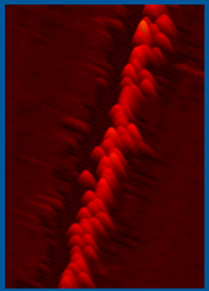
Coherent THz pulses from linear SRF accelerators: Perspectives for naturally synchronized THz pump probe experiments and novel electron beam diagnostic



M. Gensch
AG Coherent THz Radiation
Institute for Radiationphysics /
Institute for Ion-Beam Physics and Materials Research
Helmholtz-Zentrum Dresden-Rossendorf

- **THz sources**
- **Prototype facility @ FLASH**
- **TELBE: THz (Test) facility @ ELBE**

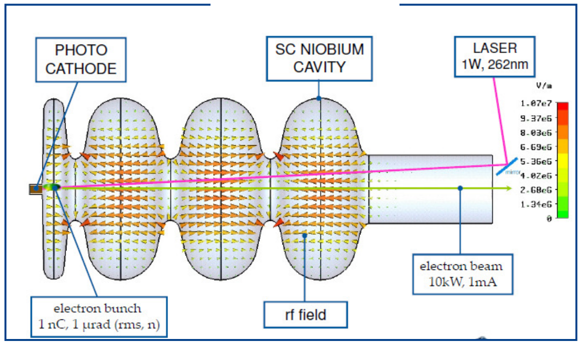
• THHz sources

- Prototype facility @ FLASH
- TELBE: THz (Test) facility @ ELBE

Accelerator-based Coherent THz sources

linear accelerators

1. electron source = „gun“



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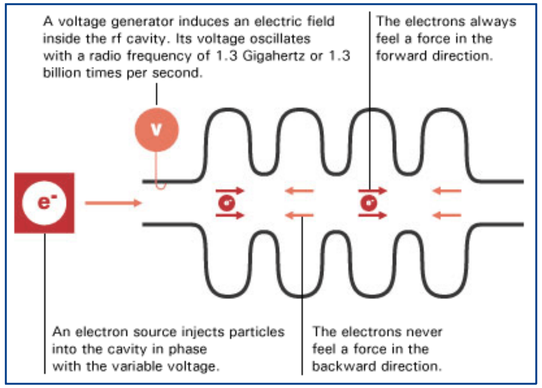

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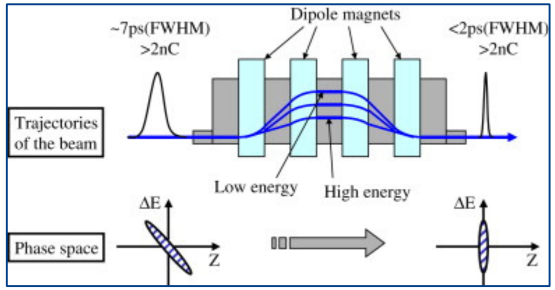

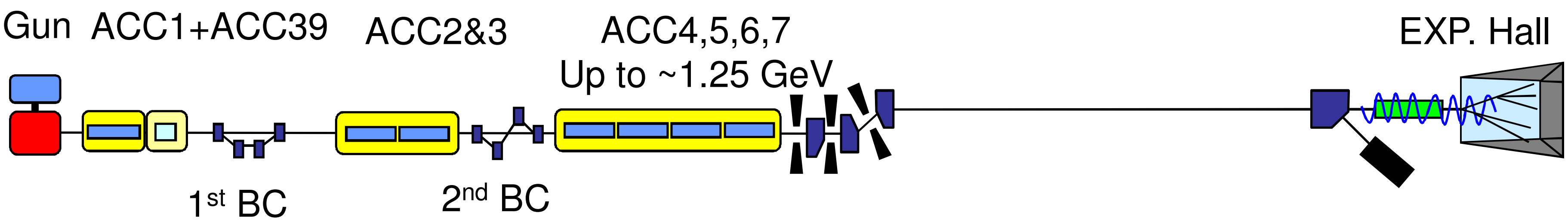

DRESDEN concept

HZDR

Accelerator-based Coherent THz sources

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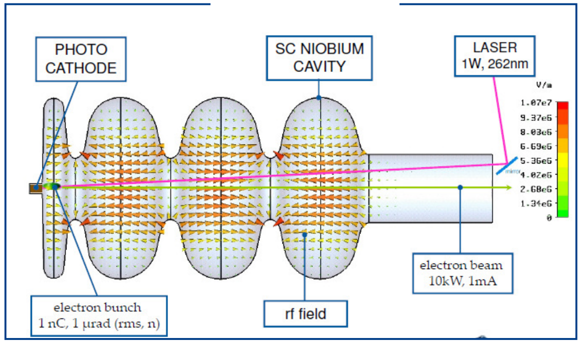

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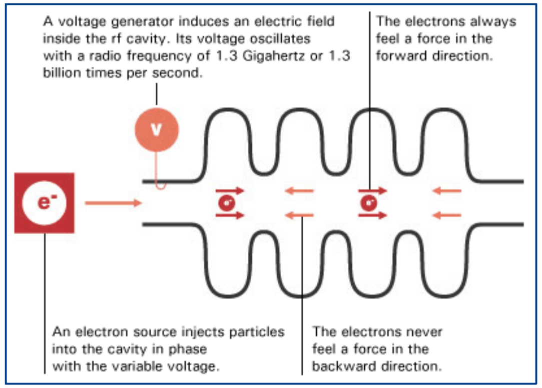

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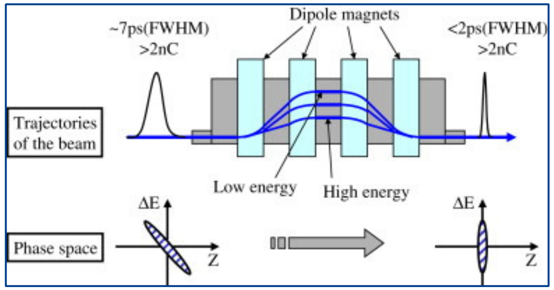
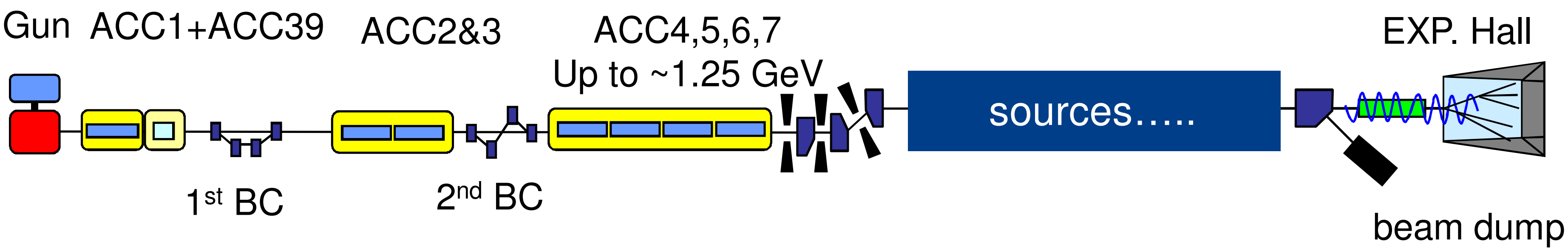
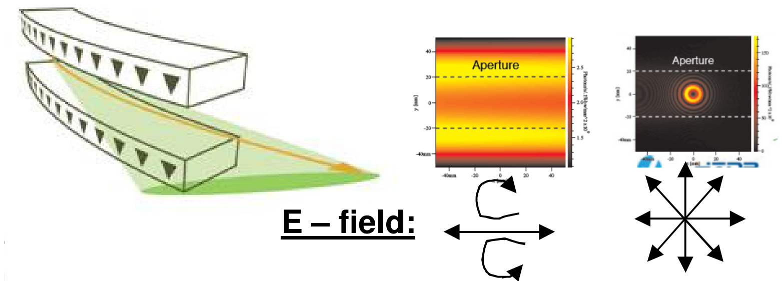


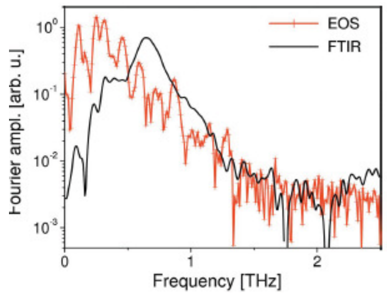


Accelerator-based Coherent THz sources

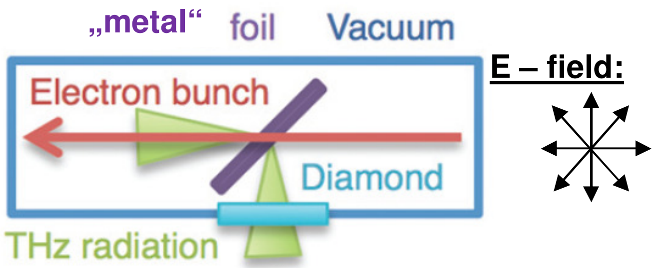
source types: „super-radiant“ sources

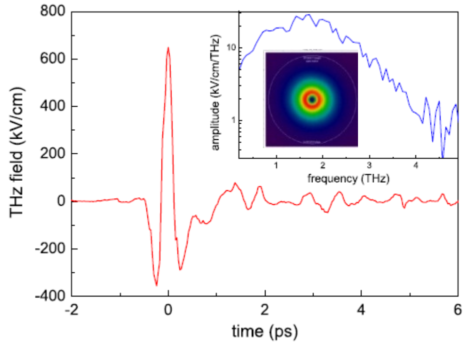
1. bending magnet: dipole + edge radiation



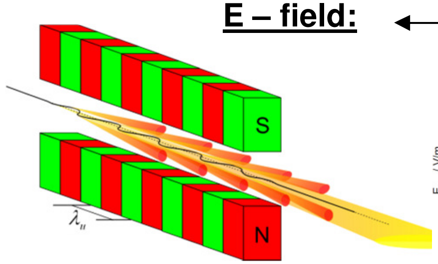


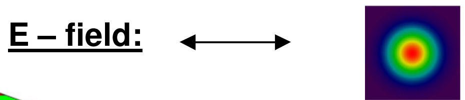
2. Coherent transition/diffraction screens

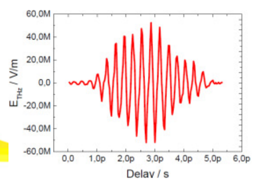


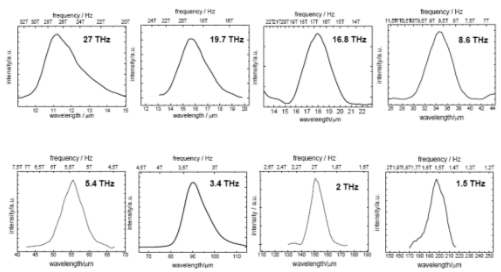


3. Undulator









@ linacs:
G.L. Carr et. al., Nature (2002)

M. Gensch et. al., Infrared Phys. Technol. (2008),
S. Casabuoni et. al., Phys. Rev. St. Accel. (2009),
M. Gensch AIP conf. Proc, (2010),
F. Tavella et. al., Nature Photonics (2011).
D. Daranciang et. al. , Appl. Phys. Lett (2011).,
M.C. Hoffmann et. al., Optics Lett. (2011),
Y. Shen et. al., Phys. Rev. Lett. (2011),
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Accelerator-based Coherent THz sources

source types: „super-radiant“ sources

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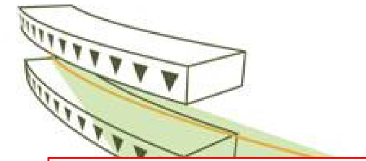

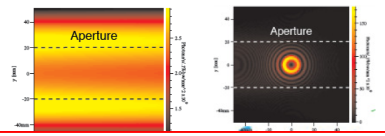

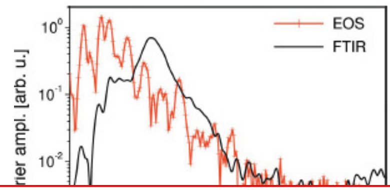

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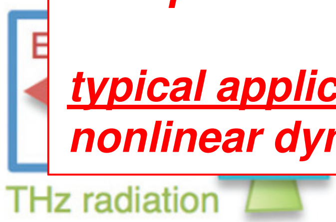
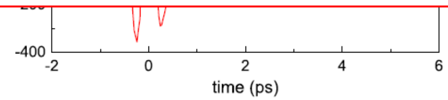




D. Daranciang et. al. ,
Appl. Phys. Lett (2011).,
M.C. Hoffmann et. al., Optics Lett. (2011),
Y. Shen et. al., Phys. Rev. Lett. (2011),
J. Park et.al., Rev. Sci. Instr. (2011)

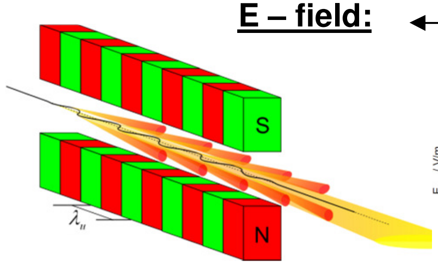
Overall properties:

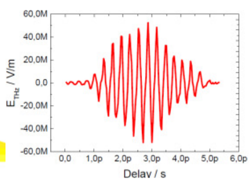
- ***pulse energies: up to mJ regime (in principle massively scalable!)***
- ***spectral bandwidth: tunable narrow band width or broad spectral bandwidth***
- ***repetition rate: few Hz to MHz (depending on rep. rate of accelerator)***

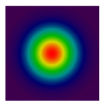
typical application:
nonlinear dynamics, diagnostics (electron bunch/X-rays), THz control

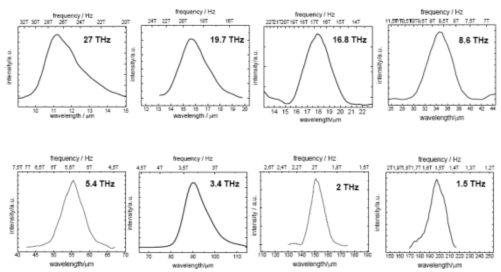
3. Undulator

E – field:









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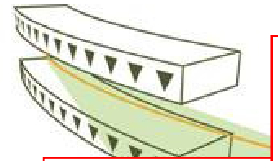

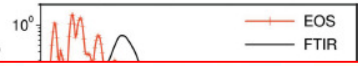

@ linacs:

Nature (2002)

Overall pr
- ***pulse e***
- ***spectra***
- ***repetiti***

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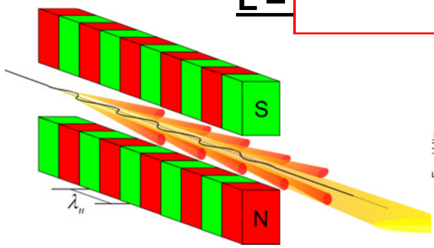
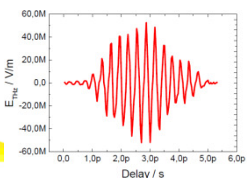
t. al. ,
(2011).,
et. al., Optics Lett.

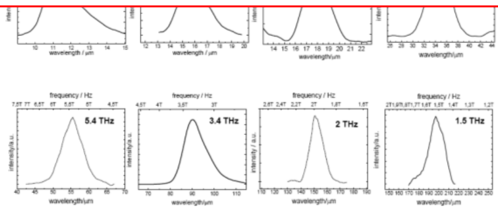
THz radiation

3. Undulator

E –

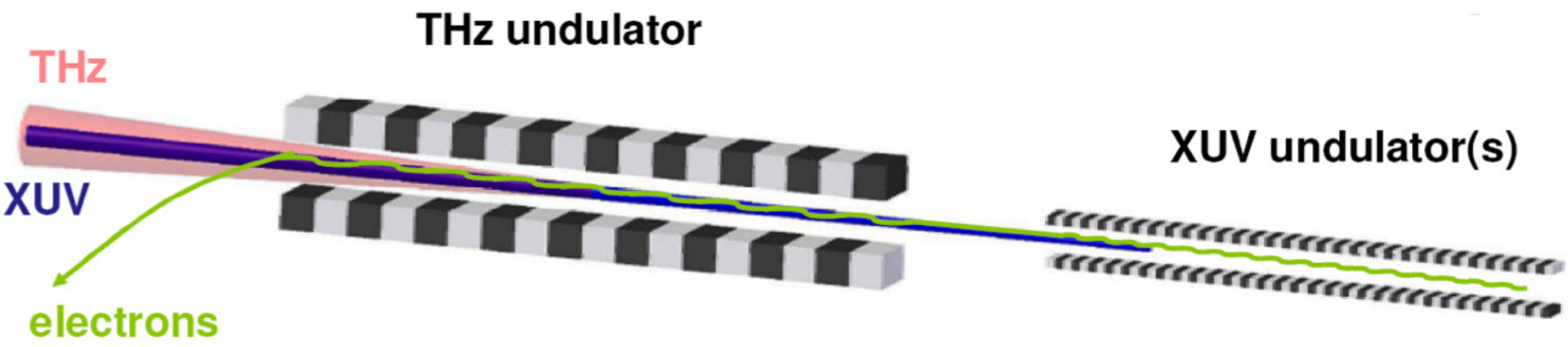






T. Shen et. al., Phys. Rev. Lett. (2011),
J. Park et.al., Rev. Sci. Instr. (2011)

Special case: X-Ray FEL´s



Cascaded design:

- Parasitic operation
- Synchronized to XUV pulse

Short electron bunch:

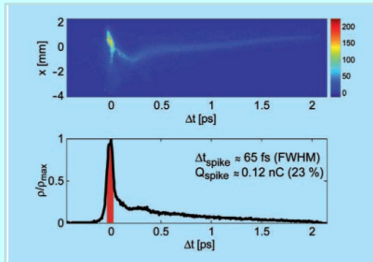
- Intensity ~ **N_e^2 (extremely high)**
- Coherent and CPE stable + **for free!**

Tunable/narrow bandwidth or broad band

Ultrashort electron bunches:

- **30-150fs**

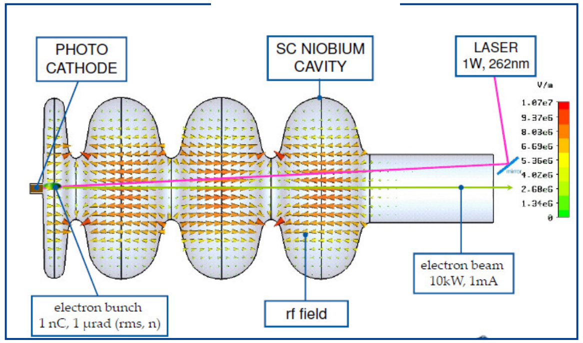
→ 10-50um



- B. Faatz et al., NIM A 475 (2001) 363.
- G. Geloni, E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Nucl. Instr. Method A 528 (2004) 184–188.

Special case: super conducting RF Linacs

1. electron source = „gun“



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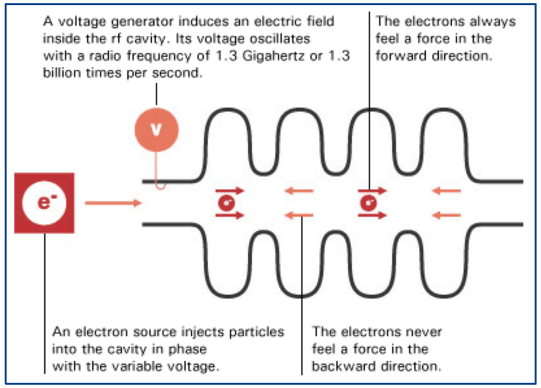

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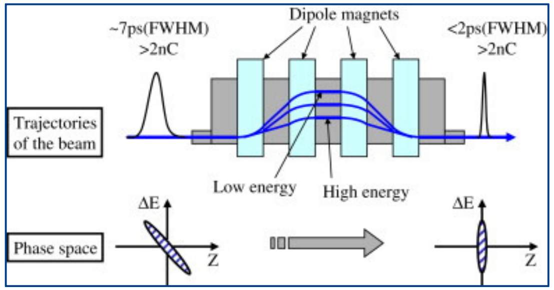
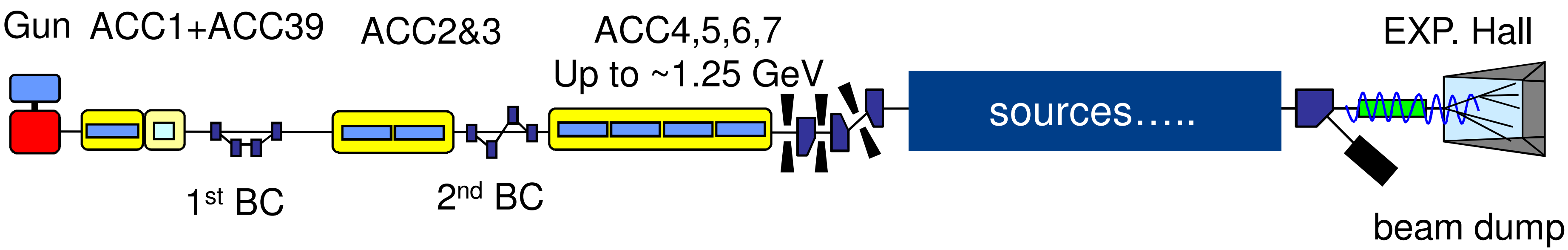
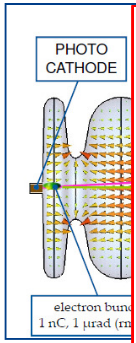
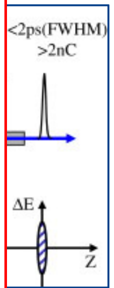




Special case: super conducting RF Linacs

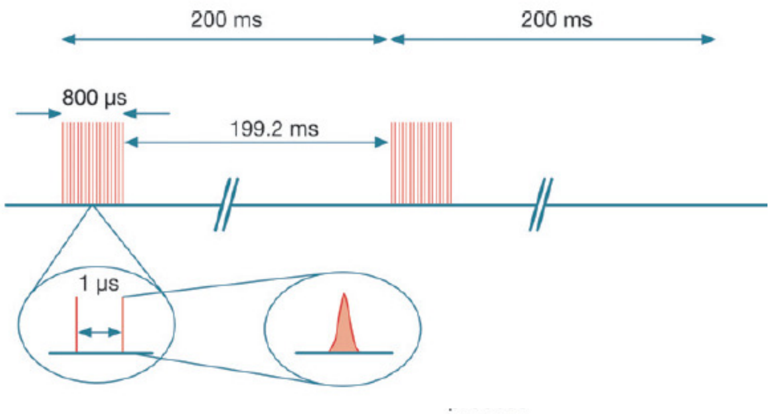
1. electron source = „gun“ **2. accelerator= „Cavity/ACC“** **3. compressor = „chicane/BC“**



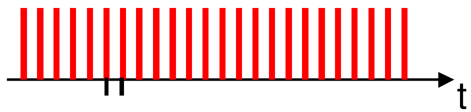


SRF Technology -> allows for very long puls trains or even quasi cw operation:

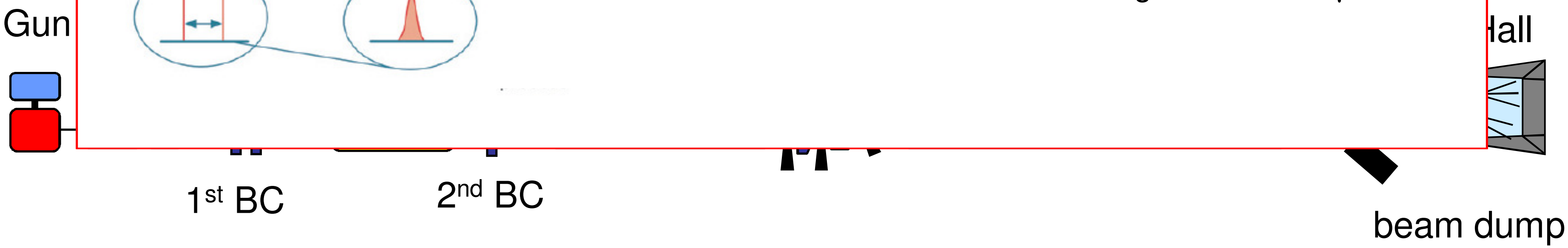
FLASH/X-FEL



ELBE/FELBE/TELBE
+ Jlab and other ERLs



e.g. 77 ns - 10 µs



take home messages:

Linac based source:

- can be upscaled tremendously by increasing charge
and optimizing bunchform (mJ regime has already been reached)

SRF linac based source:

- repetitionrates can be in the 100 kHz to even GHz regime

THz from X-ray FEL´s:

- for free (not much investment necessary)
- commensurate rep rate to X-rays
- few fs synchronization to X-rays

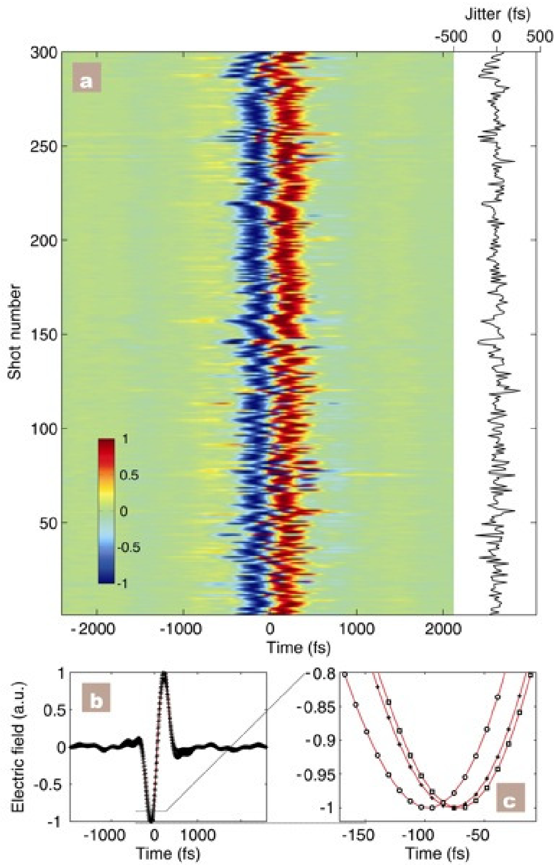
LINAC based THz Radiation

Applications

- *nonlinear dynamics*
- Diagnostics (Electron bunch/X-ray pulse)
- THz control
- THz/X-ray pump probe

LINAC based THz Radiation

Applications: electron bunch/X-ray pulse diagnostic



- *Arrivaltime*
- *Pulseduration*
- *chirp?*

- convenient
- online
- commensurate with X-ray exp.

original justification of the project

e.g. F. Tavella et. al., Nat. Photon. (2011)

LINAC based THz Radiation

Applications: non resonant high THz fields

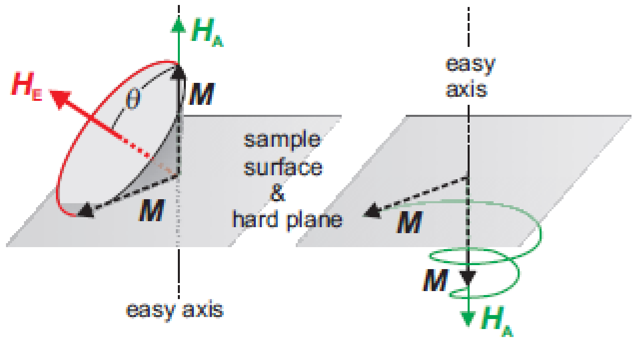
APPLIED PHYSICS LETTERS **94**, 072504 (2009)

Magnetization switching without charge or spin currents

J. Stöhr,[1,2,a)] H. C. Siegmann,[2] A. Kashuba,[3] and S. J. Gamble[2,4]
[1]*Stanford Synchrotron Radiation Lightsource, Stanford, California 94305, USA*
[2]*PULSE Center, Stanford University, Stanford, California 94025, USA*
[3]*Bogolyubov Institute for Theoretical Physics 14-b, Metrolohichna Str., Kiev 03680, Ukraine*
[4]*Department of Applied Physics, Stanford University, Stanford, California 94305, USA*

(Received 1 December 2008; accepted 25 January 2009; published online 18 February 2009)

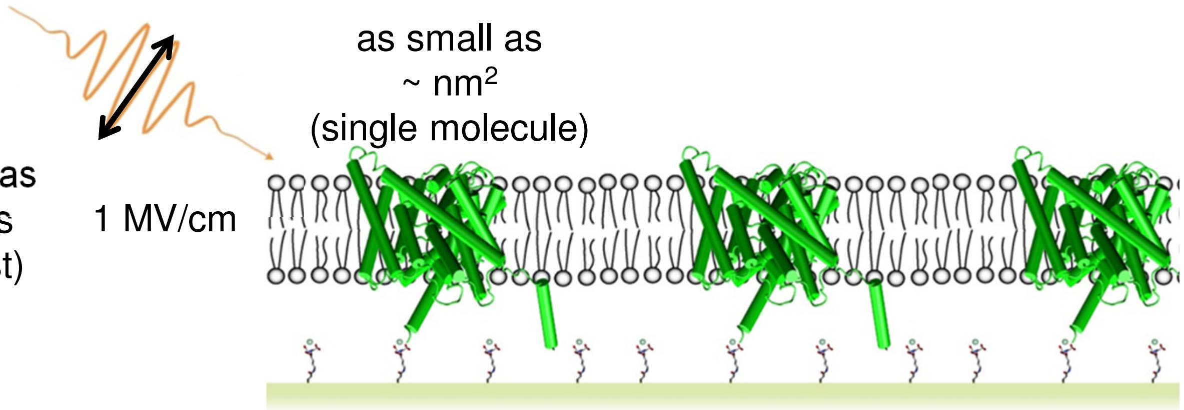
We propose schemes of reversing the magnetization of a ferromagnet by electric fields alone, without charge or spin currents or external magnetic fields. The switching is triggered by picosecond manipulation of the atomic positions or subpicosecond distortion of the valence charge distribution, which through spin-orbit coupling modifies the magnetic anisotropy. We discuss how such time-even anisotropies can be used to switch the time-odd magnetization for in-plane and out-of-plane magnetization directions. In all cases the switching process is completely determined by the appropriately chosen orientation, magnitude, and temporal length of the electric field created by a voltage or photon pulse. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3081421]



E-field required for FM
pulseduration: < 1 ps
frequencies: > 1 THz
power density: 10^{15} W/m^2
-> E~ V/nm!

LINAC based THz Radiation

Applications: non resonant high THz fields



<u>life sciences:</u>

typical voltages in life sciences (e.g. gateing ion channels in cellular membranes) are in the V/nm range!

➡ **source for non contact excitation should be in MV/cm regime or higher + repetitionrate adapted to induced cycle time**

C. Bauer, M. Gensch, J. Heberle, J. Phys. Conf. Series (2012)

LINAC based THz Radiation

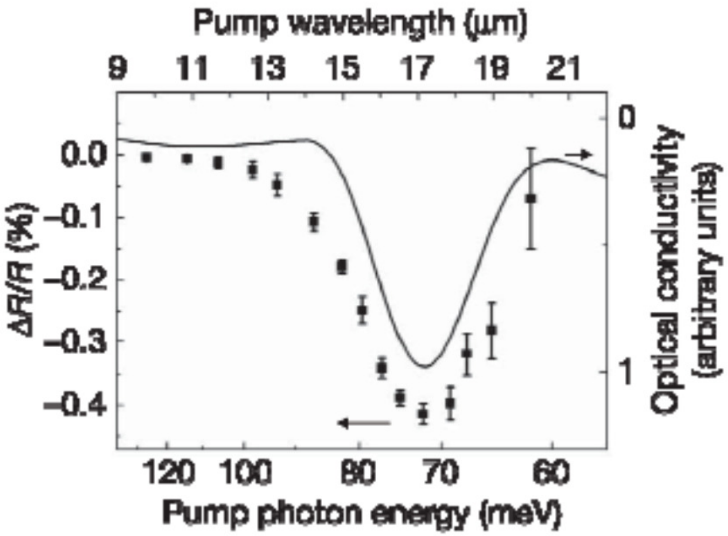
Applications: resonant THz control I

Pilot experiment: $Pr_{1-x}Ca_xMnO_3$ (PCMO)

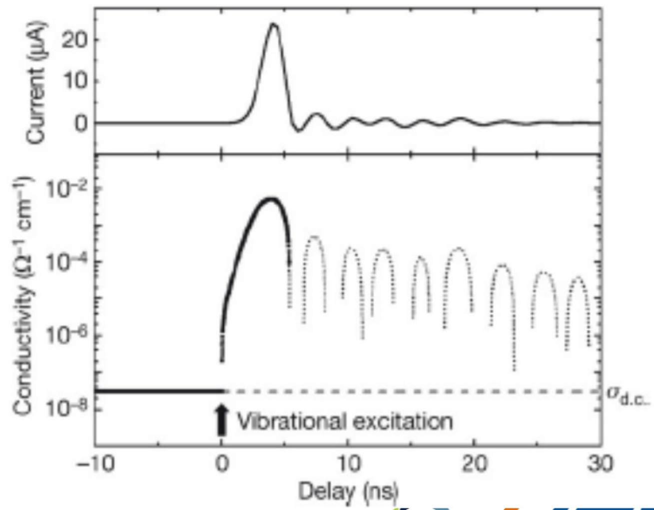
- fluence dependence
- mode selectivity at lower lying modes
- property of the transient state

?

induce insulator-metal transition



M. Rini *et al.*, Nature **449**, 72 (2007)



DRESDEN concept

HZDR

LINAC based THz Radiation

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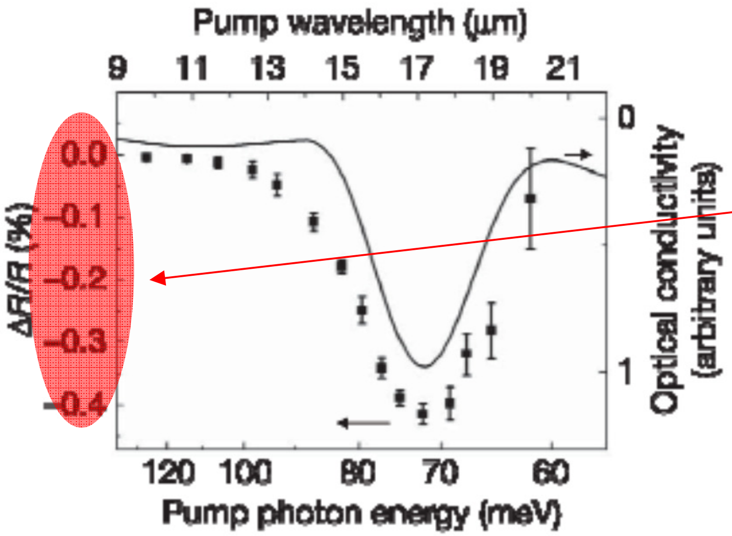
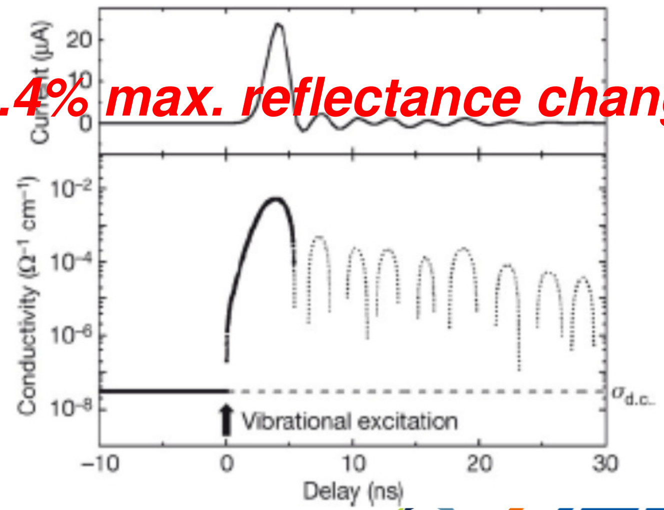


M. Rini *et al.*, Nature **449**, 72 (2007)

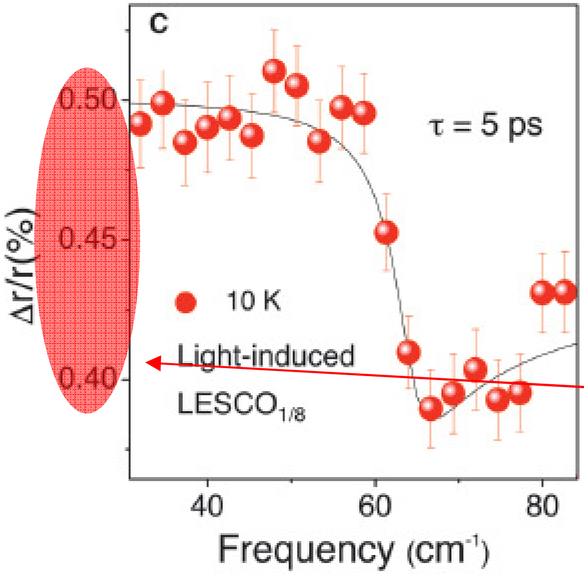
0.4% max. reflectance change!



LINAC based THz Radiation

Applications: resonant THz control II

induce superconducting phase (detected by JPR)



D. Fausti et. al., Science (2011)

- fluence dependence
- mode selectivity at lower lying modes
- property of the transient state (e.g. spectral weight shifts…)

?

such experiments require/wish:

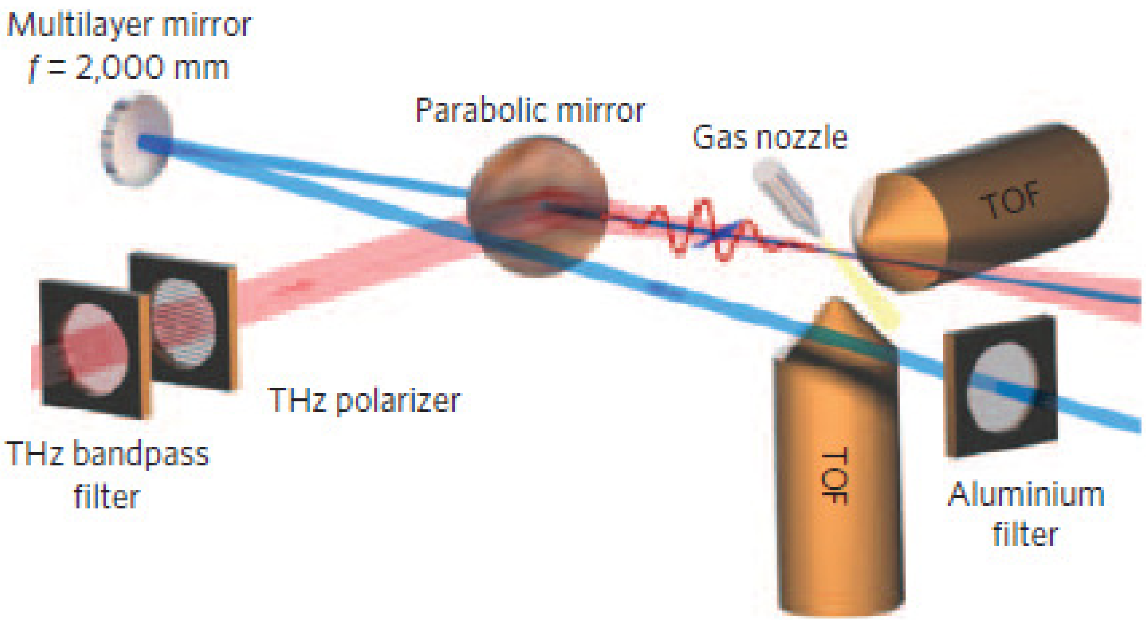
➡ „high“ repetition rates (matched to decay times of transient state)

➡ pulseenergies in the 100 μJ regime + optimal focussing properties

0.1% max. reflectance change! (in the THz)

LINAC based THz Radiation

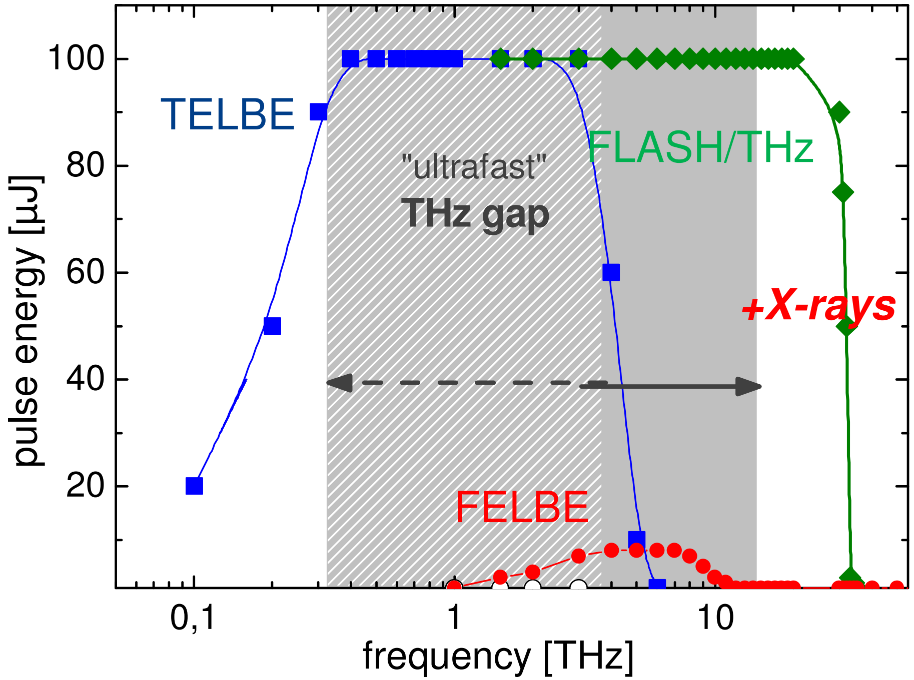
THz/X-ray pump probe



U. Frühling et. al., Nat. Photon. (2009)
B. Schütte et. al., Phys. Rev. Lett. (2012)
.....

-> repetition rate of THz should be commensurate to that of X-rays!

2 SRF Linac-based THz sources in europe



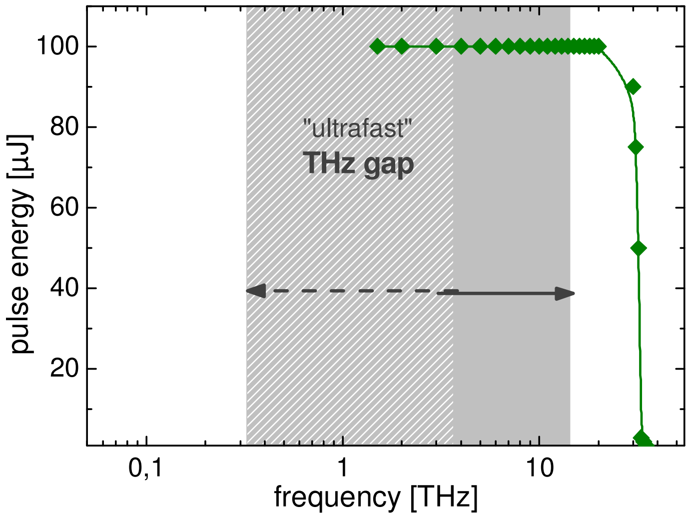
parameters:
100's fs - 10's ps,
few 1 – 500 kHz*,
< 100 µJ
combined with X-ray and/or table top lasers
***TELBE**

enabled by superconducting radiofrequency technology

DRESDEN concept HZDR

- THz sources
- **Prototype facility @ FLASH**
- TELBE: THz (test) facility @ ELBE

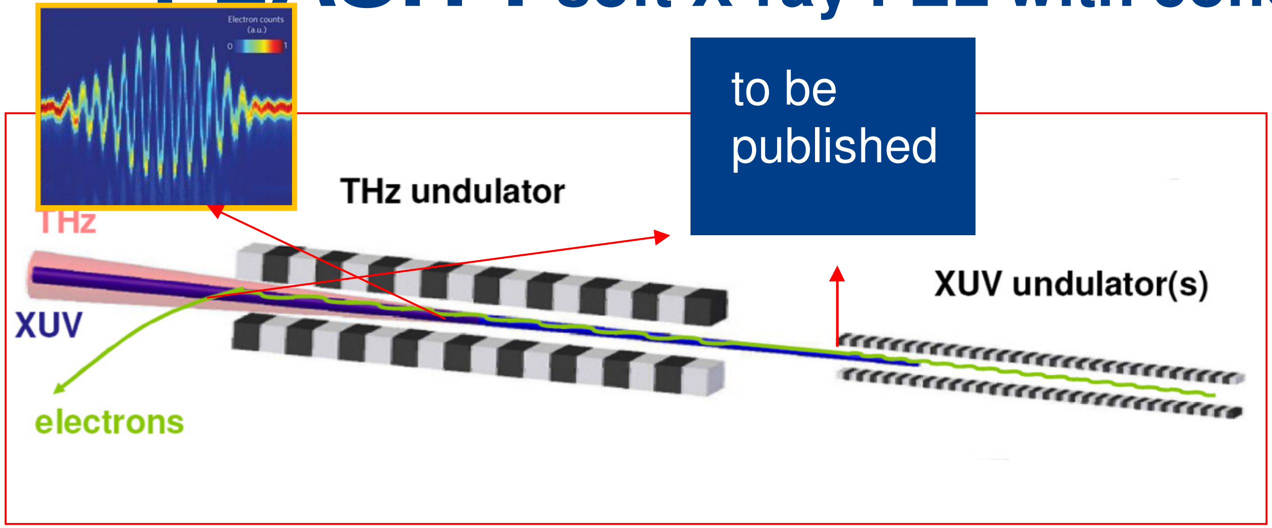
FLASH : soft X-ray FEL with coherent THz source



FLASH - THz / DESY

- Spectral range: 30 – 1 THz/(0.1 THz)
- Spectral bandwidth: 10% (undulator), 100% (edge)
- Reprate: 10 Hz (macropulse) -> up to 8000 pulses/s
- Pulse energy: several µJ to 100 +X µJ
- Average power: up to sev. mW
- polarization linear (undulator), radial (edge)
- Pulse duration: 10*τ_{THz}(undulator), < 1 ps (edge)

FLASH : soft X-ray FEL with coherent THz source



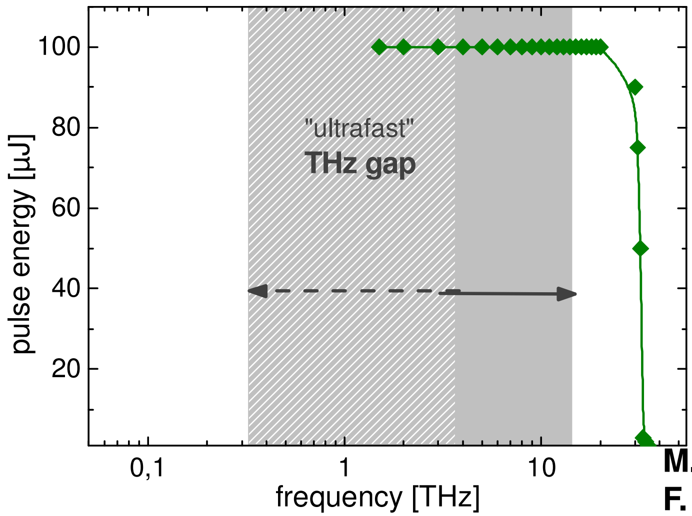
to be published

THz and X-ray pulses are intrinsically synchonized to one another on fs level!

+

rep. rate is commensurate

DRAWBACK:
XUV refocussing required!

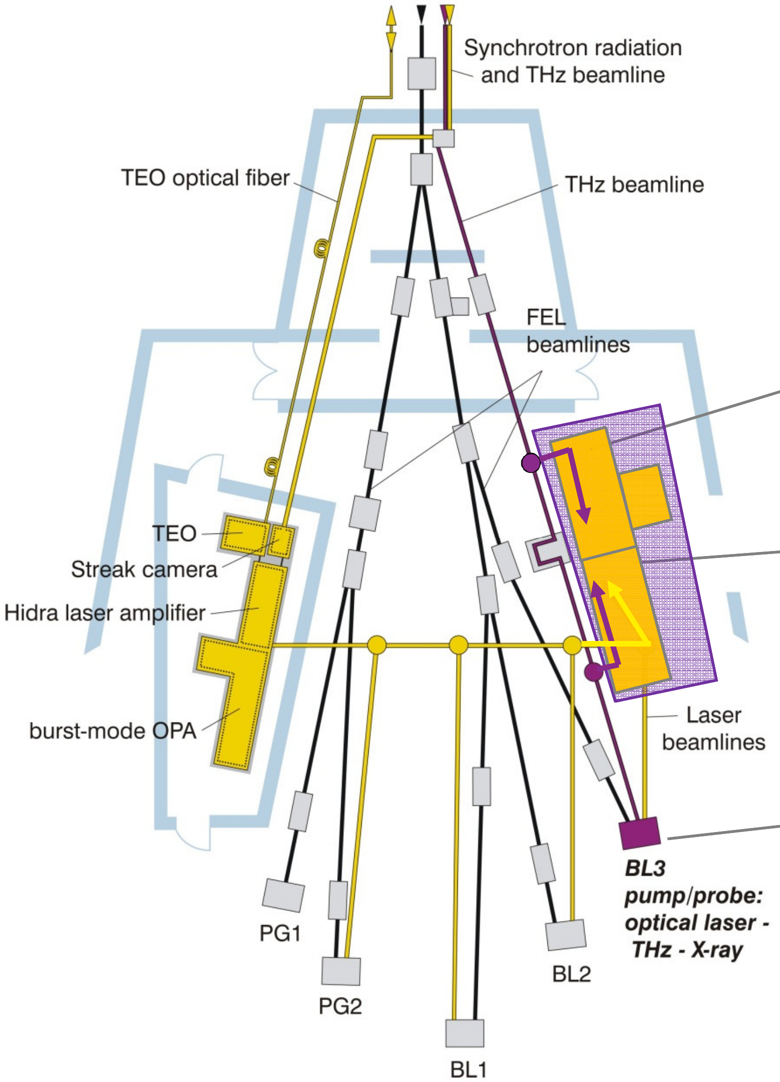


FLASH - THz / DESY

- **Spectral range: 30 – 1 THz (0.1 THz)**
- **Spectral bandwidth: 10% (undulator), 100% (edge)**
- **Reprate: 10 Hz (macropulse/burstmode)**
- **Pulse energy: several µJ to 100 +X µJ**
- **Average power: up to sev. mW**
- **polarization linear (undulator), radial (edge)**
- **Pulse duration: 10*τ_{THz}(undulator), < 1 ps (edge)**

M. Gensch et. al., Infrared Phys. Technol. (2008)
F. Tavella et. al., Nat. Photon. (2011)

FLASH : user facility

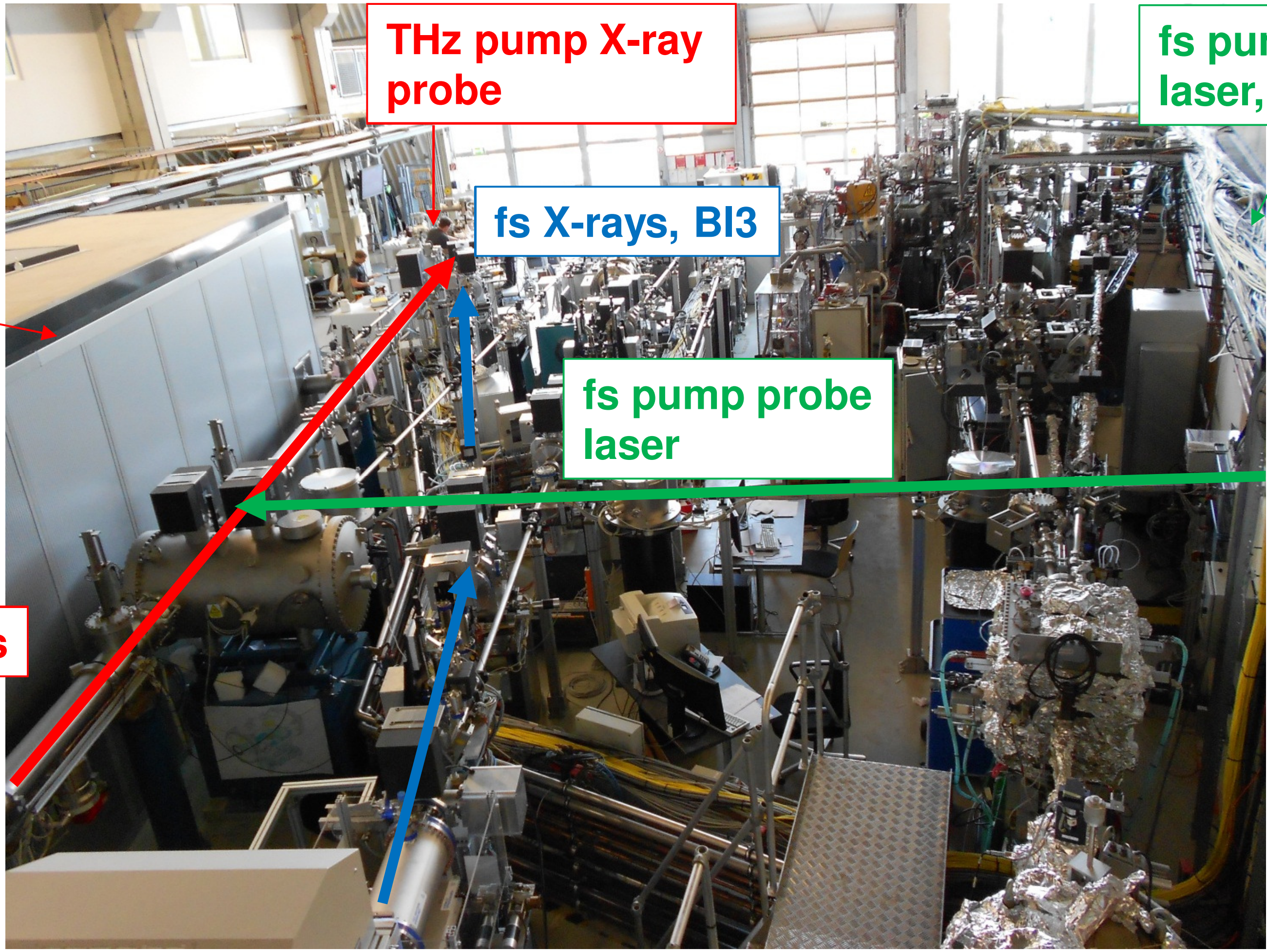


<u>THz diagnostics port - </u>THz only
Pulse energy, spectrum …

<u>THz pump/probe port - THz & VIS</u>
Pulse duration, timing, experiments…

<u>THz end station @BL3 - THz & VIS & XUV</u>
User experiments …

FLASH : user facility



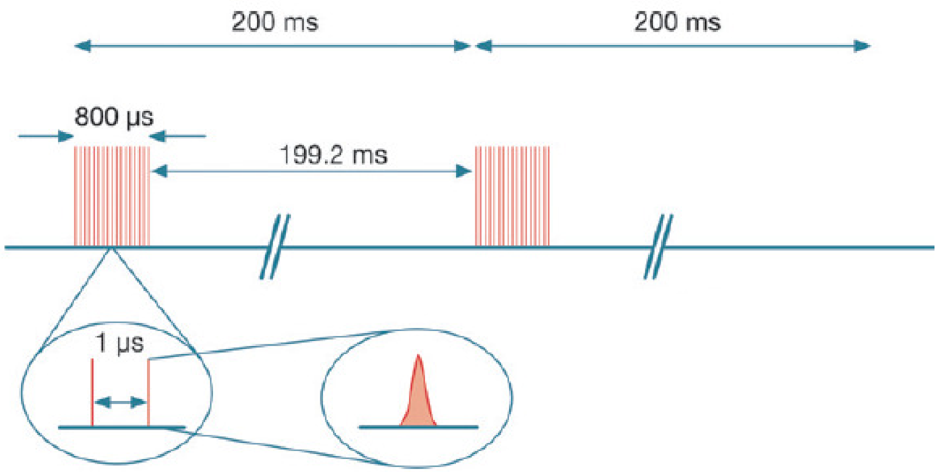
FLASH: Pump probe – relev. parameters

THz:
undulator/edge
λ = 10 – 300 µm (3000 µm)
$\Delta\lambda/\lambda$ = 10% (100%)
polarization: linear/radial
pulse energy: 1 – 100 µJ *
pulse duration: $10^*\tau_{THz}$, < 1 ps

X-rays:
λ = 4.5 – 50 nm
λ = 1%
pulse energy: few 10 to few 100 µ
pulse duration: few 10 to few 100

burst mode fs laser:
λ = 780 nm
pulse energy: up to 10 µJ
pulse duration: 100 fs
**depends on electron beam energy and bunch form*

FLASH time structure:



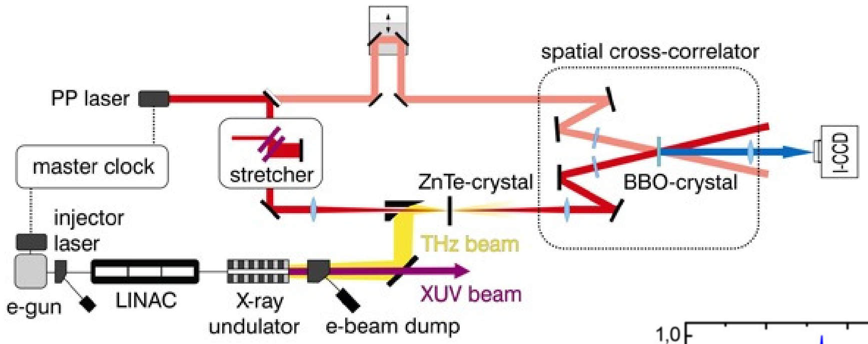
+ mJ laser system
λ = 780 nm
pulse energy: few mJ
pulse duration: 100 fs
repetition rate: 10 Hz

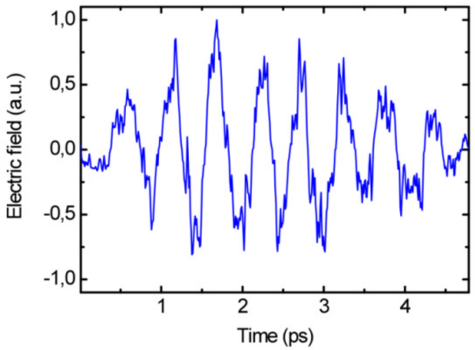
DRESDEN concept

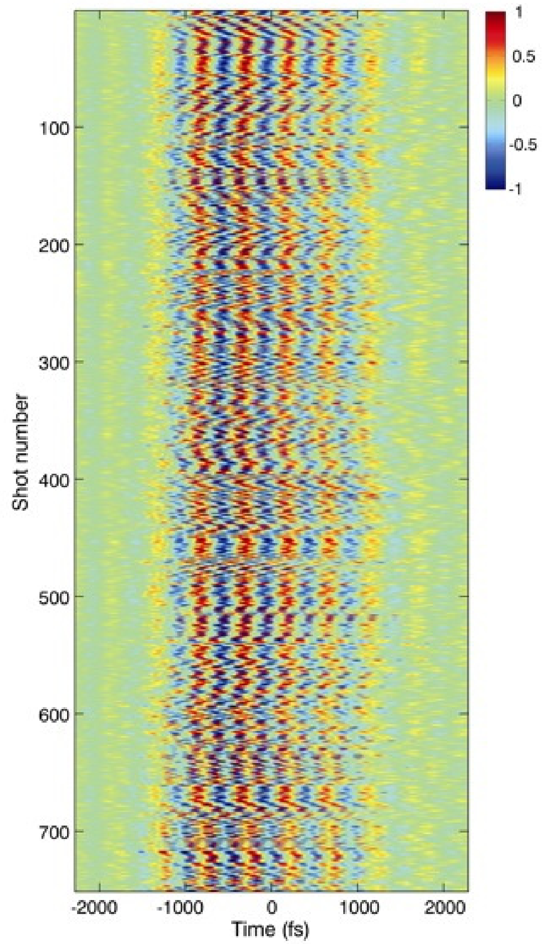
FLASH - THz: typical applications

- **X-ray pulse diagnostic**
  - ***„Photoelectron streaking“***
    - ***THz control***

X-ray pulse diagnostic
Few femtosecond timing



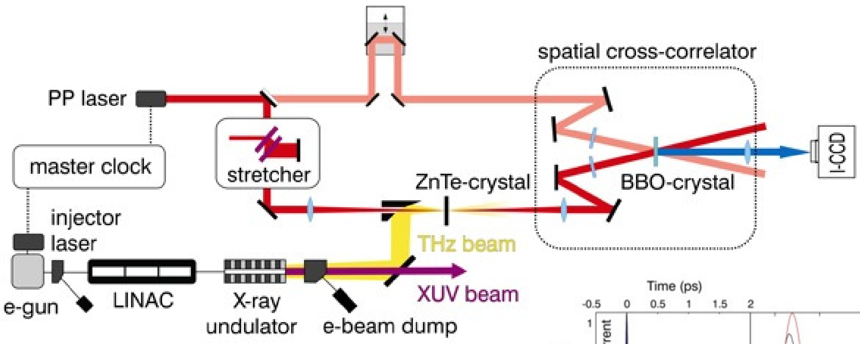


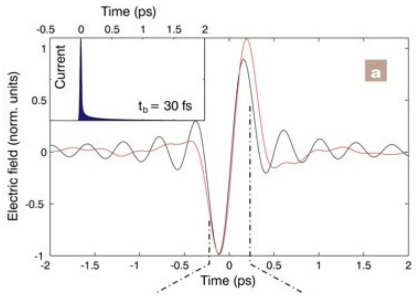


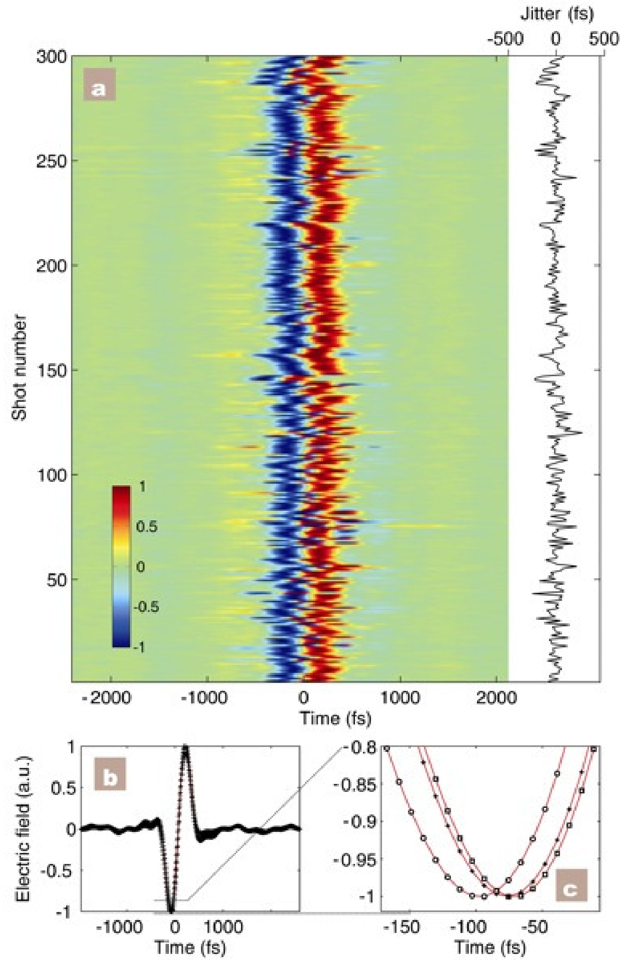
***F. Tavella, N. Stojanovic, G. Geloni, M. Gensch,**
Few fs synchronization at 4th generation light sources, *Nature Photon.* (2011)
Experimental setup based on:
van Tilborg, J. *et. al. Single-shot spatiotemporal measurements of high-field terahertz pulses, Opt. Lett.* ***32, 313-315 (2007).***

X-ray pulse diagnostic

Few femtosecond timing







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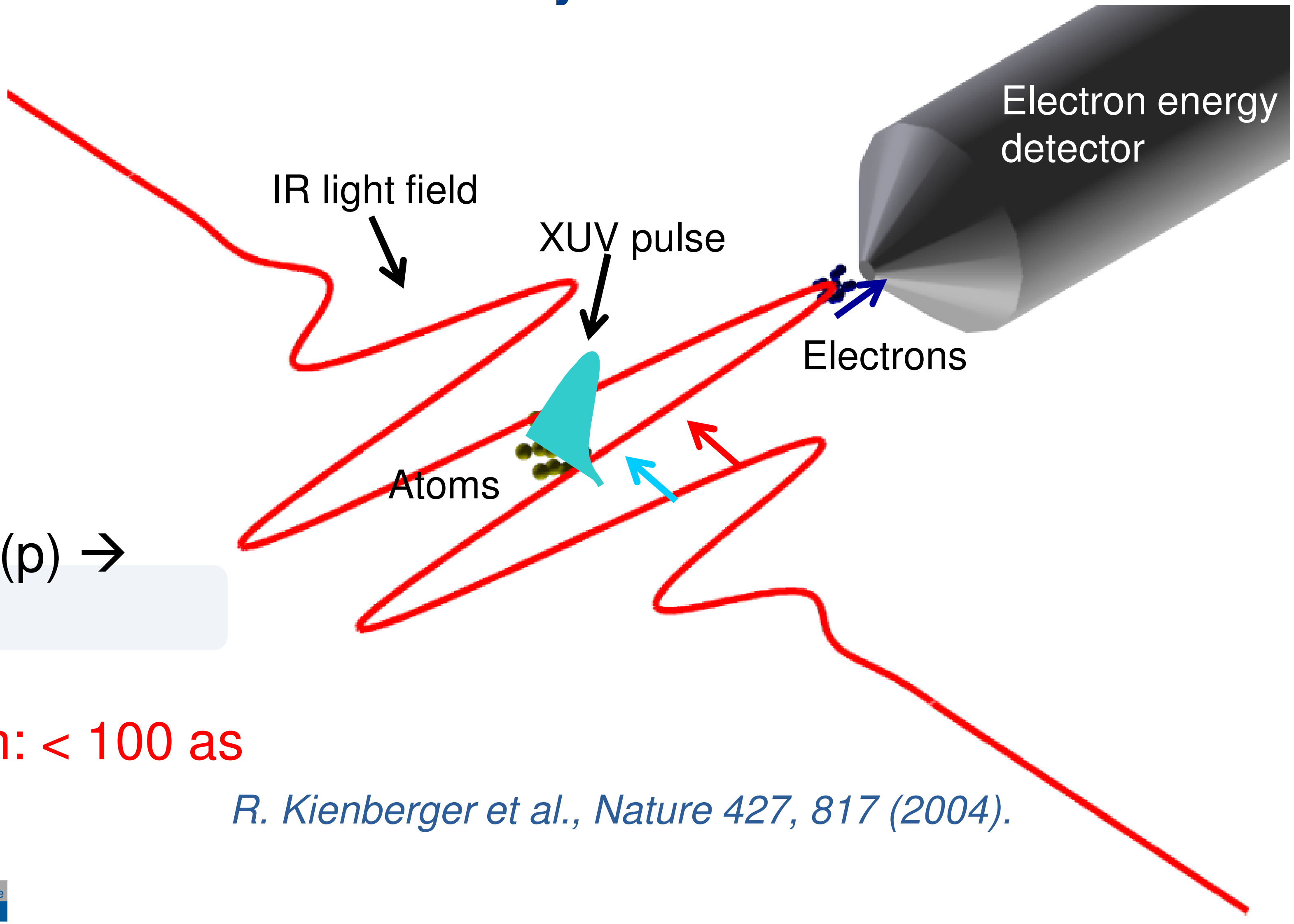
X-ray pulse diagnostic

THz-field driven X-ray streak camera



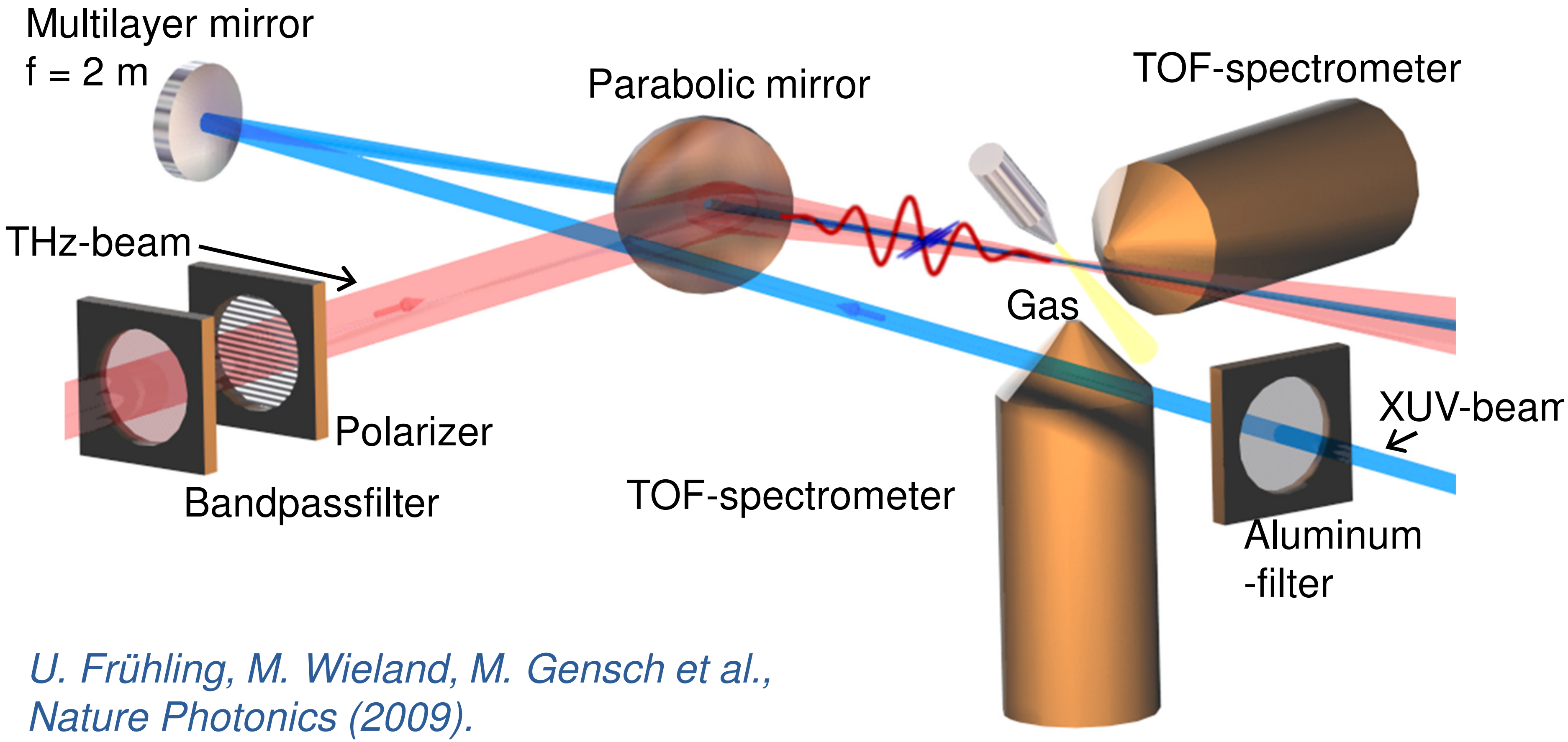
$I_{XUV}(t) \rightarrow I_e(p) \rightarrow I_e(E)$

resolution: < 100 as

R. Kienberger et al., Nature 427, 817 (2004).

X-ray pulse diagnostic

THz-field driven X-ray streak camera

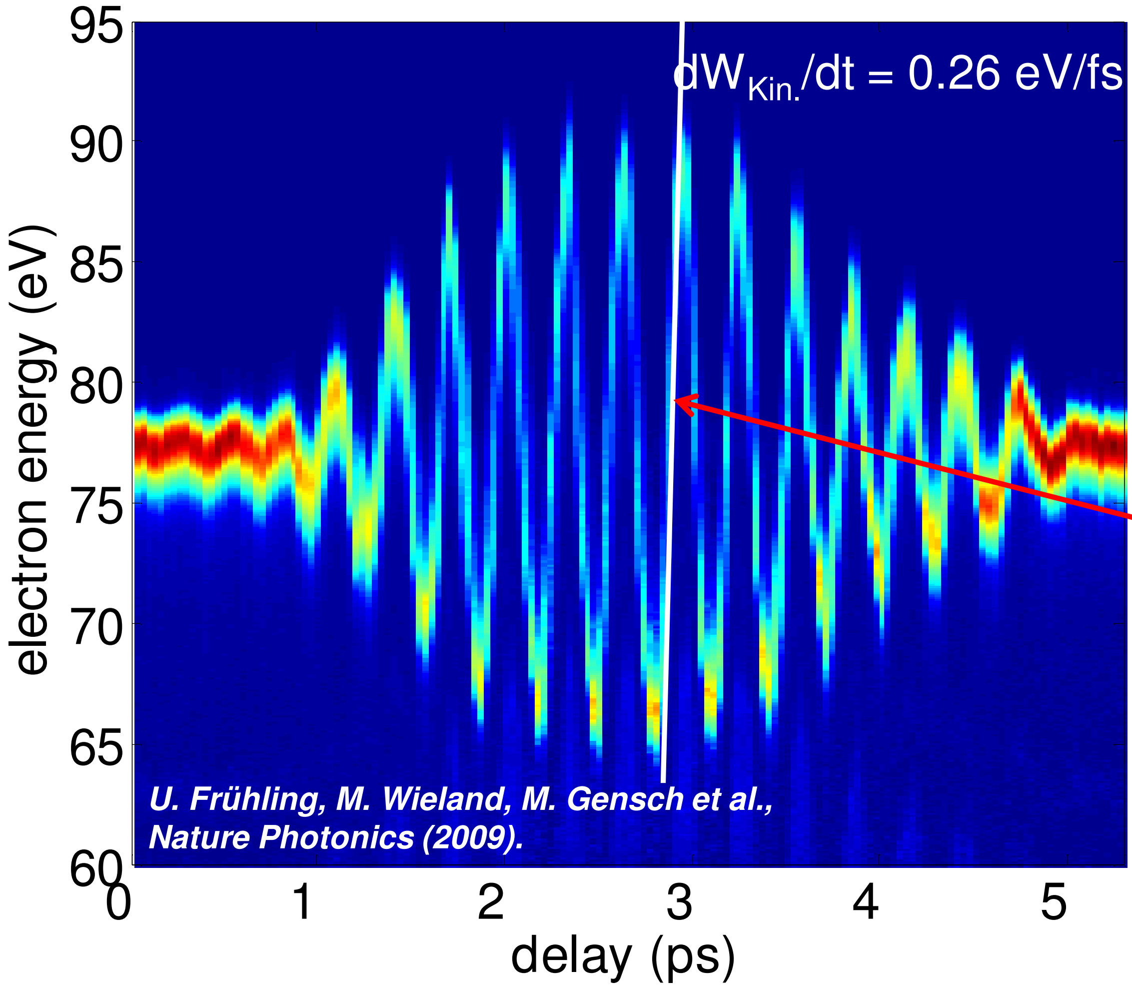


U. Frühling, M. Wieland, M. Gensch et al., Nature Photonics (2009).

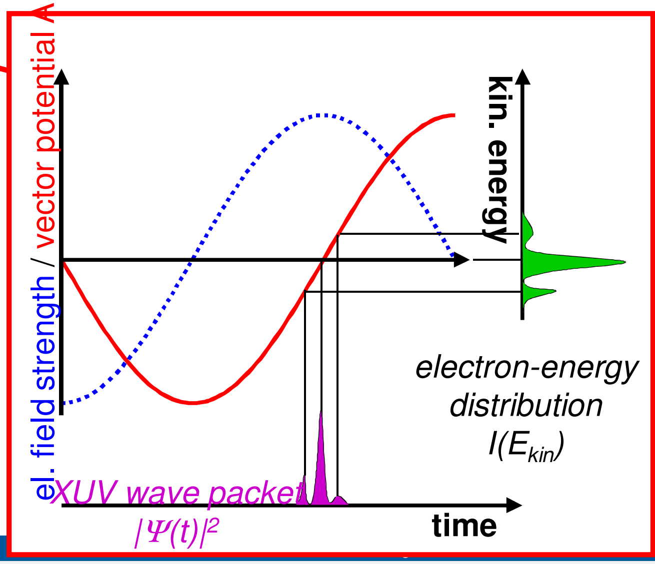
X-ray pulse diagnostic

THz-field driven X-ray streak camera

FLASH: 13.5 nm
Gas: krypton (4p)



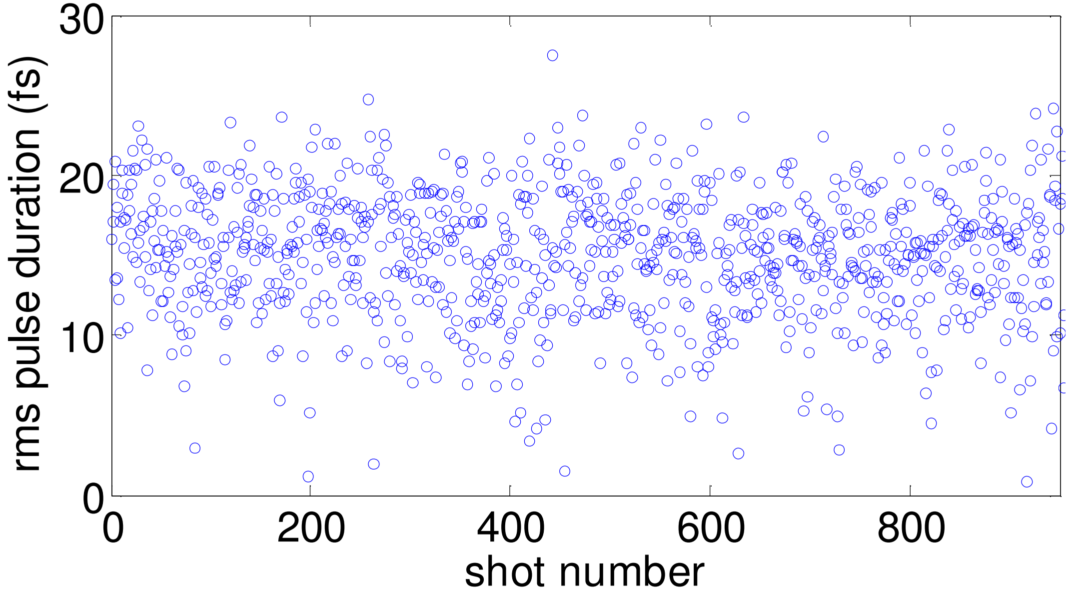
λ = 91.7 µm
FWHM = 2.27 ps
$E_{max} \approx 50\times10^6$ V/m
U_p = 0.26 eV

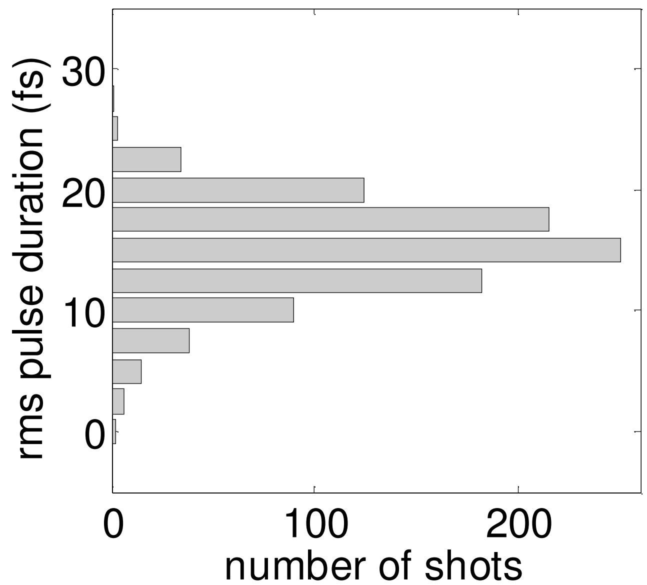


X-ray pulse diagnostic

THz-field driven X-ray streak camera

Ansatz: Gaussian pulse with linear chirp c: $E_{XUV}(t) = e^{-at^2} e^{i(\omega_0 t + ct^2)}$



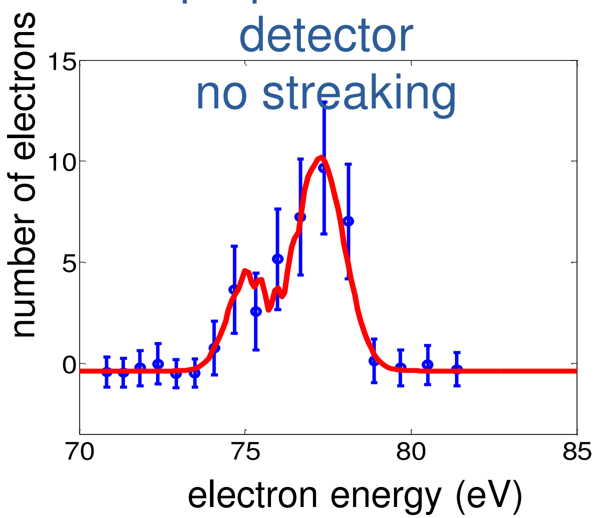


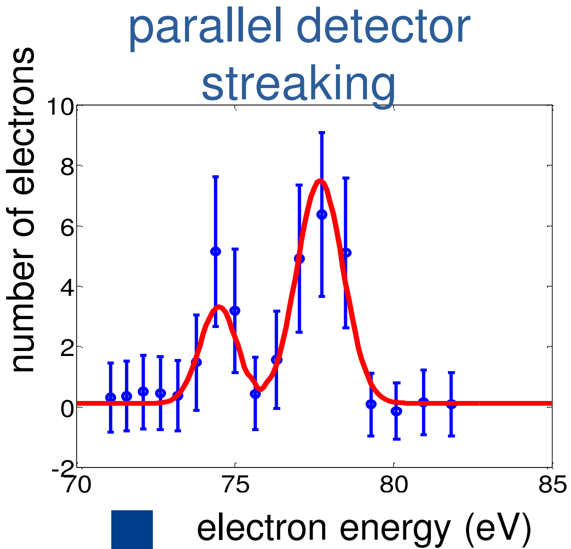
U. Frühling, M. Wieland, M. Gensch et al., Nature Photonics (2009).

Average pulse duration : 15 fs rms (35 fs FWHM)
Standard deviation: 4 fs

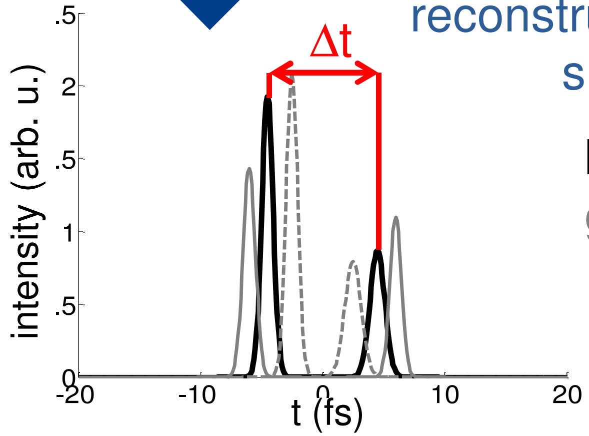
X-ray pulse diagnostic

THz-field driven X-ray streak camera





U. Frühling, M. Wieland,
M. Gensch et al.,
Nature Photonics (2009).



reconstructed pulse-shape

black: best fit
grey: 90% confidence
$\Delta t = (9 \pm 4)$ fs

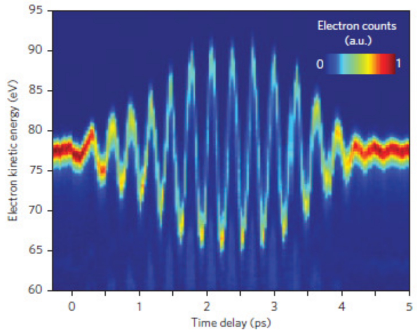
FLASH - THz: typical applications

- **X-ray pulse diagnostic**
- ***„Photoelectron streaking“***
- ***THz control***

Photoionization processes

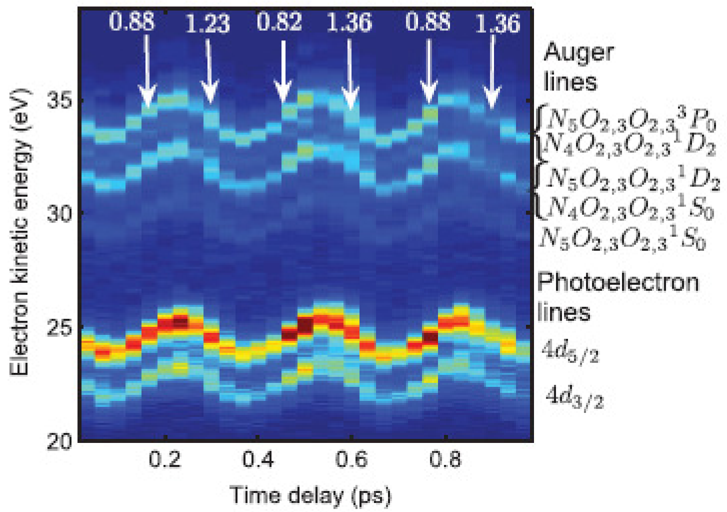
Evidence for Chirped Auger-Electron Emission

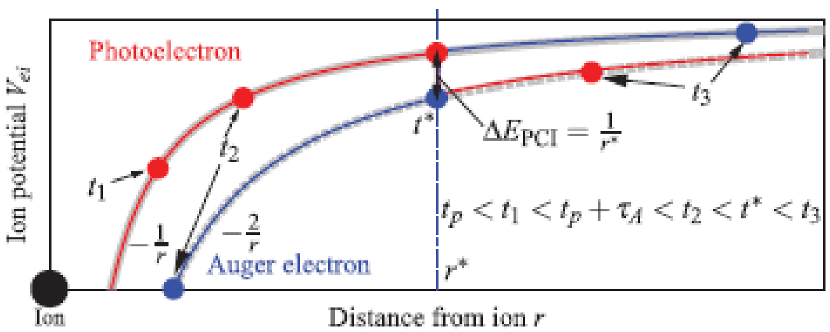
B. Schütte,[1,3] S. Bauch,[2] U. Frühling,[1] M. Wieland,[1] M. Gensch,[4,5] E. Plönjes,[4] T. Gaumnitz,[1] A. Azima,[1]
M. Bonitz,[2] and M. Drescher[1,*]
[1]*Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*
[2]*Institut für Theoretische Physik und Astrophysik, Christian-Albrechts-Universität, Leibnizstraße 15, 24098 Kiel, Germany*
[3]*Max-Born-Institut, Max-Born-Straße 2A, 12489 Berlin, Germany*
[4]*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22603 Hamburg, Germany*
[5]*Helmholtz-Zentrum Dresden Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany*
(Received 9 December 2011)



U. Frühling et al., Nature Photonics (2009).

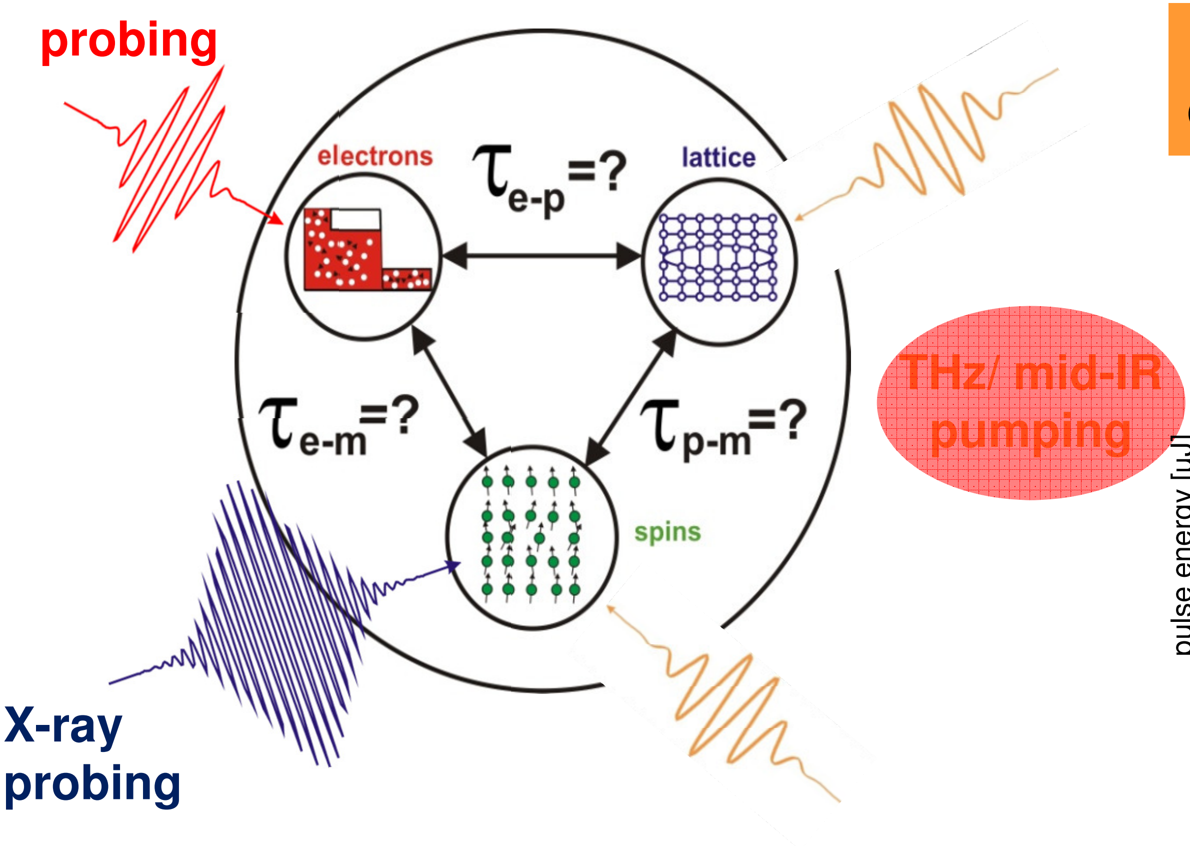
Auger electron bunch is chirped!!?



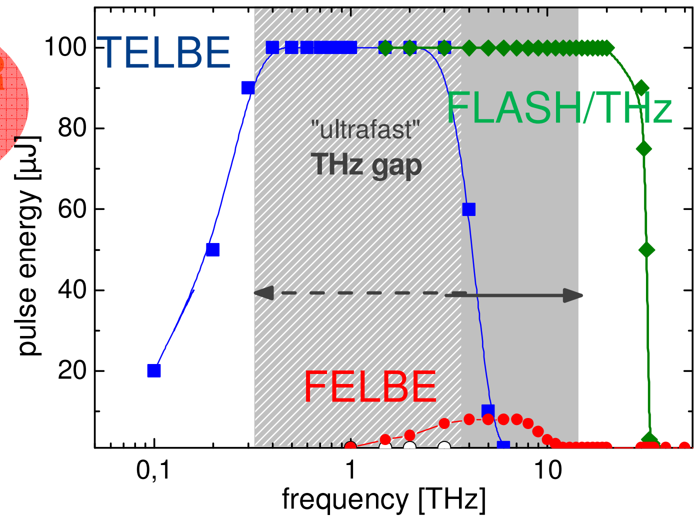


Correlation in sequential photoemission? -> shifts in 11/2012

THz control of Magnetization



Direct, resonant excitation of phonons and magnons



Probe magnetization and electron dynamics in VIS and soft X-rays

collaboration: I. Radu (HZB), T. Kampfrath (FHI)

DRESDEN concept HZDR

THz control of Magnetization

too be published

THz control of Magnetization

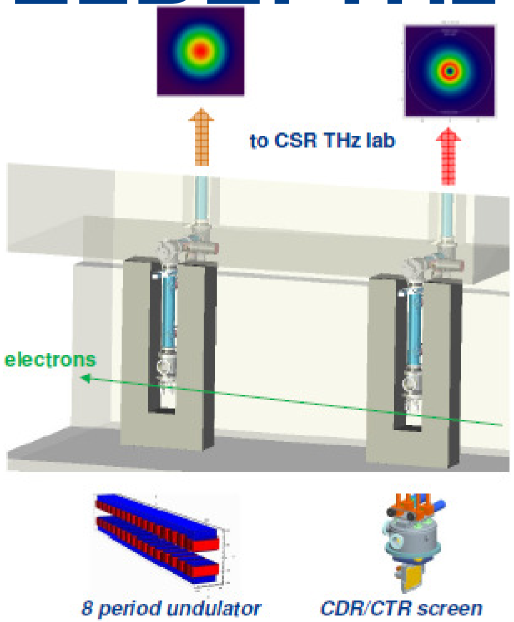
too be published

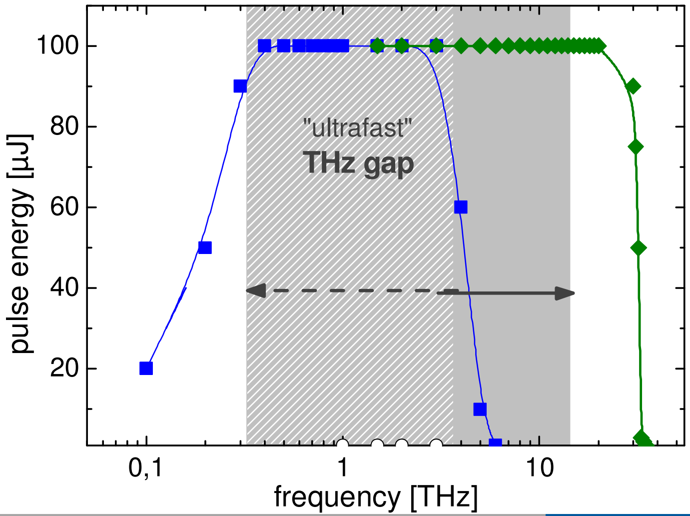
THz control of Magnetization

too be published

- **THz sources**
- **prototype facility @ FLASH**
- **THz (test) facility @ ELBE**

TELBE: THz (test) facility at ELBE

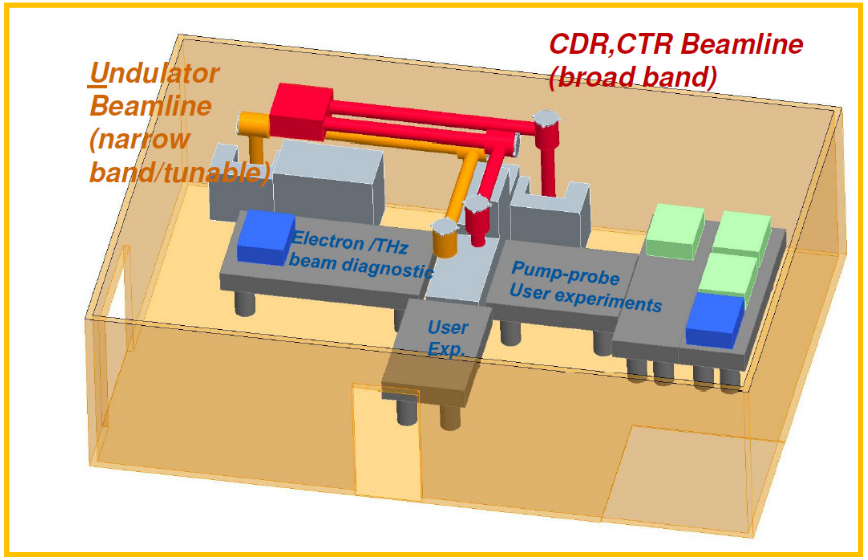


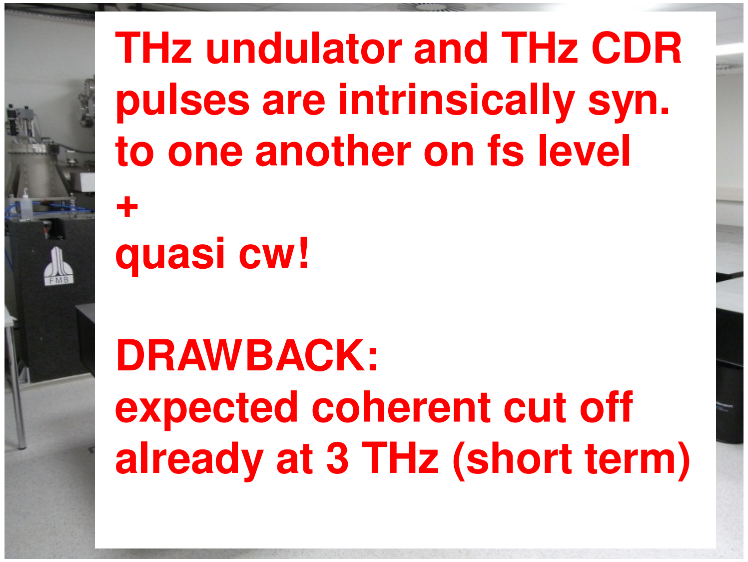


TELBE / HZDR

- Spectral range: 3 – 0.1 THz
- Spectral bandwidth: 12% (undulator), 100% (CTR)
- Reprate: 100 – 500 kHz/13 MHz
- Pulse energy: 100 (+X) µJ / 1 µJ
- Average power: 10 W
- polarization linear (undulator), radial (CTR)
- Pulse duration: $8^*\tau_{THz}$(undulator), < 1 ps (edge)

TELBE: THz (test) facility at ELBE



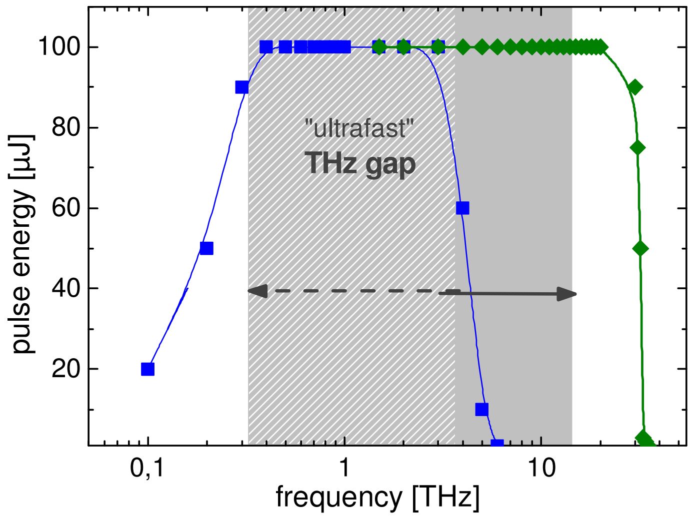


THz undulator and THz CDR pulses are intrinsically syn. to one another on fs level

+

quasi cw!

DRAWBACK:
expected coherent cut off already at 3 THz (short term)



TELBE / HZDR

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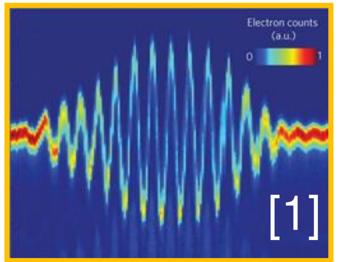
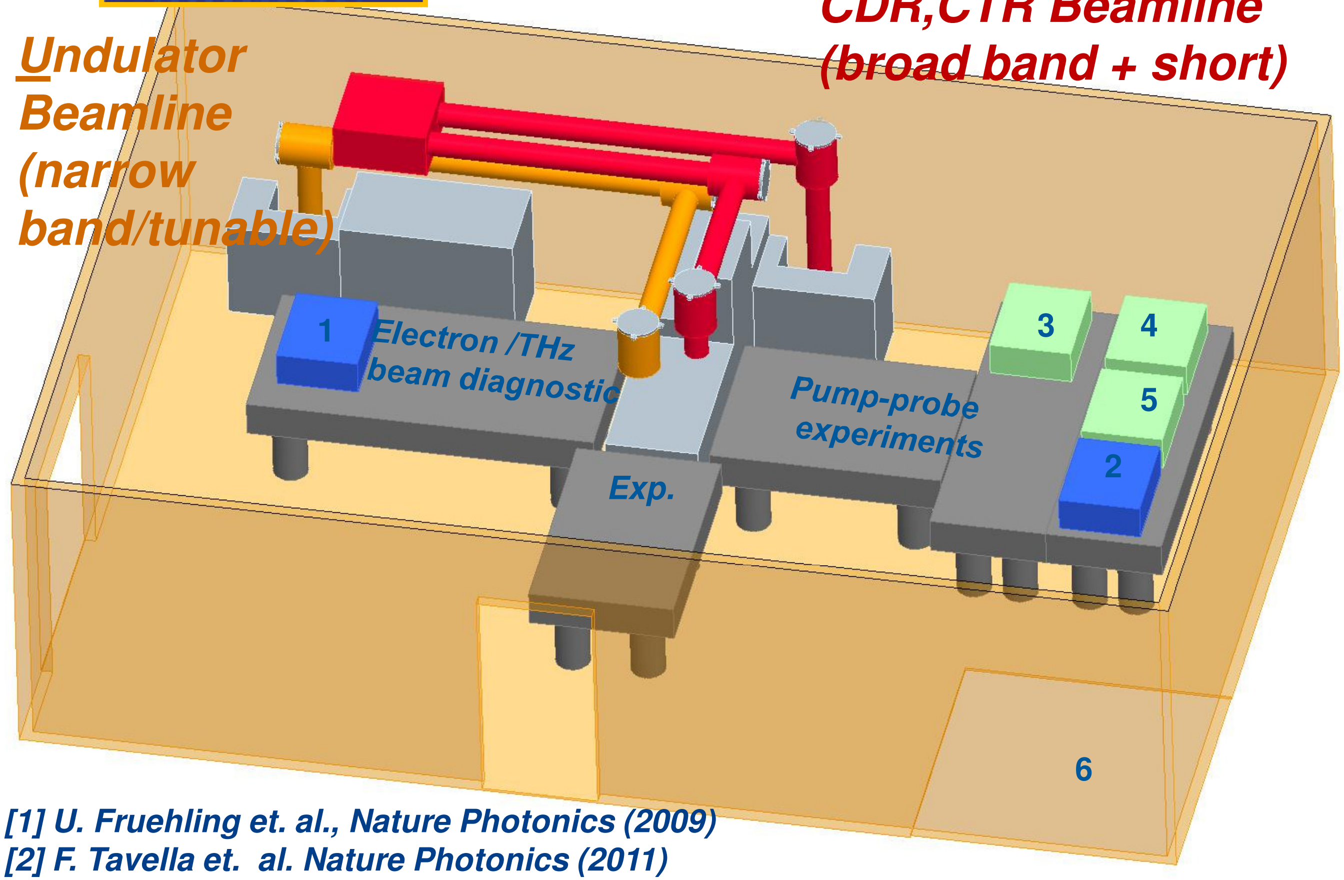
- •Reprate: 100– 500 kHz/13 MHz
- •Pulse energy: 100 (+X) µJ/ 1 µJ
- •Average power: 10 W
- •polarization linear (undulator), radial (CTR)
- •Pulse duration: 8*τ_{THz}(undulator), < 1 ps (edge)

TELBE: lab for pilot experiments



to be published



Lab infrastructure

2 x FTIR spectrometers (1&2)
- 0.03 - 119 THz
- step scan & rapid scan

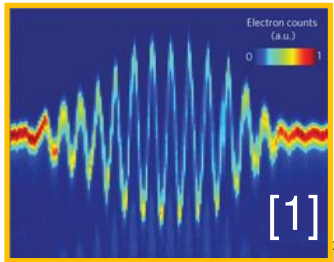
1 x laser-amplifier (3) - high peak pow.
- mJ pulse energy
- 1 kHz repetition rate
- 130 fs pulse duraction

1 x laser-amplifier (4,5) – high rep. rate
- µJ pulse energy
- up to 250 kHz repetition rate
- 100 fs pulse duration

1 x 18 T magnet (6)

[1] U. Fruehling et. al., Nature Photonics (2009)
[2] F. Tavella et. al. Nature Photonics (2011)

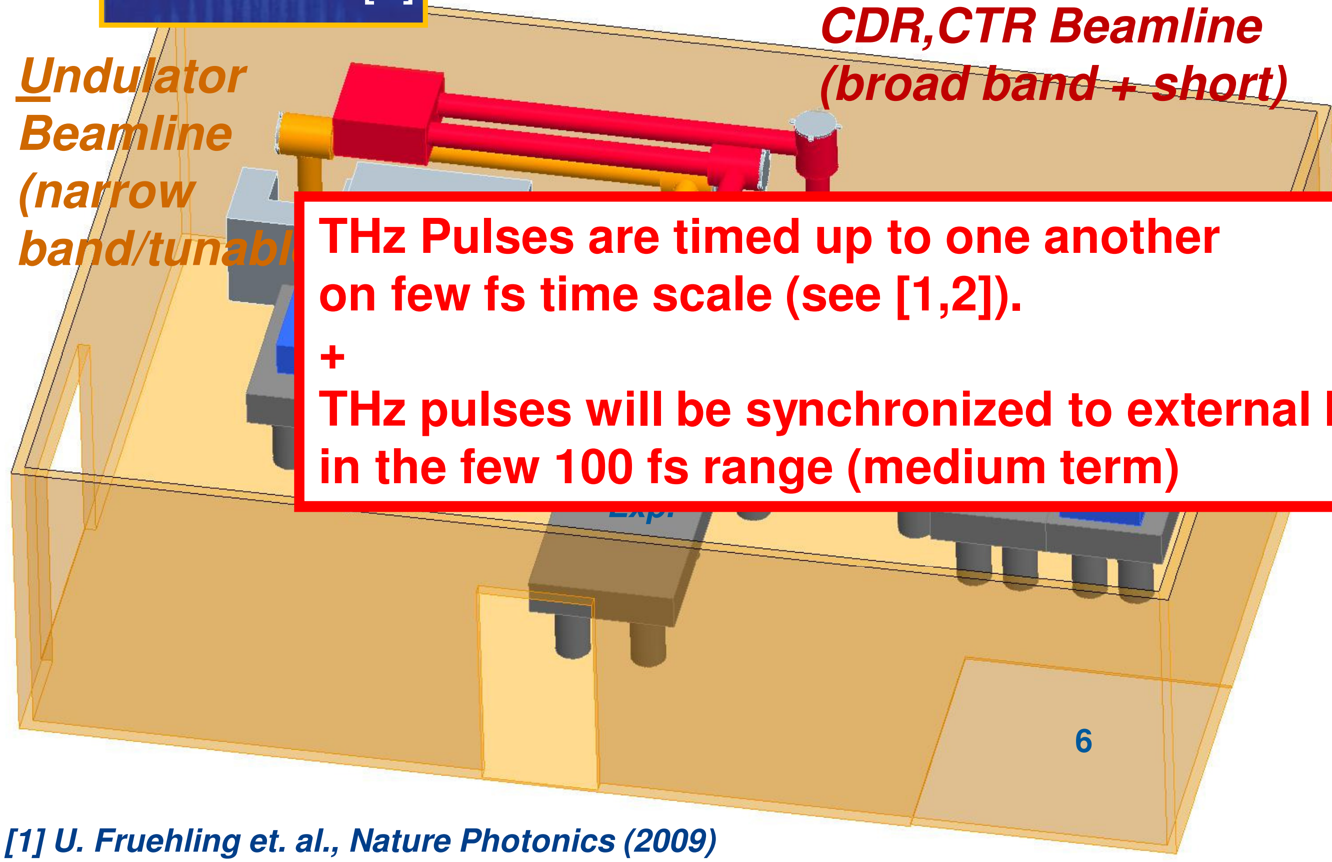
TELBE: lab for pilot experiments



to be published

CDR,CTR Beamline (broad band + short)

Undulator Beamline (narrow band/tunabl



THz Pulses are timed up to one another on few fs time scale (see [1,2]).

+

THz pulses will be synchronized to external lasers in the few 100 fs range (medium term)

infrastructure

spectrometers (1&2)
- 119 THz
scan & rapid scan
amplifier (3) - high peak pow.
ulse energy
z repetition rate
s pulse duraction
amplifier (4,5) – high rep. rate
- µJ pulse energy
- up to 250 kHz repetition rate
- 100 fs pulse duration
1 x 18 T magnet (6)

[1] U. Fruehling et. al., Nature Photonics (2009)
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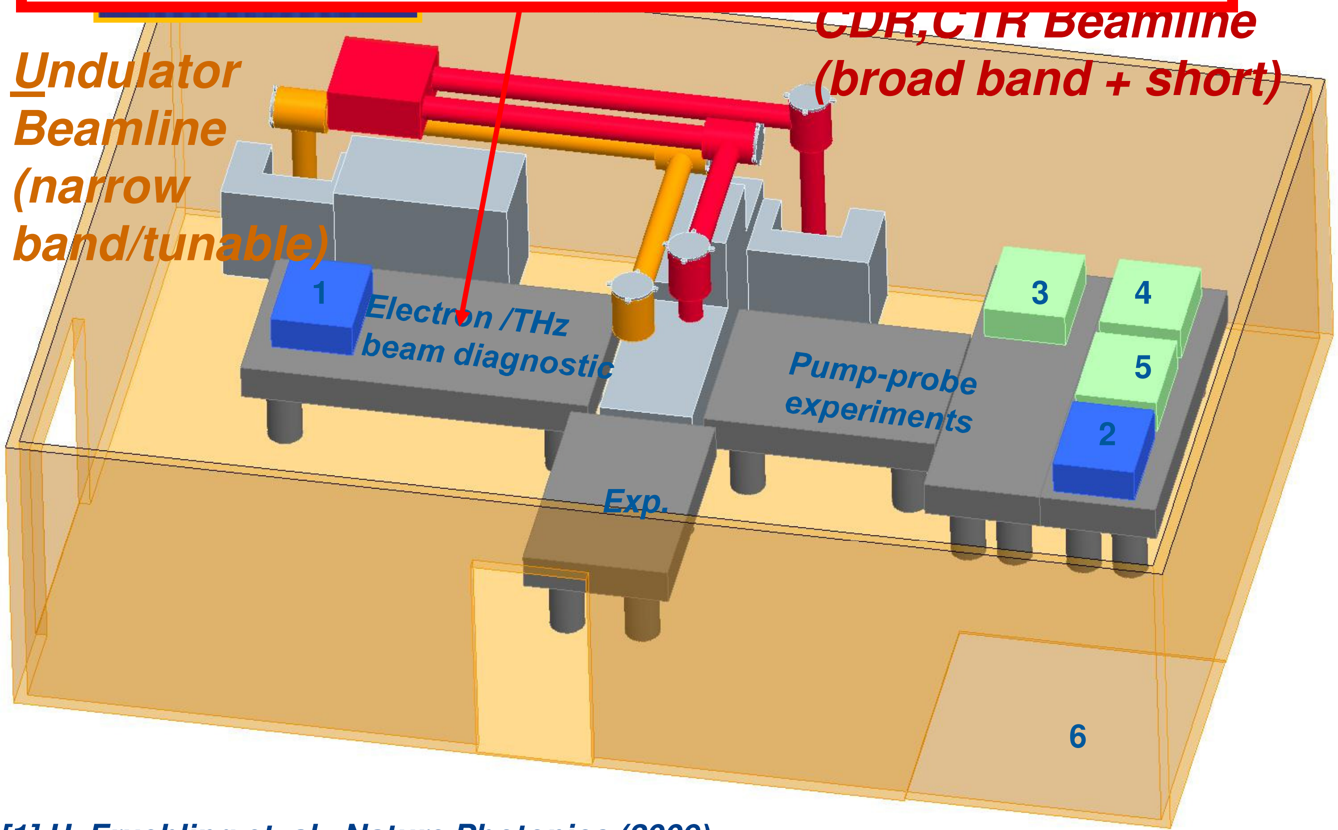
TELBE: lab for pilot experiments

Electron bunch and THz Photondiagnostis:
- FT-IR, Diffraction & Martin Puplett spectrometer
- E/O, spectral and temporal decoding techniques
- online power and pulse energy measurements
- arrivaltime clocking



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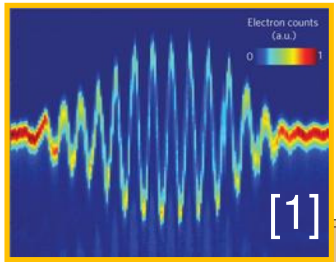
1 x 18 T magnet (6)

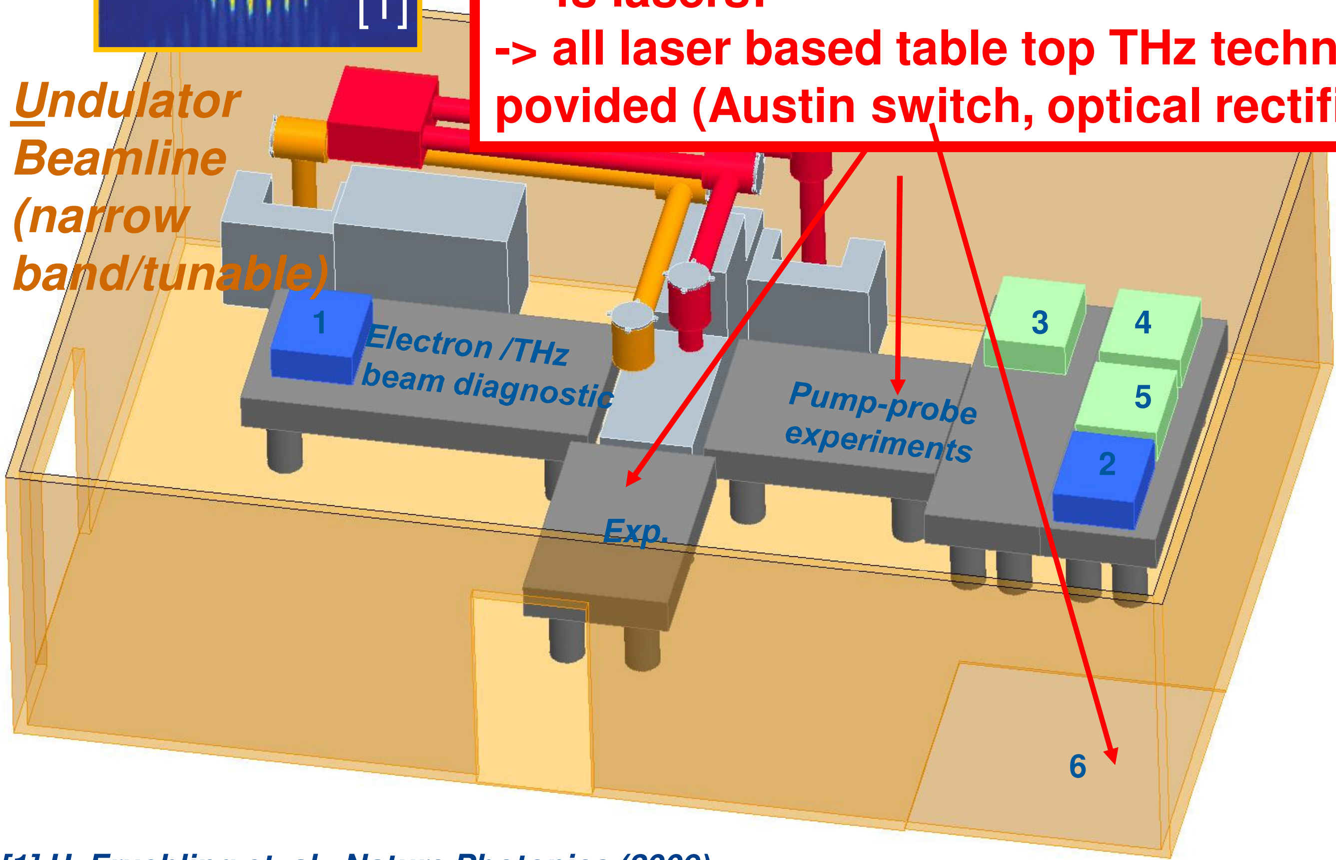
[1] U. Fruehling et. al., Nature Photonics (2009)
[2] F. Tavella et. al. Nature Photonics (2011)

TELBE

Experiments:
- **non magnetic table for 10 T magnet**
- **FTIR (Bruker 80V)**
- **20 T Magnet**
- **diverse Kryostates**
- **fs lasers:**

-> all laser based table top THz techniques shall be povided (Austin switch, optical rectification, DFG, OPA…)





Lab infrastructure

2 x FTIR spectrometers (1&2)
- *0.03 - 119 THz*
- *step scan & rapid scan*

1 x laser-amplifier (3) - high peak pow.
- *mJ pulse energy*
- *1 kHz repetition rate*
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1 x laser-amplifier (4,5) – high rep. rate
- *µJ pulse energy*
- *up to 250 kHz repetition rate*
- *100 fs pulse duration*

1 x 18 T magnet (6)

[1] U. Fruehling et. al., Nature Photonics (2009)
[2] F. Tavella et. al. Nature Photonics (2011)

TELBE: Pump probe – relev. parameters

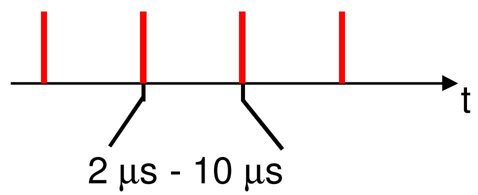
THz:
undulator/CTR
λ = 100 – 3000 μm
Δλ/λ = 12% / 100%
polarization: linear/radial
pulse energy: 100 + X μJ (high field mode)
1 μJ (high rep rate mode)
pulse duration: $8^*\tau_{THz}$, < 1 ps

μJ laser:
λ = 780 nm / 200 – 750 nm, 900 – 2600 nm
pulse energy: up to 10 μJ
pulse duration: 100 fs
rep. rate: 1 – 350 kHz

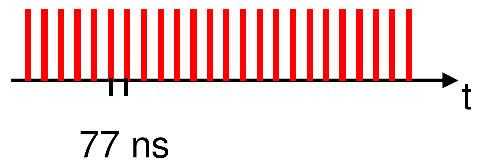
mJ laser (from 2013):
λ = 780 nm / 1000 – 20000 nm
pulse energy: up to 1 mJ
pulse duration: 100 fs
rep.rate: 1 kHz

TELBE time structure:

high field mode:



high rep. rate mode:



TELBE: Pump probe – relev. parameters

THz:

undulator/CTR

λ = 100 – 3000 µm

$\Delta\lambda/\lambda$ = 12% / 100%

polarization: linear/radial

pulse energy: 100 + X µJ (high field mode)

1 µJ (high rep rate mode)

pulse duration: 8*τ … < 1 ps

runs in cw mode and at adjustable kHz rep. rate
-> ideally suited for Lock-In technqiues!
-> ideally suited for THz control experiments!

µJ laser:

λ = 780 nm

pulse energy: up to 10 µJ

pulse duration: 100 fs

rep. rate: 1 – 350 kHz

mJ laser (from 2013):

λ = 780 nm / 1000 – 20000 nm

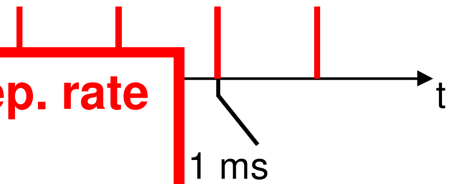
pulse energy: up to 1 mJ

pulse duration: 100 fs

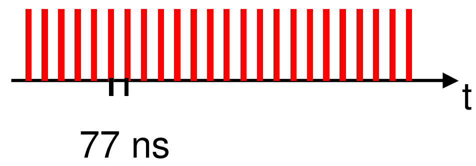
rep.rate: 1 kHz

TELBE time structure:

high field mode:



high rep. rate mode:



1. Summary: FLASH-THz/TELBE applications

- THz based electron bunch diagnostic
- THz control
- nonlinear dynamics

table top THz -> essential prep. for unique high field accel.bas. high rep rate THz exp. or THz pump X-ray probe exp.

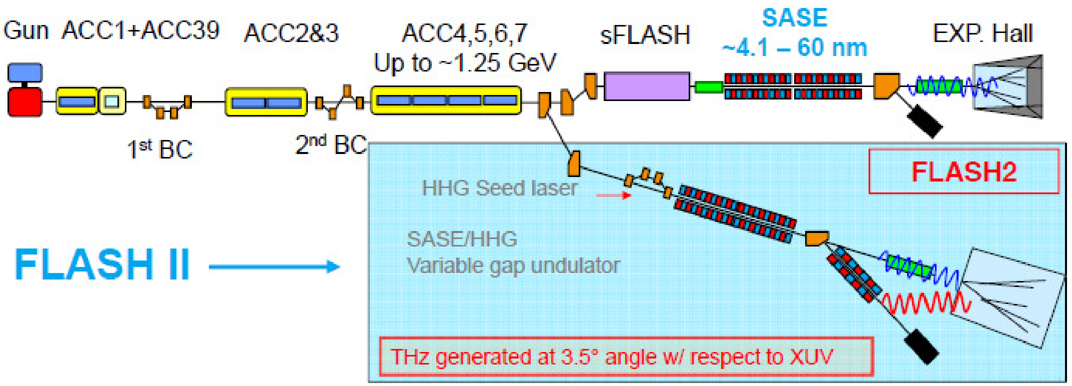
2. Summary: Sources

- all-accelerator based pump probe experiments are extremely convenient in particular for a user facility

…. other details tomorrow

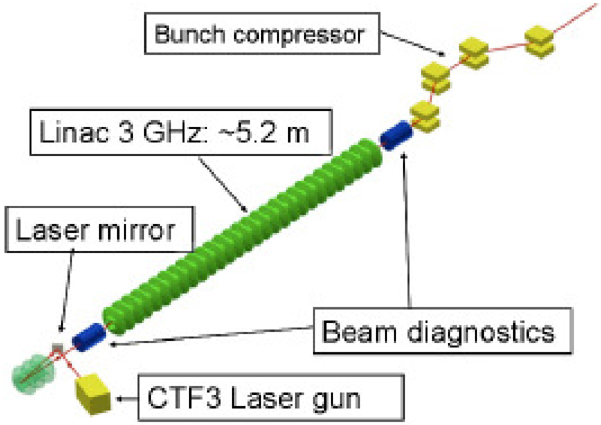
Elsewhere planned…. in Germany

THz @ FLASH II



user facility
nc (Charges)
single cycle THz (CTR): ~ few 100 µJ
narrow bandwth (undulator~ 10%): ~ few 100 µJ
rep rate: up to few KHz (burstmode)

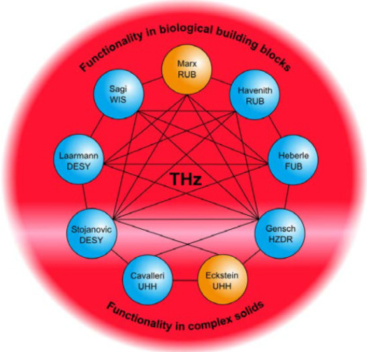
project @ KIT / Karlsruhe: FLUTE



Test facility
nc (Charges)
single cycle THz: ~ mJ -> (expected)
rep rate: few 10 Hz

DRESDEN concept HZDR

Acknowledgement



N. Stojanovic (DESY), F. Tavella(HIJ), G.A. Geloni (XFEL), B. Faatz, T. Laarmann, J. Schneider, A. Al-Shemmary, J. Feldhaus, S. Bajt, H. Wabnitz, L. Bittner, M. Röhling, U. Hahn, M. Hesse, B. Schmidt, Stephan Wesch, H. Schlarb, B. Steffen, E. Saldin, M.V. Yurkov, E. Schneidmiller (DESY), U. Frühling, M. Wieland, M. Krikunova, M. Drescher, O. Grimm, J. Roßberg (UHH), H. Ehrke, N. Dean (MPSD-CFEL), H.W. Hübers, A. Semenov (DLR), W. Seidel, S. Winnerl, C. Bauer, V. Mamidala (HZDR), R. Tobey (U Groningen)

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Bundesministerium für Bildung und Forschung

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HELMHOLTZ GEMEINSCHAFT