Production of Coherent Synchrotron Radiation at ANKA Using Low-momentum-compaction Lattices

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ANKA @ Karlsruhe
Overview

- Introduction
  - The ANKA storage ring
  - Low-alpha mode and CSR production
  - Stable vs. bursting emission
- Measurements with a hot electron bolometer (HEB)
- Measurements with a streak camera
- Spectral measurements
- Modeling the low-alpha mode with the Accelerator Toolbox
The ANKA storage ring

- C = 110.4 m
- Energy range: 0.5 - 2.5 GeV
- RF frequency 500 MHz
- DBA lattice
**Beamlines:**
- 13 in operation
- 4 in construction / commissioning

**Normal operation:**
- Energy 2.5 GeV
- Current 120-200 mA
- Multi-bunch (3 trains with 30ish bunches each)
- **Natural bunch length** \( \sigma_{z,0} \approx 13 \text{ mm} \)

**Low-alpha mode:**
- Coherent THz radiation
- Energy 1.3 GeV
- Current \( \approx 0.1 - 70 \text{ mA} \)
- Single- or multi-bunch
- **Natural bunch length** \( \sigma_{z,0} \approx 0.3 - 4.5 \text{ mm} \)
Coherent synchrotron radiation (CSR)

- Short bunches emit usable coherent synchrotron radiation
- Enormous increase in power in comparison to incoherent emission
- Dedicated optics with negative dispersion in the long and short straight sections for flexible bunch length tuning
  - Low-\(\alpha_c\) optics

Coherent radiation is produced in two regimes:
- low power stable emission
- high power radiation bursts
The low-alpha mode

- Low-alpha user operation: 12 days/year

Operation procedure:
- Fill at 0.5 GeV
- Ramp energy (regular optics) to 1.3 GeV
- Low-\(\alpha_c\) “squeeze”
  - change quadrupoles & sextupoles
  - orbit correction between steps

- Observed \(\alpha_c\) range as derived from \(Q_s\) measurements:
  - from \(8.5 \times 10^{-3}\) to \(2.4 \times 10^{-4}\)
Synchrotron (Edge) Radiation at IR1

- CSR is observed as ‘regular’ synchrotron radiation but also as ‘edge’ radiation
- Can be an advantage for a beamline
  - lower frequencies observable for the same aperture
The THz Beam Profile

incoherent, $A_{\text{max}} \approx 0.1 \text{ mV}$

coherent, $A_{\text{max}} \approx 2.9 \text{ mV}$

Courtesy E. Bründermann, Ruhr Universität Bochum

Setup of beam line and detector:
- measurement behind a Si or CaF2 vacuum window
- room temperature pneumatic (Golay) detector
- detector and aperture are mounted on a x-y imaging stage and scanned vs distance and lateral position relative to the vacuum window
The bursting stable threshold

- Hight electron densities lead to microbunching instability
- Measured bursting stable threshold with Si bolometer
- Good agreement with theoretical prediction:\n  \[ I_{thres} \propto \sigma_s^{7/3} \]

The Hot Electron Bolometer (HEB) detects the THz signal of individual bunches.

Relative bunch currents from pickup.

\[ V_{RF} = 150 \text{ kV} \]

\[ HEB \text{ Signal} \propto I_{bunch}^2 \]

\text{theor. bursting/stable threshold}
THz Signal and Beam Current

- A comparison shows a dependency of CSR on the current of the leading bunch
- Investigations with tailor made filling pattern

V. Judin
CSR of Adjacent Bunches

- Correlated bursting?

Effect is under systematic investigation
Radiation Bursts

Bursting behavior dependent on electron density

V. Judin
Double-sweep synchroscan streak camera from Hamamatsu

Optical port at IR beamline, now new dedicated beam port

Recording of sequences of 500 consecutive images

Correct for oscillations

Single image (#45) out of sequence

Fast time axis (512 pixels = 190 ps)

Slow time axis (640 pixels = 500 μs)

Entries 327680
Mean x 319.8
Mean y 253.8
RMS x 184.8
RMS y 145.7

Probability density

N. Hiller
Bunch length

- Low currents: Converging to the zero current bunch length
- Above bursting stable threshold: Turbulent bunch lengthening

\[ \sigma_z \propto I_{thresh}^{7/3} \]

N. Hiller
Measured and Expected Spectra

- CSR spectra are proportional to Fourier transform of the electron distribution
- Spectral measurements with a Michelson Interferometer
- Expectation from streak cam. measurement below cutoff
- Explanation: substructure or stronger deformation
  - Single shot measurement needed
Coherent Radiation

Comparison of single and multi-bunch fillings

 fs = 9.6 kHz / 5.3 ps

 fs = 6.6 kHz / 3.8 ps
Gain Curves

Comparison of single and multi-bunch fillings

Filter #2 < 35 cm\(^{-1}\)

fs = 9.6 kHz / 5.3 ps  
fs = 6.6 kHz / 3.8 ps
Observations

Multi bunch gain curve seems to lie significantly higher than single bunch curve for similar single bunch current for longer bunches.

For shorter bunches, the curves are closer.

Hypothesis: effects from the ring impedance are more significant if the CSR effect is less pronounced.

- $f_s = 9.6 \text{kHz}, 500 \mu\text{A}, \text{single bunch}$
- $f_s = 9.6 \text{kHz}, 490 \mu\text{A}, \text{multi bunch}$

- $f_s = 6.6 \text{kHz}, 420 \mu\text{A}, \text{single bunch}$
- $f_s = 6.6 \text{kHz}, 420 \mu\text{A}, \text{multi bunch}$

$fs = 9.6 \text{ kHz} / 5.3 \text{ ps}$

$fs = 6.6 \text{ kHz} / 3.8 \text{ ps}$
Modeling the low-alpha mode with AT

<table>
<thead>
<tr>
<th>measured $f_s$</th>
<th>model $\alpha_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  30.7 kHz</td>
<td>8.5 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td>B  29.2 kHz</td>
<td>7.8 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td>C  24.2 kHz</td>
<td>5.7 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td>D  8.5 kHz</td>
<td>0.74 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td>E  6.7 kHz</td>
<td>0.46 $\cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

Measurements for each model:
- Tunes: $Q_x$, $Q_y$, $Q_s$
- Orbit response matrix
- Dispersion
- Chromaticity

5 different low-alpha optics modeled
LOCO fits and Chroma fits

- Magnet strength calculated from currents settings
- Correction of quadrupole strength:
  - LOCO fit of response matrices and dispersions
- Additional quadrupole components
  - fit of tunes and chromaticity curve shapes
- Correction of sextupole strength
  - fit of chromaticity values

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**Graphs:**
- **Horizontal**
  - Delta Qx vs. Delta fRF
  - Models: A, B, C

- **Vertical**
  - Delta Qy vs. Delta fRF
  - Models: A, B, C

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Model A and Model E comparison

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Optics functions

- Model A
  - $\beta_x$, $\beta_y$, and $D_x$

- Model C
  - $\beta_x$, $\beta_y$, and $D_x$

- Model D
  - $\beta_x$, $\beta_y$, and $D_x$

- Model E
  - $\beta_x$, $\beta_y$, and $D_x$
Tunes

Synchrotron tune:
- approximate the measurements
- no impact seen in AT of higher order terms on synchrotron tune

Betatron tunes:
- approximate the measurements
- best agreement for lowest \( \alpha \)
- largest difference in the horizontal betatron tune
- emphasis in modeling on synchrotron tune
Higher order alpha

\[ f_s(f_{RF}) \rightarrow \alpha_p(dp/p) = \alpha_p(\delta) \]

\[ \alpha_p = \frac{dL/L}{dp/p} \quad \alpha_c = \frac{\Delta L/L_0}{\Delta p/p_0} \quad \Rightarrow \quad \alpha_p = \frac{1 + \delta}{1 + \alpha_c \delta} \frac{d(\alpha_c \delta)}{d(\delta)} \]

\[ \Rightarrow \alpha_c = \alpha_0 + \alpha_1 \delta + \alpha_2 \delta^2 + \alpha_3 \delta^3 + \ldots \]

\[ \alpha_0 = +(6.28 \pm 0.0014) \cdot 10^{-3} \]
\[ \alpha_1 = -(99 \pm 6) \cdot 10^{-3} \]

\[ \alpha_0 = +(0.447 \pm 0.004) \cdot 10^{-3} \]
\[ \alpha_1 = -(20 \pm 1) \cdot 10^{-3} \]
\[ \alpha_2 = -(2,710 \pm 300) \cdot 10^{-3} \]
\[ \alpha_3 = -(190,000 \pm 90,000) \cdot 10^{-3} \]
Longitudinal phase space

- Low $\alpha_0 \rightarrow$ higher order terms have to be considered
- Additional fixpoints at: $\frac{\Delta p}{p_{fix}} \approx \frac{\alpha_0}{\alpha_1} = -0.036$
- Measurement: $\frac{\alpha_0}{\alpha_1} = -0.023 \pm 0.001$
Dynamic aperture

model A

model C

model D

model E
DA for different chromaticities

- Small chromaticities enlarge dynamic aperture
- Low $\alpha_0$ optics are more sensitive to chromaticity changes
Summary

- Regular low-alpha user operation
- Characterized the properties of the CSR
  - calculated and observed bursting/stable threshold
  - investigated radiation behavior with HEB
- Bunch shape and length measurements with streak camera
- Spectral measurements, comparison multi and single bunch
- Beam based modeling of the low-alpha mode
  - higher order momentum compaction
  - second stable fixpoints in long. phase space
  - dynamic aperture investigation
Outlook

Simulations of microbunching instability and bursting behavior with a Vlasov-Solver

- Bunch to bunch interaction?

HEB leading bunch analysis, bursting triggering with additional wake fields

Single shot measurements of electron distribution with electrooptical sampling