Influence of a Space Charge Effect in a Femtosecond Electron Beam on Coherent Transition Radiation Spectrum

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Motivations and goals

Top Goal:

- Development of radiation source based on compact accelerator.

Subgoals:

1. estimation of bunch length in experimental area using ASTRA software for usual settings of LUCX facility;
2. optimization of LUCX parameters for suppression of space charge effect;
3. demonstration how the beam dynamics could influence on coherent radiation of electron bunches.
Report outline:

1. ASTRA simulation;
2. Experimental test;
3. Discussions and conclusion.
ASTRA - A Space Charge Tracking Algorithm written by Klaus Flöttmann from DESY (Germany)\textsuperscript{1}.

The software allows tracking charge particles bunches through different beam line components. Plus it permits to take into account space charge effect.

\textsuperscript{1}K. Flöttmann \textit{ASTRA} (DESY, Zeuthen, 2013)
We could change the next parameters in real experiment:

- solenoid current;
- bunch charge (from a dark current to 400 pC);
- maximum value of an electric field strength on the cathode (from 60 to 120 MV/m);
- laser spot size on the cathode (from $340 \times 420 \, \mu m^2$ to several mm);
- laser pulse duration (from 50 to 200 fs);
- laser pulse energy.
Electron distributions in bunch

Simulation parameters: laser pulse is 100 fs, laser spot size is $450 \times 450 \, \mu m^2$, $Q = 25 \, pC$, $MaxB = 0.225 \, T$, $MaxE = 77 \, MV/m$, $z = 1.31 \, m$. 
Simulation parameters: $Q = 25$ pC, $t = 100$ fs, $\sigma_x^l = \sigma_y^l = 0.45$ mm, $\text{MaxE} = 80$ MV/m, RF gun phase = 30 deg., $z = 1.72$ m.
Simulation parameters: MaxB=0.233, t=100 fs, $\sigma^l_x = \sigma^l_y = 0.45$ mm, MaxE=80 MV/m, RF gun phase= 30 deg., $z = 1.31$ m.
Charge scan for different value of maximum amplitude of electric field strength on the cathode

Simulation parameters: MaxB=0.2254, t=100 fs, $\sigma_x = \sigma_y = 0.45$ mm, MaxE=80 MV/m, RF gun phase= 30 deg., $z = 1.31$ m.
Simulation parameters: $Q=25$ pC, $\text{Max}\text{B}=0.2254$, $t=100$ fs, $\sigma_x^l = \sigma_y^l = 0.45$ mm, $\text{Max}\text{E}=80$ MV/m, RF gun phase= 30 deg., $z = 1.31$ m.
Simulation summary

A Magnetic field in solenoid allows compensate transverse size of electron bunches without any effects on longitudinal size;

B Increase of bunch charge using laser technique would increase the space charge forces in bunch;

C The laser pulse length does not influence on bunch length (in reasonable range);

D Transform laser spot size on the photocathode we could suppress space charge effect in electron bunches.

Let’s check!
Electron beam parameters:

- One bunch operation mode;
- Beam energy (RF gun out) is 7.9 MeV ⇒ maximum value of electric field strength on the cathode (MaxE) is 80 MV/m;
- Transverse electron beam size on the luminophore screen is 230 µm (gauss distribution);
- Bunch charge is 60 pC which is measured by FCT.
Form-Factor for coherent transition radiation

Coherent Transition Radiation:

\[
\frac{d^2W_{CTR}}{d\omega d\Omega} = \left[ N + N(N - 1) F^2(k) \right] \frac{d^2W_{TR}}{d\omega d\Omega},
\]

where \(F(k)\) is the form-factor. Formfactor for transition radiation was calculated analytically\(^2\):

\[
F(k) = F(\lambda, \theta, \eta, \psi)
= \exp \left[ - \frac{2\pi^2}{\lambda^2} \left( \sigma_x^2 \left( \frac{\tan \theta}{\beta} - \cos \psi (\cos \eta \tan \theta + \sin \eta) \right)^2
+ \sigma_y^2 \sin^2 \psi \cos^2 (\eta - \theta) + \frac{\sigma_z^2}{\beta^2} \right) \right],
\]

where is \(\lambda\) the wavelength, \(\theta\) is angle of incidence, \(\eta\) is the angle of observation, \(\psi\) is the azimuth angle of observation.

Orientation dependence of TR

![Graph showing orientation dependence of TR](graph.png)
Laser spot size on the virtual cathode

Relative distance is 12 mm

Relative distance is 13.5 mm
Laser spot size scan
Charge scan: comparison between experimental data and simulation results

Relative distance is 12 mm

Simulation parameters: Q=60 pC, MaxB=0.2335, t=100 fs, $\sigma_x = 344.91 \, \mu m$, $\sigma_y = 420.50 \, \mu m$, MaxE=80 MV/m, RF gun phase=30 deg., $z = 1.31 \, m$. 
Fit function: \( y = a + b^c \).

Simulations:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>-0.84</td>
<td>0.34</td>
</tr>
<tr>
<td>b</td>
<td>29.7</td>
<td>7.83</td>
</tr>
<tr>
<td>c</td>
<td>0.64</td>
<td>0.10</td>
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</tbody>
</table>

Experimental data:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>-0.84</td>
<td>0.34</td>
</tr>
<tr>
<td>b</td>
<td>23.95</td>
<td>6.22</td>
</tr>
<tr>
<td>c</td>
<td>0.57</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Relative distance is 13.5 mm

Simulation parameters: $Q=60$ pC, $\text{MaxB}=0.228$, $t=100$ fs, $\sigma^l_x = 727.42 \, \mu\text{m}$, $\sigma^l_y = 0.757.21 \, \mu\text{m}$, $\text{MaxE}=80$ MV/m, RF gun phase= 30 deg., $z = 1.31$ m.
Fit function: $y = a + b^c$.

Simulations:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimation</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$-0.55$</td>
<td>$0.47$</td>
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<tr>
<td>b</td>
<td>$66.92$</td>
<td>$10.55$</td>
</tr>
<tr>
<td>c</td>
<td>$0.77$</td>
<td>$0.08$</td>
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</table>

Experimental data:

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<tr>
<th>Parameter</th>
<th>Estimation</th>
<th>Standard Error</th>
</tr>
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<tbody>
<tr>
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<td>$0.19$</td>
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<tr>
<td>b</td>
<td>$71.40$</td>
<td>$5.66$</td>
</tr>
<tr>
<td>c</td>
<td>$0.79$</td>
<td>$0.04$</td>
</tr>
</tbody>
</table>
Conclusions:

- Astra software allows to estimate the bunch parameters for our experimental conditions;
- In the case of LUCX facility, the space charge effect is the main barrier to produce intense radiation source in THz range;
- Laser technique is not suitable to confirm quadratic dependence of coherent radiation intensity;
- However, laser techniques allows to suppress space charge effect in femtosecond electron bunches.

Future plans:

- We are going to decrease space charge effect in the RF gun using spatial reshaping technique for laser pulse;
- We make optimization of the LUCX settings for the multi-bunches operation mode (two and four bunches).
Thank you for attention!