Ultrashort and Coherent Radiation for Pump-Probe Experiments at the DELTA Storage Ring

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Motivation

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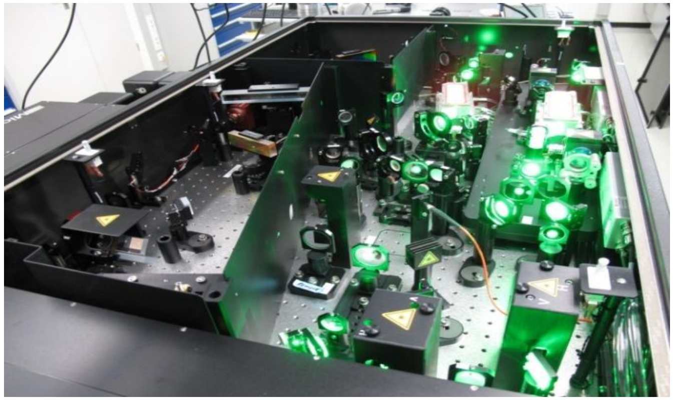
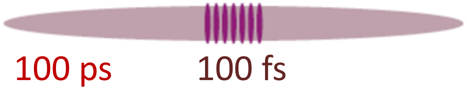


synchrotron light source

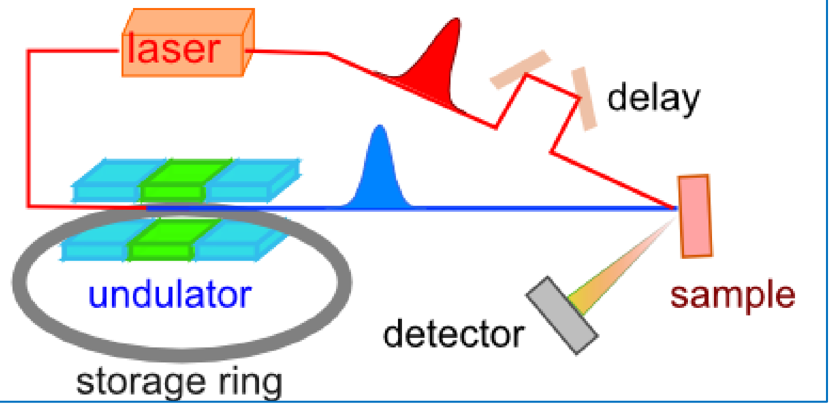
- short wavelength, long pulses

laser systems

- fs pulses, long wavelength



time resolved pump-probe experiments

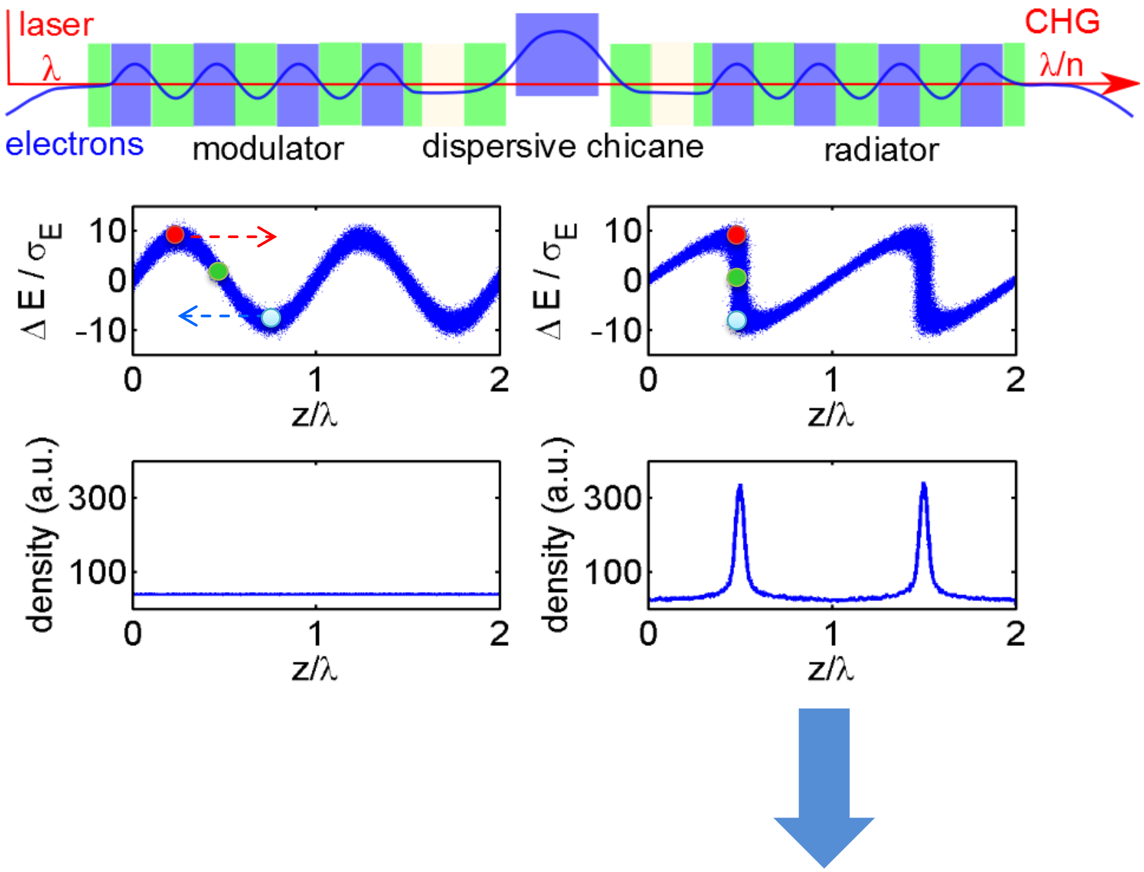


Outline

- **Coherent Harmonic Generation (CHG)**
- CHG Facility at DELTA
- Measurements and Results
- Summary and Outlook

Principle of CHG

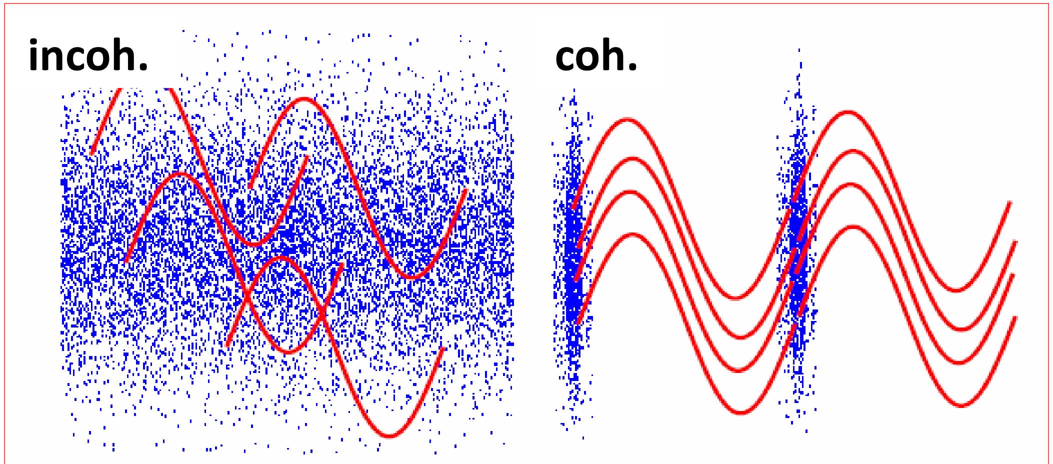
- proposed by:
  R. Coisson and F. D. Martini [1]
- first experiments at ACO in France [2]
- recently at ELETTRA in Italy [3] and UVSOR in Japan [4]
- currently only UVSOR in Japan [4] and DELTA in Germany [5]

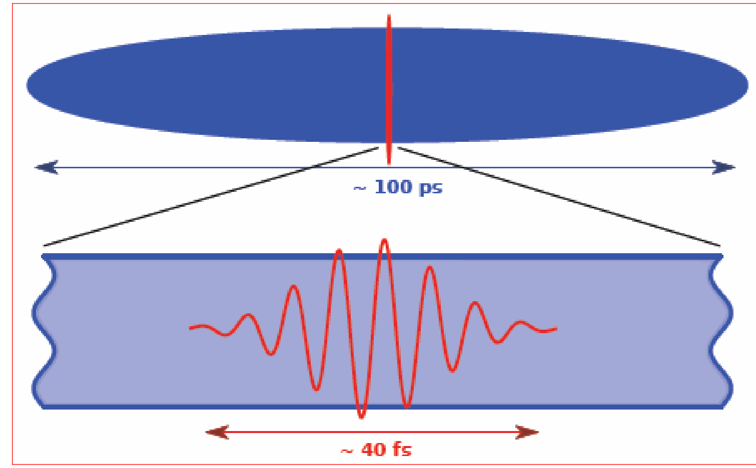


coherent ultrashort VUV pulses

[1] Phys. of Quant. Electron. 9,939 (1982).
[2] B. Girard et al., PRL 53 (1984), 2405
[3] E. Allaria et al., PRL 100 (2008), 174801
[4] M. Labat et al., PRL 101 (2008), 164803
[5] S. Khan et al., SRN 24 (2011), p. 25-29

Estimate of CHG Intensity



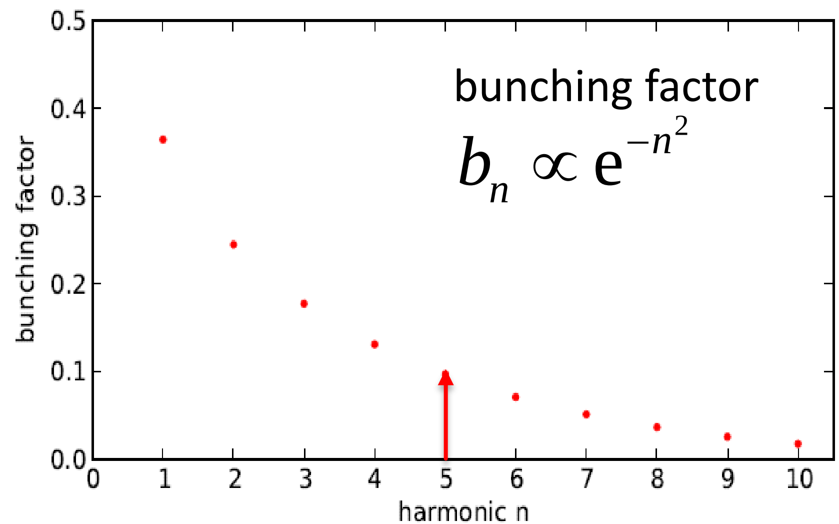


incoherent intensity : $I_{\mathrm{incoh}} = N_{\mathrm{bunch}} I_{\mathrm{e}}$

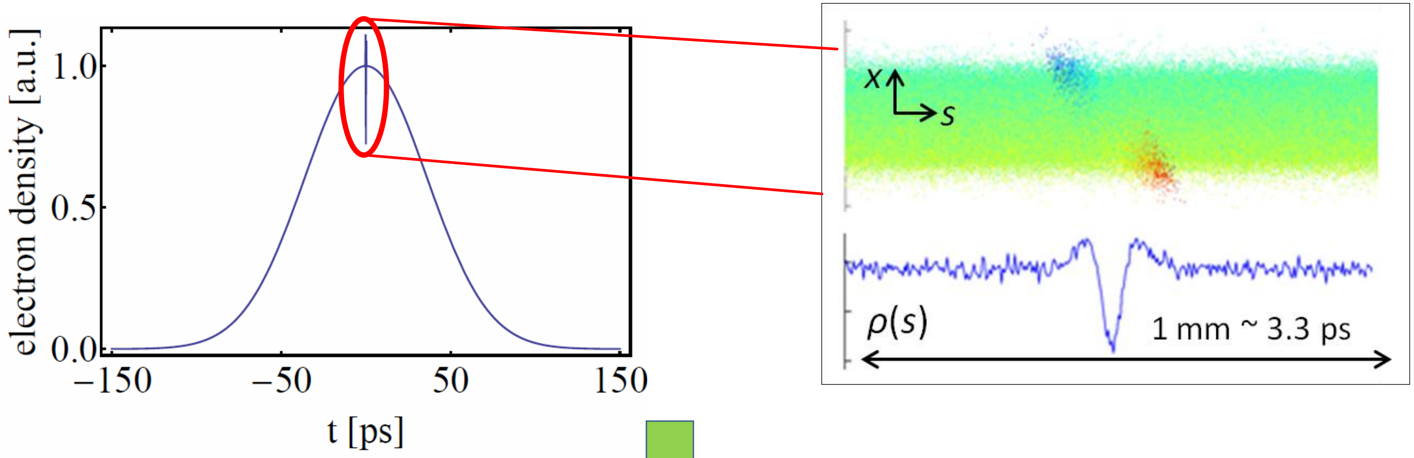
coherent intensity : $I_{\mathrm{coh}} = N_{\mathrm{slice}}^2 \, b_{\mathrm{n}}^2 \, I_{\mathrm{e}}$

$N_{\mathrm{slice}} / N_{\mathrm{bunch}} \sim 10^{-3}$, $N_{\mathrm{bunch}} \sim 10^{10}$, $b_{\mathrm{n}} \sim 0.1\text{- } 0.3$

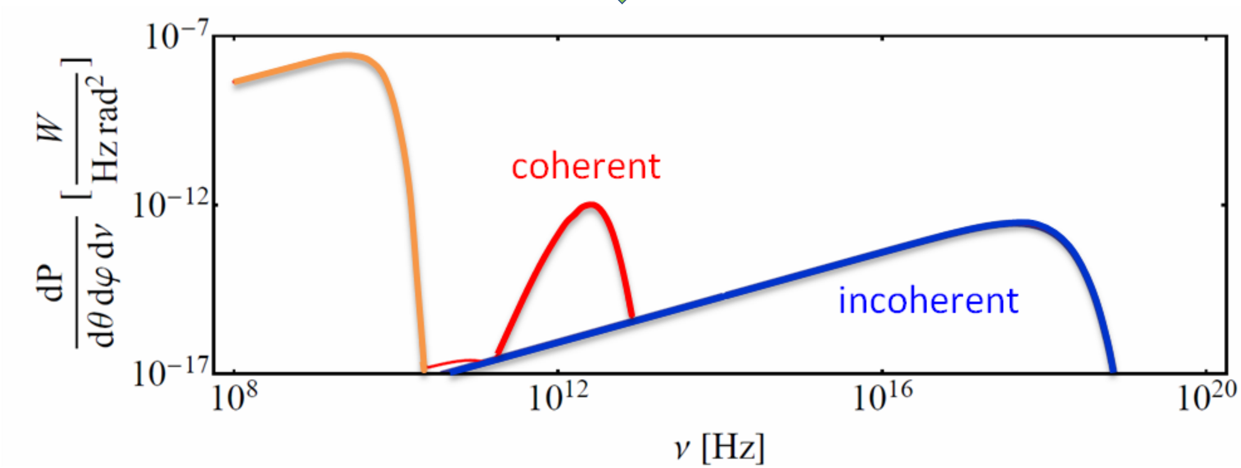
$$\boldsymbol{I_{\mathrm{coh}} / I_{\mathrm{incoh}} \sim 100 - 1000}$$



Coherent THz Radiation



Fourier transformation



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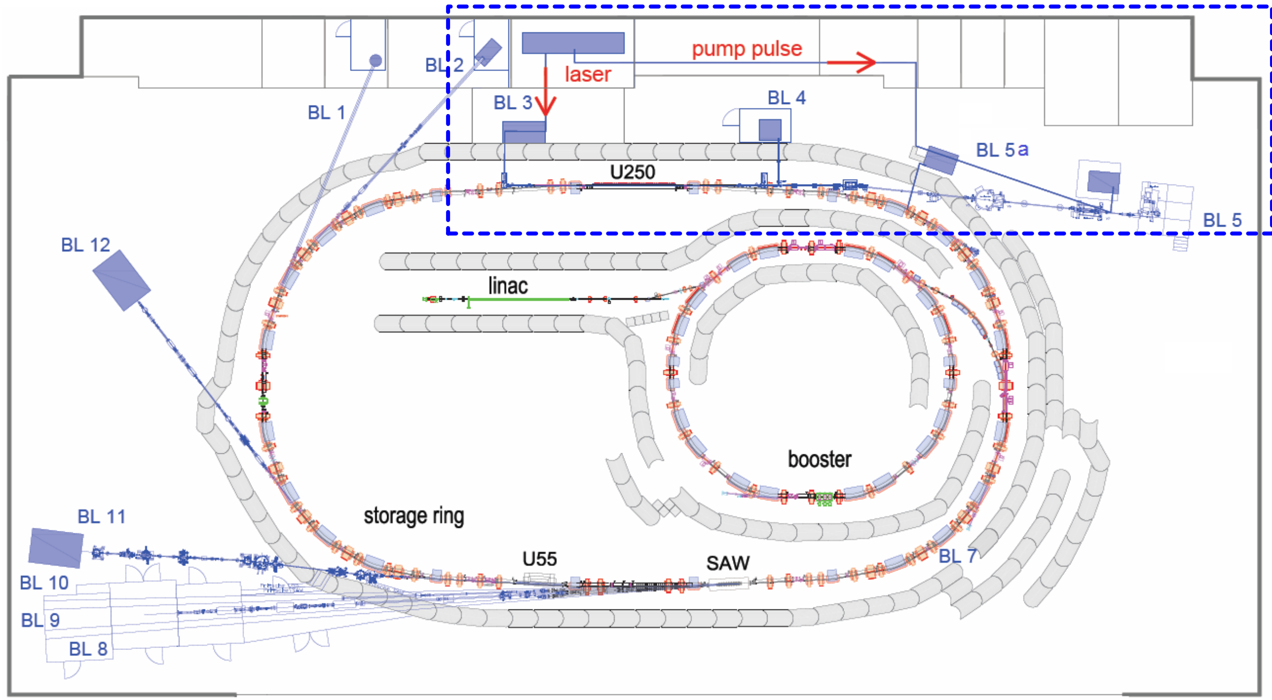
DELTA Storage Ring

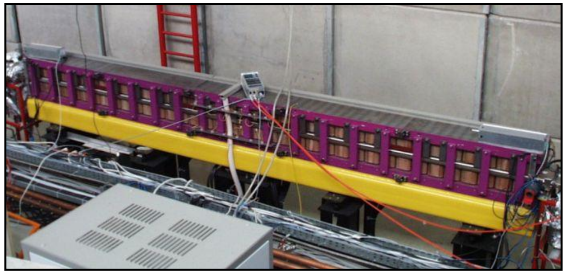
- beam energy 1.5 GeV
- circumference 115.2 m
- bunch length (FWHM) 100 ps
- beam lifetime >10 h
- horiz. emittance 15 nmrad
- energy spread 0.07 %
- multibunch current 130 mA
- single bunch current 20 mA



permanent-magnet undulator (U55)

superconducting wiggler (SAW)

electromagnetic undulator (U250)

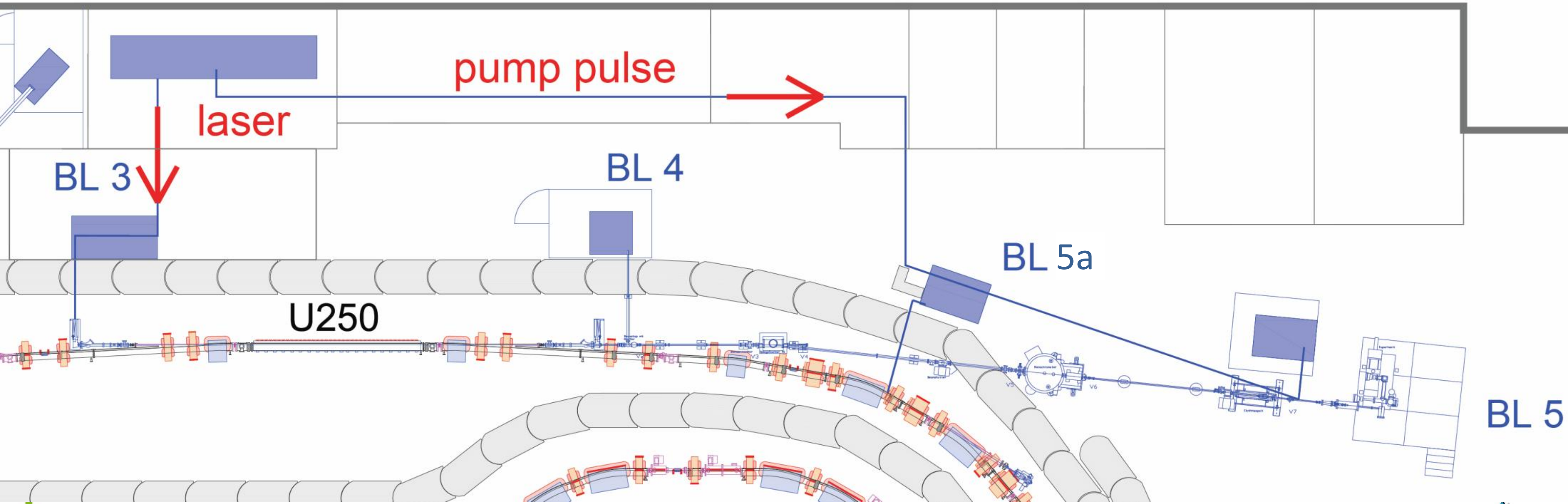


CHG Facility at DELTA

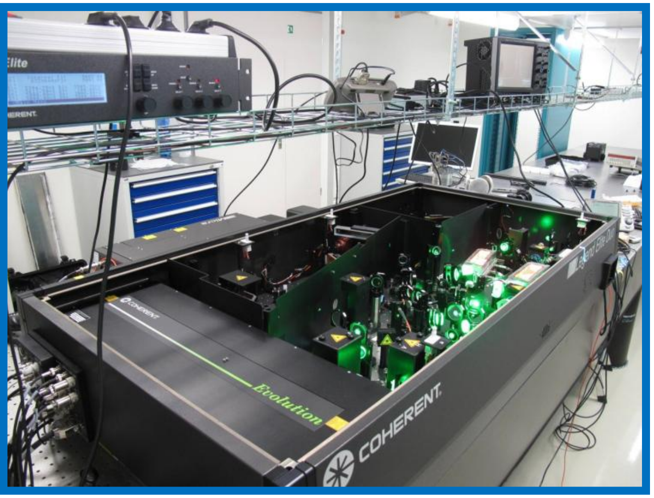
Goal:

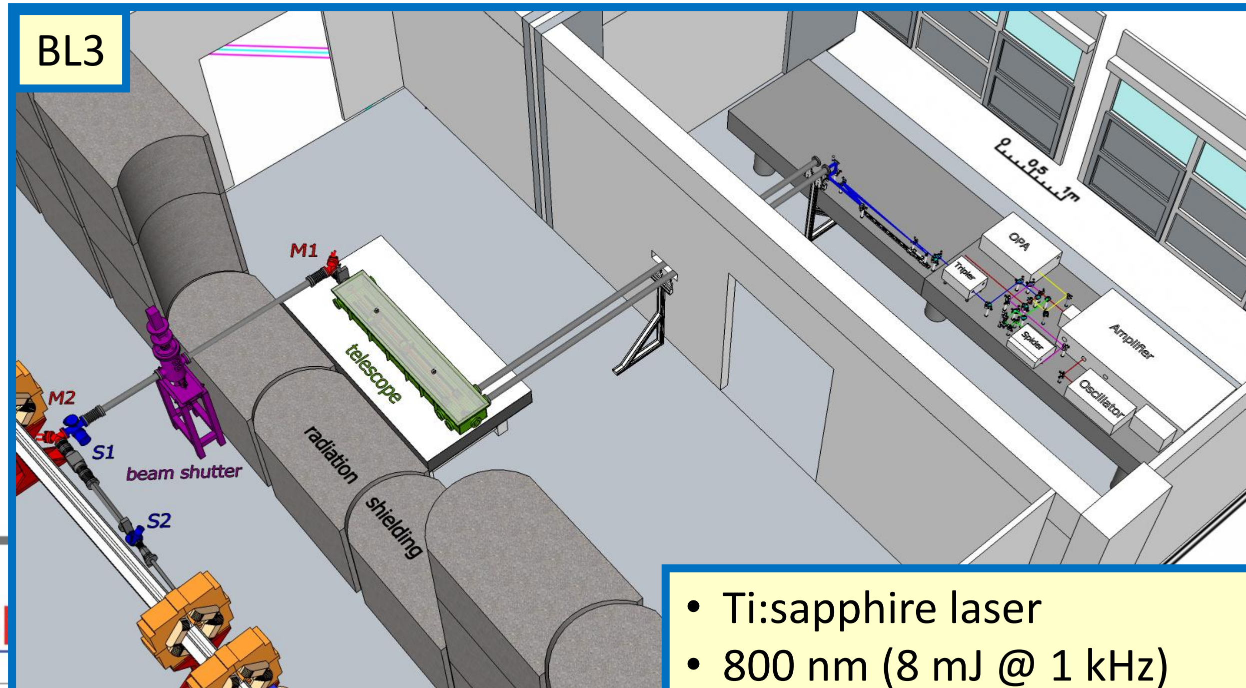
- 23 eV (5th harmonic of 266 nm)
- 100 fs pulses for users experiments

- in standard user operation!

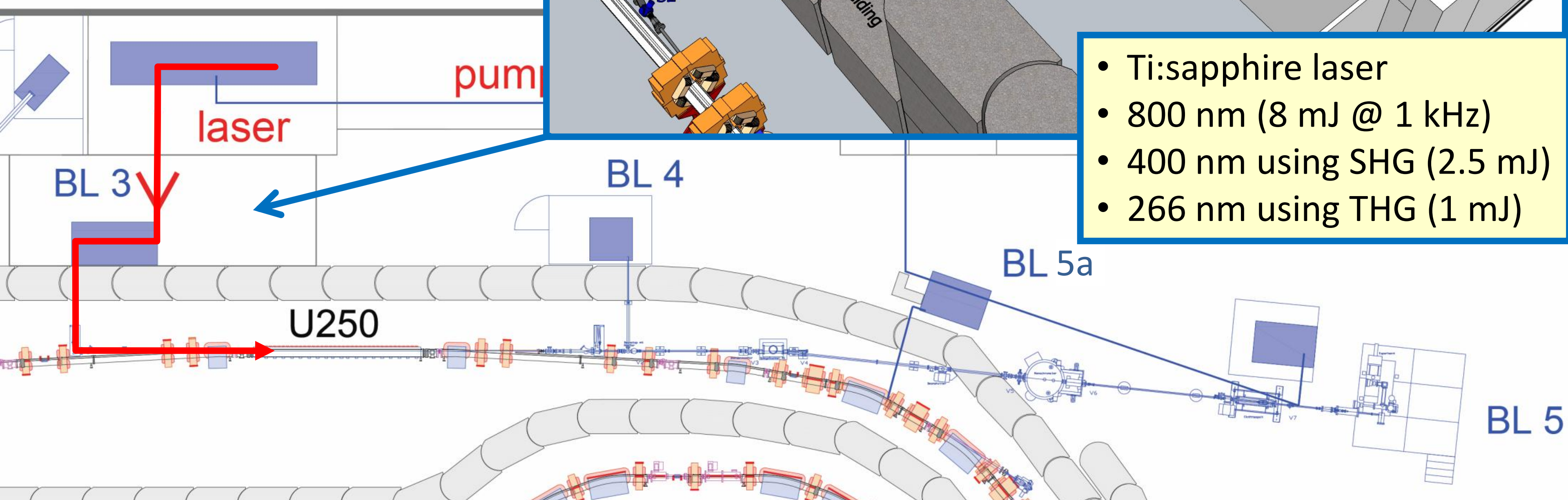


CHG Facility at DELTA: Seed Laser



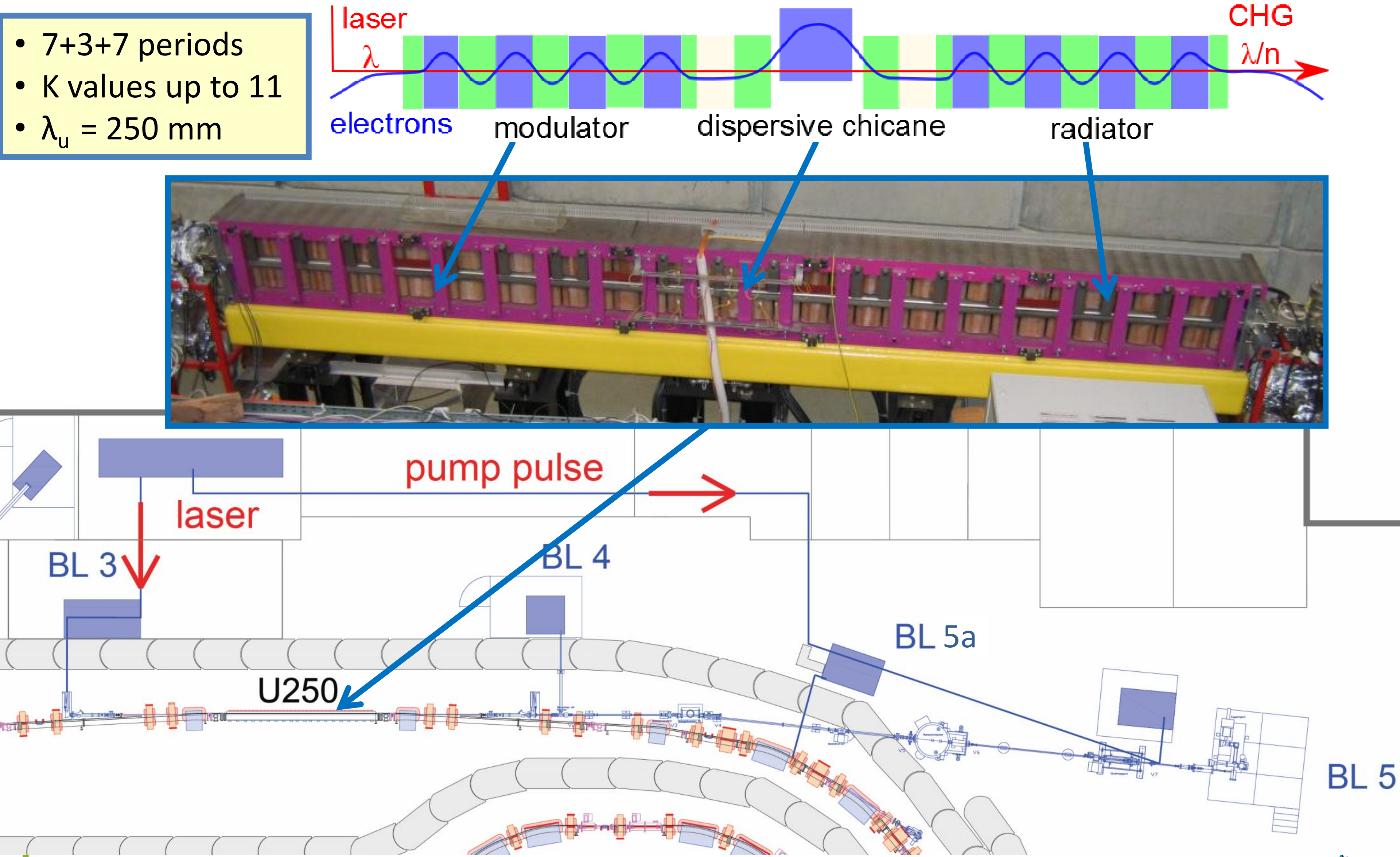


- Ti:sapphire laser
- 800 nm (8 mJ @ 1 kHz)
- 400 nm using SHG (2.5 mJ)
- 266 nm using THG (1 mJ)

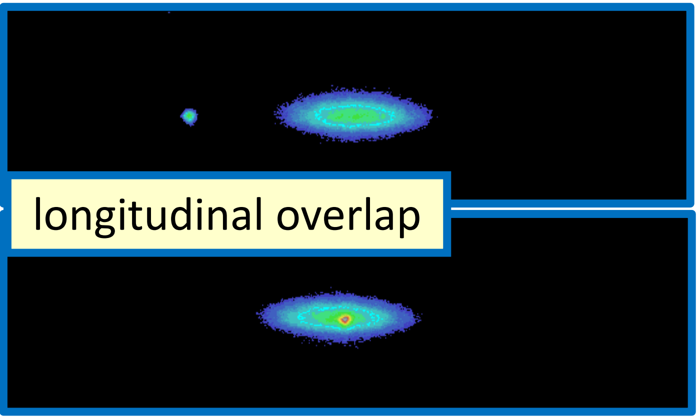


CHG Facility at DELTA: Undulator

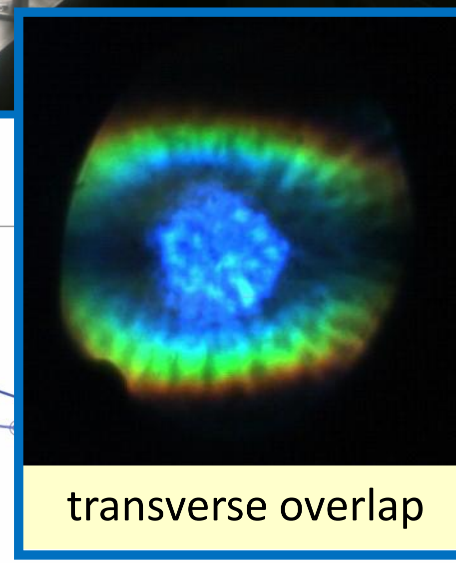
- 7+3+7 periods
- K values up to 11
- λ_u = 250 mm

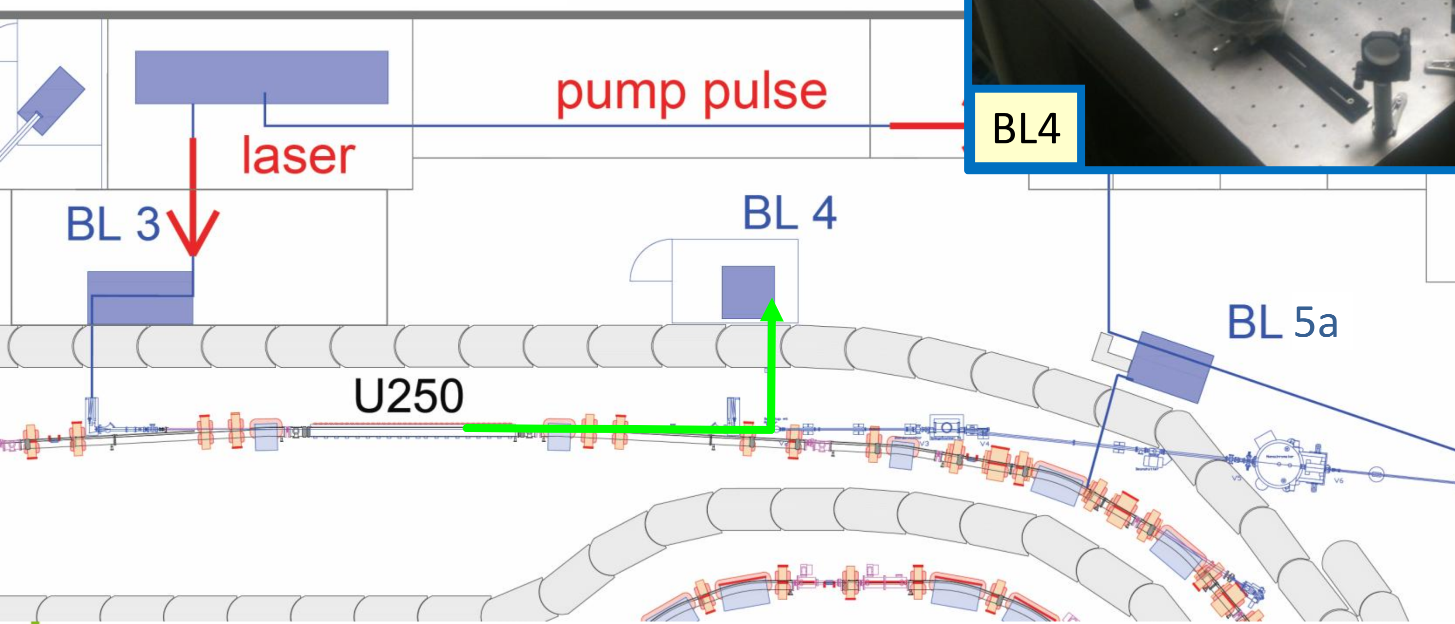


CHG Facility at DELTA: Diagnostics



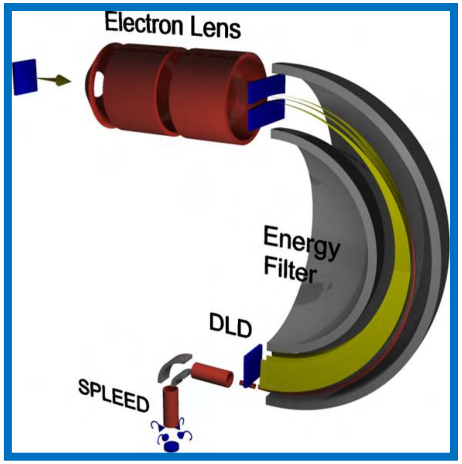
M. Zeinalzadeh et al., Proc. IPAC 2011, 2945.





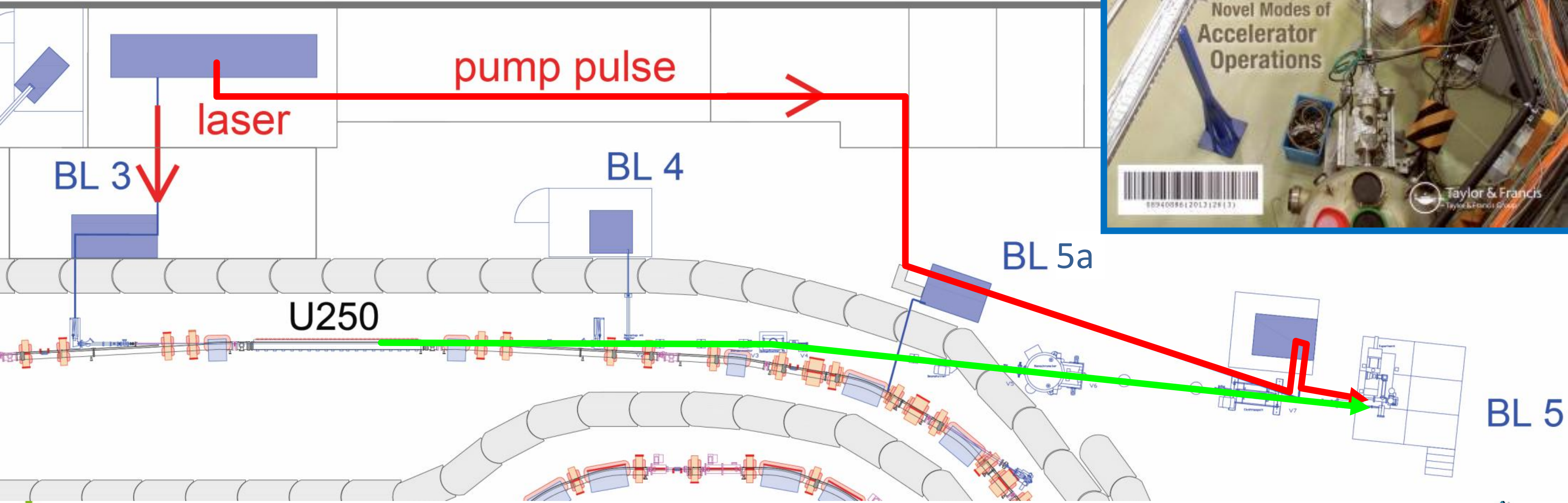
CHG Facility at DELTA: VUV Beamline

- spin-/angular-resolved photoelectron spectroscopy [1]
- modified for time-resolved experiments
- pump-probe experiments



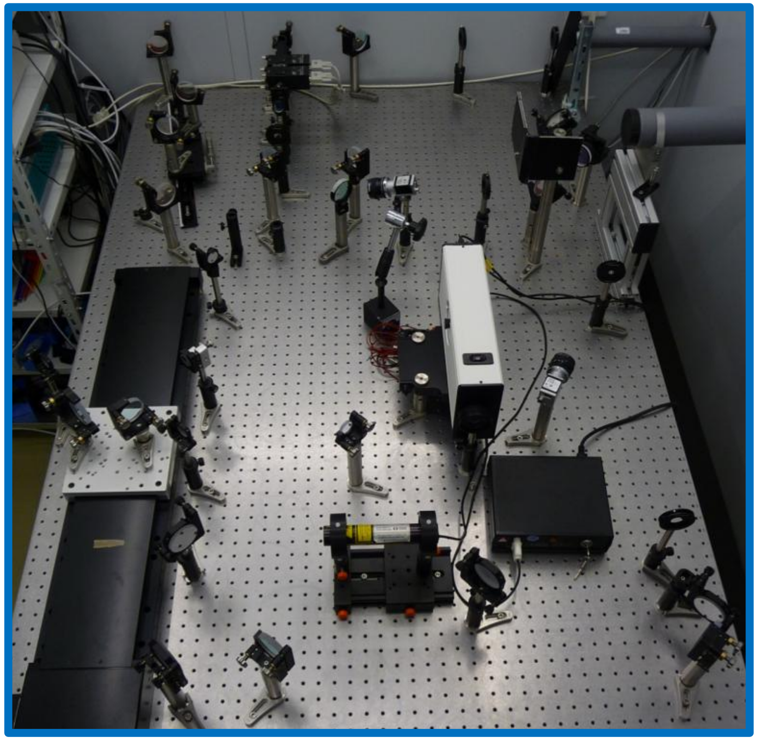
JÜLICH
FORSCHUNGSZENTRUM

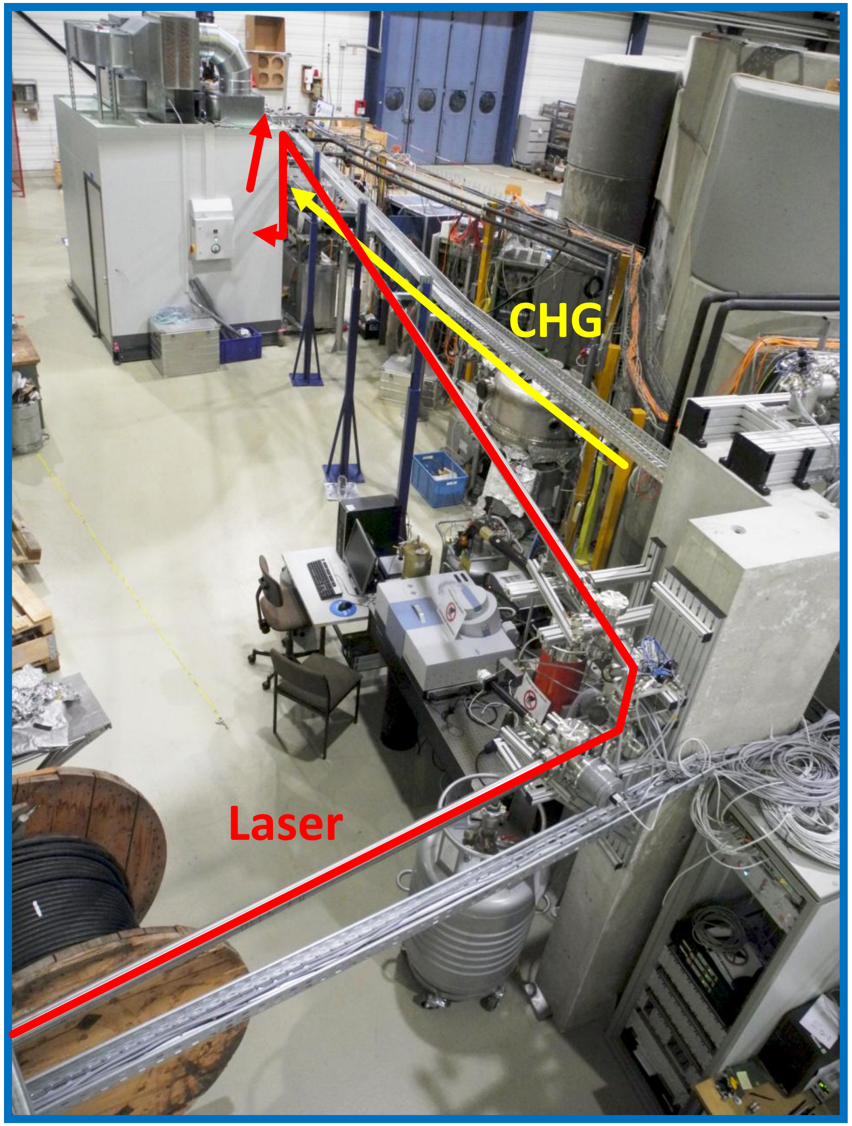
[1] L. Plucinski et al., J. Elspec., 181, 215 (2010).



CHG Facility at DELTA: Pump-Laser Beamline

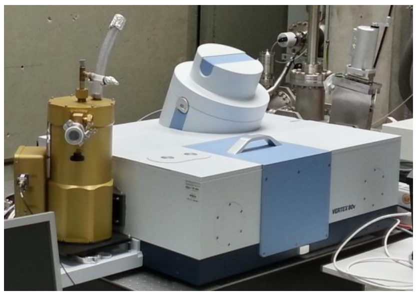
- ~ 53 m long
- mirror telescope
- optical stabilization feedback
- FROG
- delay stage





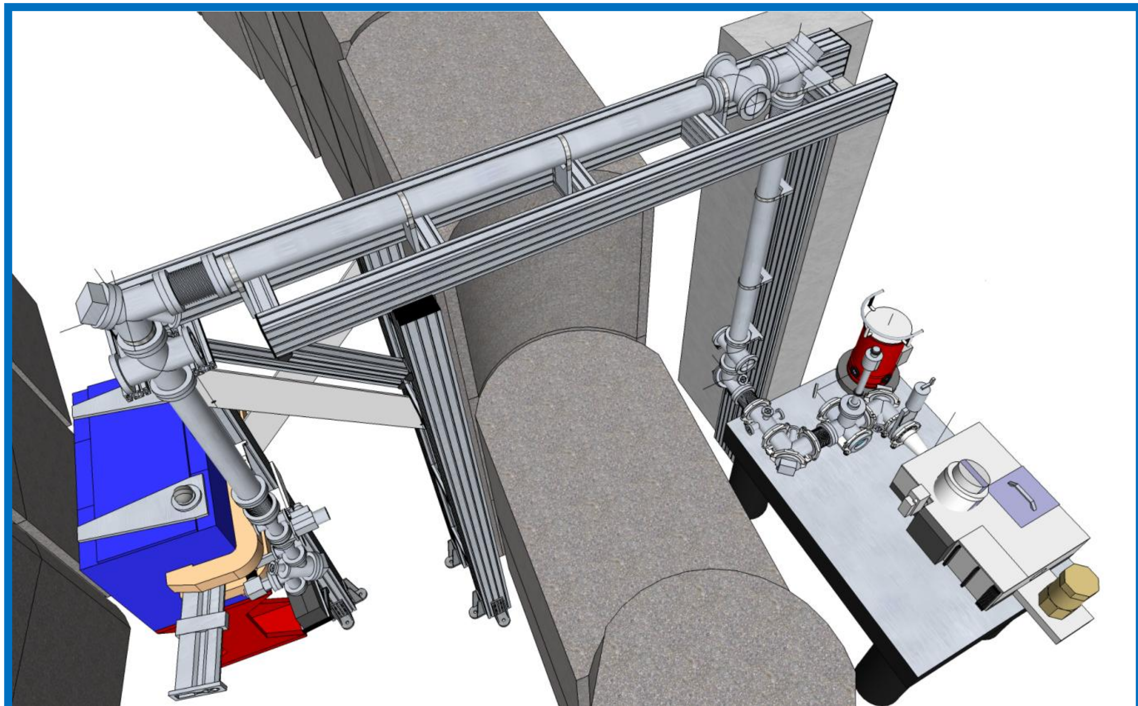
CHG Facility at DELTA: THz Beamline

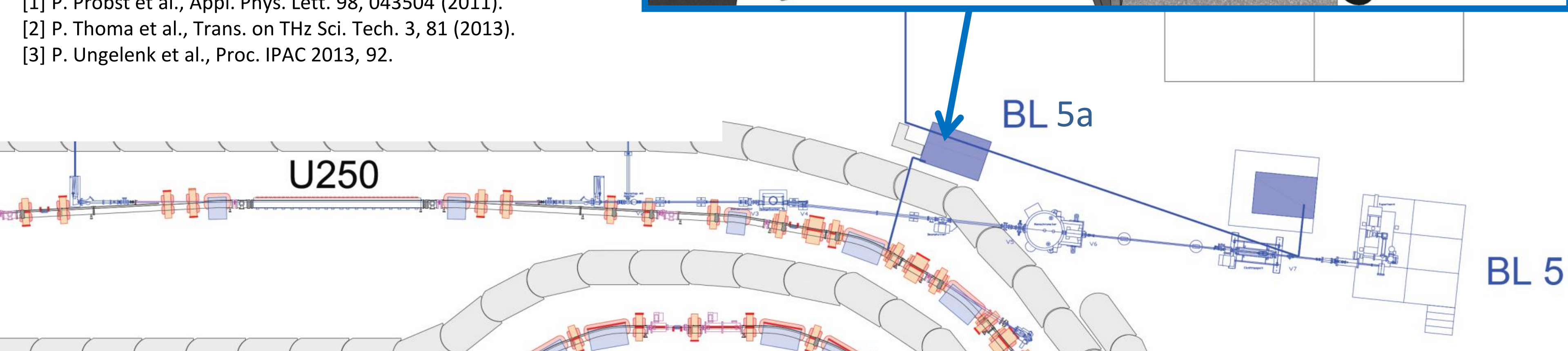
- optimizing overlap[3]
- user experiments
- accelerator studies



- InSb bolometer (response time ~ 1 µs)
- YBCO detector (response time < 17 ps) [1,2]
- FT-IR spectrometer

[1] P. Probst et al., Appl. Phys. Lett. 98, 043504 (2011).
[2] P. Thoma et al., Trans. on THz Sci. Tech. 3, 81 (2013).
[3] P. Ungelenk et al., Proc. IPAC 2013, 92.





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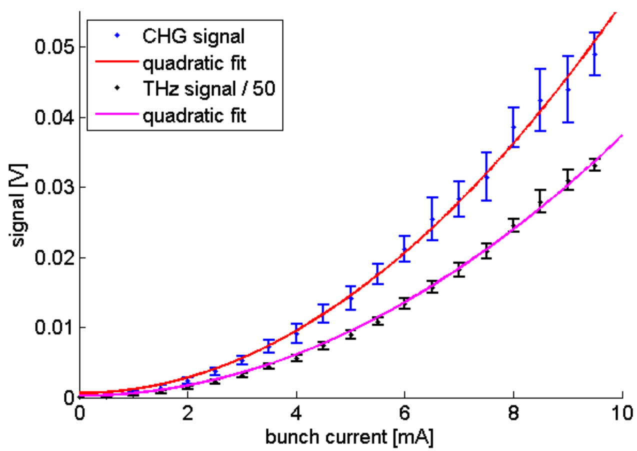
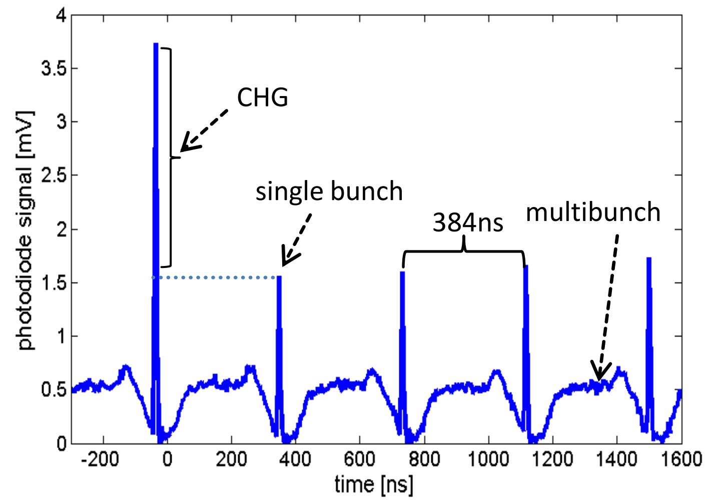
Results

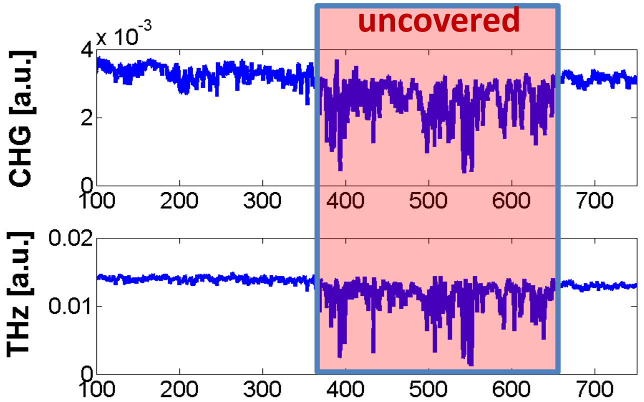
- June 2011: first CHG & THz signals [1,2]



- CHG in hybrid filling during user shifts



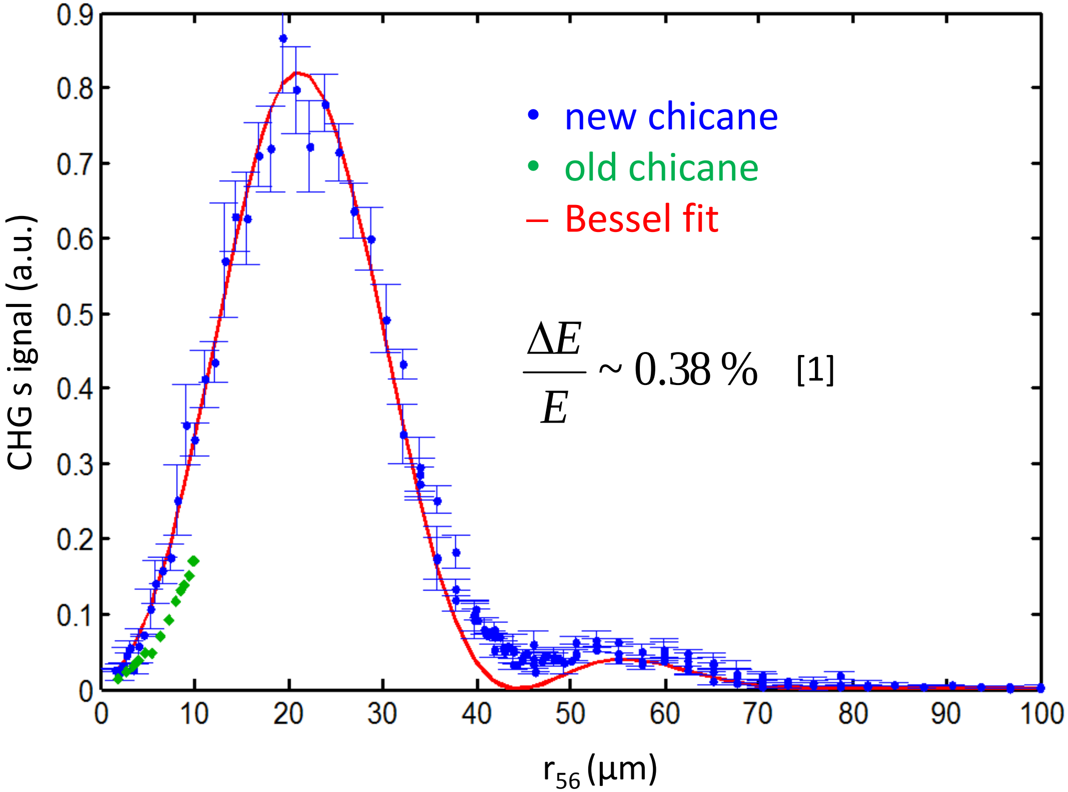
- stability and availability increased



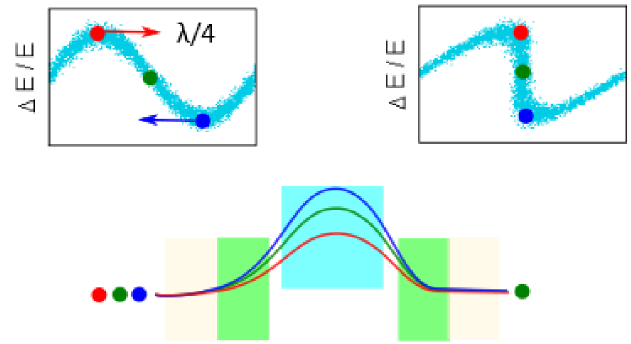
[1] S. Khan et al., Sync. Rad. News 24, 18 (2011). [2] H. Huck et al., Proc. FEL 2011, Shanghai, 5.

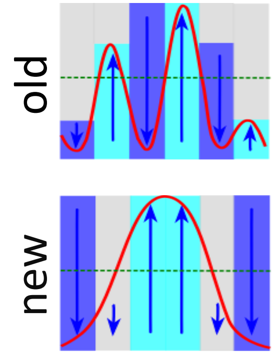
Magnetic Chicane

$$I_{\mathrm{CHG}} \propto |b_{\mathrm{n}}|^2, \quad |b_{\mathrm{n}}| \propto |J_{\mathrm{n}}(n \ r_{56}\, \Delta E / E)|$$



$$\Delta z = r_{56} \frac{\Delta E}{E} \approx \frac{\lambda}{4} \qquad \frac{\Delta E}{E} \propto \sqrt{W_L}$$





[1] S. Khan et al., Sync. Rad. News 26, 25 (2013).

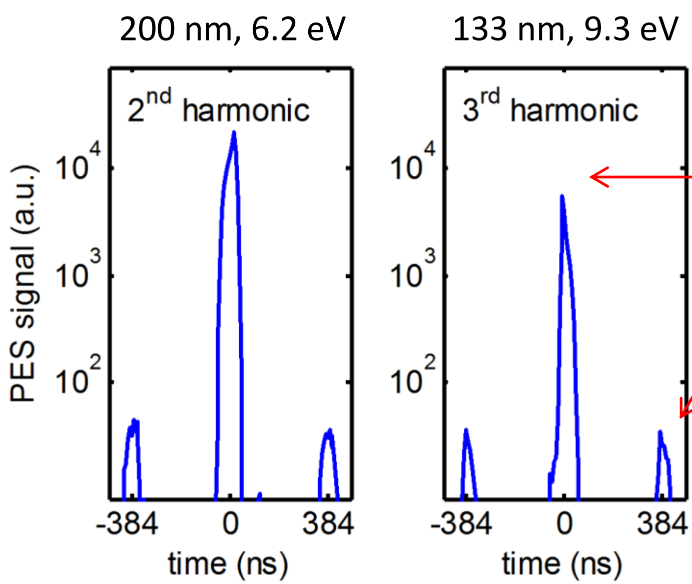
CHG Intensity at VUV Beamline

seeding with 400 nm:
up to 5th harmonic (80 nm, 15.5 eV)

seeding with 800 nm:
up to 7th harmonic (114 nm, 10.8 eV)

time-resolved photoelectron signals from an Au sample :

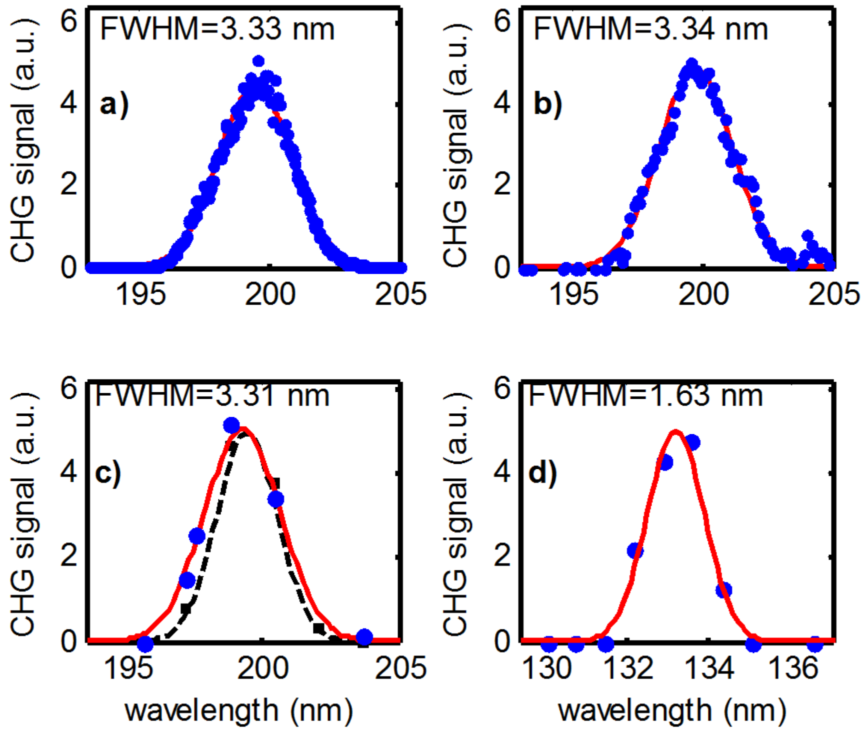
$$\frac{I_{\mathrm{CHG}}}{I_{\mathrm{Spont}}} \approx 600$$



$$\frac{I_{\mathrm{CHG}}}{I_{\mathrm{Spont}}} \approx 150$$

CHG Spectra

measured spectra with Gaussian fit:



a) Czerny-Turner spectrometer with APD
b) CCD spectrometer

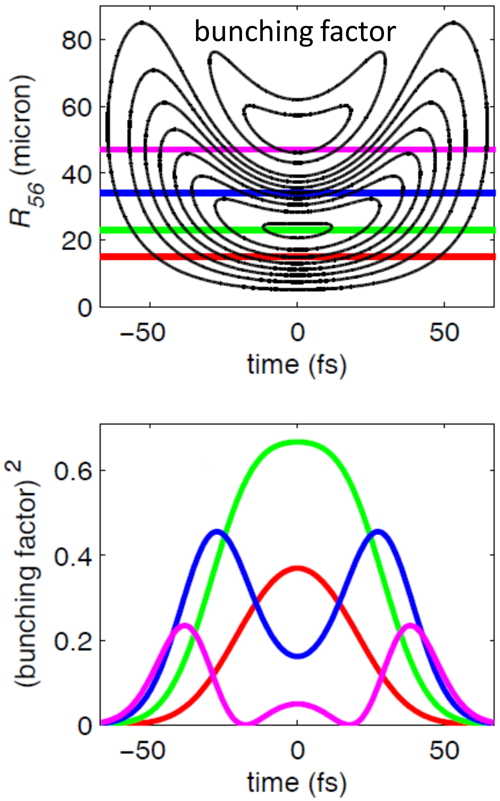
photoelectrons
c) 2nd harmonic (200 nm)
d) 3rd harmonic (133 nm)

time-bandwidth product is close to Fourier limit

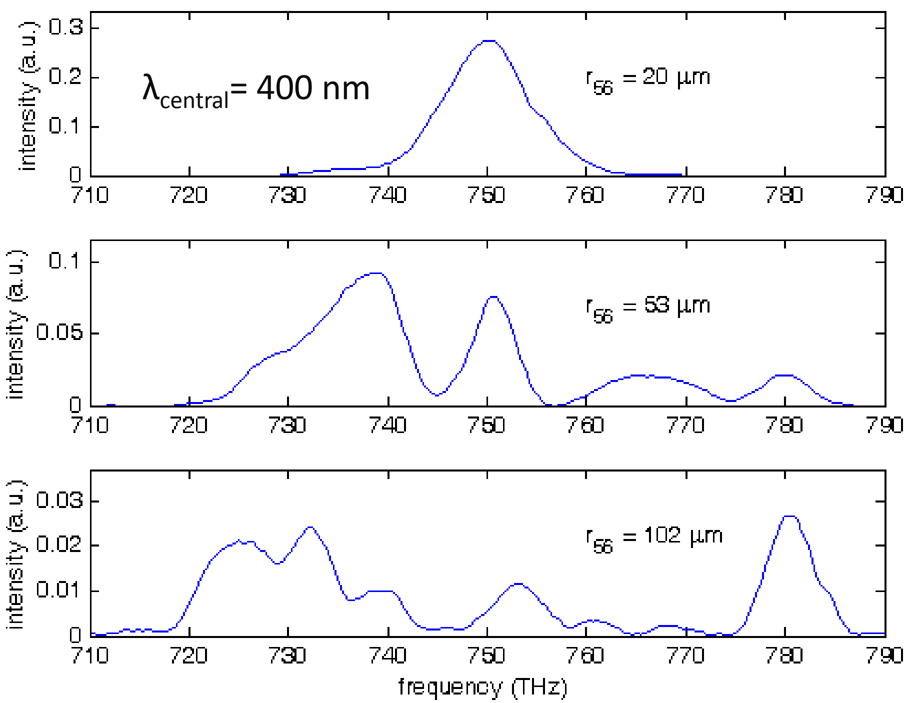
CHG Spectra

$$\Delta E(t) = \Delta E_{\max}\exp\left(-\frac{t^2}{2\sigma_t^2}\right) \qquad I_{\mathrm{CHG}}(\mathrm{t}) \propto |b_{\mathrm{n}}|^2 \propto \left|J_{\mathrm{n}}\left(n\,\Delta E(t)\;r_{56}\right)\right|^2$$

- Gaussian laser pulse → position-dependent energy modulation
- small r_{56} → Gaussian I_{CHG} → Gaussian spectrum (Fourier transform)
- large r_{56} → multiple peaks → spectra with interference fringes



measured spectra:



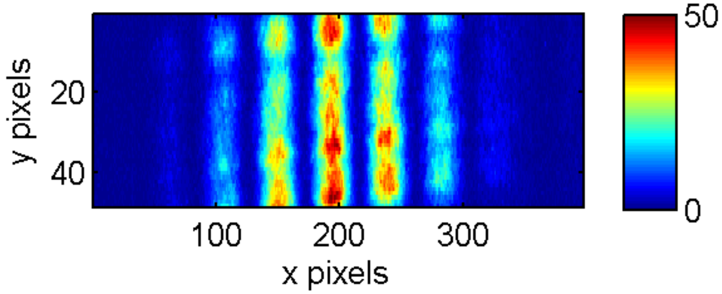
Transverse Coherence of CHG Pulses

- double-slit experiment:

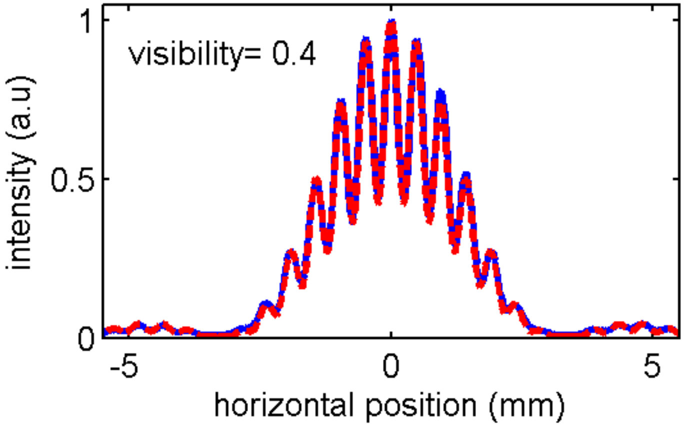
fast-gated ICCD camera (courtesy B. Schmidt, S. Wunderlich, DESY):

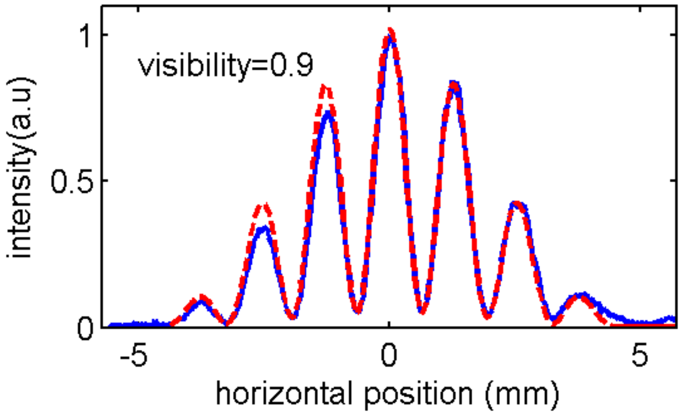
- coherence ≈ visibility $V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$

Interference pattern of 200 nm CHG



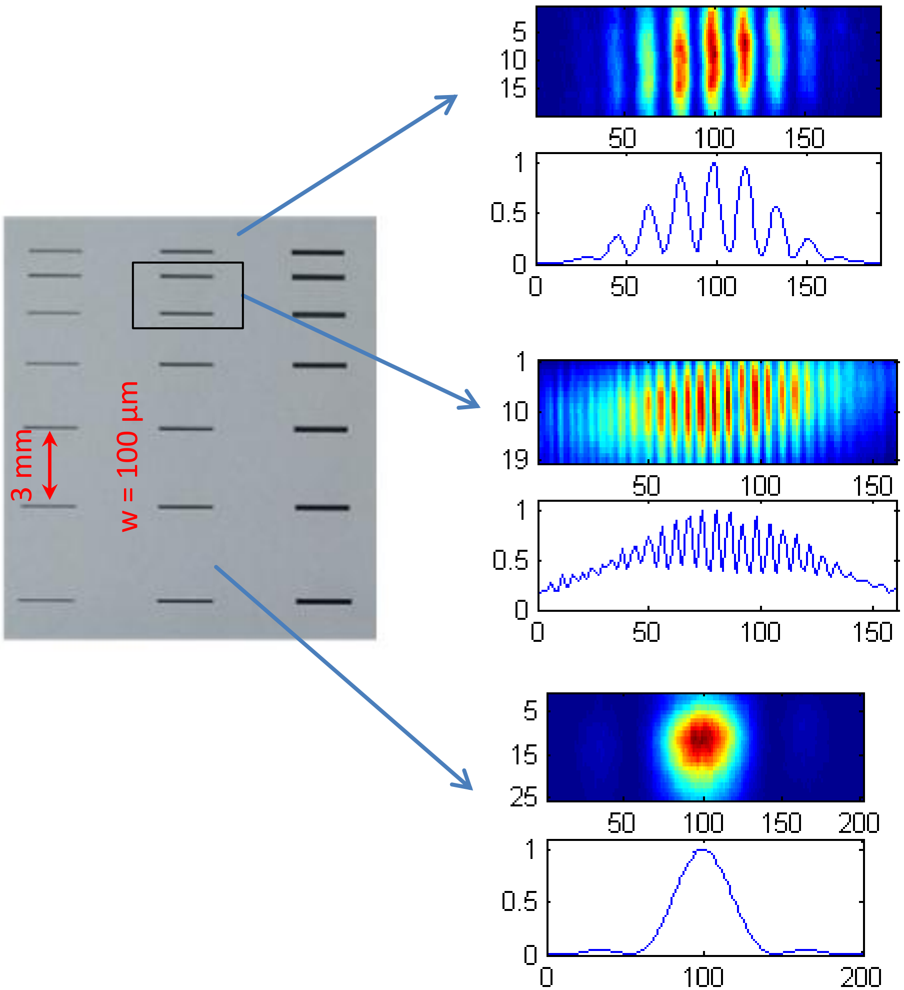
200 nm spontaneous radiation with bandpass filter:





Transverse Coherence Length

interference patterns at about 10 m from the radiator:

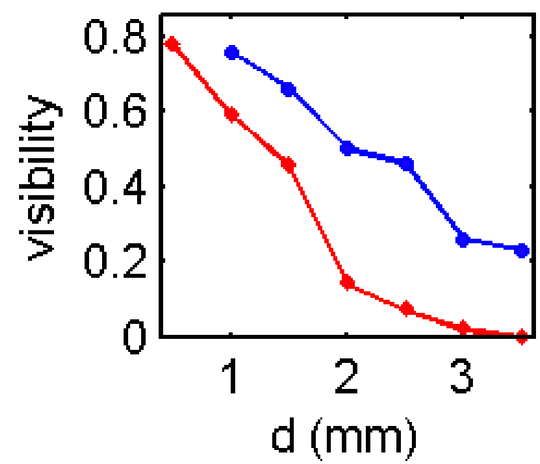


width of the coherence function:

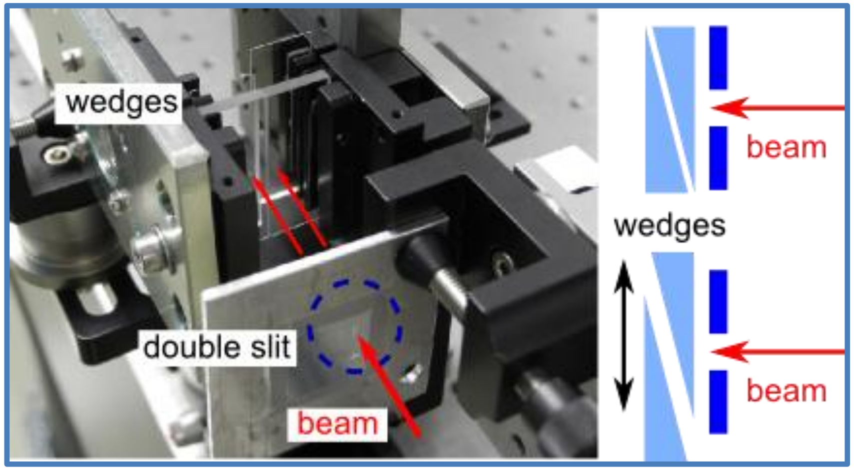
$$l_c = \int_0^\infty \left| \frac{V(x)}{V(0)} \right|^2 dx$$

- λ = 200 nm → l_c ≈ 0.8 mm
- λ = 400 nm → l_c ≈ 1.5 mm

coherence function:



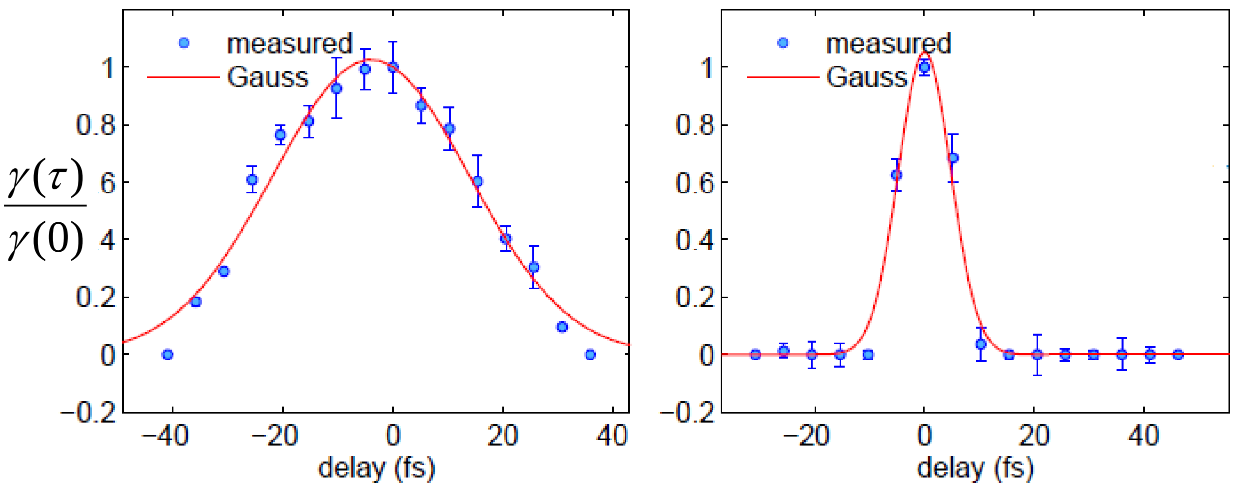
Coherence Time: Double Slit with Wedges

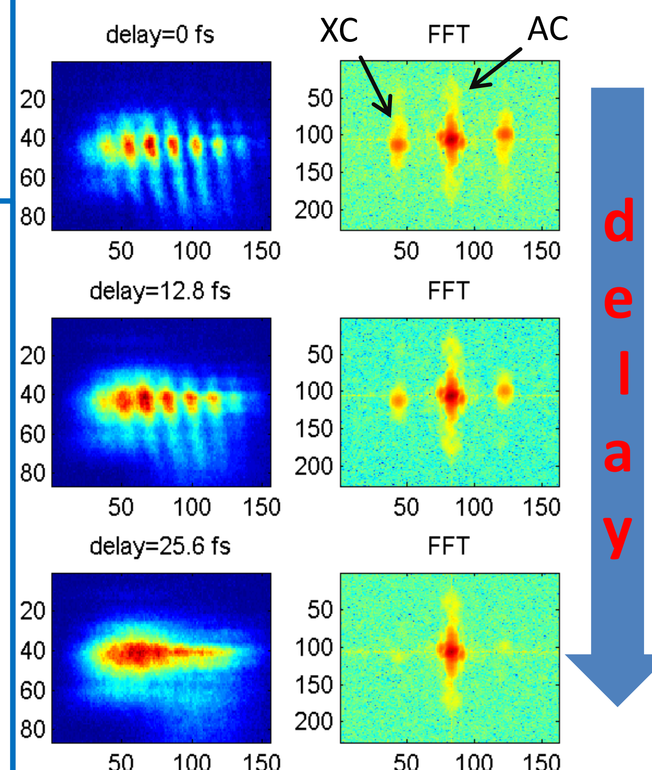


$$\gamma(\tau) = \frac{\tilde{I}_{XC}}{\tilde{I}_{AC}} \quad [1]$$

$$\tau_c = \int_{-\infty}^{\infty} \left| \frac{\gamma(\tau)}{\gamma(0)} \right|^2 d\tau \quad [2]$$

CHG : $\tau_c \approx 34$ fs SE: $\tau_c \approx 10$ fs (bandpass filter)

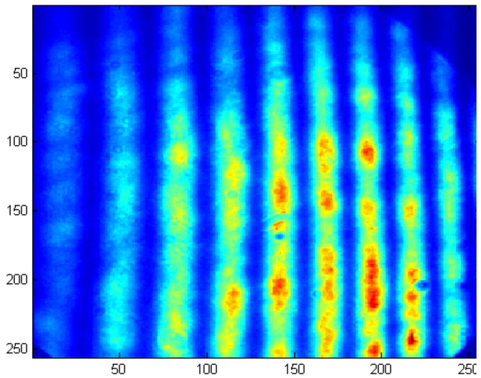


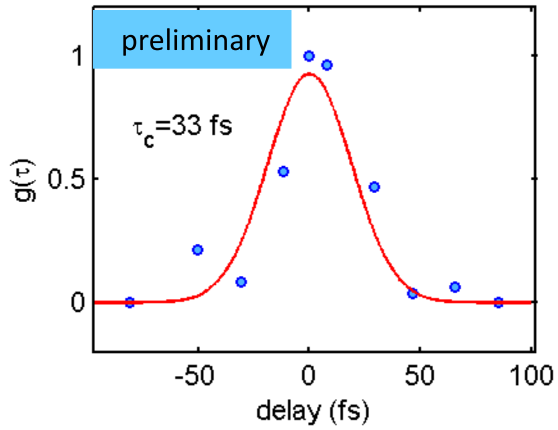


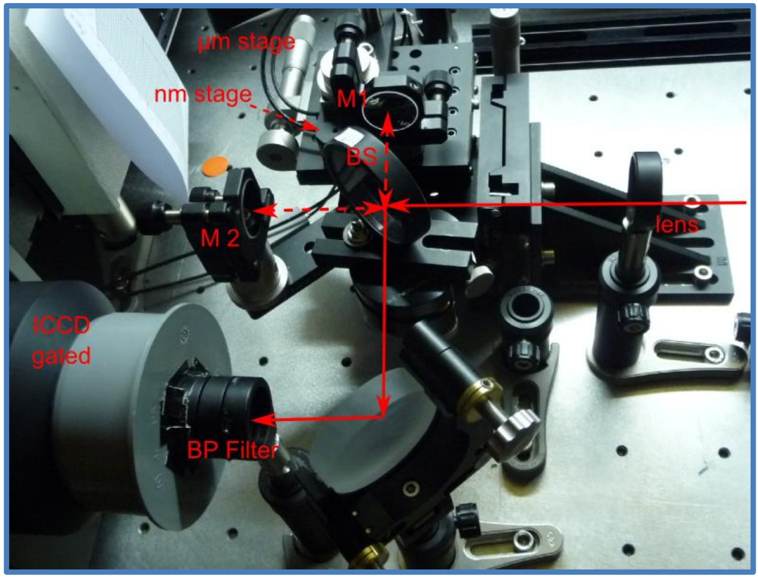
[1] A. Singer et al., Optics Express. 20, 16, 17480 (2012). [2] J.W. Goodman, Statistical Optics, Wiley, New York (1985).

Further Interference Experiments

- longitudinal: Michelson interferometer

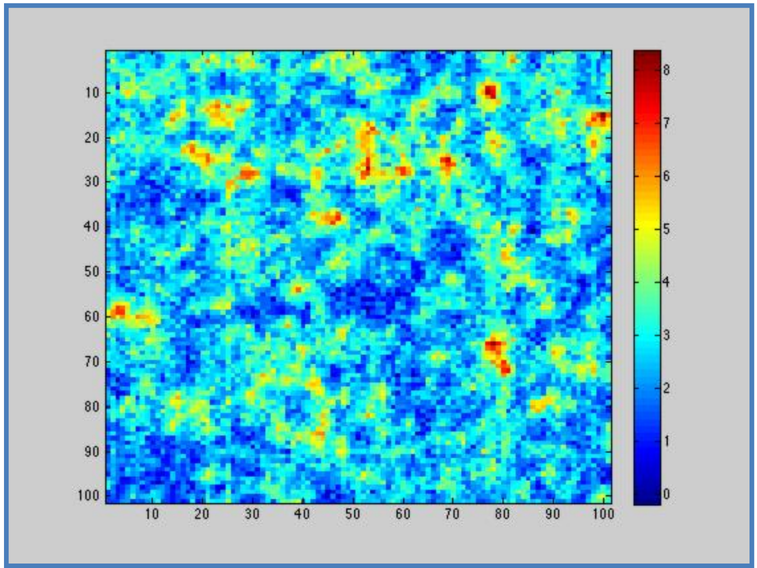






- transverse : speckle patterns

single shot of CHG scatterd from a colloidal solution (C. Gutt, Universität Siegen[1])

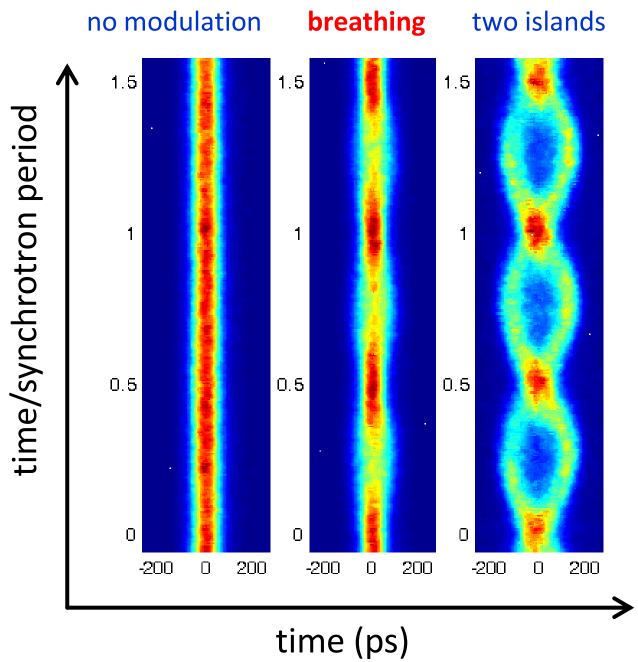


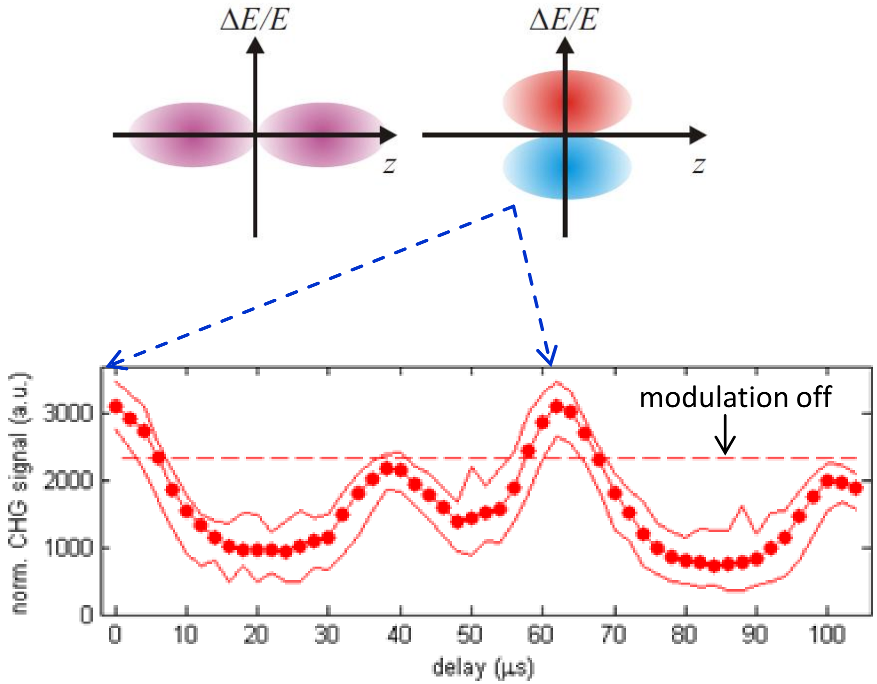
[1] C. Gutt et al., PRL 108, 024801 (2012).

RF Phase Modulation

- routinely applied to increase the beam lifetime
- modulation frequency ≈ 2 x synchrotron frequency
- when synchronized to laser, CHG increased by ≈ 30 %

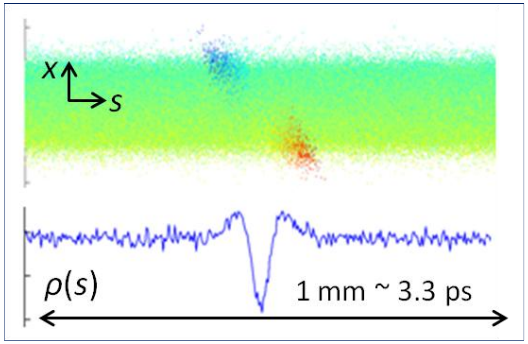
Streak camera images, increasing the modulation amplitude:

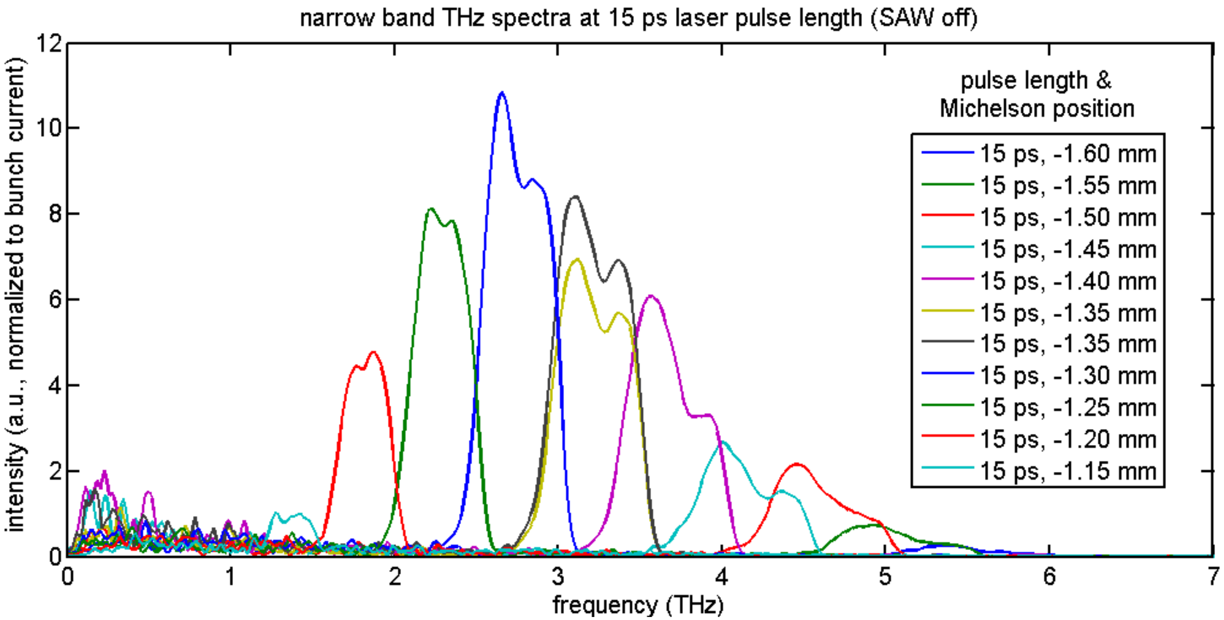




Coherent THz Pulses

- turn-by-turn THz pulses up to 11th turn [1]
- modulation of the electron bunch due to longer intensity-modulated laser pulses [2,3]
- narrowband THz radiation from multi-dips

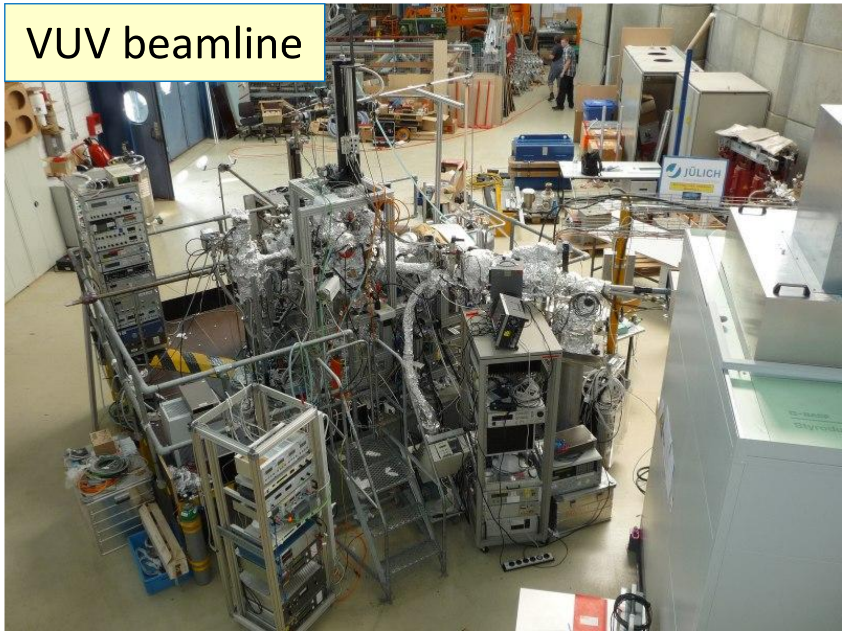




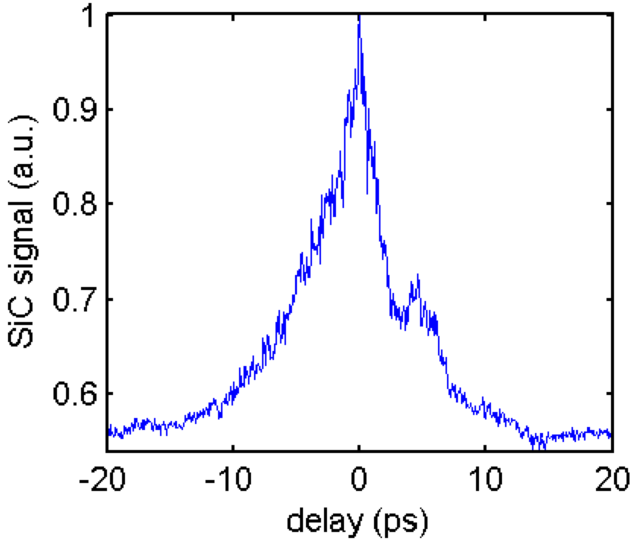
[1] P. Ungelenk et al., WEPRO002, this conference
[2] C. Evain et al., PRST-AB 13, 090703 (2010).
[3] S. Bielawski et al., Nature Physics 4, 390 (2008).

Preparations for Pump-Probe Experiments

- spatial and temporal overlap between pump and probe pulse is achieved
- first experiment planned :
  - to study the magnetization dynamics of thin films [1]
  - with 800 nm pump, 133 nm probe



zero delay:
2-photon-induced photocurrent



[1] D. Venus et al., PRB. Vol. 55, No. 4, 2594 – 2599 (1997).

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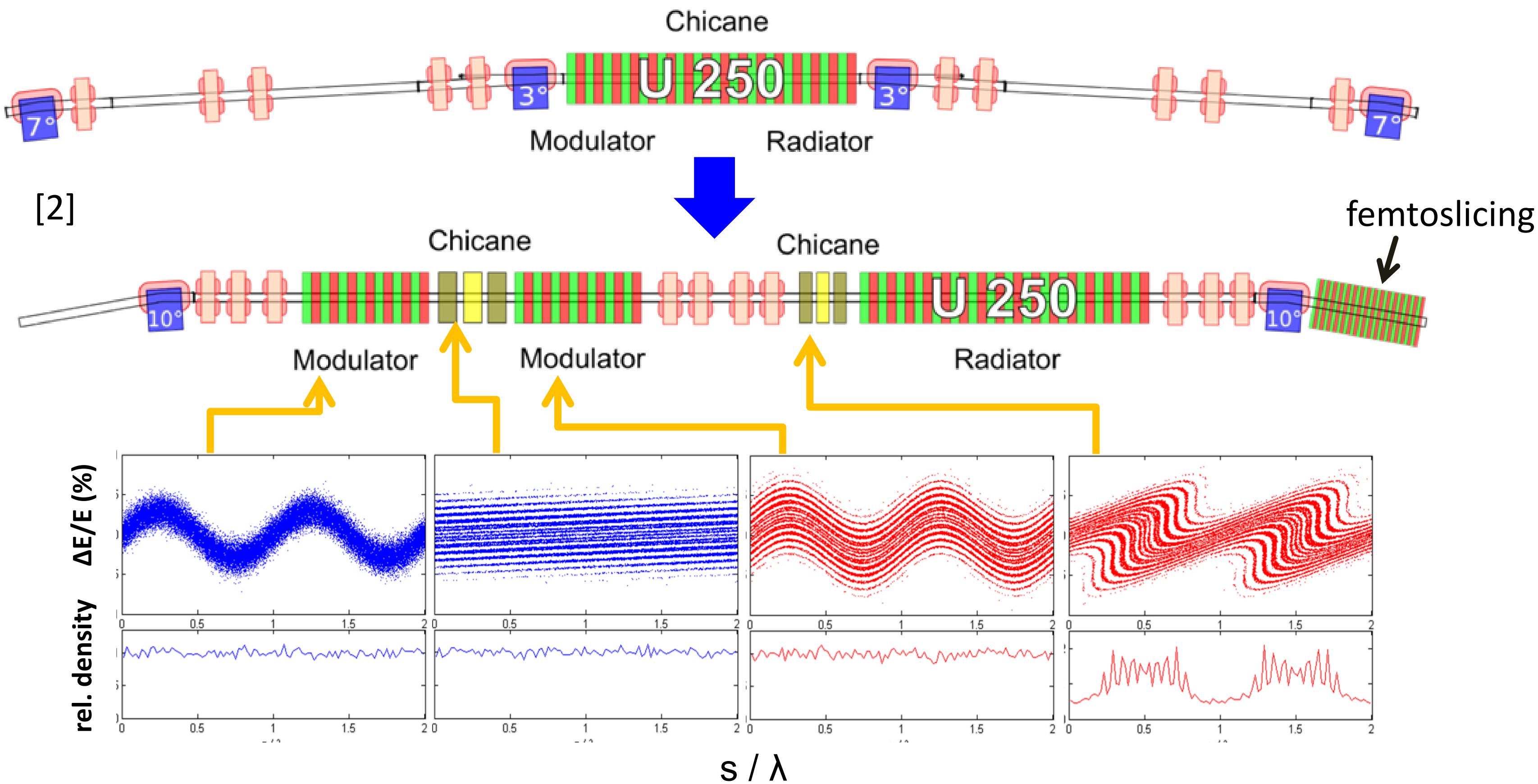
Upgrade Project: EEHG [1]

- more complex density modulation
- higher harmonics, short wavelengths ≈ 10 nm
- longer straight section required



[1] D. Xiang and G. Stupakov, Phys. Rev. ST Accel. Beams 12, 030702 (2009).

[2] R. Molo et al., Proc. FEL 2013, 549, New York .

Summary and Outlook

- CHG routinely performed
- CHG radiation characterized
- User experiments upcoming
- Upgrade to EEHG planned

Thank you for your attention!

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