Beam dynamics in the low energy part of the Low Emittance Gun (LEG)

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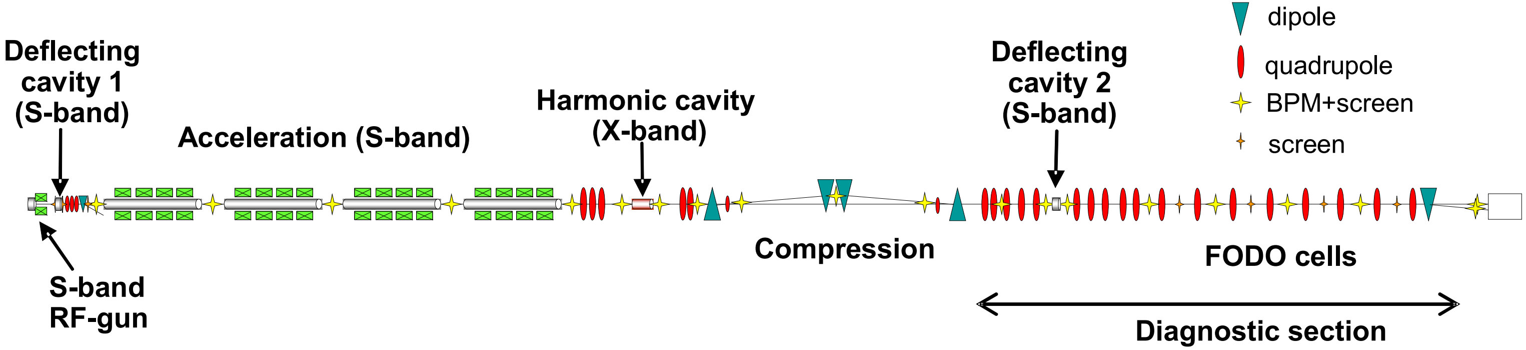
- Motivation
- Components
- Baseline performance
- Misalignment
- Conclusion

Motivation

250 MeV test injector at PSI

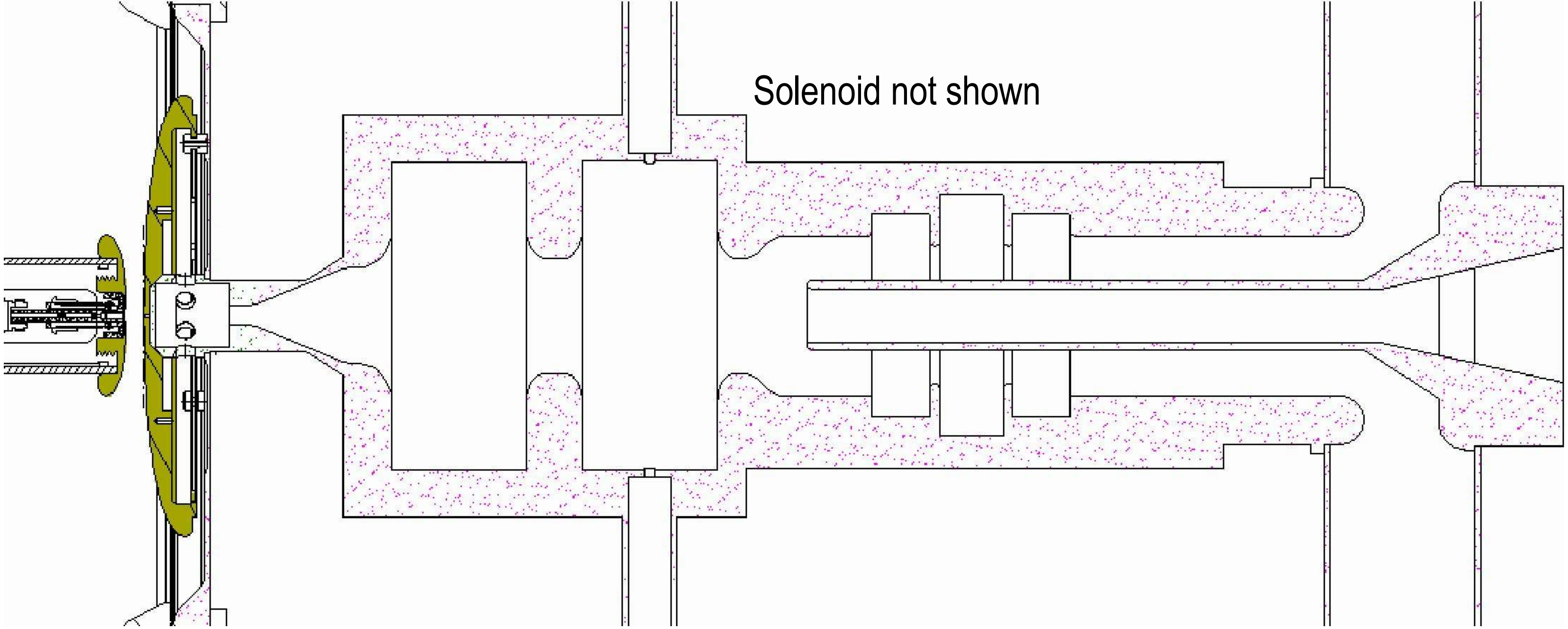


Test bed for SwissFEL project at PSI:

- Demonstrate the feasibility of a compact Free Electron Laser in the Angstrom regime
- Verify experimentally the performance predicted by the simulation codes
- Develop and test the different components/systems and optimization procedures necessary to operate the SwissFEL

Parameter	**200 pC**	**10 pC**
Energy (MeV)	**255**	
Rms Bunch Length (fs)	**193**	**33.2**
Rms Projected Emittance (nm.rad)	**370**	**100**
Rms Slice Emittance (nm.rad)	**330**	**78**
Peak Current (A)	**351**	**104**

Low Emittance Gun (LEG) as alternative e^- source



- Pulsed DC gun currently running at 125 MV/m over 4 mm gap
- Bunch at 5.5 A peak current (40 ps flat top) from photo cathode (Alternative option field emitter array)
- Two-frequency cavity provides simultaneously acceleration and correlated momentum spread for ballistic bunching in following drift
- Plug-in compatible with RF gun option in terms of phase space matching of beam

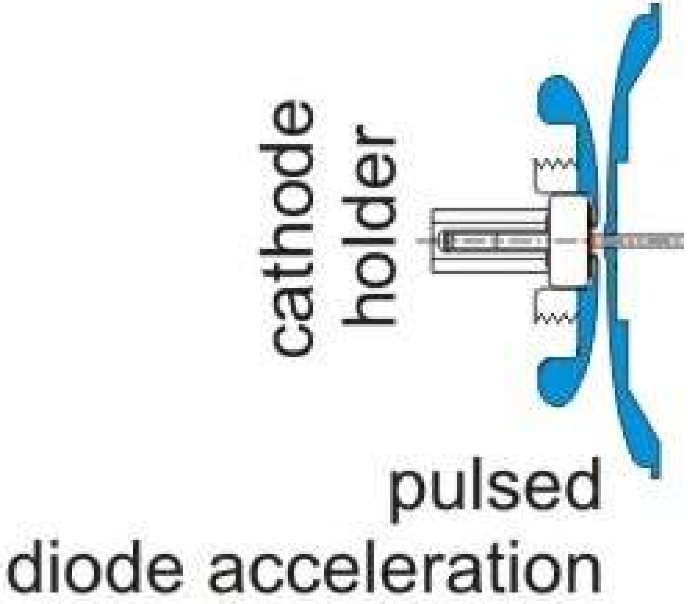
Simulation goals

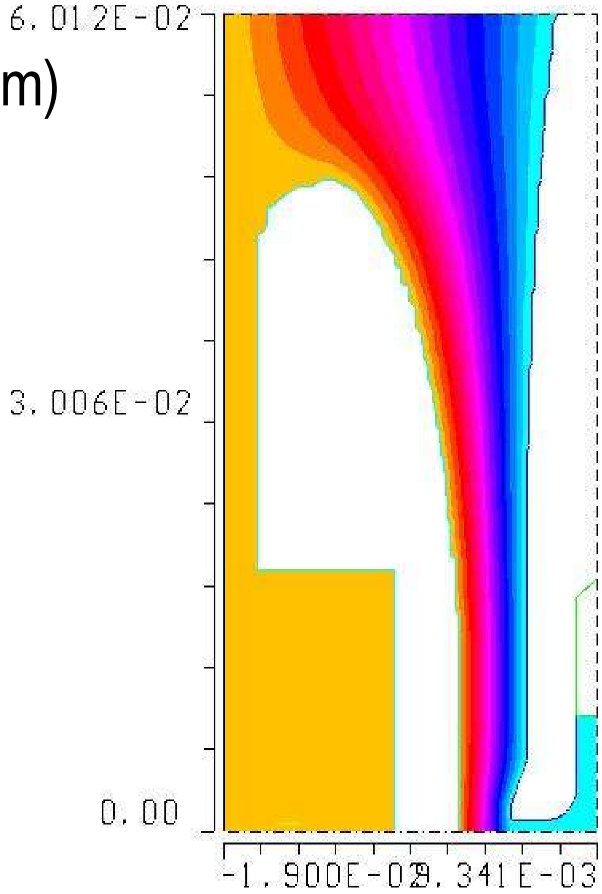
- Design has been done with tracking codes like BET (R. Bakker)
- Provide validation with true particle-in-cell code to capture effects of
  - Space charge
  - Wakes
  - More realistic phase space distribution
- Have a look at 3D effects
  - Asymmetry in particle distribution
  - Misalignments

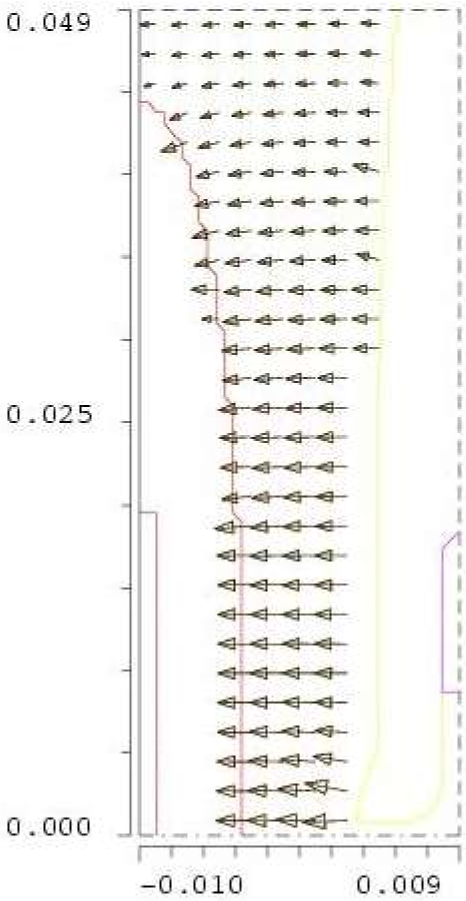
Components

Pulsed DC gun

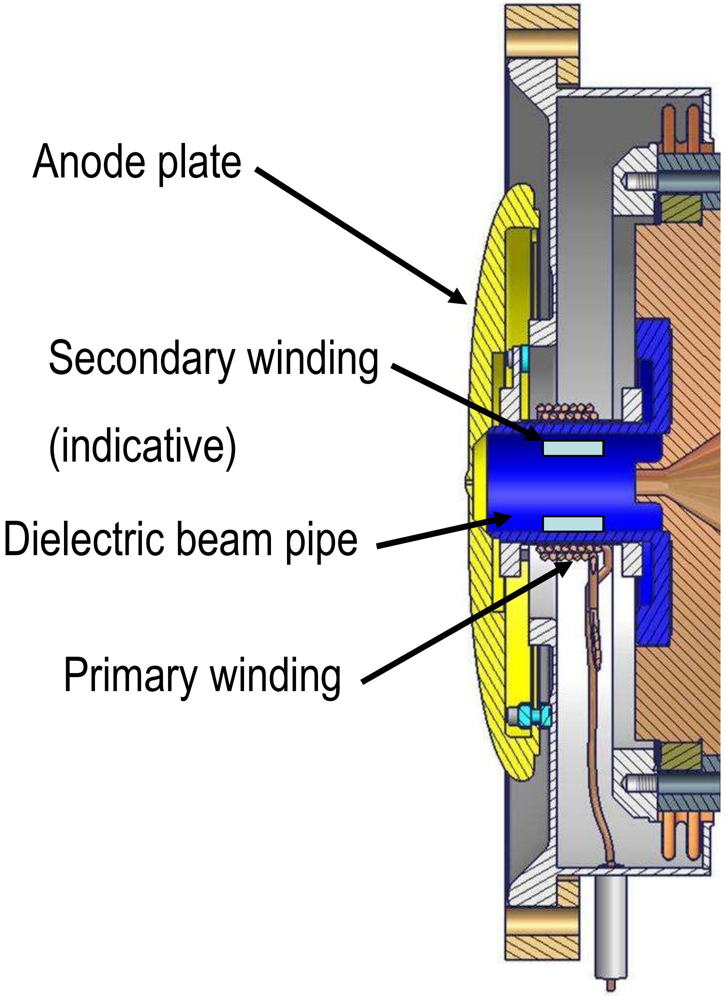
Tela coil pulser
0.5 MV over 4 mm gap (125 MV/m)
400 ns flat top







Pulsed solenoid following transformer principle (C. Gough)



•Pulse in primary winding excite induced current in secondary

•After pulse in primary winds down, current in secondary stills persists due to eddy current effect and generates focusing field

•Advantages

- Very compact to build
- Asymmetries in secondary don't affect field quality

•Question marks:

- Wakes due to dielectric beam pipe/secondary
- Alignment tolerances for secondary winding

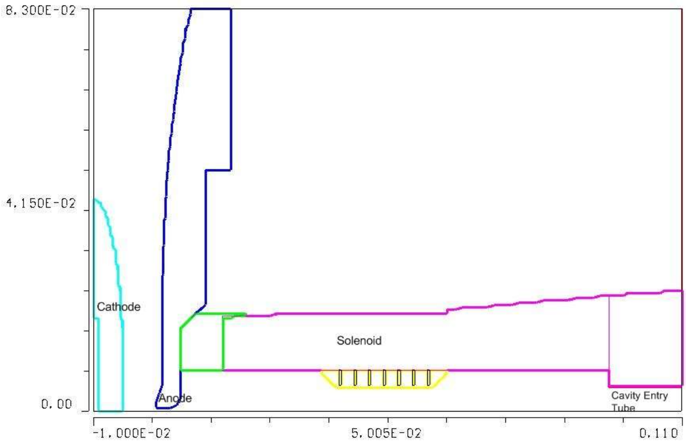
On the magnetic field distribution

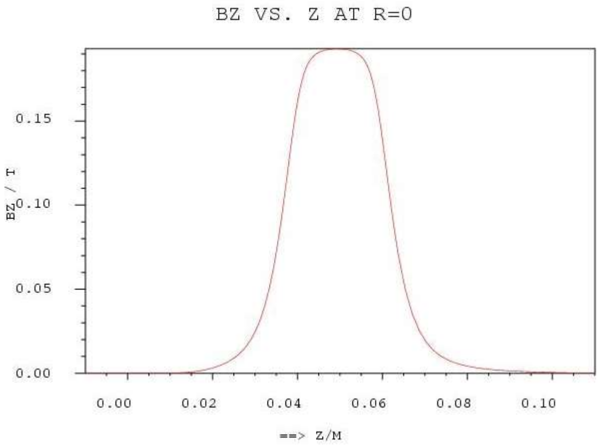
Field from solenoid is only quasi-static with following deviation from true magnetostatic solution:

Got mirror currents in all surrounding Cu parts resulting in mirror currents (For comparison: Secondary winding is stainless steel).

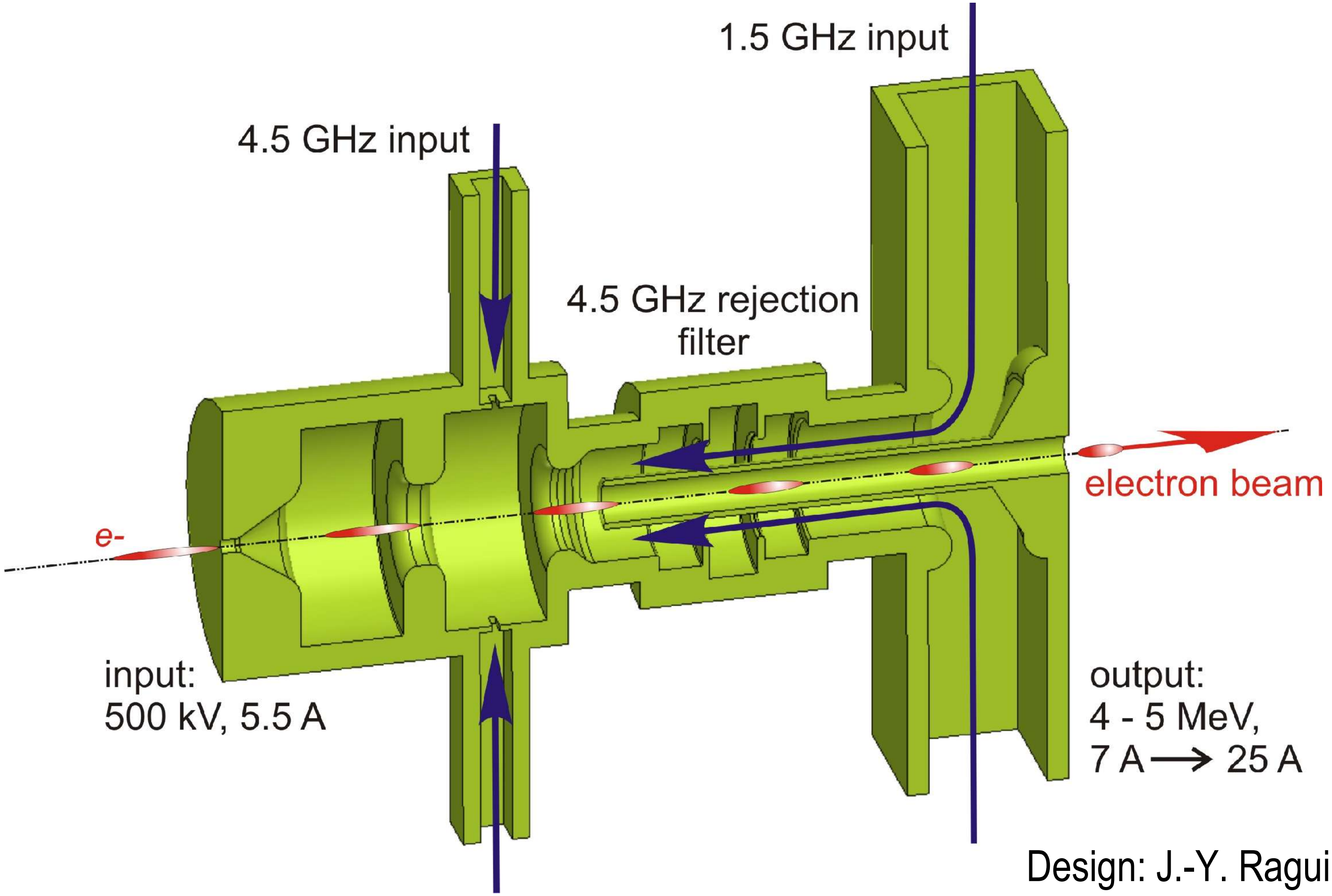
How to capture these effects in an approximative way using a magnetostatic solver:

- Assign $\mu=0.01$ to Cu parts to push out magnetic fields from bulk
- Assign homogeneously distributed current on anode plate with amplitude chosen to minimize field in anode/cathode gap





Two-frequency cavity

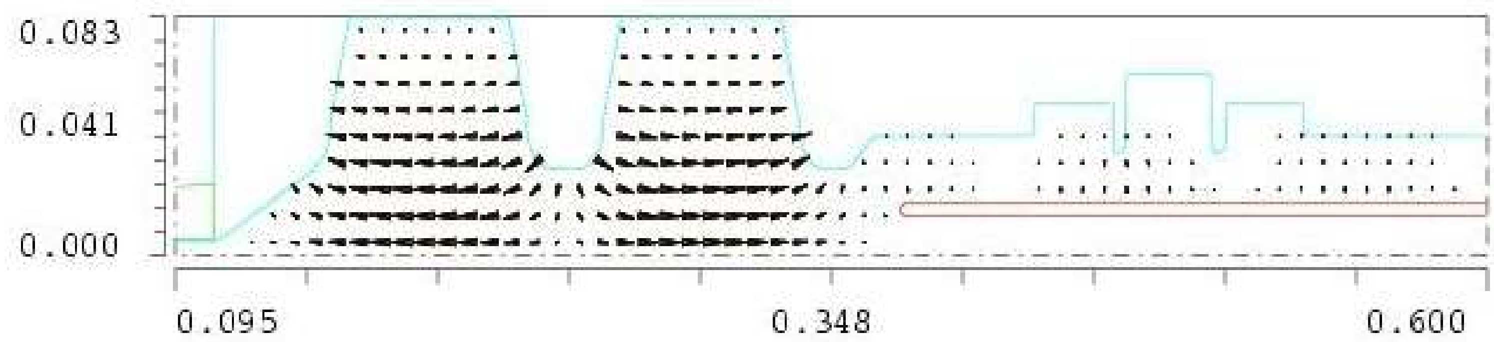


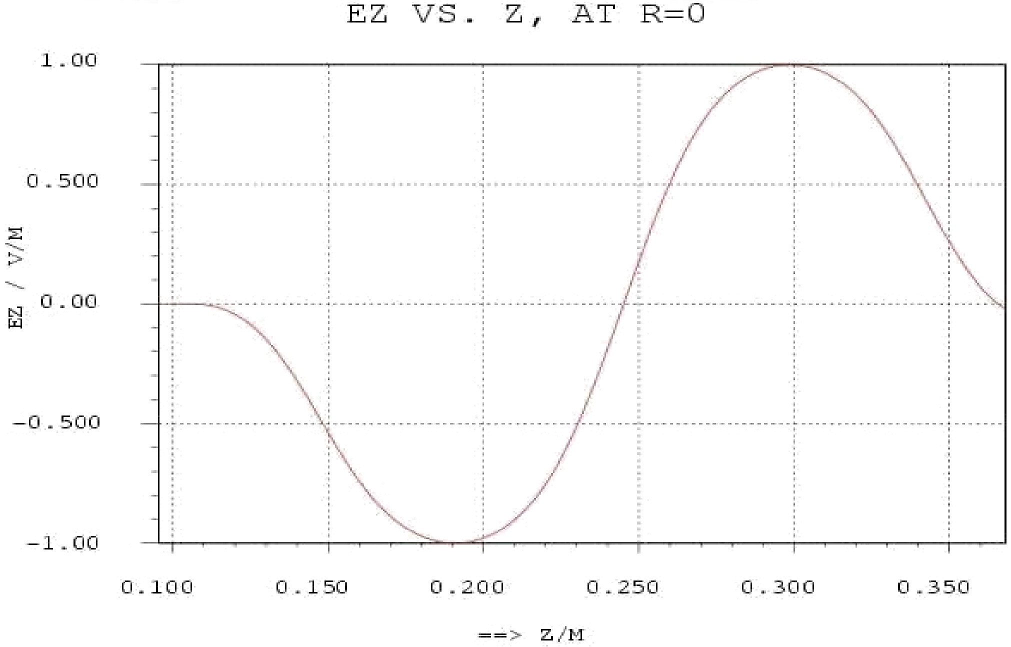
input:
500 kV, 5.5 A

output:
4 - 5 MeV,
7 A ⟶ 25 A

Design: J.-Y. Raguin

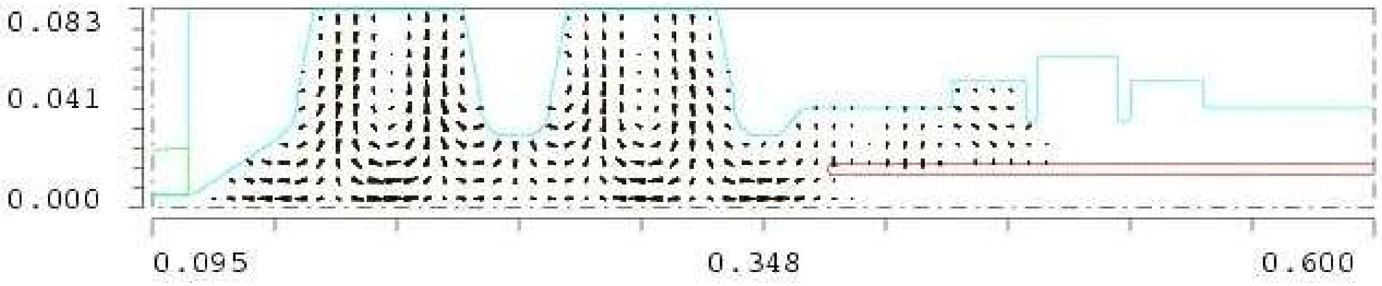
Fundamental mode

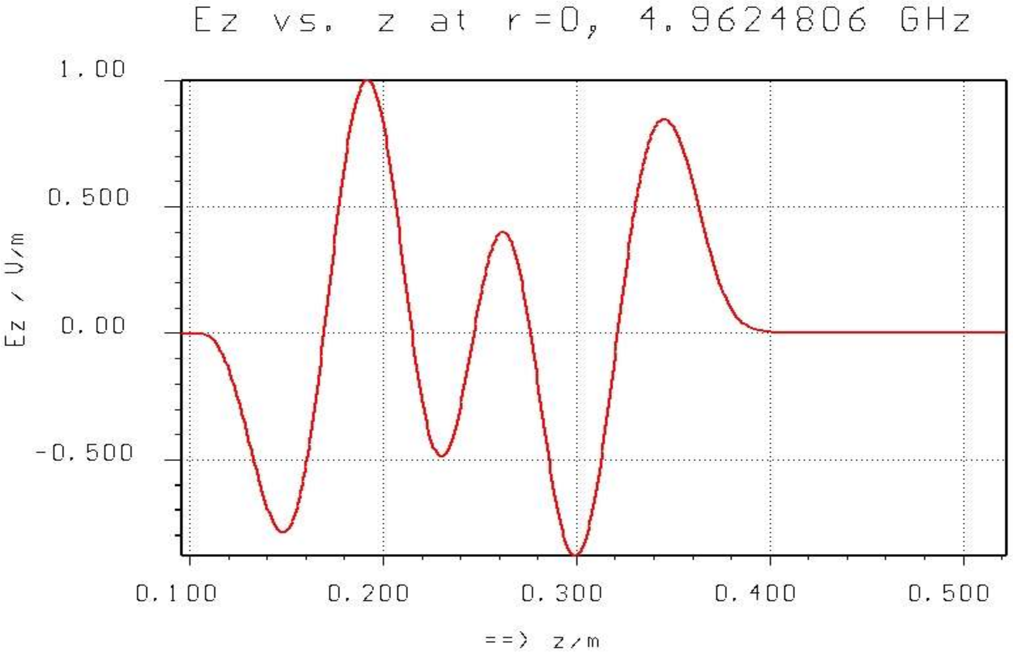




electrical field on axis

Third harmonic

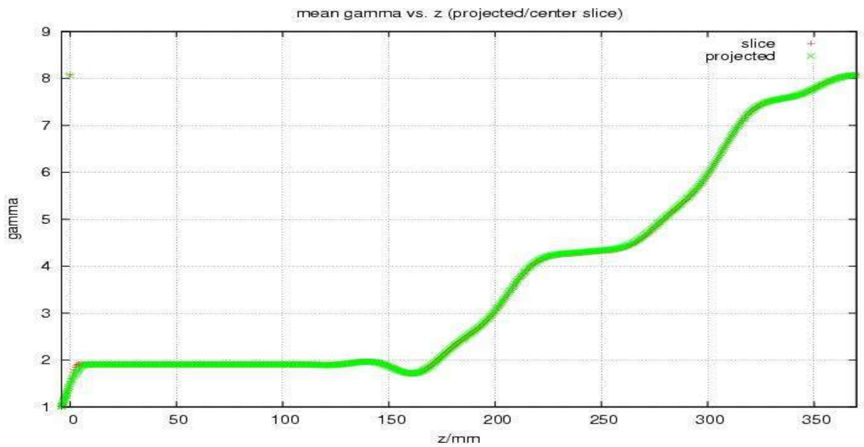




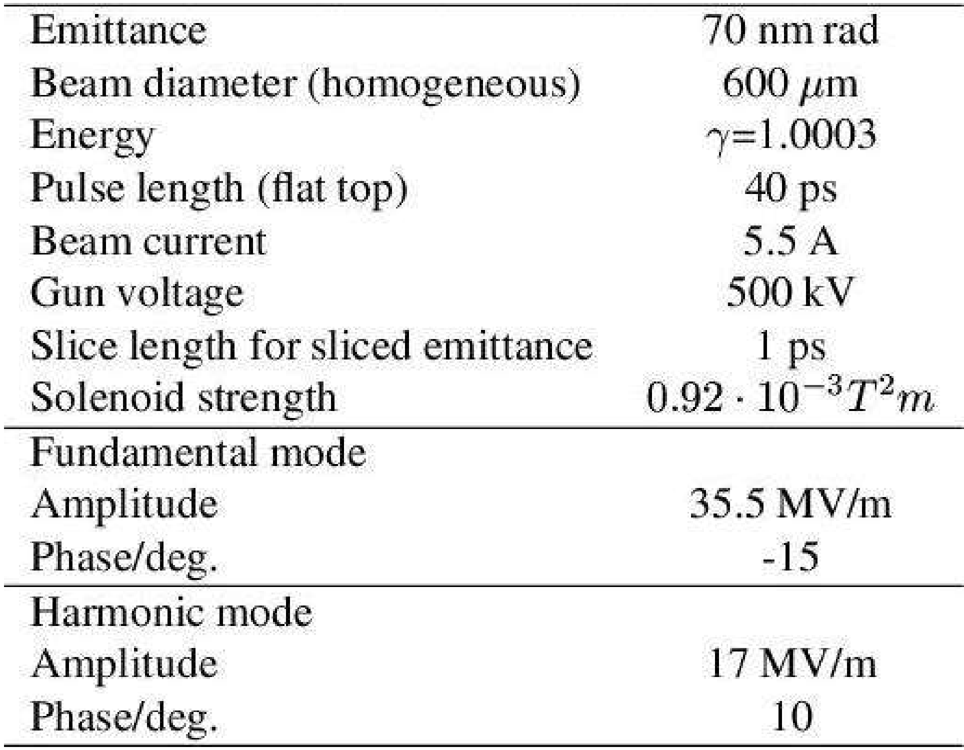
electrical field on axis

Base line performance

- Components rotationally symmetric, so can do 2 ½ D PIC with MAFIA TS2
- Validation of BET results only possible within limits
  - More up to date structure geometries
  - Beam gets focused and decelerated at cavity entry (see below): Had to search for different working point for RF amplitudes and phases

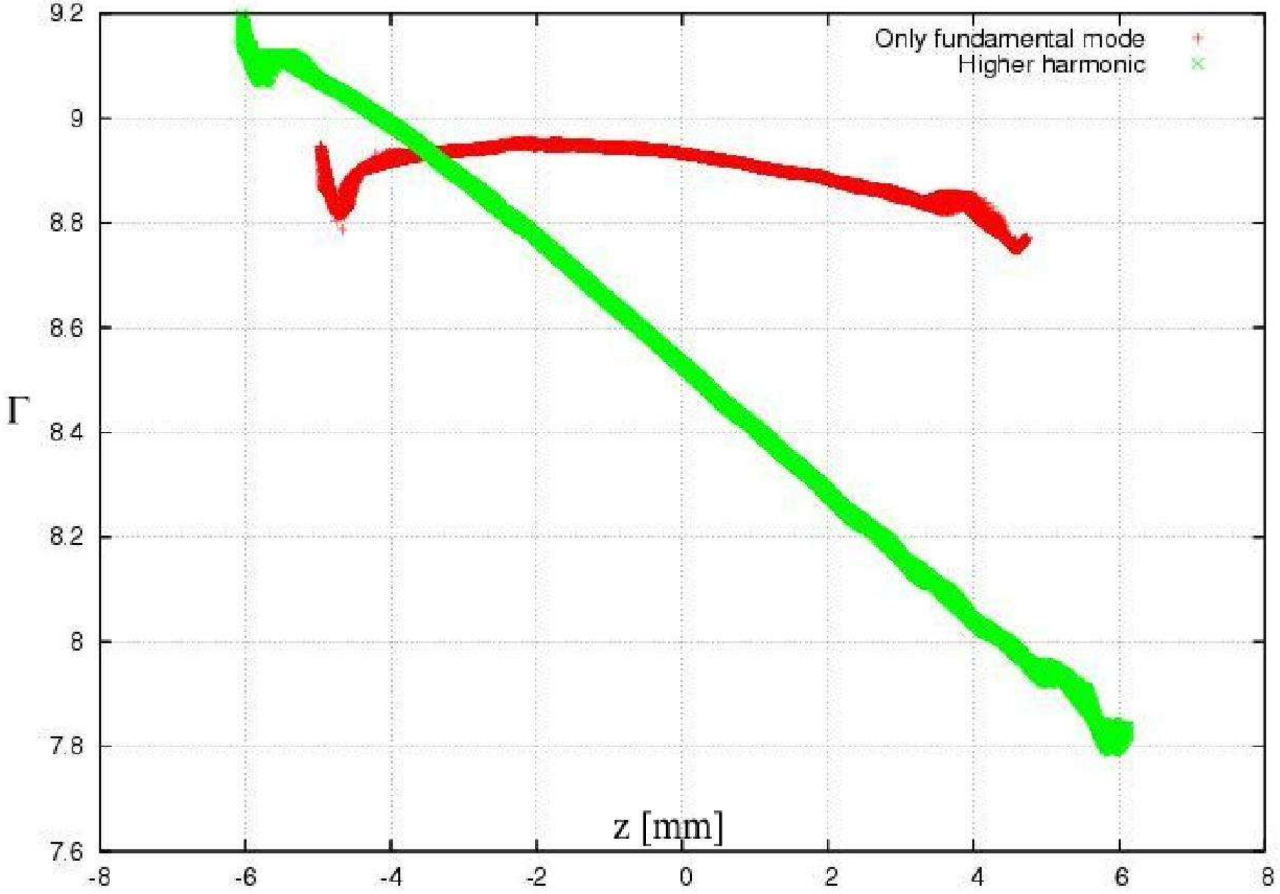


Initial beam parameters



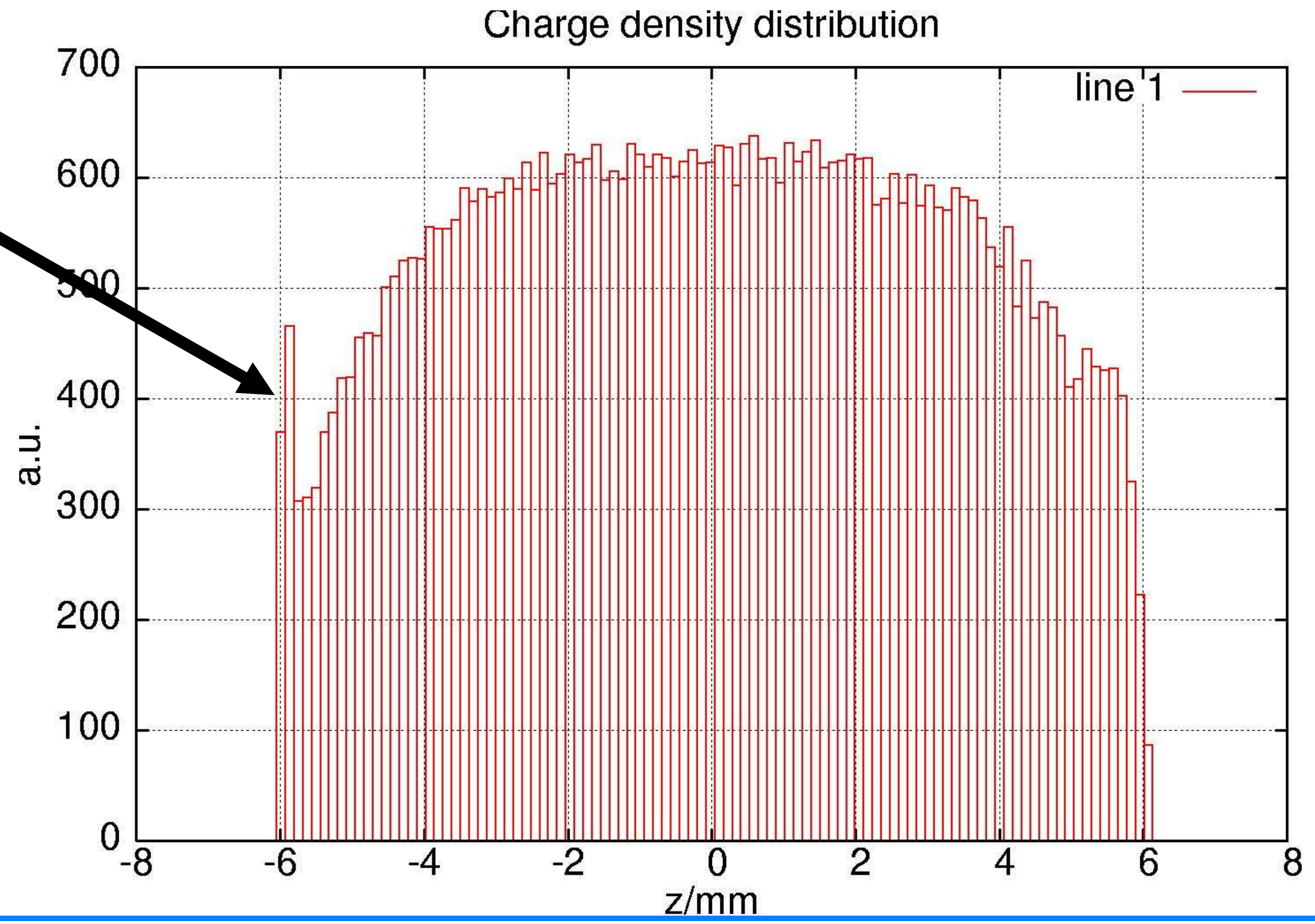
Emittance	70 nm rad
Beam diameter (homogeneous)	600 μm
Energy	γ=1.0003
Pulse length (flat top)	40 ps
Beam current	5.5 A
Gun voltage	500 kV
Slice length for sliced emittance	1 ps
Solenoid strength	$0.92 \cdot 10^{-3} T^2 m$
Fundamental mode	
Amplitude	35.5 MV/m
Phase/deg.	-15
Harmonic mode	
Amplitude	17 MV/m
Phase/deg.	10

Longitudinal phase space

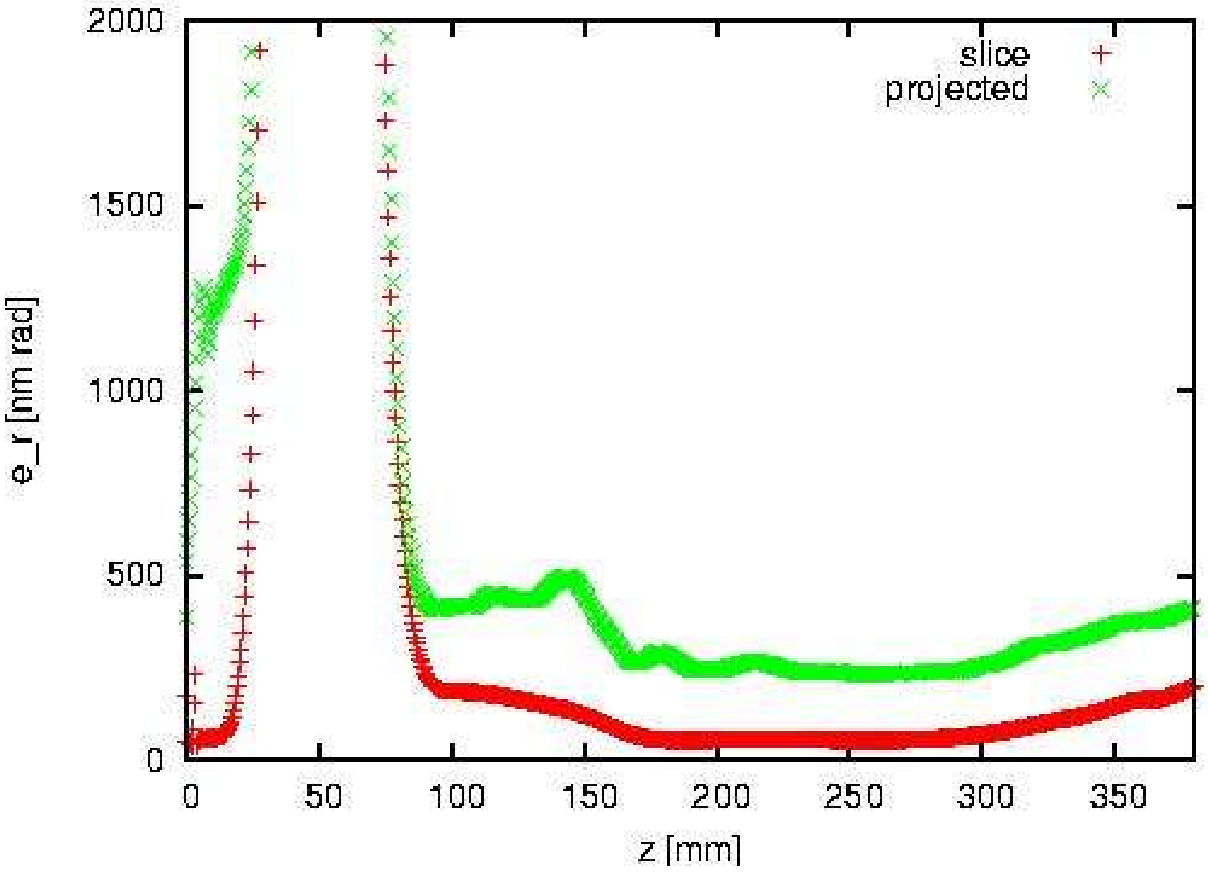


Charge density

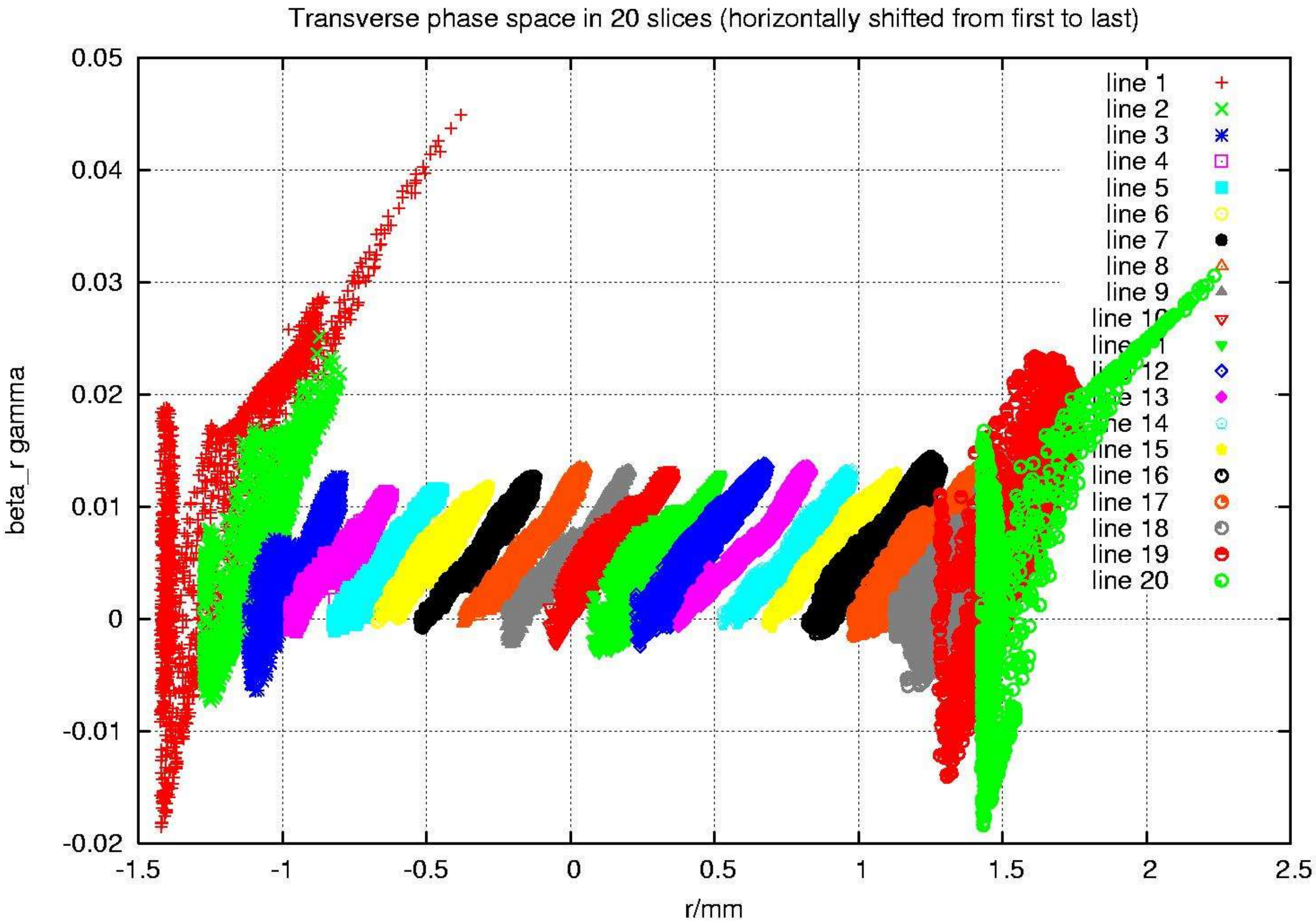
Artifact seen also in other distributions



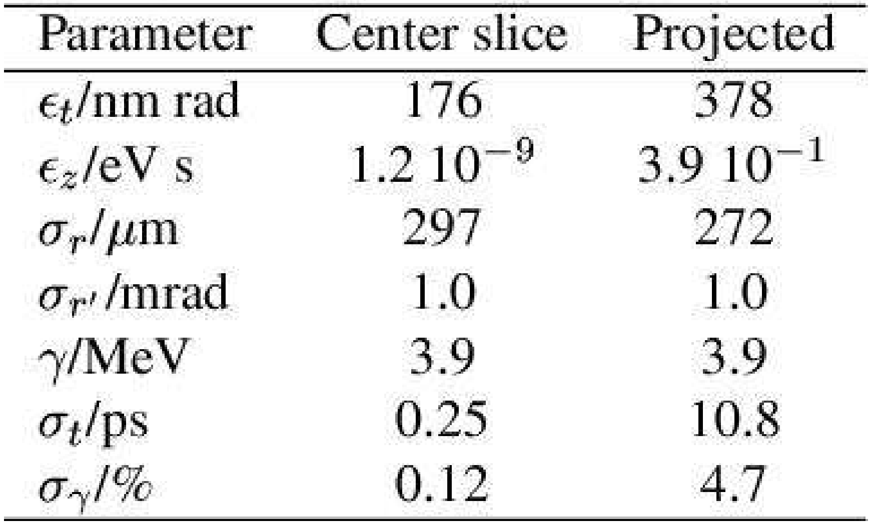
Evolution of emittance



Phase space of different bunch slices



Beam parameters at exit of RF cavity



Parameter	Center slice	Projected
ϵ_t/nm rad	176	378
ϵ_z/eV s	$1.2\ 10^{-9}$	$3.9\ 10^{-1}$
σ_r/μm	297	272
$\sigma_{r'}$/mrad	1.0	1.0
γ/MeV	3.9	3.9
σ_t/ps	0.25	10.8
σ_γ/%	0.12	4.7

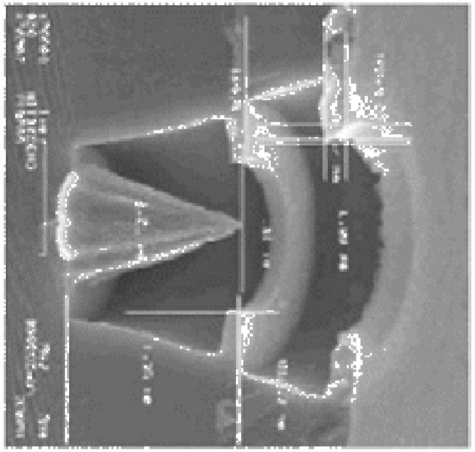
Misalignments

The tool

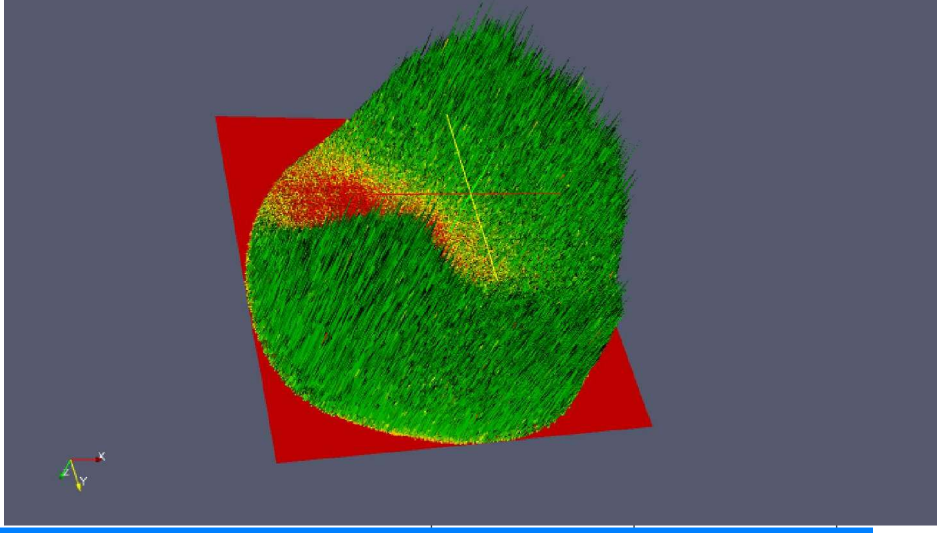
- Shifted beam and components change problem type from 2 ½ D to 3D
- Using in-house code Capone (A. Candel):
  - Originally developed to simulate electron sources based on field emitter arrays (FEA)
  - Parallel, true particle-in-cell using Pooma/MPI
  - Originally having only static driving fields

Double gated

Field emitter



Charge distribution from inhomogeneous Field Emitter Array

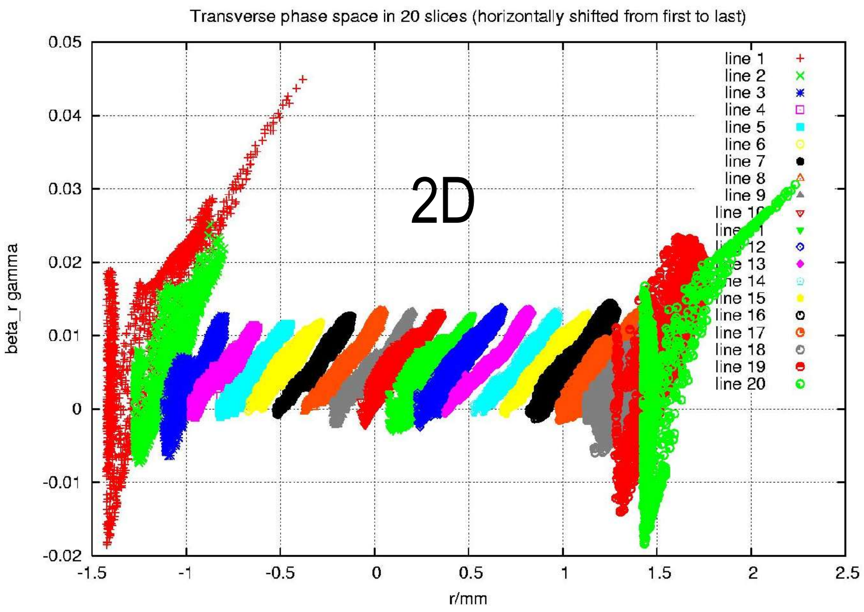


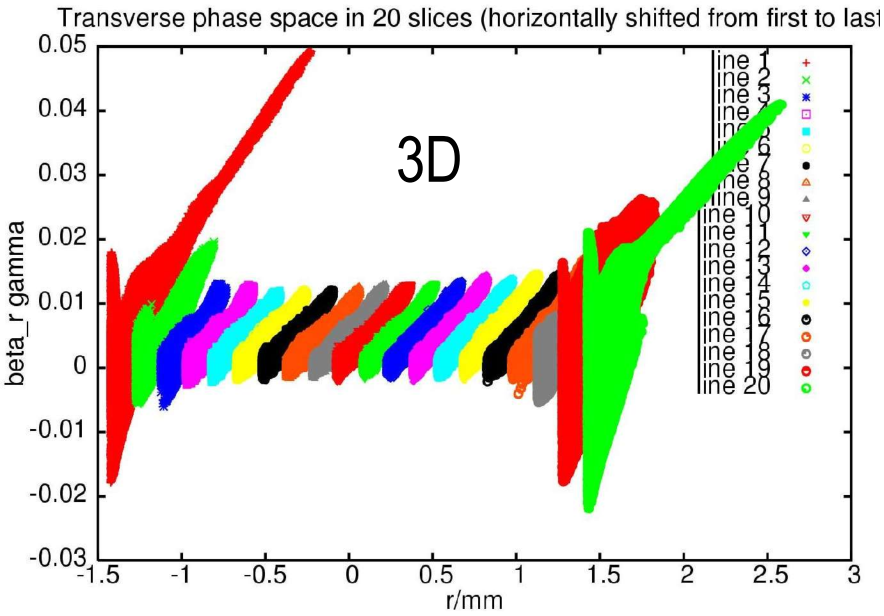
2D field maps in CAPONE

Option to load and use external fields (m/e-static, resonant, traveling wave) from 2D calculations:

- Computing third harmonic in full 3D using normal solver would require computation of first 104 modes (all lowest multipoles up to 4.5 GHz) on calculation grid (~ 1 billion grid points).
- Simple introduction of misalignments of e.g. solenoid fields by simple shift/tilt of 2D field map.
- Possibility to truncate calculation grid to region relevant for correct representation of self fields of the bunch and wakes.

Phase space comparison 2D/3D





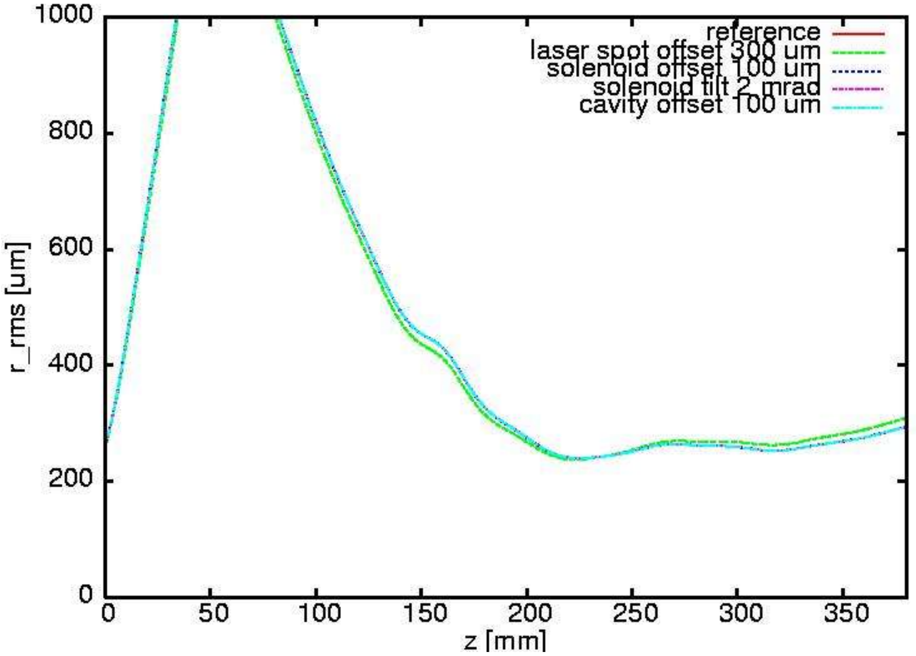
- Due to much larger number of macro particles, 3D phase space appears thicker then 2D
- In reality, got center slice emittances of 170 nm rad (2D) vs. 120 nm rad (3D)
- Difference in extreme slices due to other rise times of 0 (2D) vs. 0.5 ps (3D) of flat top pulse
- Otherwise good agreement.

Results

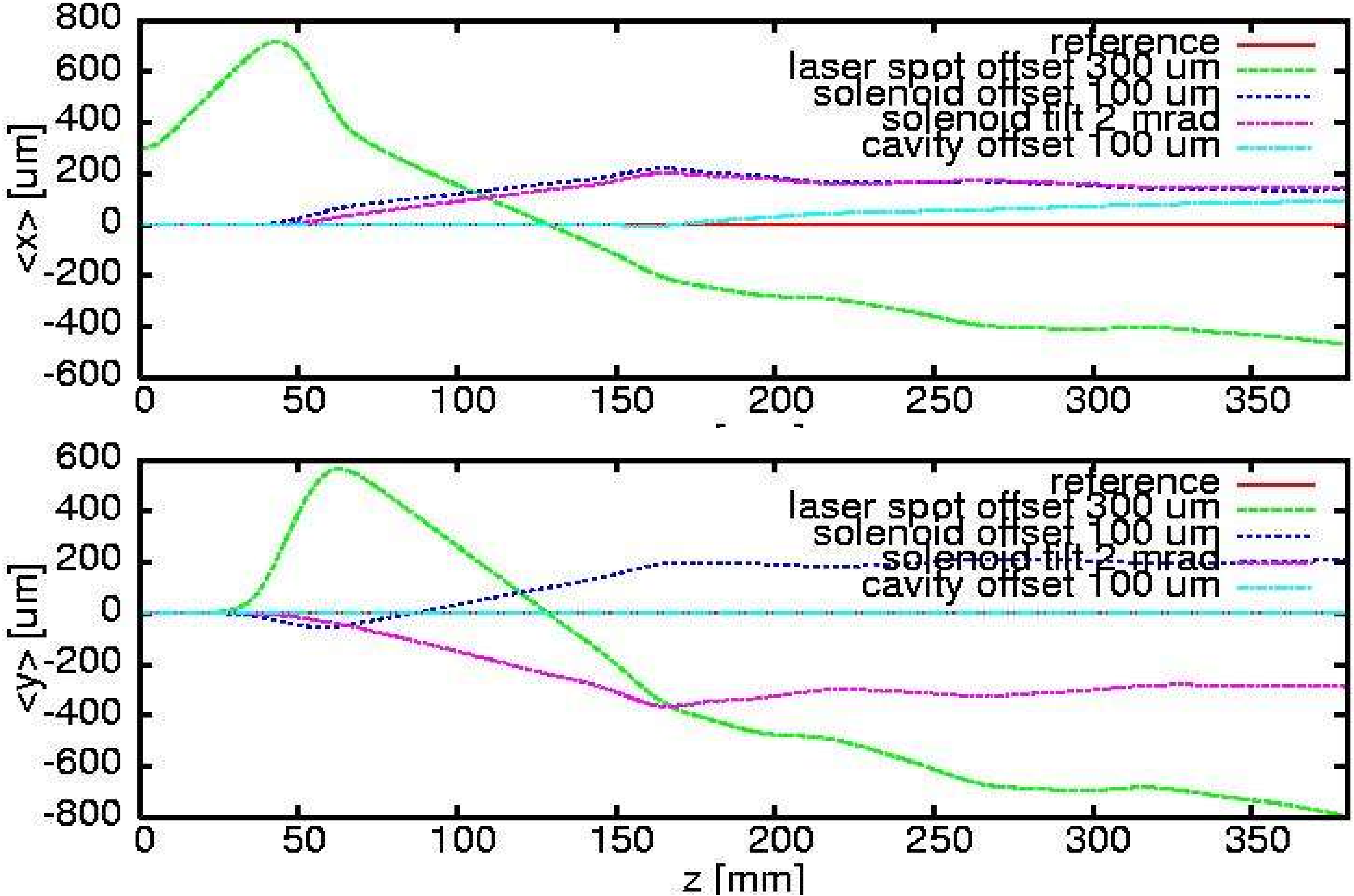
Four types of misalignment:

- Offset of laser spot
- Solenoid offset
- Solenoid tilt
- Cavity offset

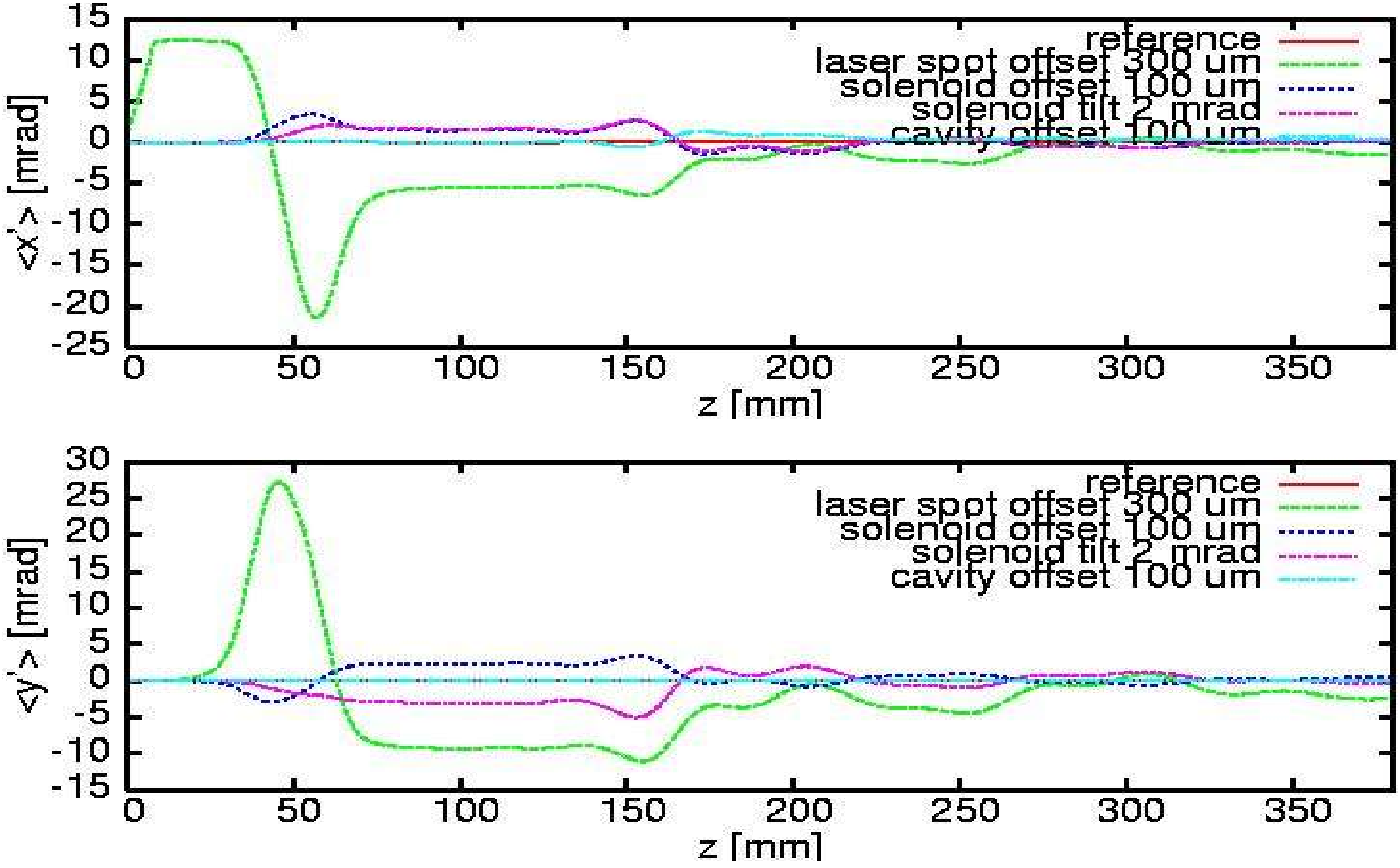
Beam envelope



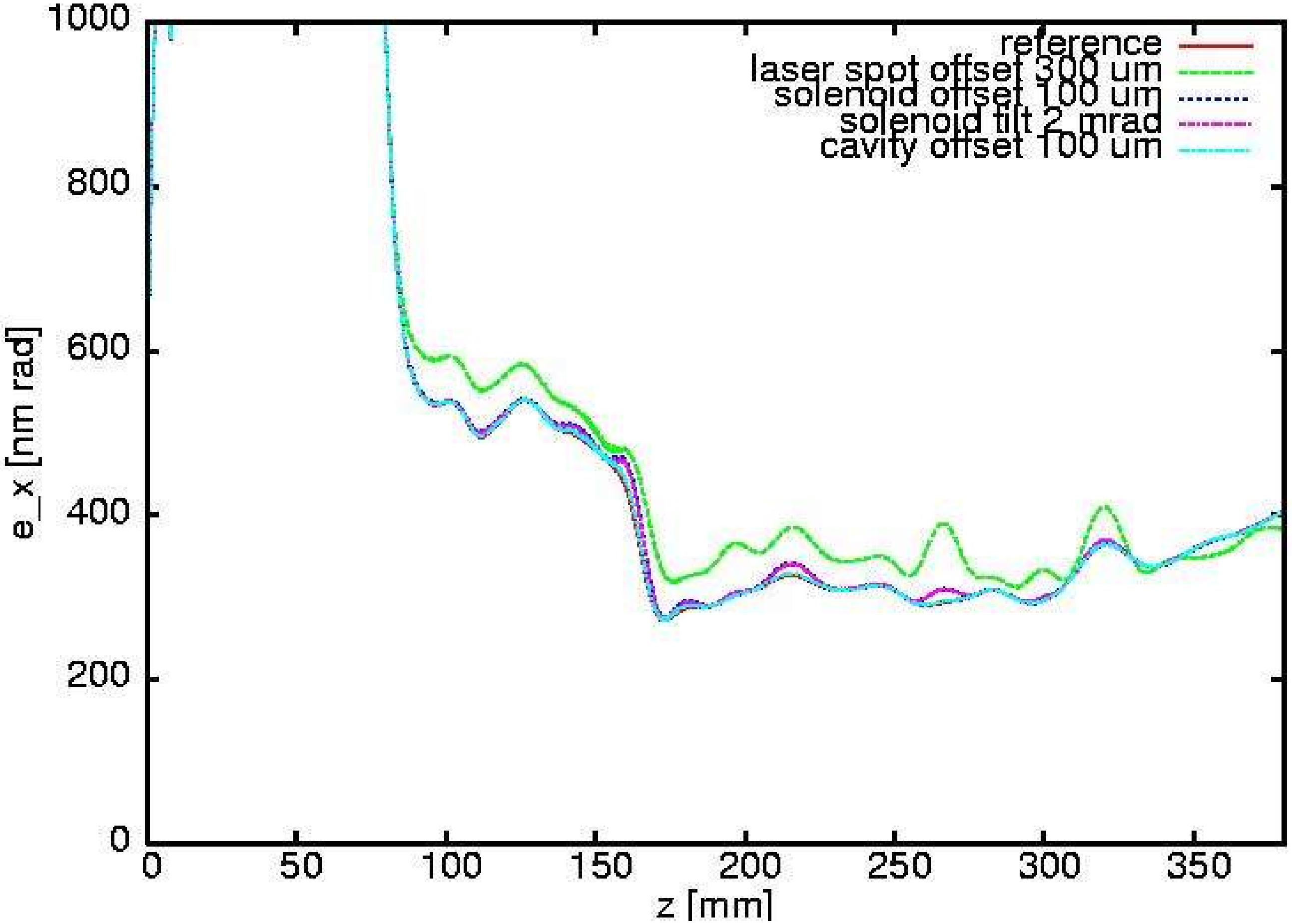
Beam offset in x/y



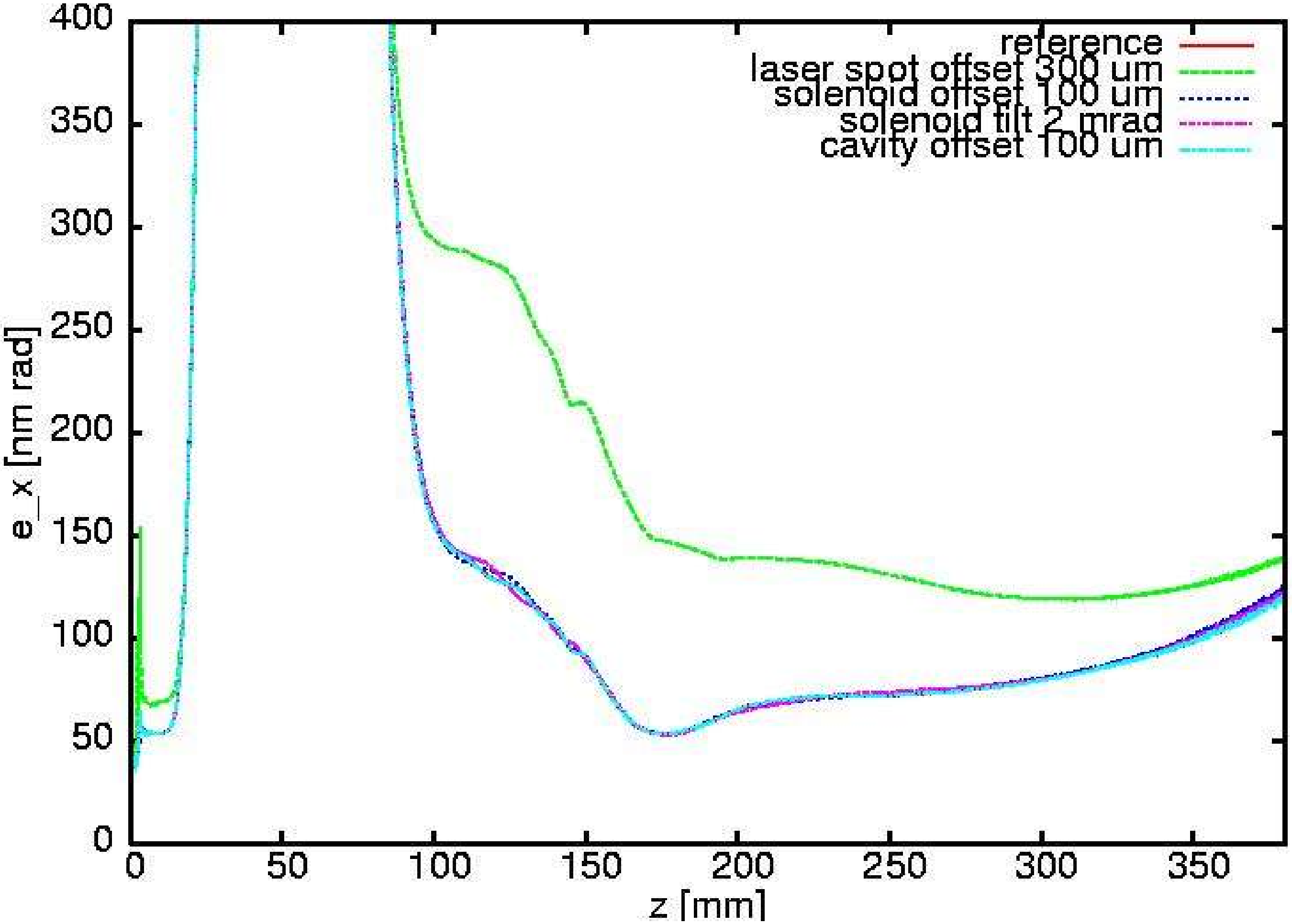
Flight angles



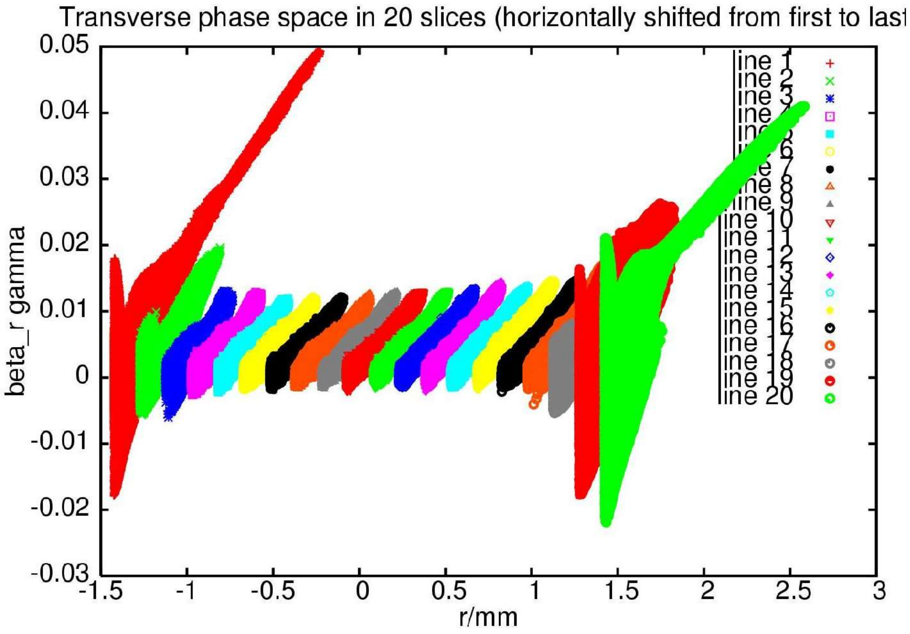
Projected emittance



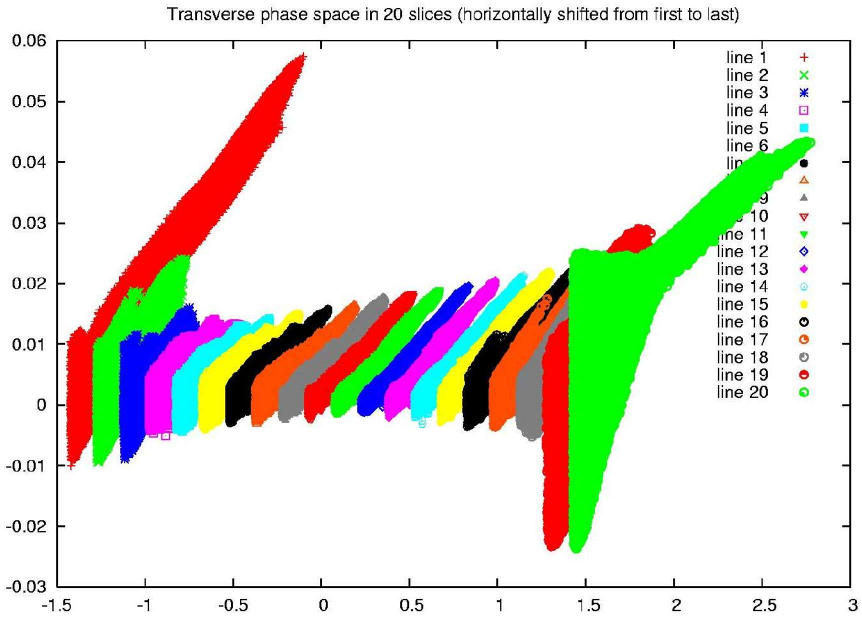
Center slice emittance



Phase space w/wo shifted laser spot



3D reference



3D shifted

Other criteria

- Normally, we would have to look at matching of all relevant slices, while taking into account effect of corrector magnets in drift after the cavity.
- Simplified criterion: The displacement of bunch centroid in transverse phase space still should fit into 400 nm rad area of projected emittance.

Parameter	**Limit**
Laser spot offset	45 μm
Solenoid offset	70 μm
Solenoid tilt	1.3 mrad
Cavity offset	140 μm

Conclusions

- With adequate working point, the Low Emittance Gun can be expected to deliver a suitable performance for the SwissFEL
- Quite critical is the choice of correct amplitudes and phases in the two-frequency RF cavity. Easy to find and adjust in real operation?
- Mechanical tolerances seem to be within reasonable limits.
- Not computed: Sensitivity to laser spot inhomogeneities (Indicative results from field emitter simulations).