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

M. Shevelev[1], A. Aryshev[1], Y. Honda[1,2], N. Terunuma[1,2] and J. Urakawa[1]

[1]High Energy Accelerator Research Organization (KEK)

[2]The Graduate University for Advanced Studies (SOKENDAI)

Tsukuba, Ibaraki, $305-0801$, Japan

30 September 2016

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.

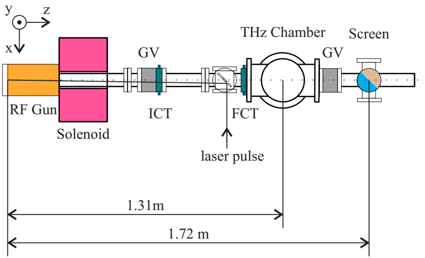
ASTRA

ASTRA - A Space Charge Tracking Algorithm written by Klaus Flöttmann from DESY (Germany)[1].

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

[1] K. Flöttmann *ASTRA* (DESY, Zeuthen, 2013)

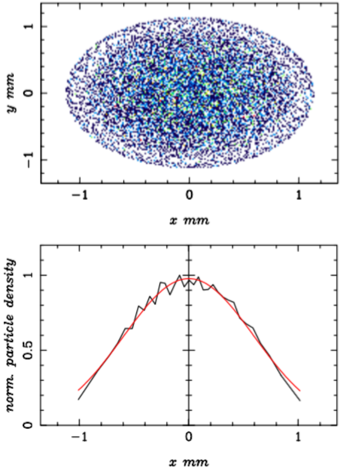
LUCX facility and controlled settings



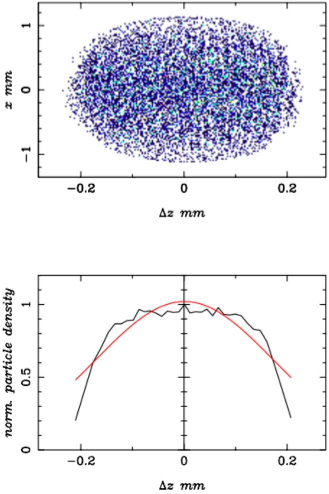
We could change the next parameters in real experiment:

- 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 340×420 μm^2 to several mm);
- laser pulse duration (from 50 to 200 fs);
- laser pulse energy.

Transverse distribution

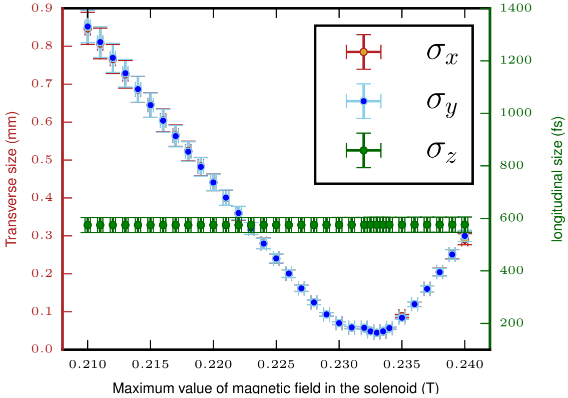


Longitudinal distribution



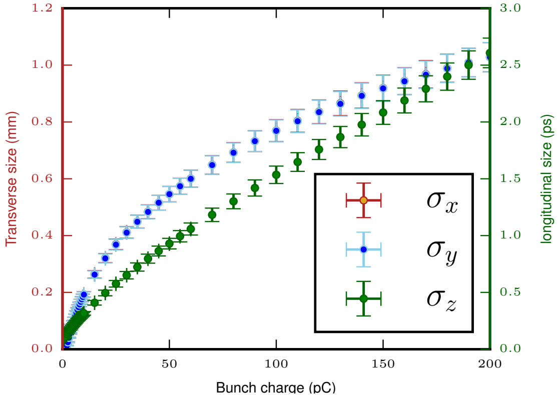
Simulation parameters: laser pulse is 100 fs, laser spot size is $450 \times 450\ \mu$m^2, $Q = 25$ pC, MaxB$= 0.225$ T, MaxE$= 77$ MV/m, $z = 1.31$ m.

Solenoid scan



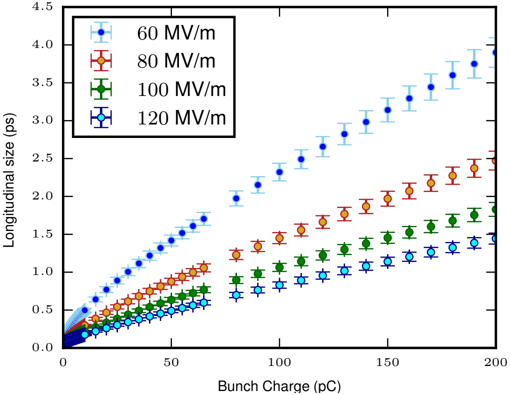
Simulation parameters: Q$=25$ pC, t$=100$ fs, $\sigma_x^l = \sigma_y^l = 0.45$ mm, MaxE$=80$ MV/m, RF gun phase$=30$deg., $z = 1.72$ m.

Charge scan



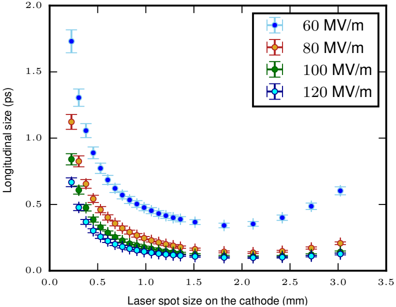
Simulation parameters: MaxB=0.233, t=100 fs, $\sigma_x^l = \sigma_y^l = 0.45$ mm, MaxE=80 MV/m, RF gun phase= 30 deg., $z = 1.31$ m.

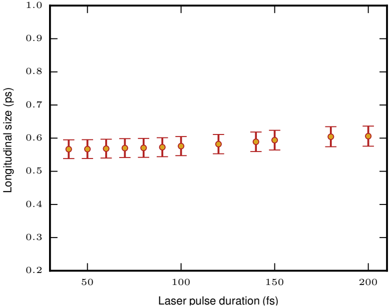
Charge scan for different value of maximum amplitude of electric field strength on the cathode



Simulation parameters: MaxB=0.2254, t=100 fs, $\sigma_x^l = \sigma_y^l = 0.45$ mm, MaxE=80 MV/m, RF gun phase= 30 deg., $z = 1.31$ m.

Laser settings





Simulation parameters: Q=25 pC, MaxB=0.2254, t=100 fs,

$\sigma_x^l = \sigma_y^l = 0.45$ mm, MaxE=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;

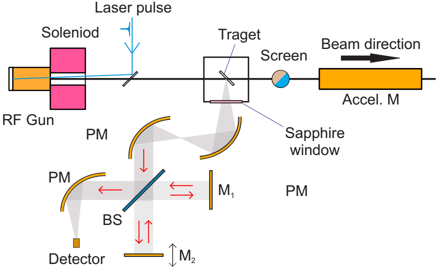
B Increase of bunch charge using laser technique would increase the space charge forces in bunch;

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!

Experimental scheme and electron beam settings



Electron beam parameters:

- One bunch operation mode;
- Beam energy (RF gun out) is 7.9 MeV $\Rightarrow$ 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 iss 60 pC which is measured by FCT.

Form-Factor for coherent transition radiation

Coherent Transition Radiation:

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

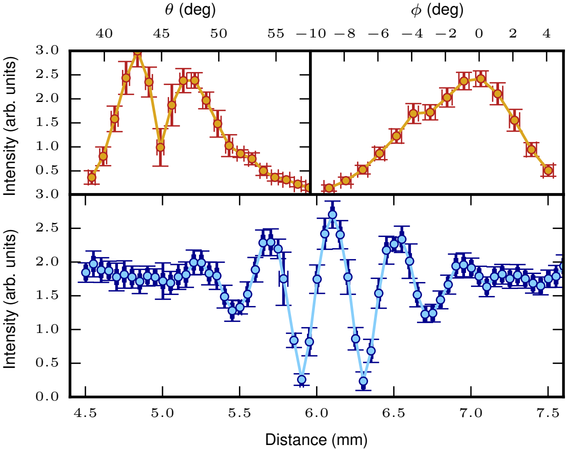
where $F\left(k\right)$ is the form-factor. Formfactor for transition radiation was calculated analytically[2]:

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

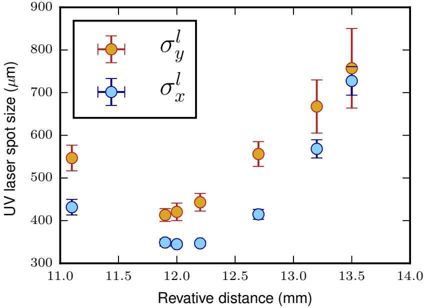
where is λ the wavelength, θ is angle of incidence, η is the angle of observation, ψ is the azimuth angle of observation.

[2] G. Naumenko *Adv. Material Res.* **1084** (2015) or A. Potylitsyn *JETP Lett.* **103** (2016)

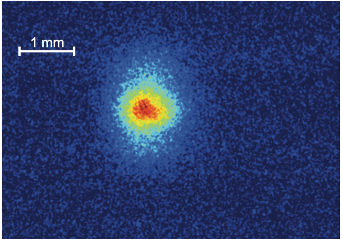
Orientation dependence of TR



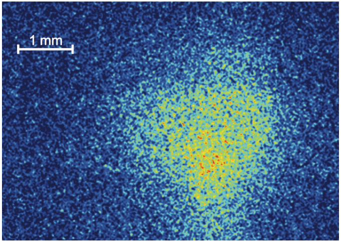
Laser spot size on the virtual cathode



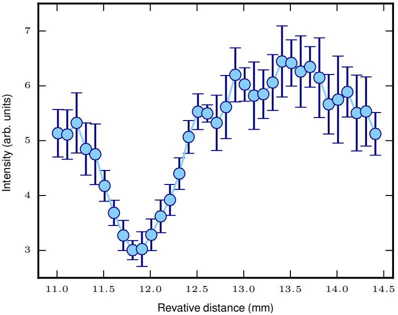
Relative distance is 12 mm

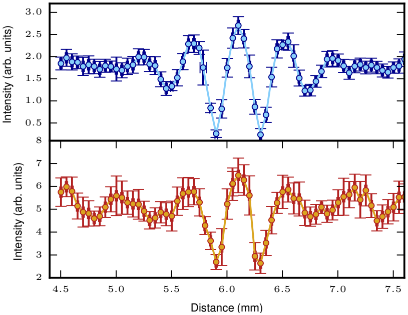


Relative distance is 13.5 mm



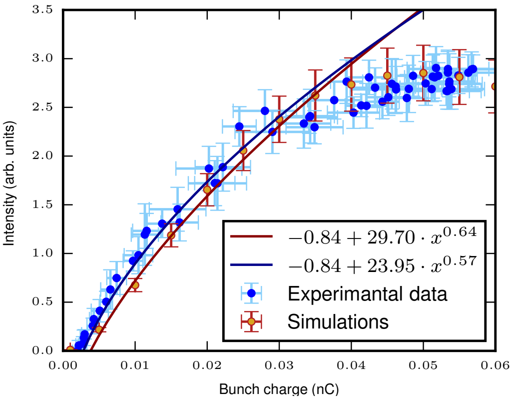
Laser spot size scan





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, $\sigma_x^l = 344.91$ μm, $\sigma_y^l = 420.50$ μm, MaxE$=80$ MV/m, RF gun phase$=30$ deg., $z = 1.31$ m.

Fit function: $y = a + b^c$.
Simulations:

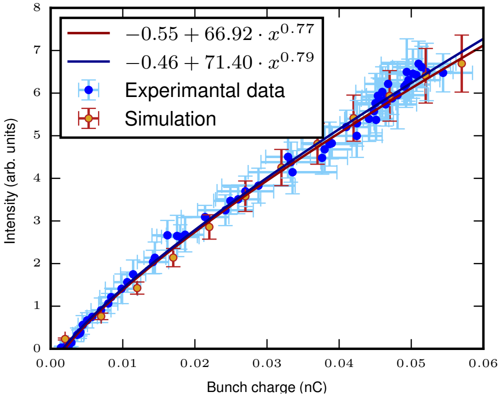
Parameter	Estimation	Standard Error
a	-0.84	0.34
b	29.7	7.83
c	0.64	0.10

Experimental data:

Parameter	Estimation	Standard Error
a	-0.84	0.34
b	23.95	6.22
c	0.57	0.10

Charge scan

Relative distance is 13.5 mm



Simulation parameters: Q$=60$ pC, MaxB$=0.228$, t$=100$ fs, $\sigma_x^l = 727.42\ \mu$m, $\sigma_y^l = 0.757.21\ \mu$m, MaxE$=80$ MV/m, RF gun phase$=30$ deg., $z = 1.31$ m.

Fit function: $y = a + b^c$.
Simulations:

Parameter	Estimation	Standard Error
a	-0.55	0.47
b	66.92	10.55
c	0.77	0.08

Experimental data:

Parameter	Estimation	Standard Error
a	-0.46	0.19
b	71.40	5.66
c	0.79	0.04

Conclusion future plans

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!