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

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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%.

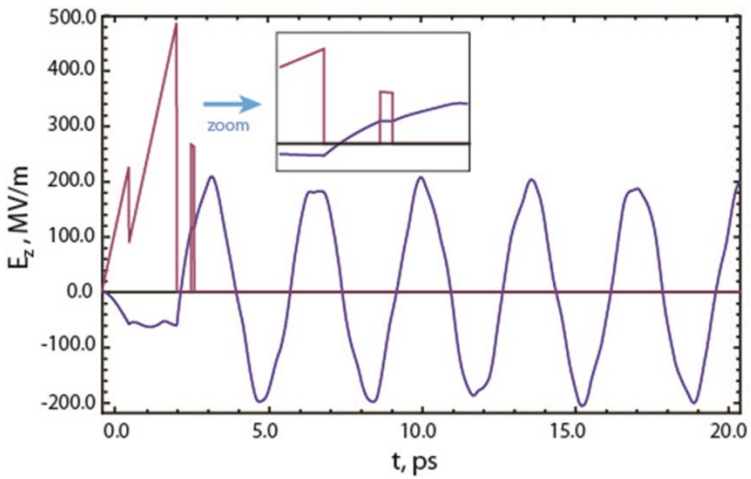
- Exactly the same phenomena, that causes the dominant energy spread effect in beams in conventional linacs can be used to generate extraordinary gradients and small energy spreads in the dielectric structures via wakefield acceleration.

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
ΔE/E	$9*10^{-6}$

High transformer ratio wake:



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

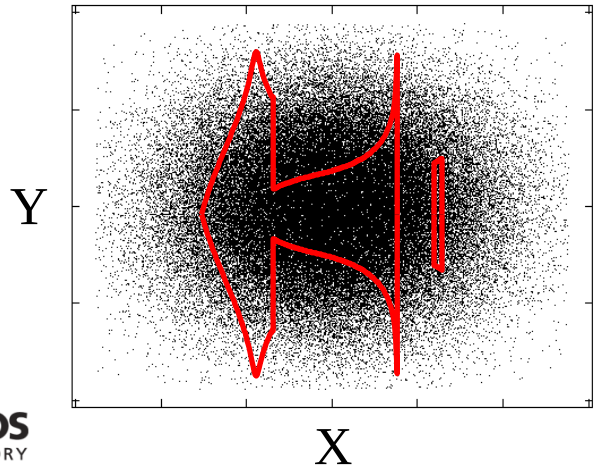
4.998 nC < drive charge < 5.002 nC
249.9 pC < witness charge < 250.1 pC
2.3494 ps < length of the drive bunch < 2.3507 ps
2.8014 ps < time between the bunches < 2.8020 ps
99.95 fs < length of the witness bunch < 100.1 fs

Cutting out the shaped bunches out of a Gaussian bunch

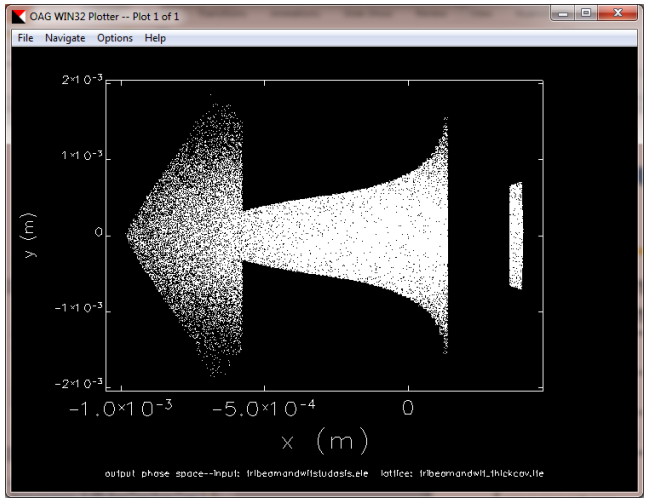
Parameters of a Gaussian bunch (from FNAL folks):

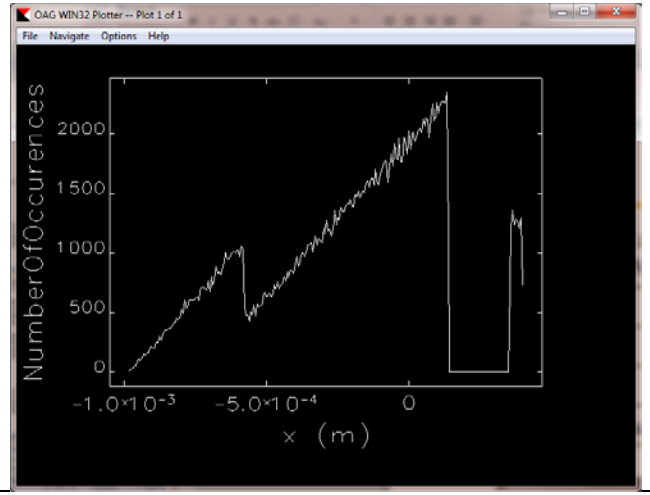
ε_{nx}	5.33 mm*mrad
ε_{ny}	10 mm*mrad
Bunch length	1.2 mm
Fract. mom. spread	0.001

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 (or whatever the stretch/compression factor is)

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

z=R_{51}*__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.

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

Up to the 3rd order nonlinearities are accounted for!

*M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000.

ELEGANT: additional capabilities

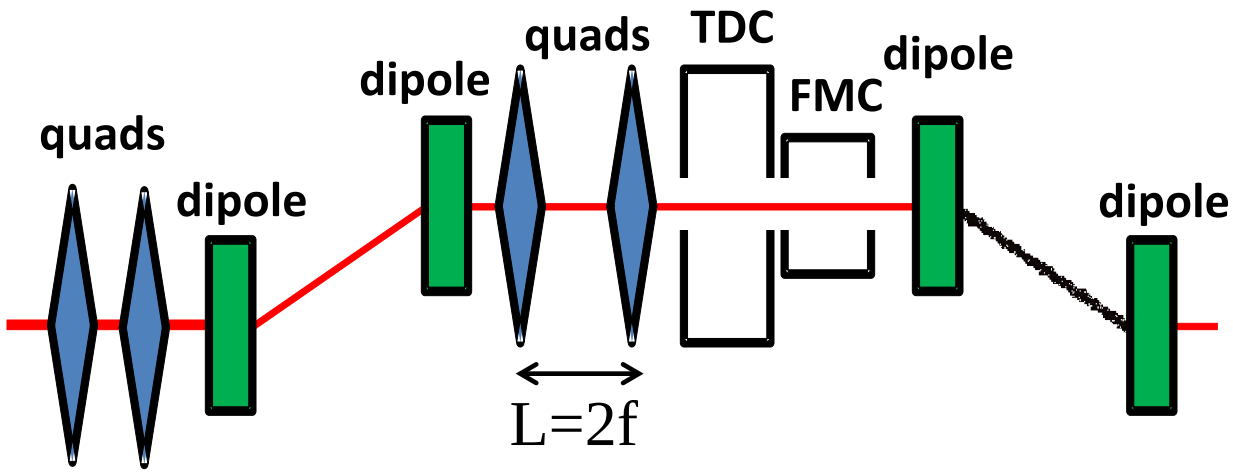
- Realized by kicks:
particles get specified number of momentum kicks on the length of a beamline element

- Capabilities realized by kicks:

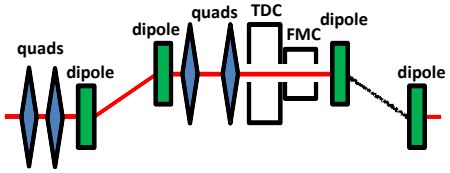
  • Longitudinal Space Charge (LSC) effect
  • Coherent Synchrotron Radiation (CSR) in the magnetic dipole bends
  • some RF elements like cavities

First order

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

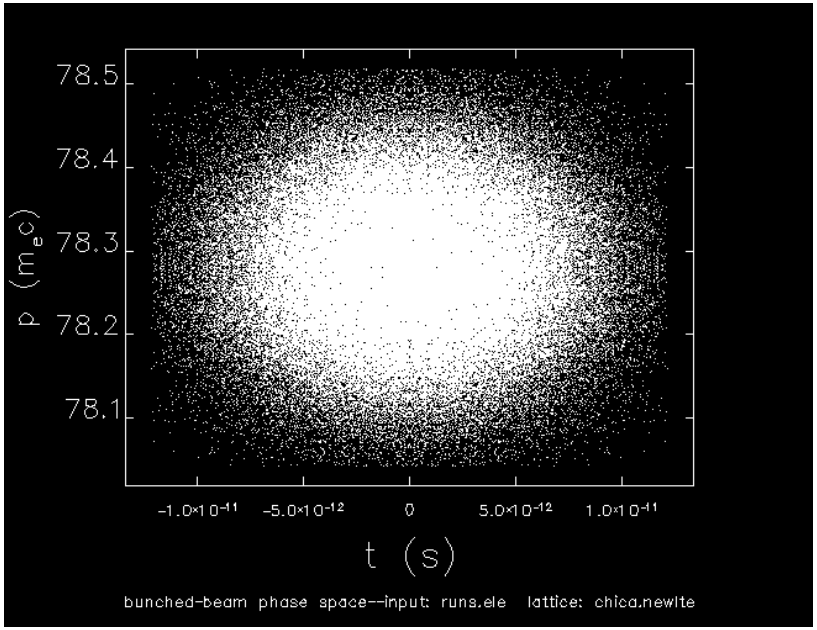


- Thick TDC produces a time-dependent momentum variation and non-zero R_{55} , R_{56}. It is compensated with a FMC.
- Two quads after the first dogleg change the dispersion sign.
- The first pair of quads allows us to have zero R_{52} and whatever R_{51}.
- R_{53}=R_{54}=0 are satisfied automatically,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

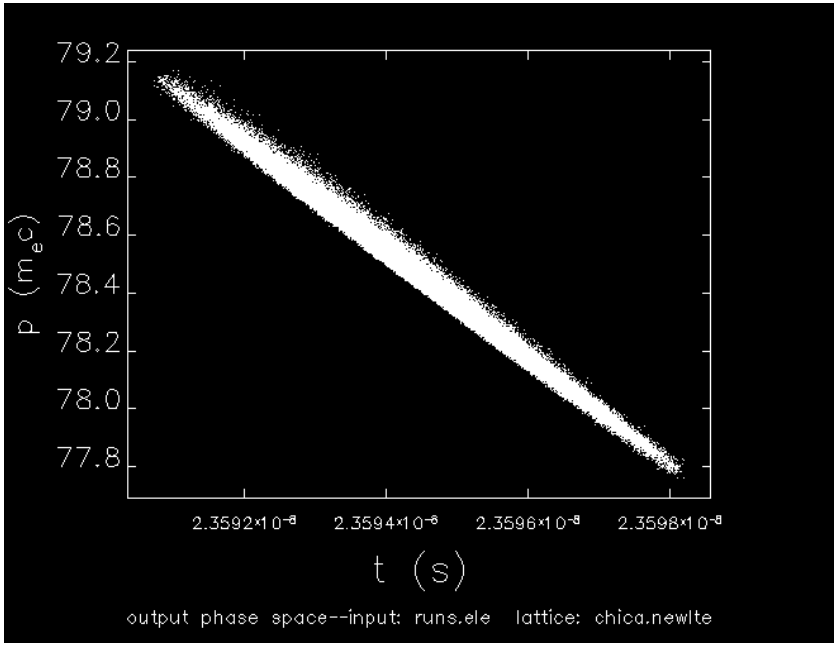


Problem #1 (comes in the 1st order)

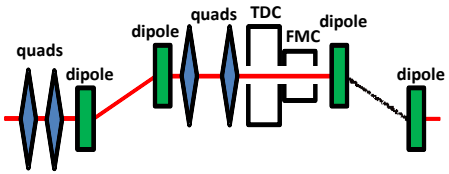
- High energy spread after the EEX due to R61.



Input beam

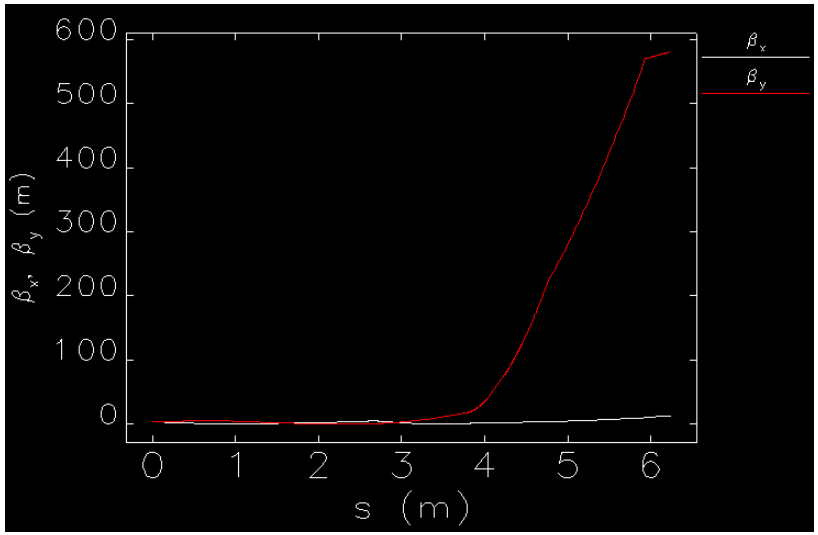


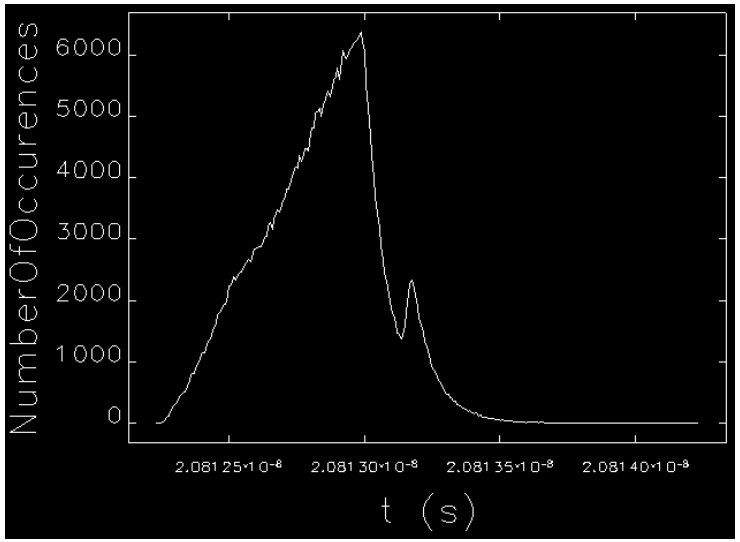
Output beam (no mask)



Problem #2 (higher order nonlinearities)

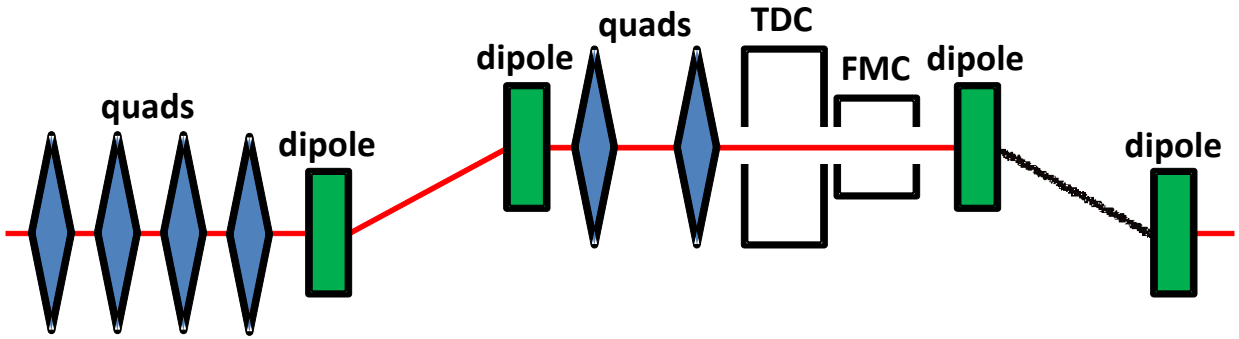
- Distortion of shape in higher order due to the big beam width.

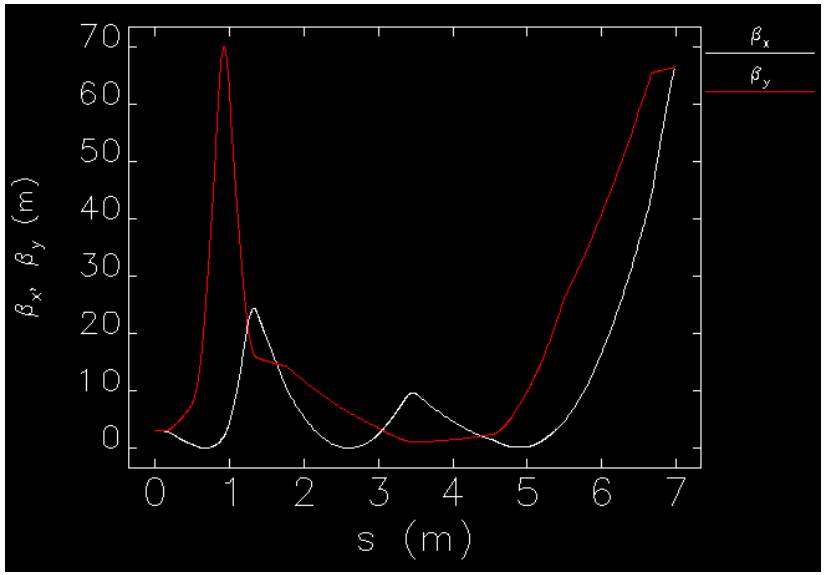


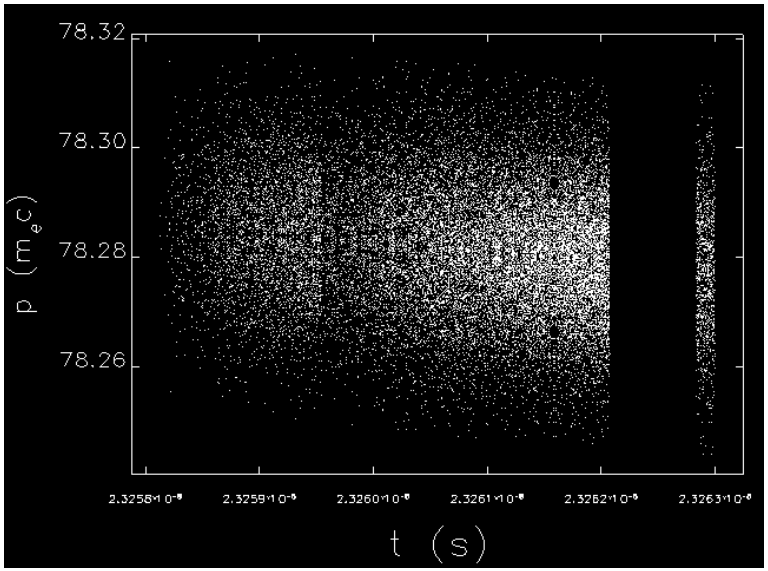


A beam width is proportional to a square root of a beta function.

First order (with additional quads)

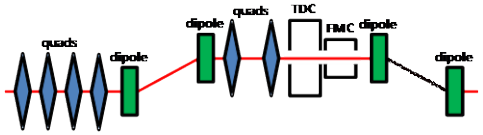


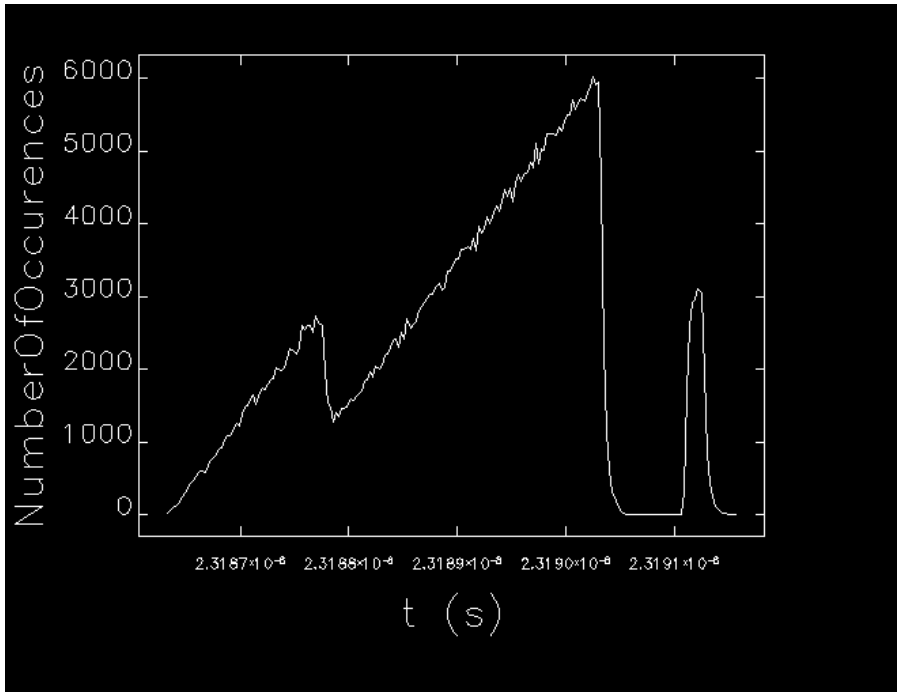


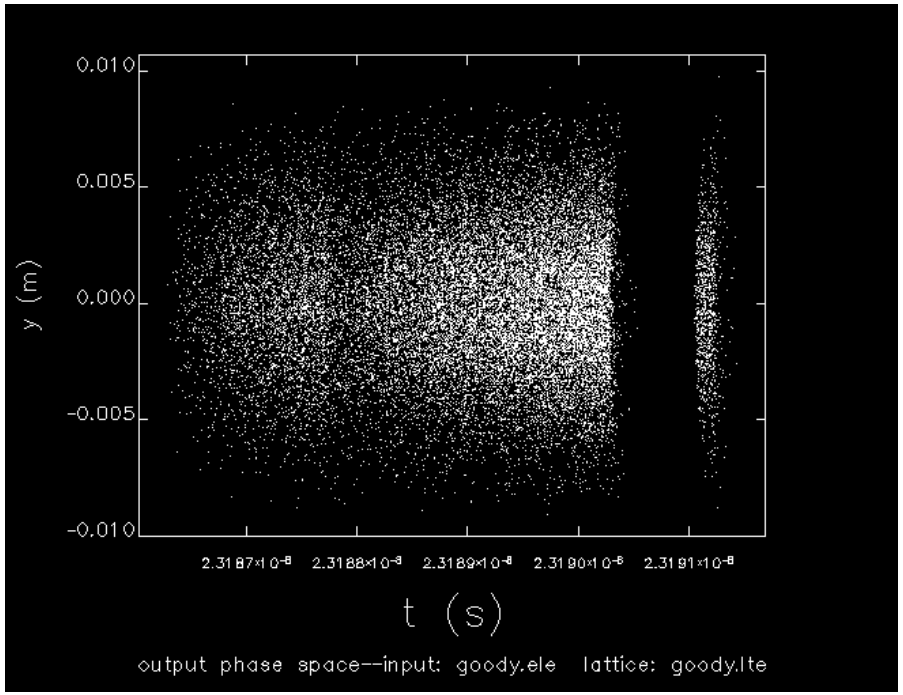


Minimized both the beam size and the R_{61}.

Third order

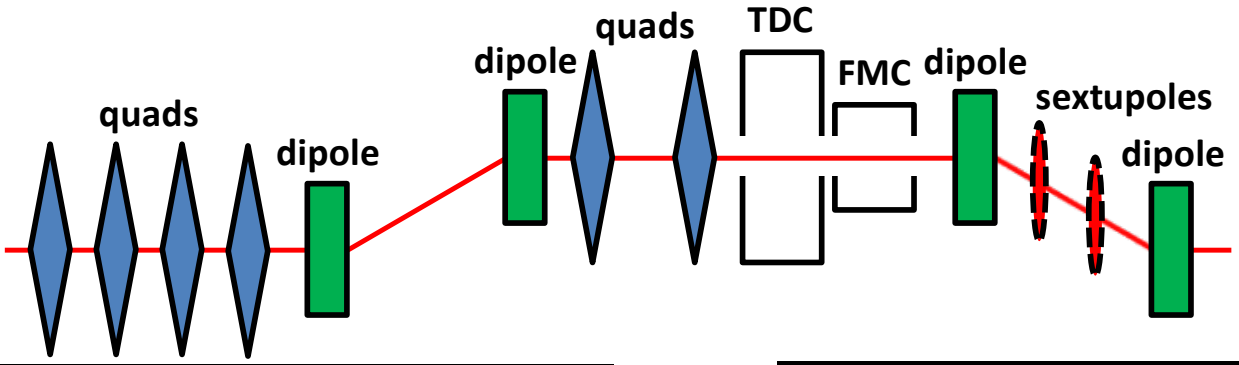


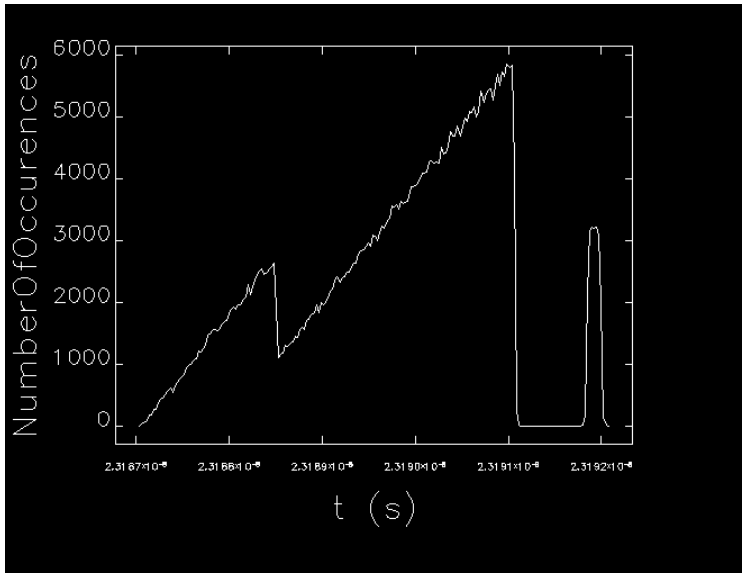


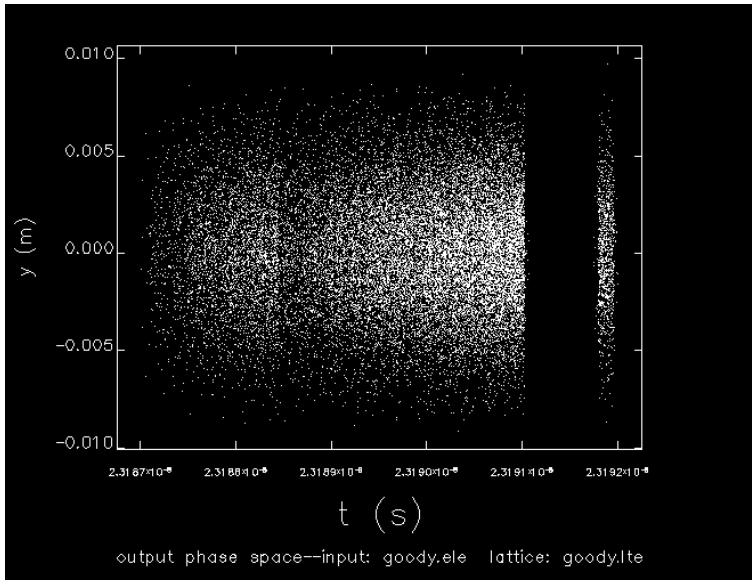


Has some distortions, high T_{555} and T_{544}.

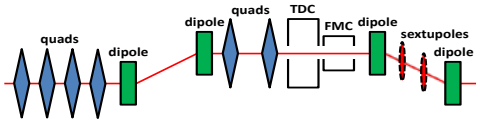
Third order (with sextupoles): matrix method



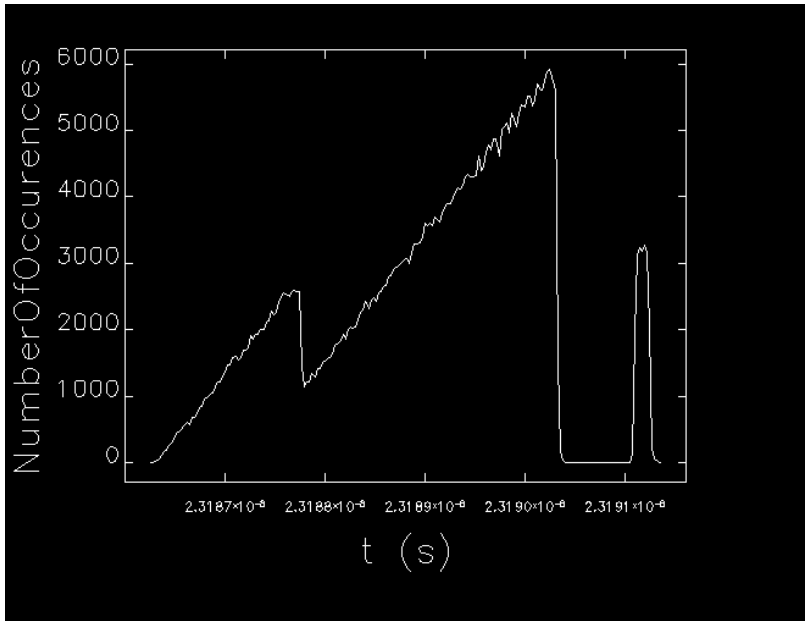


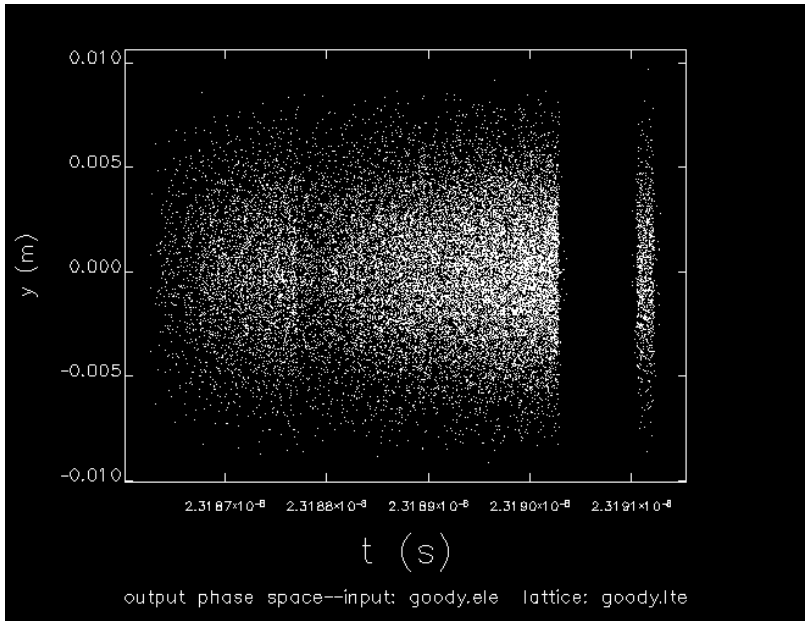


All T_{ijk} are small, perfect shape.

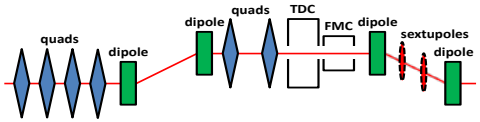


Third order (with sextupoles): kicks method





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

C: 2.7946e-005 1.2732e-005 0.0000e+000 0.0000e+000 6.9517e+000 -3.3082e-007

R1: 6.9568e-005 -3.1865e-005 0.0000e+000 0.0000e+000 4.4691e+000 -1.4560e-001

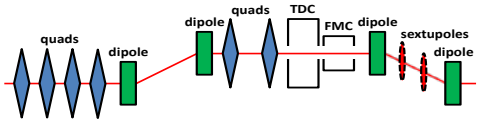
R2: 1.7188e-004 -2.0645e-005 0.0000e+000 0.0000e+000 2.0012e+000 -2.8897e-001

R3: 0.0000e+000 0.0000e+000 3.4319e-001 1.3912e+001 0.0000e+000 0.0000e+000

R4: 0.0000e+000 0.0000e+000 -4.8904e-002 9.3129e-001 0.0000e+000 0.0000e+000

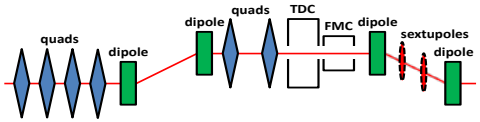
R5: 1.0720e+000 4.5637e-007 0.0000e+000 0.0000e+000 -6.4342e-007 5.7403e-006

R6: -1.3423e-001 -9.3221e-001 0.0000e+000 0.0000e+000 -5.6528e-004 8.1758e-005



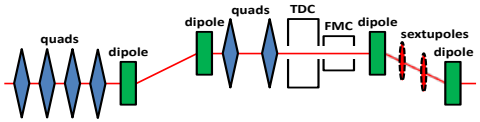
MATRIX

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)
AFTERCAV: LINE=(DRIFT,D300,DRFDRF,SS1,DRFDRF,SS2,DRFDRF,D301)
EEX: LINE=(QUADS,BEFORECAV,DCAV,DIFERENCE,FUNDCAV,AFTERCAV)

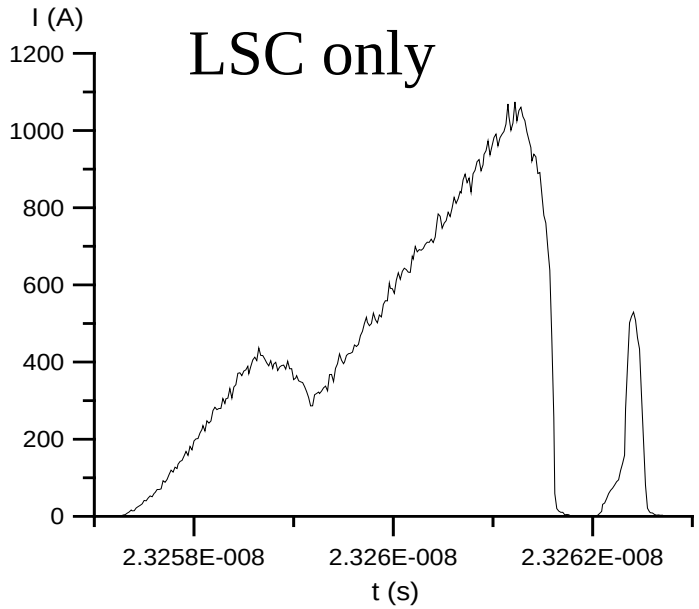


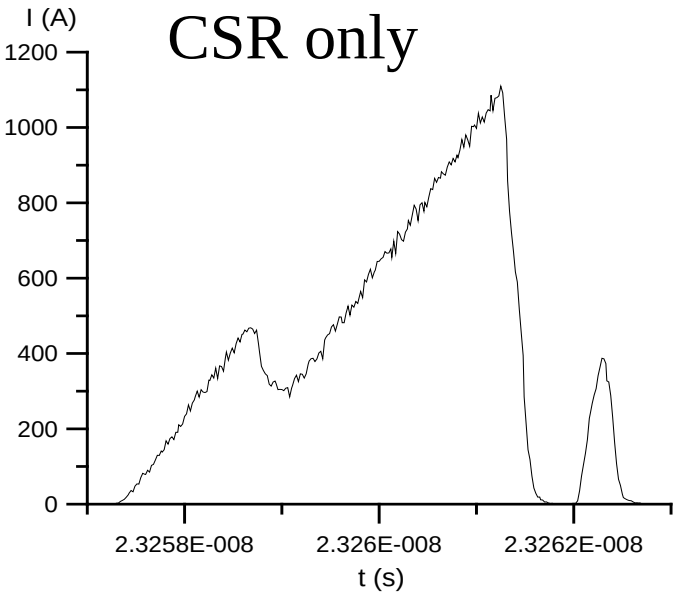
BEAM PARAMETERS

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

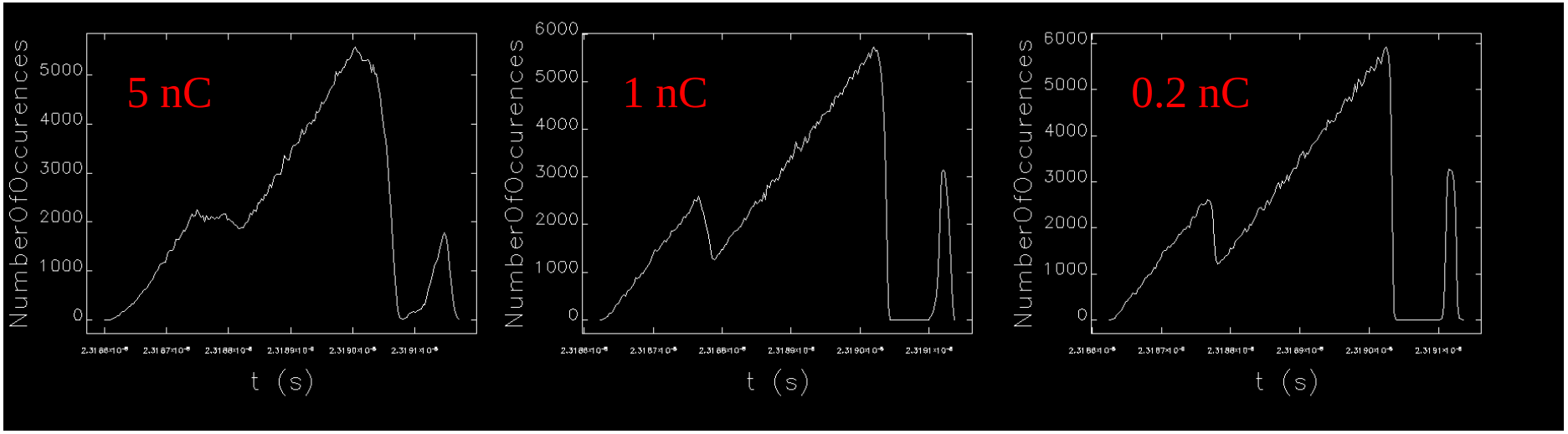
ELEGANT simulations with kicks for initially a 5 nC beam.





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)

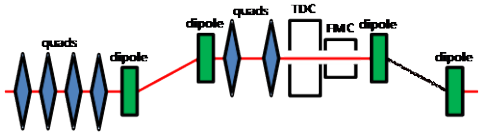
Tech-X simulated a real standing wave deflecting cavity for us and produced the 3rd order transfer matrix in Elegant format.

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

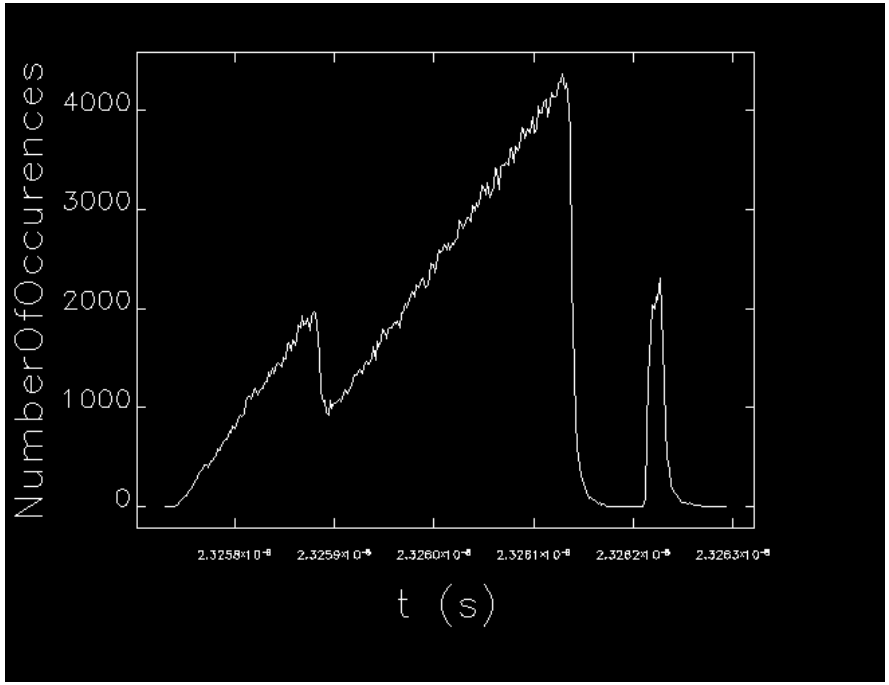
Standing wave cavity of finite thickness seems to cause aberrations even in the 1st order.

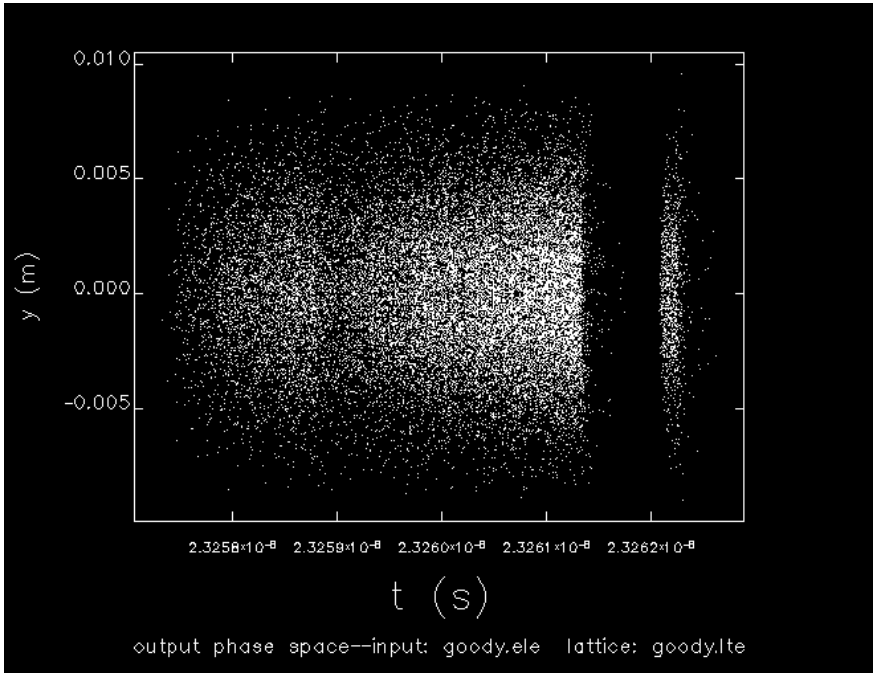
Conclusions and current plans

- 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!



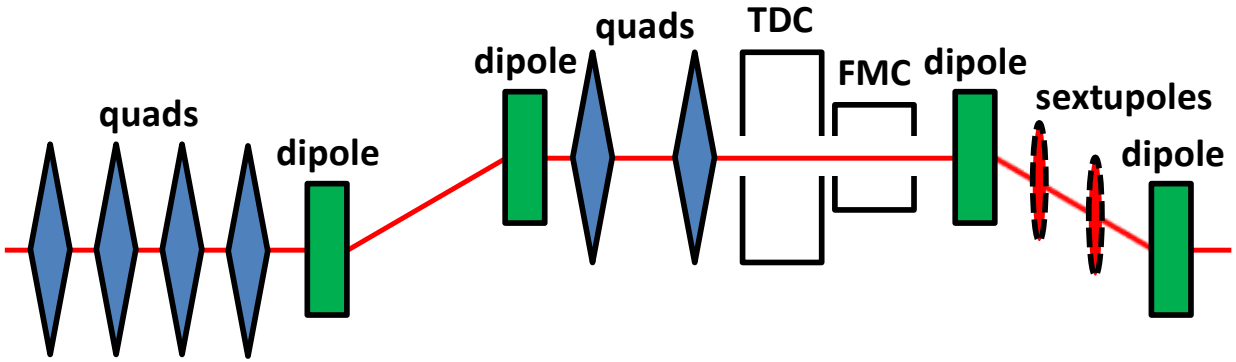
Third order

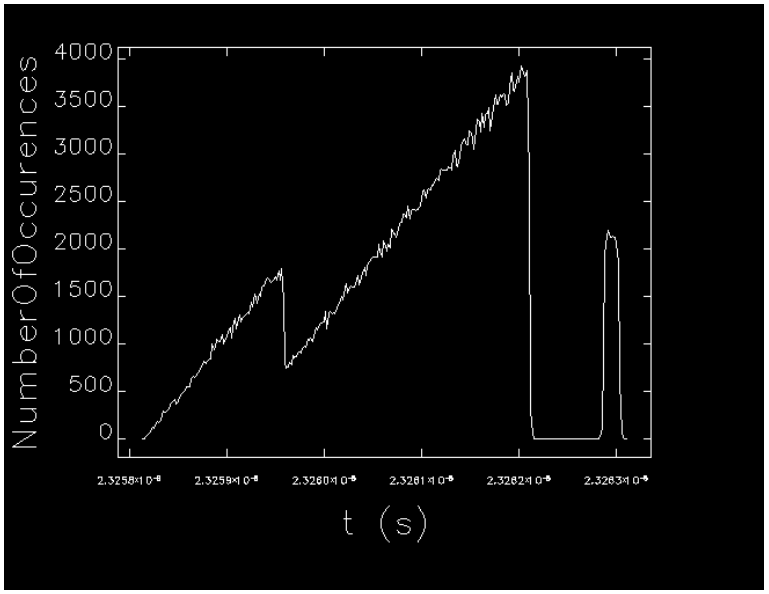


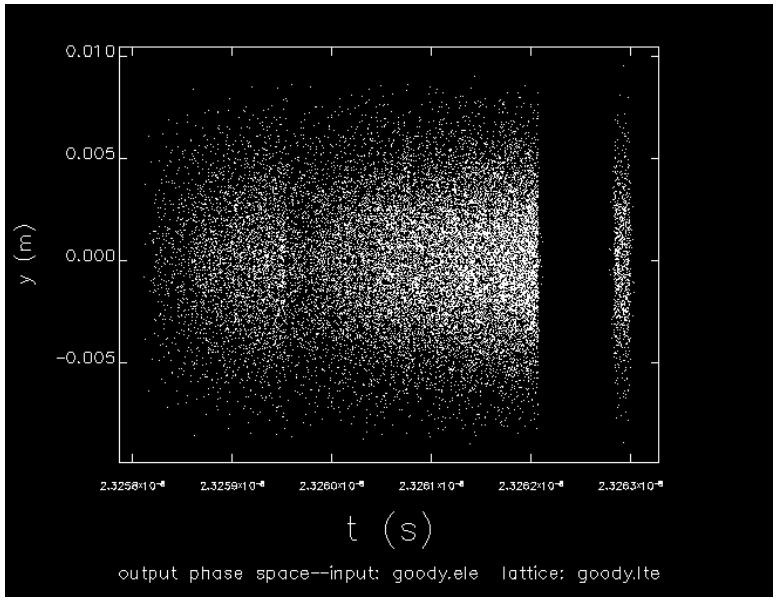


Has some distortions, high T_{555} and T_{544}.

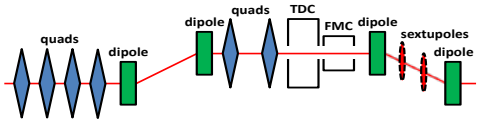
Third order (with sextupoles): matrix method



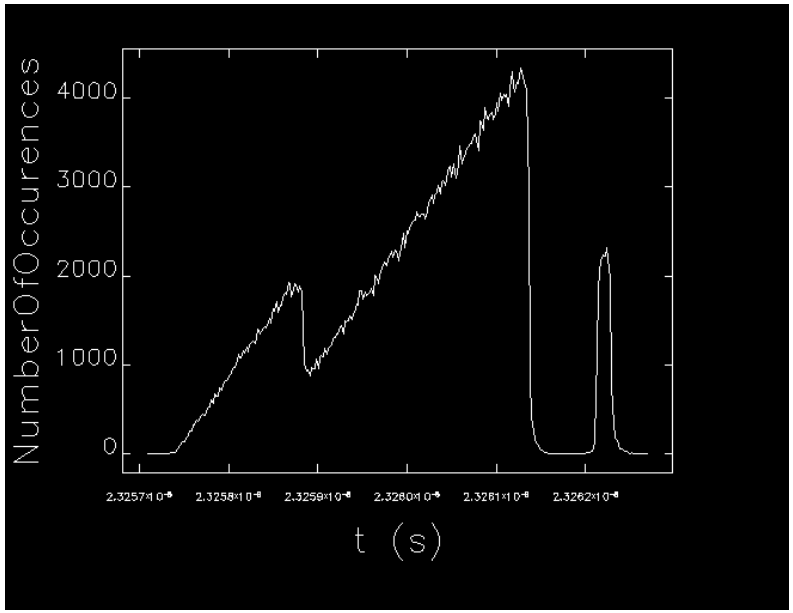


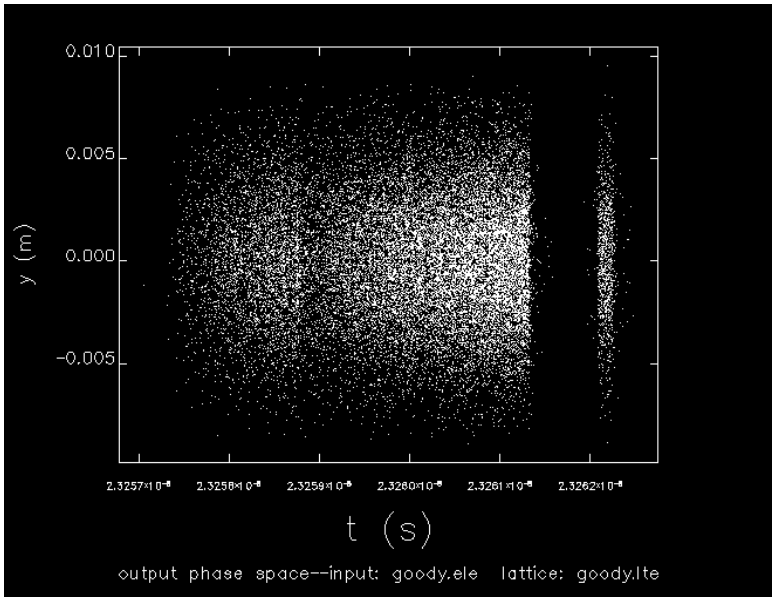


All T_{ijk} are small, perfect shape.



Third order (with sextupoles): kicks method





There is a difference. Reason – 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.