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The 2nd Workshop on Applications of Dielectric Wakefield Accelerators to Next Generation
X-ray Free-Electron Laser Facilities

December 5-6, 2013, Los Alamos, NM

Simulation studies of shaping electron bunches with a chicane type emittance exchanger for a high brightness high gradient dielectric wakefield acceleration

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CONTENT

- Our research motivation
- ELEGANT code capabilities
- Example of a chicane-based EEX designed with ELEGANT:
 - Minimization of beamline nonlinearities
 - Space charge & CSR effects contribution
 - Deflecting cavity representations

Motivation

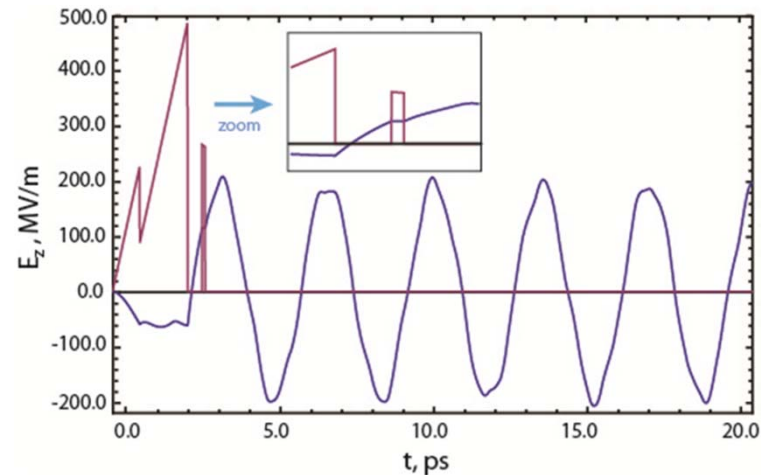
- The pre-conceptual design for MaRIE is underway at LANL, with the design of the 12 GeV electron linac being one of the main research goals.
- Requirements for the linac: high gradient and high quality electron beam:
 - electron bunch charges of 0.1 to 1 nC;
 - normalized rms emittances of 0.1 to 1 mm•mrad;
 - and rms energy spreads of less than 0.1%.
- Exactly the same phenomena, that causes the dominant energy spread effect in beams in conventional linacs can be used to generate extraordinary gradients and small energy spreads in the dielectric structures via wakefield acceleration.

DWA with a double-triangular drive bunch and a trapezoidal witness bunch

Approximate dimensions:

Beam pipe ID, $2b$	1.14 mm
Dielectric tube ID, $2a$	1.24 mm
Waveguide cutoff	298 GHz
Charge of the drive bunch	5 nC
Length of the drive bunch	2.350 ps
Charge of the witness bunch	250 pC
Length of the witness bunch	100 fs
Time between the bunches	2.8017 ps
Transformer ratio	3.38
$\Delta E/E$	$9 \cdot 10^{-6}$

High transformer ratio wake:



Tolerances. For $\Delta E/E < 10^{-4}$ we must have

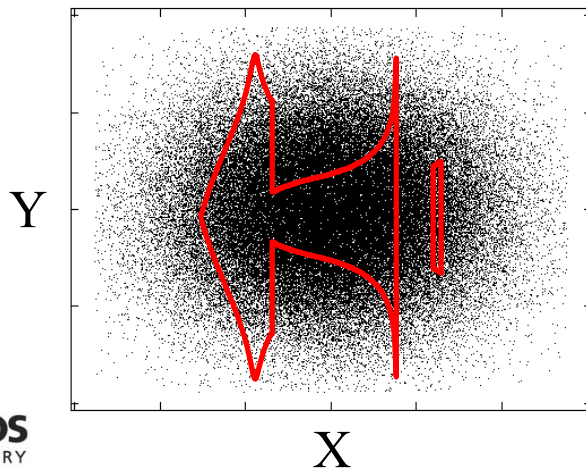
$4.998 \text{ nC} < \text{drive charge} < 5.002 \text{ nC}$
$249.9 \text{ pC} < \text{witness charge} < 250.1 \text{ pC}$
$2.3494 \text{ ps} < \text{length of the drive bunch} < 2.3507 \text{ ps}$
$2.8014 \text{ ps} < \text{time between the bunches} < 2.8020 \text{ ps}$
$99.95 \text{ fs} < \text{length of the witness bunch} < 100.1 \text{ fs}$

Cutting out the shaped bunches out of a Gaussian bunch

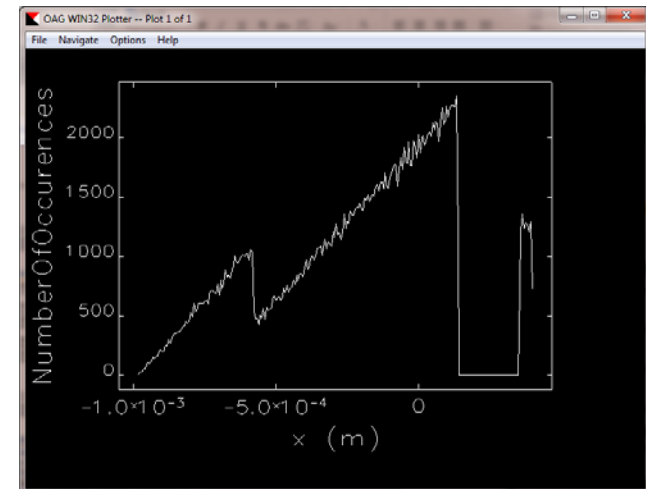
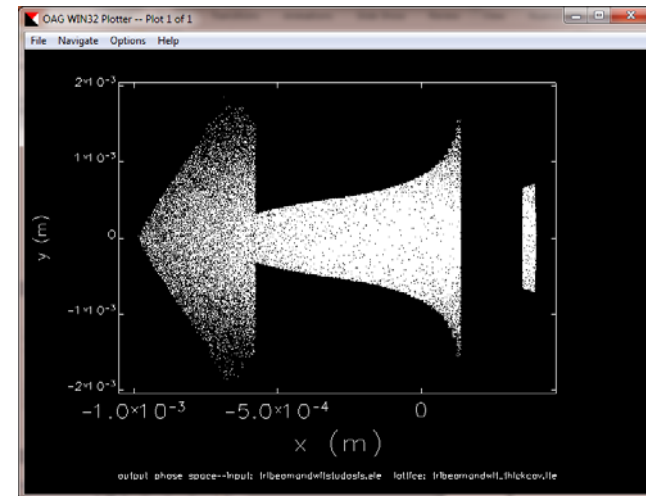
Parameters of a Gaussian bunch (from FNAL folks):

ϵ_{nx}	5.33 mm*mrad
ϵ_{ny}	10 mm*mrad
Bunch length	1.2 mm
Fract. mom. spread	0.001

The shape of the mask that cuts out the correct bunch shapes out of the Gaussian distribution.



Particle distribution in Elegant:



Emittance Exchange

We have to turn the x-distribution into z-distribution with an emittance exchanger. We need to construct the emittance exchanger with the following 1st order matrix elements:

$$R_{51}=1 \text{ (or whatever the stretch/compression factor is)}$$

$$R_{52} = R_{53} = R_{54} = R_{55} = R_{56} = 0.$$

$$\mathbf{z}=\mathbf{R}_{51}*\mathbf{x}.$$

What is ELEGANT*?

- Stands for ELEctron Generation And Tracking
- It is a matrix code with some additional capabilities

A 6D transfer matrix (tensor) is assigned by ELEGANT to each beamline element. The transfer matrix of the full beamline is calculated by multiplying matrices of individual elements.

$$X_i^F = R_{i,j}X_j + T_{i,j,k}X_jX_k + Q_{i,j,k,l}X_jX_kX_l; \quad i, j, k, l = 1, 2, \dots, 6.$$

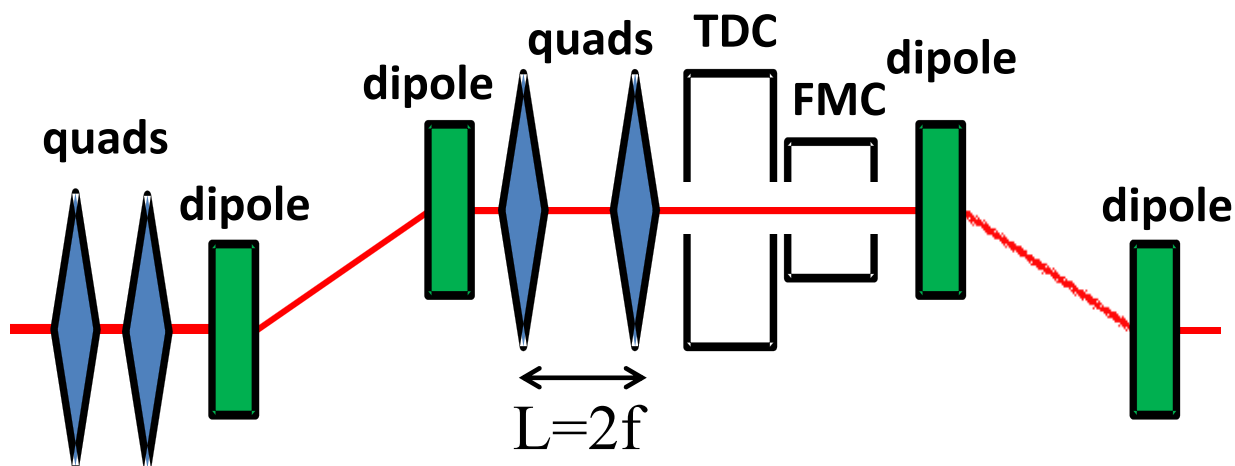
Up to the 3rd order nonlinearities are accounted for!

ELEGANT: additional capabilities

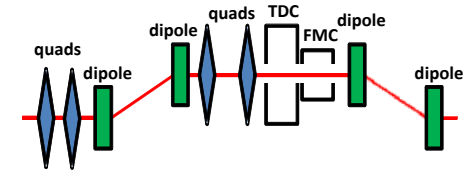
- Realized by kicks:
particles get specified number of momentum kicks on the length of a beamline element
- Capabilities realized by kicks:
 - Longitudinal Space Charge (LSC) effect
 - Coherent Synchrotron Radiation (CSR) in the magnetic dipole bends
 - some RF elements like cavities

First order

In principle, the following set of elements allows one to have the correct R-matrix in the first order:

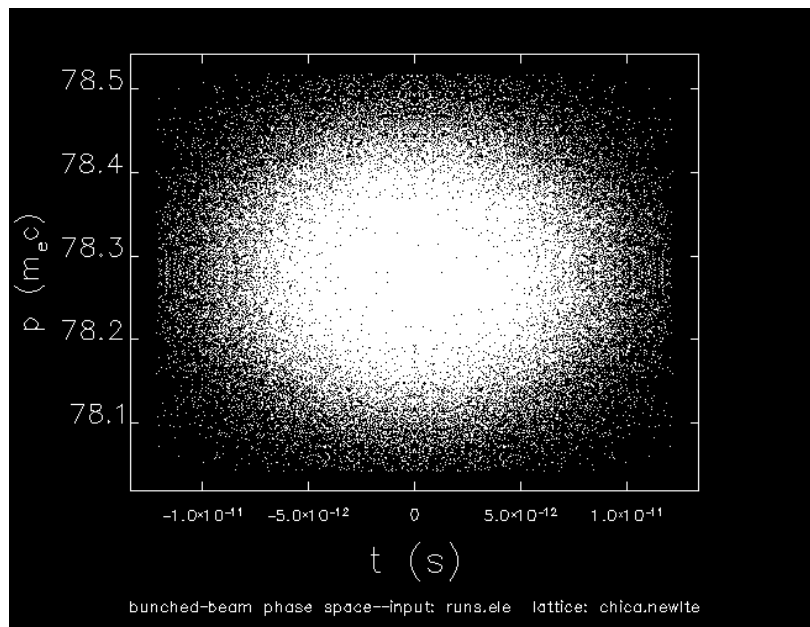


- Thick TDC produces a time-dependent momentum variation and non-zero R_{55} , R_{56} . It is compensated with a FMC.
- Two quads after the first dogleg change the dispersion sign.
- The first pair of quads allows us to have zero R_{52} and whatever R_{51} .
- $R_{53}=R_{54}=0$ are satisfied automatically, as y-plane is uncoupled.

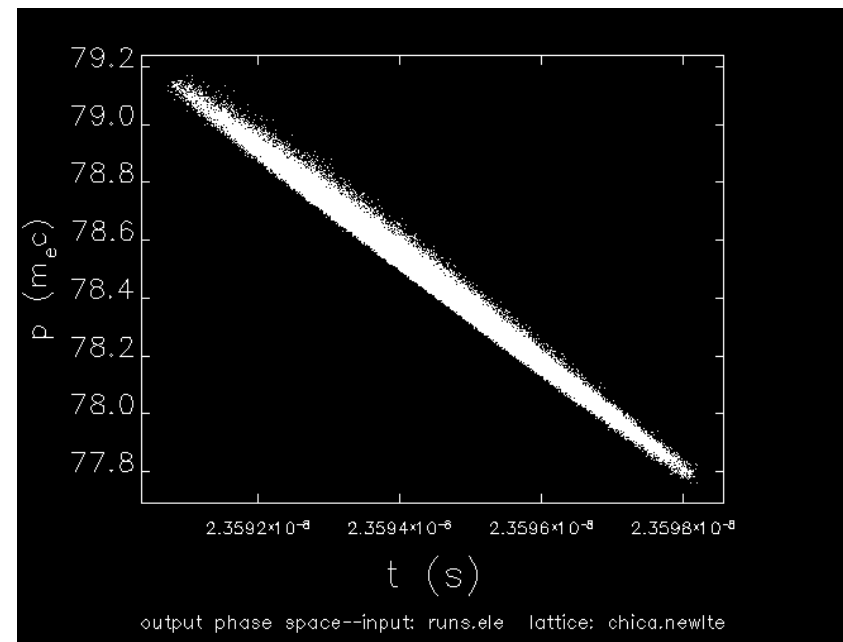


Problem #1 (comes in the 1st order)

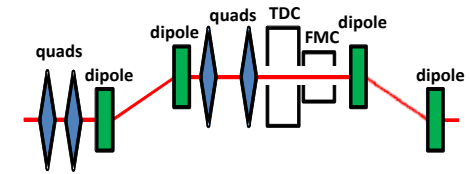
- High energy spread after the EEX due to R61.



Input beam

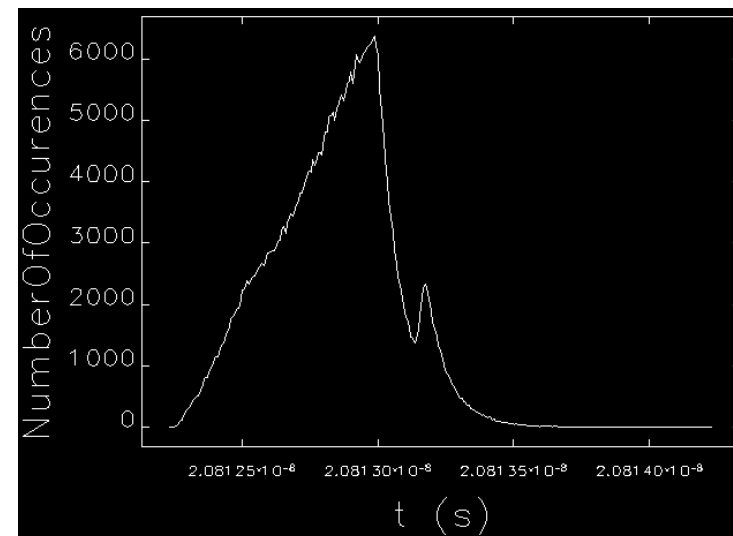
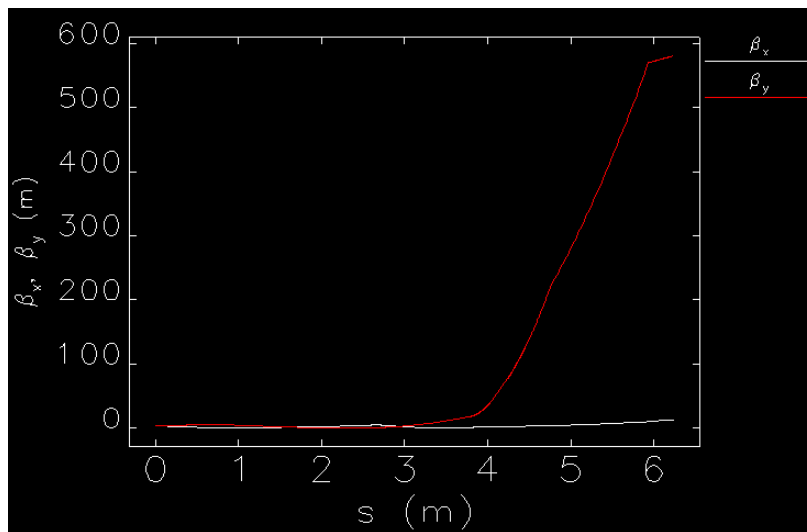


Output beam (no mask)



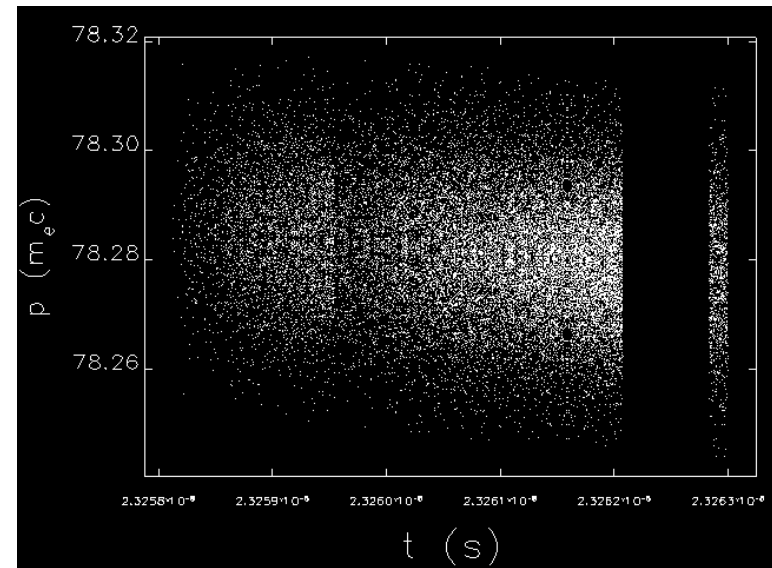
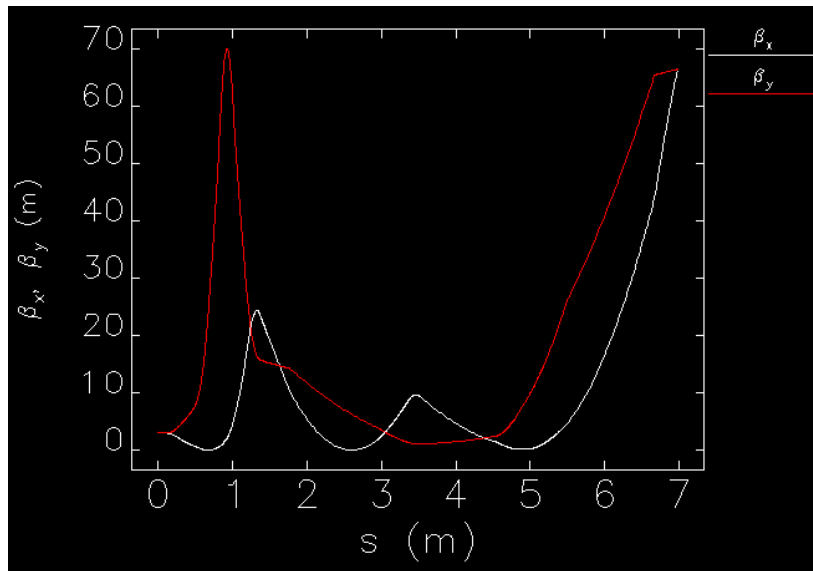
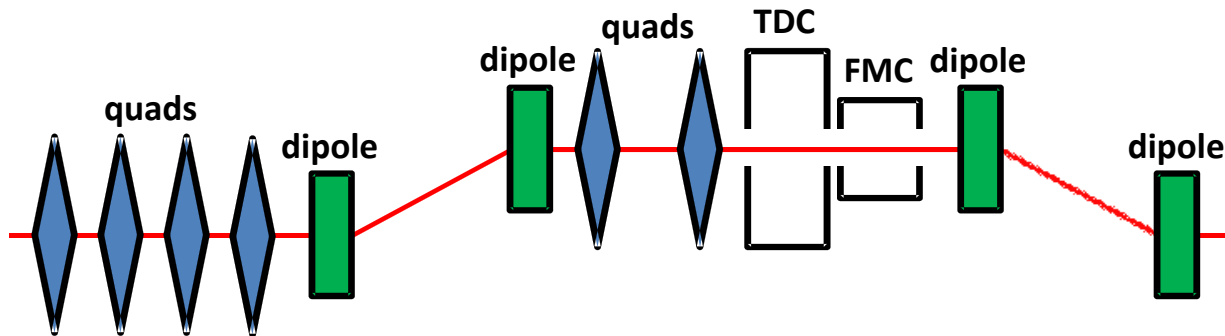
Problem #2 (higher order nonlinearities)

- Distortion of shape in higher order due to the big beam width.



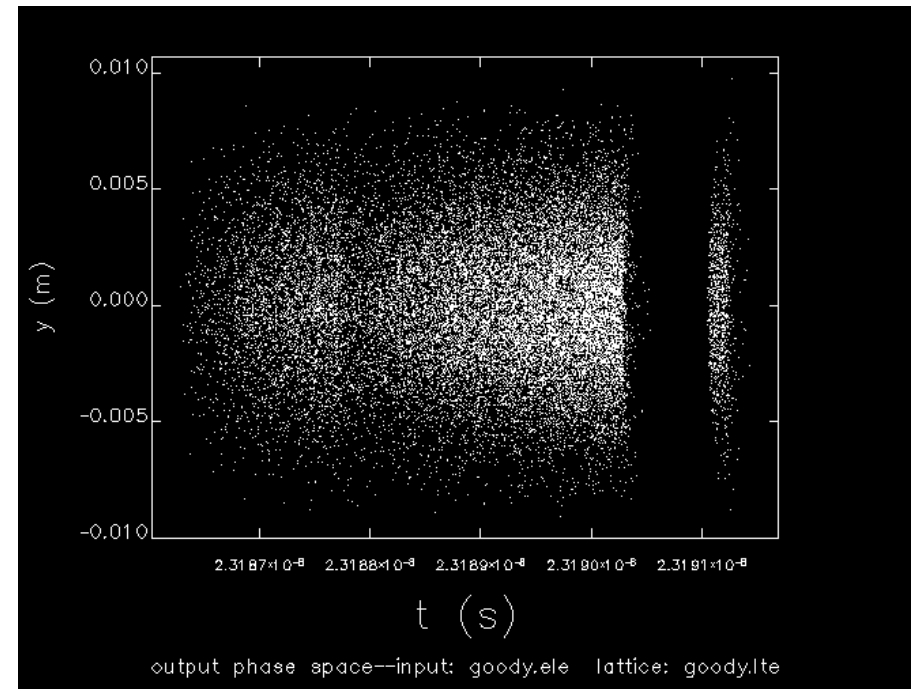
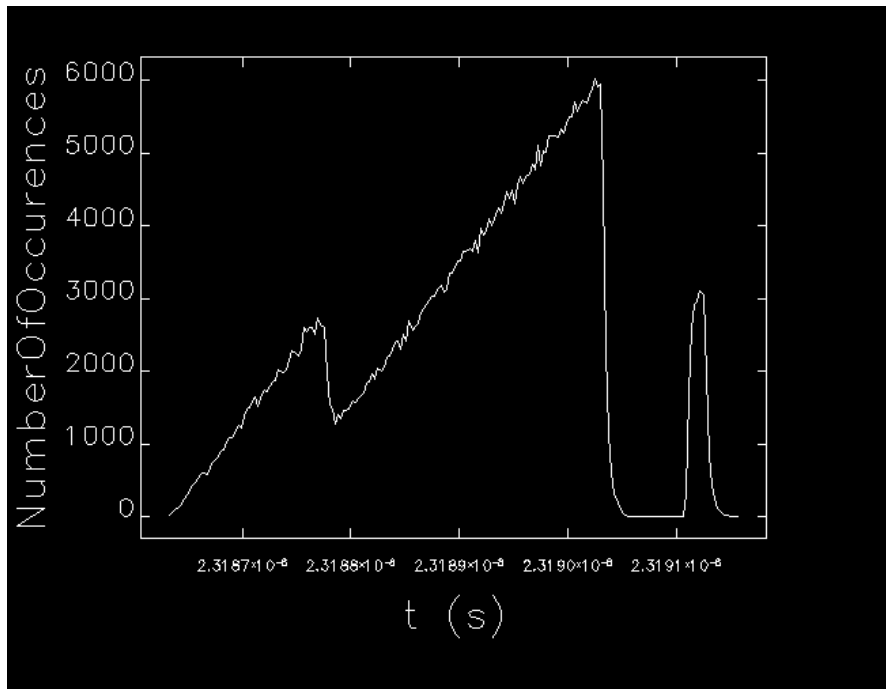
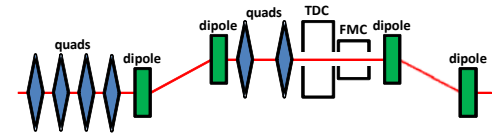
A beam width is proportional to a square root of a beta function.

First order (with additional quads)



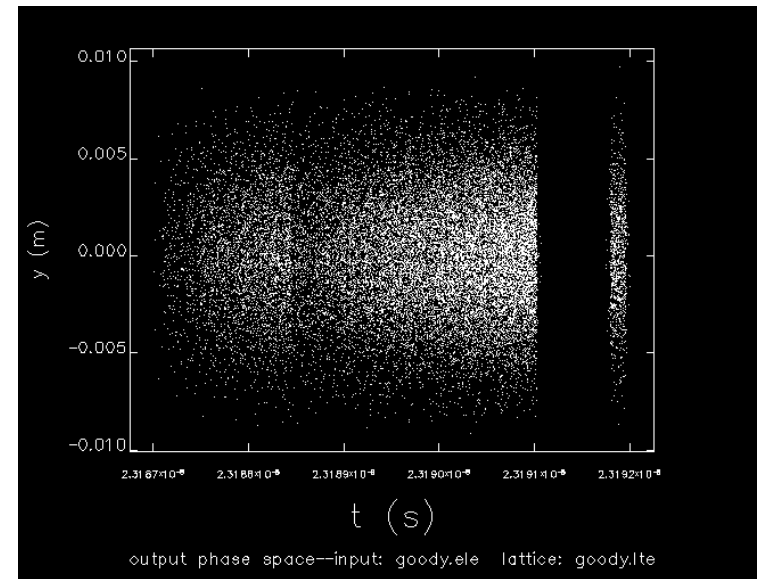
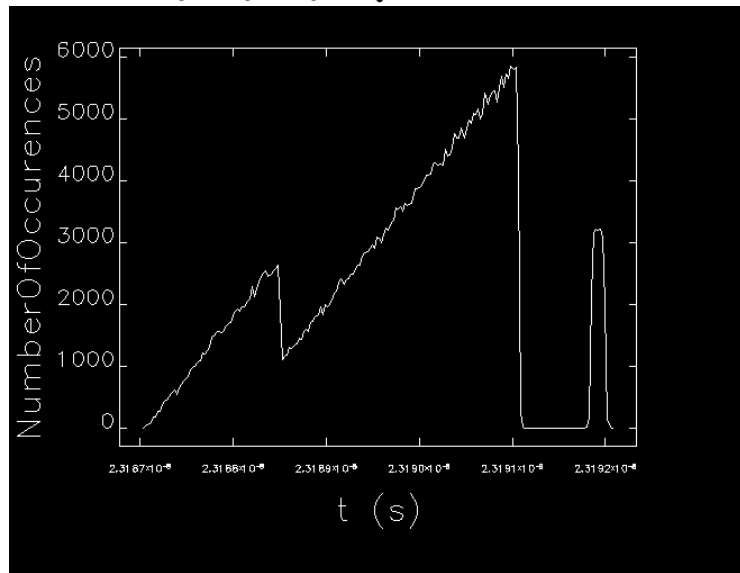
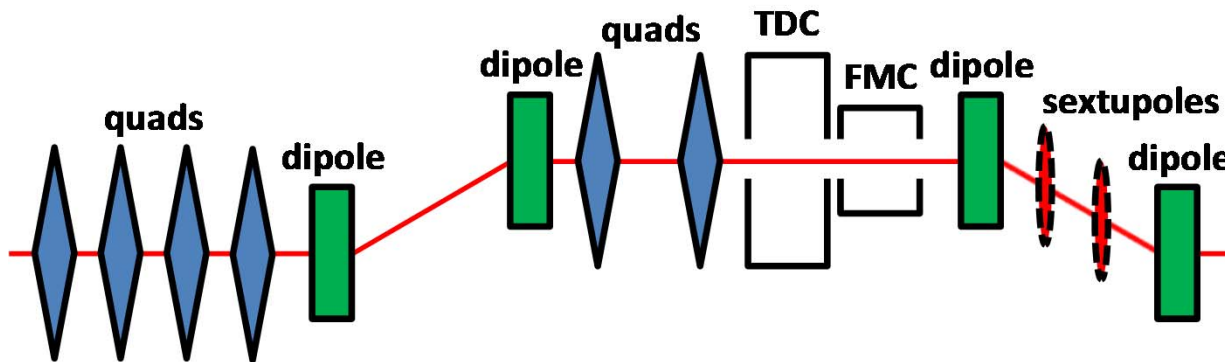
Minimized both the beam size and the R_{61} .

Third order

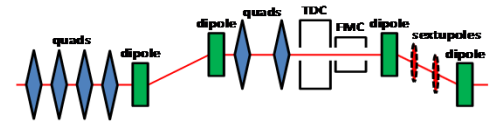


Has some distortions, high T_{555} and T_{544} .

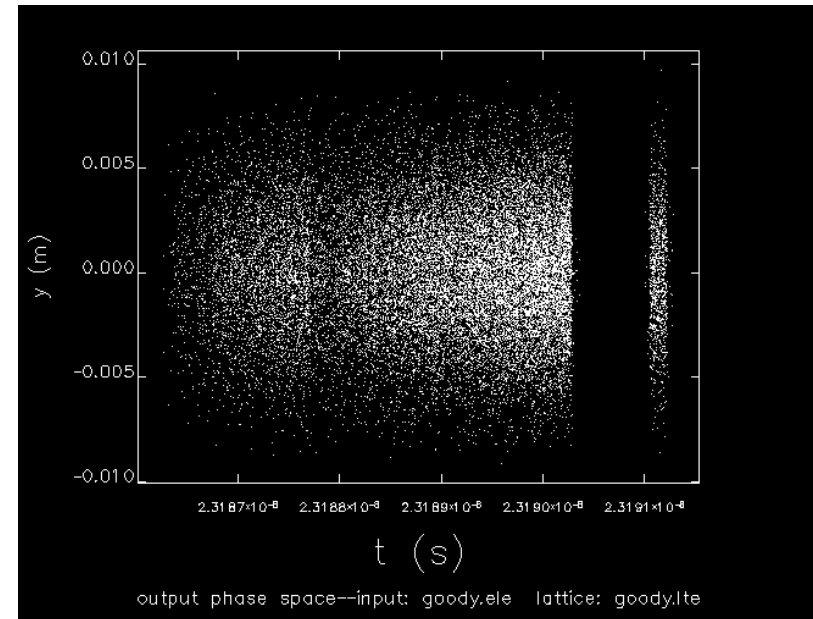
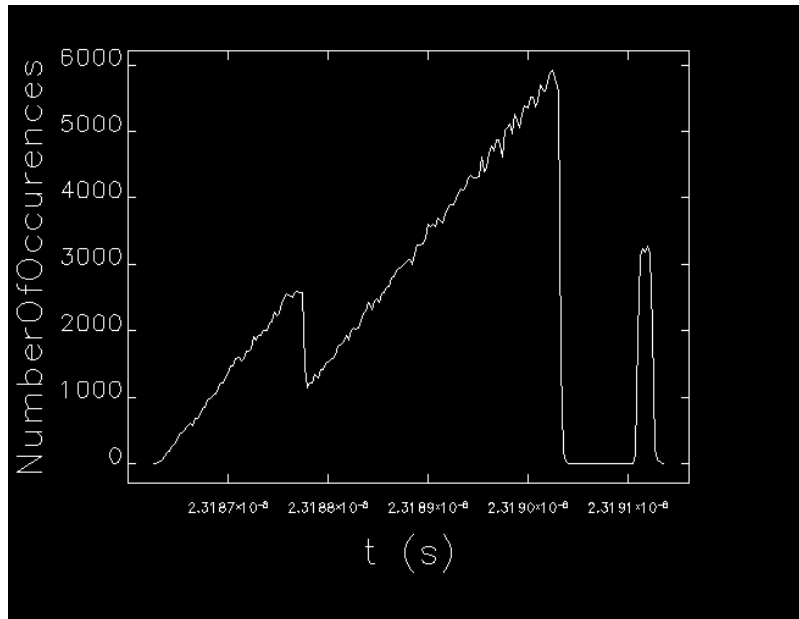
Third order (with sextupoles): matrix method



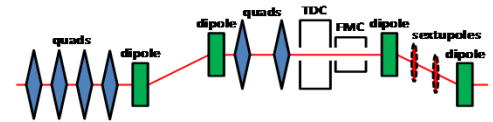
All T_{ijk} are small, perfect shape.



Third order (with sextupoles): kicks method



In ELEGANT the RFDF is implemented only either as a 1st order matrix or by kicks. Do not know higher order tensor elements to minimize RFDF nonlinearities.



MATRIX

T51: -1.035e+000

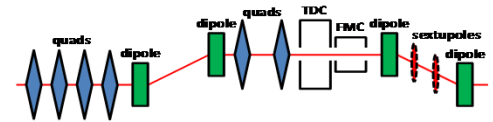
T52: 3.5543e-001 5.0662e-001

T53: 0.0000e+000 0.0000e+000 -2.3088e-001

T54: 0.0000e+000 0.0000e+000 -4.1699e+000 -1.3781e-002

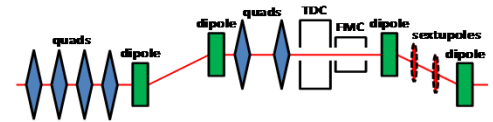
T55: 2.4496e-001 1.3696e+000 0.0000e+000 0.0000e+000 -1.3388e-003

T56: 2.1171e-001 -1.2708e+000 0.0000e+000 0.0000e+000 9.1267e-001 -8.6070e-001



LATTICE

DRF: DRIF, L=1.171900312566502
 Q1: QUAD, L=0.167,K1=10.68537645813935
 Q2: QUAD, L=0.167,K1=24.61073852700586
 Q3: QUAD, L=0.167,K1=-22.33919237078911
 Q4: QUAD, L=0.167,K1=17.90615560513161
 SS1: SEXT, L=0.167,K2=171.1020408305909
 SS2: SEXT, L=0.167,K2=-191.3945329591026
 DRF4: DRIF, L=0.2
 DRIFT1: DRIF ,L=0.1
 QUADS: LINE=(DRIFT1,Q1,DRF4,Q2,DRF4,Q3,DRF4,Q4,DRIFT1)
 Q5: QUAD, L=0.167,K1=10.75411265432099
 D300: SBEN, L=0.305,ANGLE=0.314,E2=0.314,HGAP=0.029,FINT=0.59
 D301: SBEN, L=0.305,ANGLE=-0.314,E1=-0.314,HGAP=0.029,FINT=0.59
 DD300: SBEN, L=0.305,ANGLE=-0.314,E2=-0.314,HGAP=0.029,FINT=0.59
 DD301: SBEN, L=0.305,ANGLE=0.314,E1=0.314,HGAP=0.029,FINT=0.59
 DCAV: RFDF, L=0.156,PHASE=270,FREQUENCY=1300000000,VOLTAGE=2936286.3, N_KICKS=200
 DIFERENCE: DRIF, L=0.015
 FUNDCAV: RFCA, L=0.115,VOLT=151780.61,FREQ=1300000000, N_KICKS=200
 DRIFT: DRIF, L=0.1
 DRIFTQ: DRIF, L=1
 DRFDRF: DRIF, L=0.2792999999999999
 LQ: LINE=(DRIFT,Q5,DRIFTQ,Q5,DRIFT)
 BEFORECAV: LINE=(DD300,DRF,DD301,LQ)
 AFTERCAY: LINE=(DRIFT,D300,DRFDRF,SS1,DRFDRF,SS2,DRFDRF,D301)
 EEX: LINE=(QUADS,BEFORECAV,DCAV,DIFERENCE,FUNDCAV,AFTERCAY)



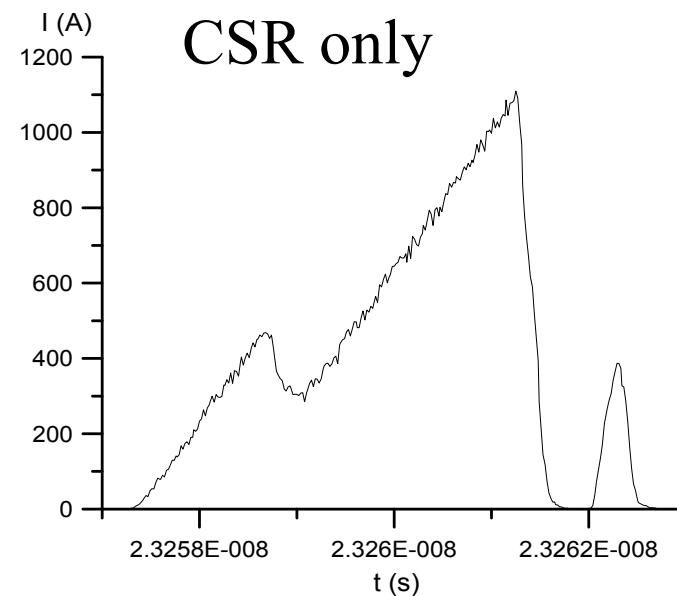
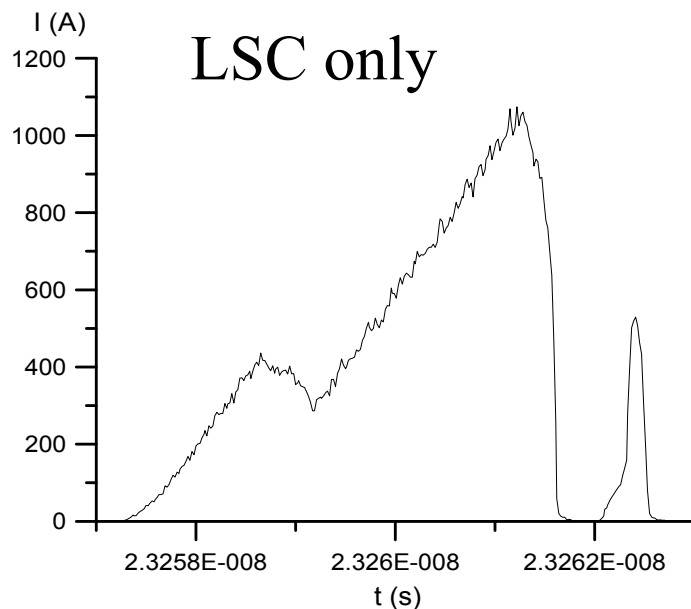
BEAM PARAMETERS

```

alpha_x= 0.00
alpha_y= 0.00
beta_x= 3.0
beta_y= 3.0
n_particles_per_bunch = 1000000,
emit_nx           = 5.33E-6,
emit_ny           = 10.0e-6,
sigma_dp          = 1.0e-3,
sigma_s           = 1.2e-3,
distribution_type[0] = "gaussian",
distribution_type[1] = "gaussian",
distribution_type[2] = "gaussian",
distribution_cutoff[0] = 3.0,
distribution_cutoff[1] = 3.0,
distribution_cutoff[2] = 3.0,
symmetrize        = 1,
enforce_rms_values[0] = 1,
enforce_rms_values[1] = 1,
enforce_rms_values[2] = 1,
momentum_chirp    = 0,
  
```

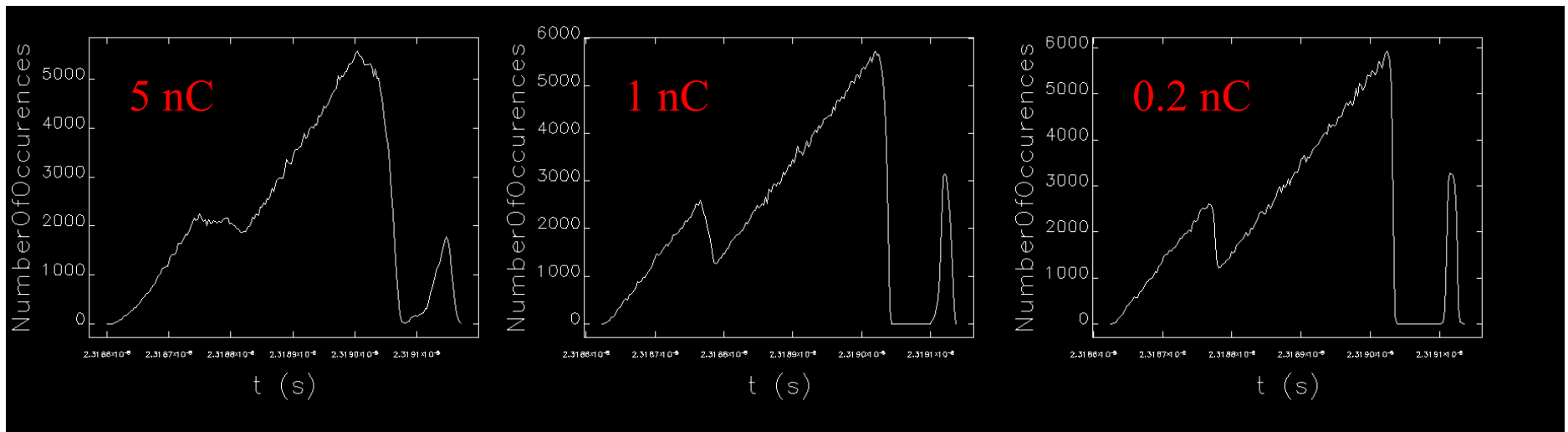
LSC and CSR caused distortions

ELEGANT simulations with kicks for initially a 5 nC beam.



Note, that the space charge effects, in contrary to the beamline nonlinearities, are stronger for tighter-focused beams, some compromise may be needed.

LSC and CSR caused distortions



Output beam pulse shape for different initial beam charges. Both CSR and LSC are accounted for.

Use of external matrix for deflecting cavity (research in progress)

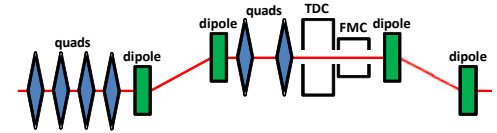
Tech-X simulated a real standing wave deflecting cavity for us and produced the 3rd order transfer matrix in Elegant format.

The deflecting cavity strength differs from the one in Elegant for the same voltage.

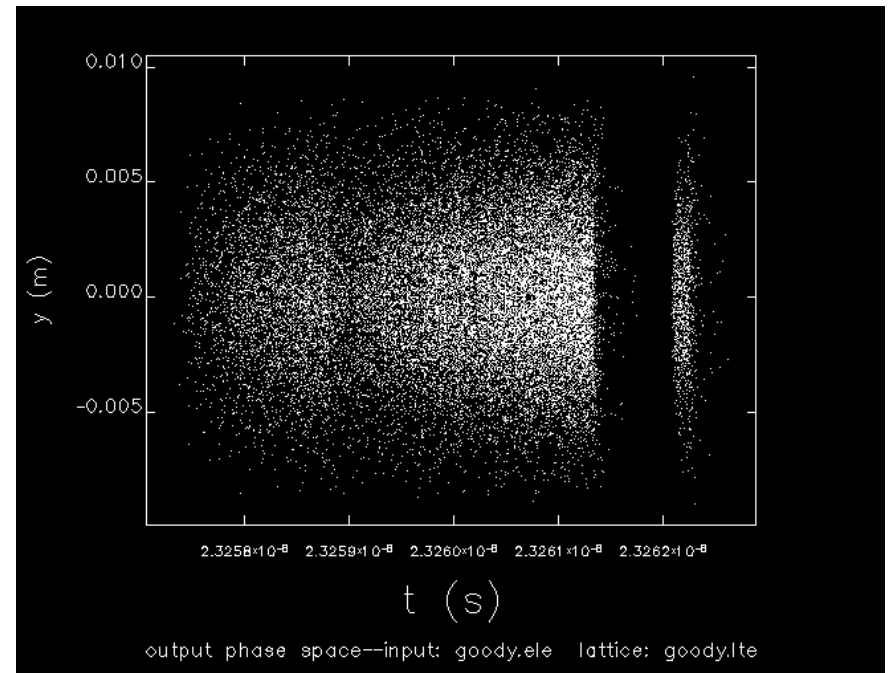
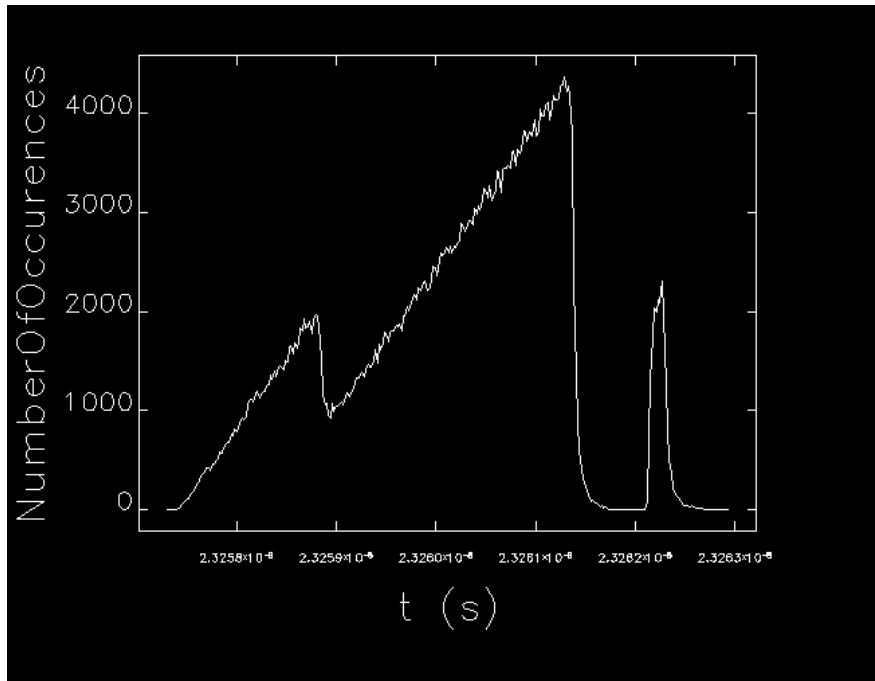
Standing wave cavity of finite thickness seems to cause aberrations even in the 1st order.

Conclusions and current plans

- Possibilities for improving the beamline are endless.
- We have some EEX designs which we are eager to adjust for a particular beamline and try in an experiment.
- We would like to learn what bunch shapes we may realistically expect.
- Apart from the nonlinear effects there are going to be the space charge and CSR effects.
- Looking forward to collaborations!

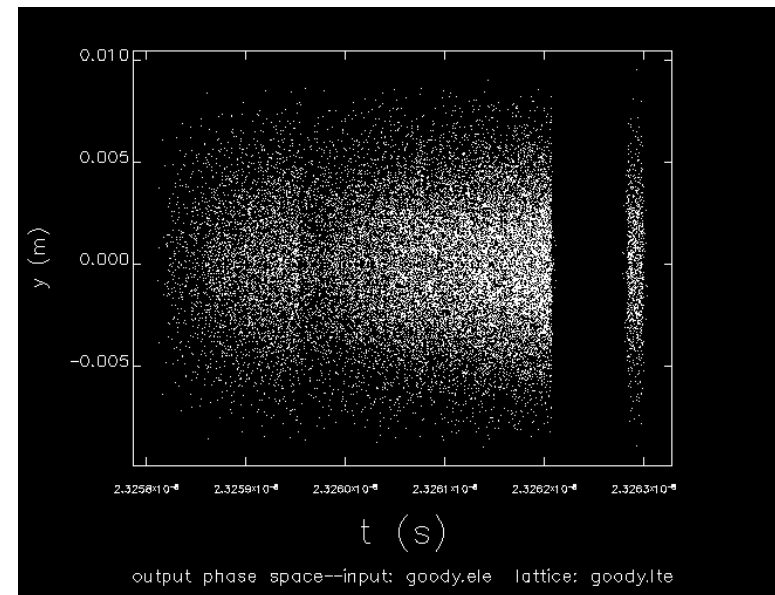
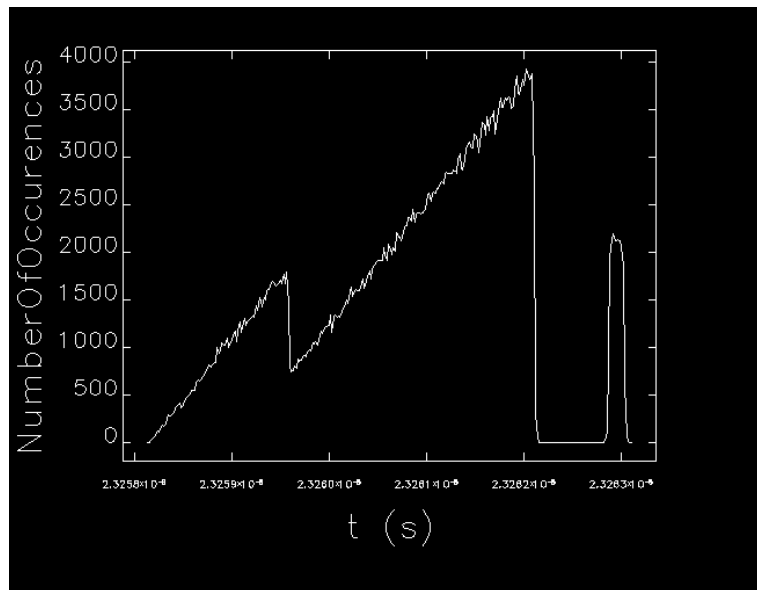
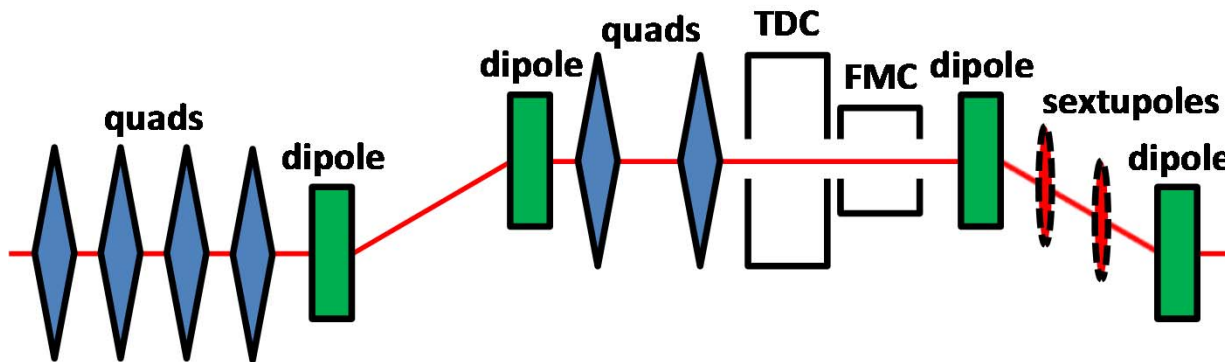


Third order

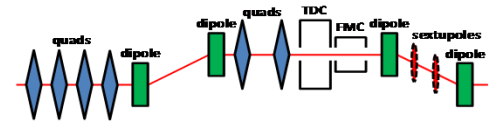


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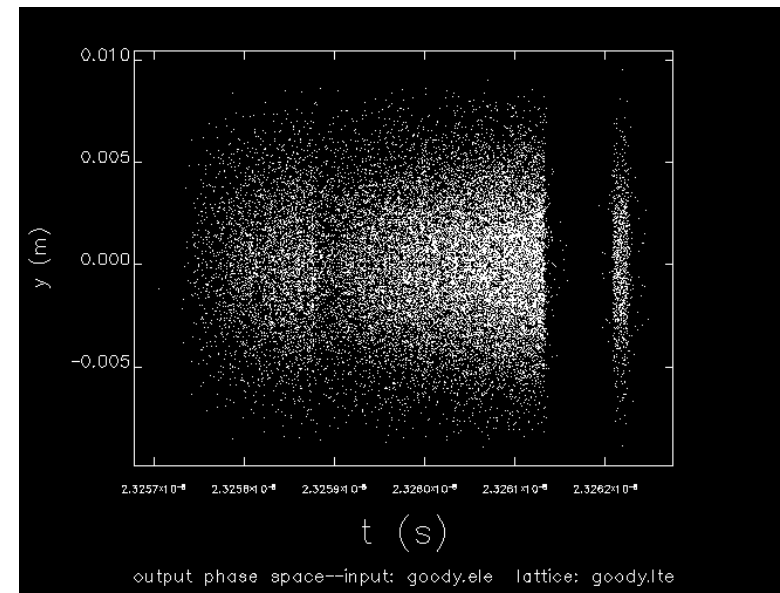
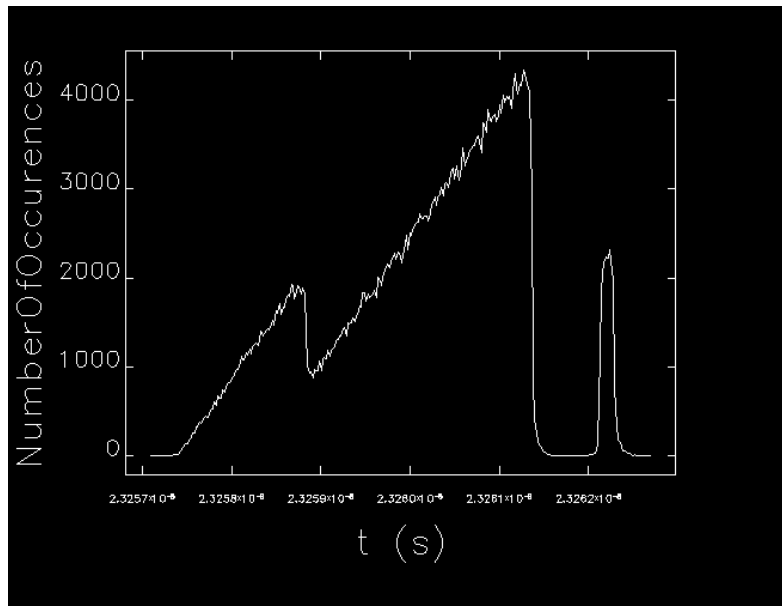
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