Short-Pulse Operation of Storage Ring Light Sources

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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)
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Overview short pulse generation

- Long bunch
- Shortened bunch
- Transverse-longitudinal coupling
- Slicing
- Modulation
- Laser-based methods

Electron bunch

Radiation pulse

100 fs - 10 ps

100 fs - 1 ps

100 fs
Overview short pulse generation

The field is too wide to be covered exhaustively therefore the key issues are discussed by means of selected examples.
Low-$\alpha_c$ optics

- Definition of momentum compaction factor $\alpha_c$: $\Delta L/L = \alpha_c \Delta p/p_0$

- Manipulate D to reduce $\alpha_c$:
  $$\alpha_c = \frac{1}{L} \int ds \frac{D(s)}{\rho(s)}$$

- DIAMOND

- 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 $\alpha_i$ needed

- Typ. bunch lengths down to 1 ps

I. Martin et al., IPAC2010, THPE037
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-\(\alpha_c\): bunches of \(~300\) fs

G. Wüstefeld et al., IPAC2011, THPC014

0.5 GHz, 1.5 MV
\[ V' = V_{xrf} = 0.75 \text{ MVGHz} \]

1.5 GHz, 25 MV
\[ V' = V_{xrf} = 37.5 \text{ MVGHz} \]

1.75 GHz, 21.4 MV
\[ V' = V_{xrf} = 75 \text{ MVGHz} \]
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

A. A. Zholents, M. S. Zoloterev, PRL 76 (1996), 912
S. Khan et al., PRL 97 (2006), 074801 (BESSY II)
P. Beaud et al., PRL 99 (2007), 174801 (SLS)
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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

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**DELTA**

- P. Ungelenk et al., MOPEA014

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    - short and intense VUV pulses from Coherent Harmonic Generation (CHG) and Echo Enabled Harmonic Generation (EEHG)
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  - Other option: electron-electro
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

Holger Huck
Ultrashort Radiation Pulses at Storage Rings
DPG 2013, Regensburg

not yet demonstrated, planned for APS and SPring-8…
- s.c. rf cavities required
- emittance growth (rf/phase errors)
- pulse length > 1 ps
  - 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

- **Synchrobetatron coupling**
  - tested e.g. at APS

- **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)

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

![Pseudo-Single-Bunch with Adjustable Frequency: A New Operation Mode](image)

W. Guo et al., PAC’05, RPAE073

W. Guo et al., PAC’05, RPAE073

S. Hillenbrand et al., poster 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

\[ \xi = I_n \rho^{1/3} / \sigma_z^{4/3} \]

\[ \chi = \sigma_z \rho^{1/2} / h^{3/2} \]

Y. Cai, IPAC2011, FRXAA01

talk P. Kuske, WEOAB102 (BESSY II, MLS)
Micro-bunching dynamics

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

Simulation of long. phase space (SOLEIL)

Poster: E. Roussel et al., WEPEA005

Streak camera measurements

C. Evain et al., EPL, 98 (2012) 40006
Bunch length and current

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

Beam Dynamics Newsletter 57 (2012) 154

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

- Beam lengthens before threshold

- Complex dynamics makes threshold determination hard

- Bursting threshold Si-Bolometer (multi-bunch)

- Bursting threshold HEB (single-bunch)

- Present RF

- Upgraded RF

- 300 mA in 350 bunches

G. Wüstefeld et al., IPAC2011, THPC014
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

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

Correlation coefficients as a function of distance between buckets


M. Caselle et al., WOBB202

ASM et al., MOPEA019
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**
- laser (long chirped pulse)
- electron bunch
- EO-crystal (GaP)
- Pol.
- Crossed pol.
- Spectrometer
- Near field: crystal close to electron beam
- Far field: CSR at beam line

\( \lambda/4 \): compensate intrinsic birefringence of crystal
\( \lambda/2 \): control transmission through crossed polariser

N. Hiller
EO sampling: wake field

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

**Graph:**
- Photodiode signal in V
- Time in ps

**Posters:**
- H. Hiller et al., MOPEA014
- B. Kehrer et al., MOPEA015
EO spectral decoding: bunch shape

- Single shot EOSD measurements indicate dynamic sub-structures

![Graph showing relative modulation over time in ps for ANKA Preliminary](image)
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-\(\alpha_c\), simultaneous long and short bunches using higher order terms of \(\alpha_c\))  
  - rotating bunches (e.g. crab cavities, synchrobetatron coupling)  
  - ultra-short modulation on longer bunches (e.g. slicing, CHG, EEHG)  

- 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
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