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Aberration and harmonic imaging

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Motivation

- Good understanding of wavefront aberration and linear wave propagation.
  - time-delays and amplitude filter / generalised screen
  - time-reversal / DORT

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- Good understanding of wavefront aberration and linear wave propagation.
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- "... but harmonic imaging works so well ... why bother ... "
- "... harmonic imaging has solved the problem of aberration ... "

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Theory

Westervelt equation

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = \frac{1}{c^2}\frac{\partial^2 \mathcal{L} p}{\partial t^2} - \epsilon_n \frac{\partial^2 p^2}{\partial t^2}$$

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Define linear and nonlinear parts

$$p = p_l + p_{nl}$$

$$\nabla^2 p_l - \frac{1}{c^2}\frac{\partial^2 p_l}{\partial t^2} = \frac{1}{c^2}\frac{\partial^2 \mathcal{L} p_l}{\partial t^2}$$

$$\nabla^2 p_{nl} - \frac{1}{c^2}\frac{\partial^2 p_{nl}}{\partial t^2} = \frac{1}{c^2}\frac{\partial^2 \mathcal{L} p_{nl}}{\partial t^2} - \epsilon_n \frac{\partial^2 p^2}{\partial t^2}.$$

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Define linear and nonlinear parts in frequency domain

$$p = p_l + p_{nl}$$

$$\nabla^2 \hat{p}_l + \frac{\omega^2}{c^2}\hat{p}_l = -\frac{\omega^2}{c^2} L \hat{p}_l$$

$$\nabla^2 \hat{p}_{nl} + \frac{\omega^2}{c^2}\hat{p}_{nl} = -\frac{\omega^2}{c^2} L \hat{p}_{nl} + \epsilon_n \omega^2 \hat{p} \underset{\omega}{*} \hat{p}.$$

Theory

Westervelt equation

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = \frac{1}{c^2}\frac{\partial^2 \mathcal{L} p}{\partial t^2} - \epsilon_n \frac{\partial^2 p^2}{\partial t^2}$$

Define linear and nonlinear parts in frequency domain for $|p_{nl}| << |p_l|$

$$p = p_l + p_{nl}$$

$$\nabla^2 \hat{p}_l + \frac{\omega^2}{c^2}\hat{p}_l = -\frac{\omega^2}{c^2} L \hat{p}_l$$

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Observations

- Aberration of linear part is well understood
- Nonlinear part is governed by the same equation with additional source term
- Source for the nonlinear part is an aberrated linear part
- Expect the nonlinear part to be as aberrated as the linear part.

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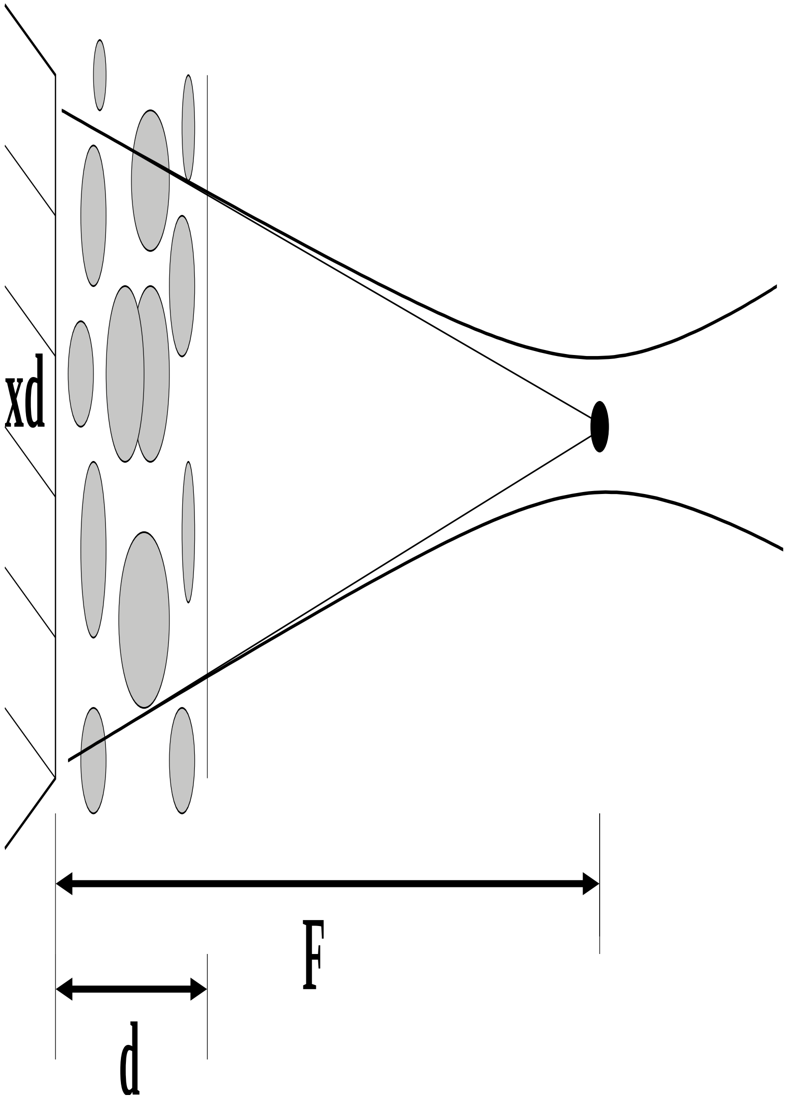
Simulations



TX frequency	: 2.5 MHz
Focal depth	: 6.0 cm
XD	: 2.0×2.0 cm
Wall model	: abdominal 2.0 cm
Tissue	: muscle
Simulation	: 3D

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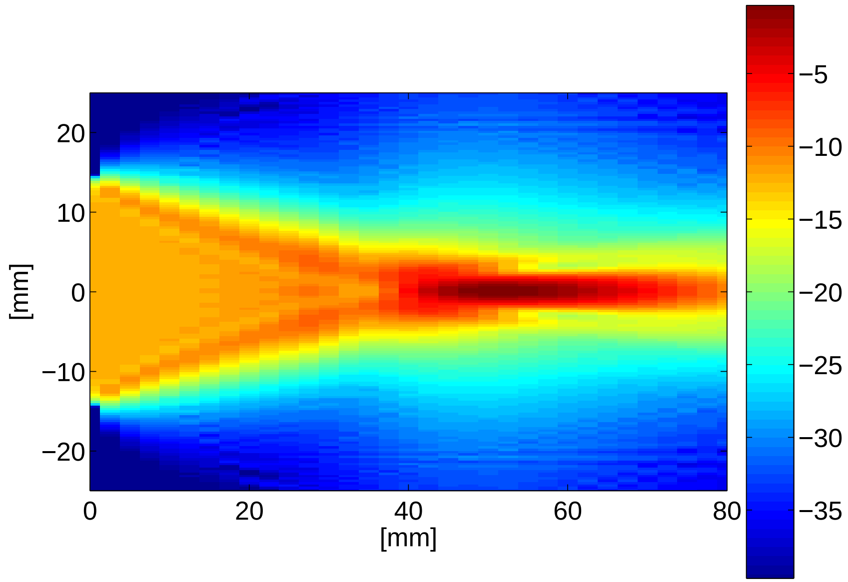
Energy distr. fundamental



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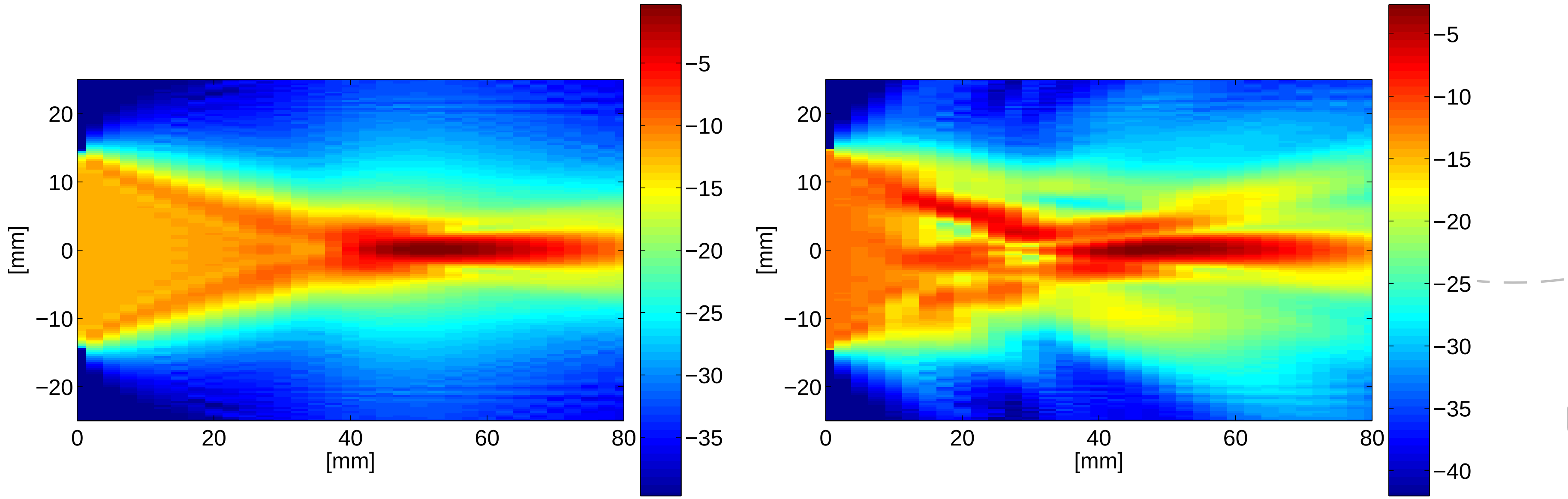
Energy distr. fundamental



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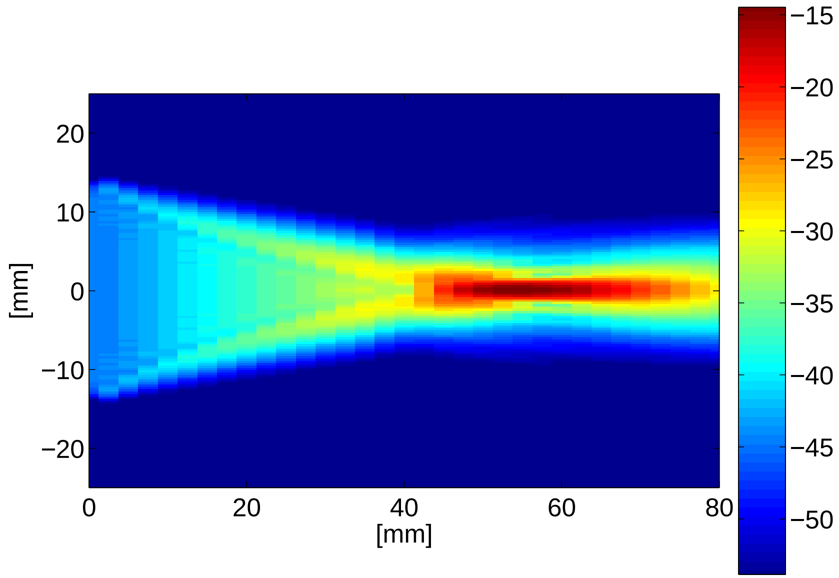
Energy distr. harmonic



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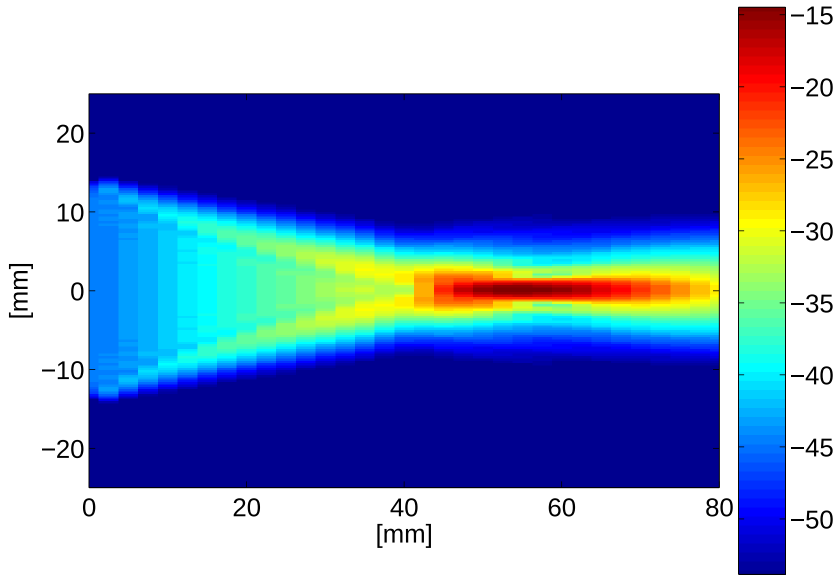
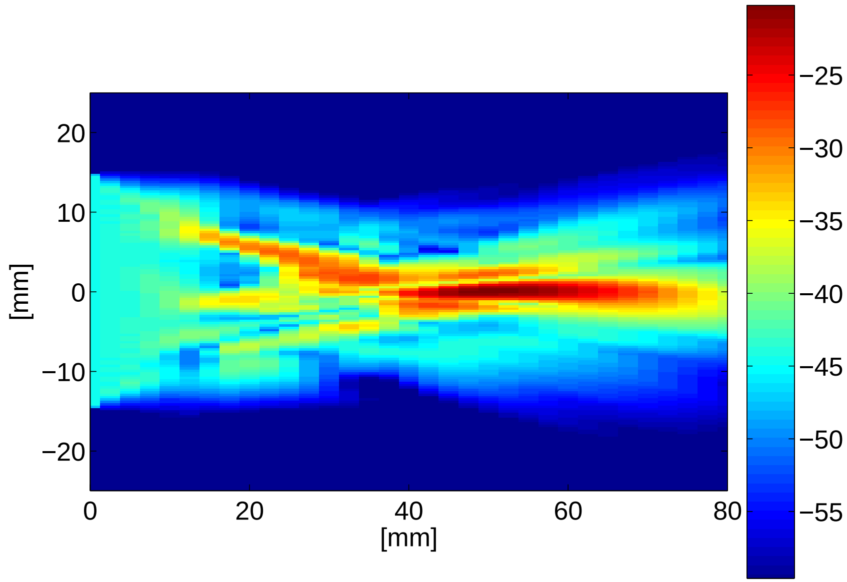
Energy distr. harmonic





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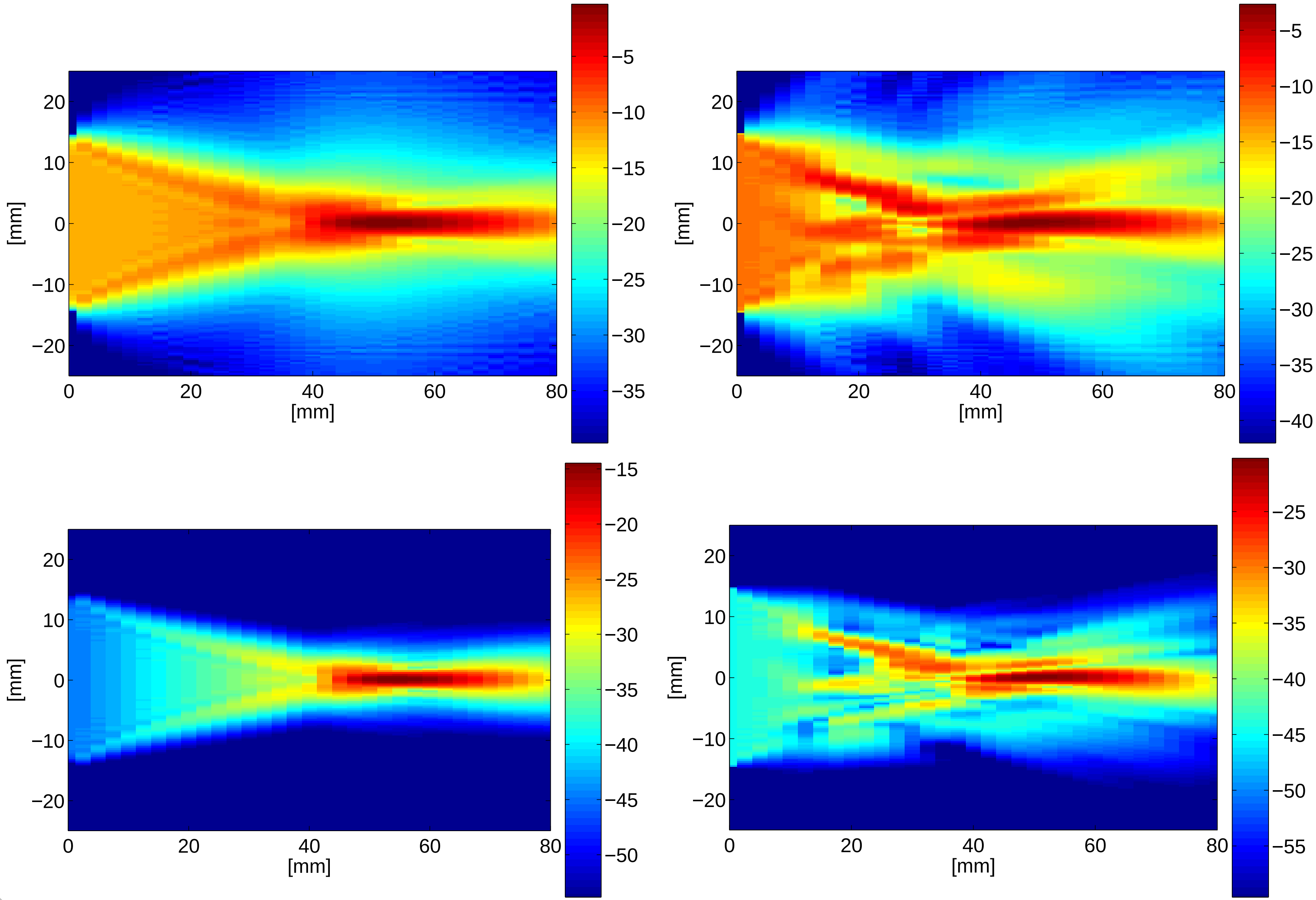
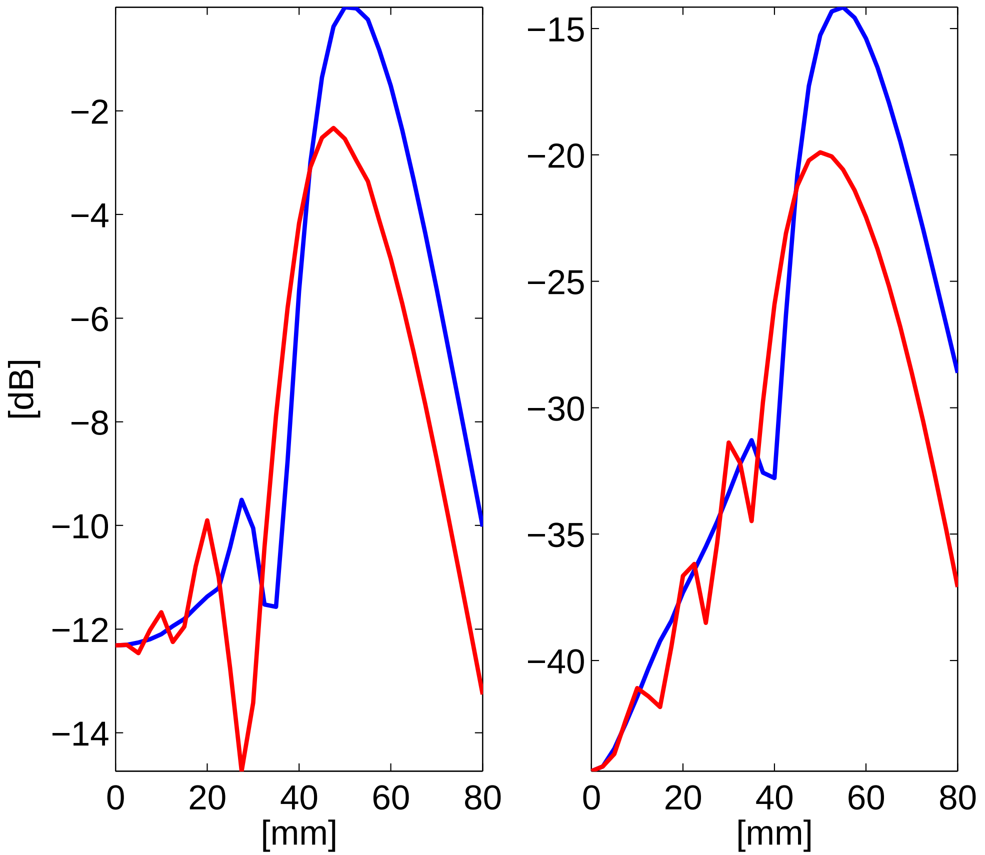
Energy distr.



Peak pressure



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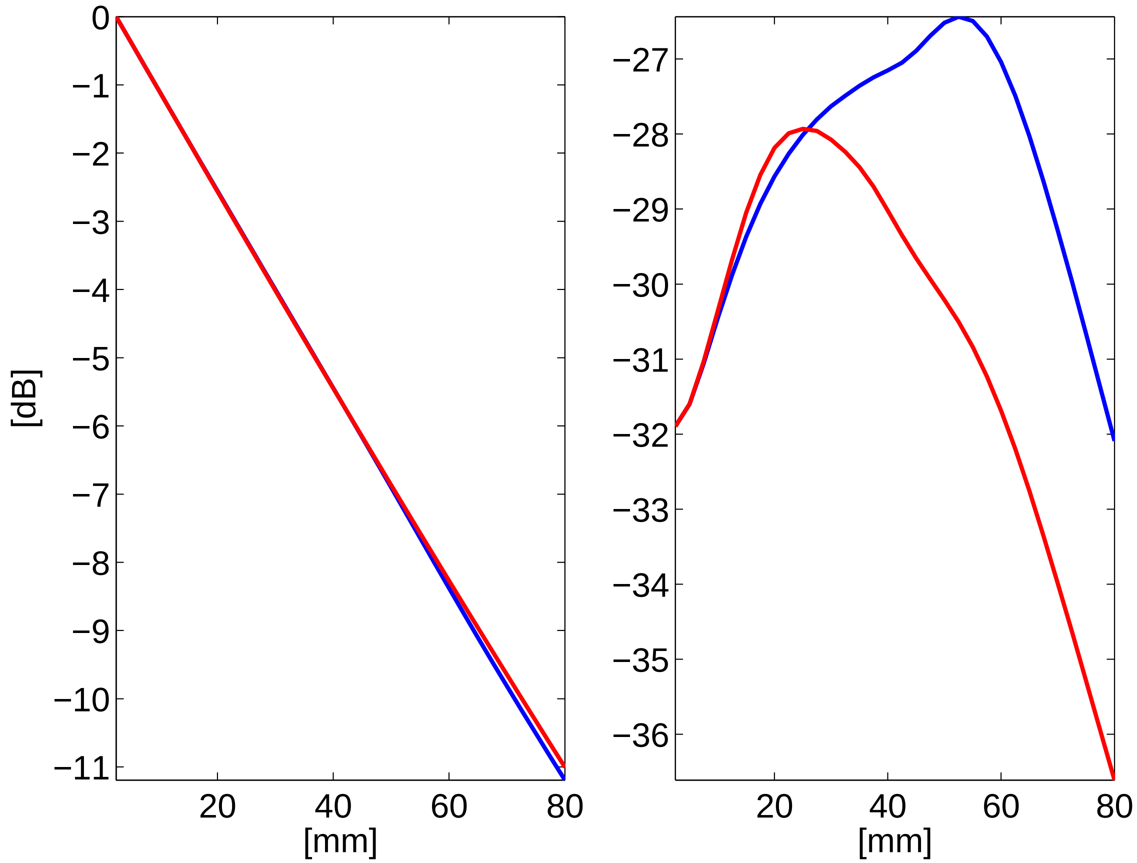
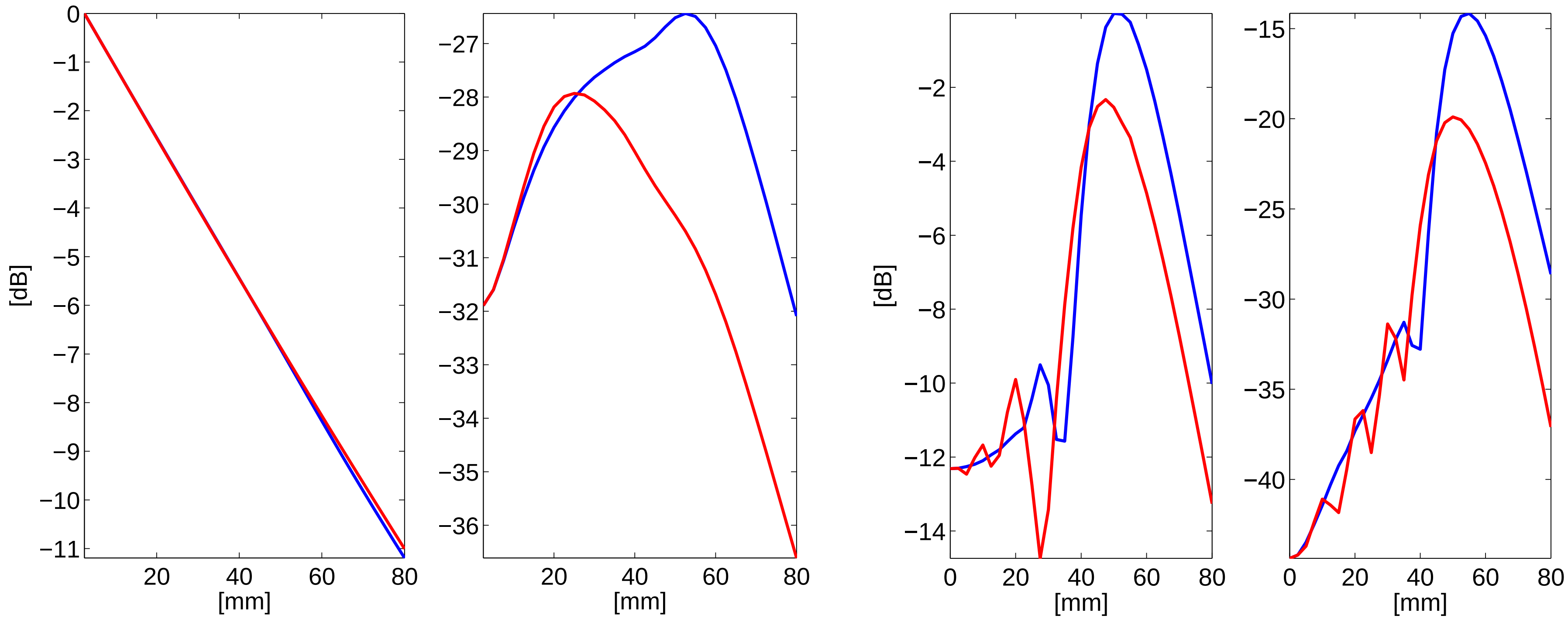
Energy



$$\mathrm{E}(z) = \int_{-\infty}^{\infty} \int_{T_z} |p(r,t)|^2 \mathrm{d}t \mathrm{d}r.$$

Energy


0
−1
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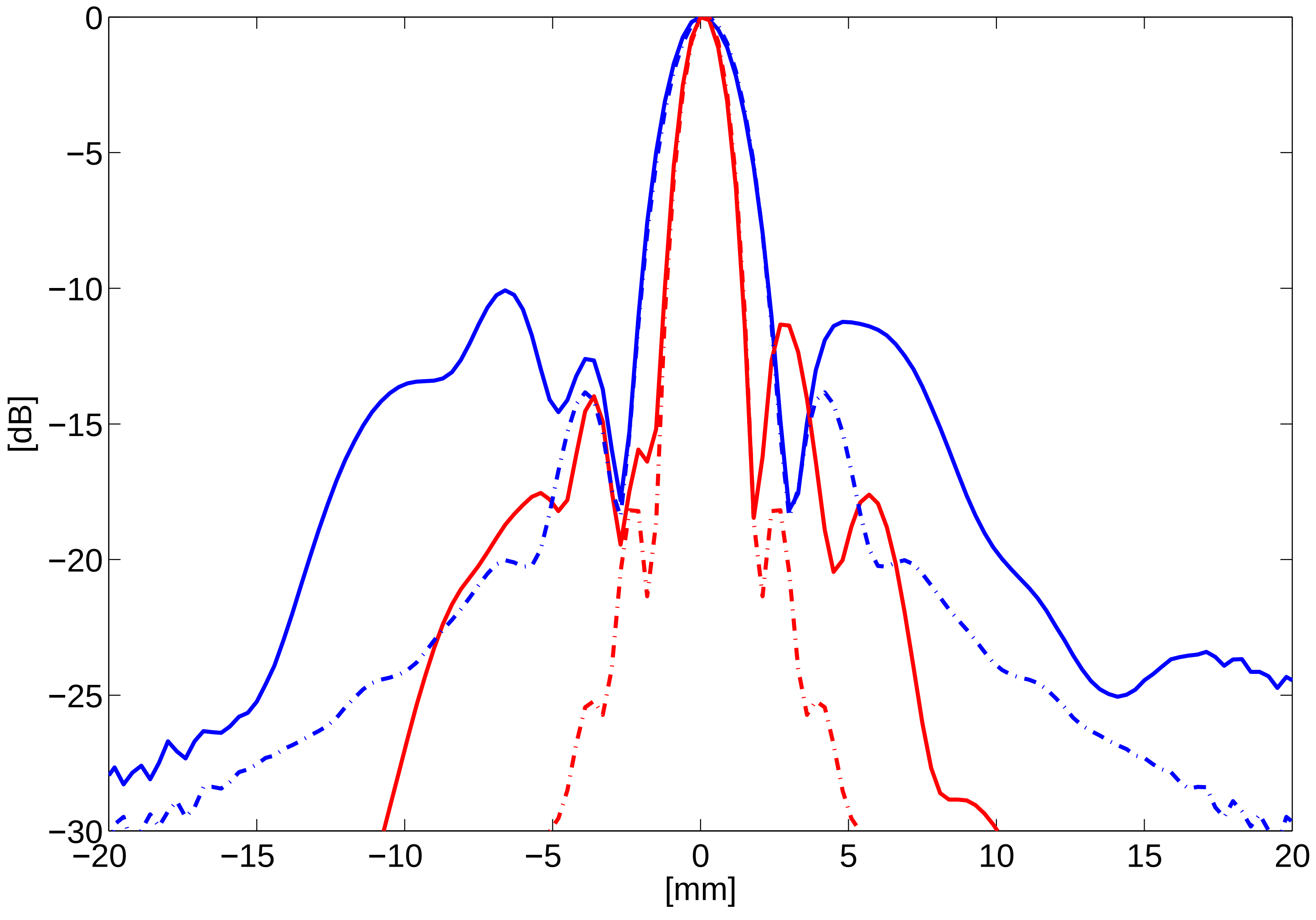
−40
0
20
40
60
80
[mm]

Beam profiles



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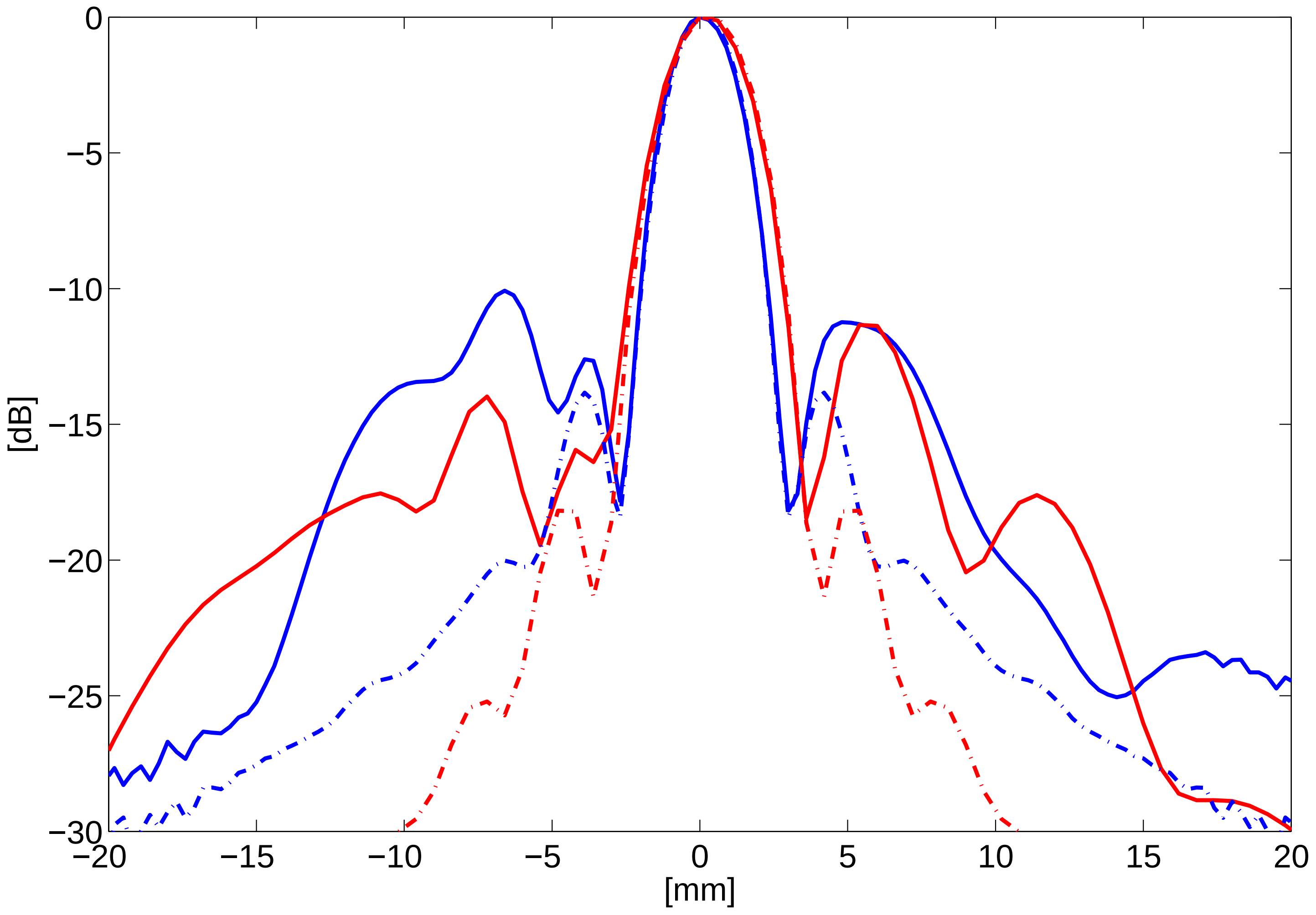
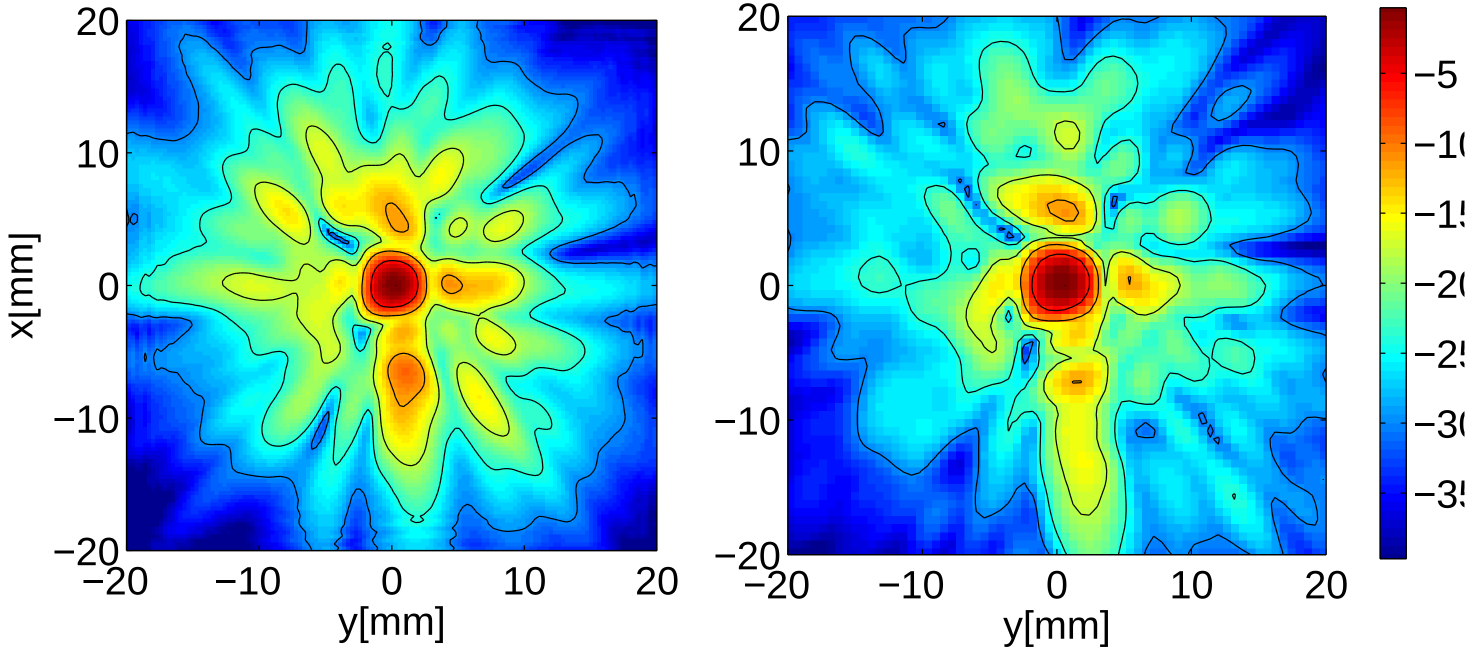


Beam profiles



Summary

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- Second harmonic is governed by the same equation as fundamental, with additional source term
- Source for the second harmonic is aberrated fundamental
- Aberration of second harmonic is similar to that of fundamental
- Reduced aberration for fundamental at lower frequency
- Other sources for improved image quality in harmonic imaging

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