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Nonlinear effects in ultrasound fields of diagnostic-type transducers used for kidney stone propulsion: characterization in water

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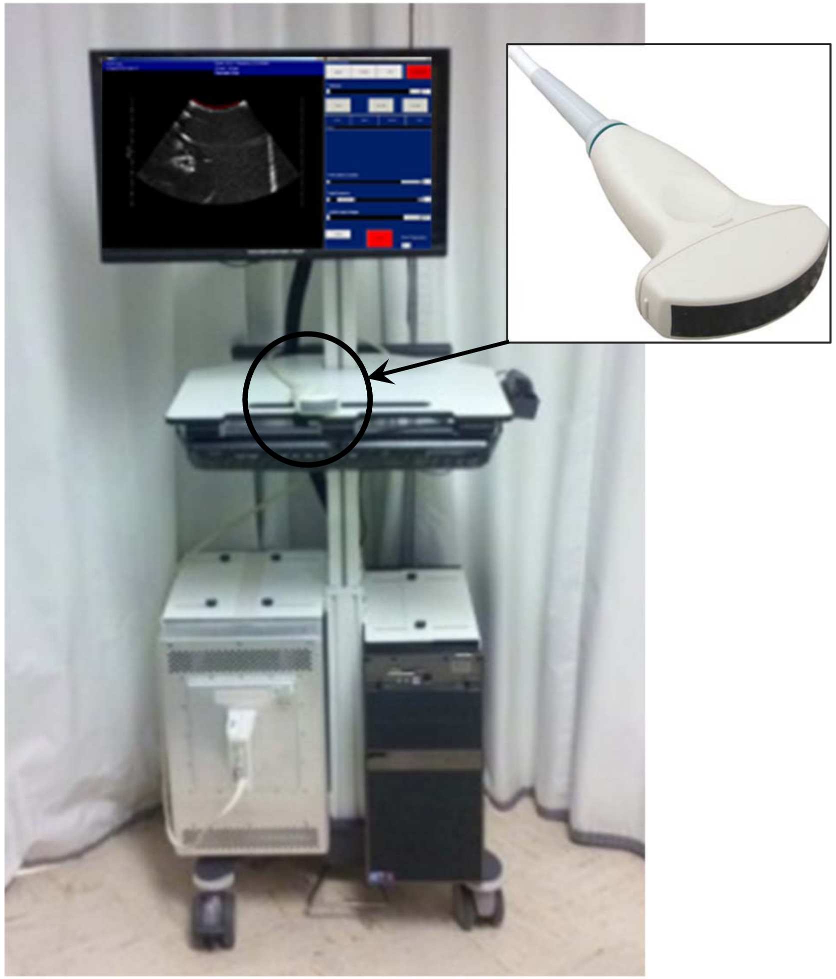
Outline

- Ultrasonic propulsion of kidney stones
- Pressure saturation was observed at high power levels
  Question: what is the mechanism?
  Hypothesis to test: nonlinear propagation effects
- Approach: 3D Westervelt equation to model nonlinear acoustic fields and saturation effects
- Conclusions

Ultrasonic propulsion of kidney stones

Ultrasonic propulsion system



Pushing residual fragments

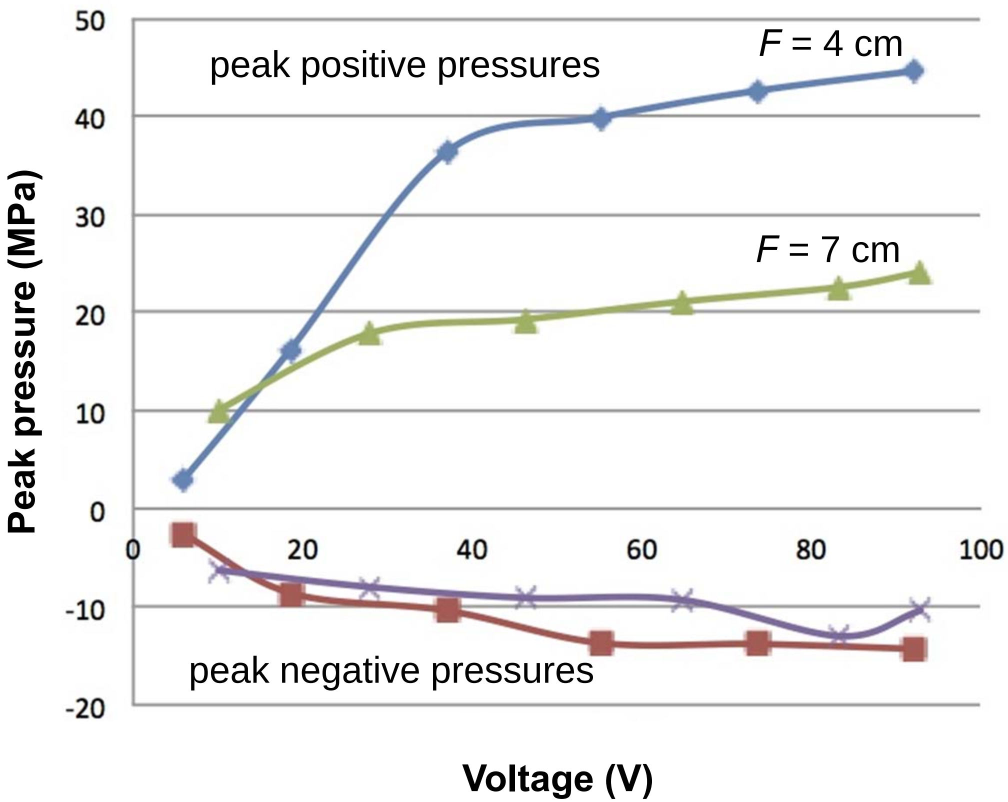
2.3 MHz,
Philips C5-2

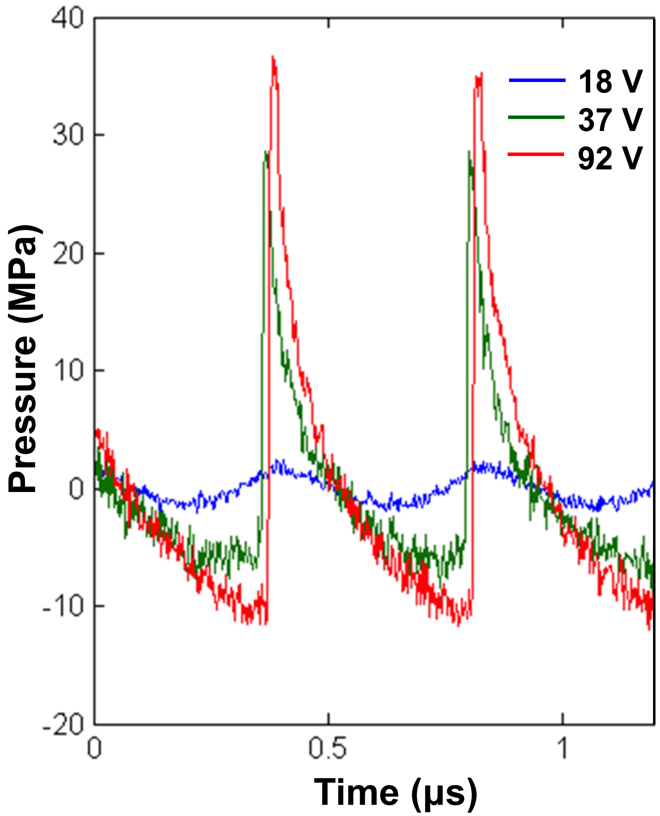
Harper, Bailey *et al.*, J. Endourol. 26 (11), 1494–1499, 2012.

The goal: use ultrasound radiation force to push stone fragments toward the exit of the kidney

Saturation effects observed at high voltages

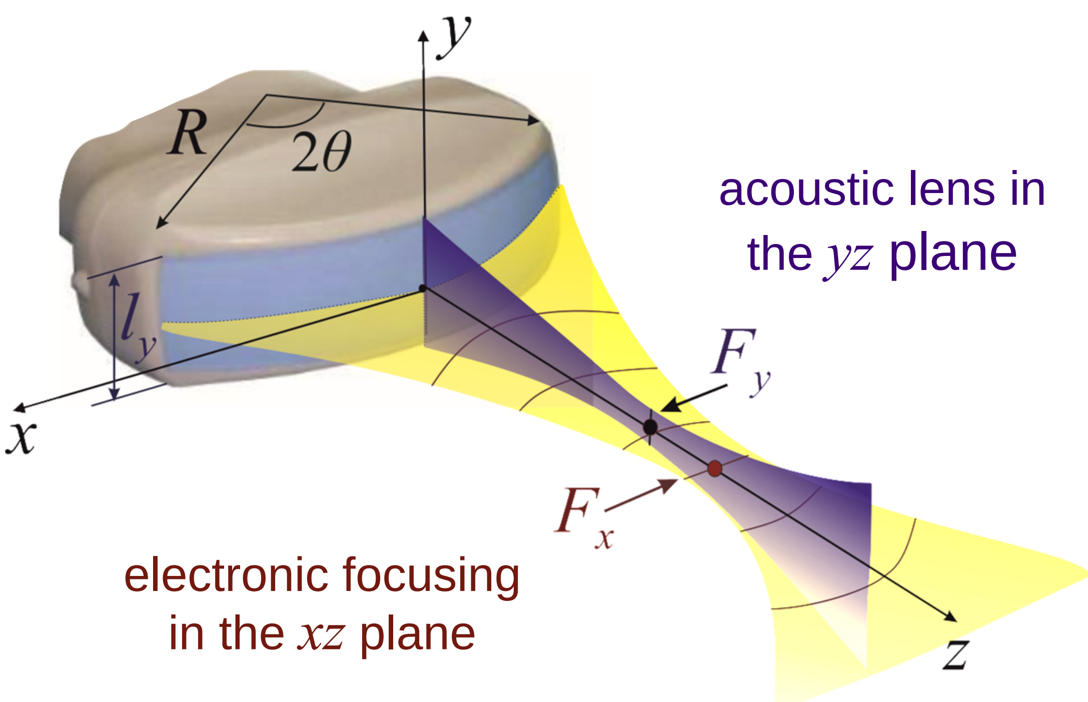
Saturation effects were observed for acoustic pressures in the focal region – what is the reason?





Hypothesis: **nonlinear acoustic saturation effect is a limiting factor to provide sufficient radiation force for stone propulsion**

Theoretical model



Boundary condition:
- cylindrical surface
- uniform amplitude distribution
- continuous phase distribution
- fitting parameters: $\boldsymbol{R}, \boldsymbol{\theta}, \boldsymbol{l_y}, \boldsymbol{F_{x,y}}$

Parameters:

$\boldsymbol{R}$ = 38 mm, $\boldsymbol{l_y}$ =12.5 mm,
$\boldsymbol{F_x}$ = 50 mm, $\boldsymbol{F_y}$ = 70 mm

3D Westervelt equation in the retarded time coordinates

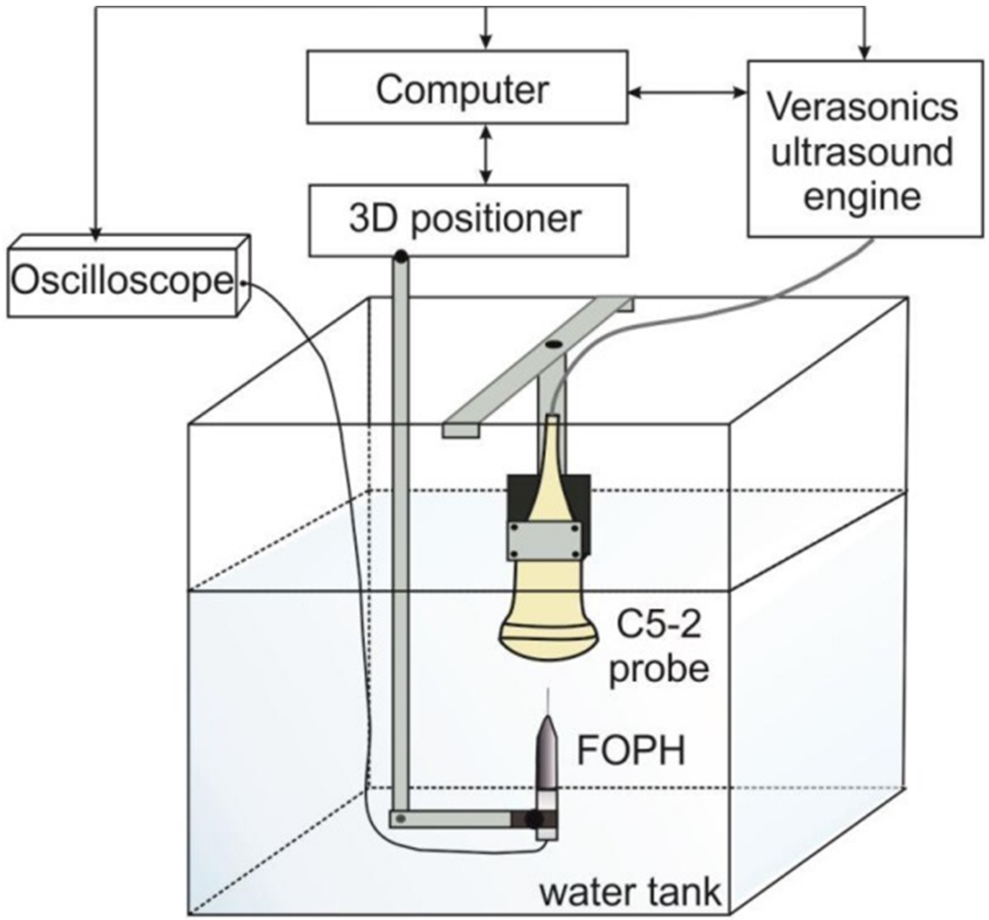
$$\boxed{\frac{\partial^2 p}{\partial \tau \partial z} = \frac{c_0}{2}\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}\right) + \frac{\varepsilon}{2\rho_0 c_0^3}\frac{\partial^2 p^2}{\partial \tau^2} + \frac{\delta}{2c_0^3}\frac{\partial^3 p}{\partial \tau^3}} \qquad \boxed{\tau = t - z/c_0}$$

Combined time-domain and frequency-domain approach

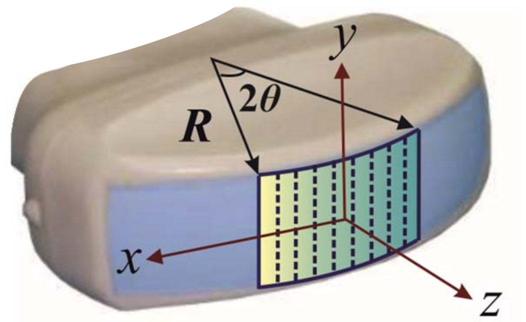
$$p(x,y,z,\tau) = \sum_{n=-N_{\max}}^{N_{\max}} p_n(x,y,z)\exp(-in\omega_0\tau)$$

Setting a boundary condition using linear scans

Experimental setup



Equivalent source

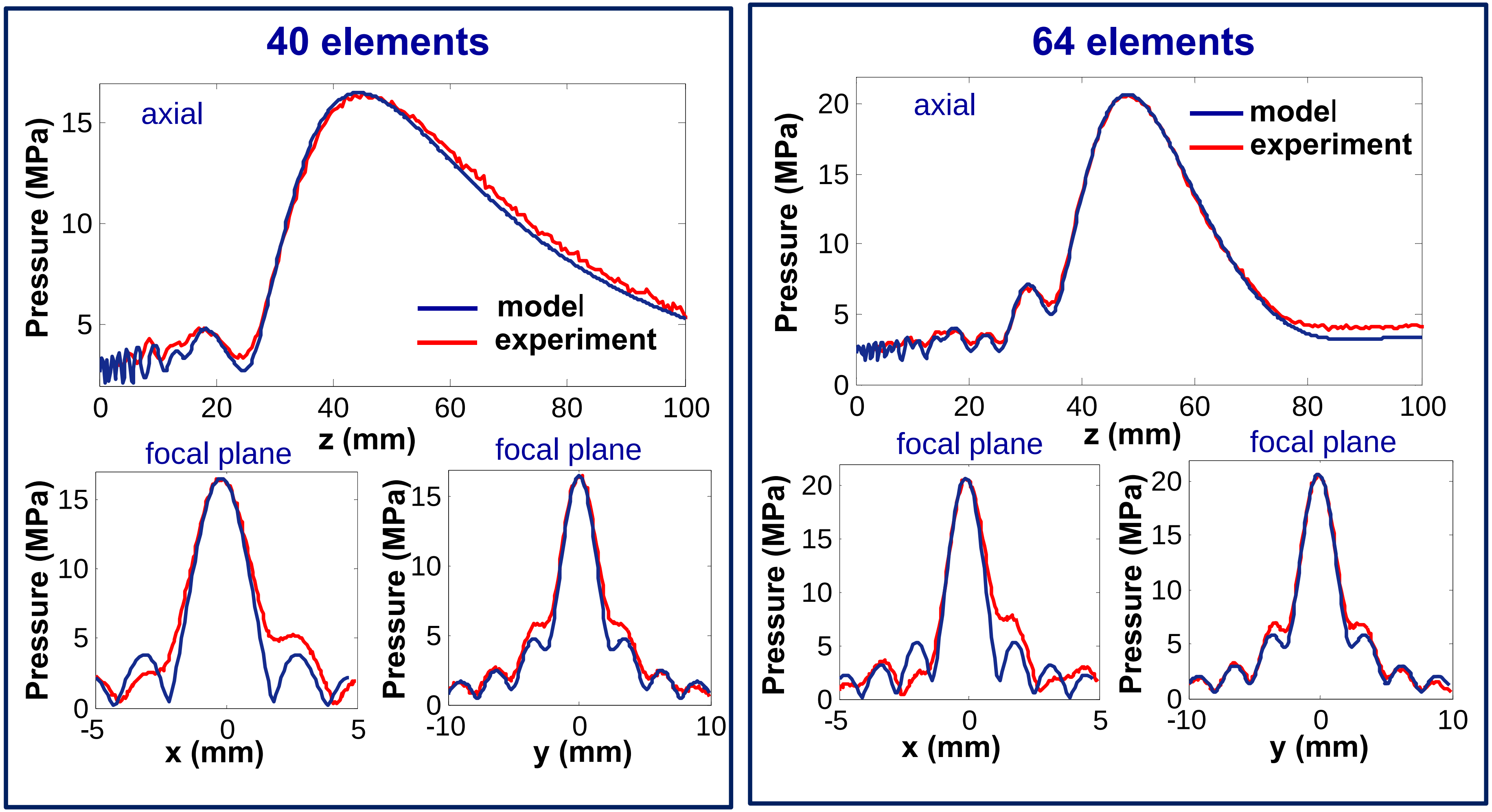


The 'best fit' parameters:

$\boldsymbol{R}$ = 38 mm, $\boldsymbol{l_y}$ =12.5 mm,
$\boldsymbol{F_x}$ = 50 mm, $\boldsymbol{F_y}$ = 70 mm,
$\boldsymbol{\theta}$ = 0.2$N/\boldsymbol{R}$,
$\boldsymbol{p_0}$ = 2.75 MPa for 40 elements,
2.2 MPa for 64 elements

- Low power measurements on the axis and in the focal plane of the transducer
- Setting the boundary condition by calculating Rayleigh integral to match experimental data

Setting a boundary condition using linear scans



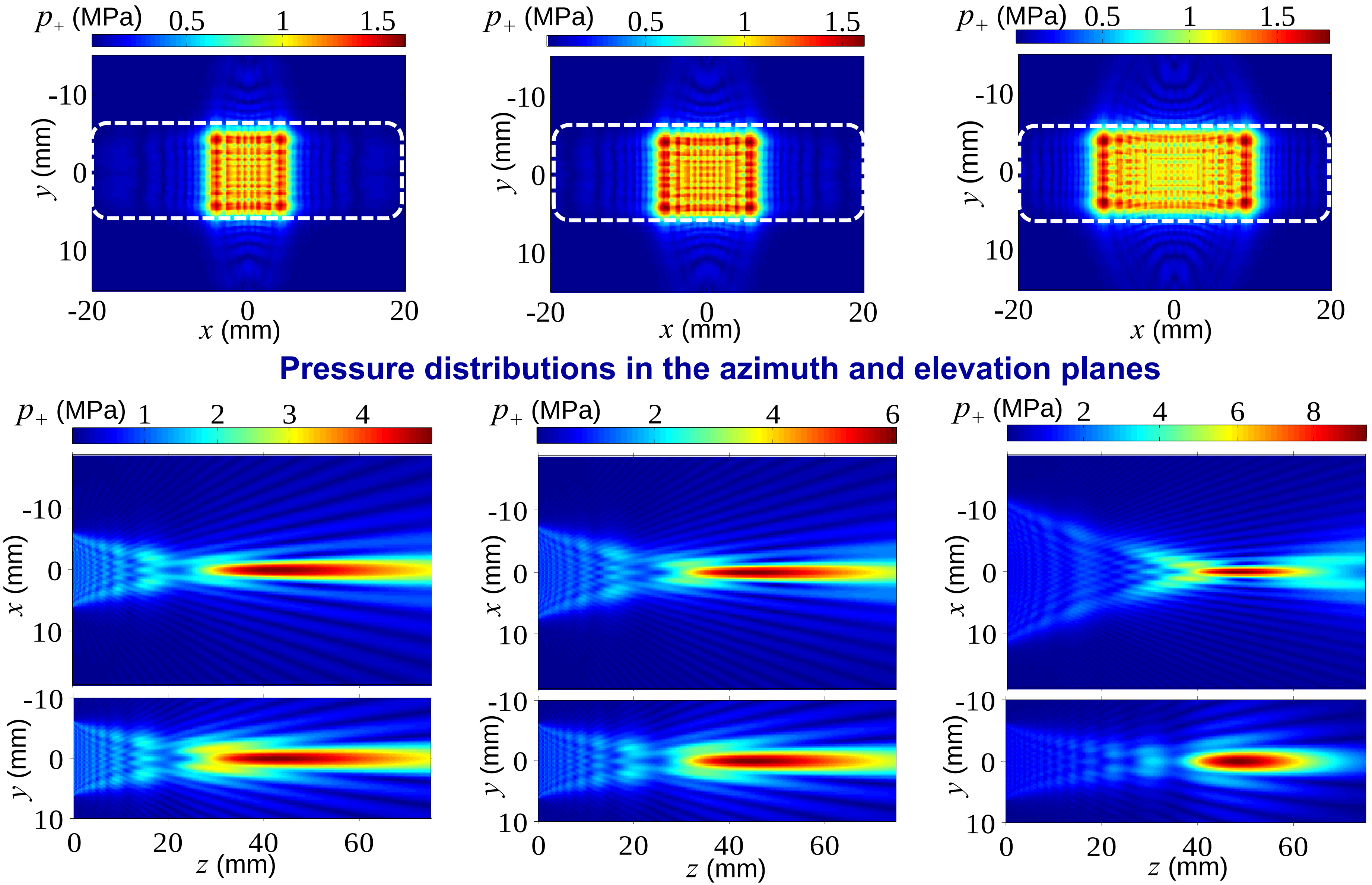
Simulation results are in good agreement with the experimental data

Modeling results: linear case

32 elements	40 elements	64 elements

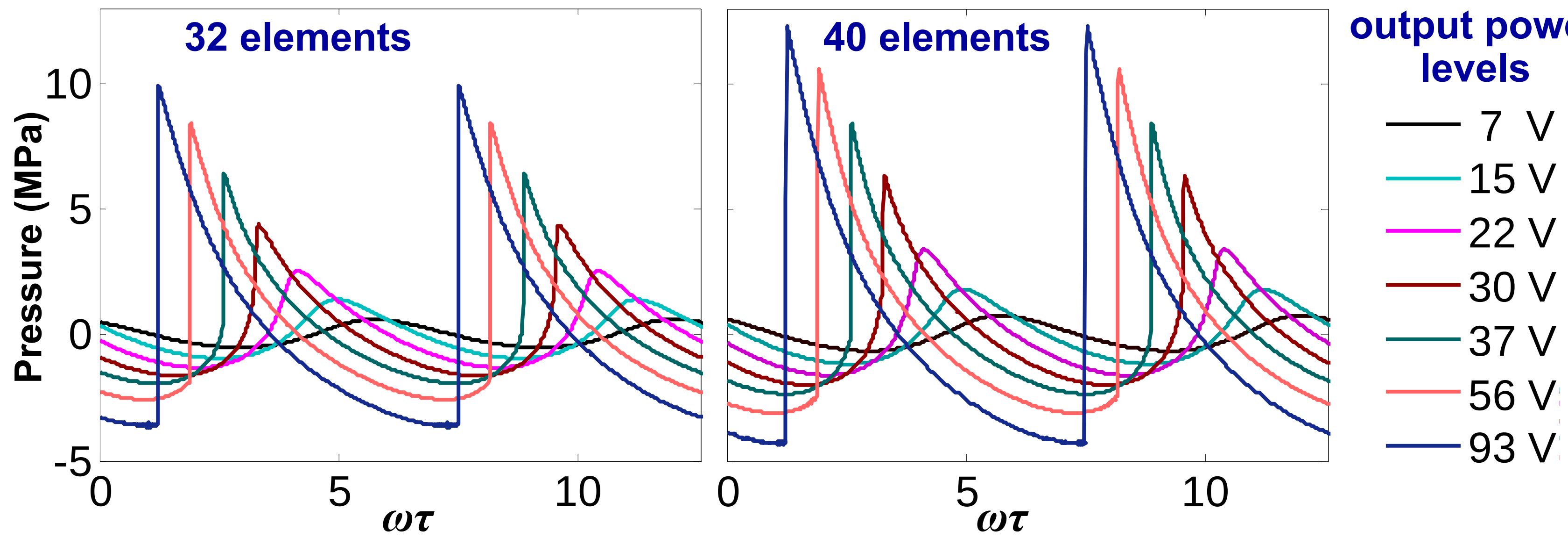
Pressure distributions in the initial plane 2 mm from the transducer

Pressure distributions in the azimuth and elevation planes

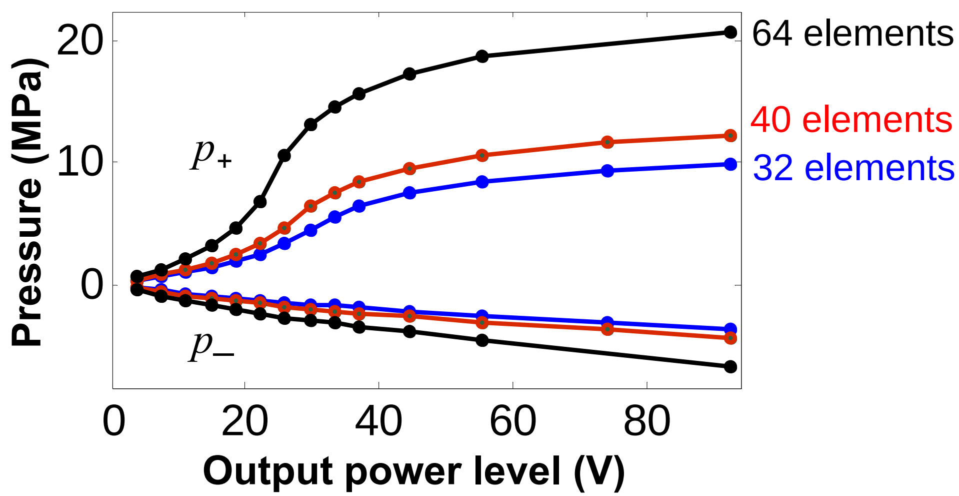


Modeling results: nonlinear propagation

Waveforms at the focus



Saturation of peak pressures



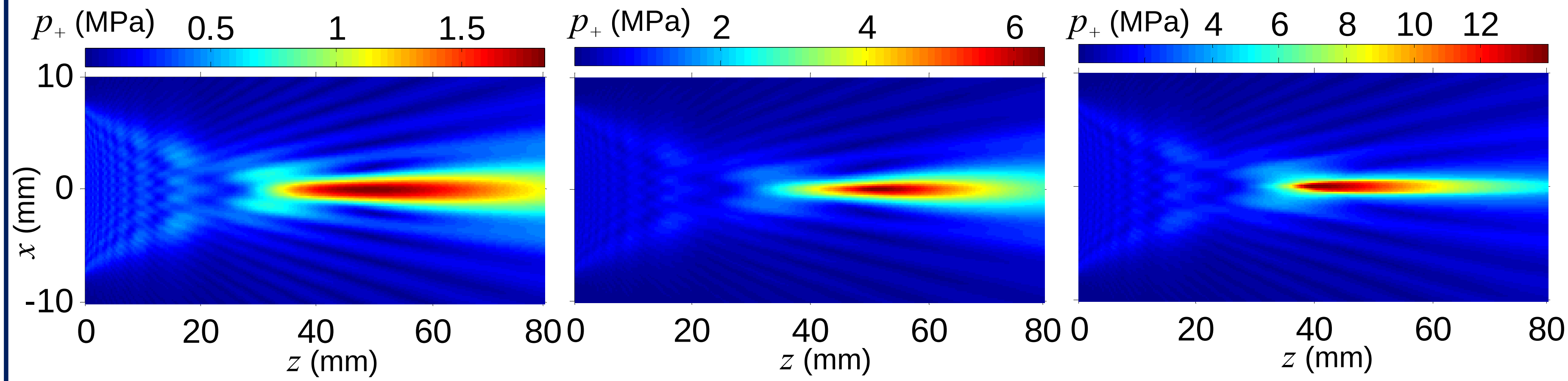
- Saturation effects do limit peak positive and negative pressures
- Shock front formation occurs starting at ~ 30 V source level
- Using of a larger number of elements provide higher peak pressure values

Modeling results: field structure in the elevation plane

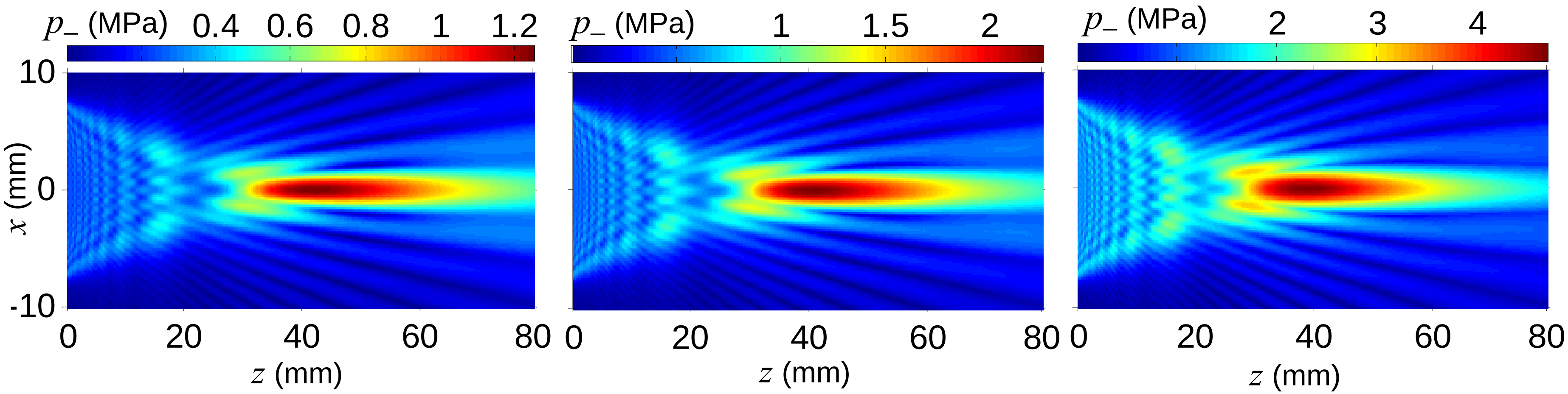
Quasilinear case	Nonlinear case	Saturation regime

40 elements

Peak positive pressure

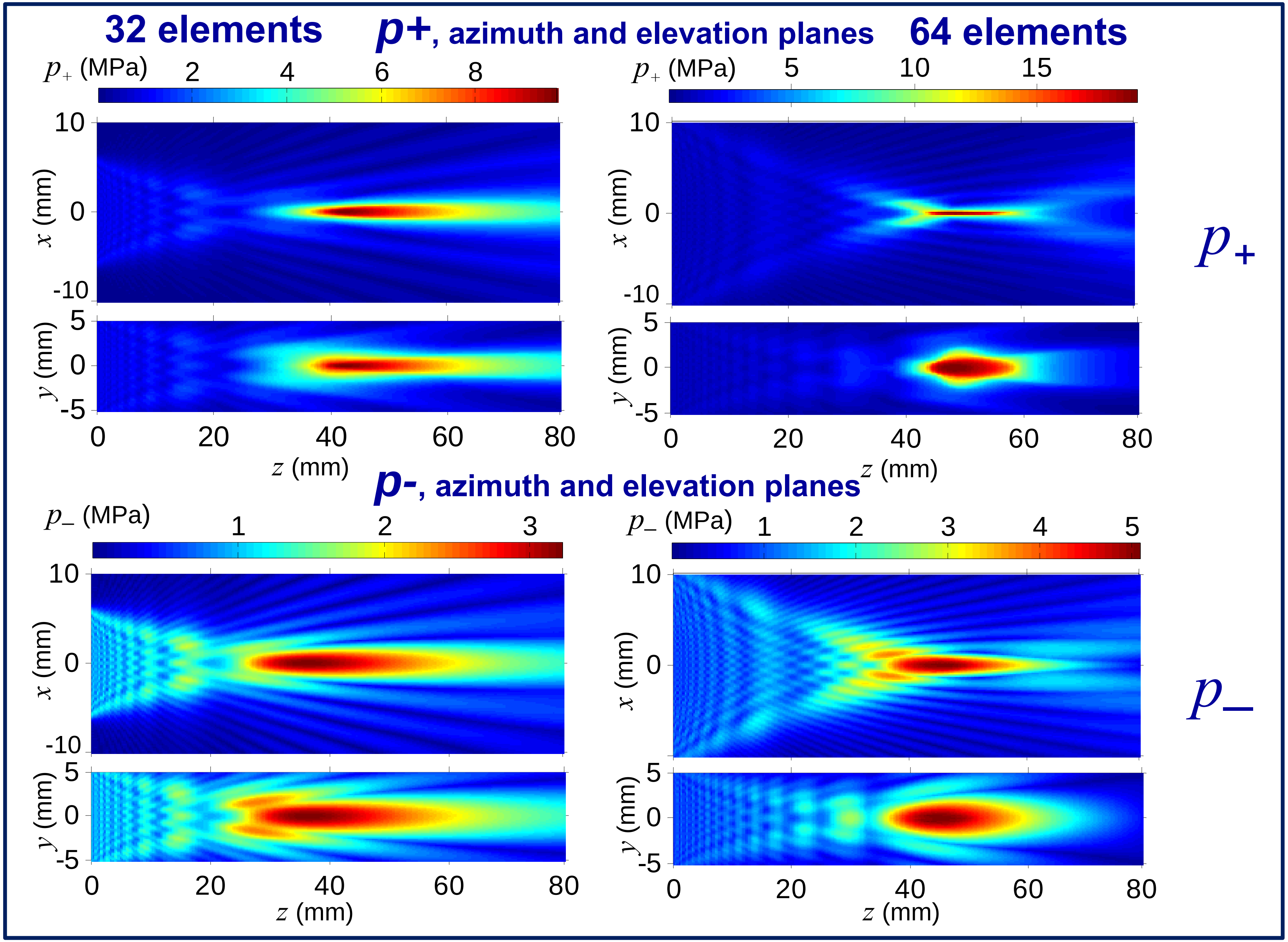


Peak negative pressure

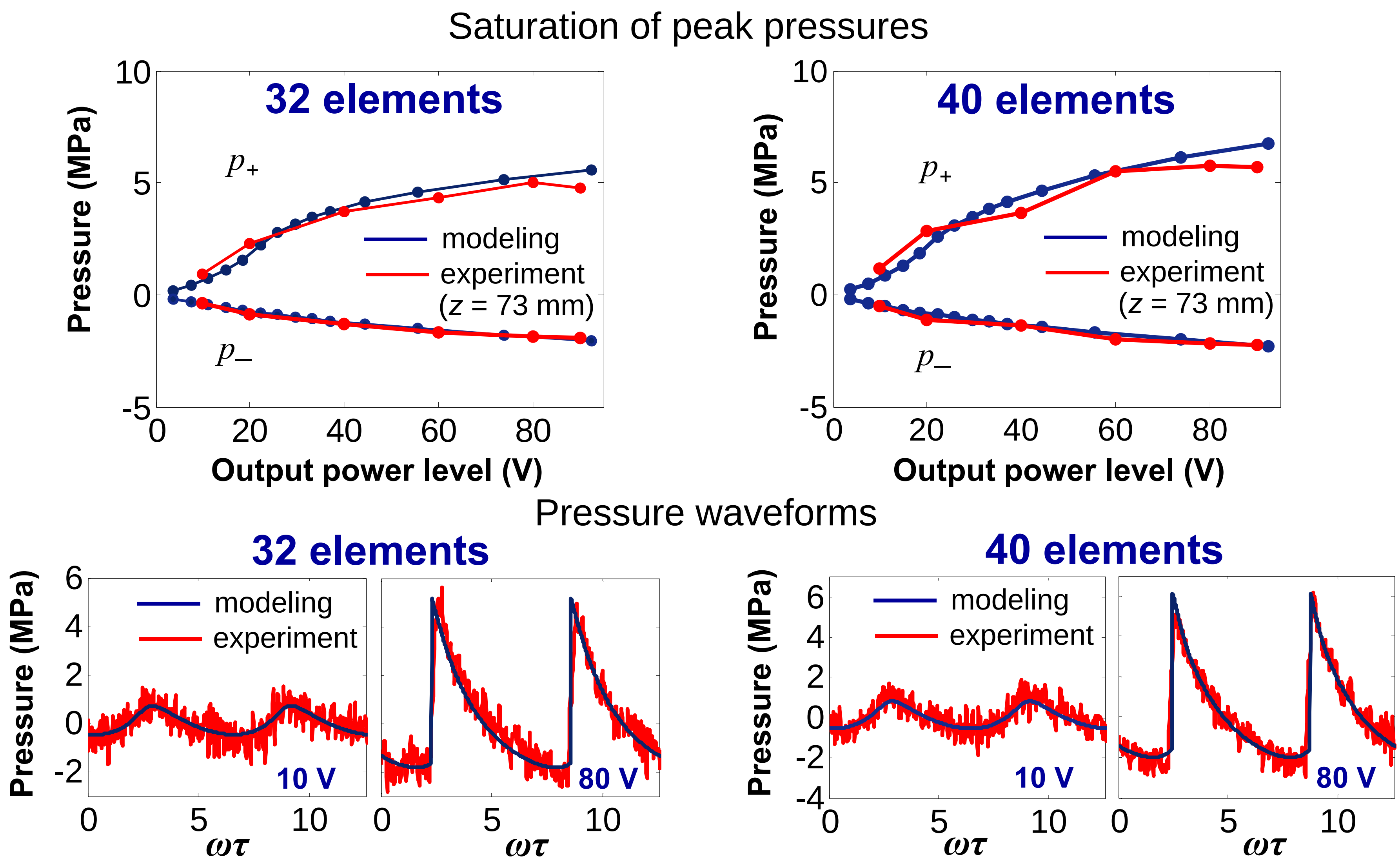


(output 15 V) (output 30 V) (output 74 V)

Modeling results: saturation regime (output 56 V)



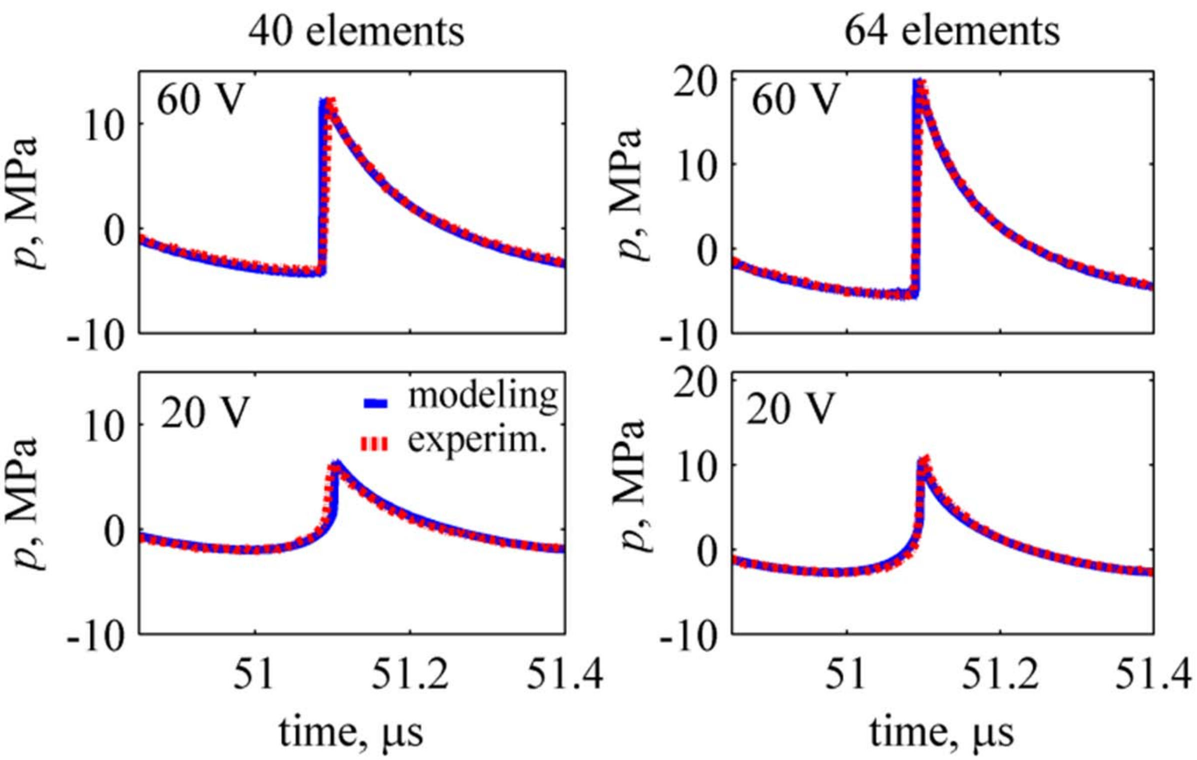
Validation measurements to confirm modeling



Good agreement between measurements and simulations through a whole range of power outputs

Validation measurements to confirm modeling

Pressure waveforms at z = 50 mm



Conclusions

- Combined measurement and modeling method is capable to calibrate acoustic fields of diagnostic-type transducers (C5-2)
- Saturation effect limits the peak positive and negative pressures at the focus for stone pushing application outputs
- Peak positive pressure saturation level is about 20 MPa for 64 active elements and 10 MPa for 32 active elements
- Shock formation occurs at the output power level about 1/3 (30 V) of the one clinically used (90V)

Future work

Use modeling to optimize transducer parameters for stone propulsion technology

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