Two-frequency RF cavity for the PSI-XFEL

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Goal: Maximum flexibility in shaping the bunch profile with minimum deterioration of the emittance

A compact XFEL for Switzerland

Target parameters:

photons:

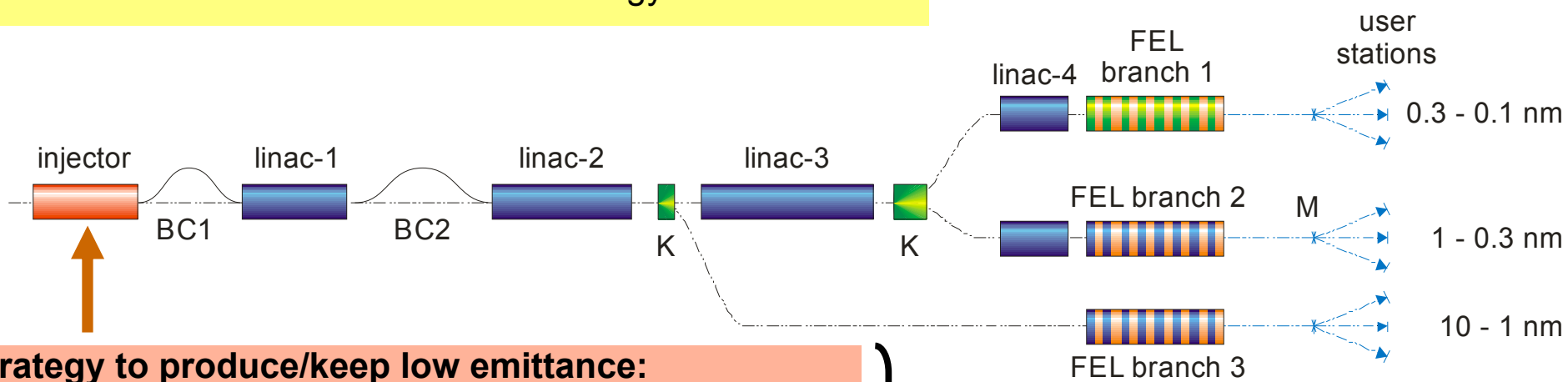
- 1–100 Å
- 10–100 Hz rep. rate
- 0.2–5 × 10^{12} ph./pulse

electron beam at undulator:

- 0.2 nC charge
- 0.1 mm mrad slice emittance
- 1.5 kA peak current
- 6 GeV energy

Time line (tentative):

- Ongoing: gun R&D, 500 kV test stand
- 2007/08: 4 MeV test stand
- 2008–2011: 250 MeV injector
- 2011–2016?: full XFEL



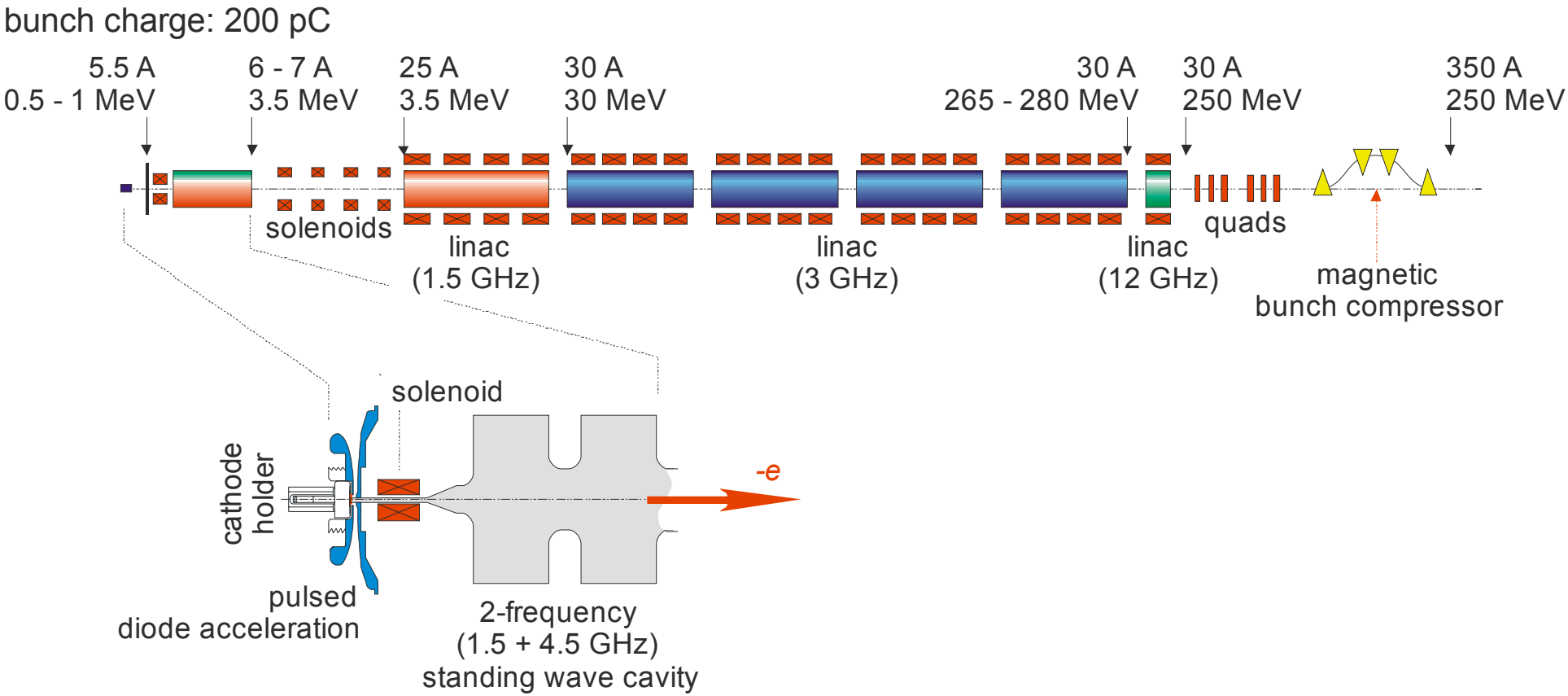
Strategy to produce/keep low emittance:

1) Gun initially based on scaled conventional photocathode, later Field Array Emitter technology
2) Fast acceleration after emission (pulsed diode, 1 MV / 4 mm) to avoid beam blow up
3) Initially low current to reduce space charge effects, increase later by 3-fold bunch compression system

These steps need to be proven!

⇒ Construction of a 250 MeV injector test facility 2008–2011

PSI XFEL Injector (schematic)



RF cavity design parameters

- Fundamental frequency of 1.5 GHz for large acceptance (beam parameters: Q = 200 pC, Δt = 40 ps)
- 2-cell design for smooth transition from diode to RF cavity (reduction of transverse RF fields)
- 2-frequency operation for immediate bunch compression while at the same time preserving the longitudinal bunch profile (linearization of longitudinal phase space)

- Advantages:
  - Compact design
  - Immediate bunch compression and linearization in one step
  - Less danger of emittance dilution due to self-induced space charge fields induced by a separate 3rd harmonic cavity
- Disadvantage: Technically challenging

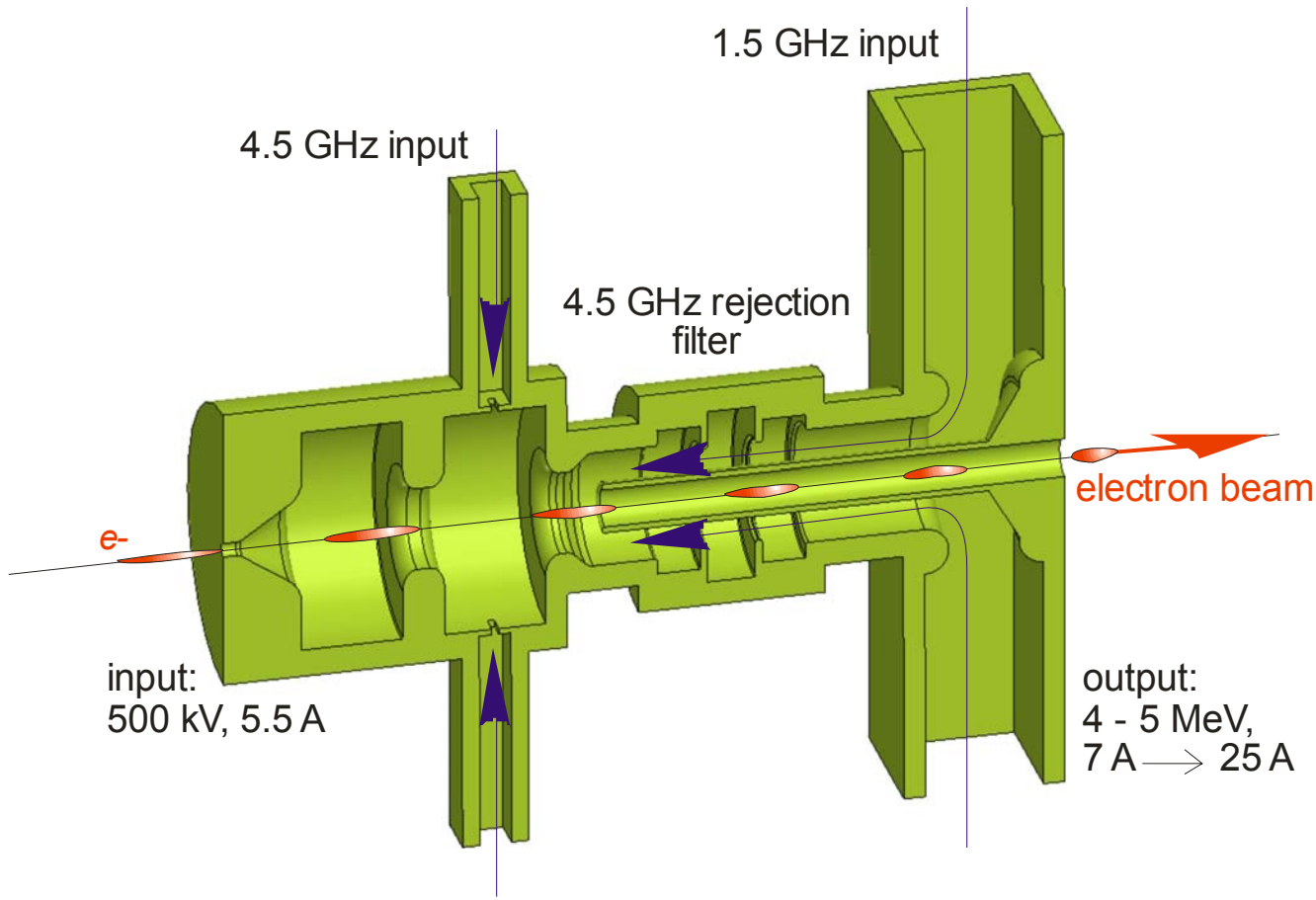
Two-frequency RF design

	Fundamental	Harmonic
Modes	$TM_{010-\pi}$	$TM_{012-\pi}$
Coupling	Coaxial	Side
Coupling factor	$\beta=2$	$\beta=1$

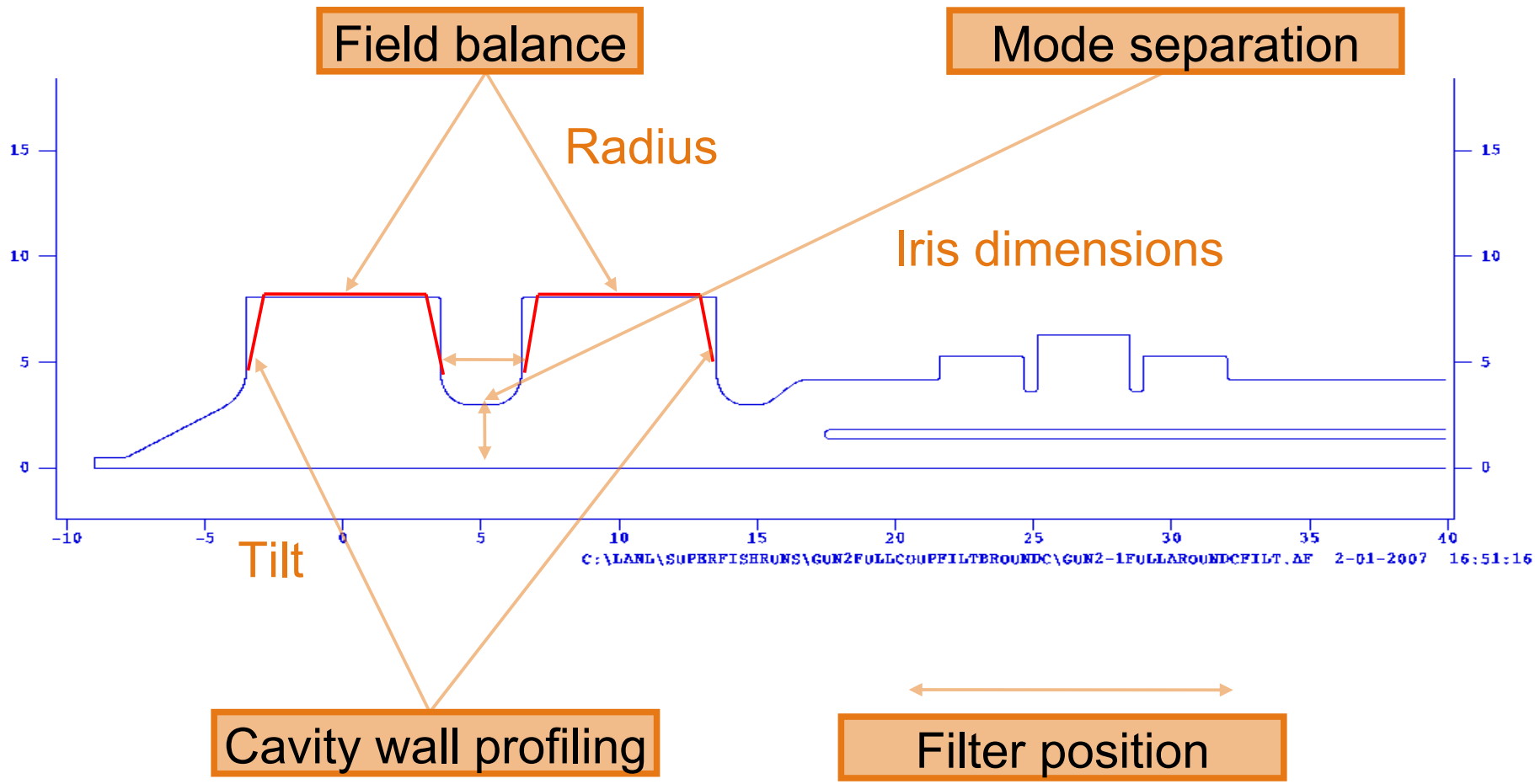
The third harmonic mode is trapped in the cavity using a rejection filter

minimizing field distortion due to the coupling → two waveguides diametrically located

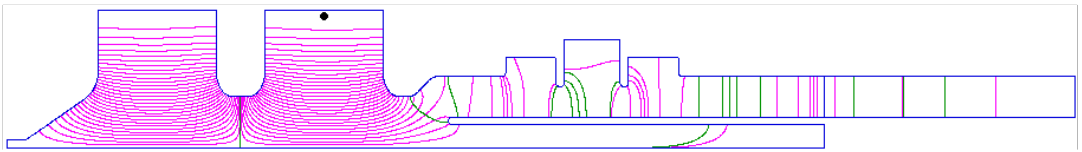
- Field balance (flatness)
- Same peak locations of on-axis electric fields for both modes
- Elliptical iris profiles to decrease peak surface electric fields
- Large mode separation of 0-mode and π-mode
- Spectral purity around 4.5 Ghz (no mode mixing)

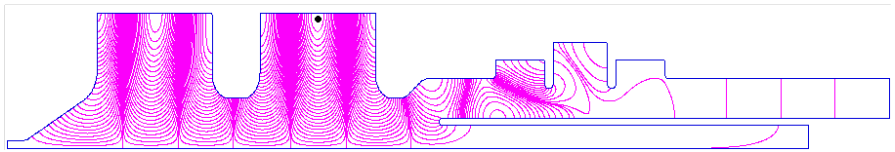


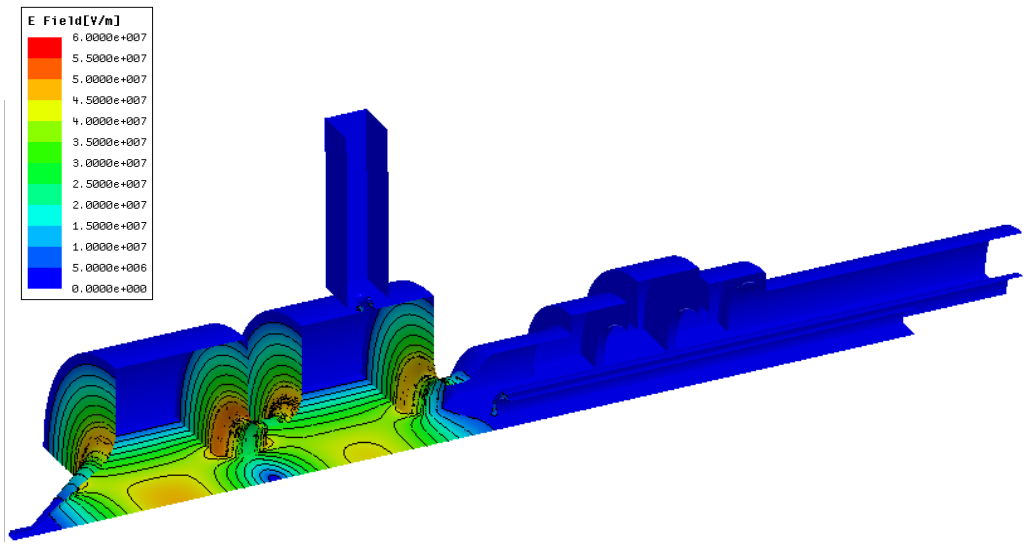
Meeting the design considerations

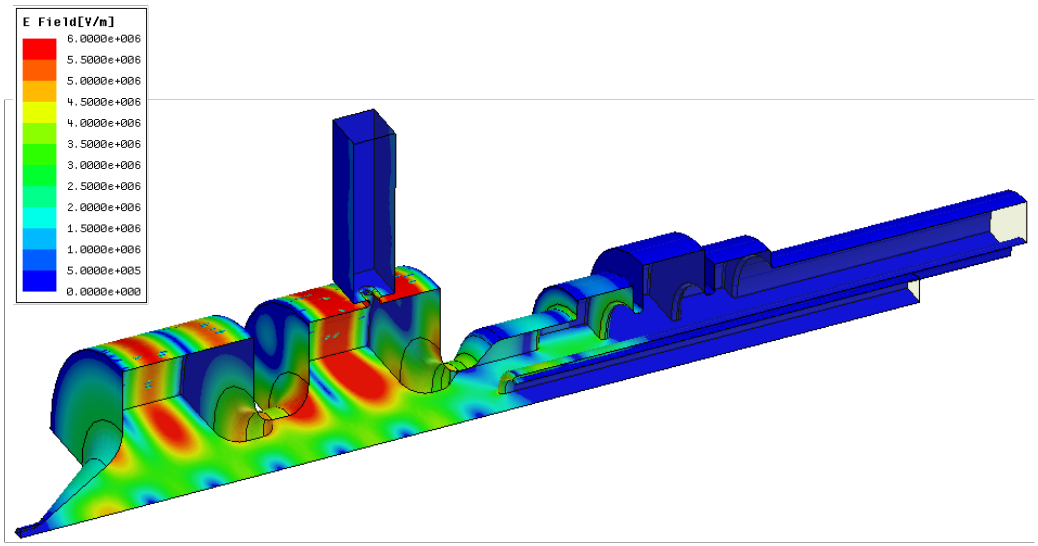


Straight walls case



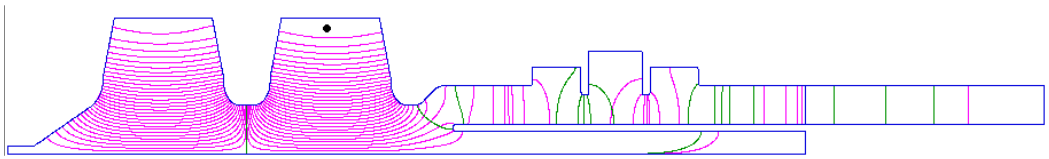


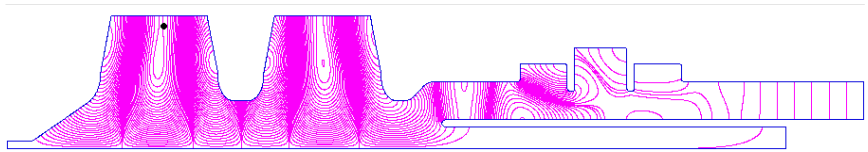


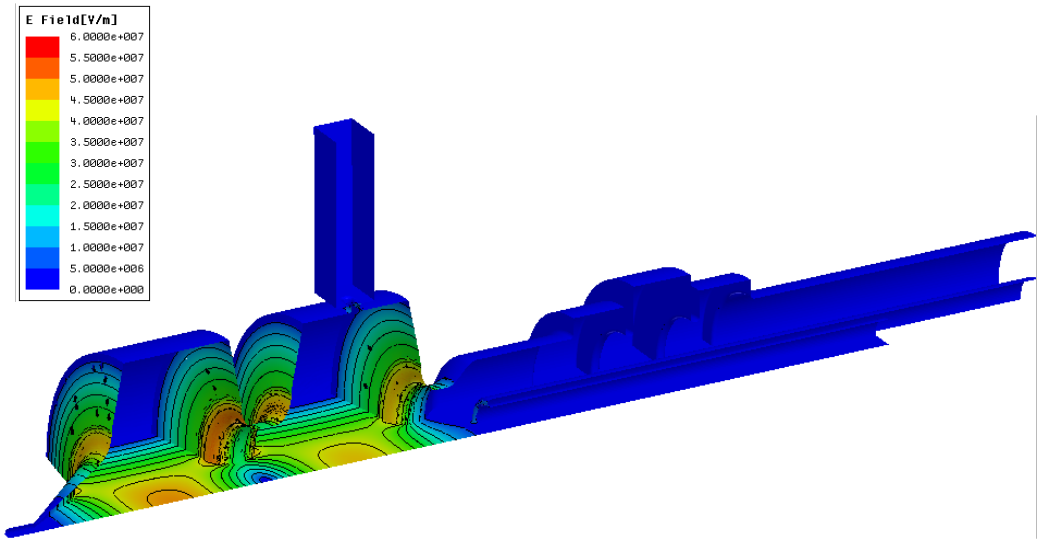


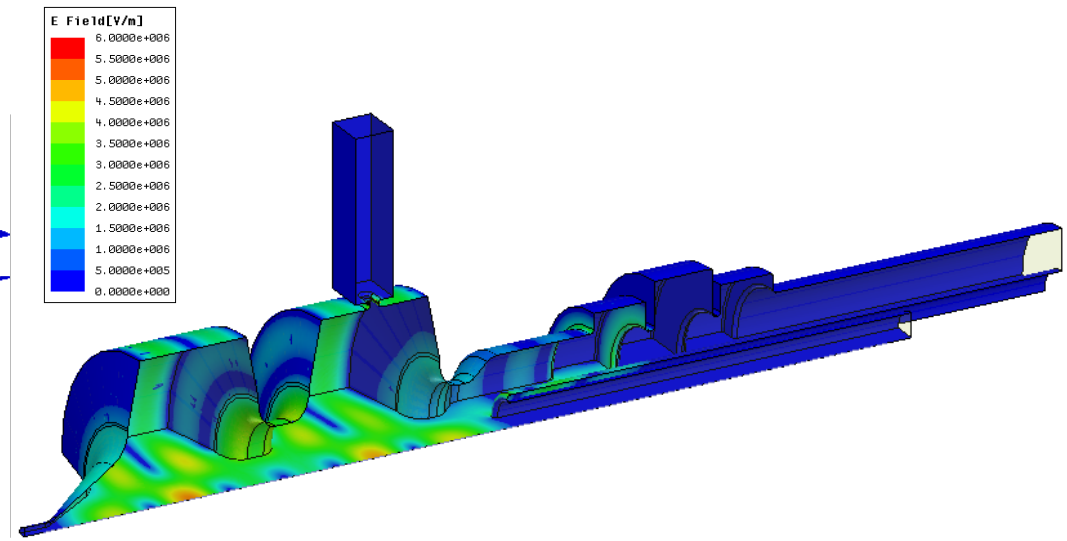
	Fundamental	Harmonic
Modes	$TM_{010-\pi}$ (HFSS: 1,499.01 MHz)	$TM_{012-\pi}$ (HFSS: 4,496.32 Mhz)
Coupling	Coaxial	Side
$E_{on\text{-}axis,\,max}$	43 MV/m	4.1 MV/m
P_{in}	4.49 MW	290 kW
β	$\beta=2.04$	$\beta=1.05$

Tilted walls case



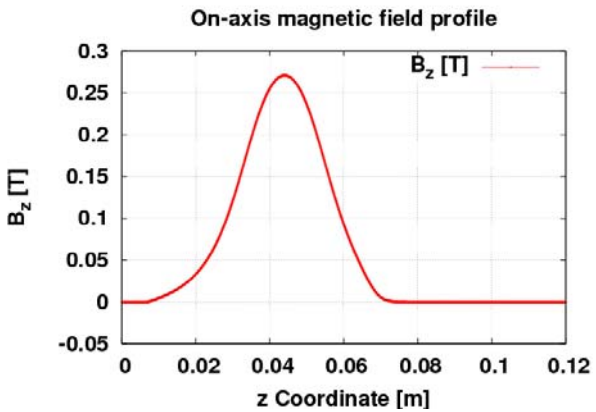




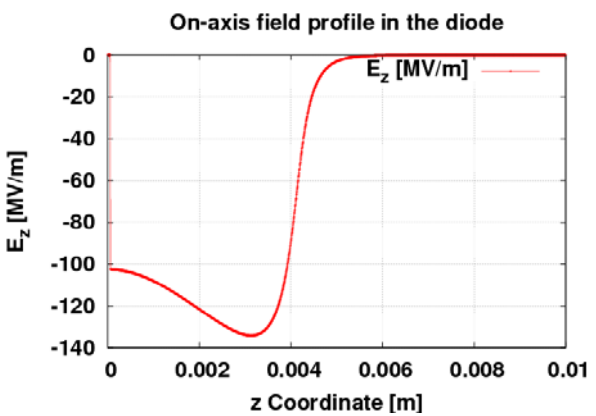


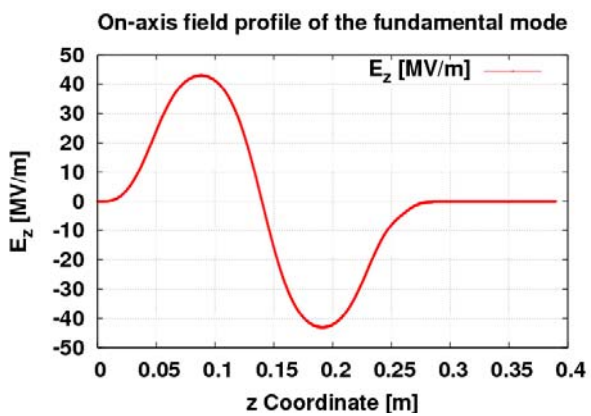
	Fundamental	Harmonic
Modes	$TM_{010-\pi}$ (HFSS: 1,498.90 MHz)	$TM_{012-\pi}$ (HFSS: 4,496.91 Mhz)
Coupling	Coaxial	Side
$E_{on\text{-}axis,\,max}$	45 MV/m	4.8 MV/m
P_{in}	4.78 MW	75 kW
β	β=2.00	β=1.06

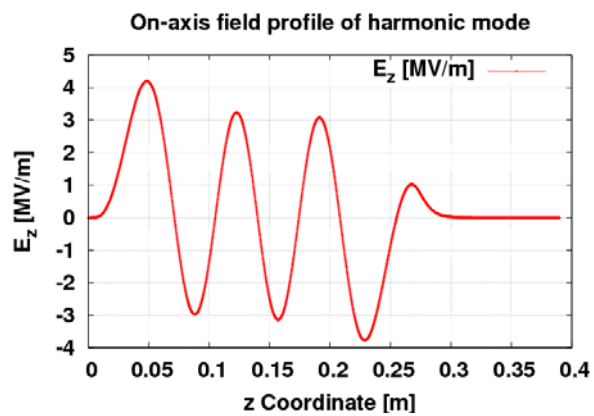
Gun Layout



Fields calculated by Poisson Superfish

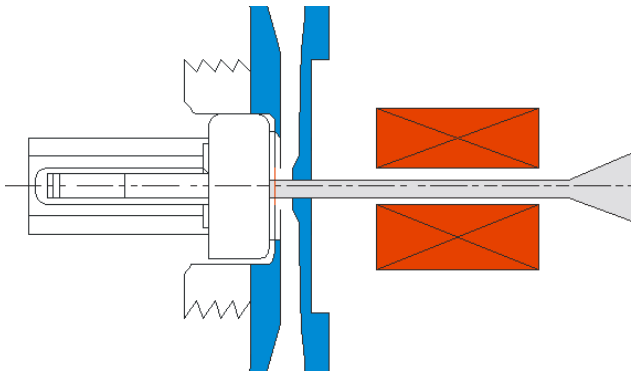






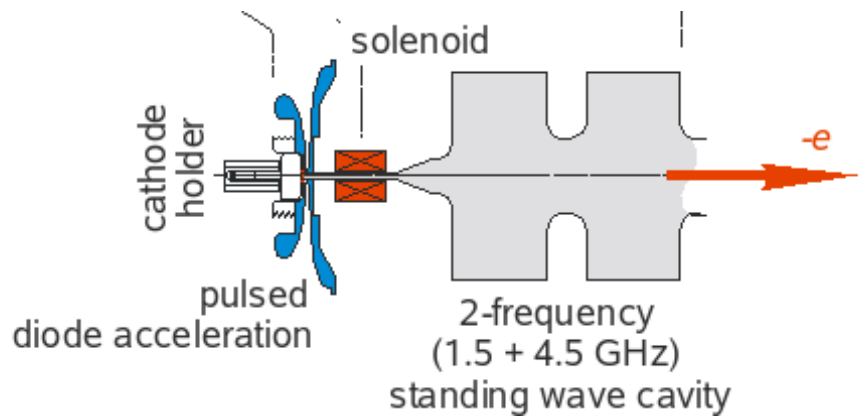
Beam dynamics

- The setup needs to be tuned for optimum beam matching



- Beam parameters:
  - I = 5.5 A
  - δT = 40 ps uniform
  - r_b = 0.3 mm uniform

- The effects of the combined fundamental and harmonic mode on the emittance as well as on the particle distribution need to be studied



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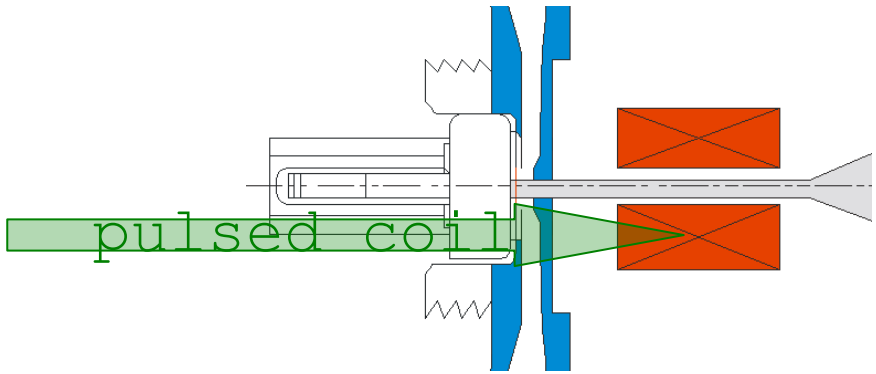

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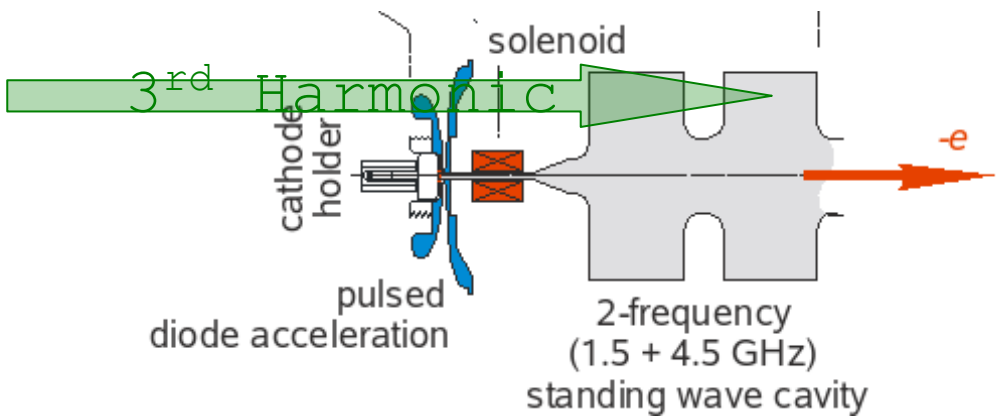
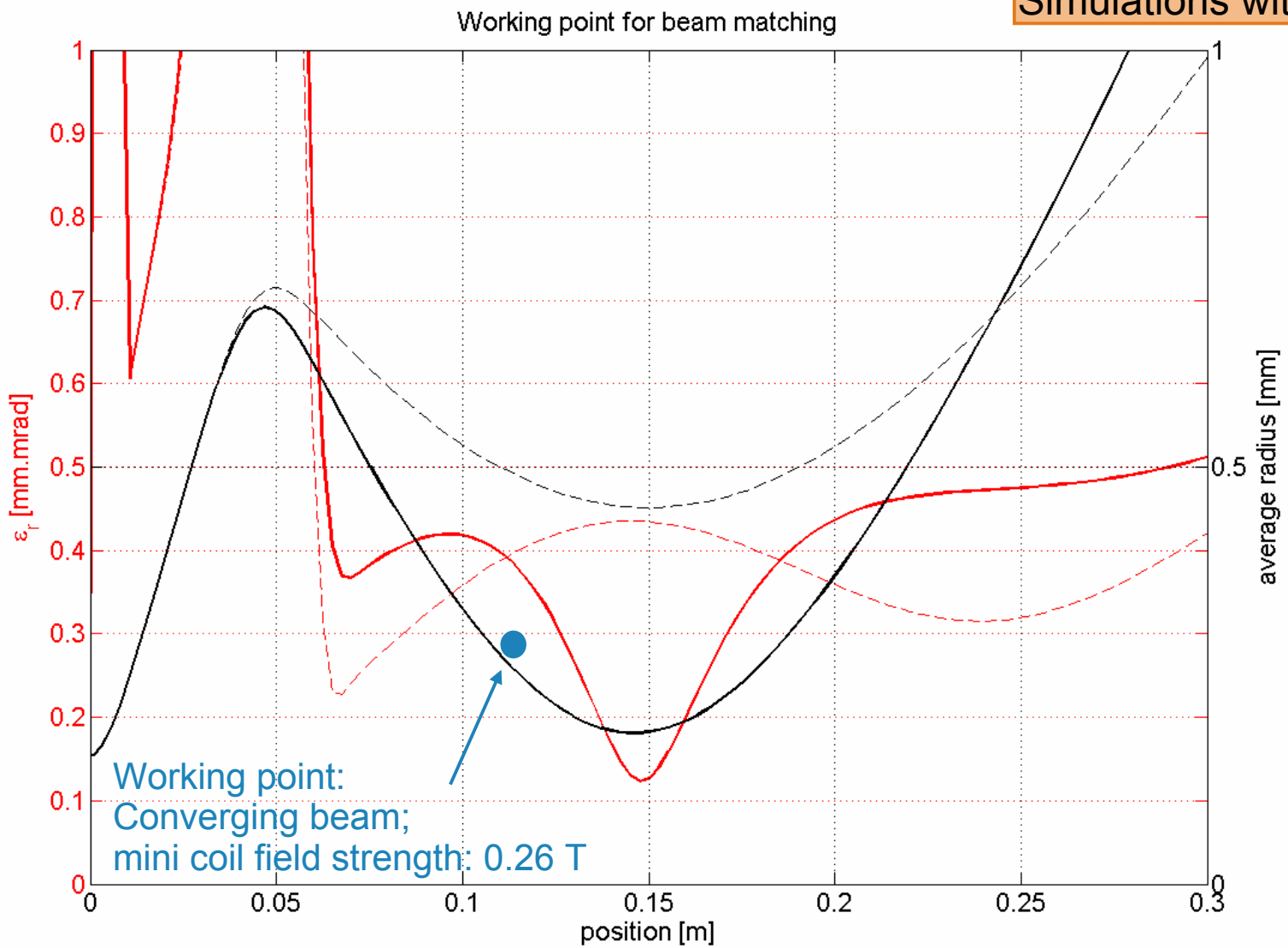


Results: Beam matching

Simulations with Homdyn



Results: Beam matching

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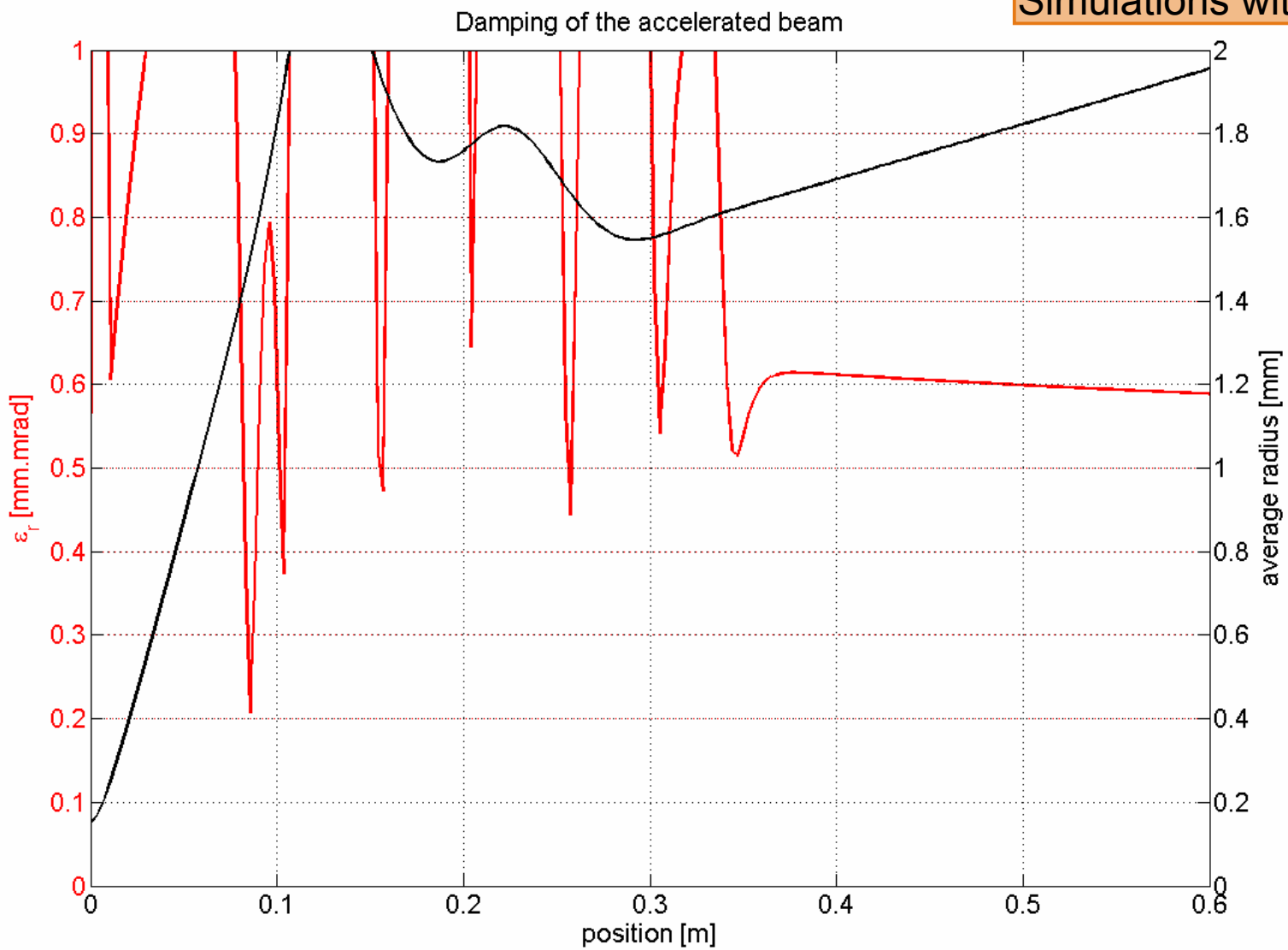
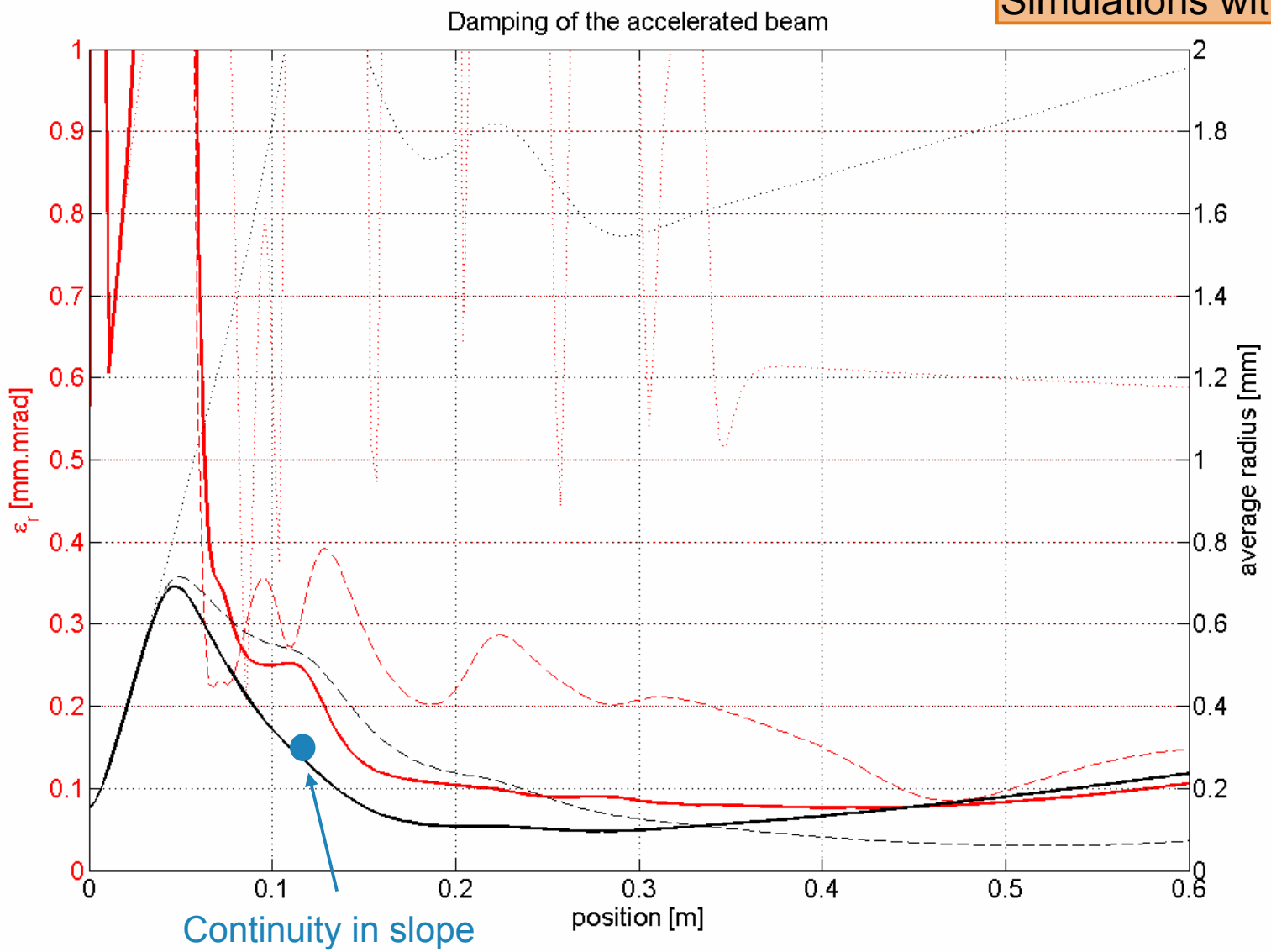
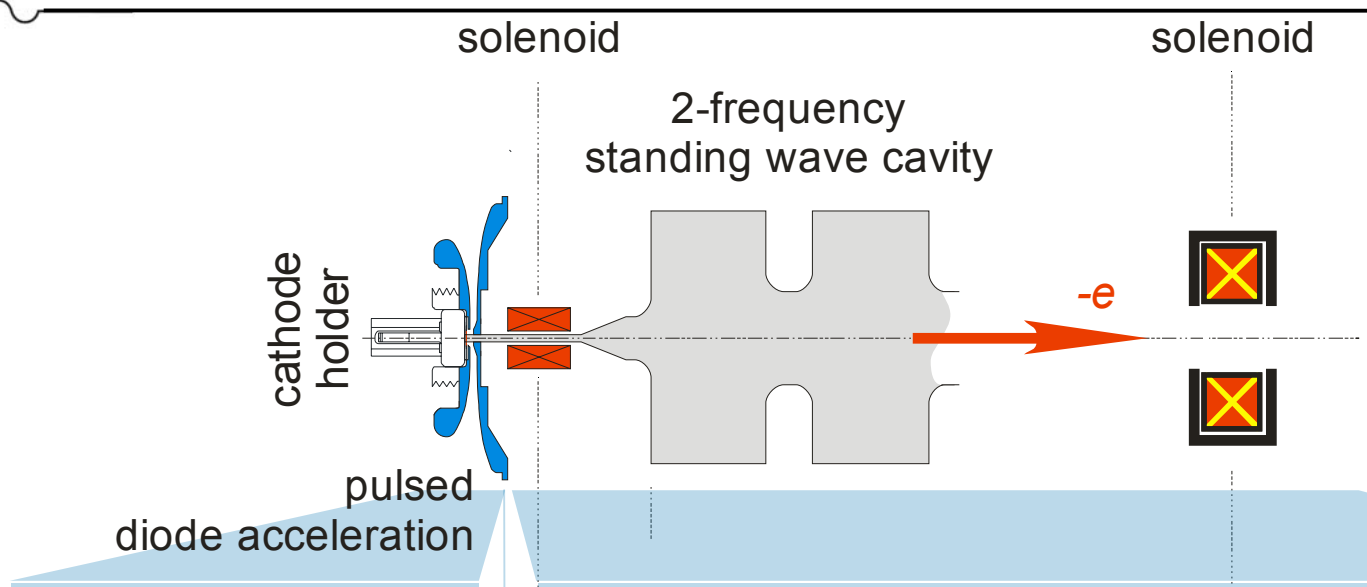


Results: Beam matching

Simulations with Homdyn



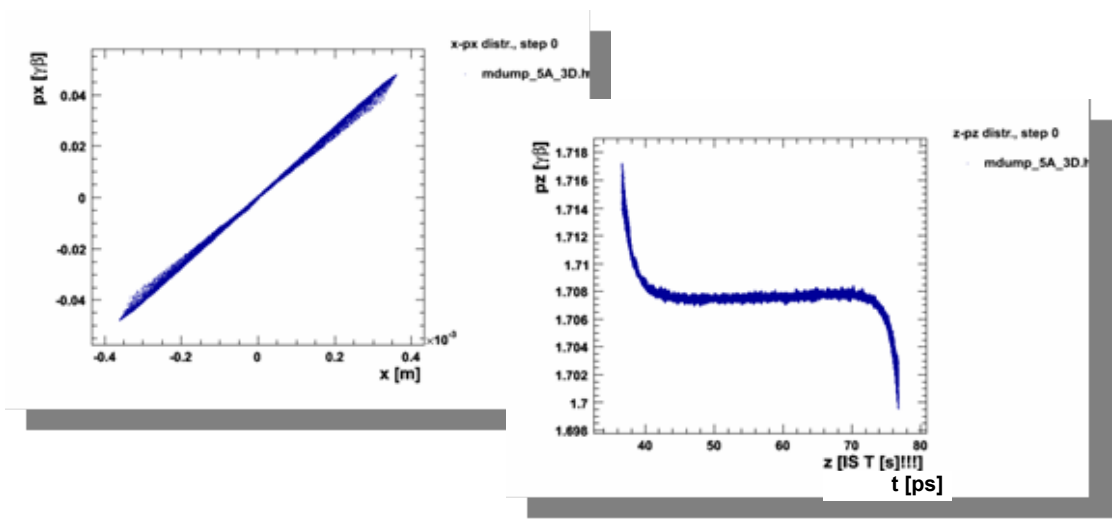
Simulation methods for 3D particle tracking



Fully self-consistent tracking with MAFIA

Continued tracking with GPT using a simplified space charge model: solving Poisson's equation on a grid in the average rest frame of the bunch → much faster!

phase space dump on a screen at 6 mm (no external fields)



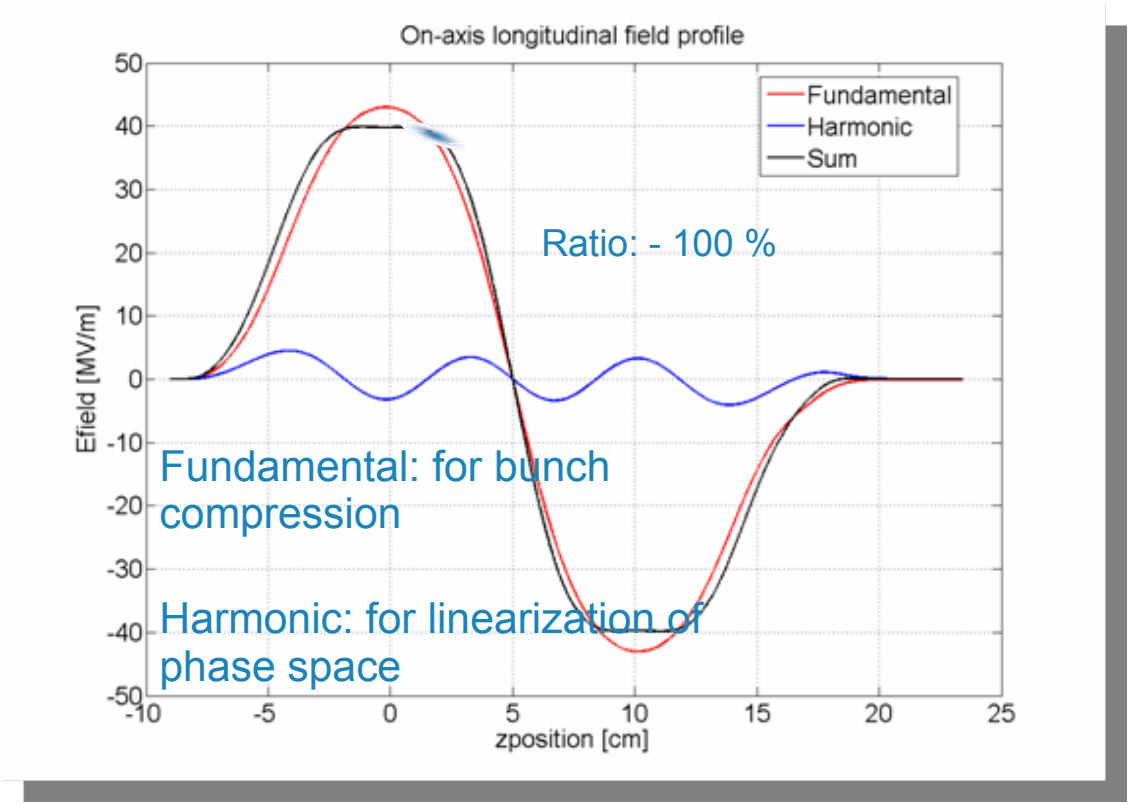
Bunch shaping

- Parameters:
  - Injection phase
  - Phase shift
  - Amplitudes

Injection phases		
#	Absolute	Relative
1	120 deg	-20 deg
2	130 deg	-10 deg
3	140 deg	0 deg
4	150 deg	10 deg
5	160 deg	20 deg

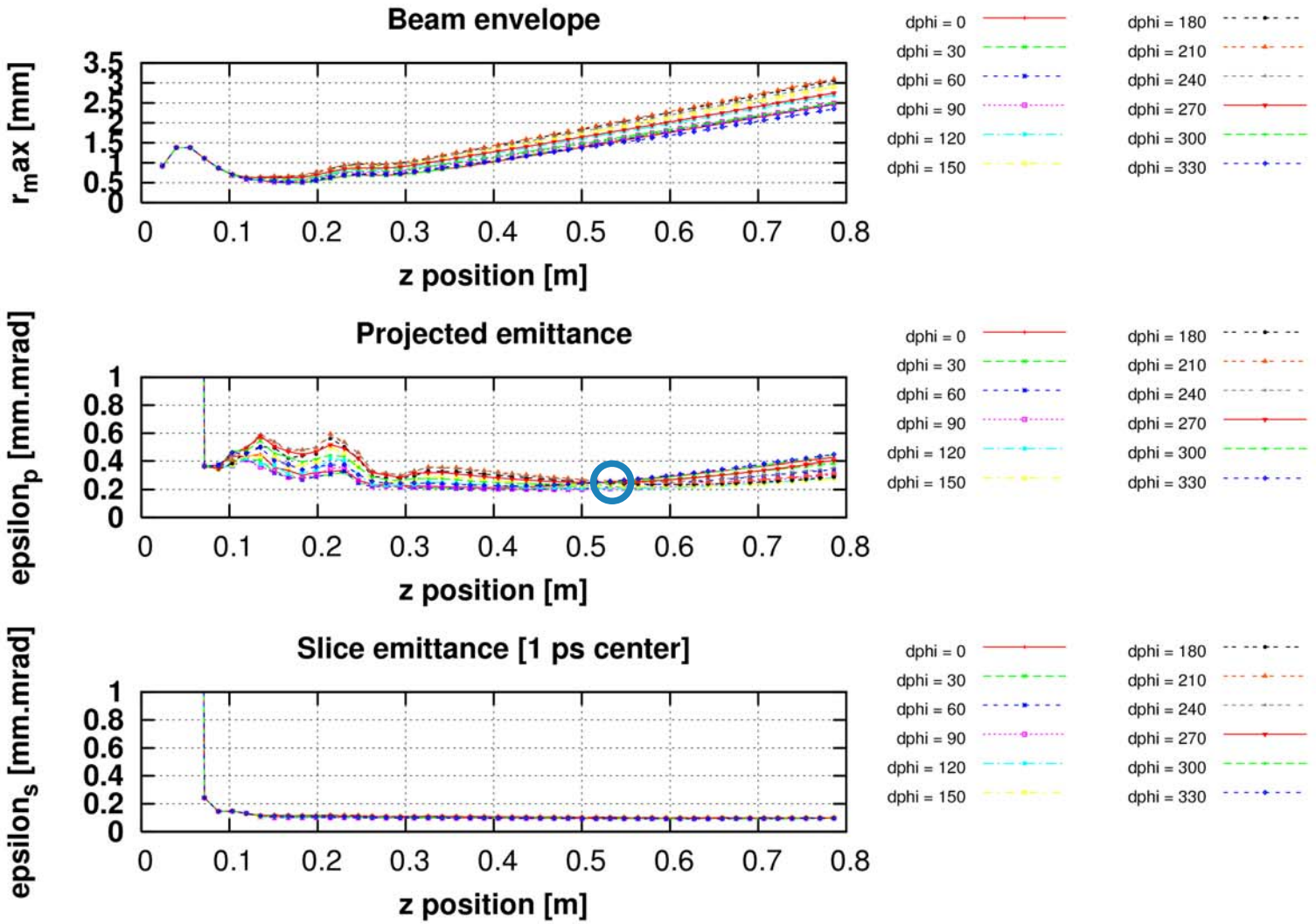
Relative phases
0:30:330 deg

Amplitudes			
#	$A_{fund.}$	$A_{harm.}$	Ratio
1	0.82	1.64	50.00%
2	0.84	1.26	60.00%
3	1	-1	-100.00%
4	1.01	-1.52	-60.00%
5	1.02	-2.04	-50.00%



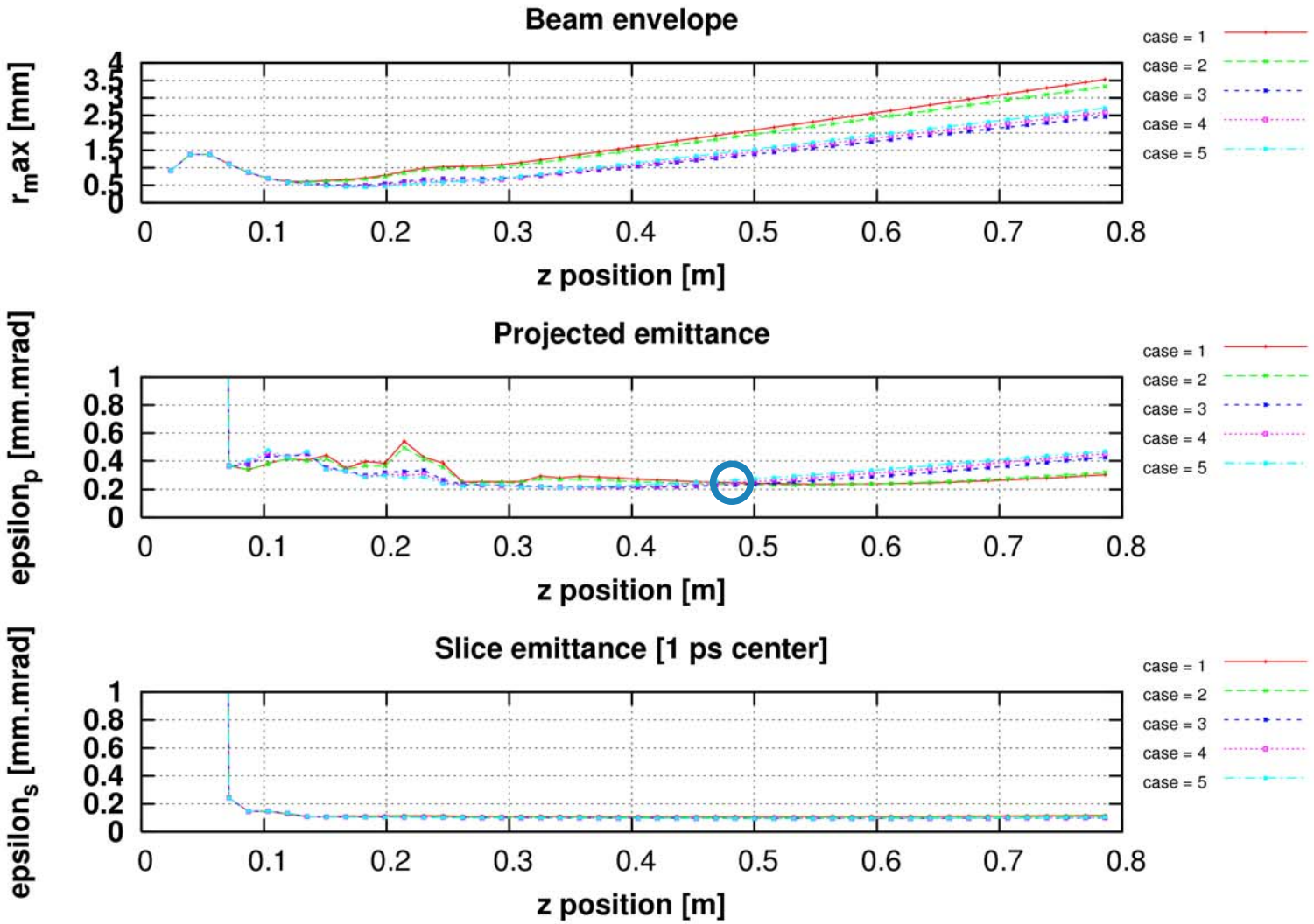
Example: Relative phase

20 deg bunching side off crest acceleration



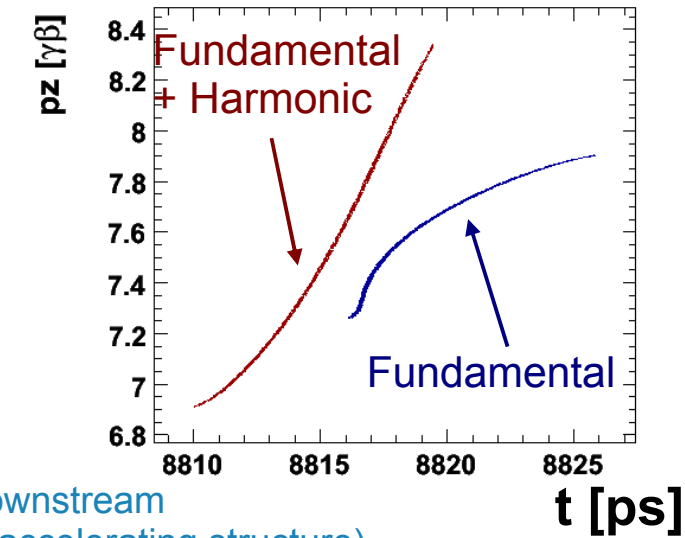
Example: Amplitudes

20 deg bunching side off crest acceleration

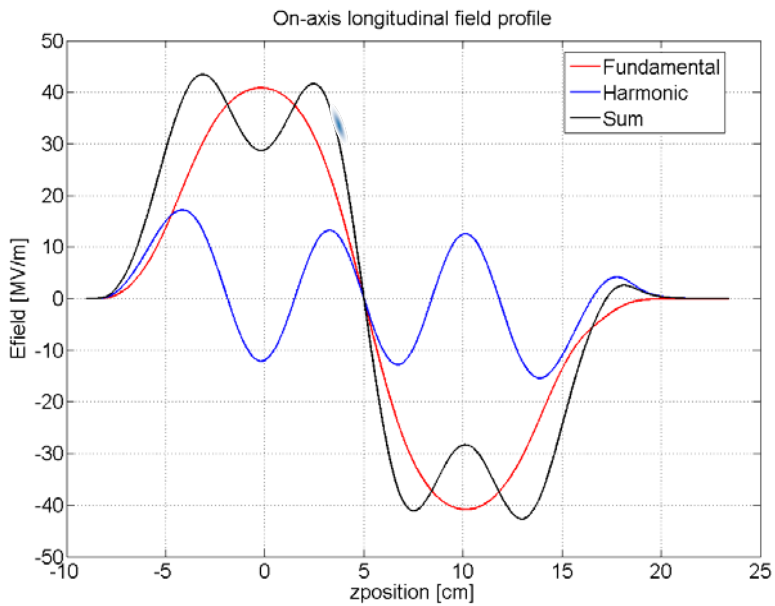


Bunch shaping

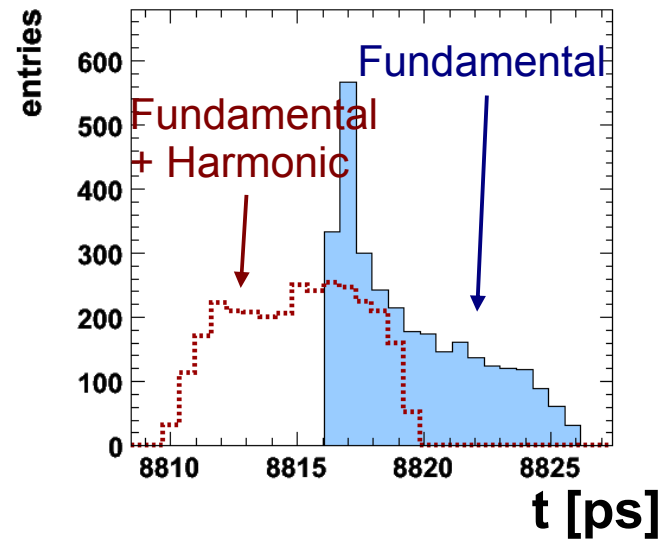
- Required profile for linear compression: $\frac{\partial \gamma}{\partial t} \sim \gamma^3$
- Bunch profile approaches gaussian distribution



Data taken at 2.6 m downstream
(location of the L-band accelerating structure)



+ 54 deg phase shift;
bunching factor ~ 5



Summary

- First two-frequency RF design completed
- Improved design for mode purity around 4.5 GHz nearly completed
- Beam matching by insertion of pulsed mini coil leading to a suppression of transverse RF effects
- Flexible shaping of longitudinal bunch profile
- Profiling the longitudinal phase space for further bunch compression possible