Transport of ~~the space charge dominated~~ electron beam through the LCLS-I undulator at PITZ

Progress Report

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DESY Zeuthen, 08.08.2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

- Introduction
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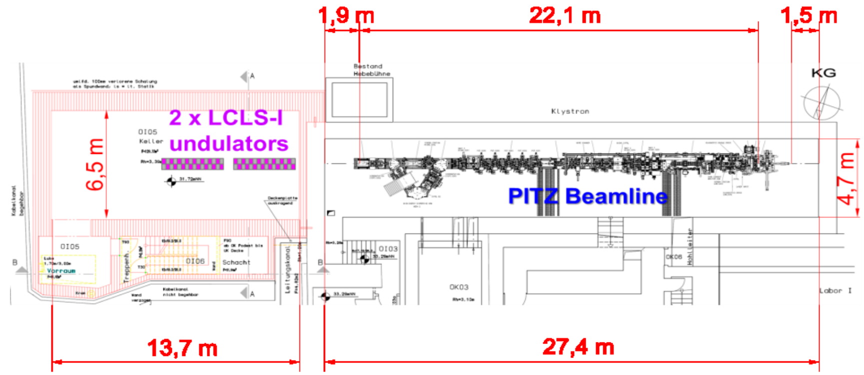
  - Motivation & goals
- Single particle simulations
  - Methodology & simulation setup (ASTRA code)
  - Results
- Electron beam simulations (w/o space charge)
  - Methodology & simulation setup (ASTRA code)
  - Results
- Summary & Outlook

Introduction

The LCLS-I undulator

Properties of the LCLS-I undulator

Properties	Details
Type	**fixed gap planar hybrid** (NdFeB)
Nominal gap	6.8 mm
K-value	**3.49**
Support diameter / length	30 cm / 3.4 m
Vacuum chamber size	11 mm x **5 mm**
Period length	**30 mm**
Poles / a module	226 poles (= **113 periods, 3.4 m**)
Total weight w/o vac. chamber	1000 kg



Layout of PITZ tunnel

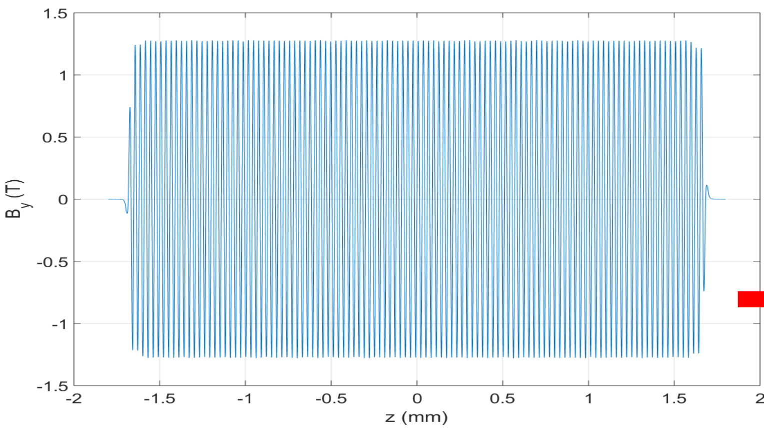
Figure of the LCLS-I undulator

Reference: LCLS conceptual design report, SLAC-0593, 2002.

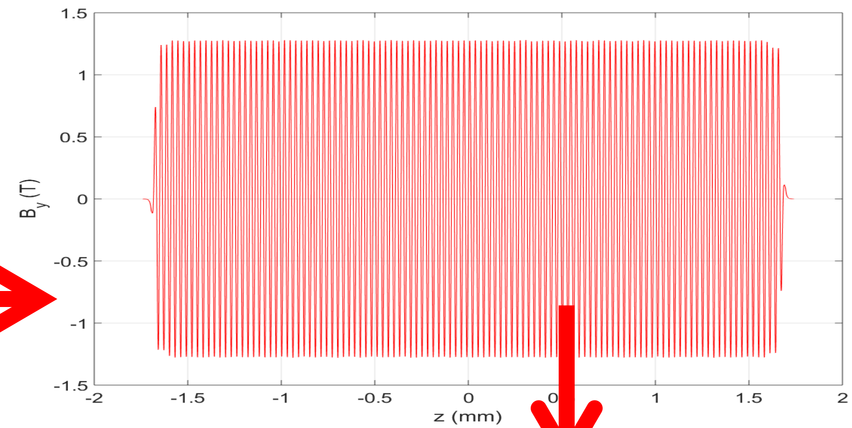
Introduction

Magnetic filed of the LCLS-I undulator

Measurement field

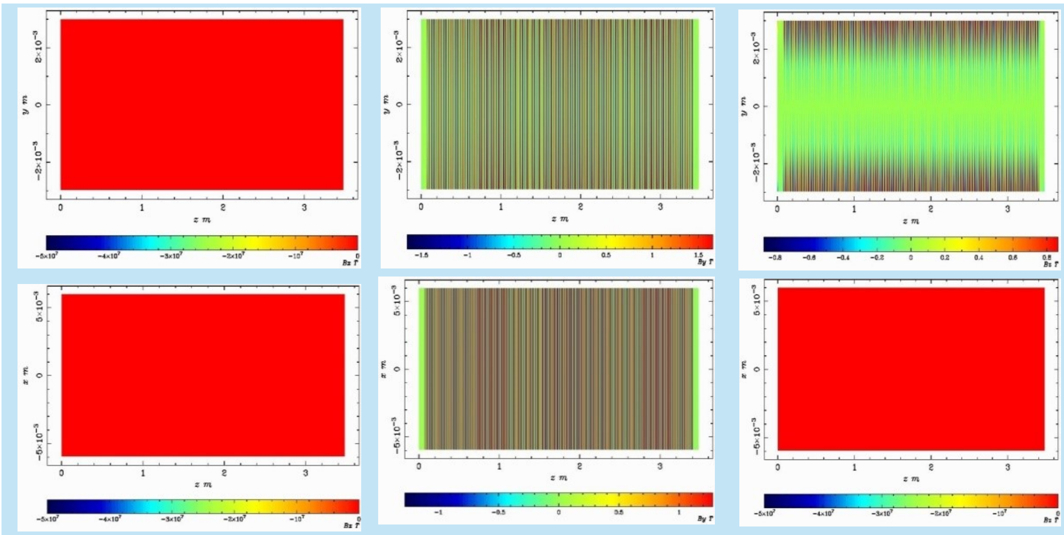


Reconstruction field



3D field

B_x B_y B_z



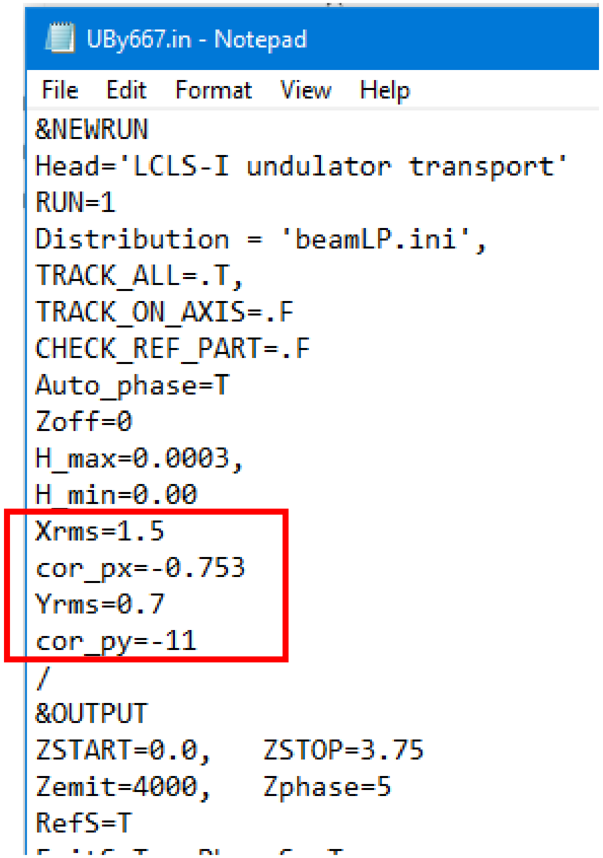
yz plane
at *x* = 0 mm

xz plane
at *y* = 0 mm

Introduction

Motivation & goals

ASTRA input file



```
UBy667.in - Notepad
File  Edit  Format  View  Help
&NEWRUN
Head='LCLS-I undulator transport'
RUN=1
Distribution = 'beamLP.ini',
TRACK_ALL=.T,
TRACK_ON_AXIS=.F
CHECK_REF_PART=.F
Auto_phase=T
Zoff=0
H_max=0.0003,
H_min=0.00
Xrms=1.5
cor_px=-0.753
Yrms=0.7
cor_py=-11
/
&OUTPUT
ZSTART=0.0,   ZSTOP=3.75
Zemit=4000,   Zphase=5
RefS=T
```

Optimize input beam which have least beam lost when traveling through the undulator.

x_{rms}	horizontal rms beam size
y_{rms}	vertical rms beam size
cor_px	horizontal correlated divergence of bunch
cor_py	vertical correlated divergence of bunch

Goals

- Determine function of *cor_px*(x_{rms}) and *cor_py*(y_{rms}) which deliver the minimum Goal Function (GF)*.
- Determine function of $x'_0(x_0)$ and $y'_0(y_0)$ which deliver the minimum GF.

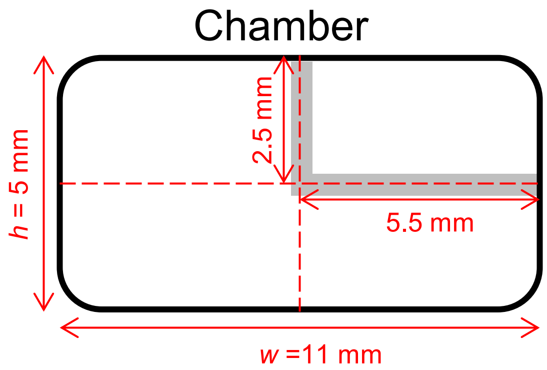
Tracking electron beam takes long simulation time. ➔ Track single electron first.

x'_0 :horizontal trajectory angle y'_0 : vertical trajectory angle

*The GF represents the area under the electron trajectory.

Single particle simulations

Methodology & Simulation setup



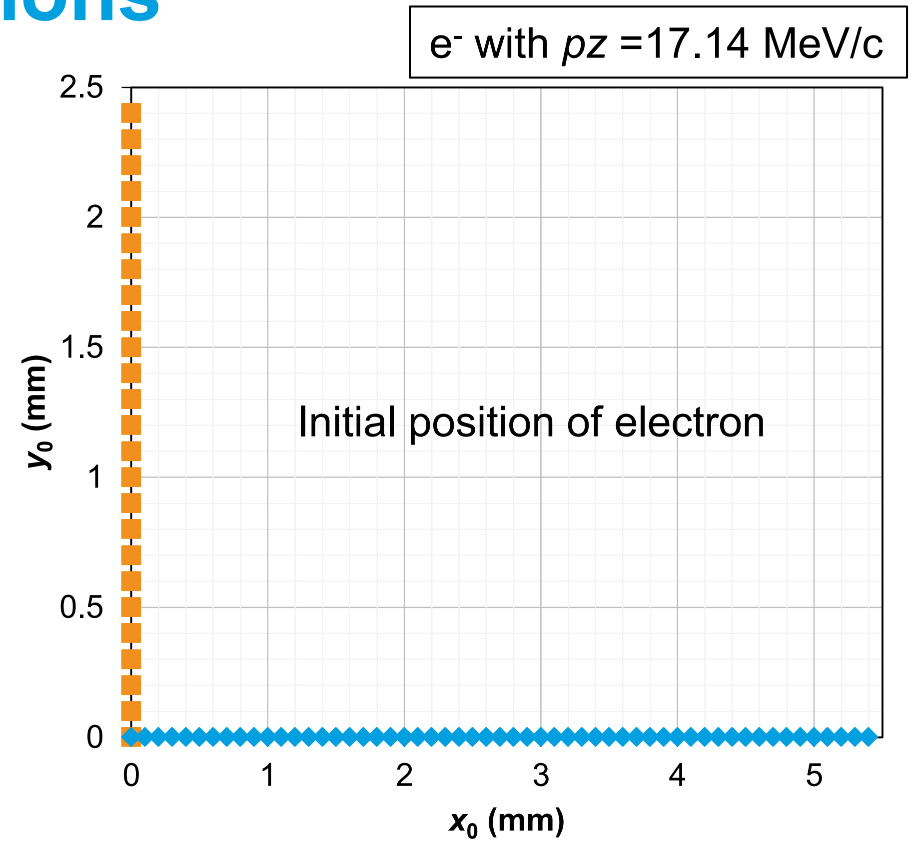
Scan on *x*-axis

x_0 = 0 to 5.4 mm (0.1 mm step size)
y_0 = 0 mm
x'_0 = -2.1 to 0.4 mrad (0.1 mrad step size)
y'_0 = 0 mrad

Scan on *y*-axis

x_0 = 0 mm
y_0 = 0 to 2.4 mm (0.1 mm step size)
x'_0 = 0 mrad
y'_0 = -11.2 to 0.3 mrad (0.1 mrad step size)

Then track the electron from z = 0 to z = 3.4 m



Goals

➤ Determine function of $x'_0(x_0)$ and $y'_0(y_0)$ which deliver the minimum GF.

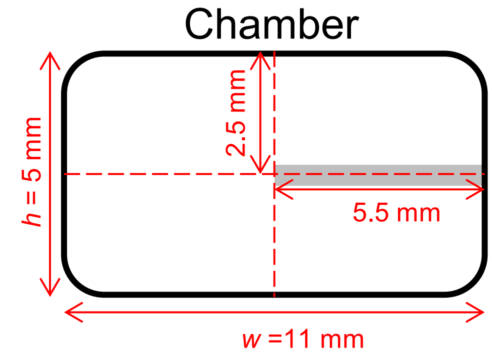
$$GF = \int \frac{|x(z)|dz}{w} + \int \frac{|y(z)|dz}{h}$$

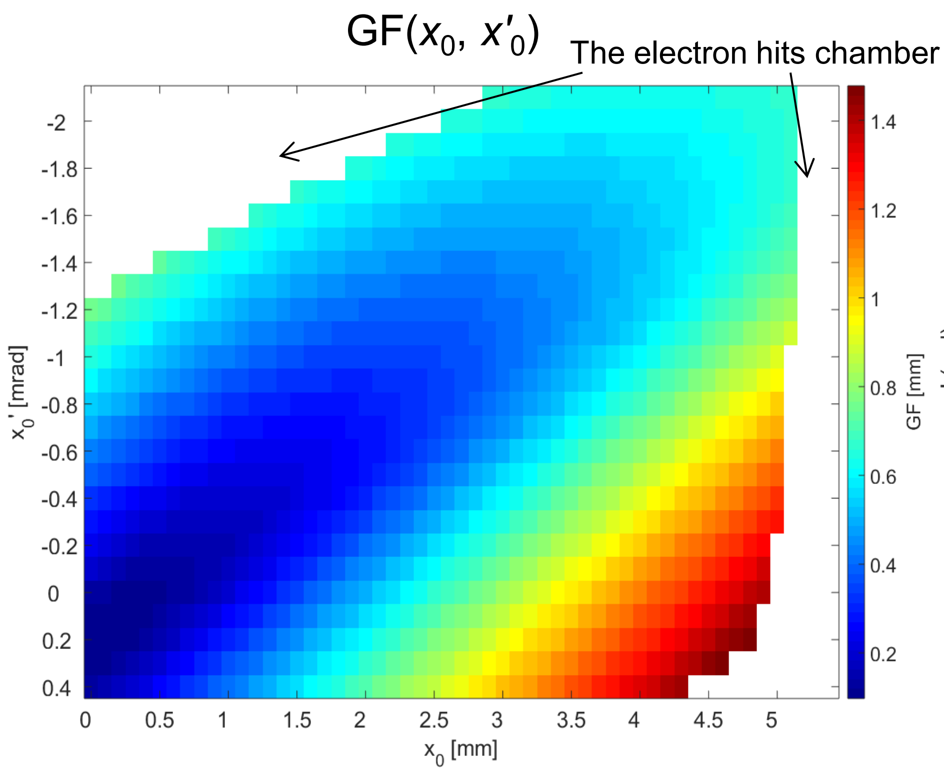
x'_0 :horizontal trajectory angle y'_0 : vertical trajectory angle

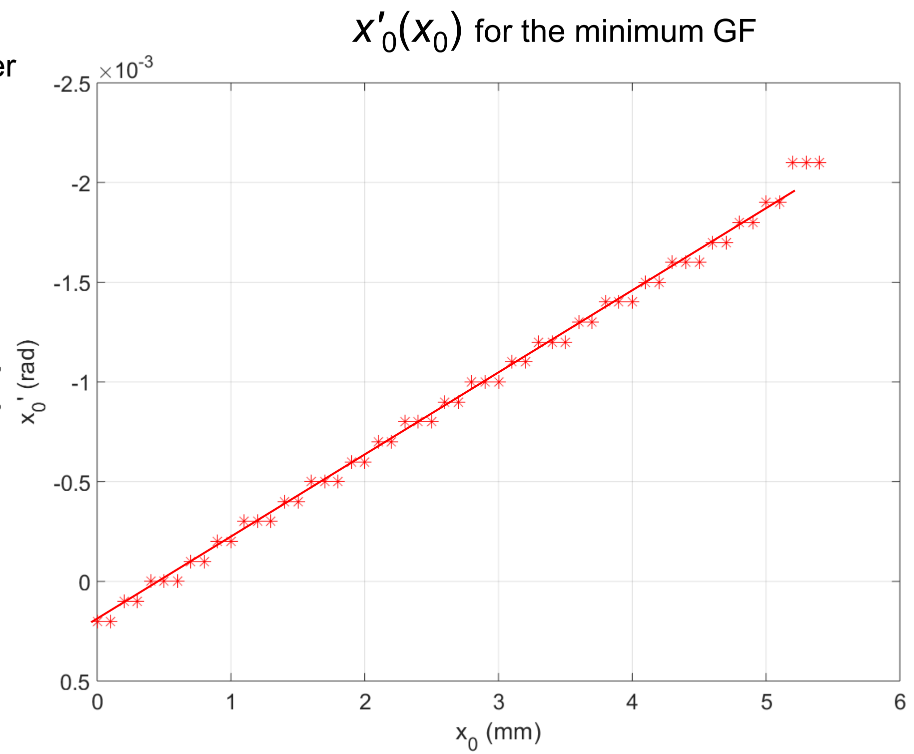
Single particle simulations

Results

Scan on *x*-axis







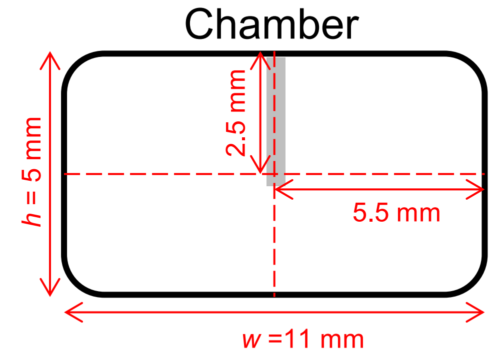
$$x'_0[mrad] = -0.4x_0[mm] + 0.2$$

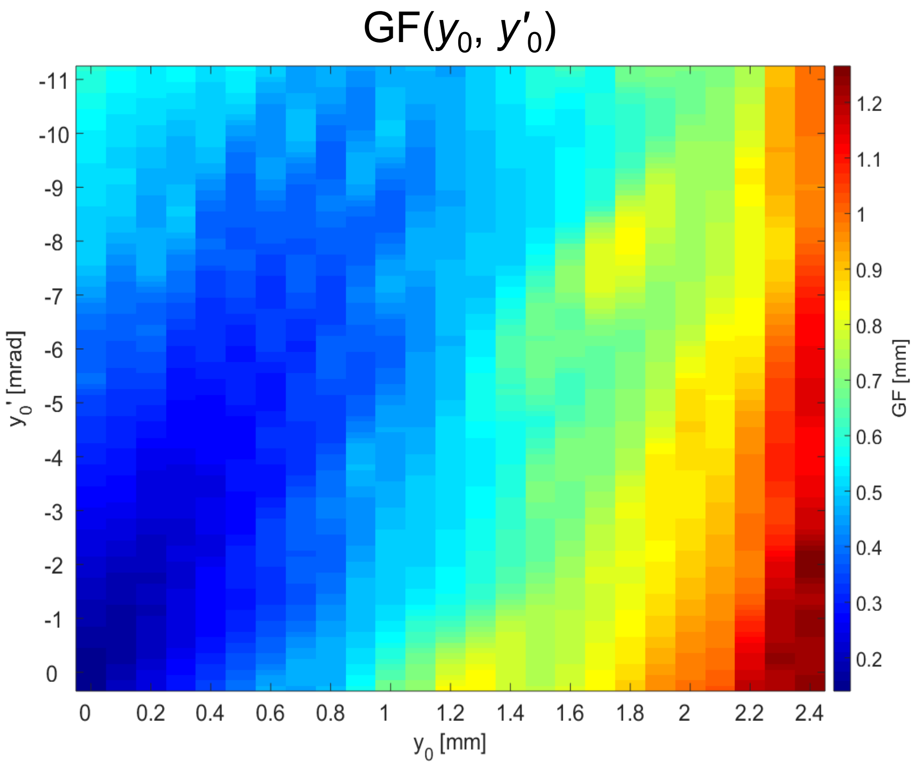
$R^2 = 0.9978$

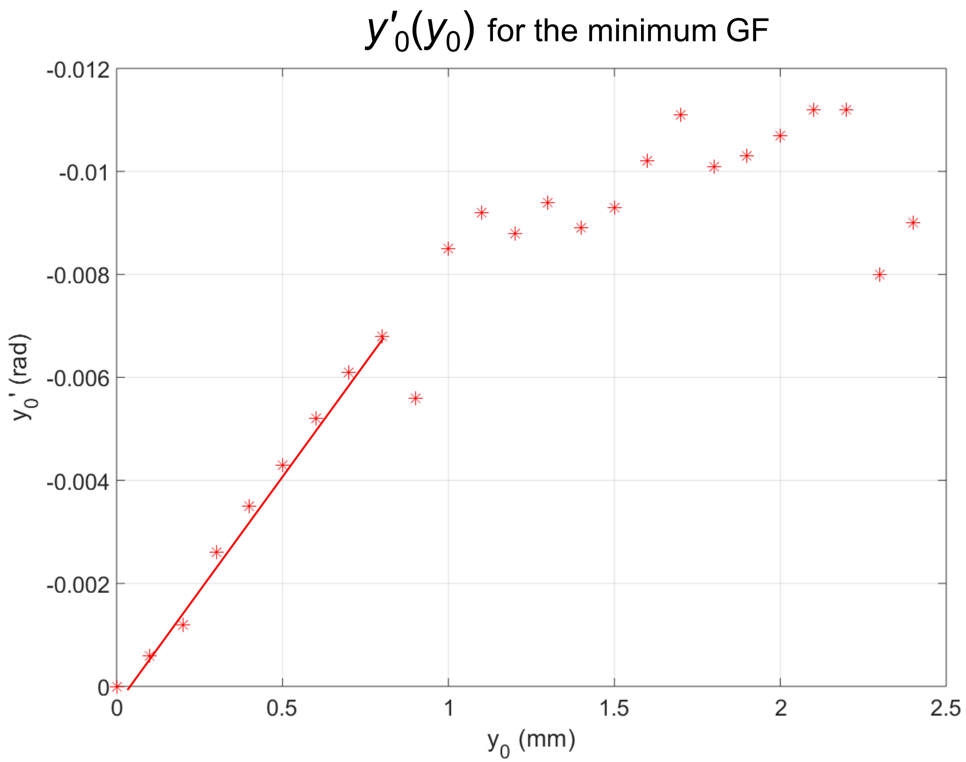
Single particle simulations

Results

Scan on *y*-axis







$$y'_0[mrad] = -8.9y_0[mm] + 0.2$$

$R^2 = 0.9947$

Electron beam simulations

Methodology & Simulation setup (ASTRA code)

beam with pz =17.14 MeV/c

$$x'_0[mrad] = -0.4x_0[mm] + 0.2$$

x'_0 → *cor_px*, x_0 → x_{rms}

$$y'_0[mrad] = -8.9y_0[mm] + 0.2$$

y'_0 → *cor_py*, y_0 → y_{rms}

1st step

x_{rms} = 0.5 to 2.5 mm (0.1 mm step size)
y_{rms} = 0.5 mm
cor_px = -2.1 to 0.4 mrad (0.1 mrad step size)
cor_py = 0 mrad

2nd step

x_{rms} = 1.5 mm
y_{rms} = 0.1 to 1.2 mm (0.1 mm step size)
cor_px = -0.753 mrad **(*cor_px*(x_{rms}) 1st)**
cor_py = -11 to 0 mrad (0.1 mrad step size)

3rd step

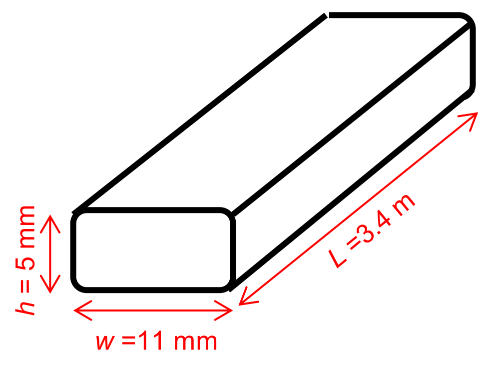
x_{rms} = 0.1 to 2.5 mm (0.1 mm step size)
y_{rms} = 0.1 to 1.2 mm (0.1 mm step size)
cor_px = ***cor_px*(x_{rms}) 1st**
cor_py = ***cor_py*(y_{rms}) 2nd**

Then track the electron beam from z = 0 to z = 3.4 m (w/o space charge)

Goals

- Determine function of *cor_px*(x_{rms}) and *cor_py*(y_{rms}).
- Minimum Goal Function (GF).

$$GF = \int \frac{x_{rms}(z)dz}{w \cdot L} + \int \frac{y_{rms}(z)dz}{h \cdot L}$$



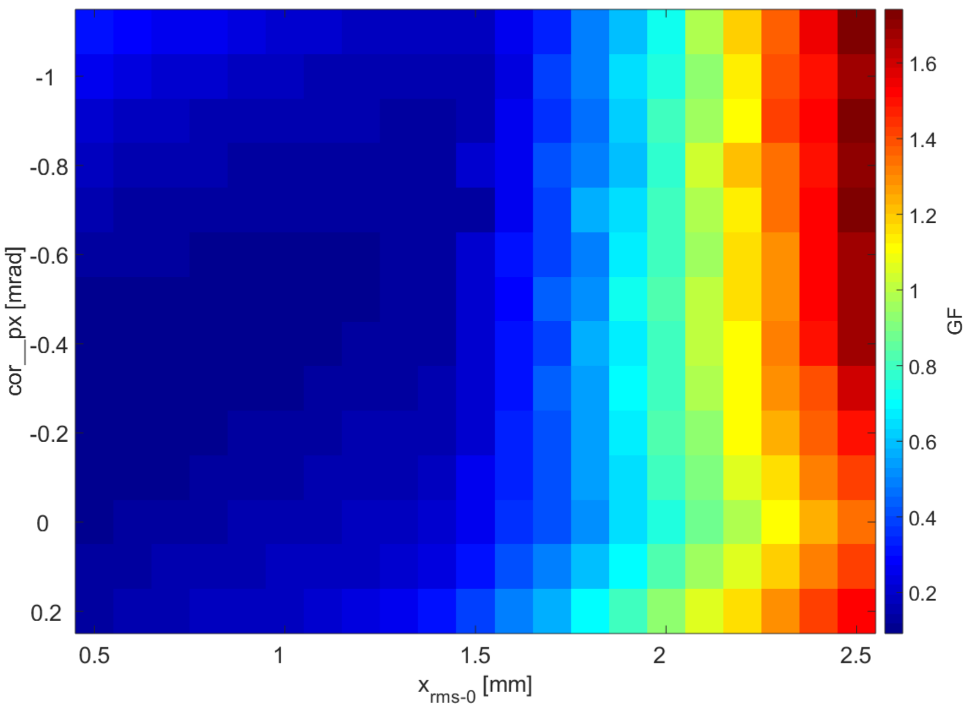
Vacuum chamber size

Electron beam simulations

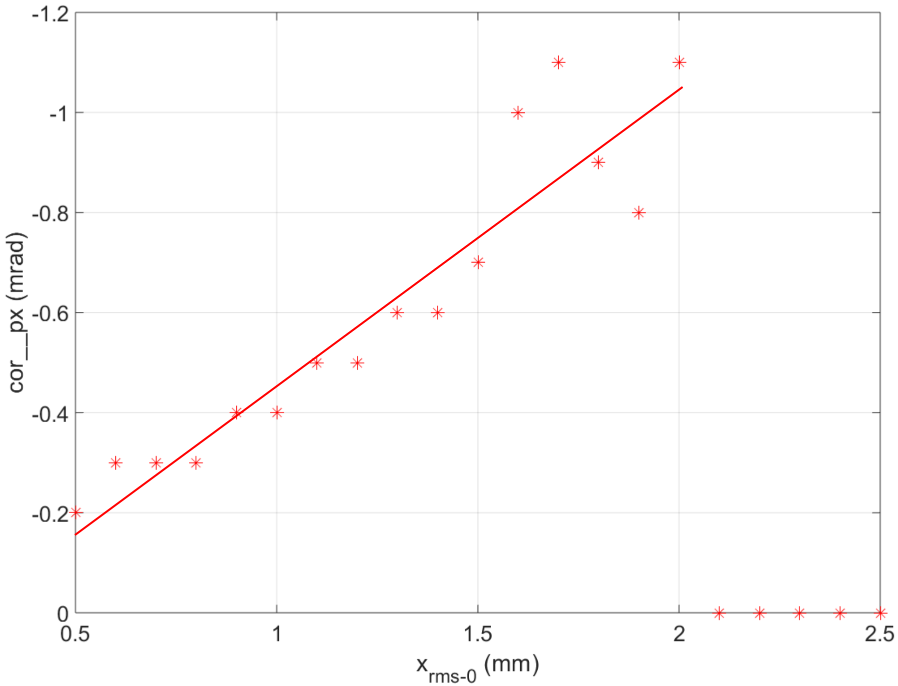
Without space charge

1st step

GF(x_{rms-0}, cor_px)



$cor\_px(x_{rms-0})$ for the minimum GF



$$cor\_px[mrad] = -0.59x_{rms-0}[mm] + 0.13$$

$R^2 = 0.88$

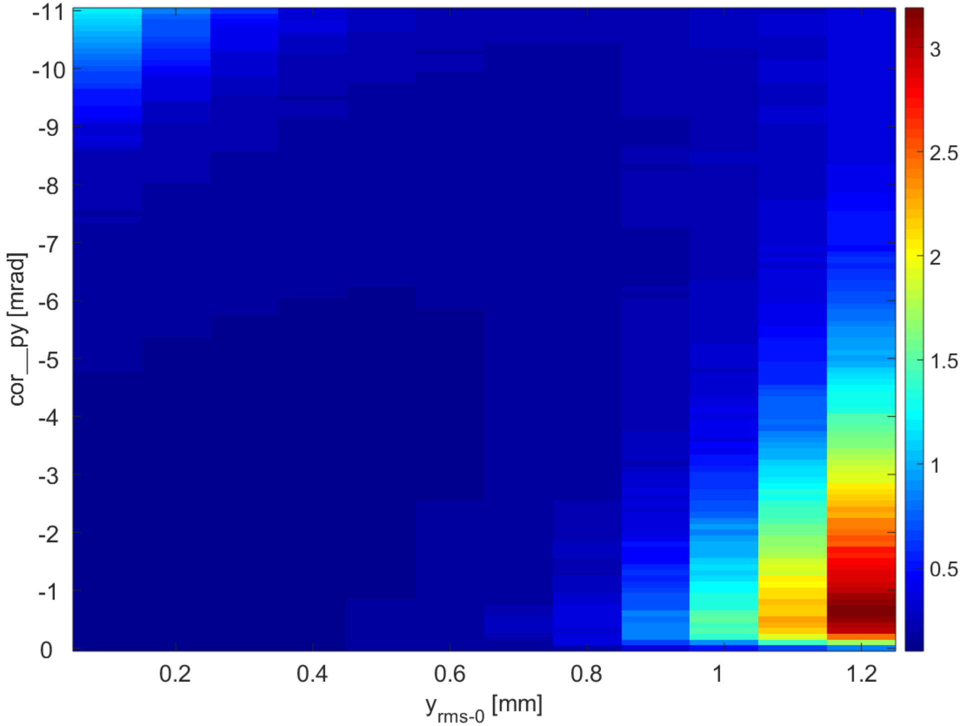
Electron beam simulations

Without space charge

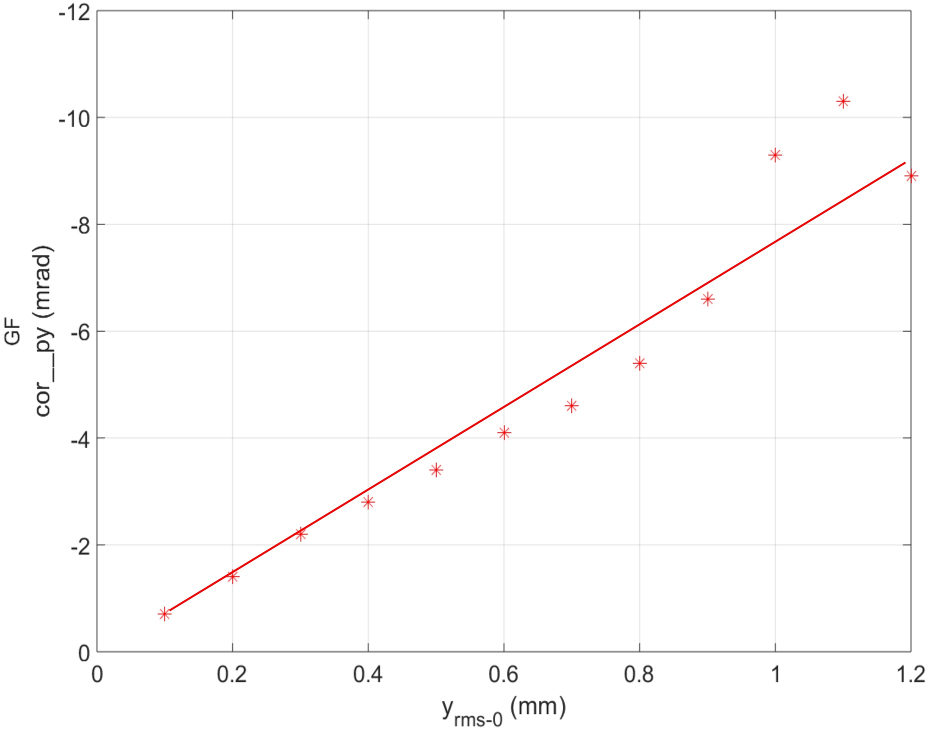
from 1st step: x_{rms} = 1.5 mm
cor_px = -0.753

2nd step

GF(y_{rms-0}, cor_py)



$cor\_py(y_{rms-0})$ for the minimum GF



$$cor\_py[mrad] = -8.58y_{rms-0}[mm] + 0.60$$

$R^2 = 0.94$

Electron beam simulations

Without space charge

3rd step

from 1st step:

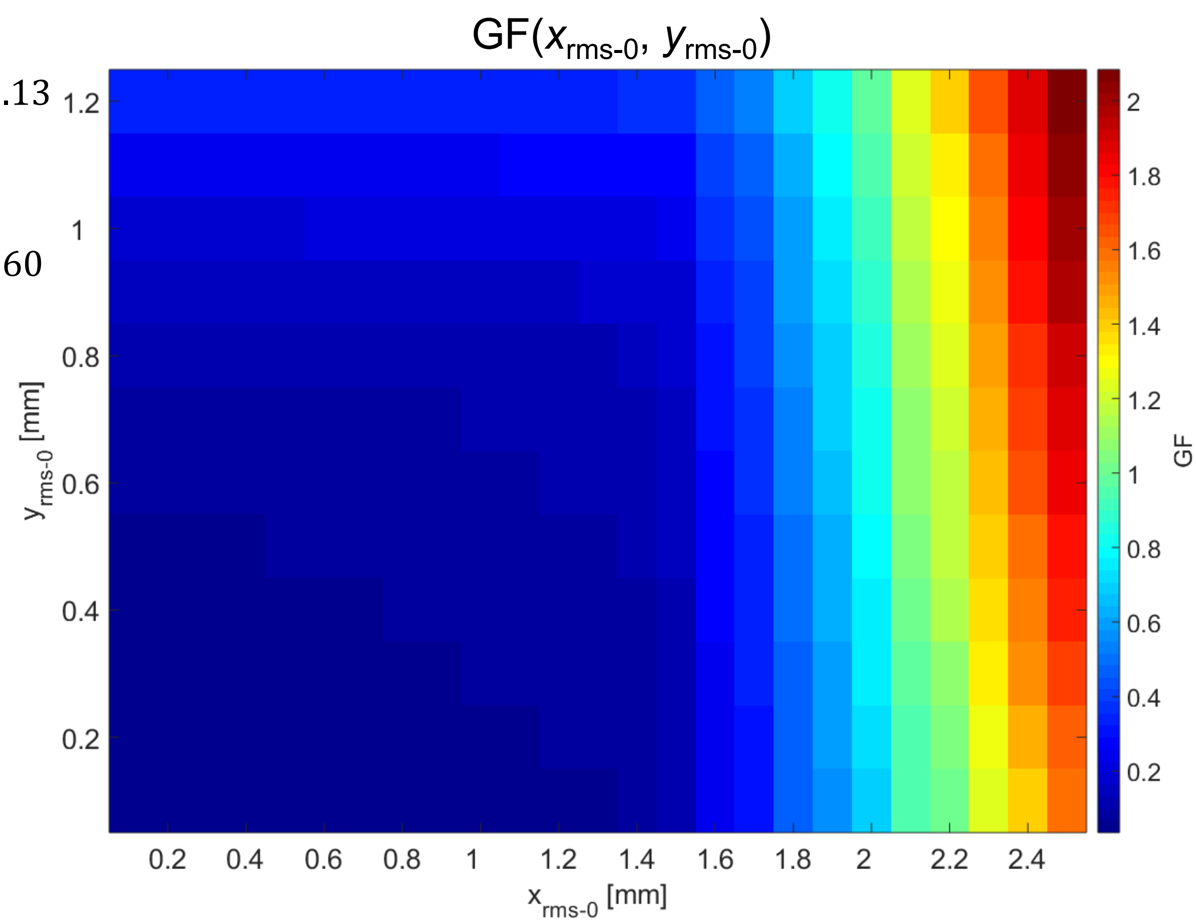
$$cor\_px[mrad] = -0.59x_{rms-0}[mm] + 0.13$$

from 2nd step:

$$cor\_py[mrad] = -8.58y_{rms-0}[mm] + 0.60$$

Small rms beam size ➔ small GF

Simulations with space charge may get a different conclusion!



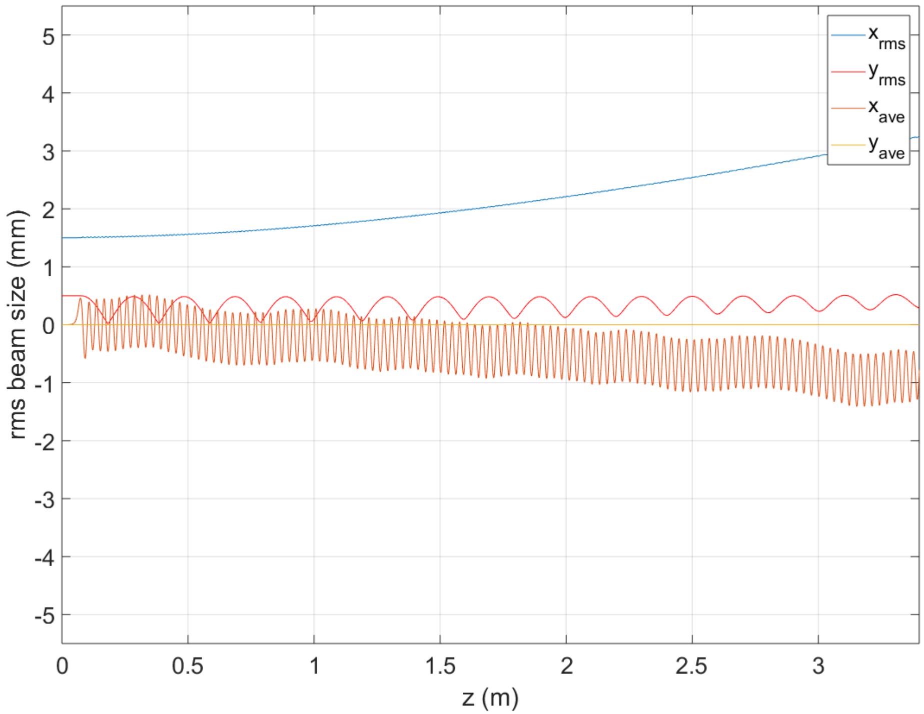
Electron beam simulations

Without space charge

beam with *pz* =17.14 MeV/c

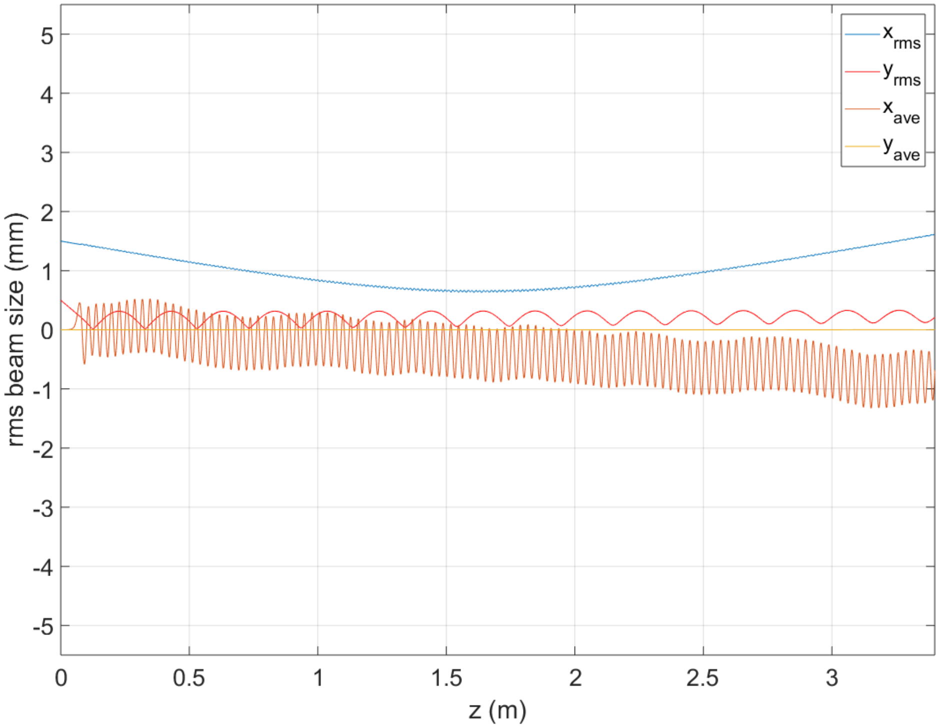
Compare rms beam size along the undulator

0th step (non-optimize)



x_{rms} = 1.5 mm
y_{rms} = 0.5 mm
cor_px = 0
cor_py = 0

3rd step (optimize)



x_{rms} = 1.5 mm
y_{rms} = 0.5 mm
cor_px = -0.753 mrad **(*cor_px*(x_{rms}) from 1st step)**
cor_py = -3.687 mrad **(*cor_py* (y_{rms}) from 2nd step)**

Summary

Single particle simulations

- x'_0 as a function of x_0 which delivers the minimum GF is $x'_0[mrad] = -\ 0.4x_0[mm] + 0.2$
- y'_0 as a function of y_0 which delivers the minimum GF is $y'_0[mrad] = -\ 8.9y_0[mm] + 0.2$

Electron beam simulations

- cor_px as a function of x_{rms-0} which delivers the minimum GF is

$$cor\_px[mrad] = -\ 0.59x_{rms-0}[mm] + 0.13$$

- cor_py as a function of y_{rms-0} which delivers the minimum GF is

$$cor\_py[mrad] = -8.58y_{rms-0}[mm] + 0.60$$

Outlook

- Perform electron beam simulations with space charge.
- Determine the tolerants of x_{rms-0}, y_{rms-0}, cor_px and cor_py

Thank you

Backup

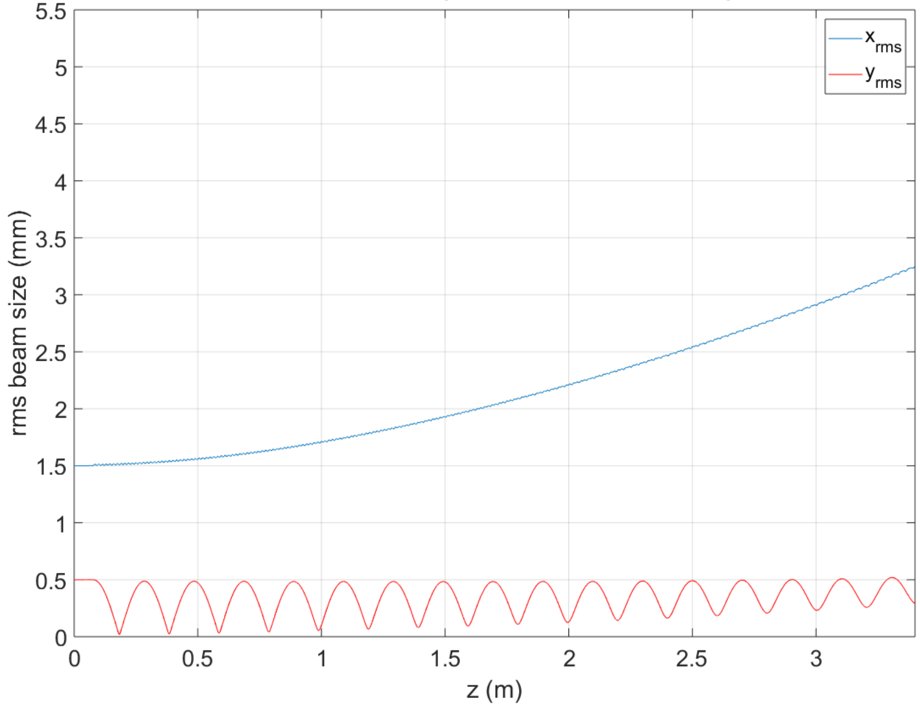
Electron beam simulations

Without space charge

beam with *pz* =17.14 MeV/c

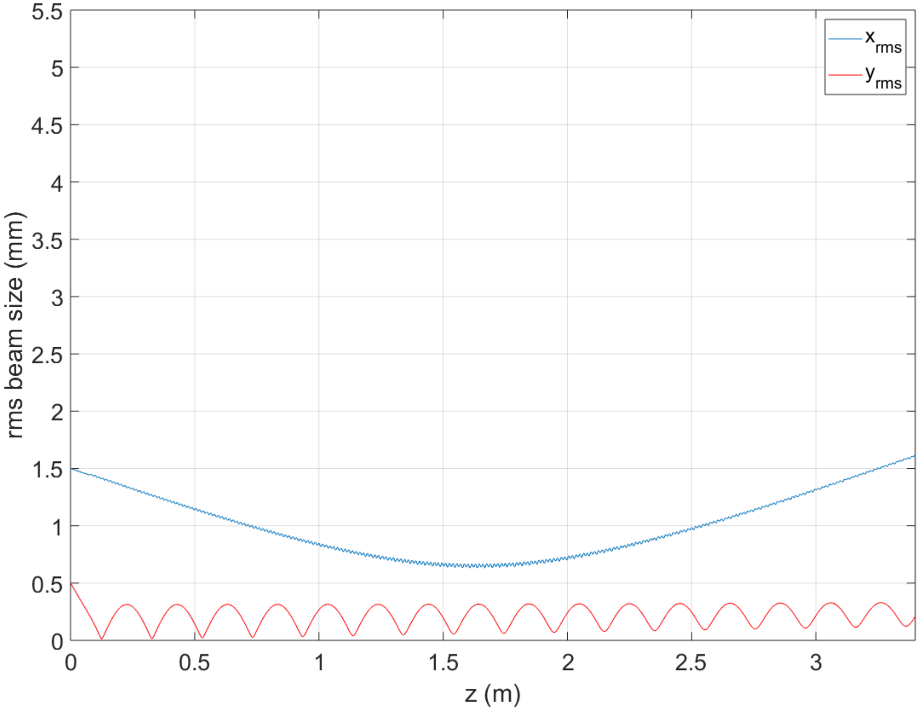
Compare rms beam size along the undulator

0^{th} step (non-optimize)



x_{rms} = 1.5 mm
y_{rms} = 0.5 mm
cor_px = 0
cor_py = 0

3^{rd} step (optimize)



x_{rms} = 1.5 mm
y_{rms} = 0.5 mm
cor_px = -0.753 mrad **(*cor_px*(x_{rms}) from 1st step)**
cor_py = -3.687 mrad **(*cor_py* (y_{rms}) from 2nd step)**

Outlook

- Simulation electron beam with space charge.
- Optimize parameters number of harmonics and number of magnetic field period. Then follow the steps of single particle simulations and electron beam simulations.
- Fine the tolerant of xrms0 and y rms0

Introduction

Magnetic filed of the LCLS-I undulator

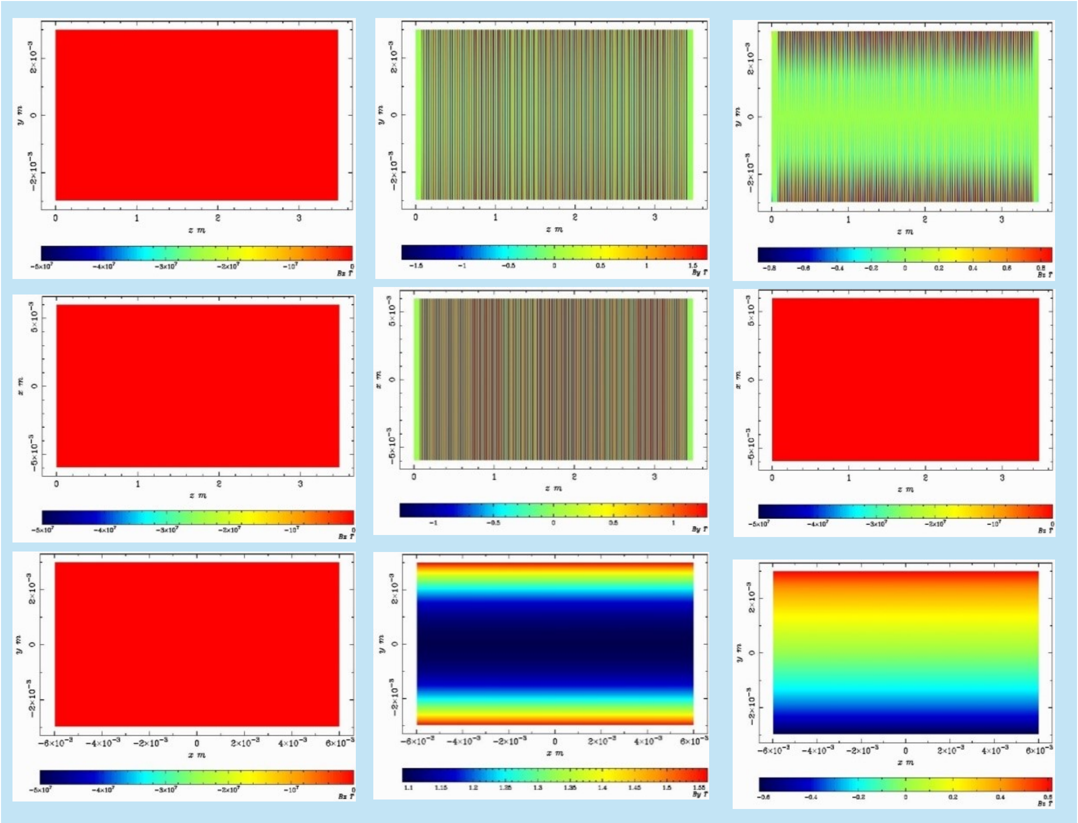
Undulator Magnetic Field in 3 Dimensions

B_x B_y B_z

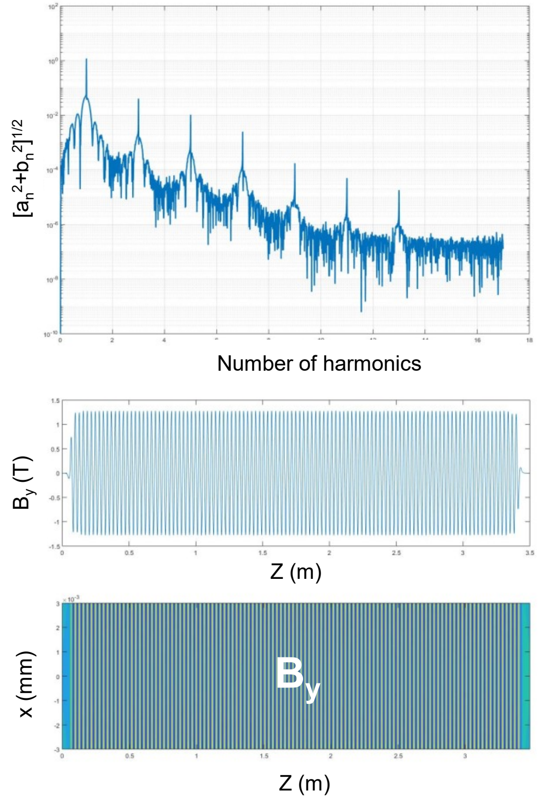
along *z*-axis and *y*-axis at *x* = 0 mm

along *z*-axis and *x*-axis at *y* = 0 mm

along *x*-axis and *y*-axis at *z* = 2 m



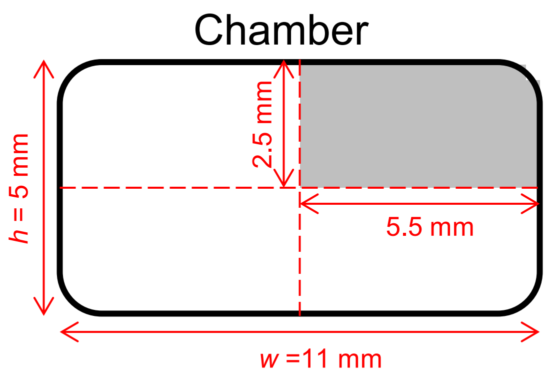
\# of harmonics = 17
\# of undulator field period = 116

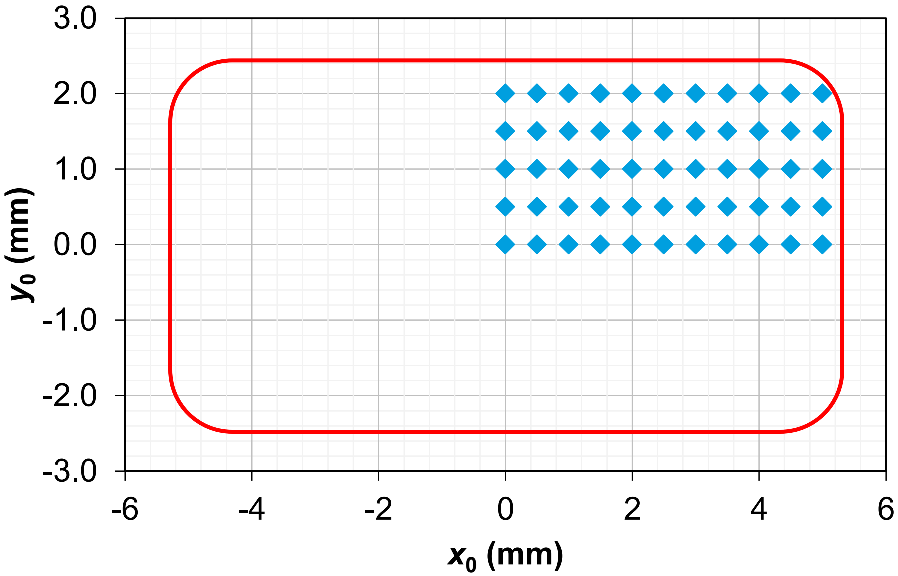


Single particle simulations

Methodology & Simulation setup

Rough scan





Goals

- Find cases that ref.electron can survive in the LCLS-I undulator.
- Maximum initial transverse area.
- Minimum Goal Function (GF).

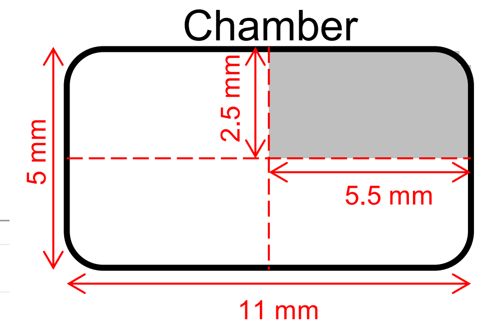
$$GF = \int \frac{|x(z)|dz}{w} + \int \frac{|y(z)|dz}{h}$$

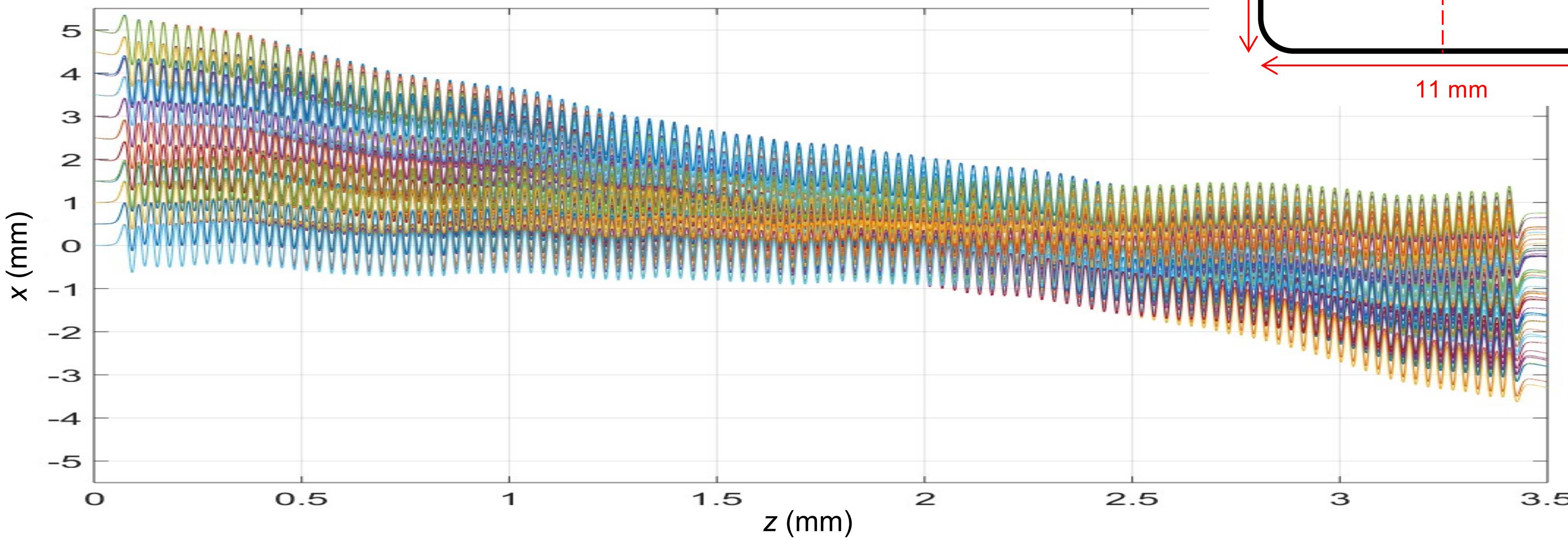
x_0 = 0 to 5 mm
y_0 = 0 to 2 mm
(0.5 mm step size)

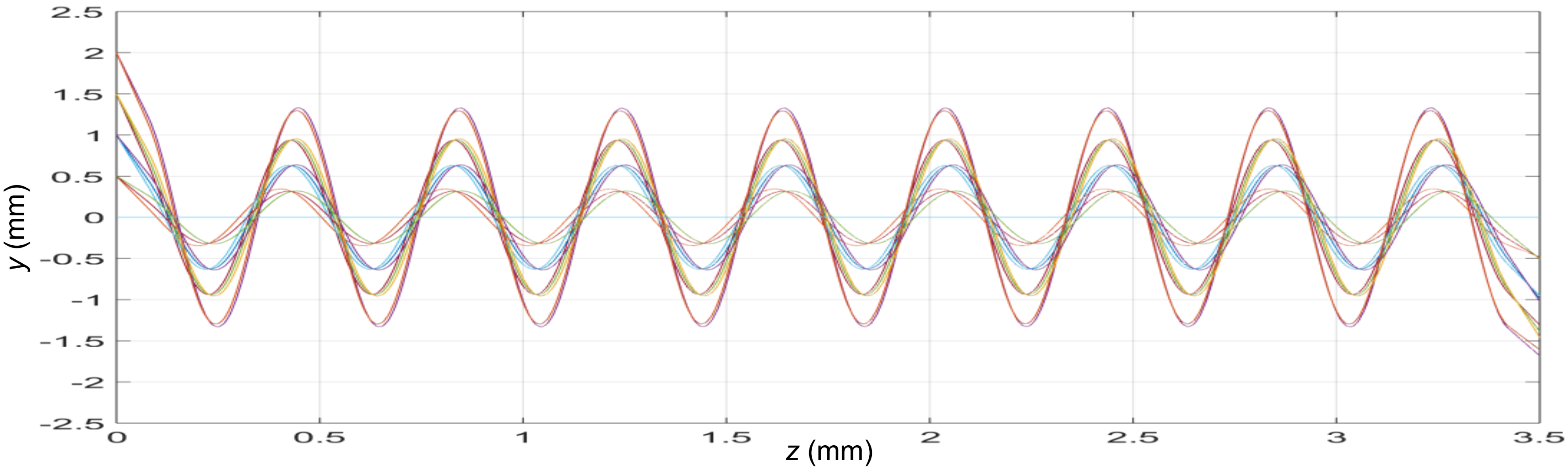
x_0' = -3 to 2 mrad
y_0' = -11 to 11 mrad
(1 mrad step size)

Single particle simulations

Rough scan







Single particle simulations

Rough scan