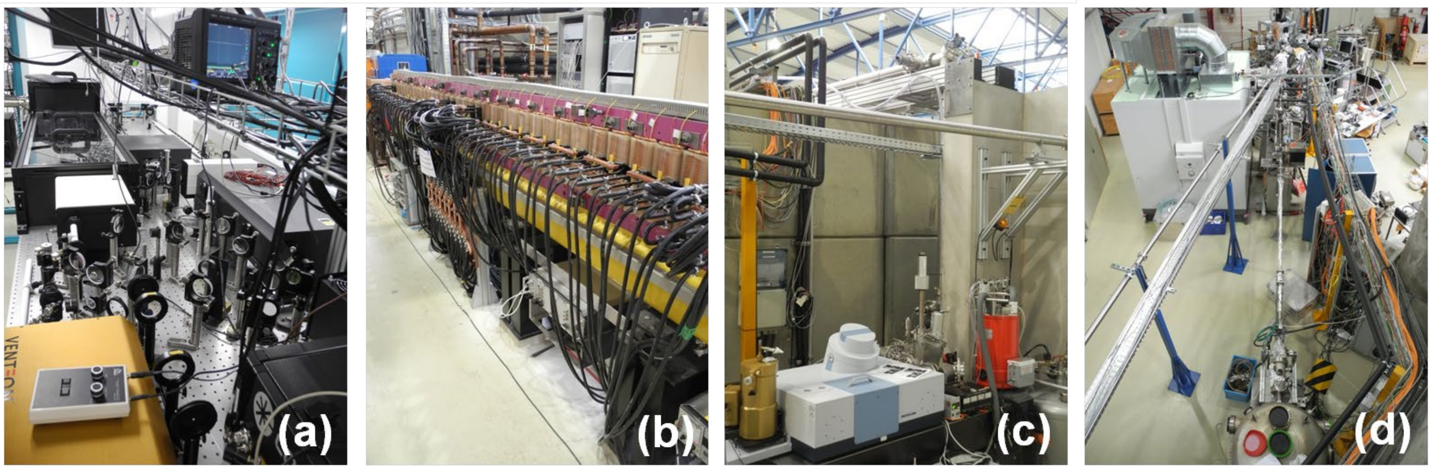
density modulation
→ VUV radiation

→ THz: broadband **→ THz: narrowband**

The DELTA short-pulse facility

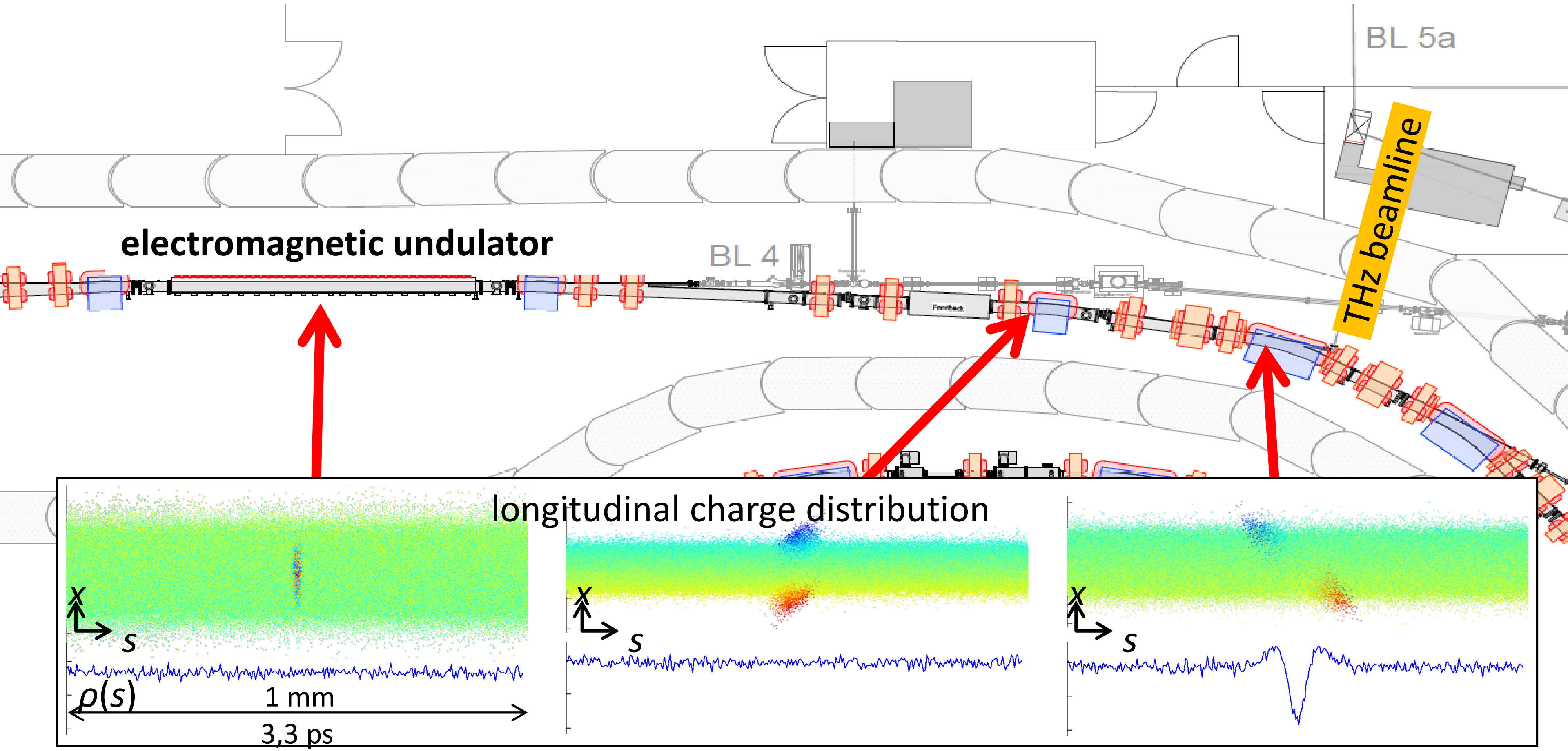


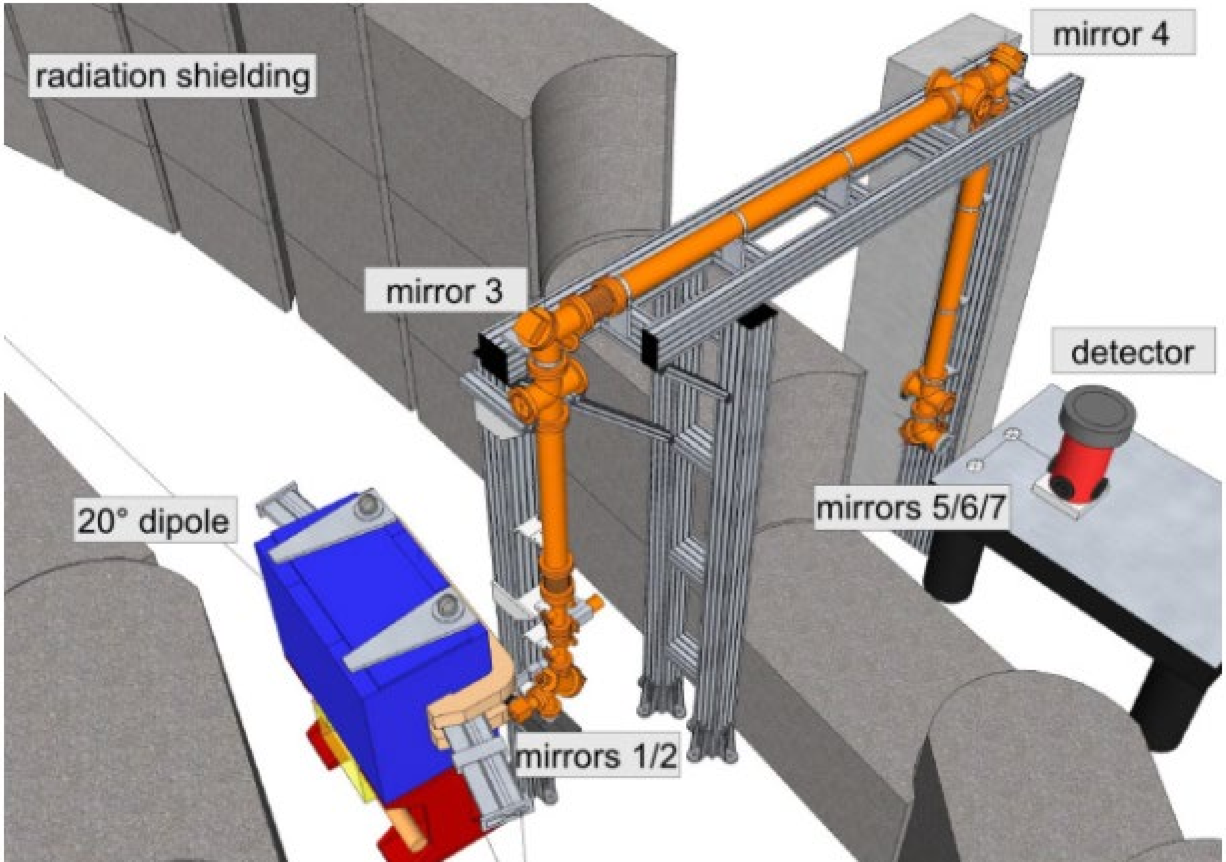
laser parameters	
wavelength	800 nm
pulse length	40 fs
pulse energy	8 mJ
repetition rate	1 kHz



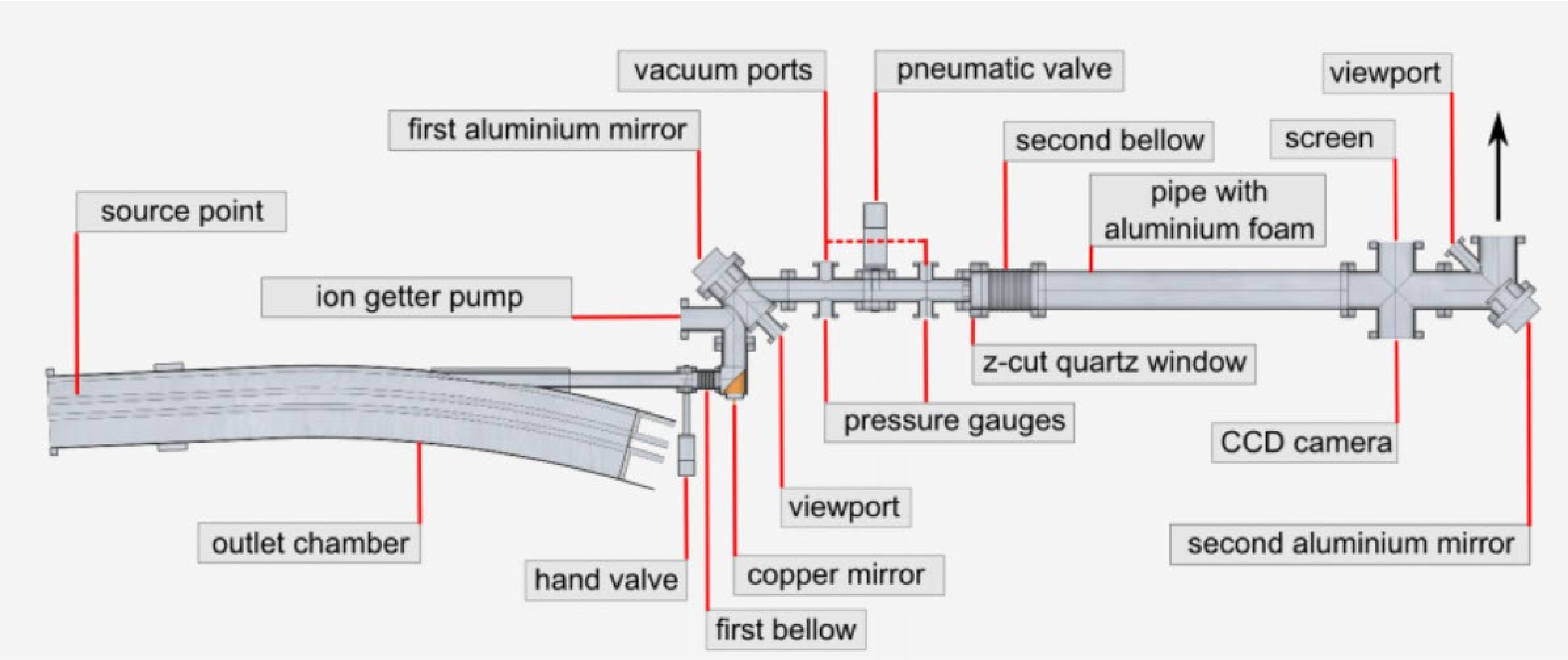
fs laser system **undulator U250** **THz beamline** **VUV beamline for pump-probe experiments**

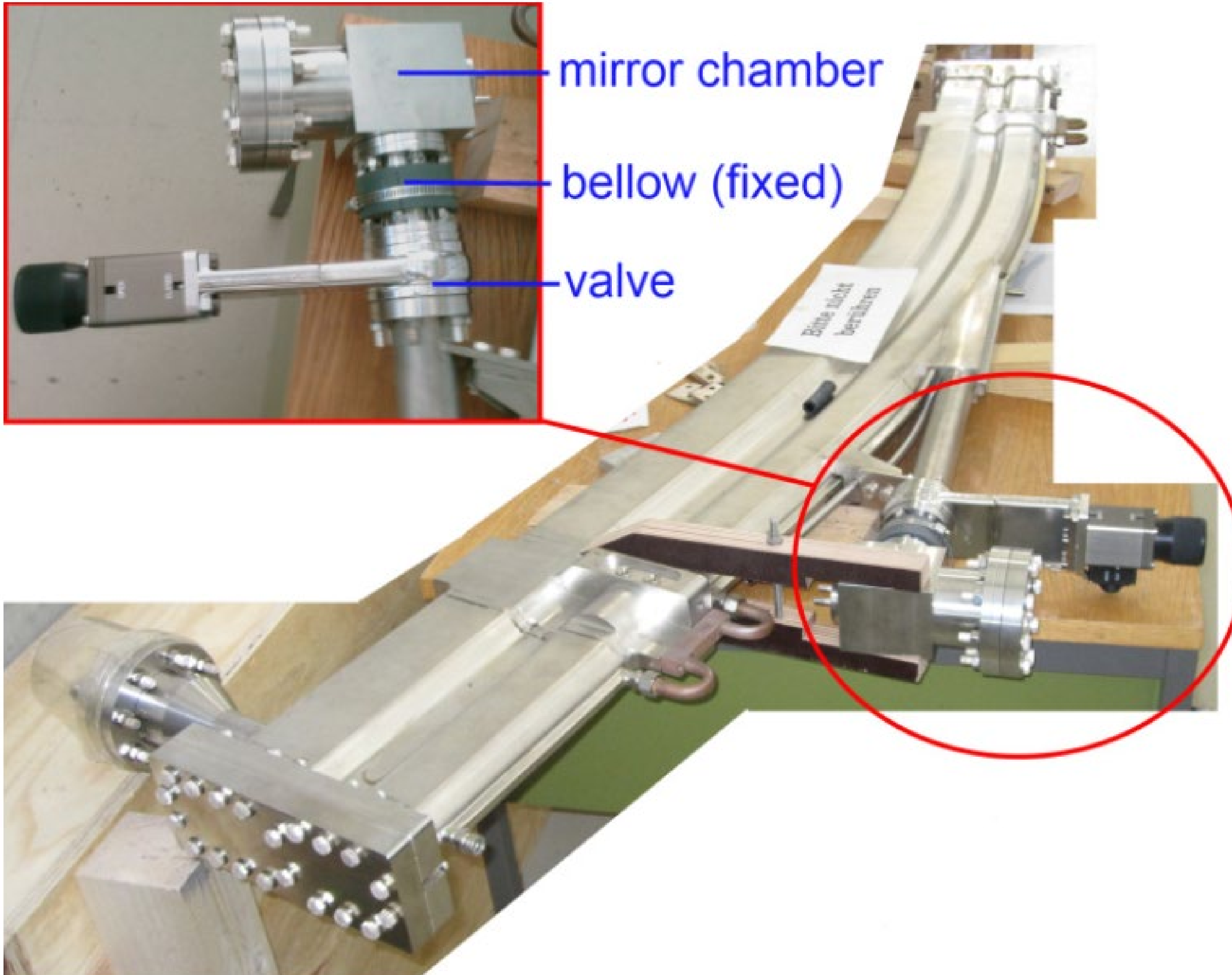
Coherent emission of THz radiation



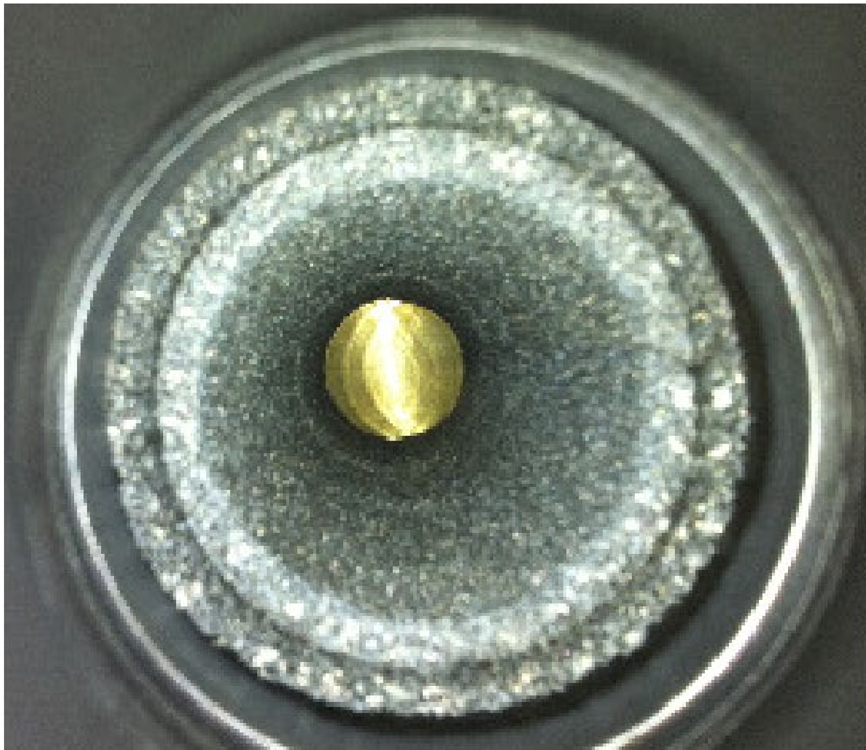


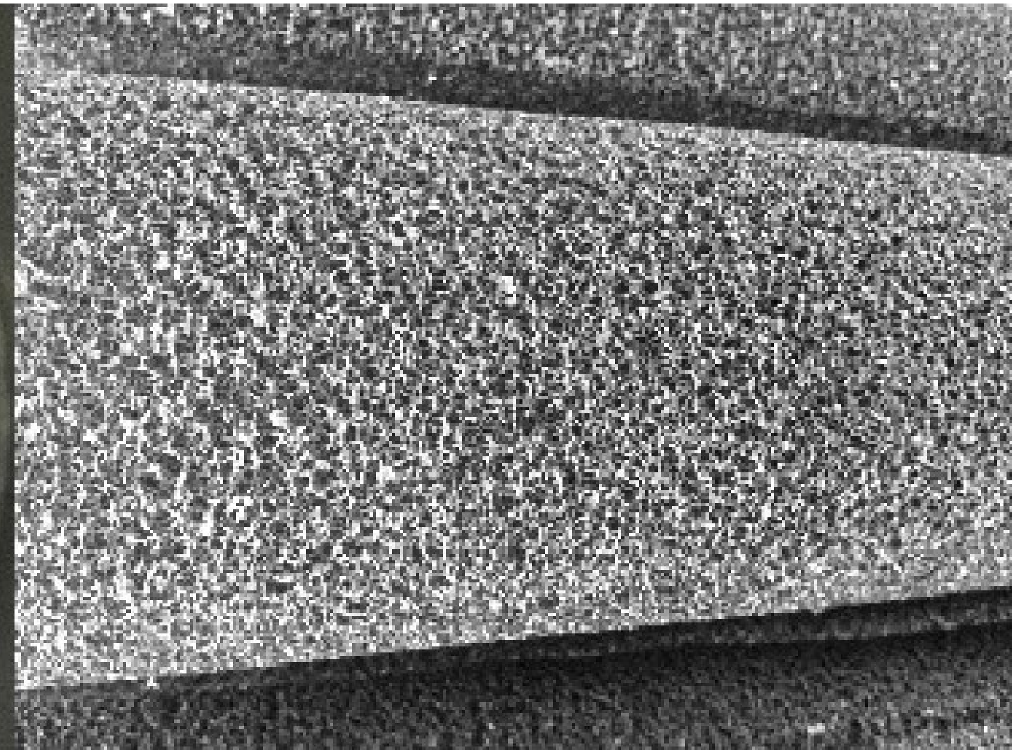
radiation shielding
mirror 4
mirror 3
detector
20° dipole
mirrors 5/6/7
mirrors 1/2

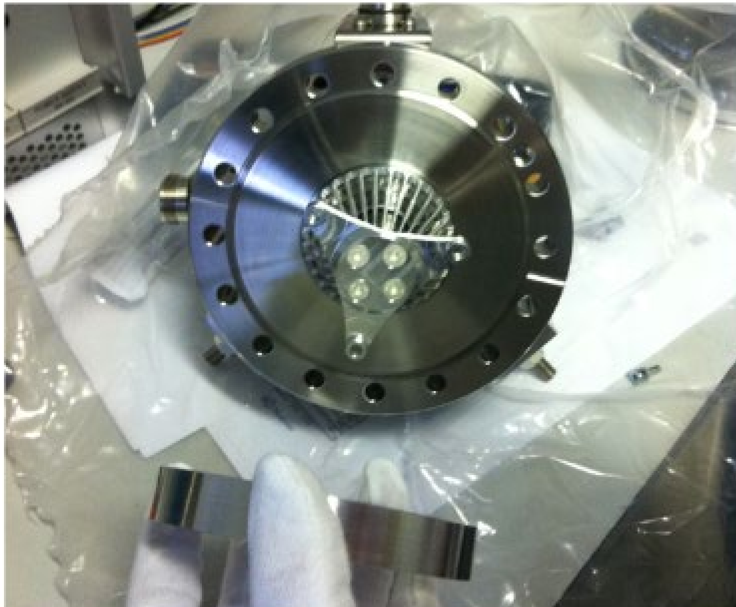

vacuum ports
pneumatic valve
viewport
first aluminium mirror
second bellow
screen
source point
pipe with
aluminium foam
ion getter pump
z-cut quartz window
pressure gauges
CCD camera
viewport
outlet chamber
second aluminium mirror
hand valve
copper mirror
first bellow


mirror chamber
bellow (fixed)
valve

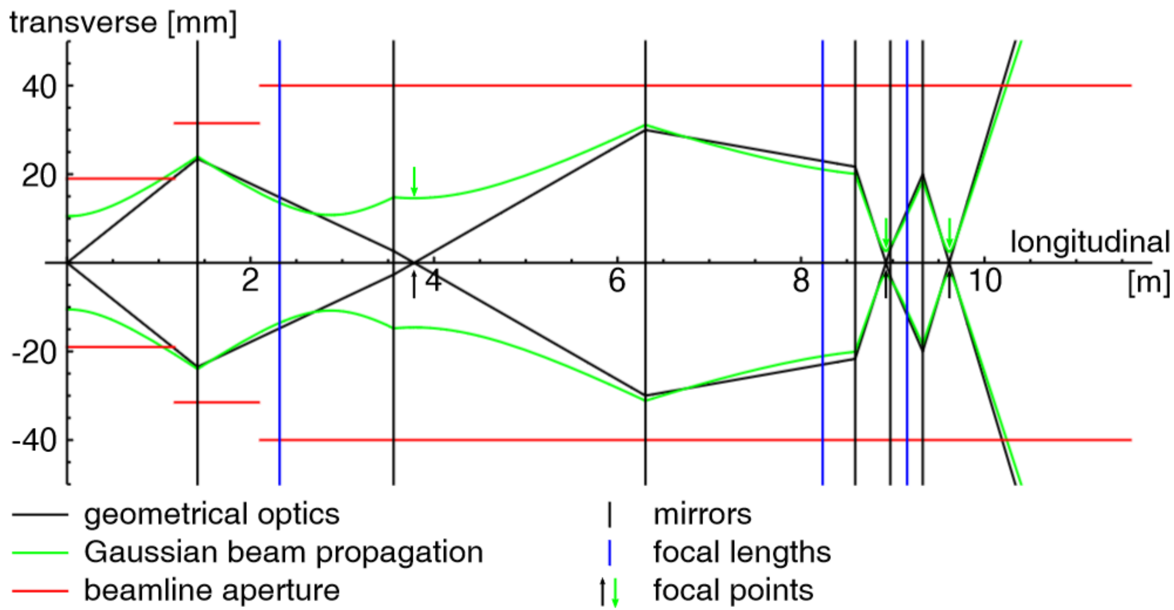
Reflectionless Beam transport



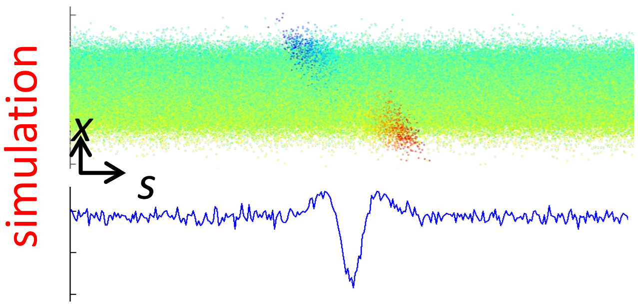


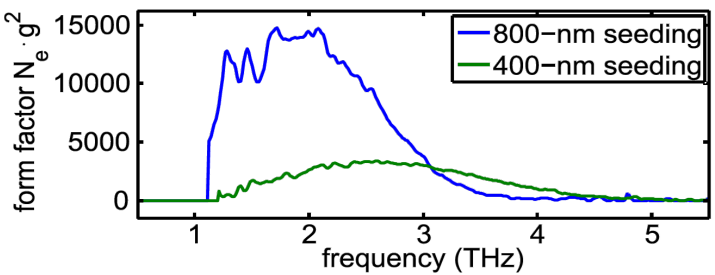


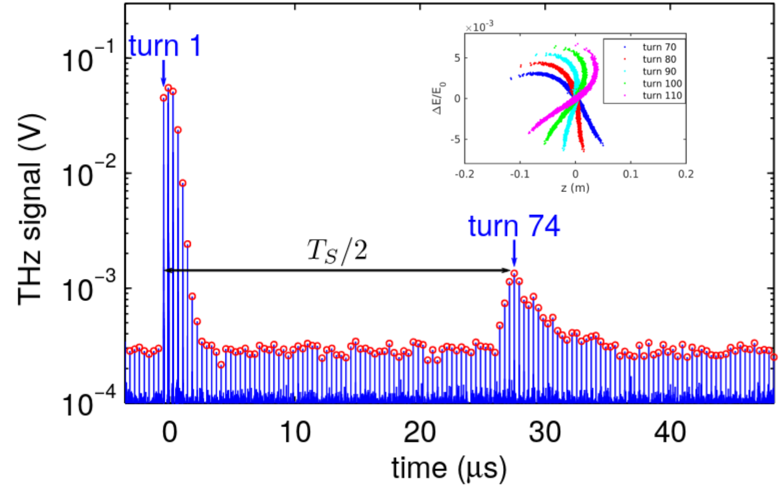
Beam propagation

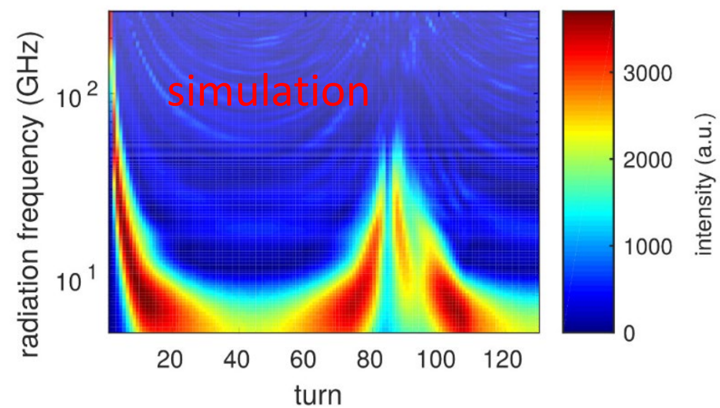


Broadband THz generation: spectrotemporal evolution







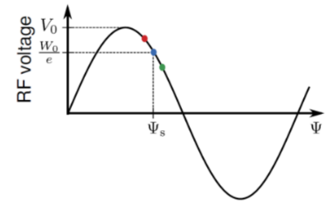


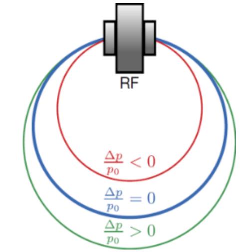
Energy-modulated electrons

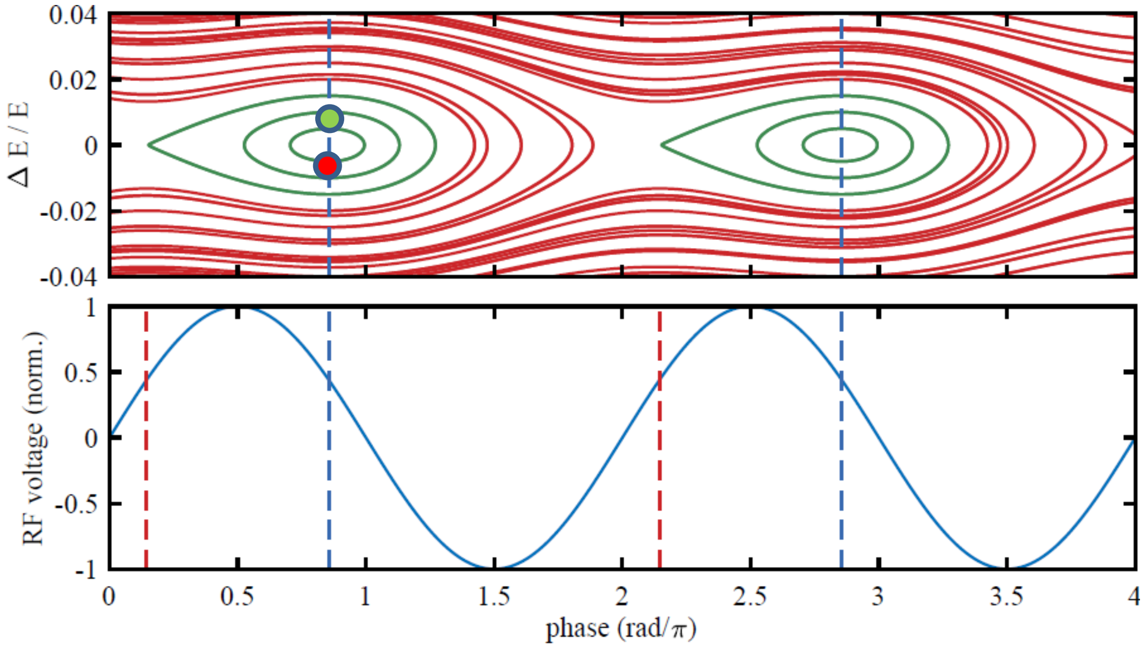
 14

synchrotron frequency:

$$\Omega^2 = \omega_{\text{rev}}^2 \left(\frac{\alpha_c h}{2\pi E_0} \right) e \frac{dV}{d\psi}(\psi_s)$$







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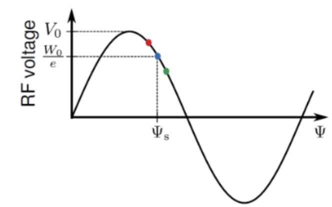

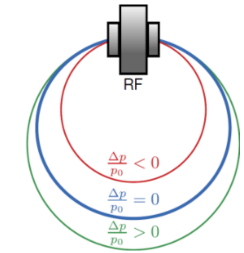

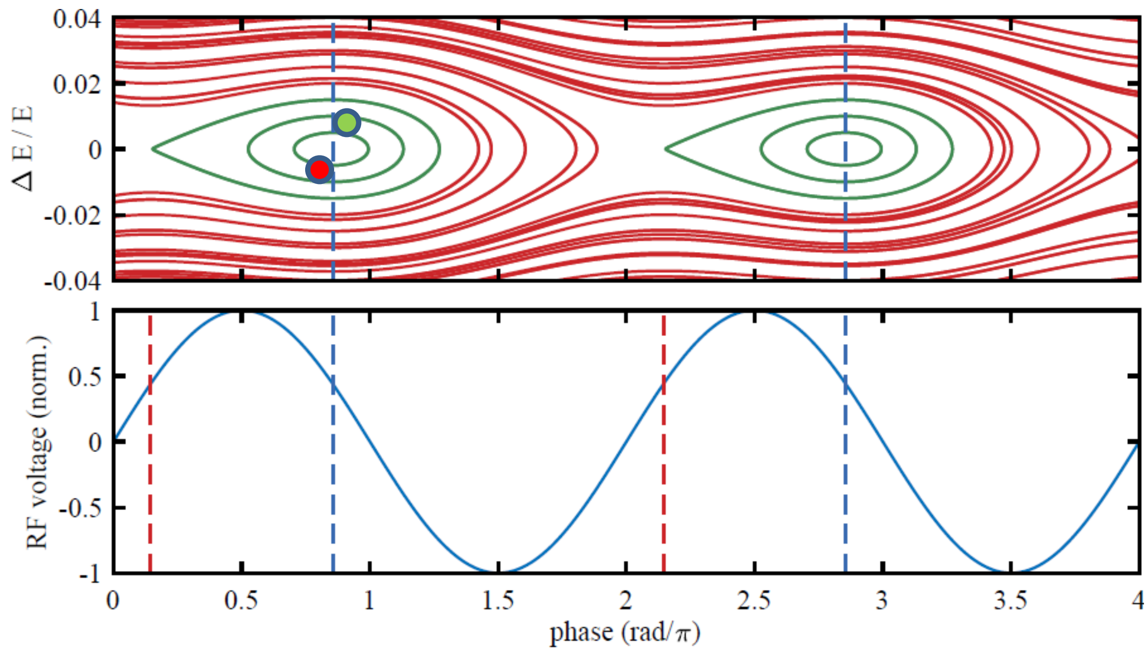

Energy-modulated electrons

 16

synchrotron frequency:

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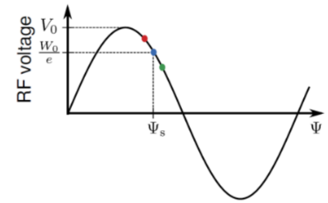

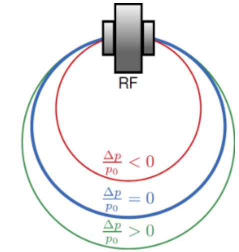

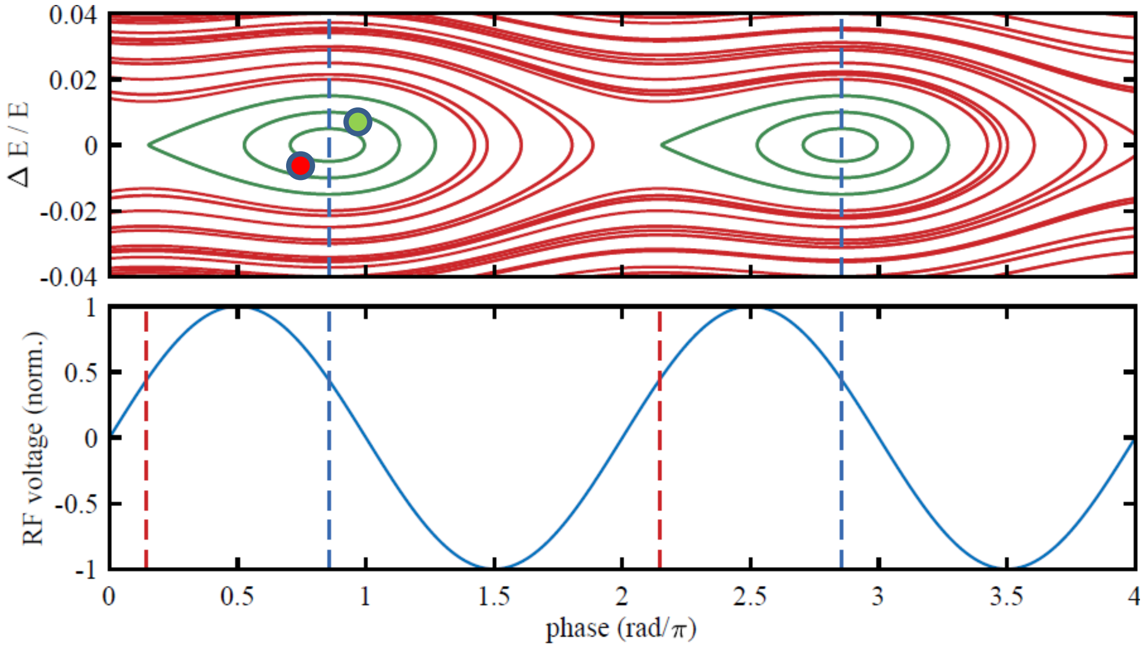

Energy-modulated electrons

17

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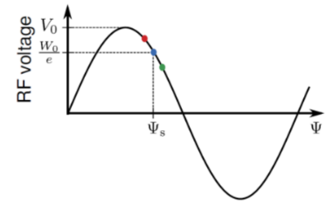

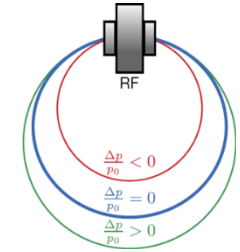

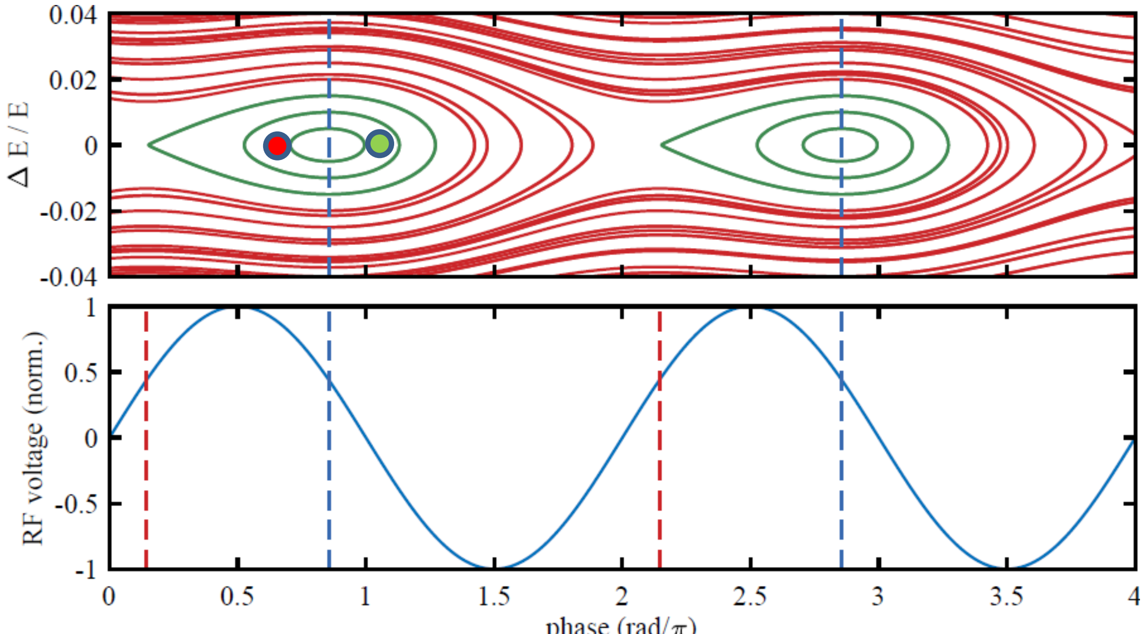

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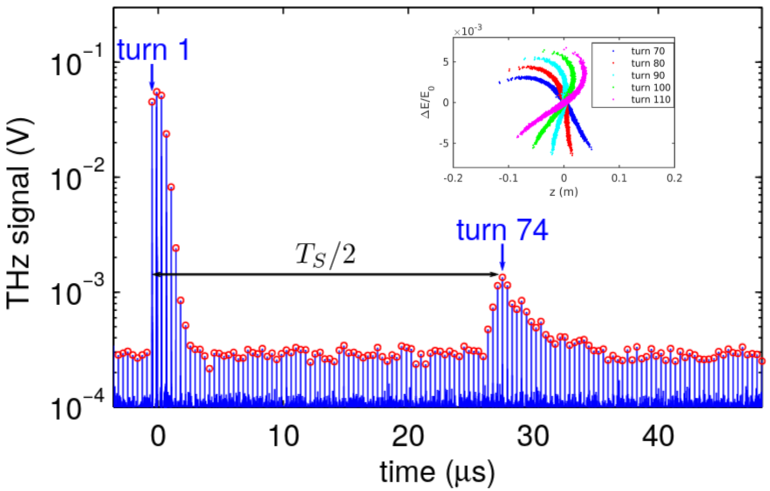
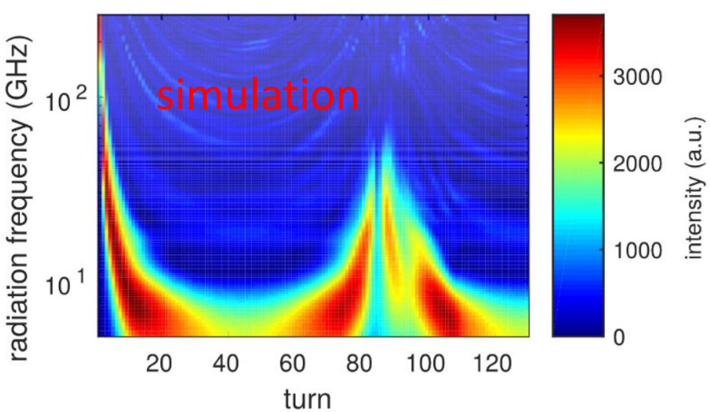
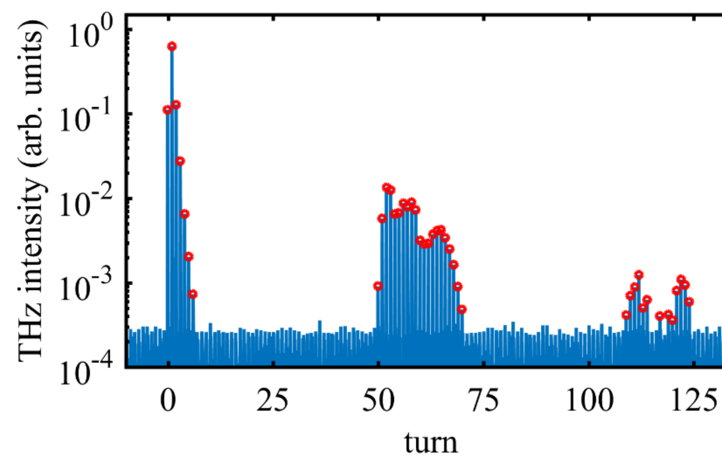
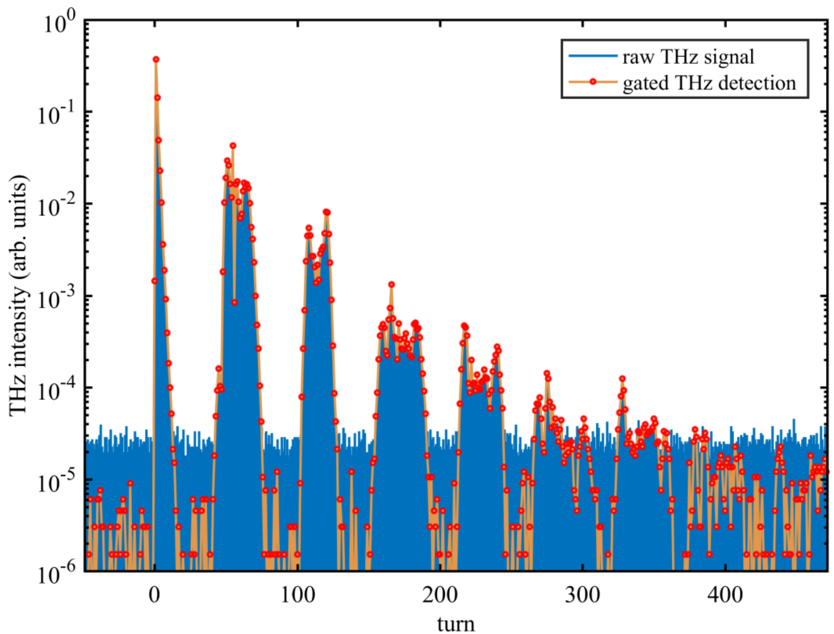


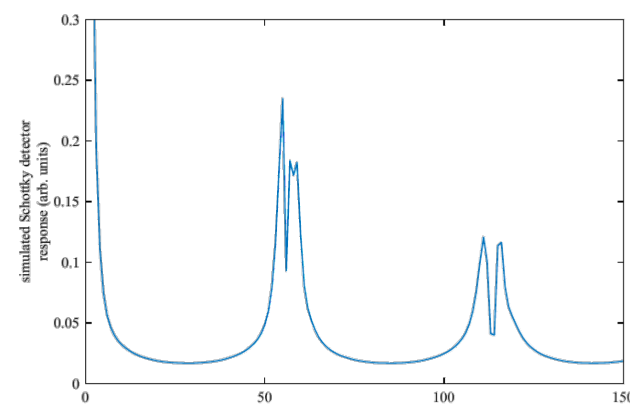


- RF Upgrade (second cavity)
- improved detector readout

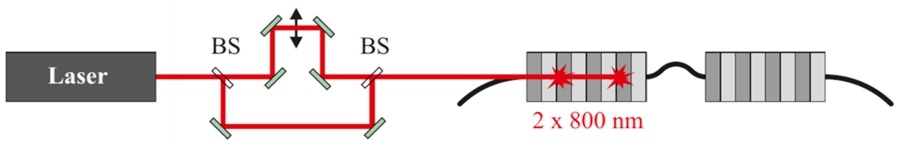


More accurate measurement: gated detection

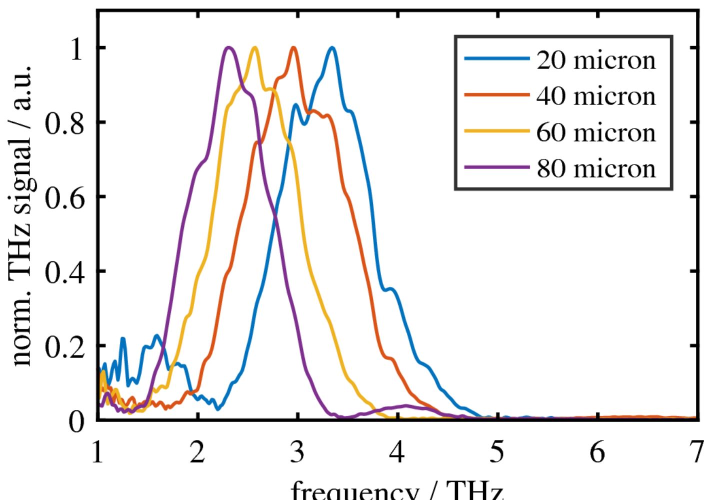


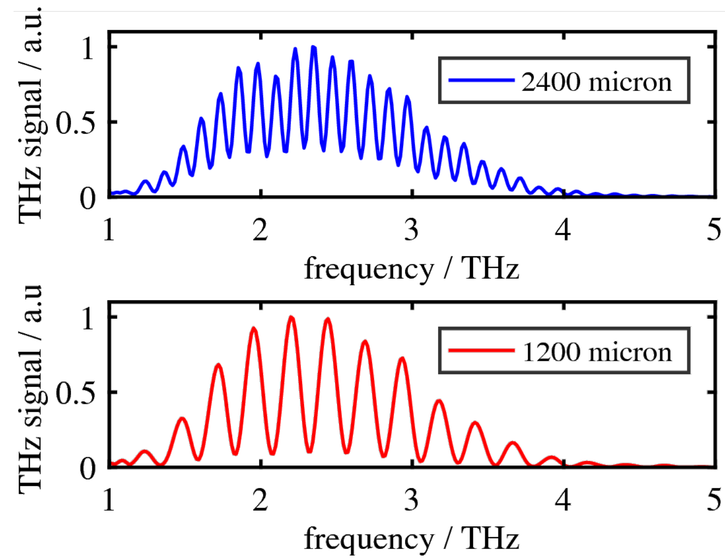


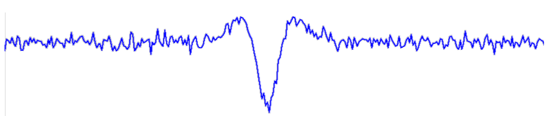
Increasing spectral control of THz generation



Step 1: replicate textbook knowledge…

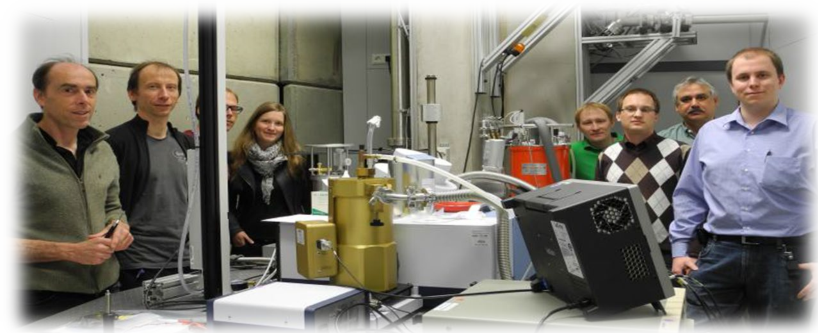






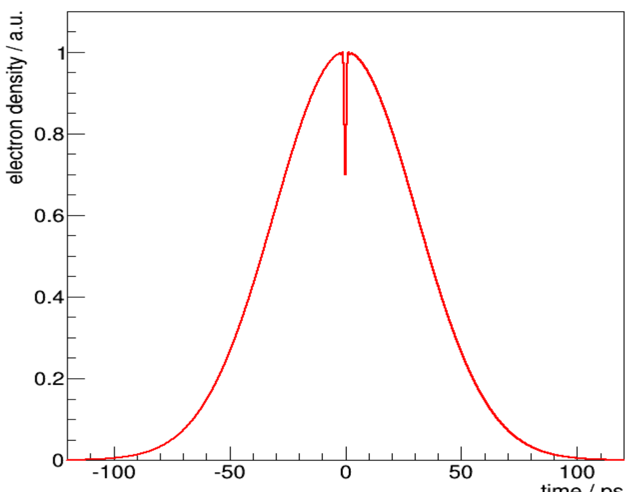
Towards tunable narrowband radiation

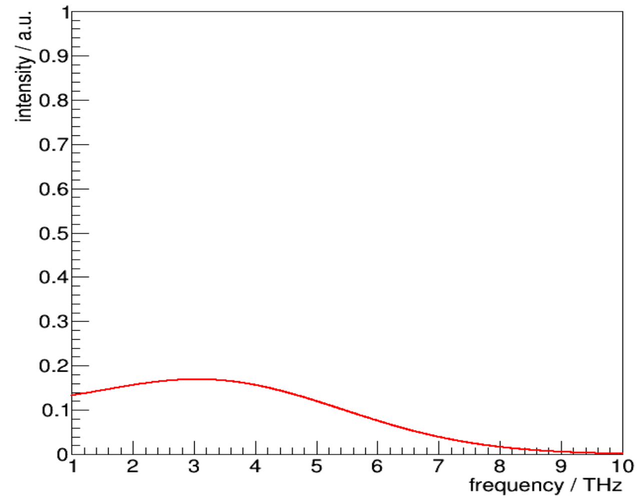
cooperation with PhLAM, Lille



- 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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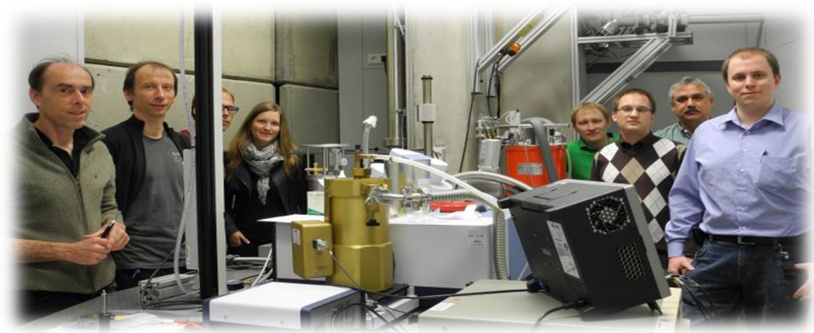

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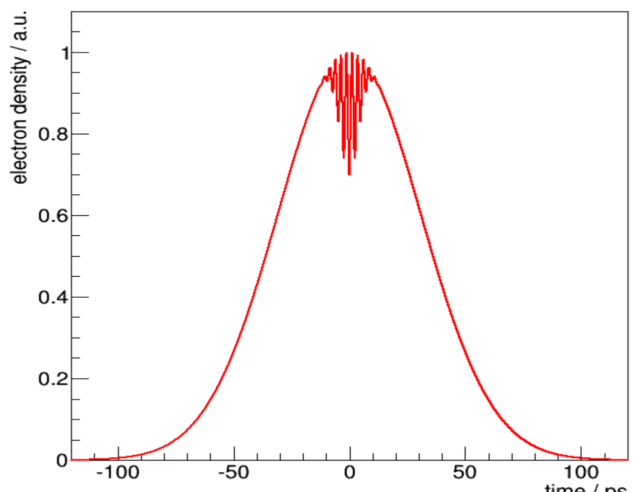

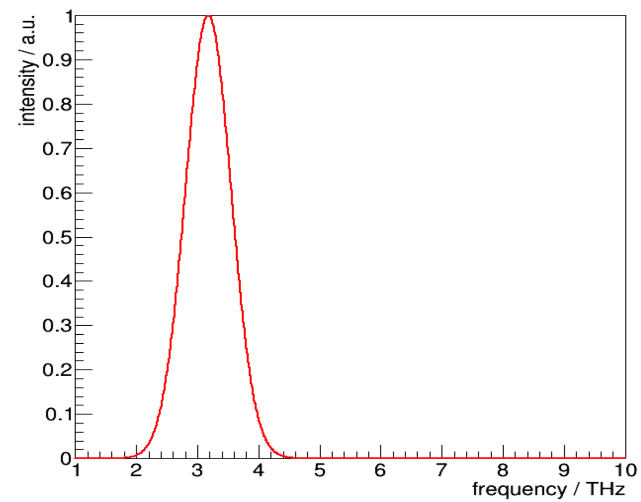

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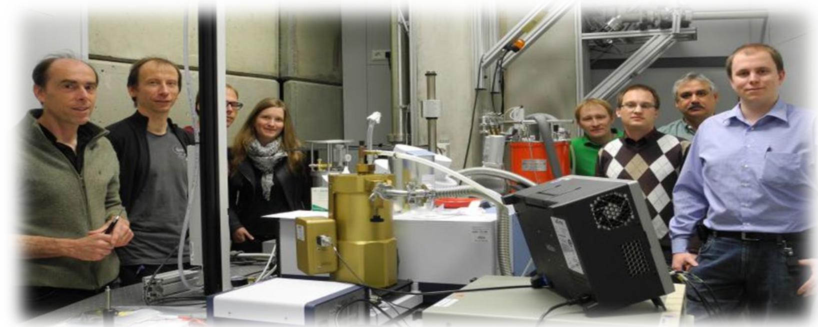

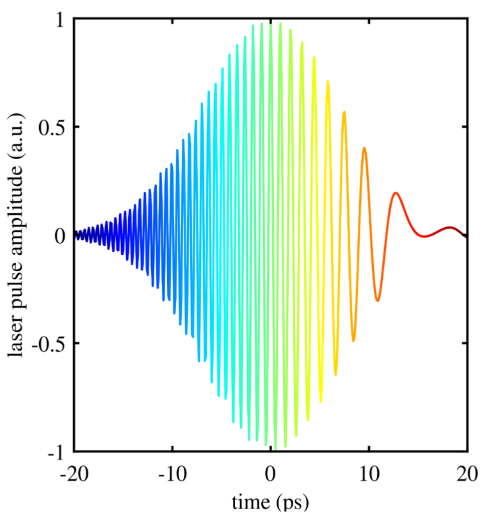

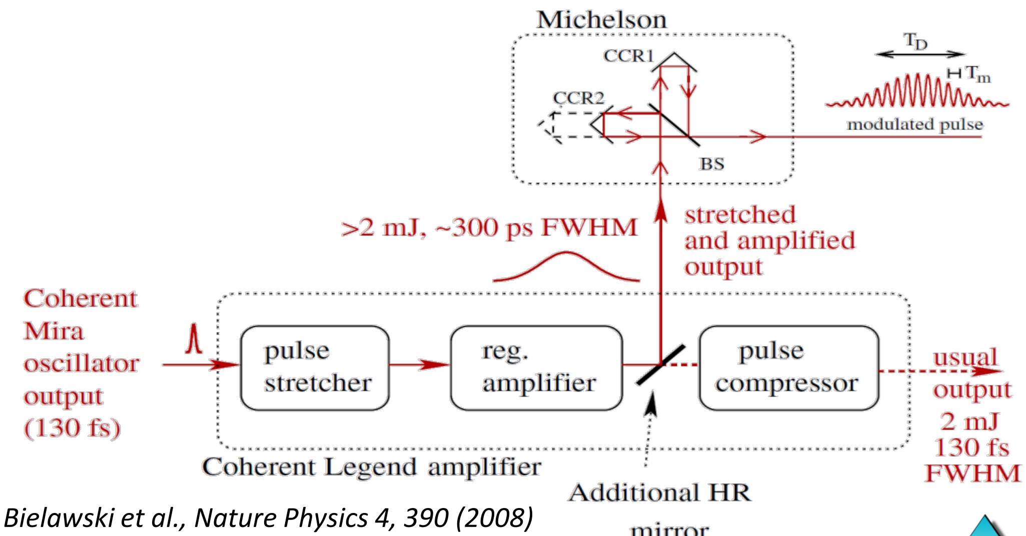

S. Bielawski et al., Nature Physics 4, 390 (2008)
C. Evain et al., PRST-AB 13, 090703 (2010)

Towards tunable narrowband radiation

cooperation with PhLAM, Lille

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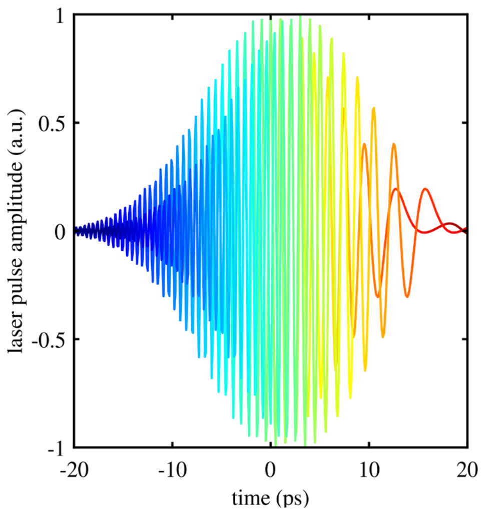

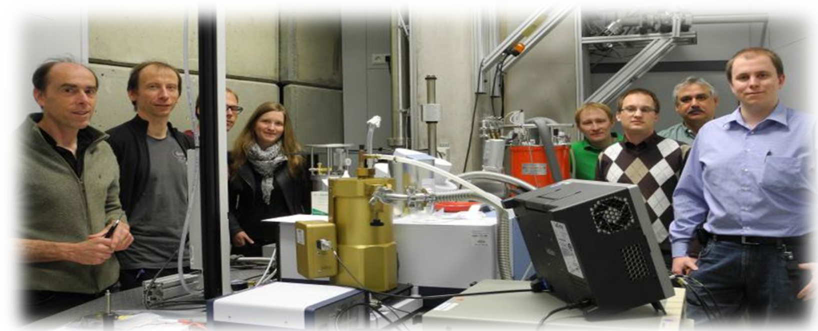

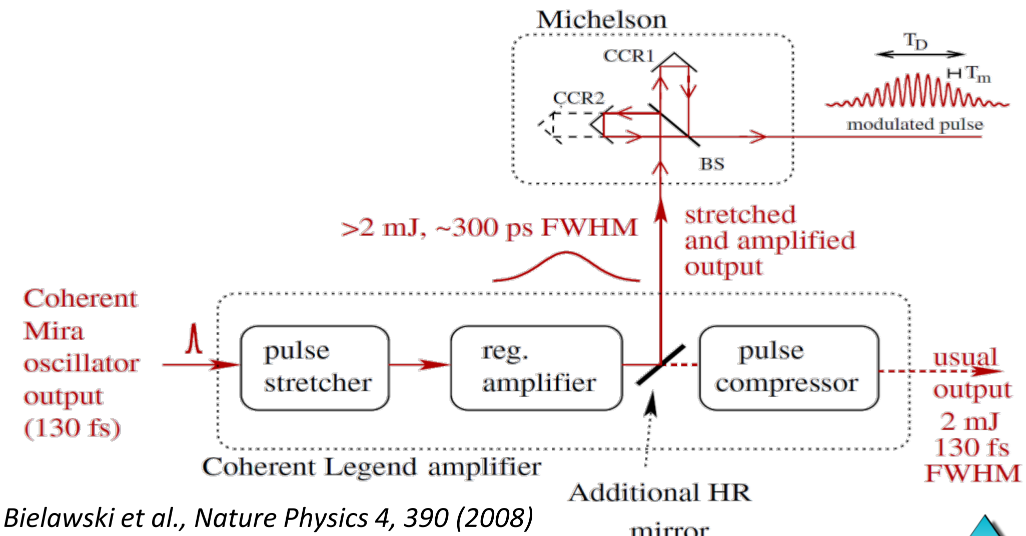

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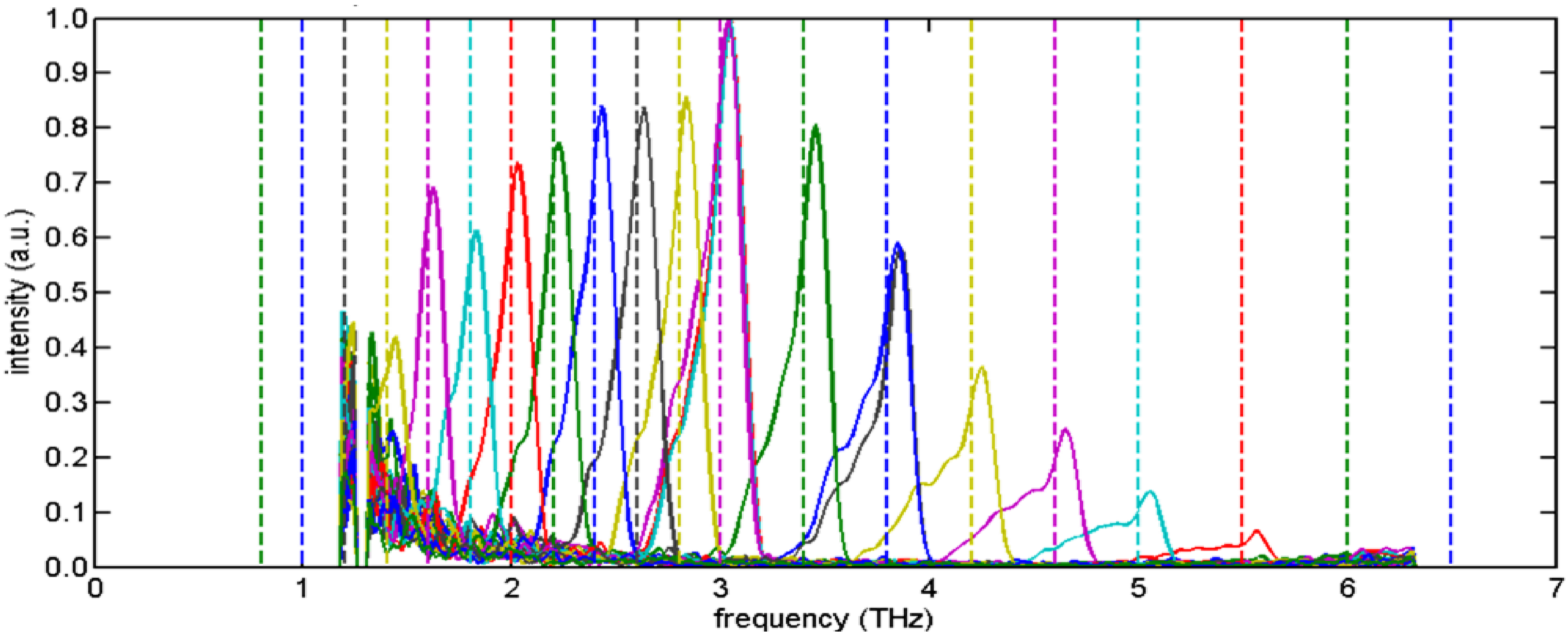
Tunable THz radiation



- selectable target frequency (dashed)

- higher order chirp introduces spectral broadening
- asymmetric shape

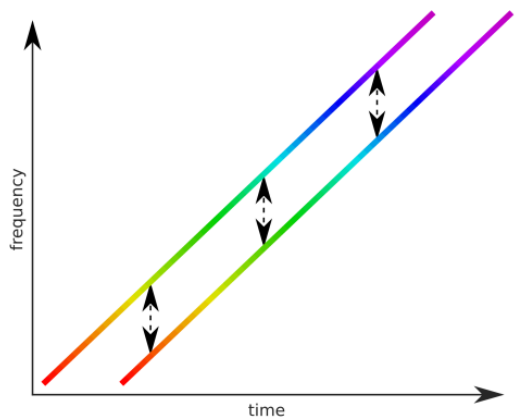
Higher Order Dispersion

- Taylor expansion of the optical phase:

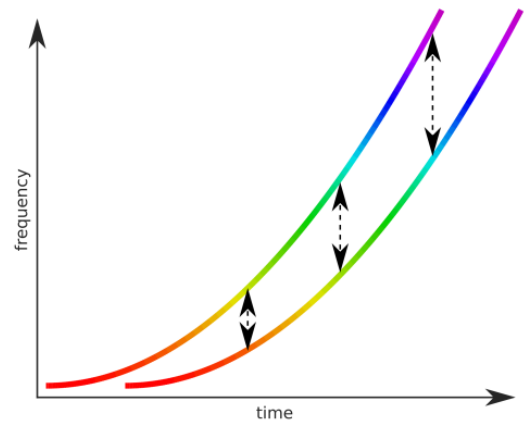
$$\phi(\omega) = D_0 + D_1 \cdot (\omega - \omega_0) + D_2 \cdot (\omega - \omega_0)^2 + D_3 \cdot (\omega - \omega_0)^3 + \ldots$$

D_2 : linear chirp of the pulse

linear chirp



non-linear chirp

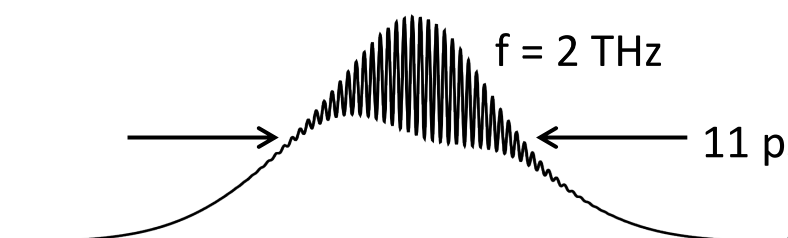


Dispersion measurement

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

- D_2 and D_3 must be known
- FROG?  SPIDER?  autocorrelator!
- pulses are too long for our usual diagnostics

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



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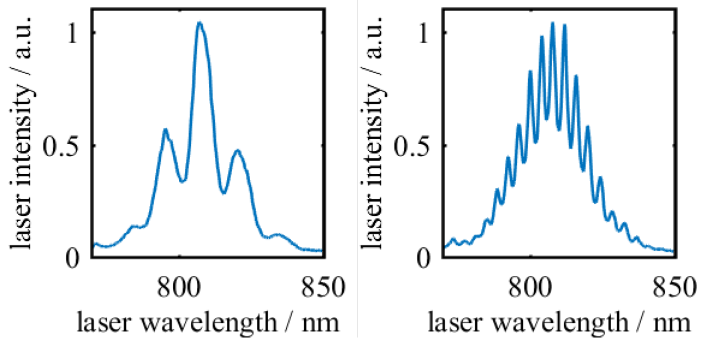
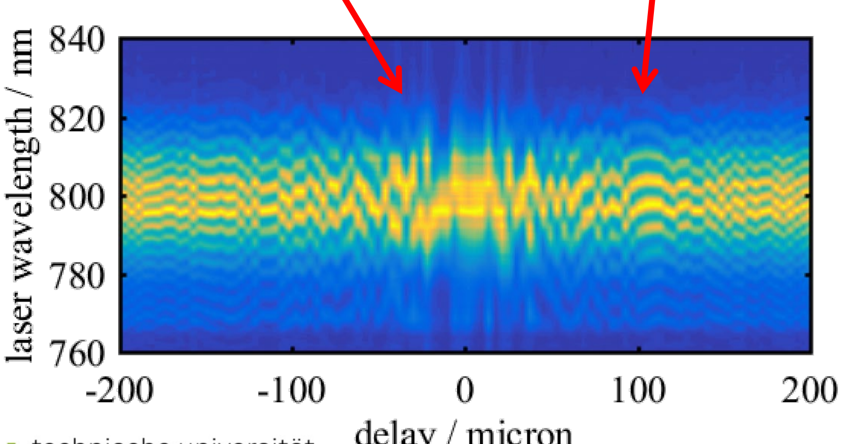
spectra:





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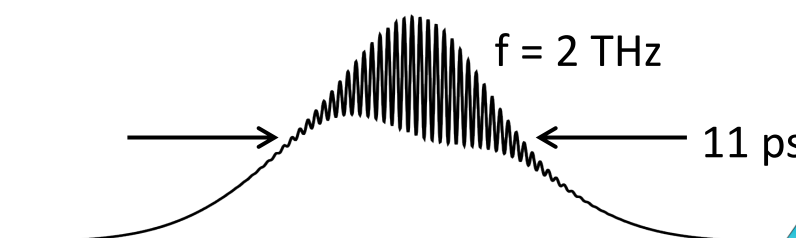
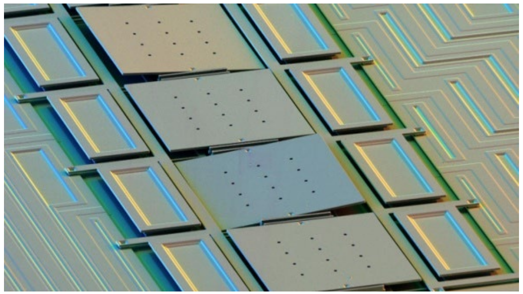
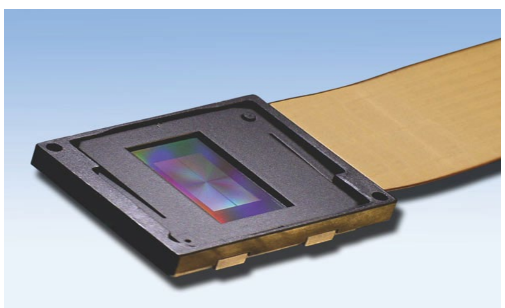


Adaptive optics for spatial light modulation

micro-mirror arrays (MEMS)

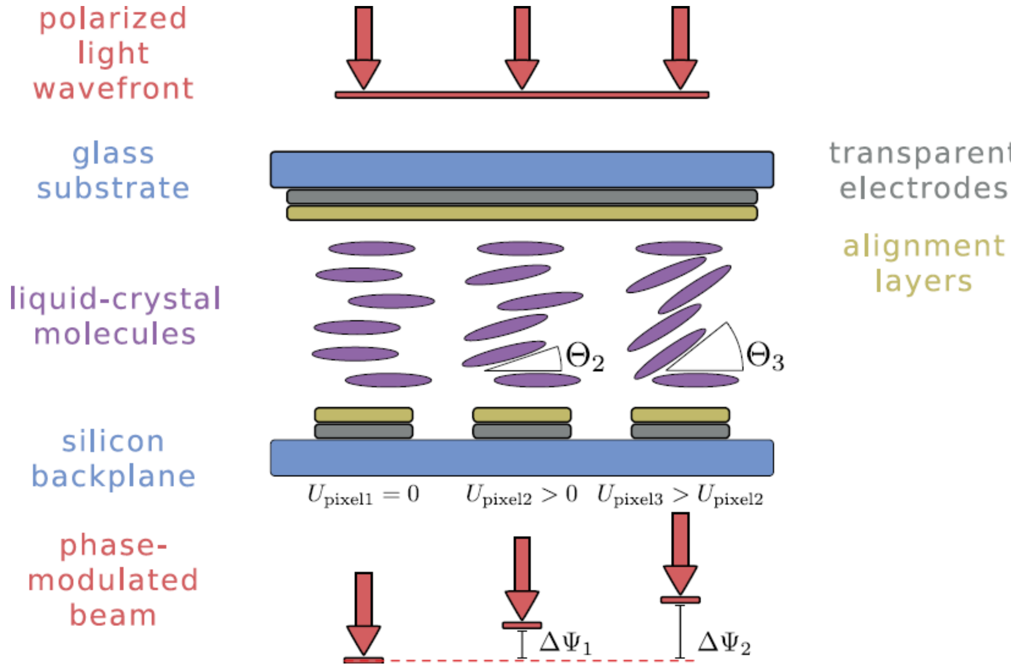


Texas Instruments



Holoeye AG

liquid-crystal modulators



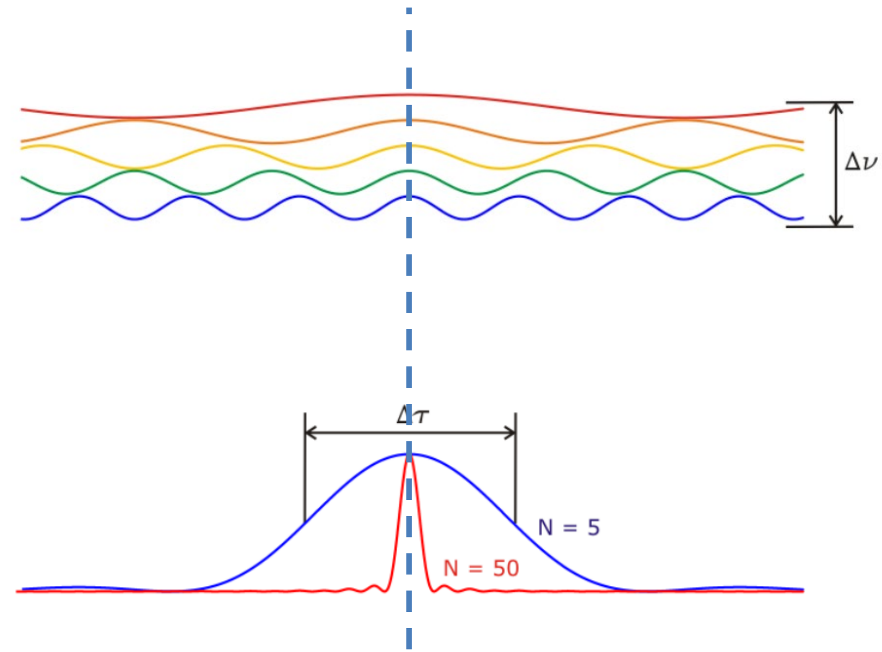
- amplitude and phase modulation
- amplitude- only modulation
- phase-only modulation

Spectrotemporal corrections

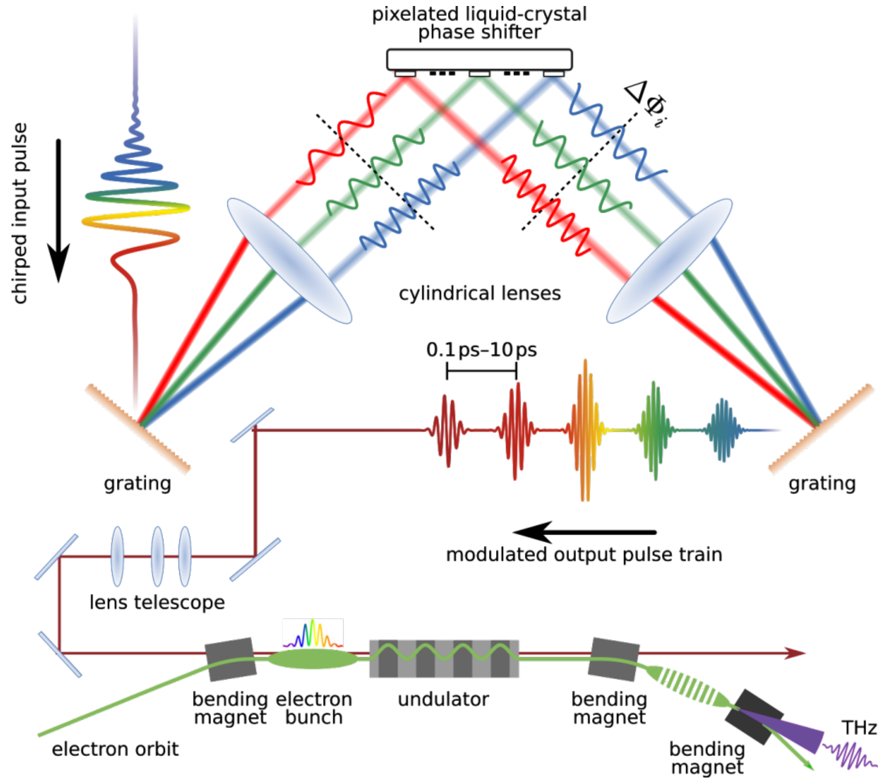
modelocked laser pulse:

contributing laser modes

resulting laser pulse



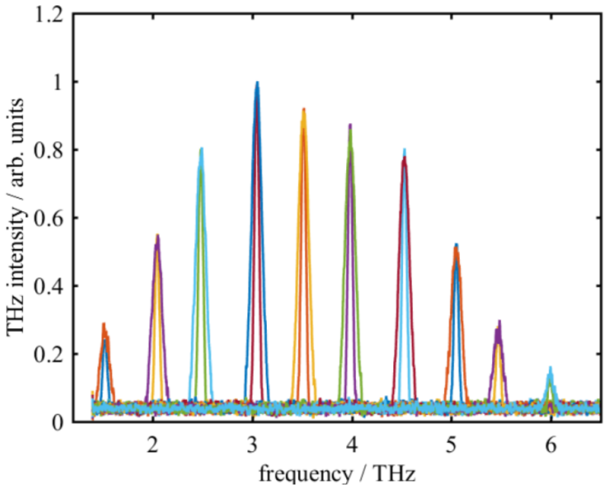
Phase corrected optical setup for laser seeding

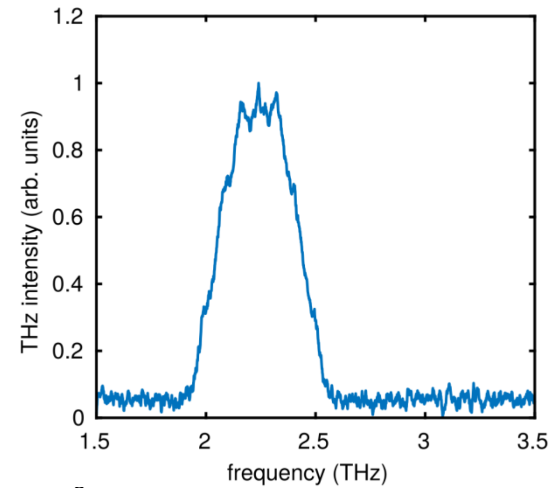


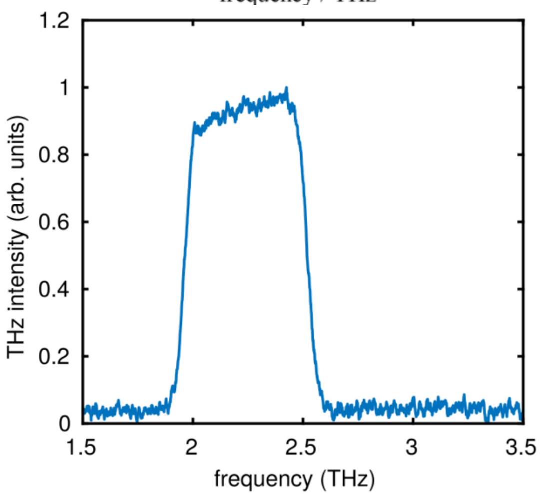
zero-dispersion compressor
(4-f shaper)

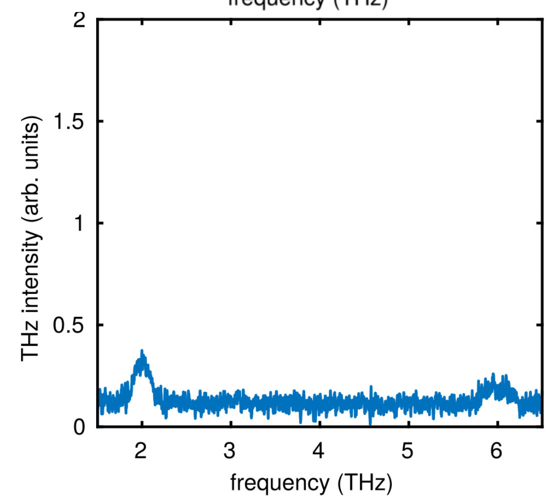
C. Mai et al., “Pulse shaping methods for laser-induced Generation of THz radiation at the DELTA storage ring”, IPAC 2019.

Results


1.2
1
0.8
0.6
0.4
0.2
0
THz intensity / arb. units
2
3
4
5
6
frequency / THz


1.2
1
0.8
0.6
0.4
0.2
0
THz intensity (arb. units)
1.5
2
2.5
3
3.5
frequency (THz)

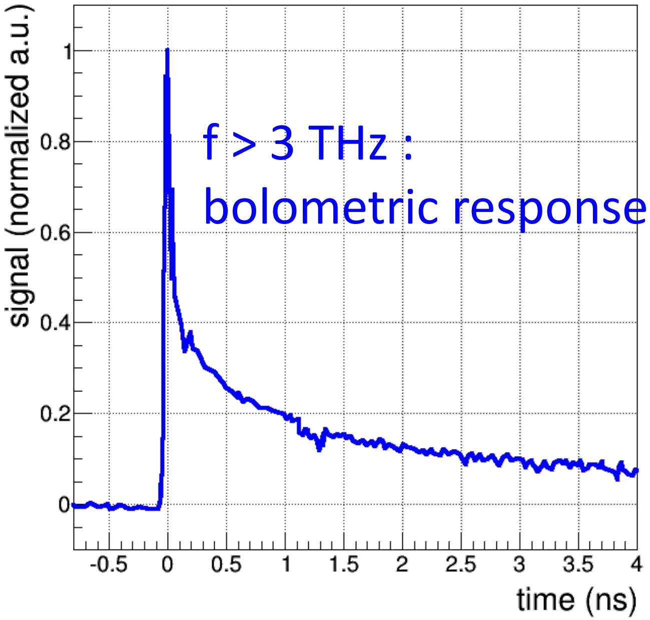

1.2
1
0.8
0.6
0.4
0.2
0
THz intensity (arb. units)
1.5
2
2.5
3
3.5
frequency (THz)

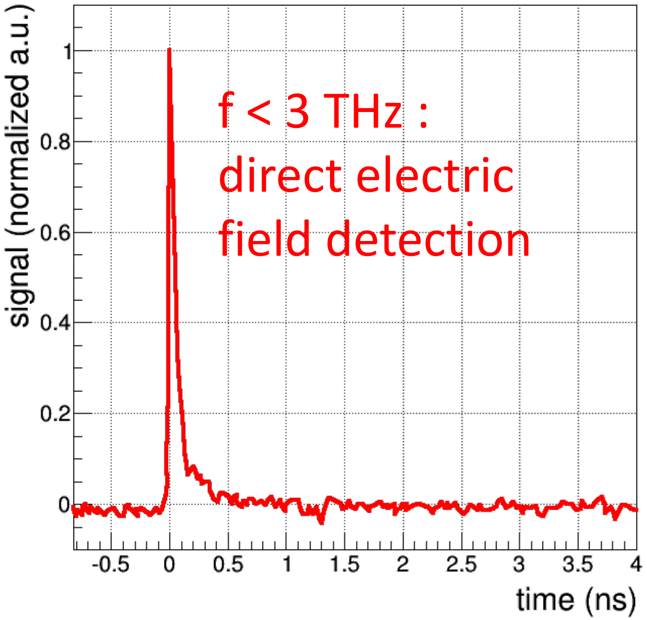

2
1.5
1
0.5
0
THz intensity (arb. units)
2
3
4
5
6
frequency (THz)

First Applications

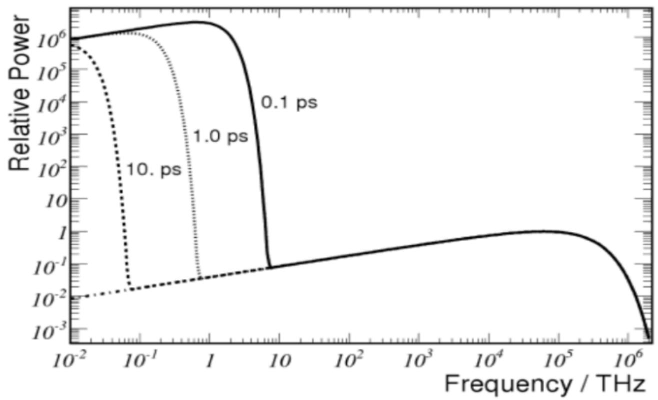
- close collaborations to detector development
- frequency dependent behavior of $YBa_2Cu_3O_{7-x}$ –based detectors

J. Raasch, KIT

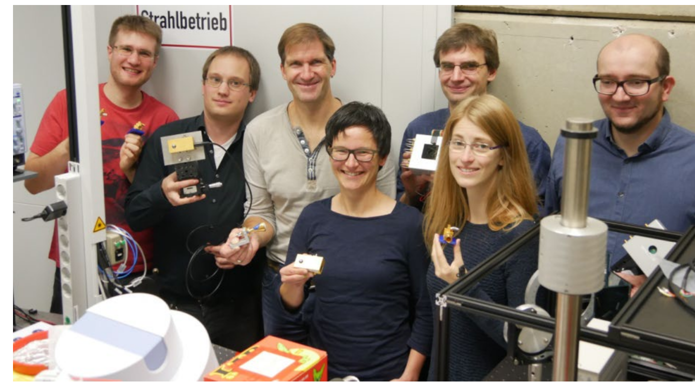




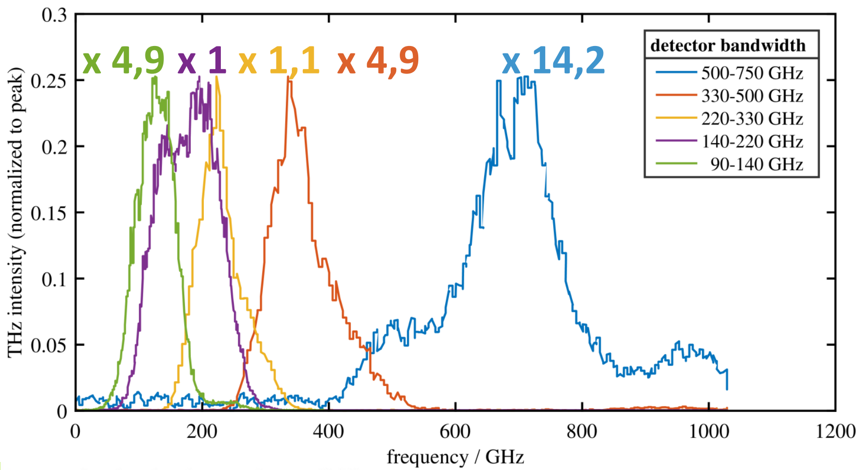
First Applications

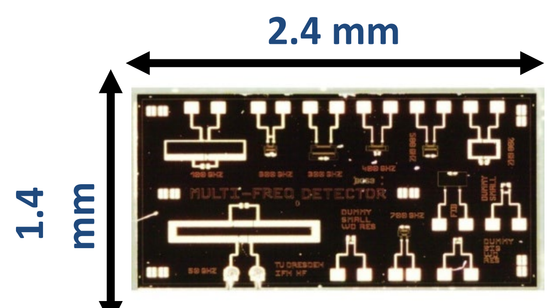


- *best* detector for bunch length diagnostics?
- spectral response?
- pulse response?
- comparison under same conditions



direct detector comparison

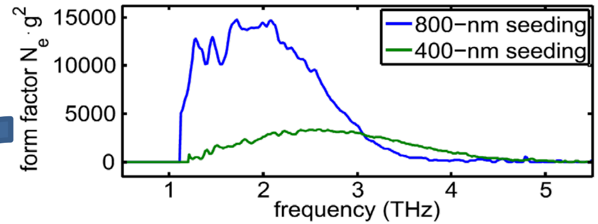




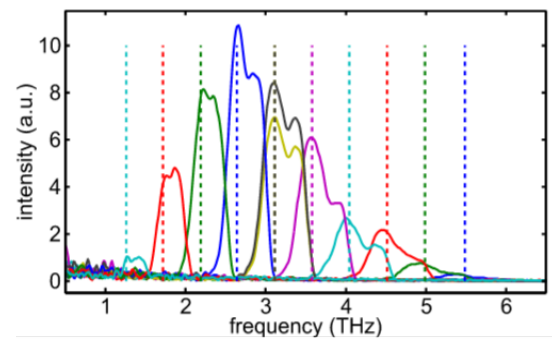
M. Laabs et al., JSR 25, 1509 (2018)

Summary

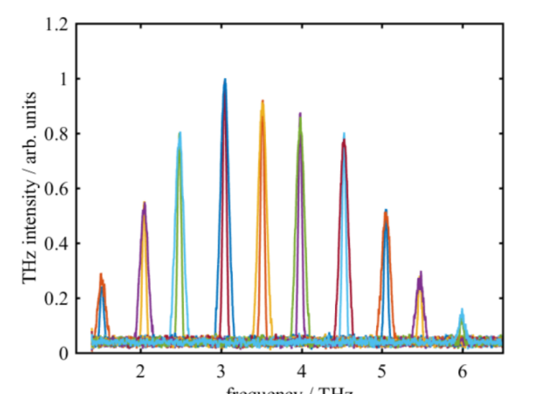
broadband generation



chirped-pulse beating



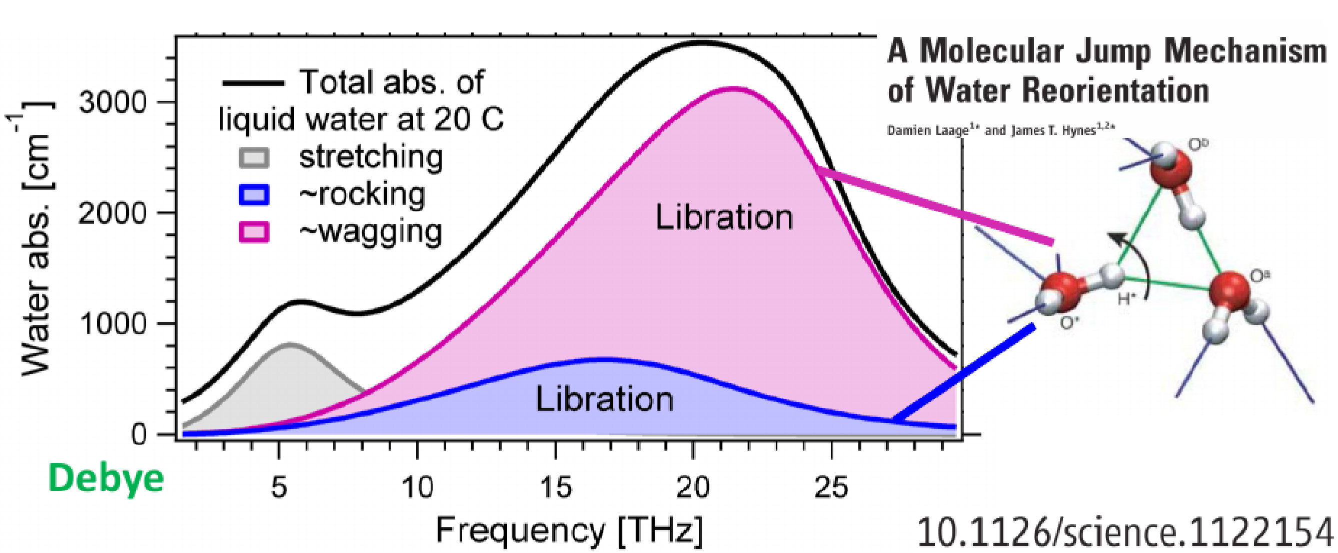
pulse shaping by phase modulation



Outlook

- shaping of laser pulses leads to highly flexible THz source
- full control of optical setups from DELTA control room
- new optics is promising: frequency shift, intensity scaling
- happy users from accelerator R&D groups

- user interest from physical chemistry: water absorption at 6 THz



F. Novelli, Ruhr Universität Bochum

Thank you for your attention!

Thanks for the support of:

KIT Karlsruhe Institute of Technology

PAUL SCHERRER INSTITUT PSI

HZB Helmholtz Zentrum Berlin

PTB

Bundesministerium für Bildung und Forschung

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

TU berlin

DESY

Université Lille 1 Sciences et Technologies

DFG Deutsche Forschungsgemeinschaft

TECHNISCHE UNIVERSITÄT DRESDEN

HOLOEYE

ACST Technology Solutions for Terahertz Electronics

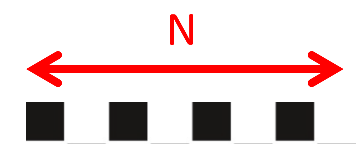
BACKUP

Imaging with spatial light modulators

- image is a diffraction pattern
  - ➢ Fourier transform (Fraunhofer approximation)

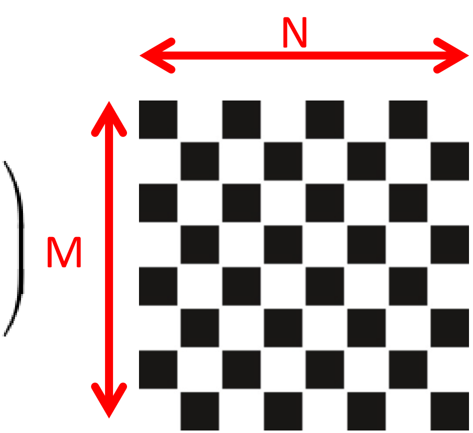
one dimension:

$$F(u) = \sum_m f(n) \cdot \exp(-i \cdot 2\pi / N \cdot n \cdot u)$$

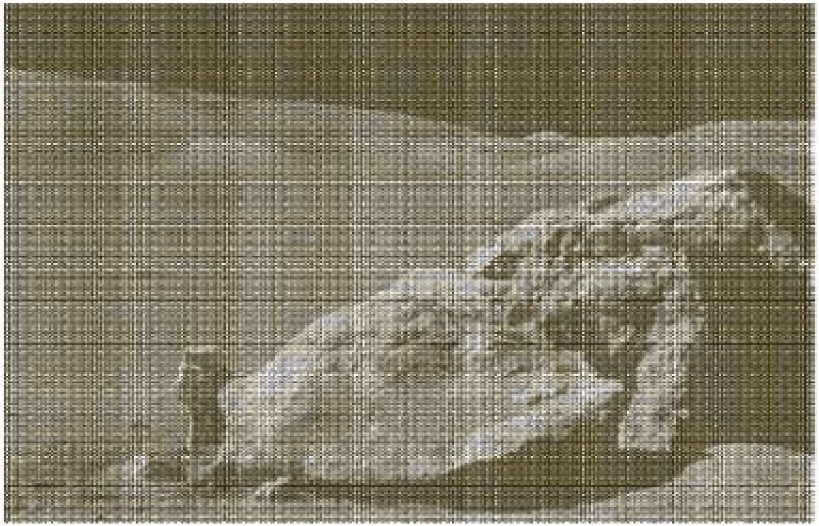


two dimensions:

$$F(u,v) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} f(m,n) \cdot \exp\left(-i2\pi\left(\frac{um}{M} + \frac{vn}{N}\right)\right)$$

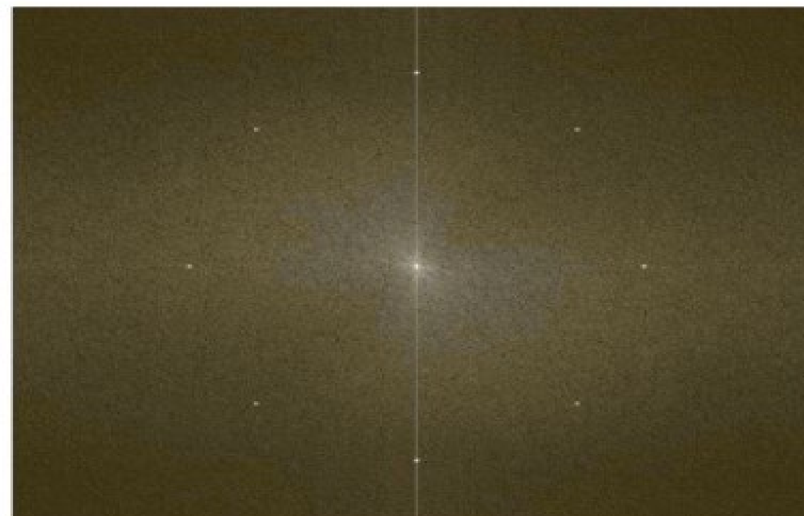


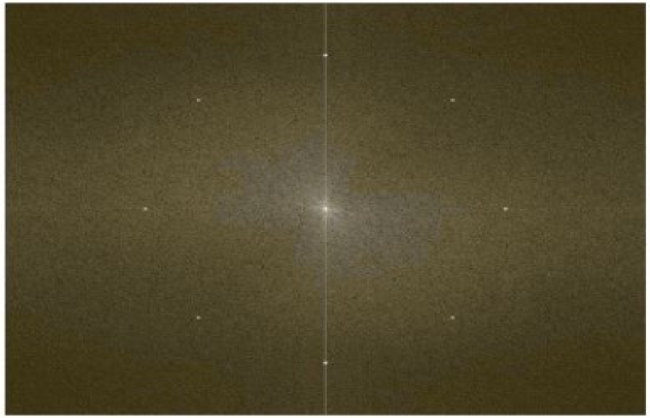
Is optics in Fourier domain of any use?



NASA (1969)

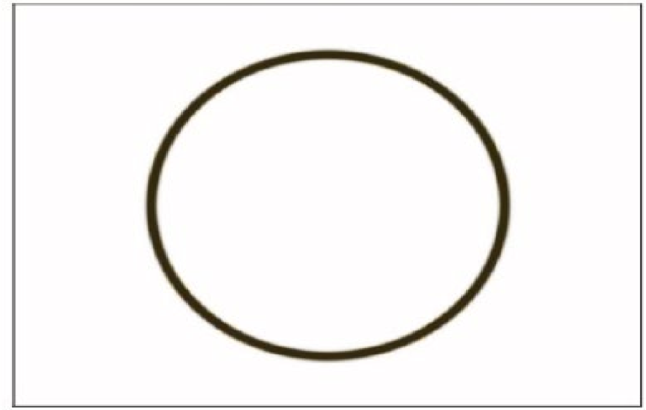
2D-FFT, amplitude spectrum





2D-FFT, amplitude spectrum

X

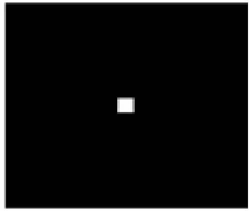


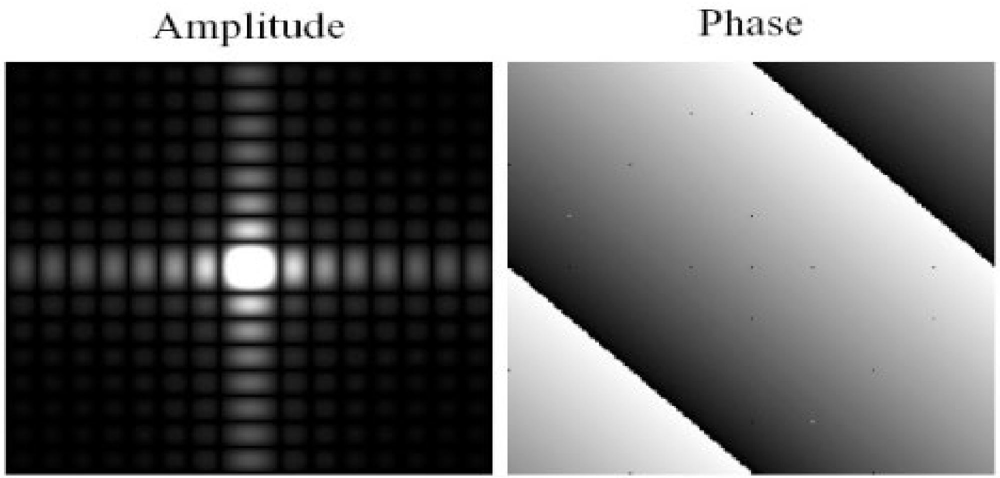
spectral filter

=

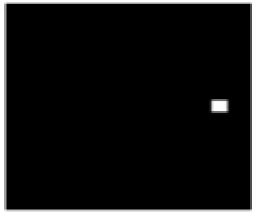
NASA (1969)

Phase and amplitude

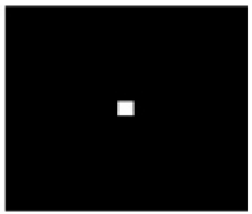


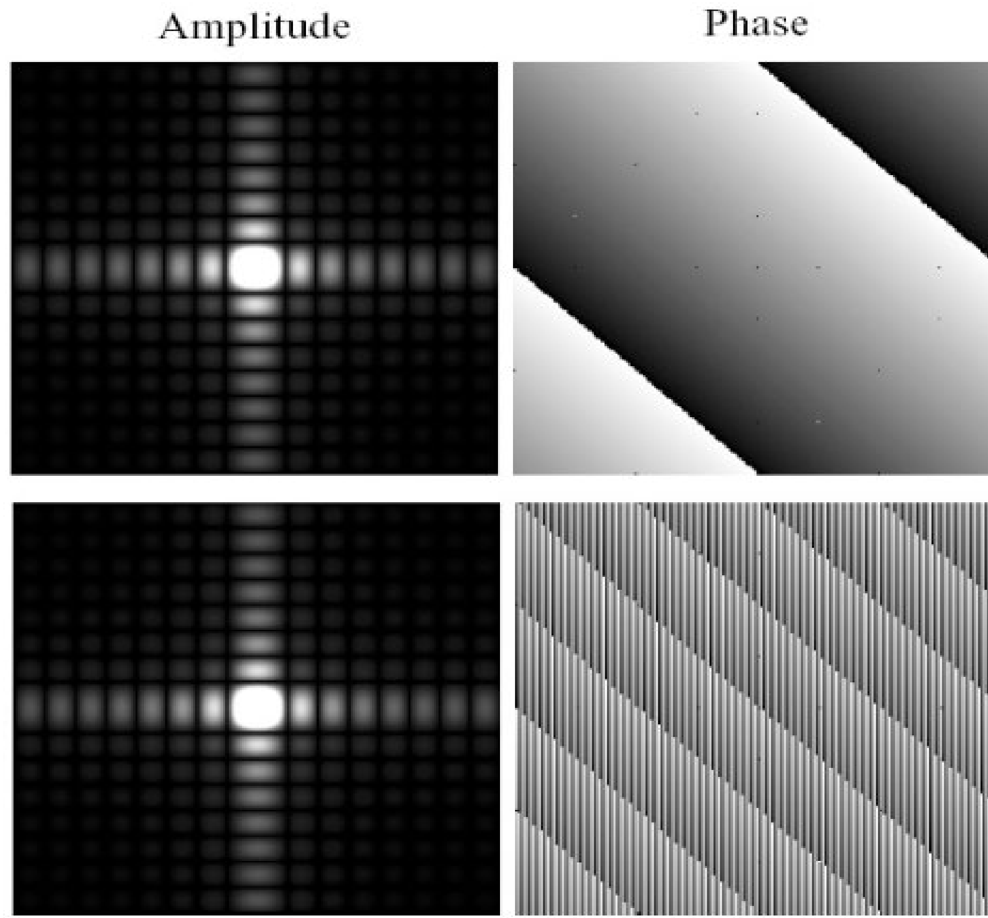


translation:

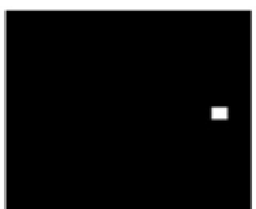


Phase and amplitude





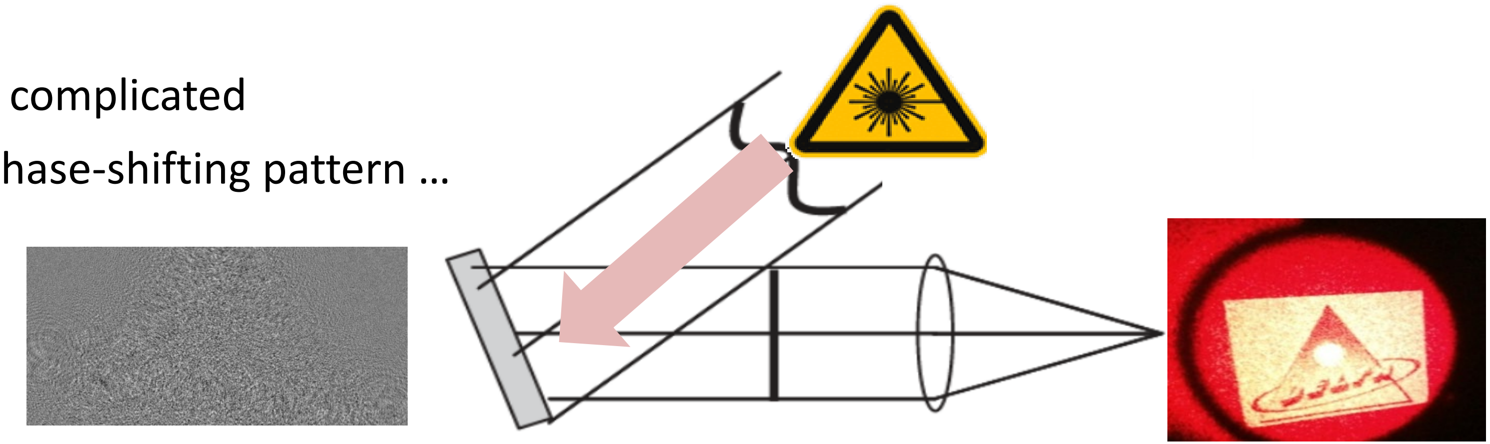
translation:



Holographic imaging by phase modulation

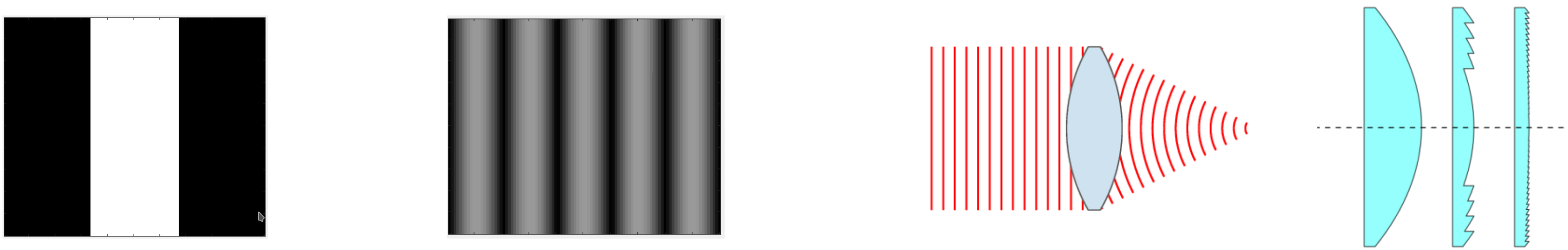
a complicated

phase-shifting pattern …



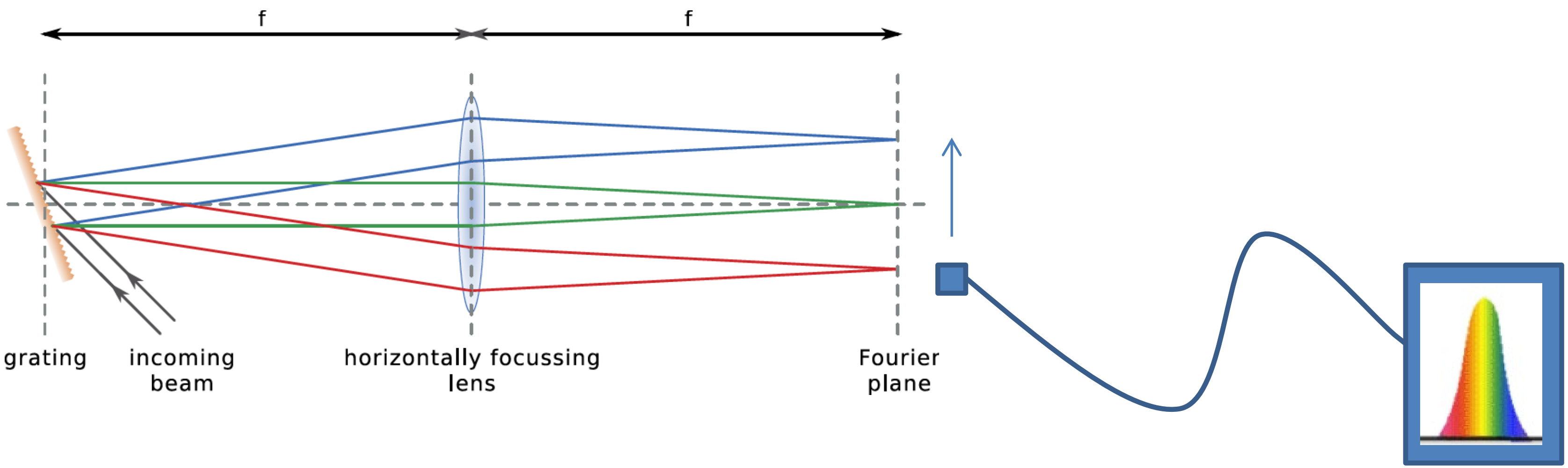
spatial modulator

elementary optics that can be implemented:



How to calibrate a 4-f pulse shaper

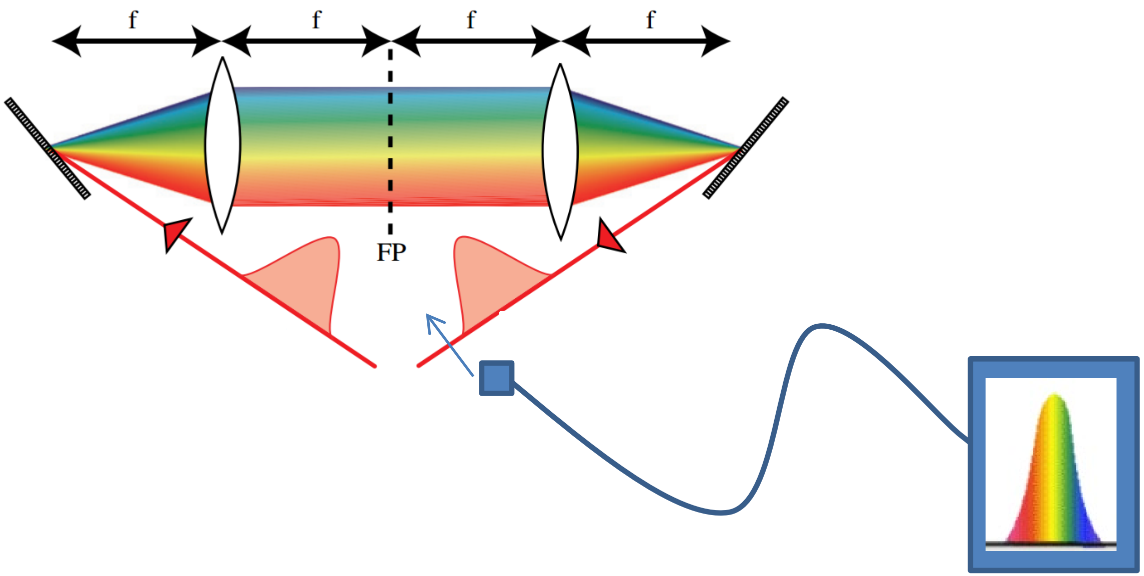
Step 1: tuning the focussing



spectrometer with single-fiber coupling

How to calibrate a 4-f pulse shaper

Step 2: match the other half, check for transverse chirp of the beam

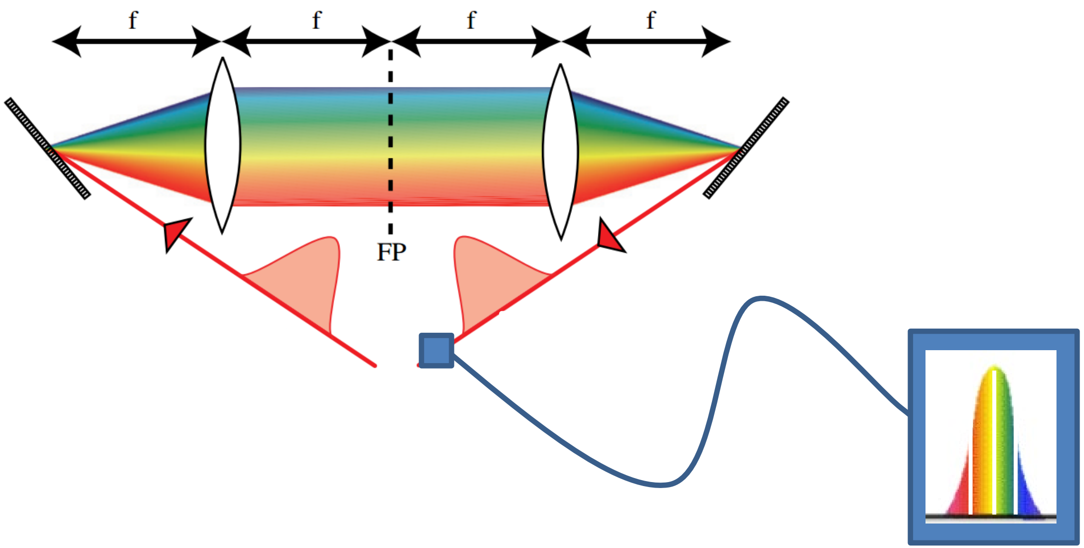


spectrometer with
single-fiber coupling

How to calibrate a 4-f pulse shaper

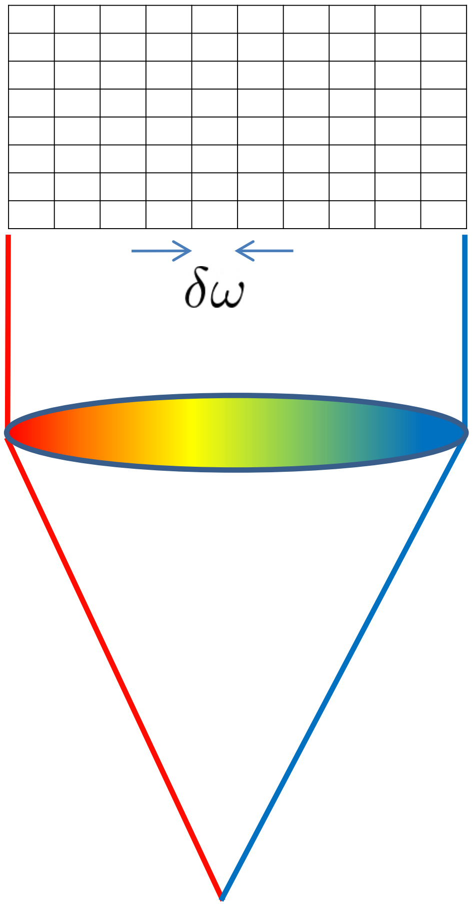
Step 3: calibrate spatial dispersion, apply phase shifts of π for single pixels(/columns)

$$X(\omega_k) - X_0 = f \cdot \tan\left[\arcsin\left(\frac{2\pi c}{\omega_k d} - \sin(\theta_i)\right) - \arcsin\left(\frac{2\pi c}{\omega_0 d} - \sin(\theta_i)\right)\right]$$



spectrometer shows
destructive interference
(intensity drops)

Limitations / Masking effect of the modulator



Spatial modulator: linear complex filter

$$\tilde{E}_{\mathrm{out}}(\omega) = \tilde{M}(\omega) \cdot \tilde{E}_{\mathrm{in}}(\omega)$$

frequency dependent phase and amplitude ($\tilde{M}(\omega)$)

input field ($\tilde{E}_{\mathrm{in}}(\omega)$)

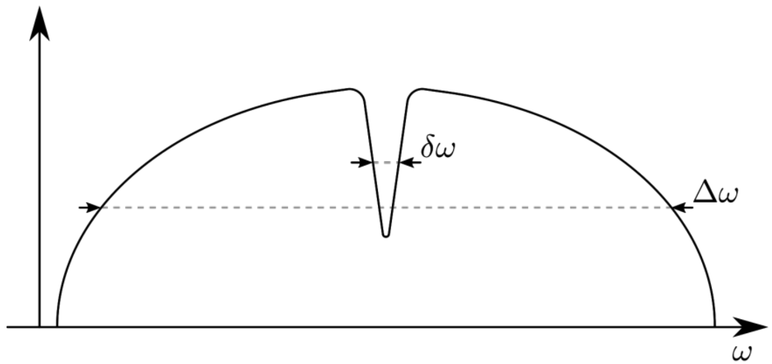
$$\tilde{M}(\omega) = \left(\tilde{F}(\omega) \sum_{n=-N/2}^{n=N/2} \delta(\omega - n\,\delta\omega) \right) * \mathrm{rect}\left(\frac{\omega}{\delta\omega}\right)$$

$$E_{\mathrm{out}}(t) \sim \left(E_{\mathrm{in}}(t) * \sum f\left(t - n\frac{2\pi}{\delta\omega}\right)\right) \mathrm{sinc}\left(\frac{\delta\omega t}{2}\right)$$

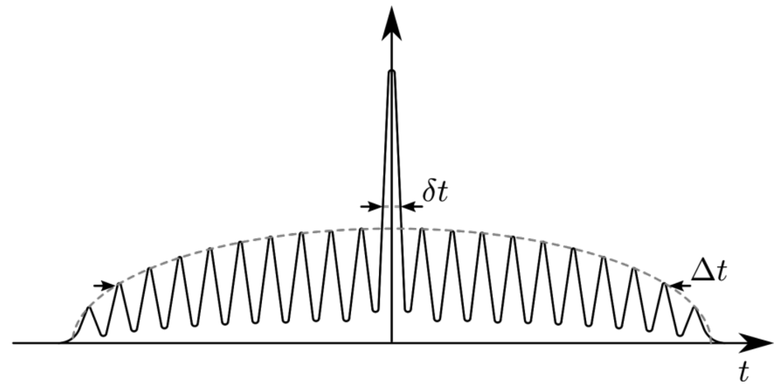
pulse copies

Limitations / What is a (too) *complex* pulse?

spectrum



time domain



time-bandwidth product (TBP):

$$TBP = \Delta t \cdot \Delta\omega$$

complexity:

$$\eta = \frac{\Delta t}{\delta t} = \frac{\Delta\omega}{\delta\omega}$$

$$= \frac{TBP}{4\ln 2} \quad \text{(gaussian pulse)}$$

$$\overset{!}{\leq} \text{ number of modulator pixels}$$

Spectral limitations of the beamline

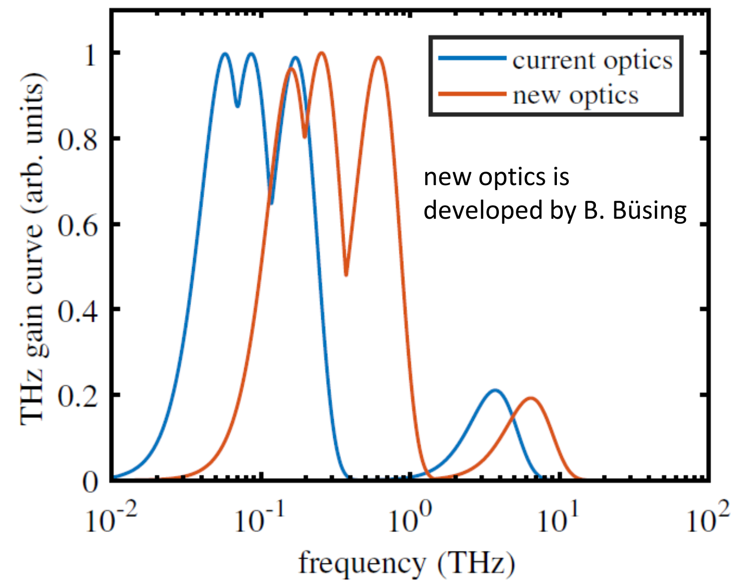
gain factor

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

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

- storage ring optics: $\mathbf{r_{51}}$, $\mathbf{r_{52}}$, $\mathbf{r_{56}}$

Gain function of DELTA / accessible frequency region



- new optics leads to modulation of more electrons
- increase of pulse energy