Report on the ICFA/FLS workshop:

Coherent synchrotron radiation and its impact on the dynamics of high brightness beams

(http://www.desy.de/csr)

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Motivation

• gather people working on simulation theory and experiment,

• review and benchmark the various algorithms used in simulation codes,

• review the current status of theoretical model,

• analyze the potential CSR-induced instability,

• discuss how to manage/cure CSR-induced effect in new accelerator (LCLS, TESLA,...),

• review the current experimental work and discuss possible new experiment.
Background (CNT’D)

- radiation emitted at a retarded time can interact with e- ahead in the bunch.
- \( S' \) e- bunch at present time
- \( S' \) e- bunch at retarded time

- interaction effective if bunch travel on a curved path for a distance > \( L_o \sim (24\sigma_z\rho)^{1/3} \)
  self-interaction via field component with \( \lambda \sim \sigma_z \).

- NA: TTF1, \( \rho=1.6 \text{ m} \), \( \sigma_z = 250\mu\text{m} \), \( L_o \sim 0.25\mu\text{m} \)
  so \( L_o > \) path length in bend.
Background (CNT’D)

the csr-induced energy loss along the bunch is:

\[
\frac{dE}{cdt}(s) = -\frac{2Ne^2}{\sqrt{2\pi}3^{1/3}\rho^{2/3}\sigma_z^{4/3}}F\left(s/\sigma_z\right),
\]

where:

N: number of e-
R: bending radius
\(\sigma_z\): rms bunch length
\(F(x) = \int_{-\infty}^{x} \frac{dx'}{(x-x')^{1/3}} \frac{\partial}{\partial x'} \exp\left(-\frac{x'^2}{2}\right)\)

example: 1 nC, \(\sigma_z = 250 \mu m\), \(\rho = 1.6 m\)
Background (CNT’D) (from Dohlus)

Transient Longitudinal Field: Injection

\[ \hat{x} = \frac{s}{\sqrt[3]{24R_0^2\sigma}} \]

\[ E_\parallel / E_c \]

\[ c_0 t / \sigma \]
Background (CNT’D) (from Dohlus)

Transient Longitudinal Field: Ejection

\[ \hat{x} = \frac{s}{\sqrt[3]{24 R_0^2 \sigma}} \]

\[ \frac{E_\parallel}{E_c} \]

\[ c_0 t / \sigma \]
CSR-induced instability (Schneidmiller et al.)

\[ Z: \text{impedance} \]
\[ R_{56} = \frac{\partial s}{\partial \delta} \]

- initial density \( (\rho_o) \) modulation \( \xrightarrow{Z(\omega)} \gamma \) modulation
- \( \gamma \) modulation \( \xrightarrow{R_{56}} \rho_f \) modulation
- if one forgets about phase relations \( \rightarrow \) define the gain \( G = \frac{|\rho_f|}{|\rho_o|} \)
\[ G(\omega) \sim \frac{R_{56}\omega Z(\omega)}{c\gamma o} \]
\[ \rightarrow G(\omega) \text{ can be } \gg 1 \]
 CSR-induced instability – Gain vs $s$

- $\lambda = 4 \, \mu m$
- $\lambda = 2 \, \mu m$
- $\lambda = 10 \, \mu m$
- $\lambda = 1 \, \mu m$
CSR-induced instability – Gain curve

start with: \( I(t) = I_o(t) \times (1 + m \times \cos(2\pi c/\lambda \times t)) \)

1: cold beam \( <\delta^2>^{1/2} = 0 \)
2: beam with \( <\delta^2>^{1/2} = 2 \times 10^{-5} \)

• triangles and squares: M. Dolhus 1D-code
• red squares: TraFiC\(^4\)
# Simulation codes

<table>
<thead>
<tr>
<th>Code Name</th>
<th>Algorithm</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>JLAB Code (R. Li)</td>
<td>self cons. 2D tracking</td>
<td>insensitive to structure $&lt; \sigma_z^{MA}$</td>
</tr>
<tr>
<td>TraFiC$^4$</td>
<td>self cons. 3D tracking</td>
<td>insensitive to structure $&lt; \sigma_z^{MA}$</td>
</tr>
<tr>
<td>Tredi (ENEA)</td>
<td>3D macr. tracking (?)</td>
<td>CSR still in test stage</td>
</tr>
<tr>
<td>Elegant (Borland)</td>
<td>1-D model tracking</td>
<td>overestimates long. field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no trans. dep. long. field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no transverse field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q-density frozen a $t$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BUT VERY FAST !</td>
</tr>
<tr>
<td>M. Dohlus 1Dmod</td>
<td>1-D model Green function</td>
<td>idem as elegant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>back track several dipoles</td>
</tr>
<tr>
<td>P. Emma MATLAB</td>
<td>1-D model tracking</td>
<td>idem as elegant</td>
</tr>
</tbody>
</table>
One dimensional models

• project particles on $s$ and compute (=binning) the charge density $\Lambda(s)$
• apply the rigid line charge formula
  $\rightarrow$ assume the bunch shape has not varied from last time step
• apply an "energy kick" only
• need a lot of (point-like) particles to accumulate statistics (remember one needs to compute $\frac{\partial \Lambda}{\partial s}$...)
Two/Three dimensional Self consistent models

1 bunch is reduced to an ensemble of (e.g. Gaussian) distributed sources
2 track initial dist. sources with no field
3 new extrapolated path
4 use extrapolated path to compute field
5 track initial dist. source in field
6 compare path from (5) and (2)
7 if path has not converged
   → iterate (1) to (6) but this time:
      (2) reads ”track initial dist. sources with field generated from (6)”
transverse beam size impact (Dohlus)

CSR Field of a Tilted Thin Beam

\[ \hat{x} = \frac{\sigma_w}{\sqrt[3]{R_0 \sigma_p^2}} \]

\[ \hat{x} = 0 \]

\[ E_{CSR,||} \]

\[ E_c \]

\[ s/\sigma \]

\[ x \]

\[ s \]

\[ w \]

\[ p \]

\[ R_0 \]

\[ \sigma_p \]

\[ \sigma_w \]

\[ c \]

\[ E \]

\[ E \parallel , \]

\[ s \]

\[ 3 \]

\[ 2 \]

\[ 0 \]

\[ \hat{p} \]

\[ w \]

\[ R \]

\[ x \]

\[ \hat{x} = 0 \]

\[ \hat{x} = 0.5 \]

\[ \hat{x} = 1 \]

\[ \text{e.g. } R_0 = 10 \text{ m, } \sigma_p = 100 \mu \text{m, } \sigma_w = 2 \text{ mm } \rightarrow \hat{x} = 0.43 \]
code comparison on a simple 5 GeV chicane

<table>
<thead>
<tr>
<th>code name</th>
<th>$\langle \delta \rangle$</th>
<th>$\sigma_\delta$</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>mm-mrad</td>
</tr>
<tr>
<td>TraFiC4</td>
<td>-0.058</td>
<td>-0.002</td>
<td>1.40</td>
</tr>
<tr>
<td>TREDI</td>
<td>-0.041</td>
<td>0.017</td>
<td>2.3</td>
</tr>
<tr>
<td>Program by Li</td>
<td>-0.056</td>
<td>-0.006</td>
<td>1.32</td>
</tr>
<tr>
<td>elegant</td>
<td>-0.045</td>
<td>-0.0043</td>
<td>1.55</td>
</tr>
<tr>
<td>Program by Emma</td>
<td>-0.043</td>
<td>-0.004</td>
<td>1.52</td>
</tr>
<tr>
<td>Program by Dohlus</td>
<td>-0.045</td>
<td>-0.011</td>
<td>1.62</td>
</tr>
</tbody>
</table>
EXPERIMENTS

• characterize beam properties **before** and after the magnetic compression: measure emittance, energy, energy spread, bunch length,

• try to get a better handle on full phase space (do tomography when possible, or simply look for correlation i.e. between energy and bending plane coordinate – using a spectrometer in the orthogonal plane of the chicane bending plane)

• measure so dependence of the above parameter versus: amount of compression, charge, incoming lattice functions,

• characterize the coherent emission (power, polarization, dependence versus parameter being varied).
experiment at CTF-2 of CERN (L. Gröning)
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Observables after bunch compressor (5 nC):

- $q_{\text{bunch}} = 5 \text{nC}$
- Exp. CTF II
- TraFiC
experiment at CTF-2 of CERN (L. Gröning)

Bunch energy spectra after compressor (5 nC):

$$dN/dp$$ [arb. units]
experiment at DUV-FEL of BNL/NSLS (W. Graves)

SDL FACILITY

Goal is to reach deep UV wavelength using High Gain Harmonic Generation (HGHG) process seeded by conventional laser for full longitudinal coherence.

Currently commissioning undulator with SASE at 400 nm.
experiment at DUV-FEL of BNL/NSLS (W. Graves)
experiment at DUV-FEL of BNL/NSLS (W. Graves)

IR Spectrum from scanning interferometer courtesy of L. Carr (10 minutes/scan).

Mild compression case shows ~7 periods in ~1 ps = 45 um wavelength.

Strong compression case shows ~5 periods in 0.8 ps = 60 um wavelength.

Data from March, 2001. Charge = 250 pC.
experiment at LEUTL of Argonne/APS (M. Borland)

APS Linac and Bunch Compressor

L1gun 30 MeV
APS Linac and Bunch Compressor
APS CSR Experiments and Comparison with Simulation M. Borland
L4 L5
L2
150 MeV

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experiment at LEUTL of Argonne/APS (M. Borland)

- used a scaled PARMELA long phase space (scaling as free parameters) to fit $\sigma_z$, $\delta$ data.
- compared so-simulated emittance number with data
  → found decent agreement.
experiment at LEUTL of Argonne/APS (M. Borland)

- Images as L2 phase is varied from over-compression to decompression

- Shot-to-shot variation in images at 266pC/bunch
experiment at LEUTL of Argonne/APS (M. Borland)

• Simulation of a phase scan with 200pC beam, $R_s = -65$mm, B4 fully downstream.

• Simulation with 1nC beam, same conditions.
experiment at TTF

- RF gun
- Booster cavity
- Dump
- Laser
- E=17MeV
- Acc #1
- Acc #2
- Bunch Compressor
- OTR1
- OTR2
- E~135 MeV
- CTR1
- Undulator
- E~230 MeV
- OTR/FLU3
- Beam transverse density monitor (OTR/fluorescent flag)
- Variable Phase Shifter
- High energy Spectrometer
- FEL
- Dump
experiment at TTF

- energy spread vs $\phi_{ACC1}$
- fragments $\sim$ max compr. phase
experiment at TTF

4th bend
mirror
grid polarizer
Suprasil window
air
vacuum
e- beam

pyroelectric
detector

only bending plane polarization transmitted

only vertical polarization transmitted

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experiment at TTF

Comparison between measurements and TraFiC4 simulations

- MEAS.
- SIMU
  - spectro exit
  - bc exit

Population [a.u.]

$\Delta E$ [MeV] (zero arbitrary)
The cures?

- double chicane with transform,
- small gap vacuum chamber ("shielding" effect),
- to reduce micro-bunching (if it turns out to be a problem and not a simulation artifact): LCLS (P. Emma) foreseen to incorporate a compact (1 m) wiggler chicane (with 4 T field) to increase the local energy spread ($\times 10$).
Summary

- theory: simple analytical model widely use for semi-analytic calculation, effort toward: a 2D semi-analytic model, and the understanding of the "transverse force cancellation",

- simulation: many code have been developed but not thoroughly compared up to now (a working group as been settled and is working on this comparison) – observation of micro-bunching in simulations should be analyzed with care,

- experiment: few facilities have dedicated diagnostic to study the impact of bunch compressor; still sparse data for thorough comparison with simulation/theory