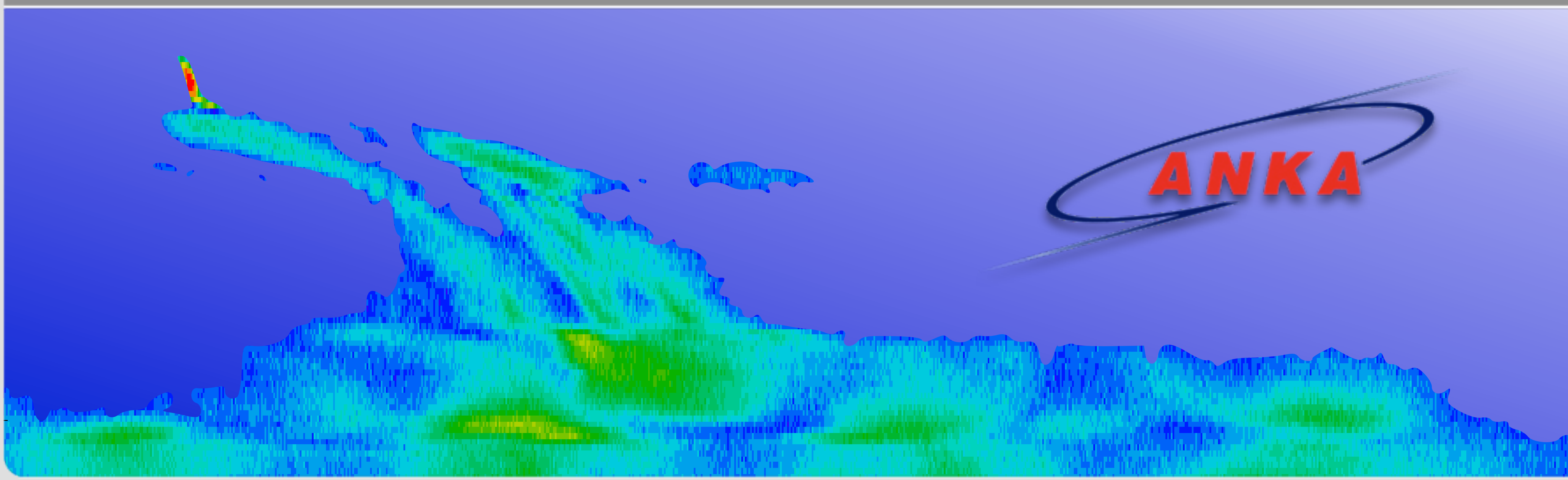
Short-Pulse Operation of Storage Ring Light Sources

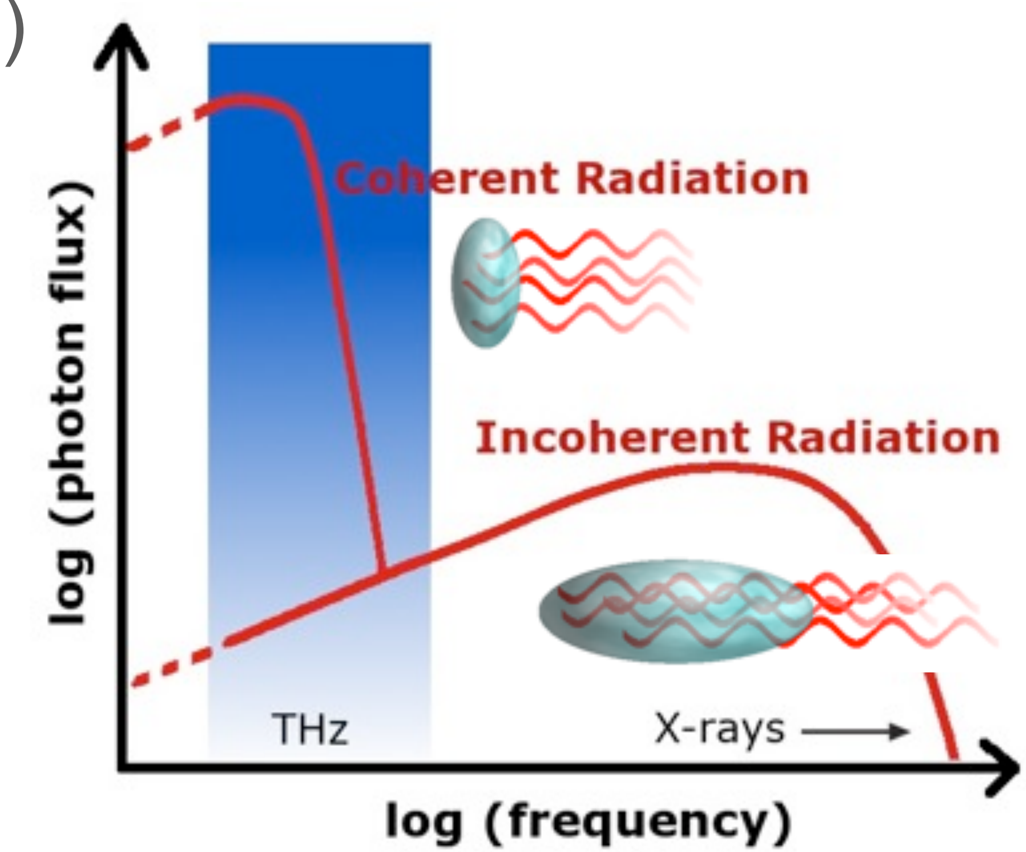
A.-S. Müller
ANKA, Institute for Photon Science and Synchrotron Radiation and Laboratory for Applications of Synchrotron Radiation

ANKA Synchrotron Light Source at **KIT**



Applications of short pulses

- Short electron pulses emit incoherent X-rays and coherent THz radiation
- Applications for both **X-rays** and (coherent) **THz radiation**



Examples for ultrafast science

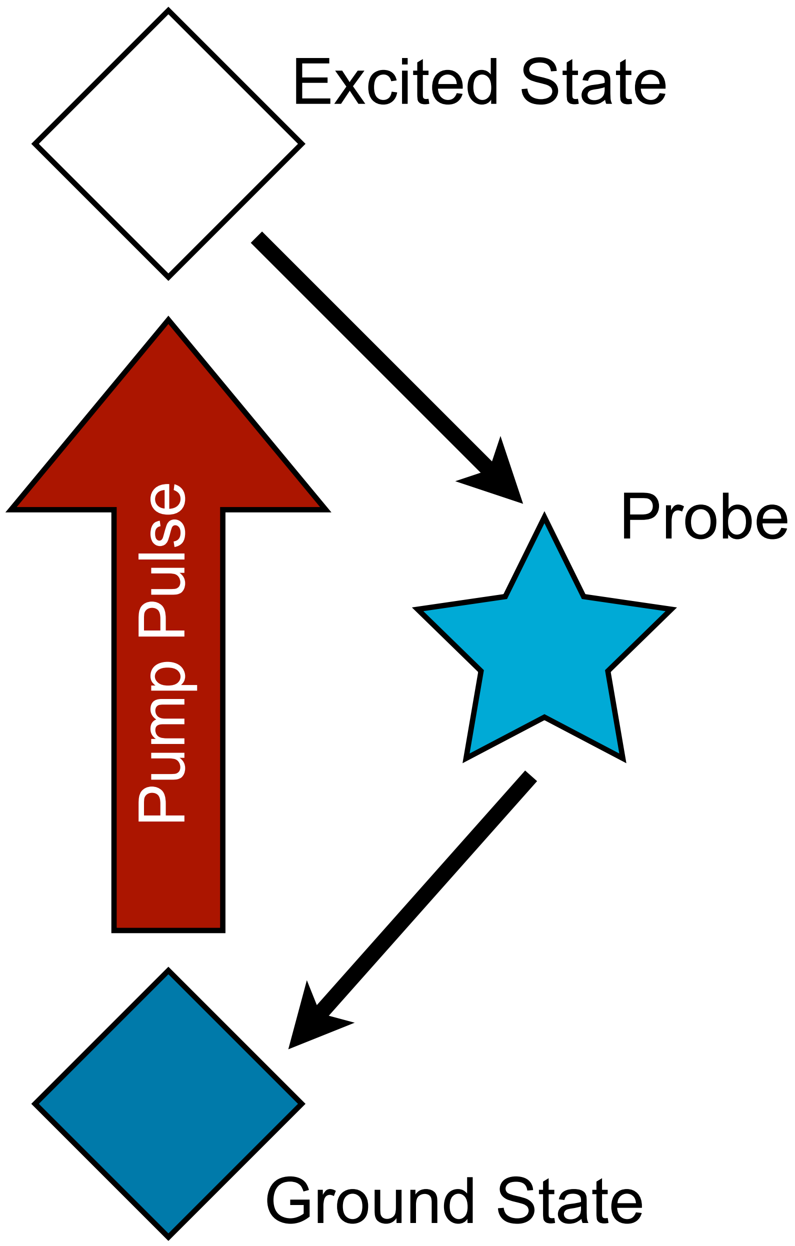
- Time domain spectroscopy
  - regaining phase information
- Pump-probe studies
  - intermediate states of chemical reaction
  - time resolved x-rays: watching nuclear motion in phonon excitation or chemical reactions (thermal e-phonon equilibration time typ. 1–10 ps)

Applications of short pulses

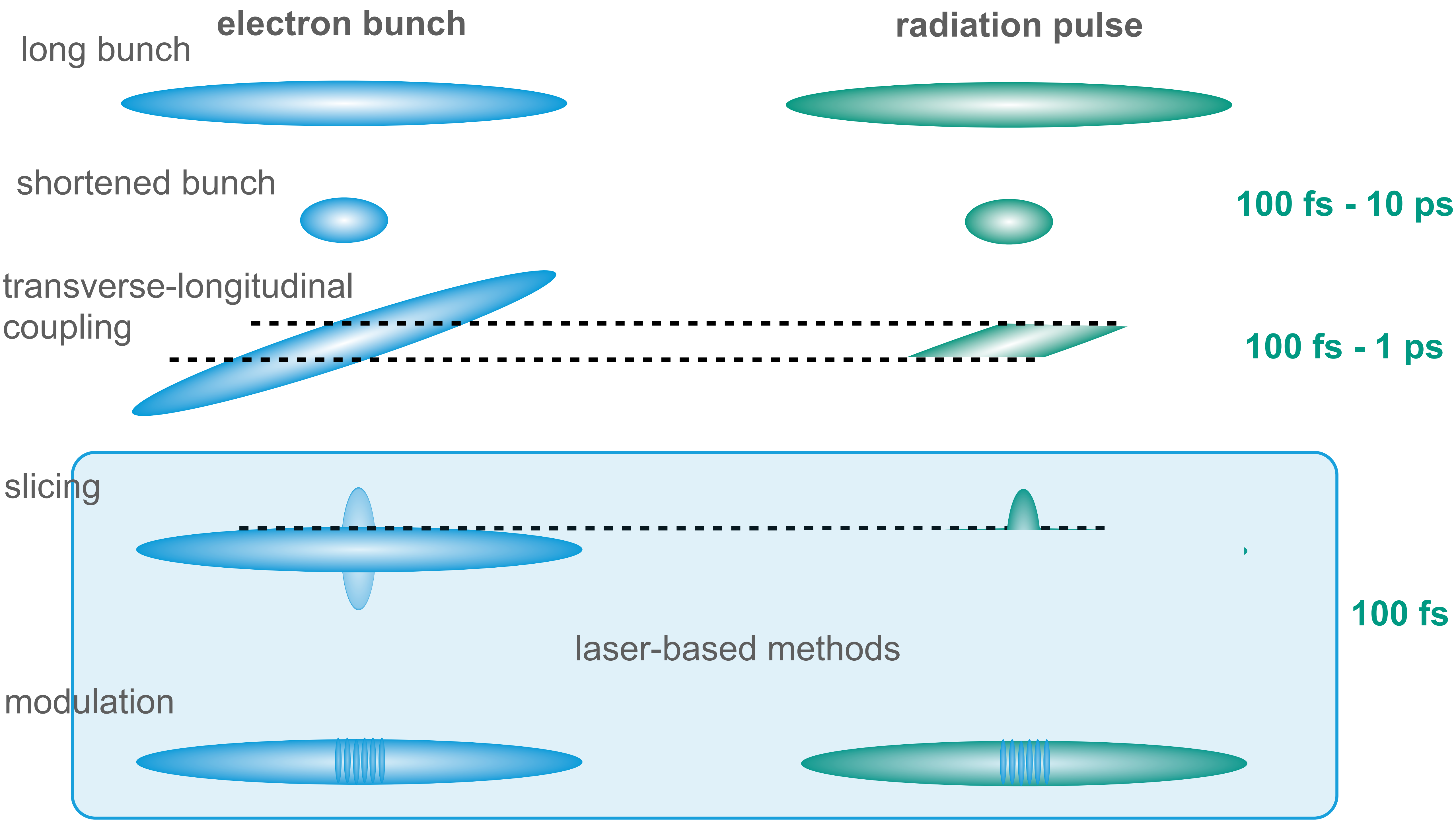
- Short electron pulses emit incoherent X-rays and coherent THz radiation
- Applications for both **X-rays** and (coherent) **THz radiation**

Examples for ultrafast science

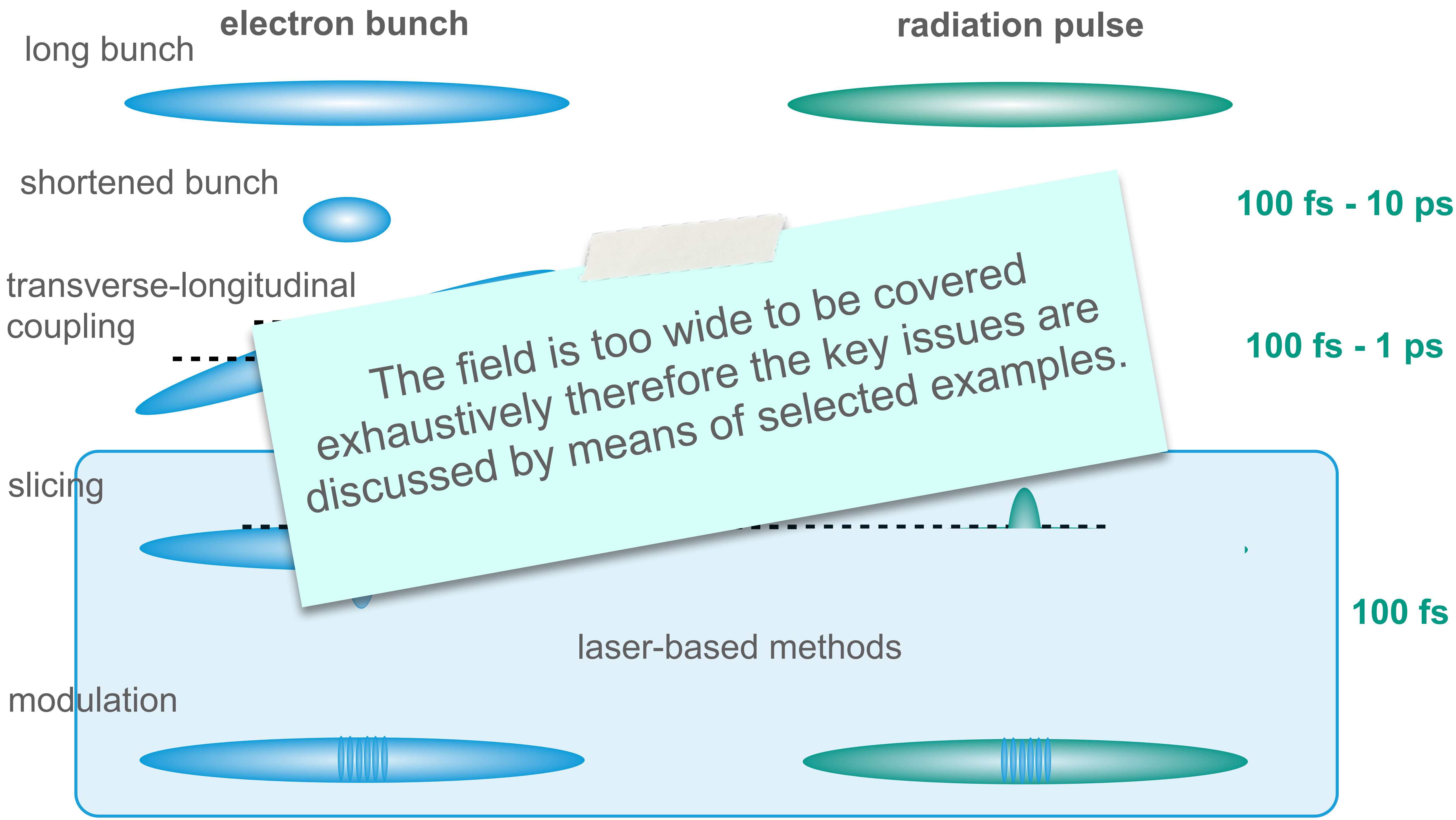
- Time domain spectroscopy
  - regaining phase information
- Pump-probe studies
  - intermediate states of chemical reaction
  - time resolved x-rays: watching nuclear motion in phonon excitation or chemical reactions (thermal e-phonon equilibration time typ. 1–10 ps)



Overview short pulse generation



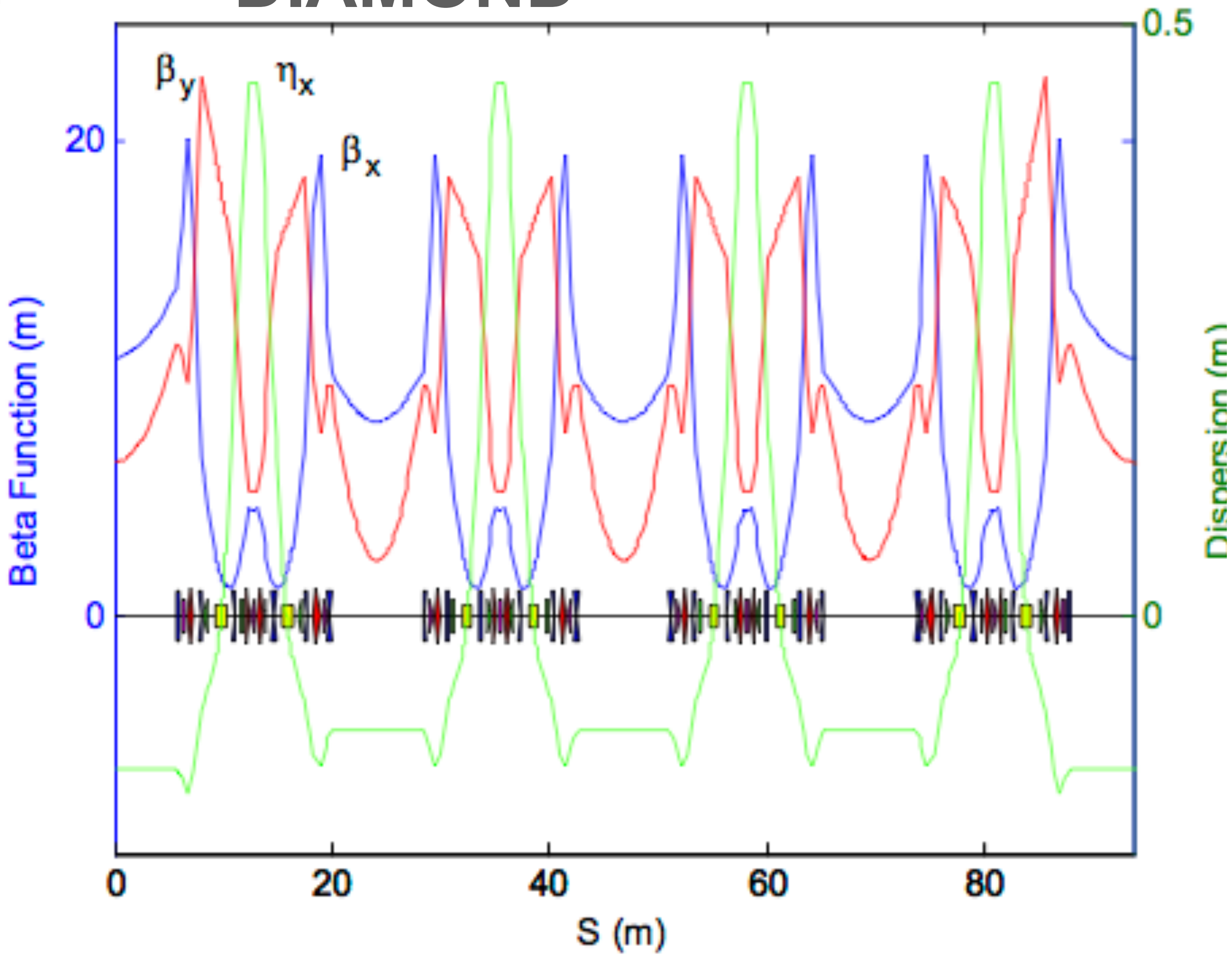
Overview short pulse generation



Low-α_c optics

- Definition of momentum compaction factor α_c $\Delta L/L = \alpha_c \, \Delta p/p_0$
- Manipulate D to reduce α_c $\alpha_c = \frac{1}{L}\oint ds \frac{D(s)}{\rho(s)}$

DIAMOND



I. Martin et al., IPAC2010, THPE037

- Momentum dependence:

$$\alpha_c = \alpha_0 + \alpha_1 \frac{\Delta p}{p_0} + \alpha_2 \left(\frac{\Delta p}{p_0}\right)^2 + \ldots$$

- good control of higher order terms α_i needed
- typ. bunch lengths down to 1 ps

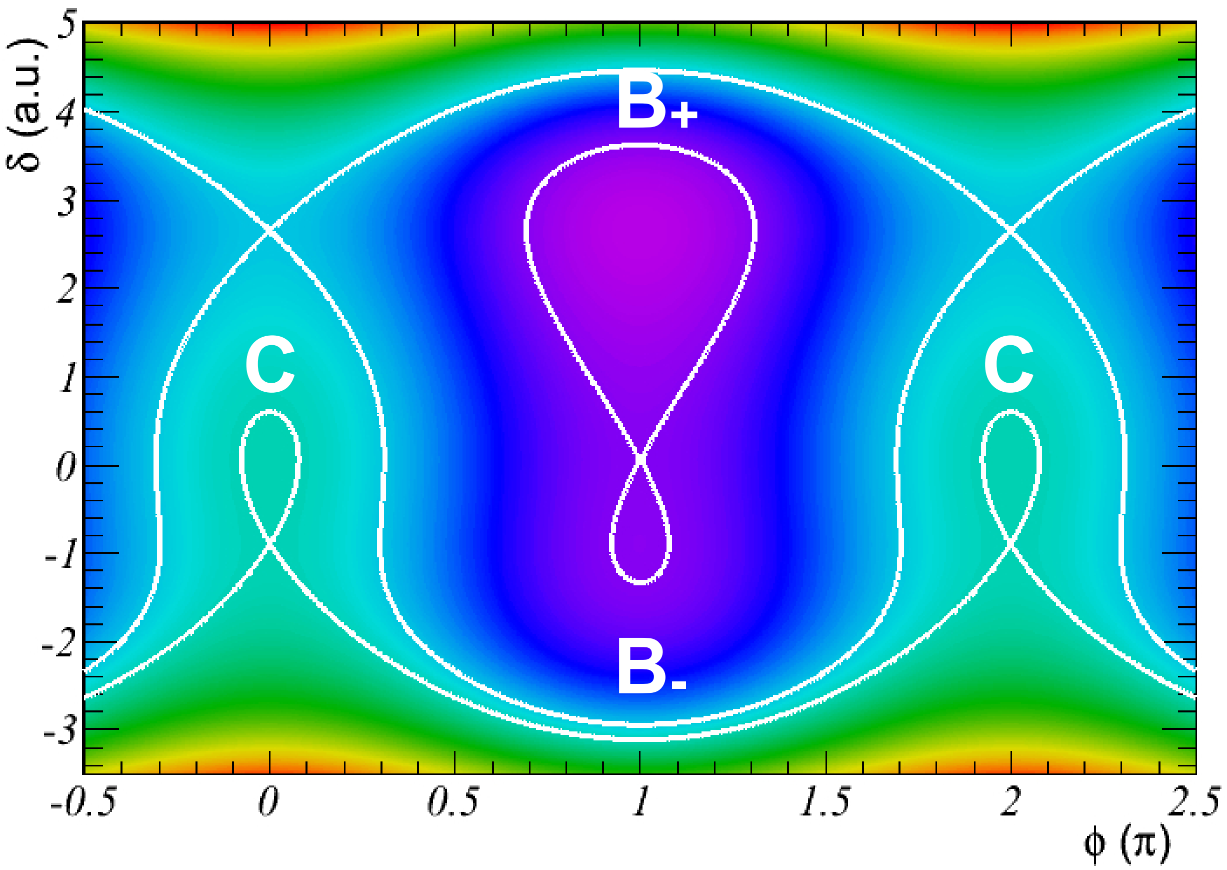
Storage rings with low-α_c operation

- Many storage ring light sources around the world can run with reduced momentum compaction factor, e.g.
  - ALS
  - ANKA
  - Australian Synchrotron
  - BESSYII
  - DIAMOND
  - Elettra
  - MLS
  - NewSUBARU
  - SLS
  - SOLEIL
  - SPEAR3

poster
I. Martin et al.,
MOPEA070

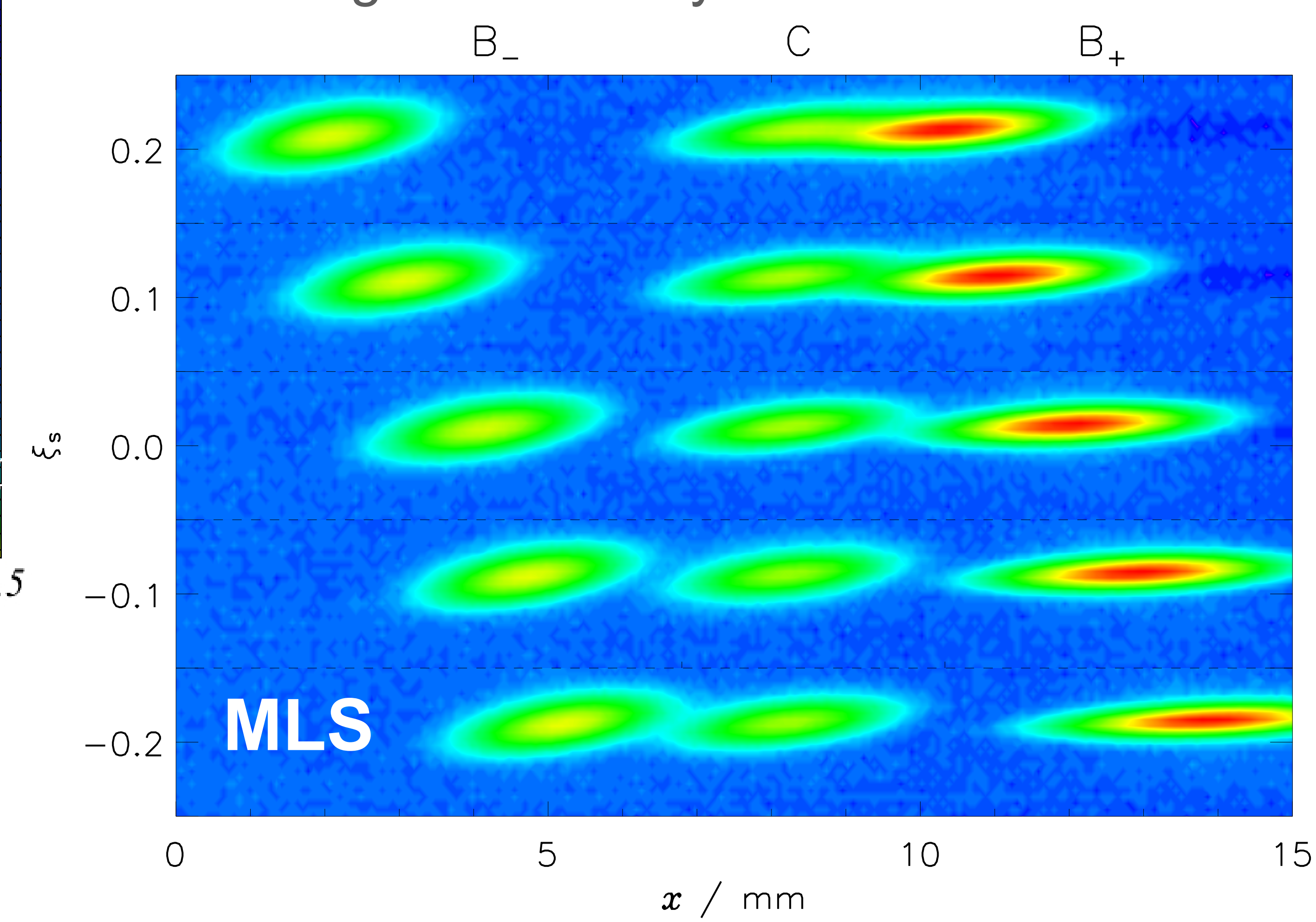
Simultaneous long & short bunches

- Simultaneous operation with buckets of different bunch lengths using higher order terms of alpha



nonlinear longitudinal phase space

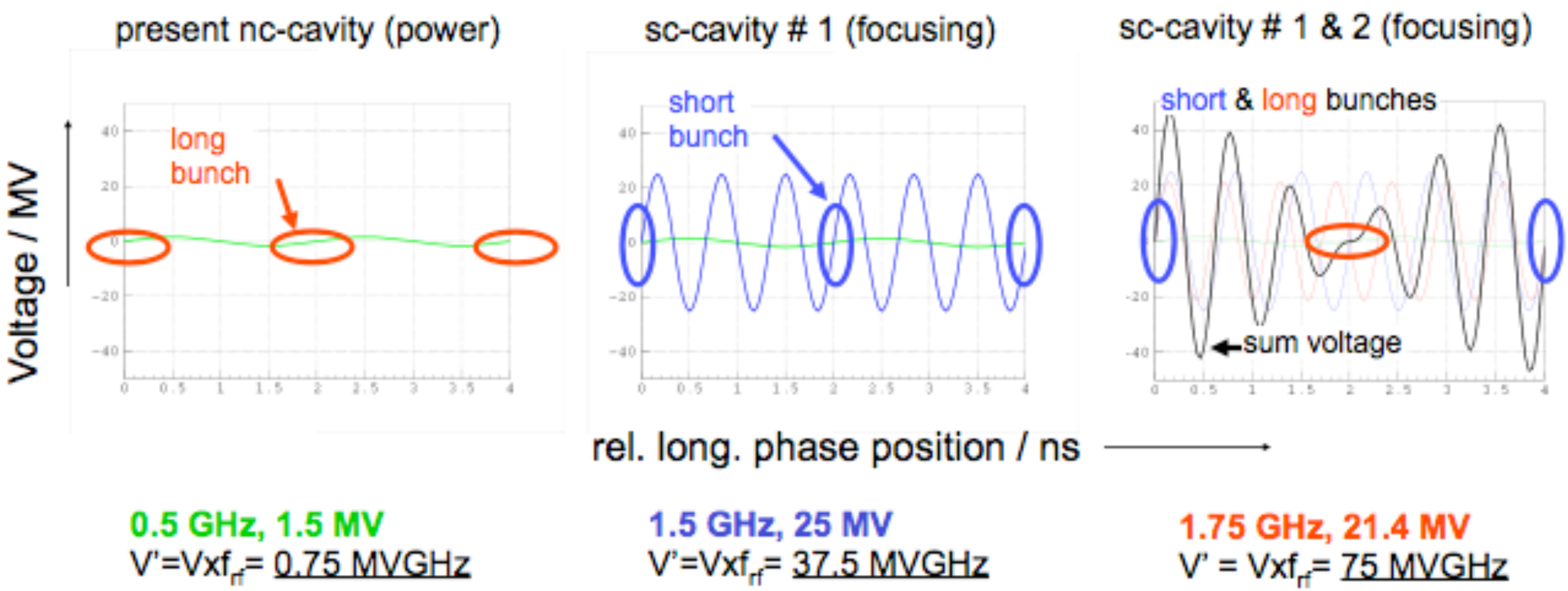
separation in dispersive region depending on long. chromaticity



M. Ries et al., IPAC2011, TUOAB02

Simultaneous long & short bunches

- Proposal for **BESSY II**



- flexible fill pattern, I<300 mA
- 15 ps & 1.5 ps pulses simultaneous at all beam ports
- low-α_c: bunches of ~300 fs

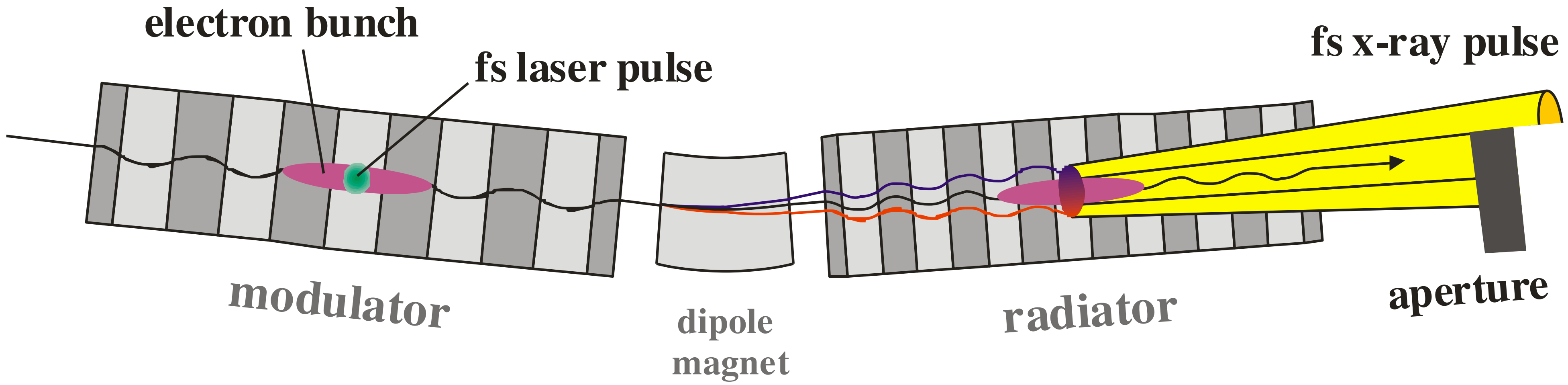
talk
M. Ruprecht,
WEOAB101

G. Wüstefeld et al., IPAC2011, THPC014

Femtoslicing

- Short radiation pulses from laser-induced density modulation
  - 'Femtoslicing' established at ALS, BESSY, SLS, UVSOR II
  - ~100 fs pulse lengths (but relatively low photon rates)

H. Huck

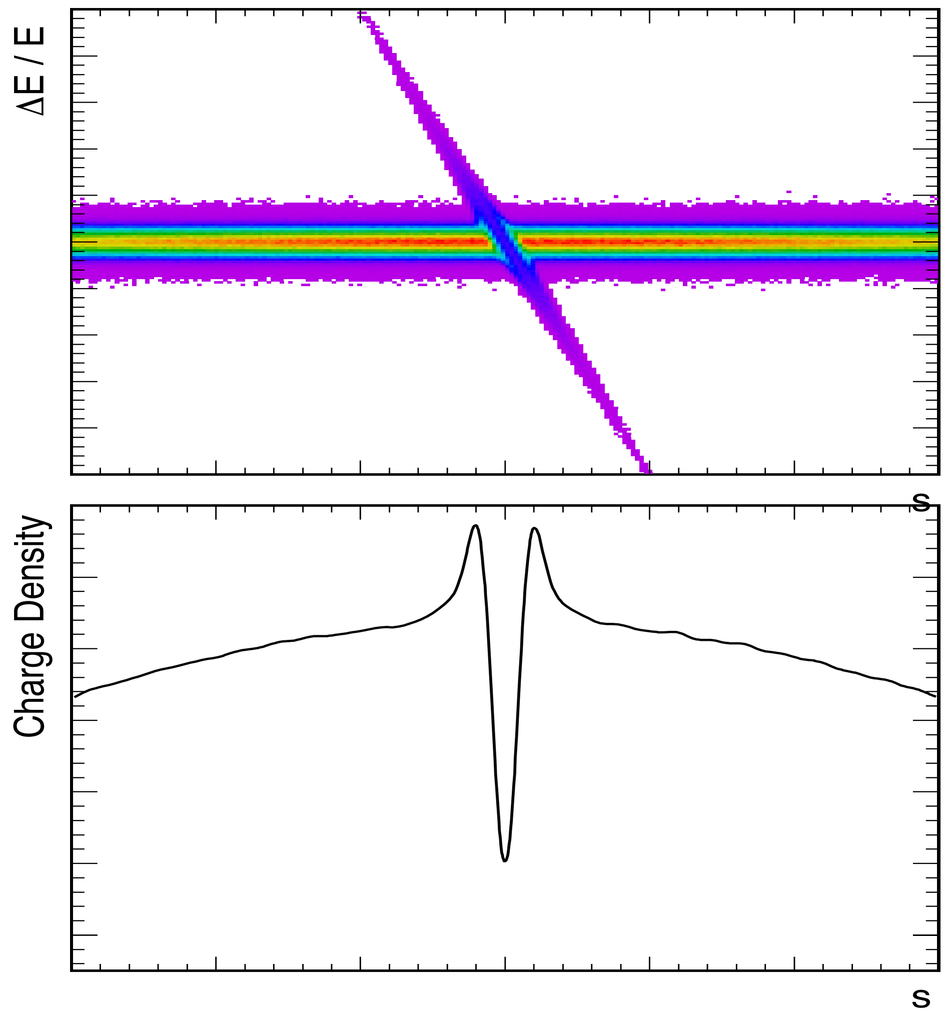


S. Khan, J. Mod. Optic., 55(21), (2008), 3469

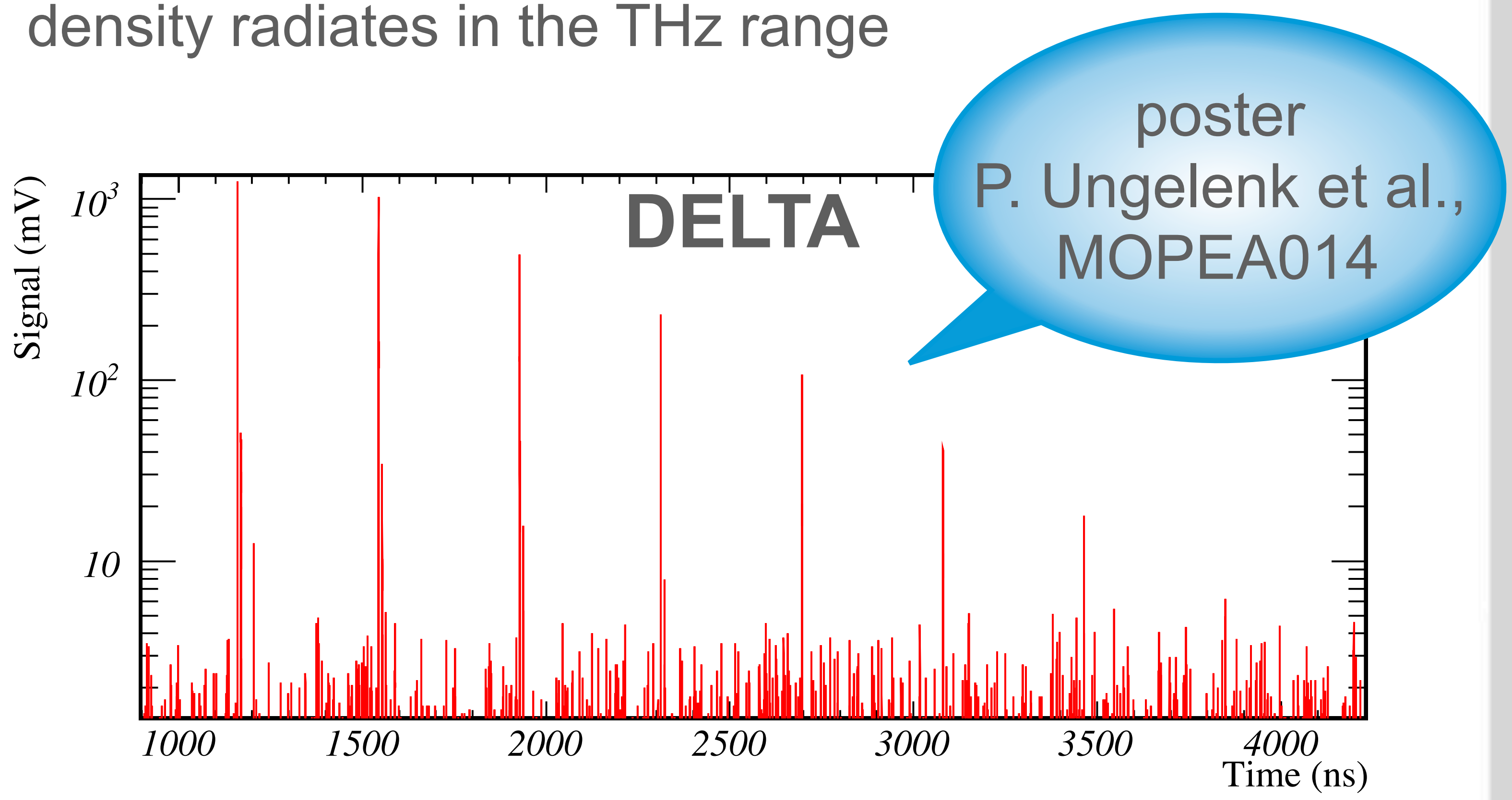
A. A. Zholents, M. S. Zoloterev, PRL 76 (1996), 912
R. W. Schoenlein et al., Science 287 (2000), 2237 (ALS)
S. Khan et al., PRL 97 (2006), 074801 (BESSY II)
P. Beaud et al., PRL 99 (2007), 174801 (SLS)
M. Shimada, et al., Jpn. J. Appl. Phys. 46(12), (2007), 7939 (UVSOR II)

Femtoslicing

- Short radiation pulses from laser-induced density modulation
  - ‘Femtoslicing’ established at ALS, BESSY, SLS, UVSOR II
  - ~100 fs pulse lengths (but relatively low photon rates)



energy modulation translates into spatial separation in dispersive section: rapidly decaying dip of few 100 fs width in charge density radiates in the THz range



Femtoslicing

- Short radiation pulses from laser-induced density modulation
  - ‘Femtoslicing’ established at ALS, BESSY, SLS, UVSOR II
  - ~100 fs pulse lengths (but relatively low photon rates)

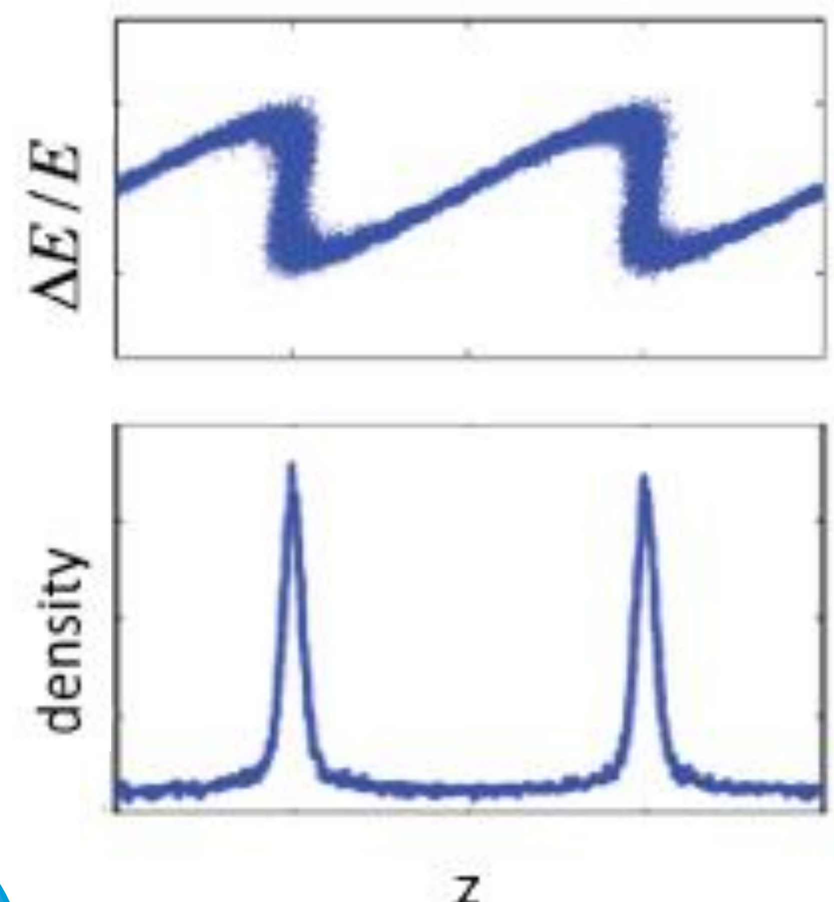
posters CHG @ DELTA:
R. Molo et al., TUPWO007 &
H. Huck et al., WEPWA005

- Further developments:
  - short and intense VUV pulses from Coherent Harmonic Generation (CHG) and Echo Enabled Harmonic Generation (EEHG)

- Other option:
  - electron-electron interaction

next talk
L. Yu,
TUOAB201

DELTA *H. Huck*

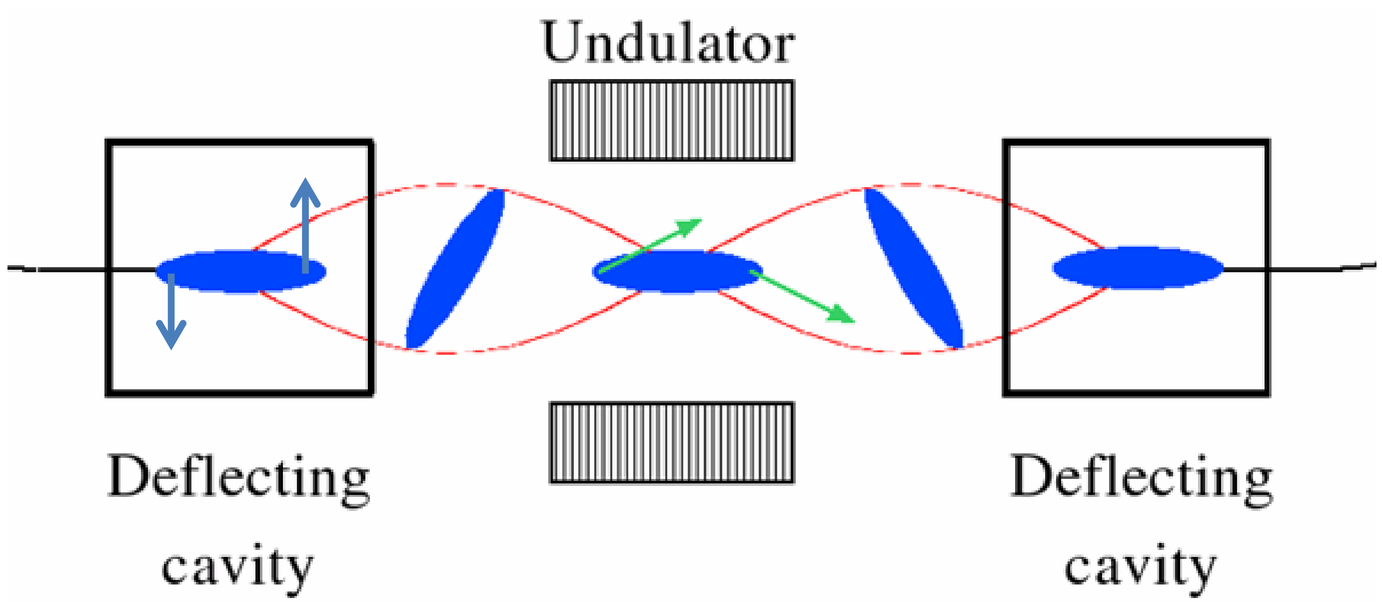


energy modulation causes density modulation after a chicane

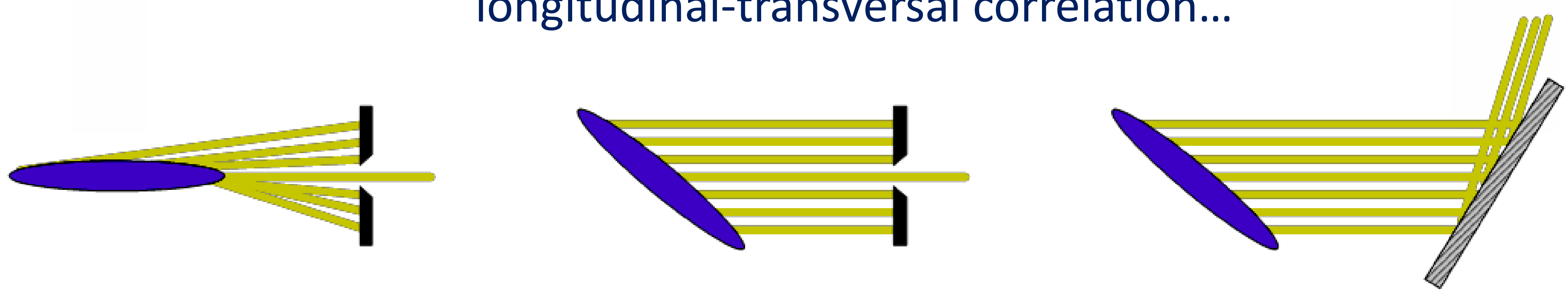
Transverse-longitudinal coupling

- Bunch rotation by RF orbit deflection
  - successful use of crab cavities for HEP (e.g. KEKB, under study for LHC)
  - under development for the Short Pulse X-ray project at APS

A. Zholents et al.,
NIM A 425 (1999) 385



longitudinal-transversal correlation…



H. Huck

angular slicing

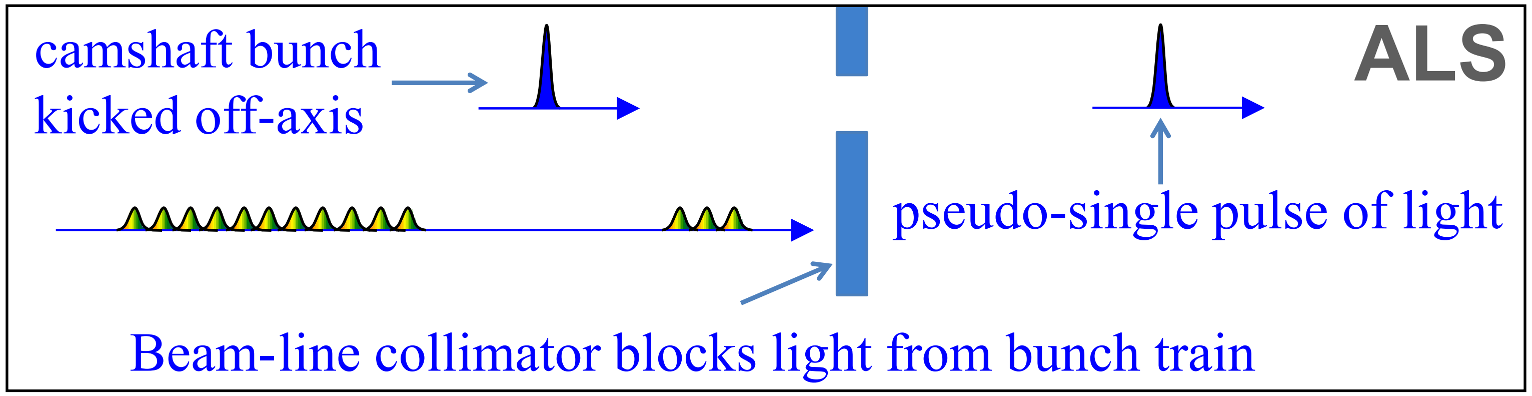
spatial slicing

pulse compression with asymmetrically-cut crystal

Other methods

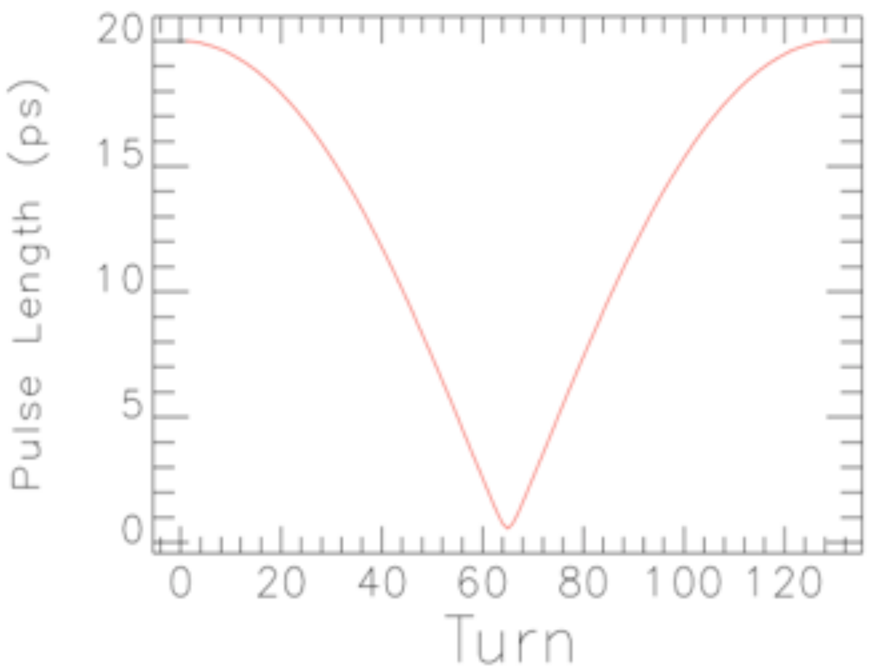
- Pseudo single bunch
  - camshaft bunch kicked on a different orbit
  - e.g. at ALS and SOLEIL

C. Sun et al., PRL 10 (2012) 264801



- Synchrobetatron coupling
  - tested e.g. at APS

W. Guo et al.,
PAC'05, RPAE073

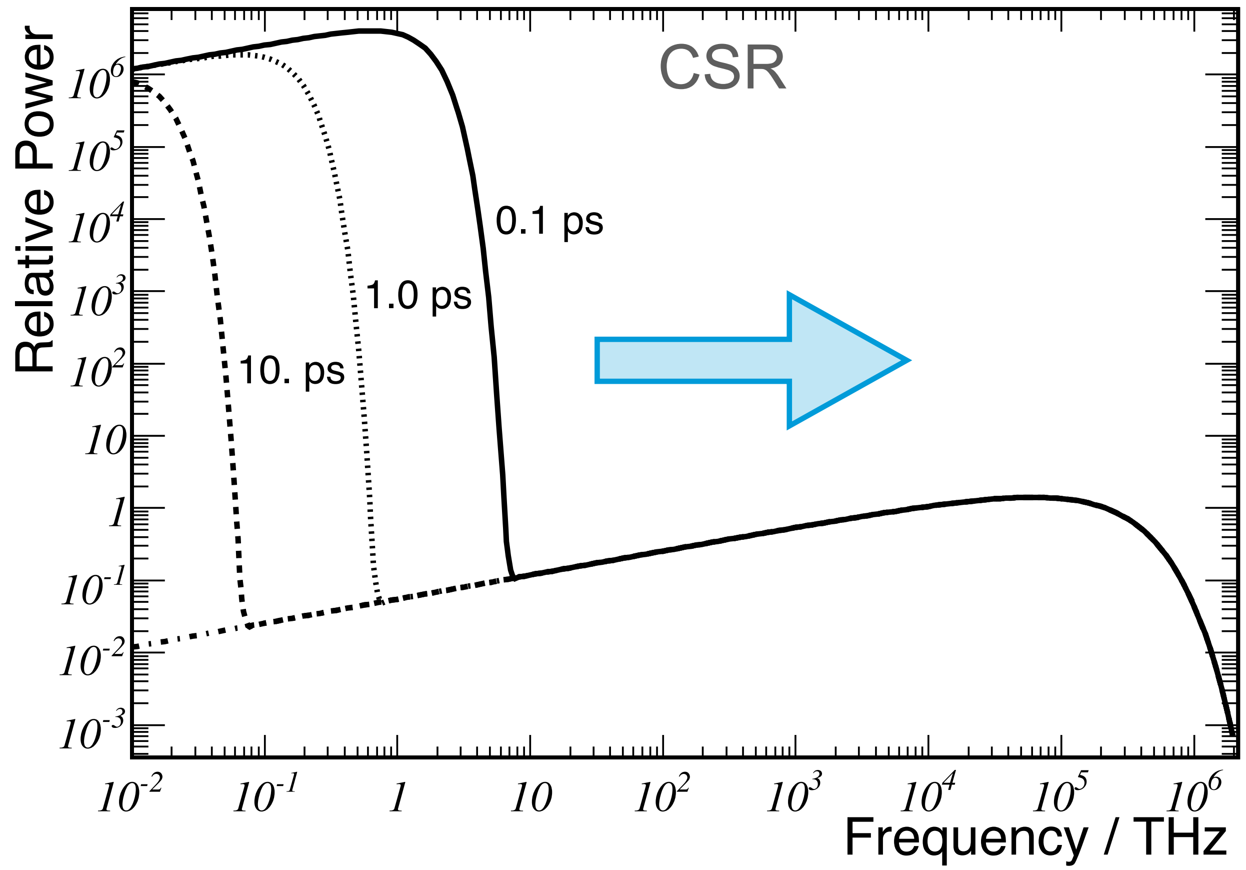


- Injection of short pulse into storage ring
  - short bunch for a few turns
  - injection from linac (e.g. newSUBARU, Y. Shoji et al., EPAC'06, MOPCH055) or Laser Wakefield Accelerator (LWFA)

poster
S. Hillenbrand et al.,
WEPEA012

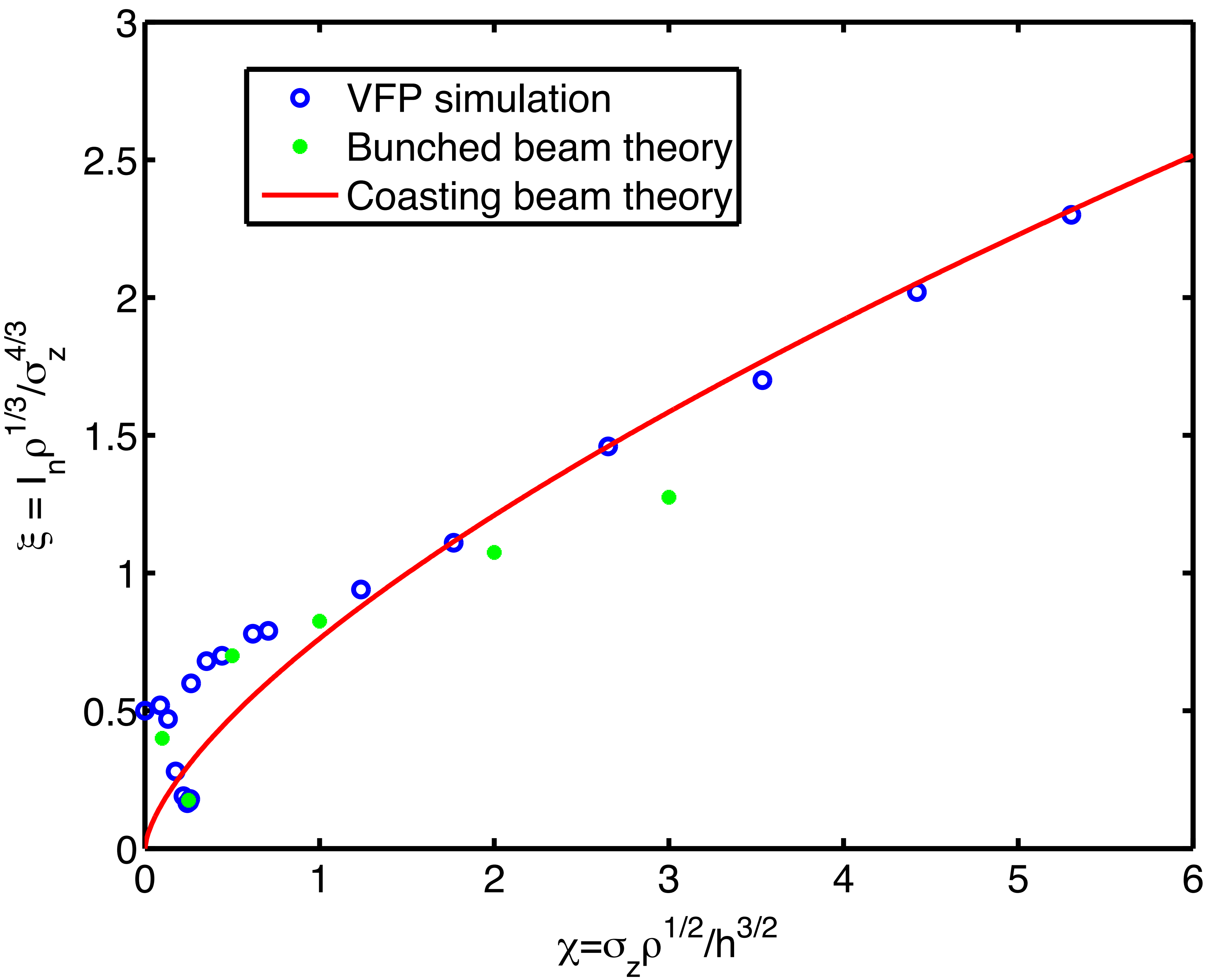
Physics & phenomenology

- Common issues for all types of short bunches in e^- storage rings
- CSR spectrum
  - high radiation power
  - strong e.m. fields
  - self-interactions
- Instabilities
  - micro-bunching instability above a threshold current
  - threshold depends on, e.g. RF voltage, vacuum chamber geometry, bending radius, but also on the filling pattern
  - really short bunches only for low bunch currents
- Key issues for short bunch studies
  - high resolution (ps) - high rate (500 MHz) - long term observation (secs - hrs)
  - 2 categories:
    indirect: *detection of coherent and incoherent radiation (microwave - vis)*
    direct: *detection of bunch Coulomb fields*



Micro-bunching instability threshold

- Theoretical predictions verified at many machines



instability threshold as a function of shielding parameter

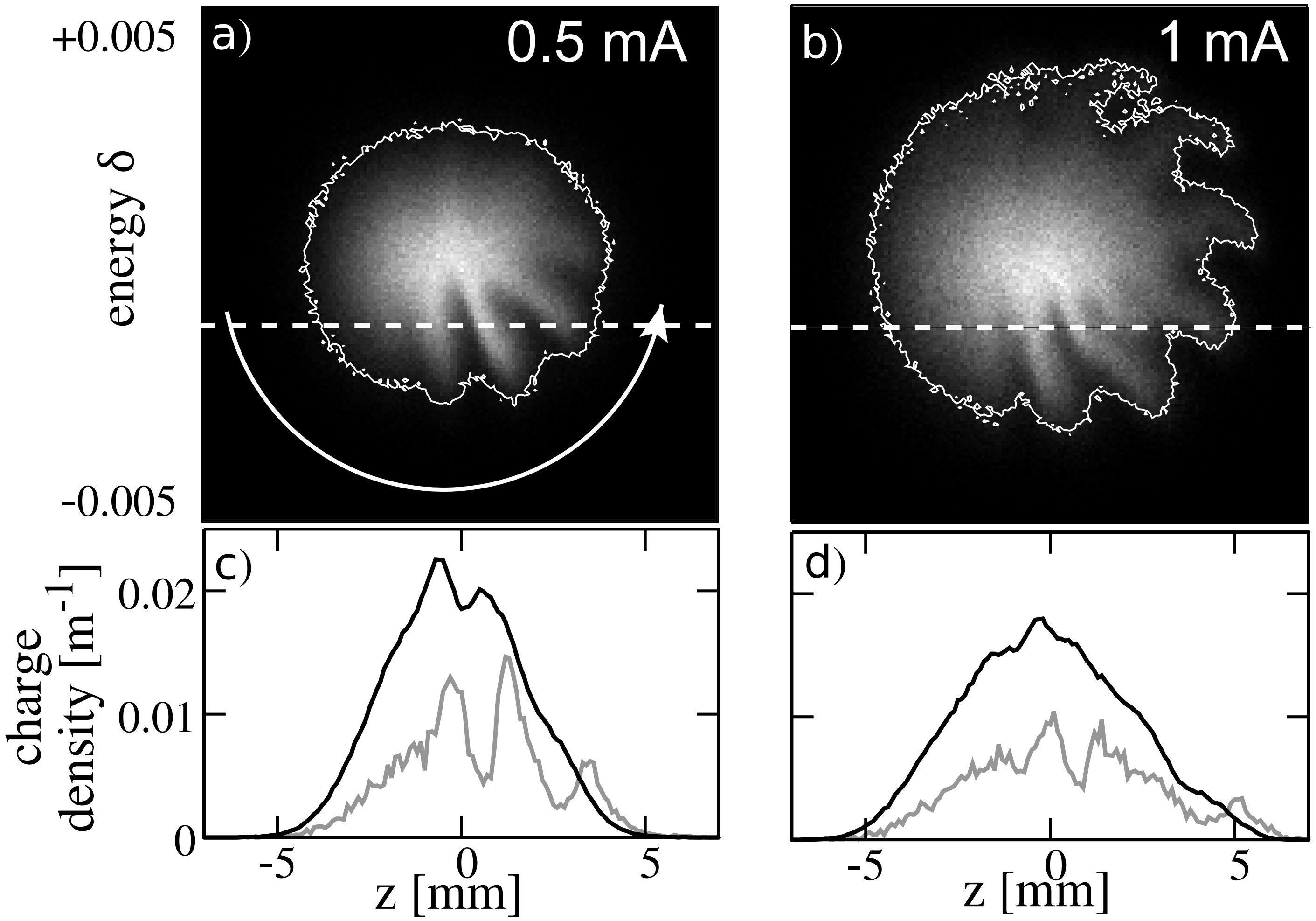
talk P. Kuske, WEOAB102 (BESSY II, MLS)

Y. Cai, IPAC2011, FRXAA01

Micro-bunching dynamics

- Dynamic sub-structures & effective bunch length blow-up

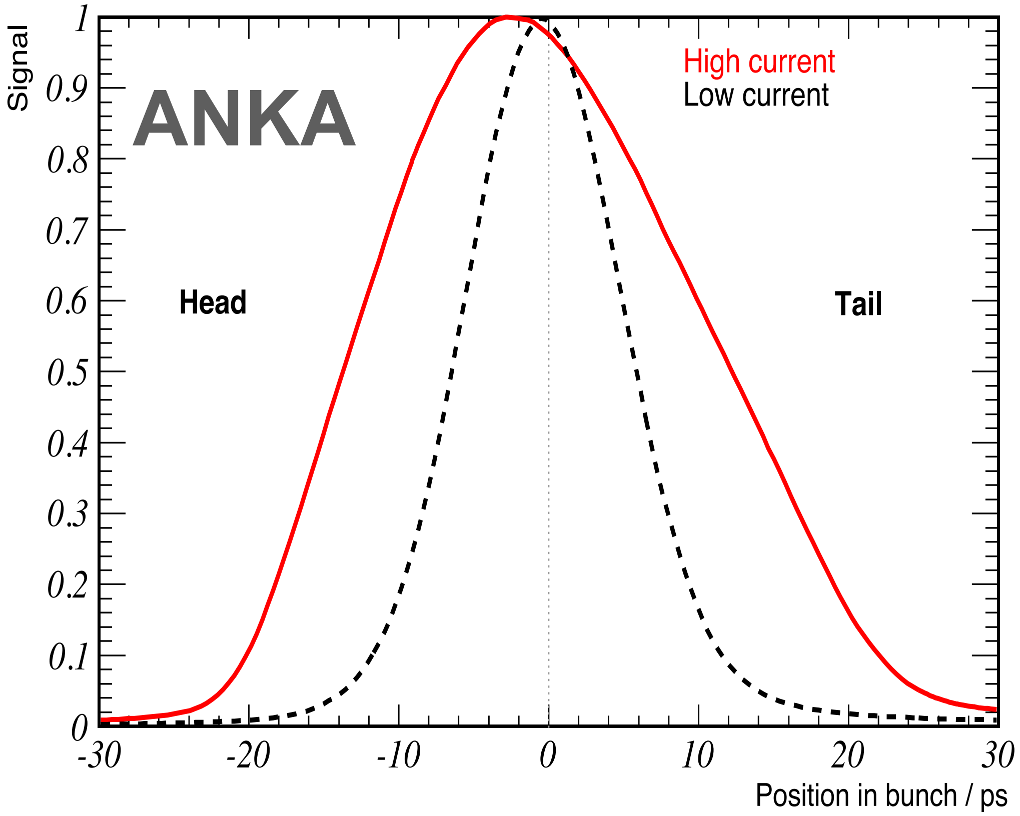
simulation of long. phase space (**SOLEIL**)



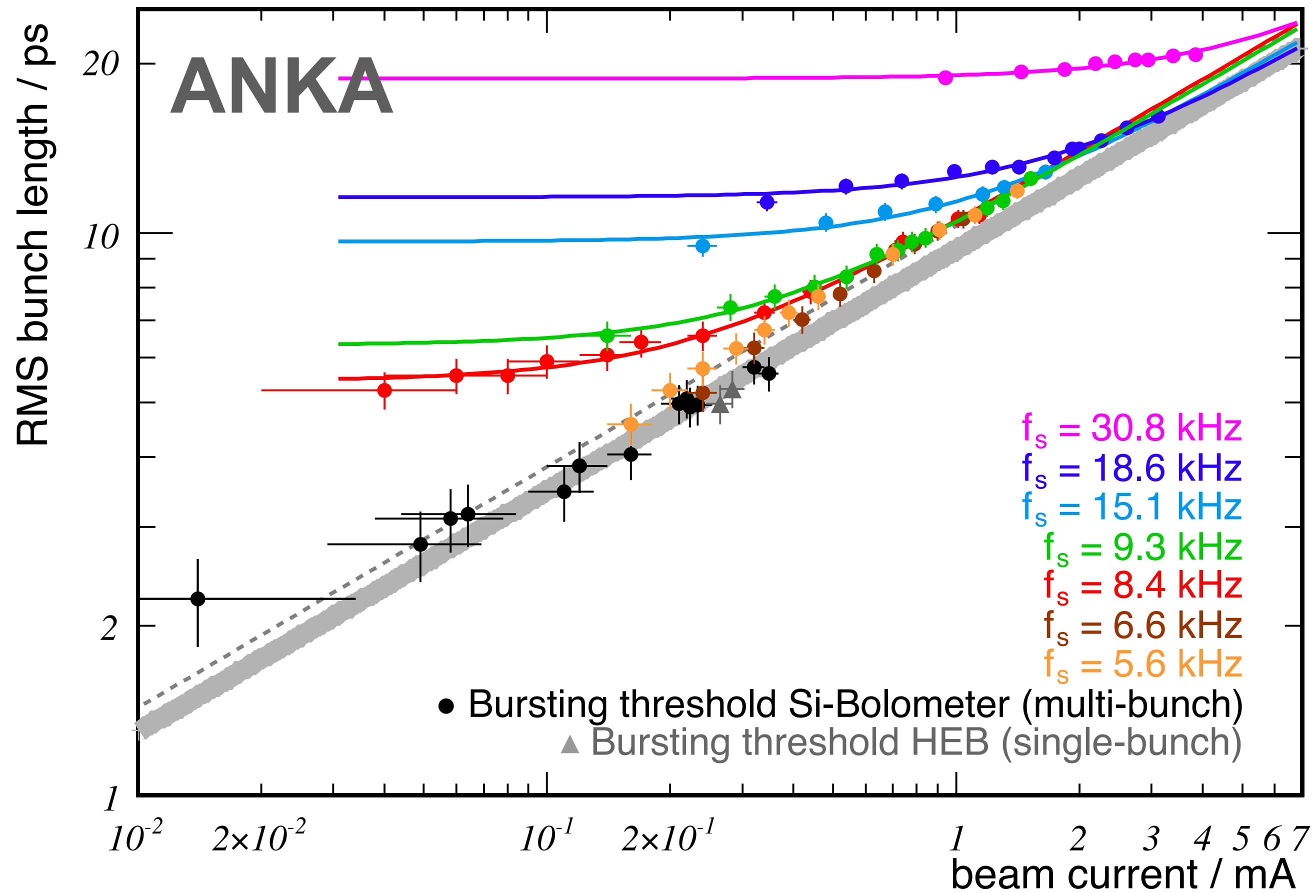
C. Evain et al., EPL, 98 (2012) 40006

poster
E. Roussel et al.,
WEPEA005

streak camera measurements



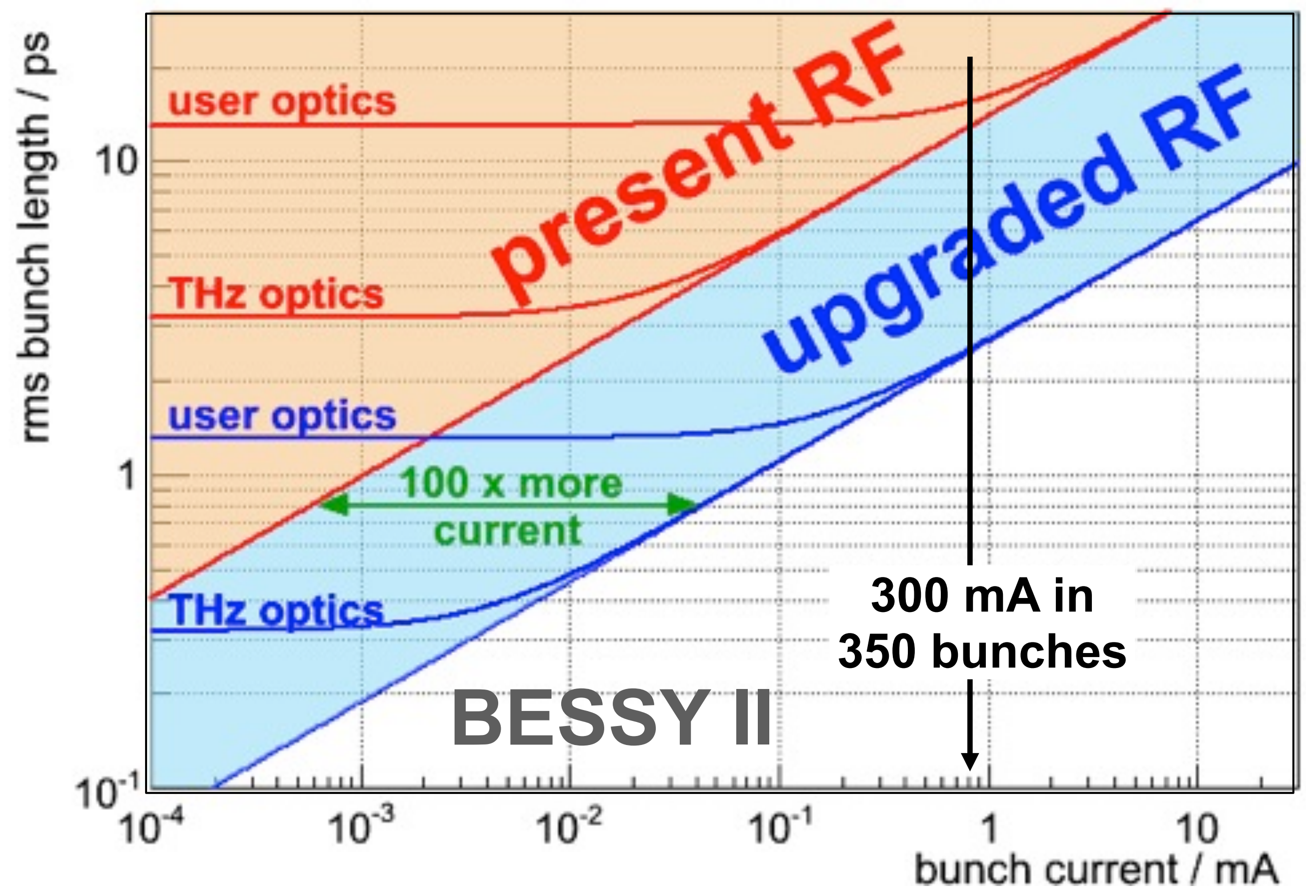
Bunch length and current



Beam Dynamics Newsletter 57 (2012) 154

- bunch lengthens before threshold
  - ➜ complex dynamics makes threshold determination hard

poster
P. Schönfeldt et al., MOPEA020

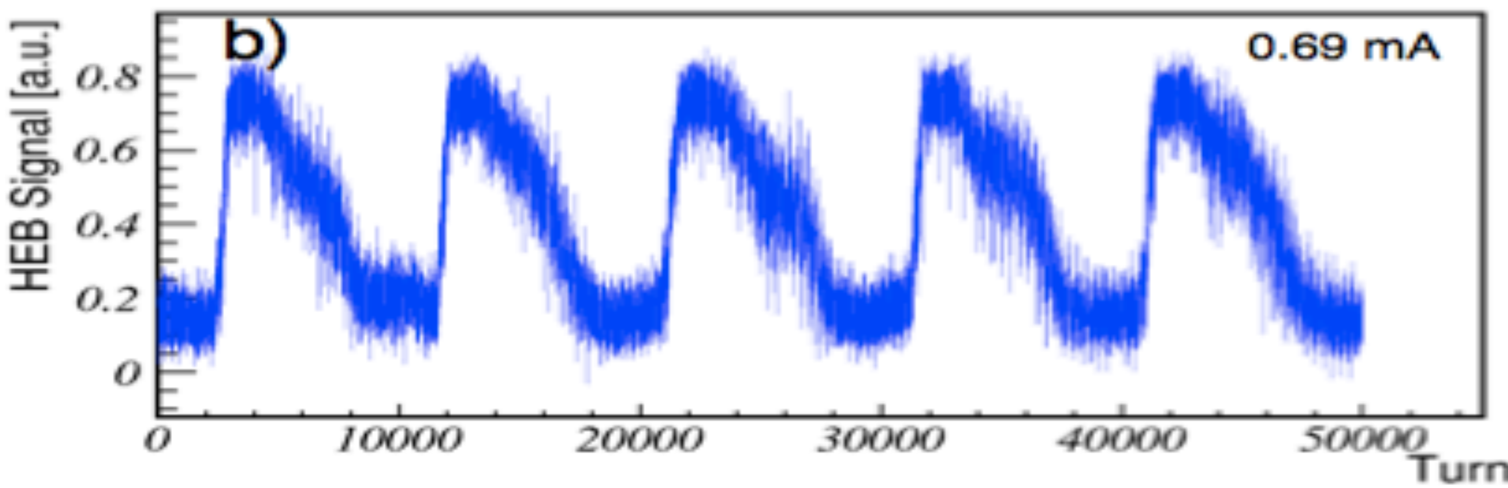


G. Wüstefeld et al., IPAC2011, THPC014

- Increased RF gradient allows substantially shorter bunches for the same bunch current

Bursting patterns

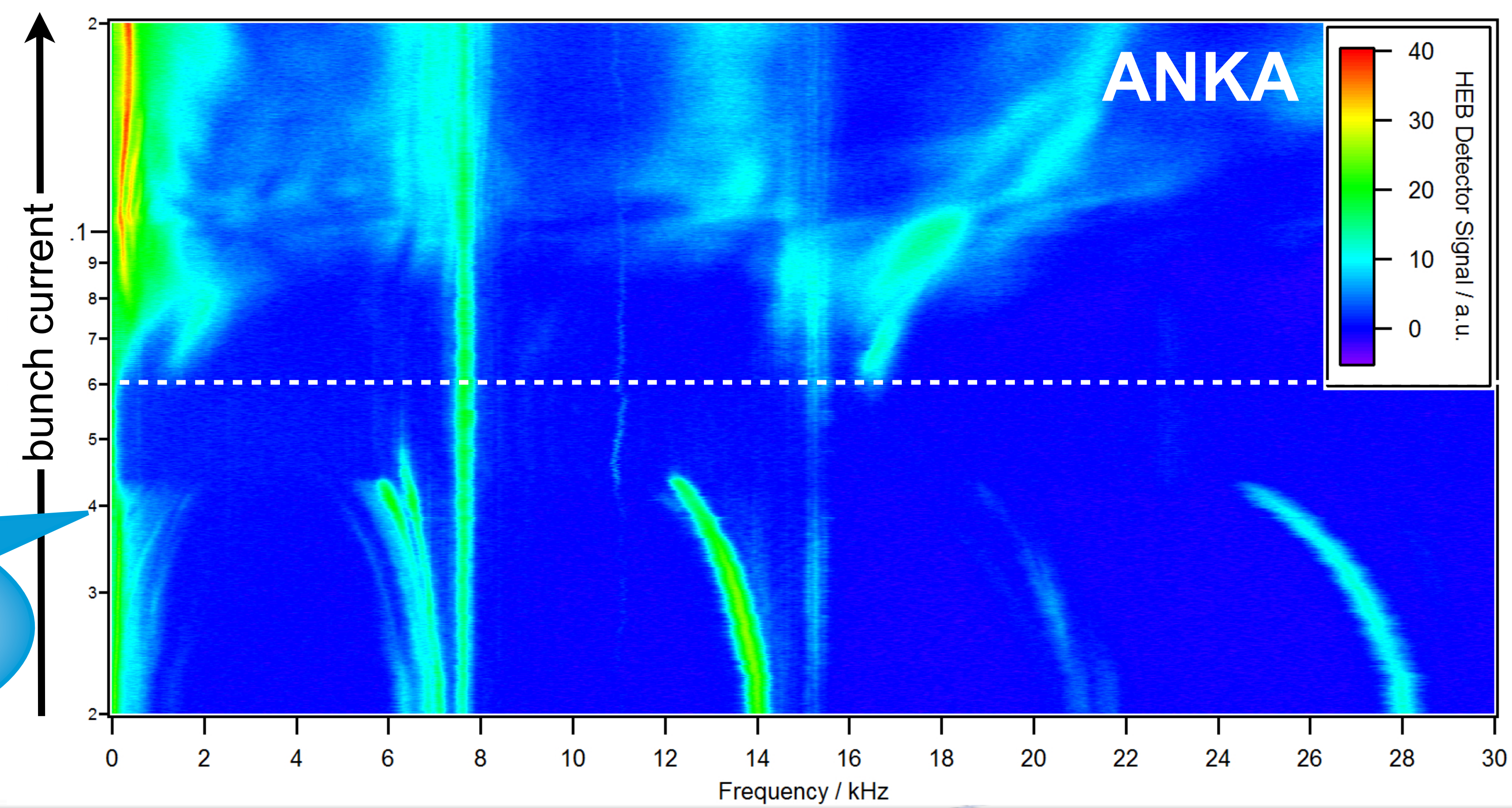
- Dynamic sub-structures lead to bursts of CSR



THz signal measured with an ultra-fast detector system

V. Judin et al., IPAC2010, WEPEA021

FFT of THz signal as a function of bunch current

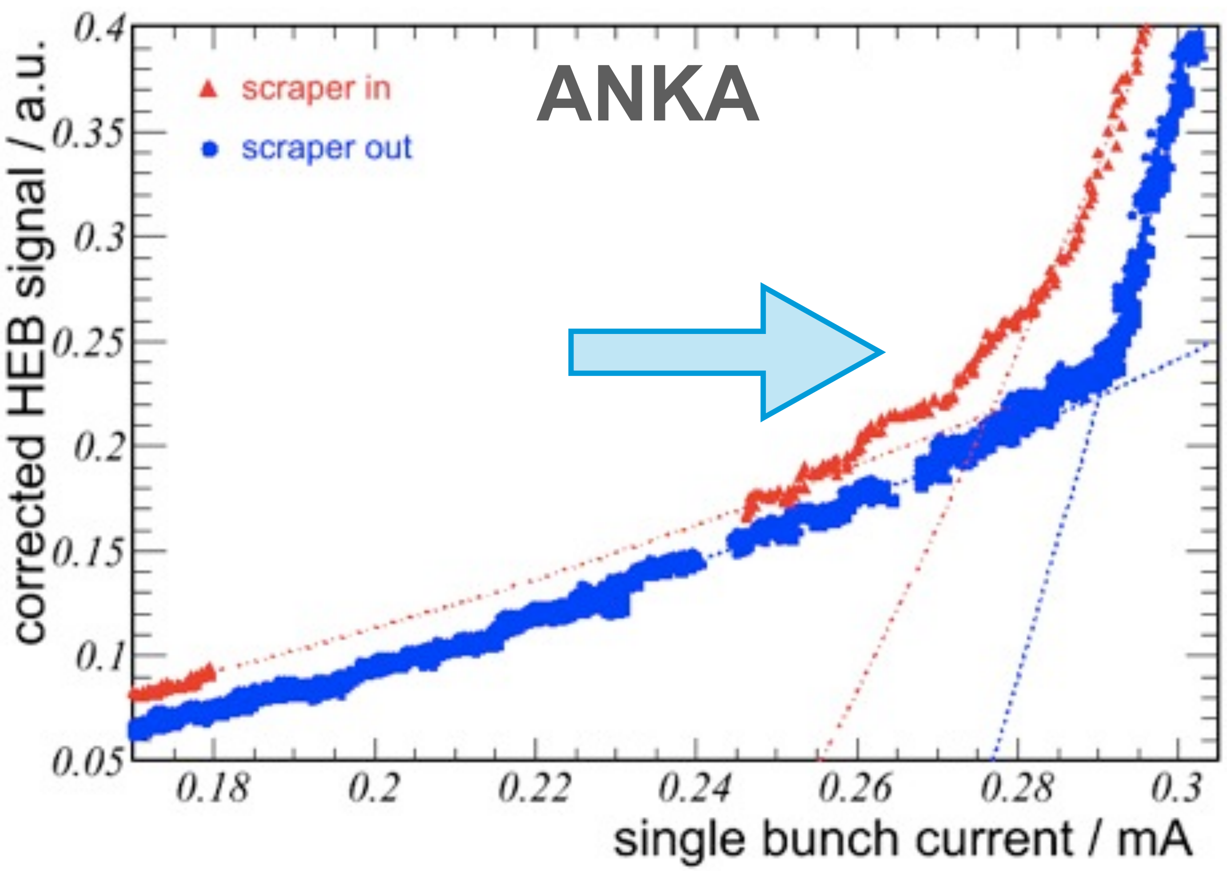


posters
ASM et al., MOPEA019
V. Judin et al., WEPEA011

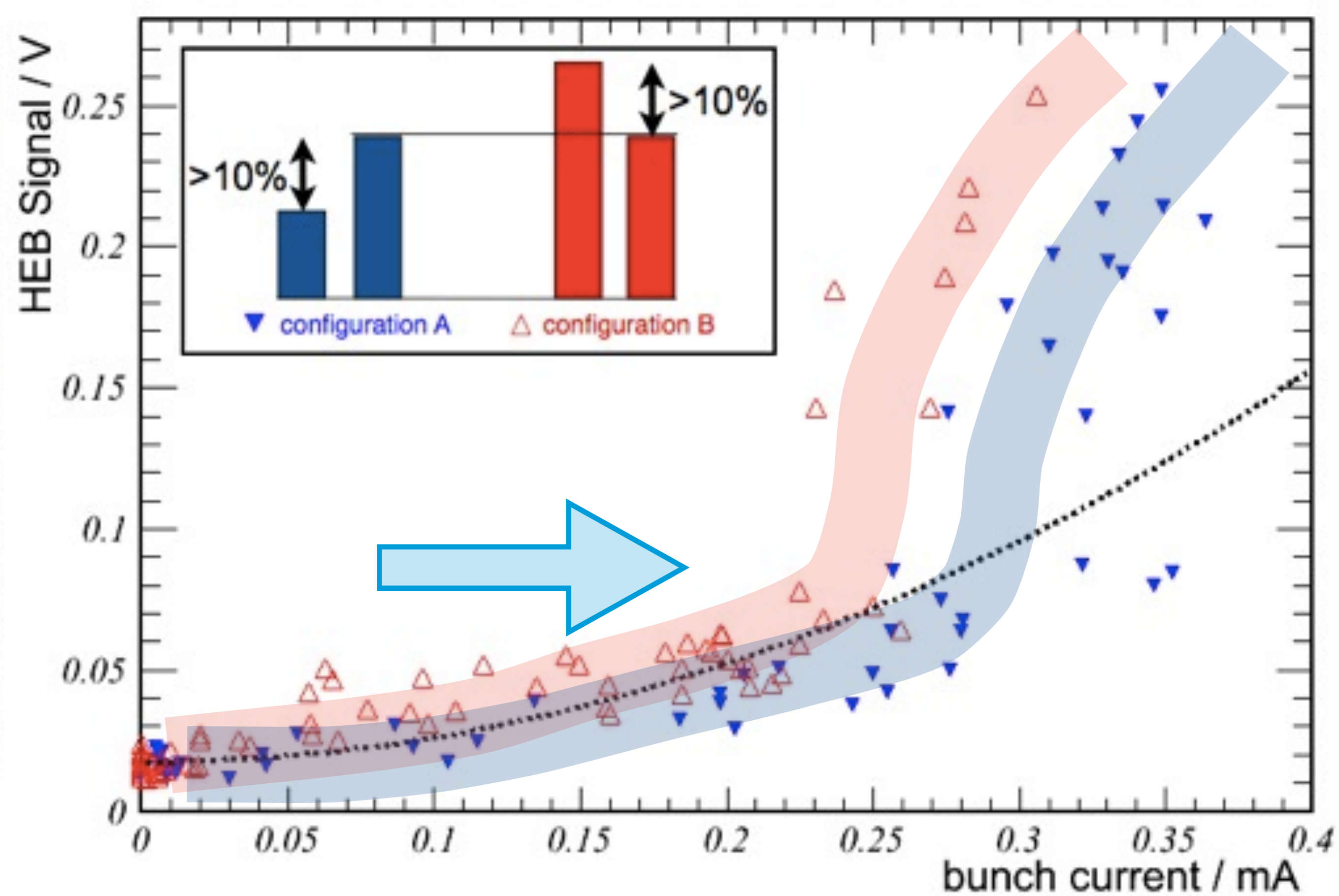
Impedances & wakes

- Geometric impedance (e.g. a scraper) and the filling pattern influence the bursting threshold and radiation power (-> form factor change)

THz signal of a **single bunch** as a function of single bunch current with and without the influence of a scraper



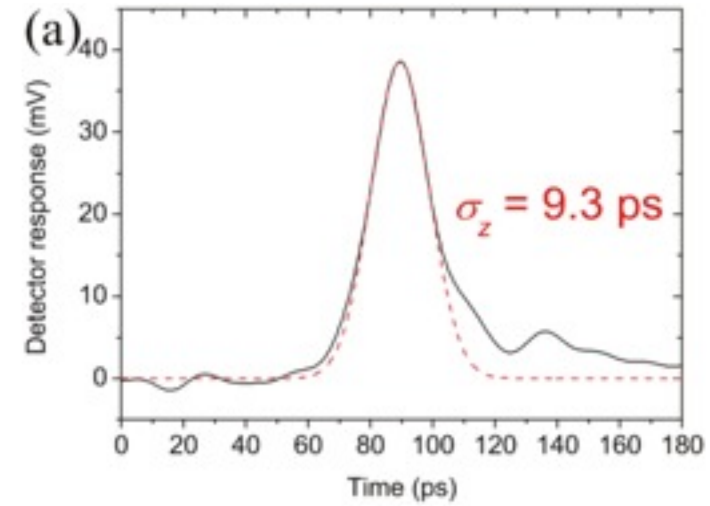
THz signal individual bunches in a **bunch train** as a function of single bunch current

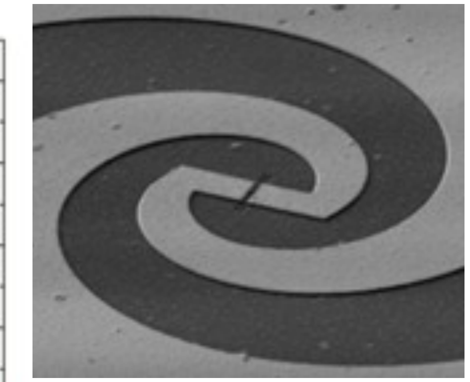


Beam Dynamics Newsletter 57 (2012) 154

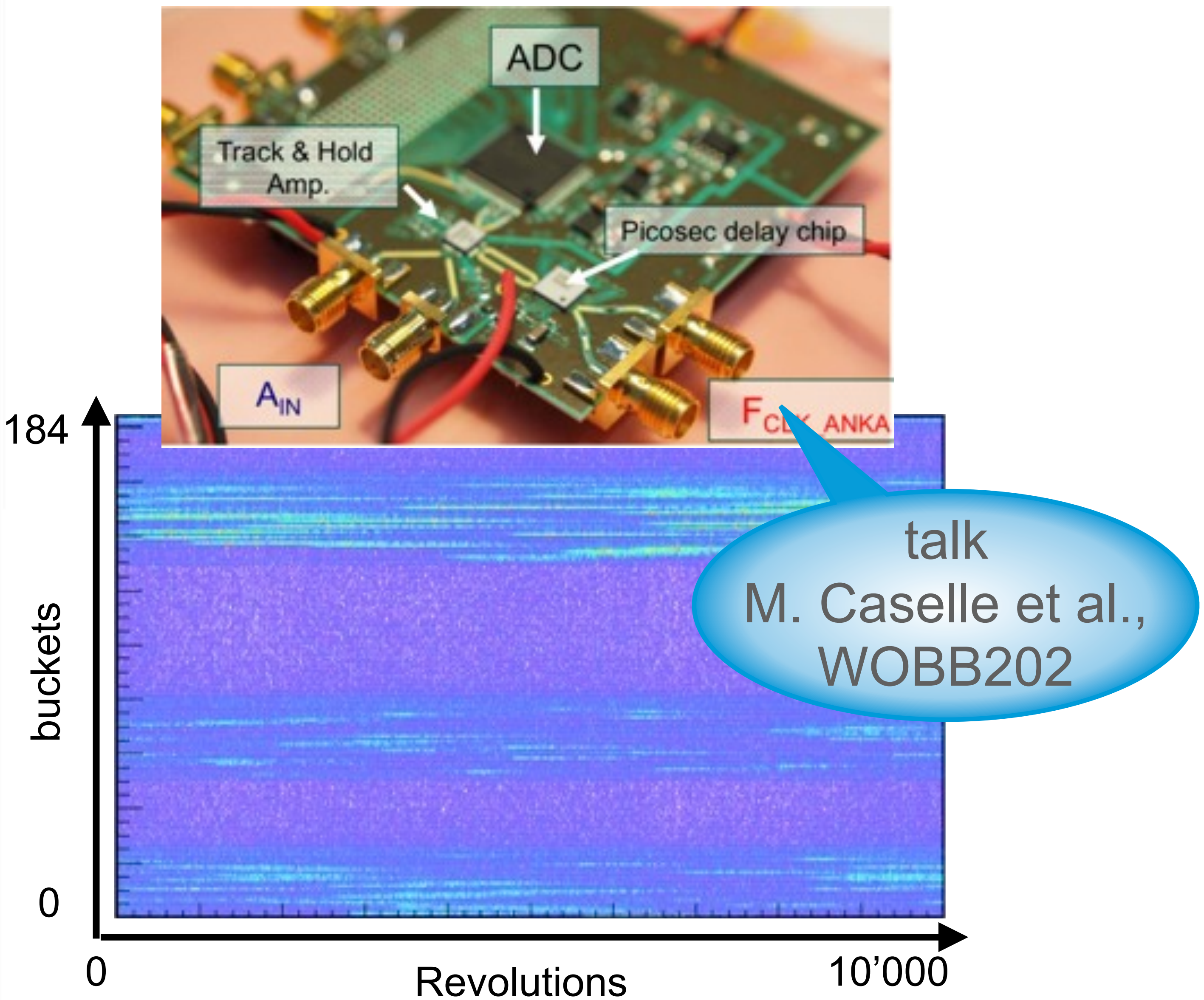
Long range bunch-bunch correlations

- More information by use of ultra-fast detectors & data acquisition

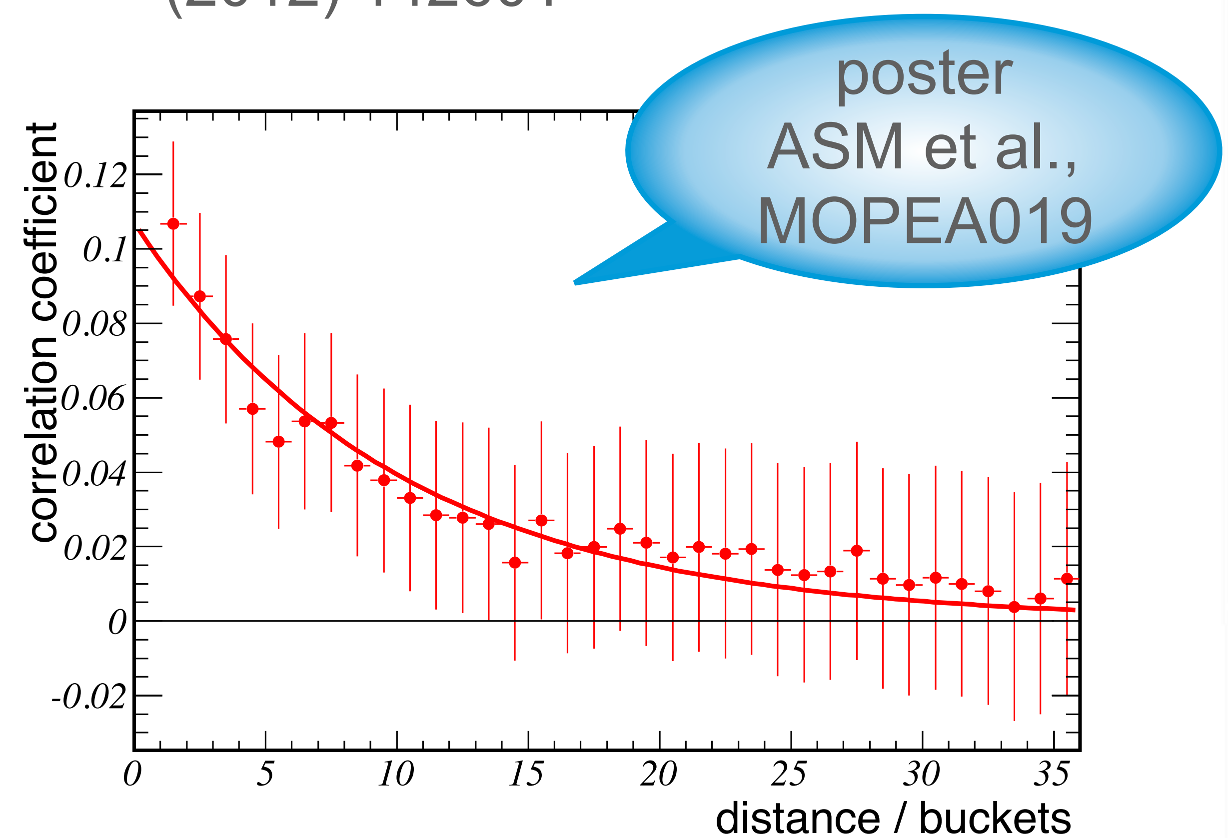




P. Thoma et al., Appl. Phys. Lett. 101 (2012) 142601



Ultra-fast simultaneous detection of THz signal from all bunches over many revolutions



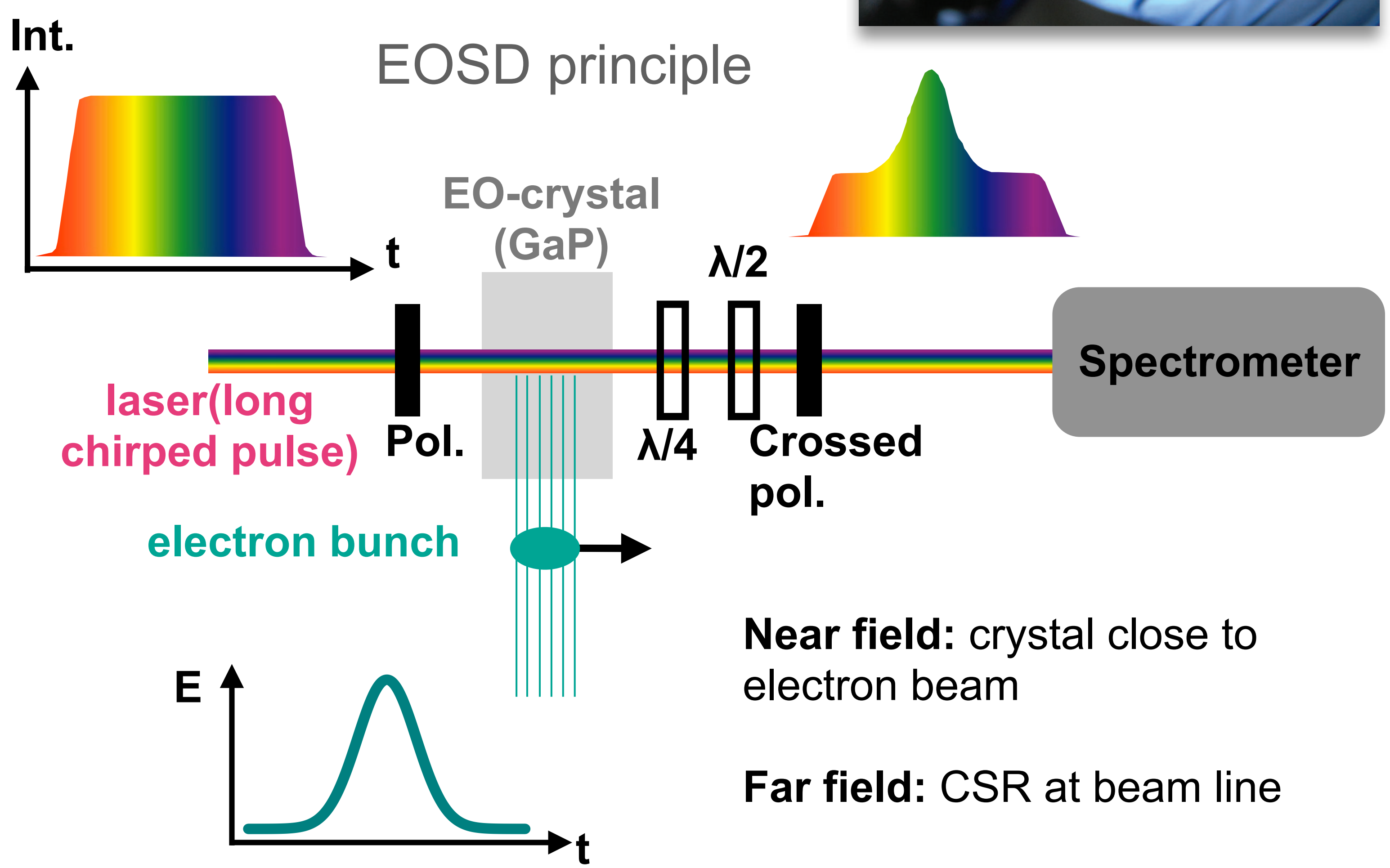
Correlation coefficients as a function of distance between buckets

Direct detection of bunch fields

- Electro-optic (EO) methods measures
  - wake field (EO sampling)
  - bunch shape (EO spectral decoding, single shot!)

EO set-up in the ANKA vacuum chamber

EOSD principle



Near field: crystal close to electron beam

Far field: CSR at beam line

λ/4: compensate intrinsic birefringence of crystal
λ/2: control transmission through crossed polariser

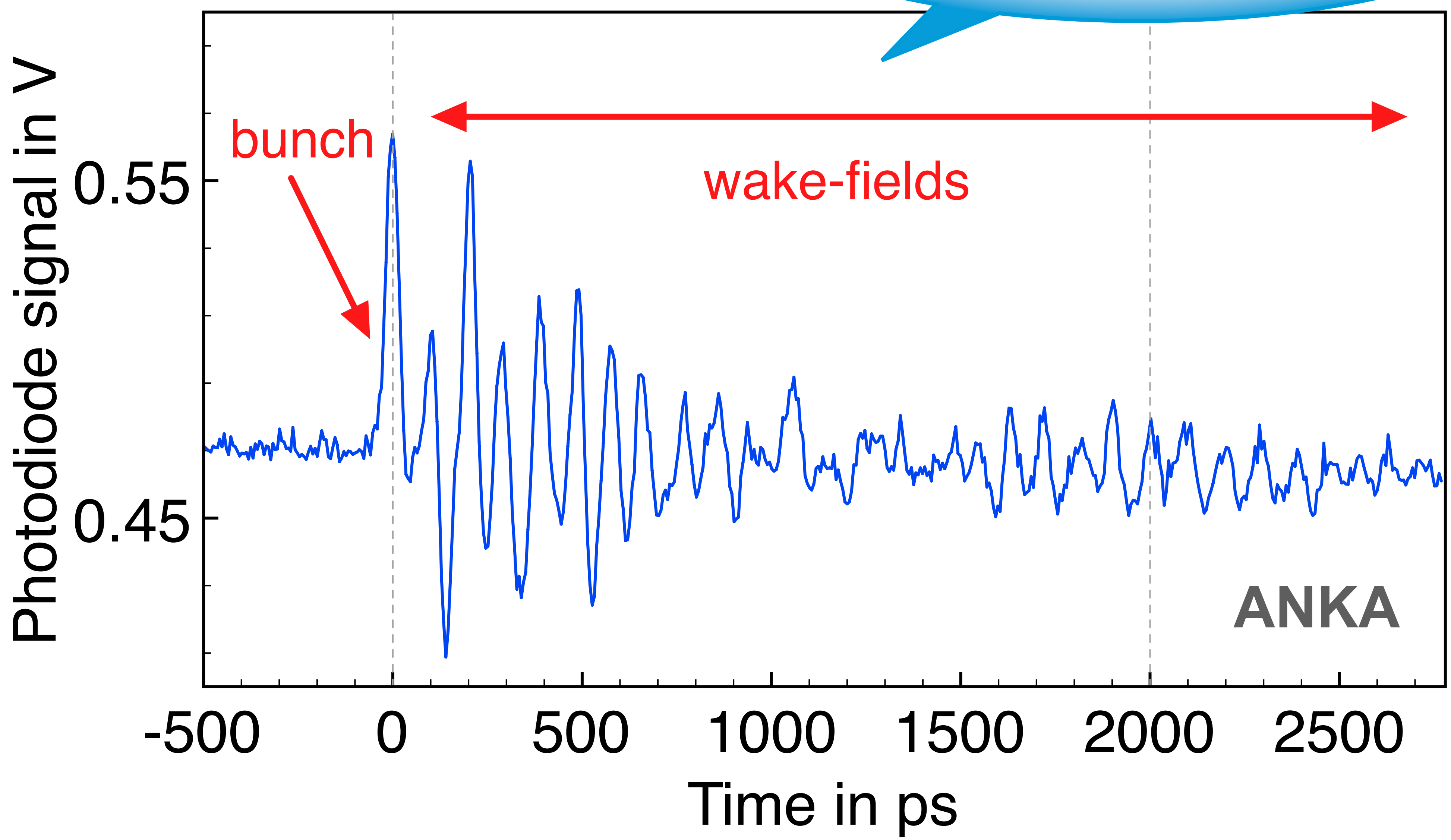
N. Hiller

SPONSORED BY THE
Federal Ministry of Education and Research

EO sampling: wake field

- EOS measurement of the E-field induced birefringence inside GaP crystal from passing bunch

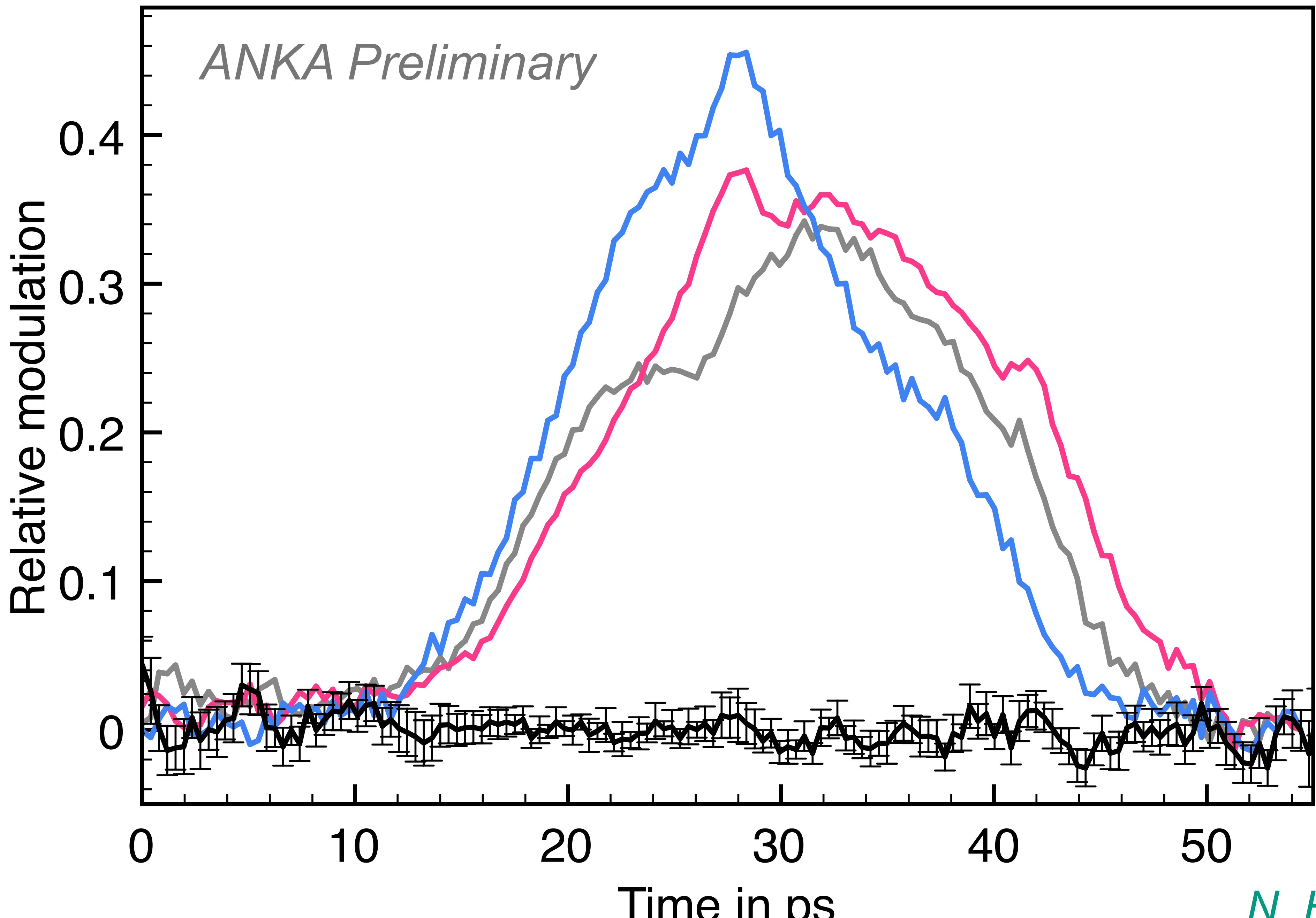
posters
H. Hiller et al., MOPEA014
B. Kehrer et al., MOPEA015



SPONSORED BY THE
Federal Ministry of Education and Research

EO spectral decoding: bunch shape

- Single shot EOSD measurements indicate dynamic sub-structures



N. Hiller

SPONSORED BY THE

Federal Ministry of Education and Research

Summary

- Strong science case for short pulses (THz to X-rays)
- Many different ways to generate short photon pulses from ...
  - short bunches (e.g. low-α_c, simultaneous long and short bunches using higher order terms of α_c) — **100 fs - 10 ps**
  - rotating bunches (e.g. crab cavities, synchrobetatron coupling) — **100 fs - 1 ps**
  - ultra-short modulation on longer bunches (e.g. slicing, CHG, EEHG) — **100 fs**
- New developments, e.g. simultaneous long and short bunches with strong alternating RF focussing scheme (BESSY^{VSR})
- Physics & phenomenology
  - micro-bunching causes bunch lengthening & dynamic substructures
  - studies require:
    high resolution (ps) - high rate (500 MHz) - long term observation (secs - hrs)
  - new developments in diagnostics: turn-by-turn and single shot measurements

Acknowledgements

- My colleagues at KIT V. Judin, N. Hiller, J. Steinmann, and the rest of the ANKA THz team, A. Plech (KIT-IPS), P. Thoma (KIT-IMS) and M. Caselle (KIT-IPE)
- G. Wüstefeld (HZB), H. Huck and S. Khan (TU Dortmund/DELTA), Y. Cai, R. Warnock, and A. Novokhatski (SLAC), E. Roussel and S. Bielawski (Université de Lille), for instructive discussions and for providing material and plots