Ultraschall-Sensorarrays
Ultrasound arrays

1. **Introduction**
2. **Theory**
3. **Arrays with linear elements for complex NDT-Problems**

3.1 Plane Array for testing of half finished products with immersions technique

- Discussion of the sound field in water: steering, grating lobes, limitation of steering
- Testing with immersion technique: Sound field in a water/steel configuration

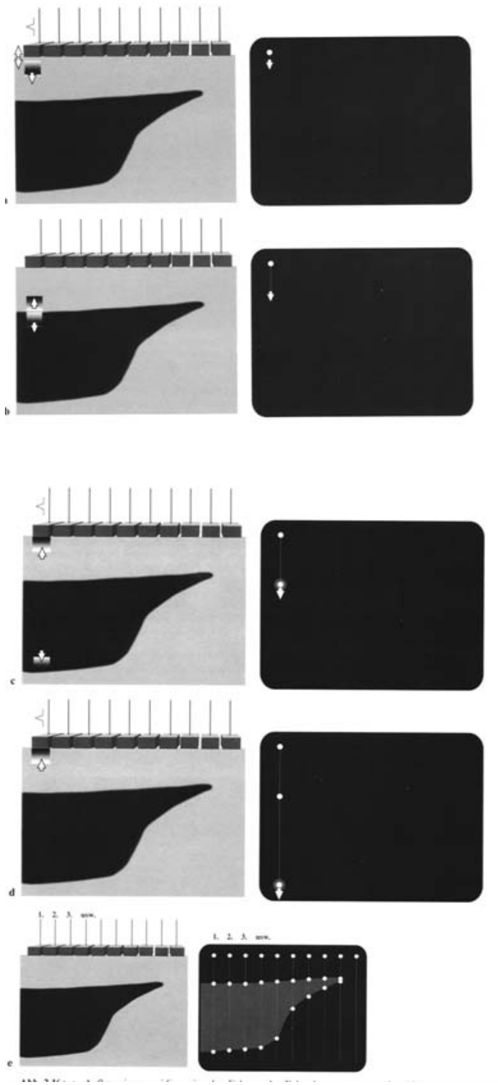
3.2 Curved array for testing of a pipe wall with immersions technique

- Discussion of the sound field in water: geometrical determined delay times, classification of side lobes
- Testing of a pipe wall: Sound field in a water/steel configuration

4. Annular Arrays

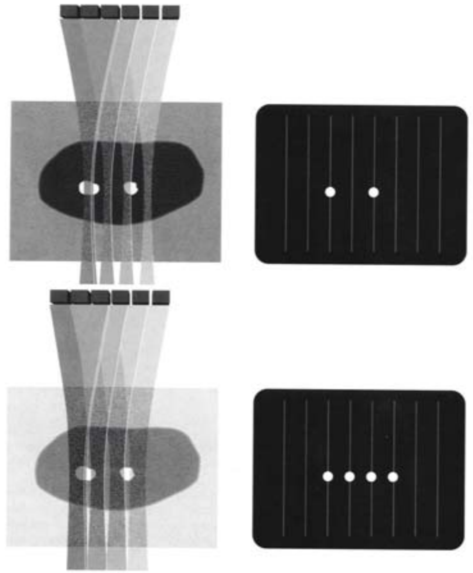
1. Introduction: ultrasound - principles, resolution, problems

B-scan

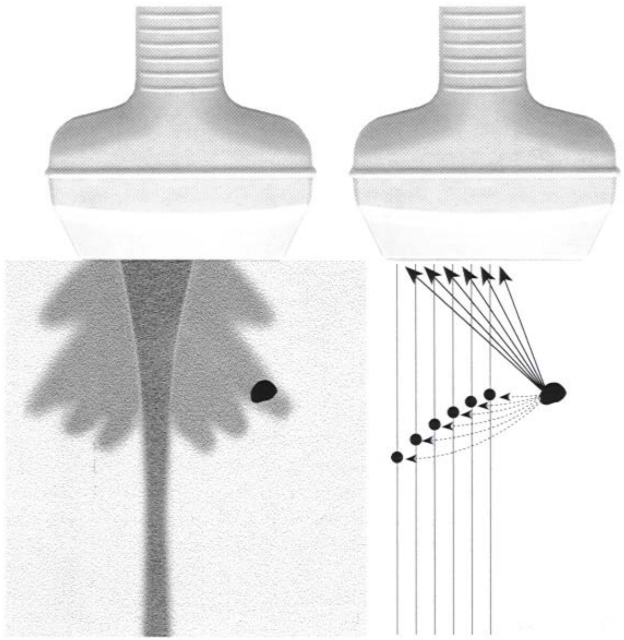


Lateral resolution

- maximal in dimension of the wavelength
- depending on beamwidth

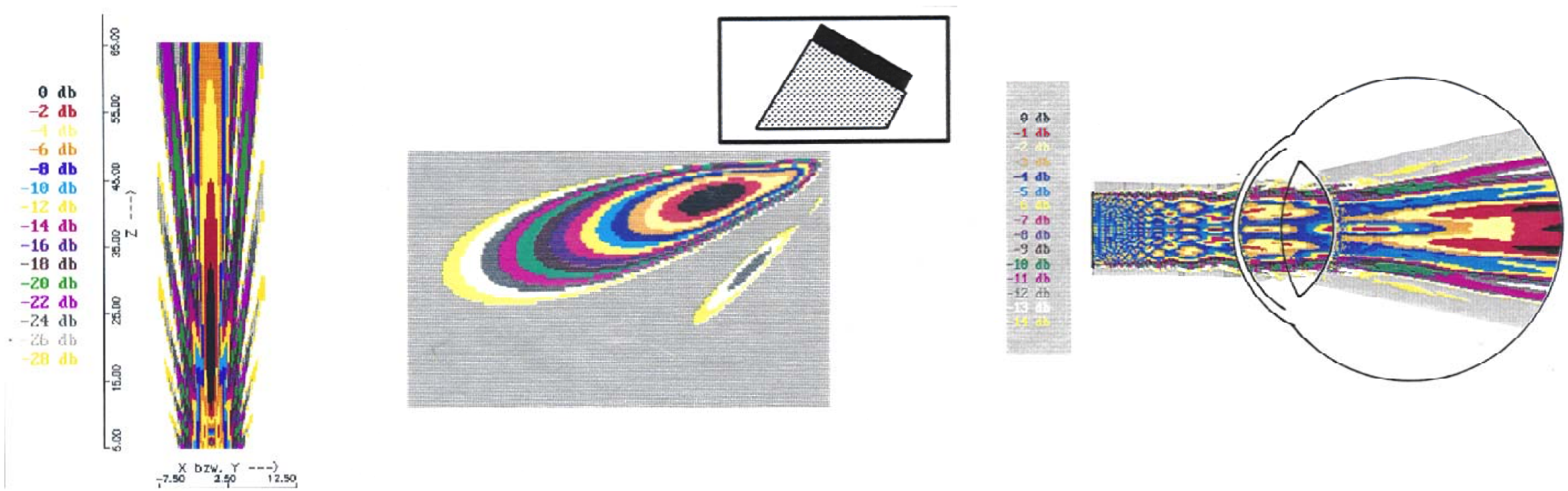


Artifacts



Appearance of the sound field → ability to measure, **resolution,** inspection **quality**

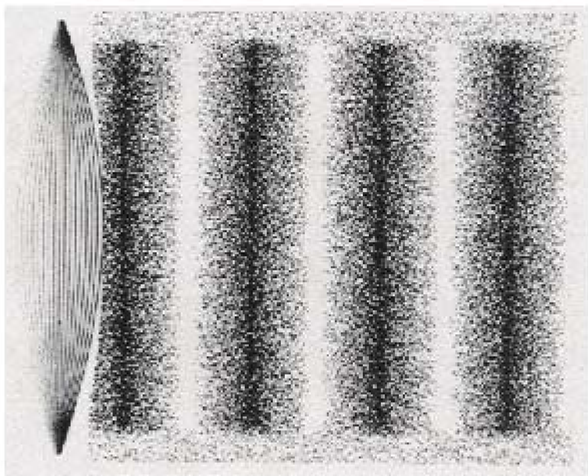
- **Near field, far field** $N = \frac{d^2}{4\lambda} = \frac{d^2 f}{4c}$
- Width of sound field ~1/f ~1/d, **secondary structures**
- Sound field in the test object: depends on **transducer** + **test object** parameters
- **Demands on the sound field**
  - Small beam, no secondary structures → **resolution**
  - Focus (sensitive area) in a defined distance
  - Sound radiation with a defined angle



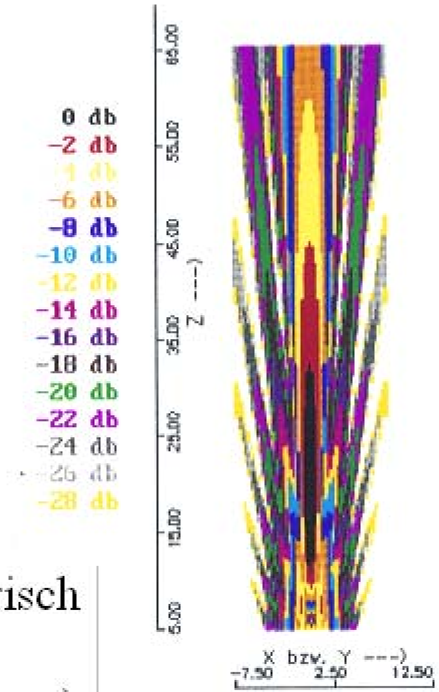
Appearance of the sound field

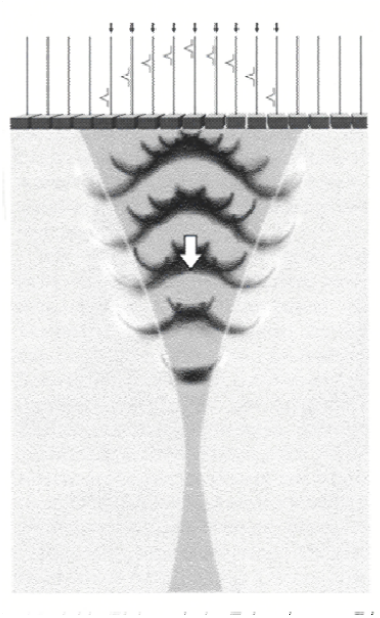
Dependance of the sound field on frequency and size of element

Ultrasound: element size *d*=3-8 mm to some square centimeter
frequency: 3-10 MHz → λ < 1mm
element > λ → non diffuse sound field



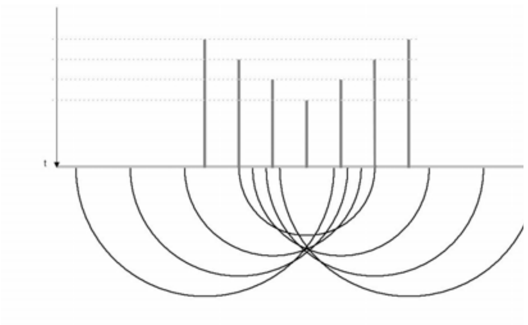
Schallfeld in Wasser für zylindrisch **fokussierenden Prüfkopf** (Schwinger: d=6 mm, f_{geom}=50 mm)



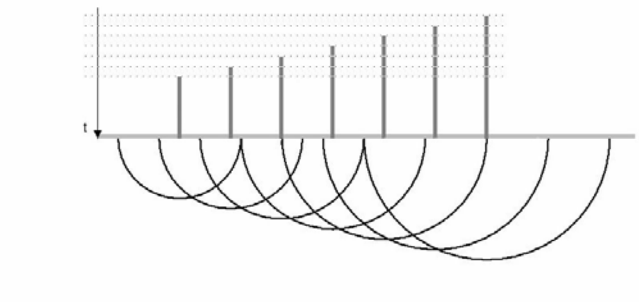


Array:
- Using of some elements → non diffuse sound field
- Focusing in different depth
- Steering

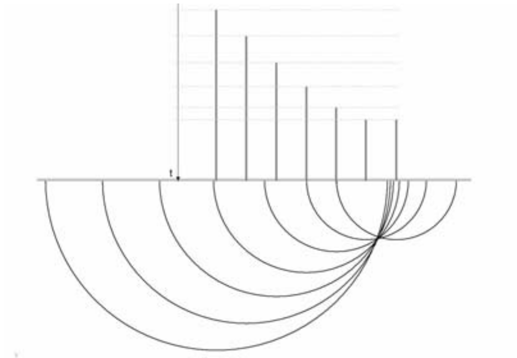
Focusing



Steering



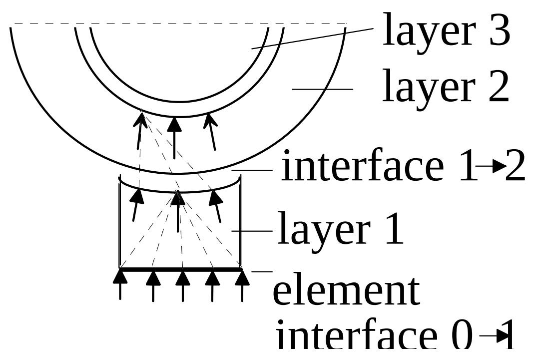
Focusing + Steering



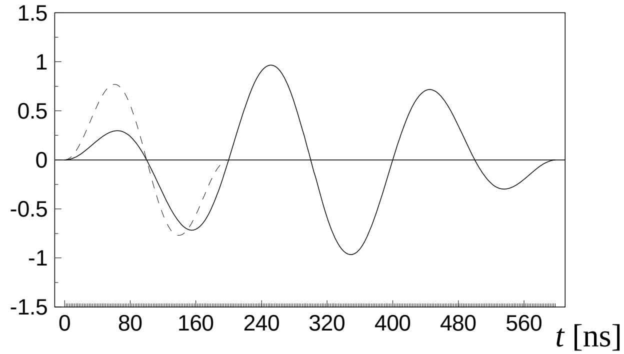
2. Theory: Calculation of the Array Field

- **Harmonic GREEN's functions** in stepest descent approximation
  - Source functions - satisfy boundary conditions
  - Propagation terms - interference of waves

- **Separation method**



- **Transient field**
  - Convolution between impulse response and excitation function

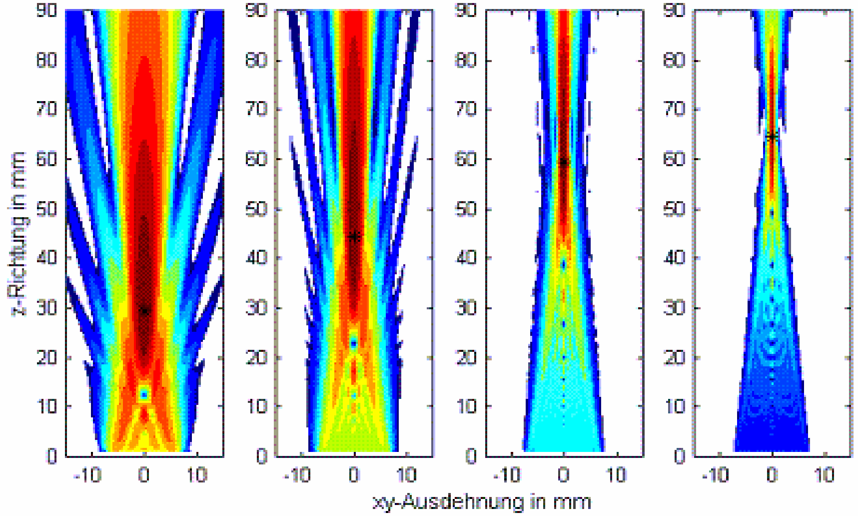


- **Array**
  - superposition of time delayed fields of particular elements
  - fields of the single elements are stored

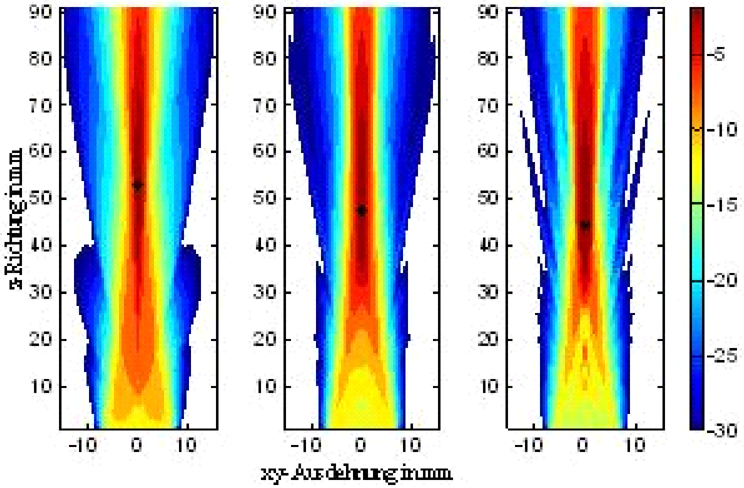
2. Theory: Calculation of the transient field (2)

Foci at: a) 1 MHz, z=34 mm; b) **2 MHz**, z=50 mm; c) 5 MHz, z=63.5 mm; d) 10 MHz, z=64.5 mm

Harmonic



Transient
f_M=2MHz



Excitation Foci at: 0.5 periods, z=52 mm; 1 period, z=50 mm; 5 periods, z=50 mm

Fig.3_9 Sound field in water of a focussing 2MHz-Transducer

Time harmonic sound field:
by increasing frequency
- Sensitivity zone shifts away from the probe
- Sound field becomes smaller

Transient:
- Superposition of the harmonic fields according to the time excitation of the input signal

Comparison of transient and time harmonic fields:
harmonic field at centre frequency
- good approximation for the transient fields
- predicts eventually appearing of secondary structures for longer excitations

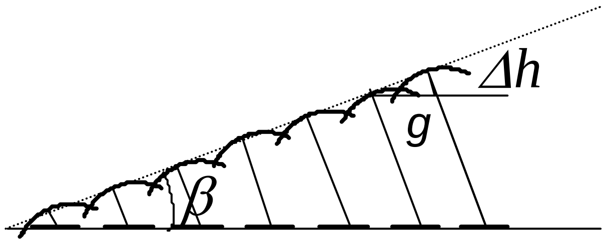
3. Arrays with linear elements for complex NDT-Problems

3.1 Plane Array for testing of half finished products with immersions technique (1)

Setup:

- 16 elements, element width b=0.9 mm, f=3MHz,
- grating constant g=1mm - $\lambda/2$ in steel, 2λ in water

Steering with a plane array



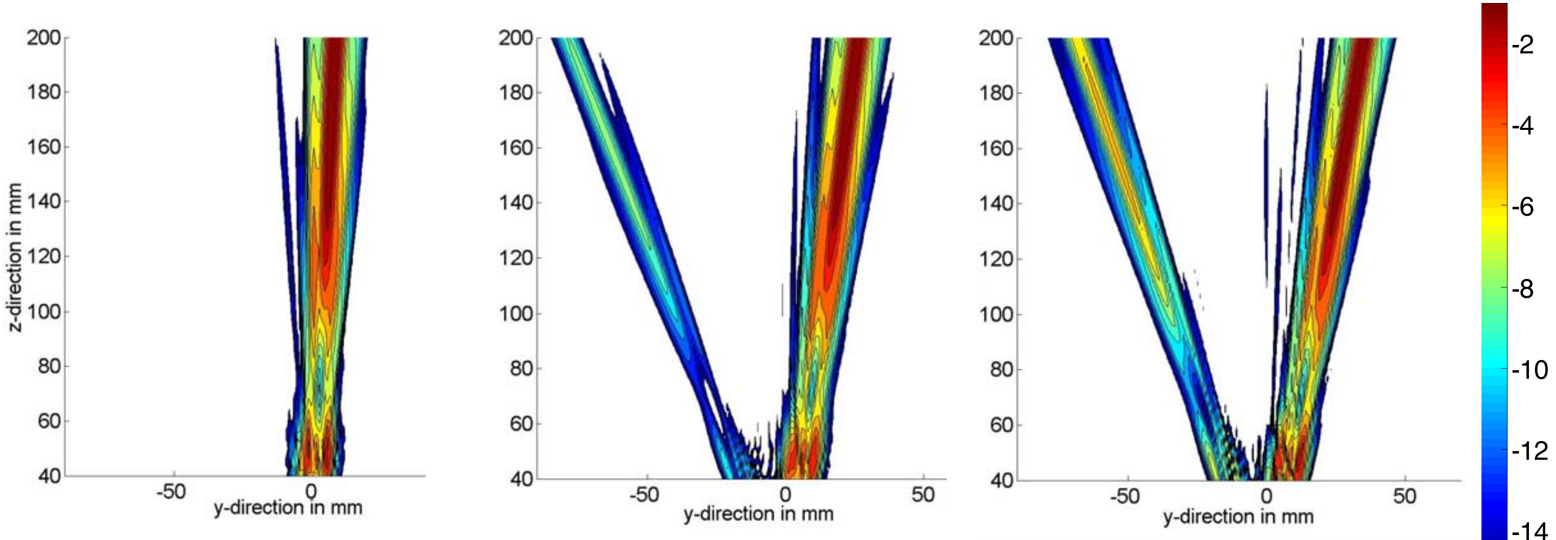
$$\sin\beta = \frac{\Delta h}{g}$$

$$\Delta t = \frac{\Delta h}{c} = \frac{g \cdot \sin\beta}{\lambda} \cdot T$$

Steering take place in water – properties in water

- Discussion of the sound field in water: steering, grating lobes, limitation of steering
- Testing with immersion technique: Sound field in a water/steel configuration

1. grating lobes



a) steering angle: β=2.5° α_m=2.5°

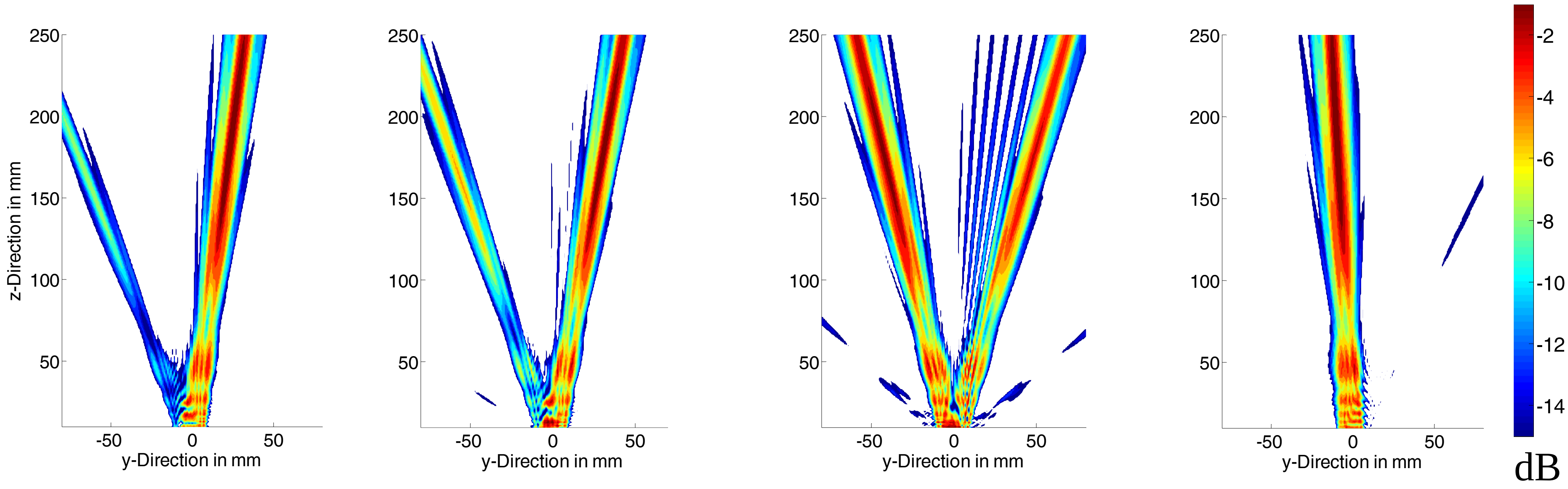
b) steering angle: β=7.5° α_m=7.5° α_g= -21.5°

c) steering angle: β=10° α_m=10° α_g= -19°

Fig.1: **Influence of steering angle β on the grating lobes - Time harmonic sound fields in water**
plane array (16 elements, frequency: f= 3 MHz, distance of the elements g=1mm)
α_m angle of main lobe, α_g angle of grating lobe (angles regarding to z-axis)

- Increases of grating lobes by an increased steering angle!
- β=10°: grating lobe is -6dB in comparison to the main structure

2. limitation of maximum steering angle



a) β= 7.5° Δt= 87ns=0.26T α_g=-21.7° α_m=7.3°

b)) β= 10° g=2λ, Δt=0.36T α_g=-19° α_m=10.1°

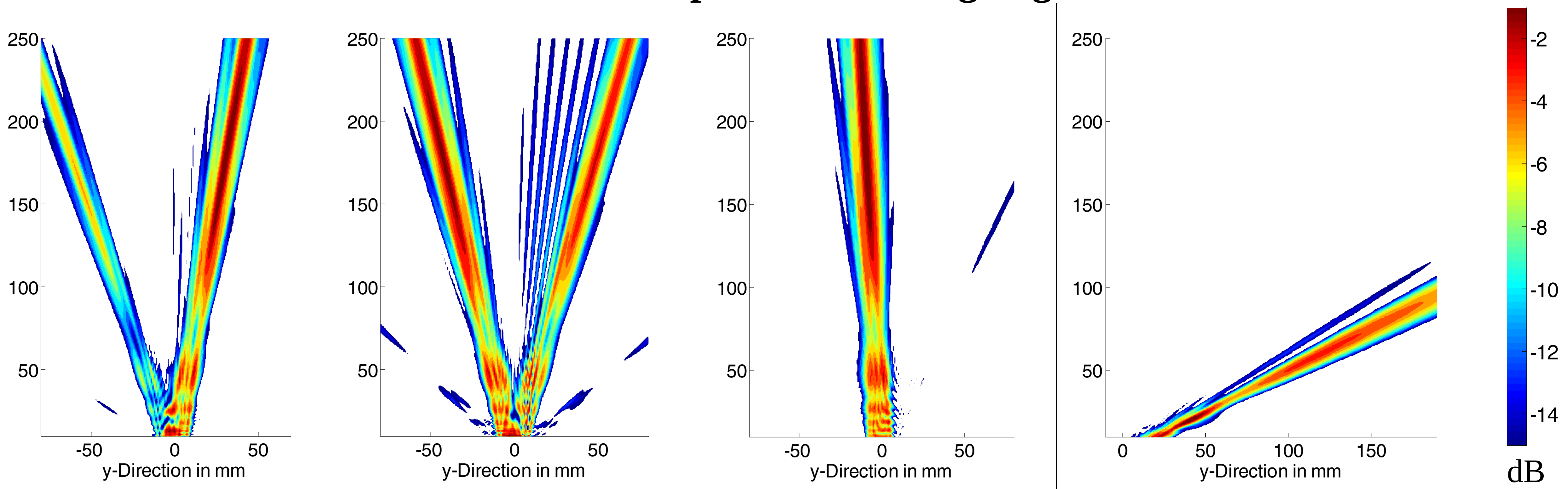
c) β= 15.6° Δt=179ns=0.54T α_g=-13.5° α_m=16.3°

d) β= 26.7° Δt=300 ns=0.9T

Fig.2: **Influence of steering angle β on the grating lobes - Time harmonic sound fields in water**
plane array (16 elements, frequency: f= 3 MHz, distance of the elements g=1mm=2λ)
α_m angle of main lobe , α_g angle of grating lobe (angles regarding to z-axis)

- steering is limited
- β=10° is the maximum possible steering angle

Sound field in water – limitation of the possible steering angles



b) β=10°
g=2λ, Δt=0.36T
α_g=-19° α_m=10.1°

c) β= 15.6°
Δt=179ns=0.54T
α_g=-13.5° α_m=16.3°

d) β= 26.7°
Δt=300 ns=0.9T

16 elements, element distance g=1mm=2λ with respect to water

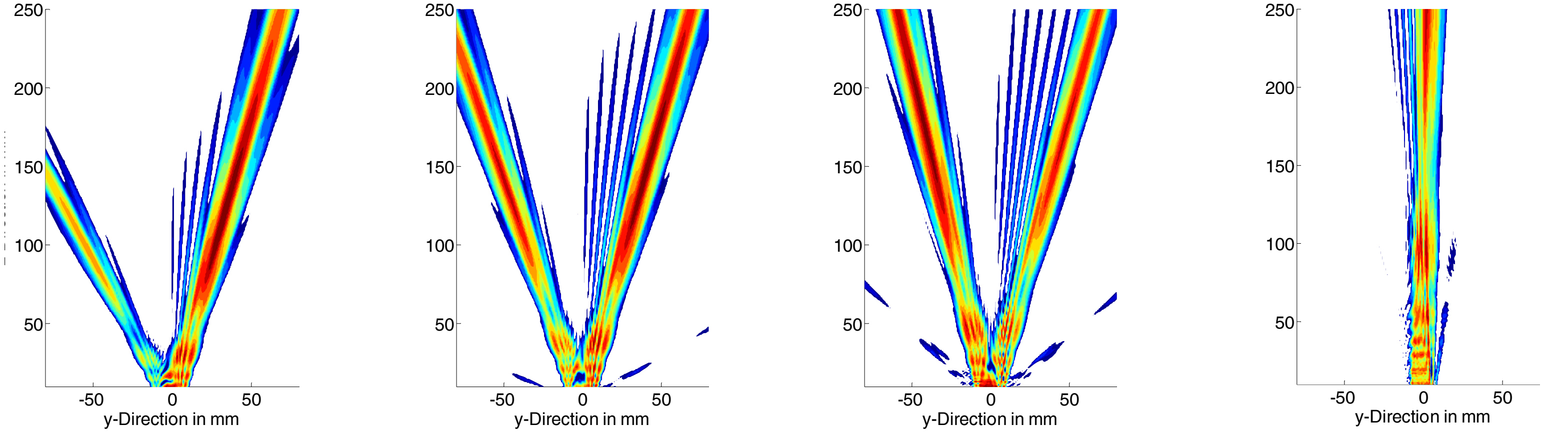
c) β=64.2°,Δt=150 ns=0.45T
α_m=63.3°

64 elements, g =0.25 mm =λ/2

Fig.3: Time harmonic sound fields in water for a **plane array** at **frequency: *f*= 3 MHz**
α_m angle of main lobe , α_g angle of grating lobe (angles regarding to z-axis)

- **Steering angle is limited**
- **Large steering angle by keeping the λ/2-condition!**

Steering with a plane Array – Time harmonic and transient fields in water (5)

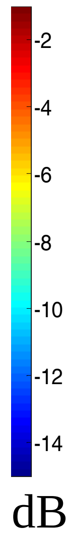


a) f=2 MHz, Δt=0.36T α_q=-28.9° α_m=15.5°

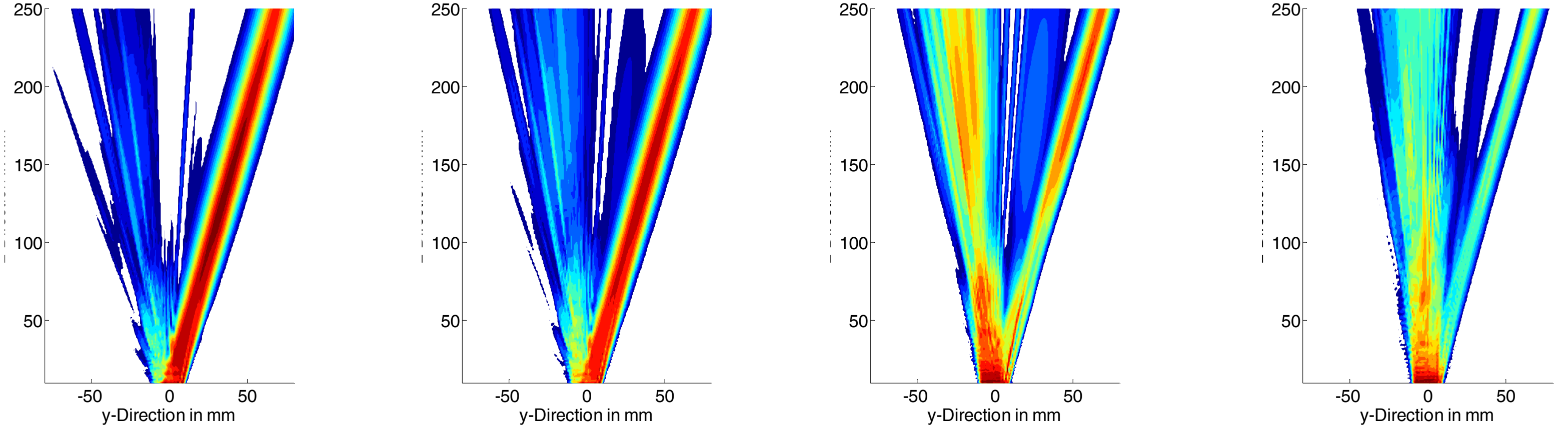
b) f=2.5 MHz, $g<2\lambda$, Δt=0.45T α_g=-19.4° α_m=15.5°

c) f=3 MHz, $g=2\lambda$, Δt=0.54T α_g=-13.5° α_m=16.3°

d) f=6 MHz, $g=4\lambda$, Δt=0.93T



Limitation of steering angle also in the transient case



e) f_M =2 MHz

f) f_M =3 MHz

g) f_M =4 MHz

h) f_M =6 MHz

Fig.4: **Time harmonic and transient** sound fields in water for a plane array (16 elements b=0.9mm, distance of the elements g=1mm β= 15°, transient: 1 period)

Steering with a plane Array – Time harmonic fields in water and steel (6)

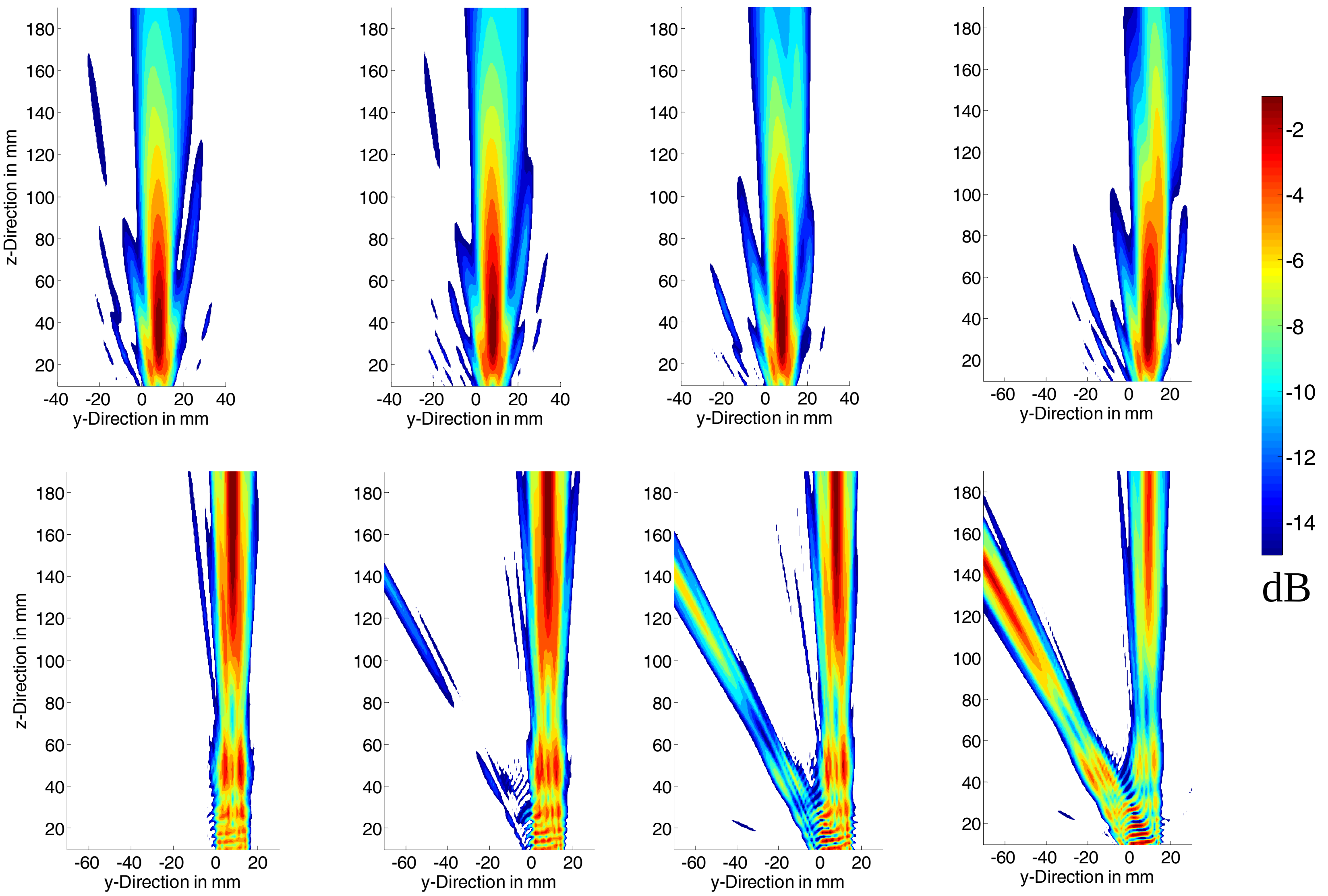
Fig.5: **Time harmonic sound fields of a plane array**

(16 elements, f=3MHz) for different steering angles β

in steel behind a water path of 40 mm

in water

p=10.1 (0,8,33.5) p=9.4 (0,0,33) p=8.5 (0,8,32.5) p=6.3 (0,9,31.0)



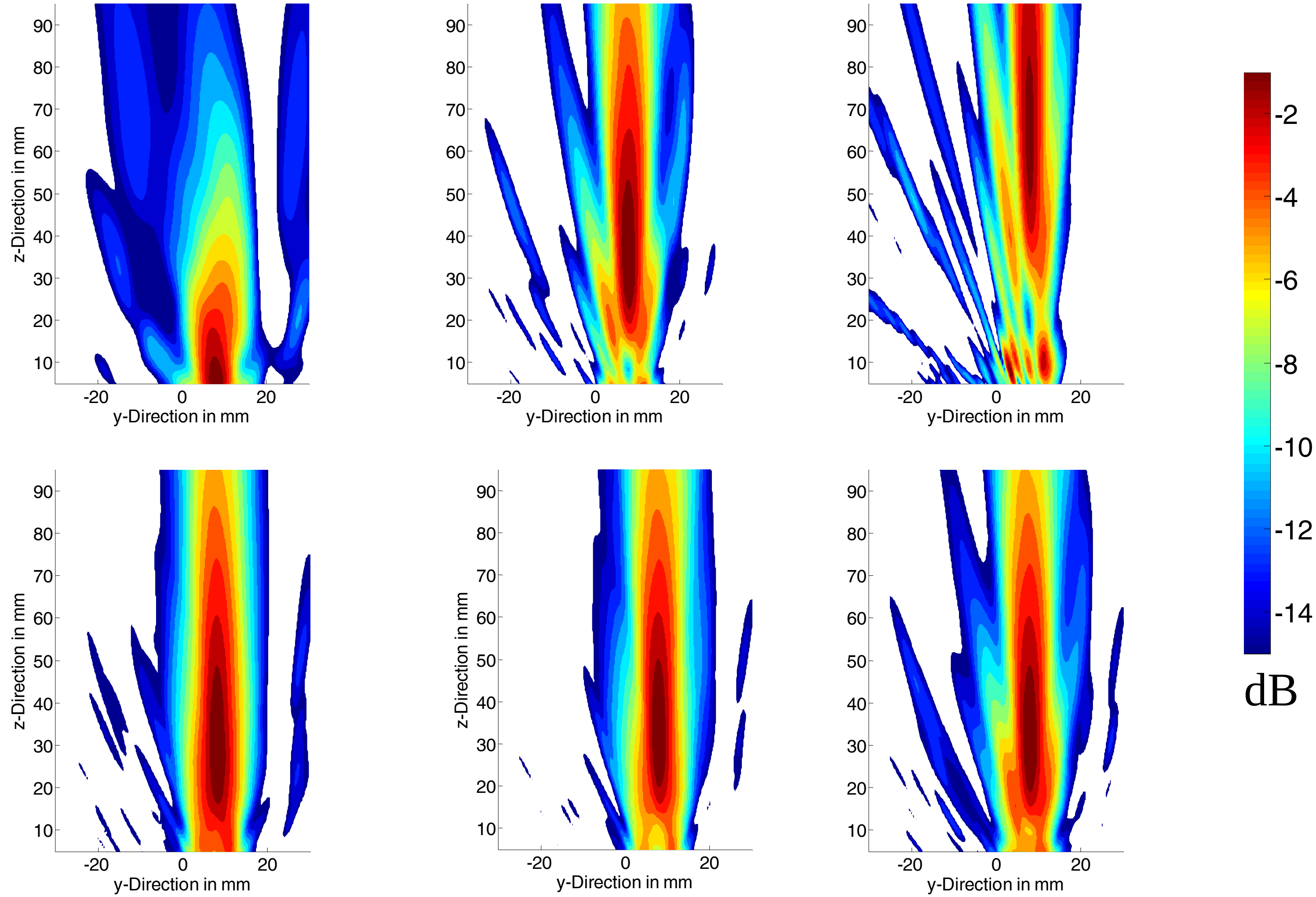
p=935 (0,8,174) p=879 (0,8,176) p=783 (0,8,172) p_g=661 p_m=587

a) β=2.5° b) β= 5° c) β=10° d) β=15°

a) f=1MHz p =83.8 (0,8,5.5)   b) f=3MHz p = 25.4 (0,8,32.5)   c) f=5MHz p =10.7 (0,8,62.0)

Harmonic

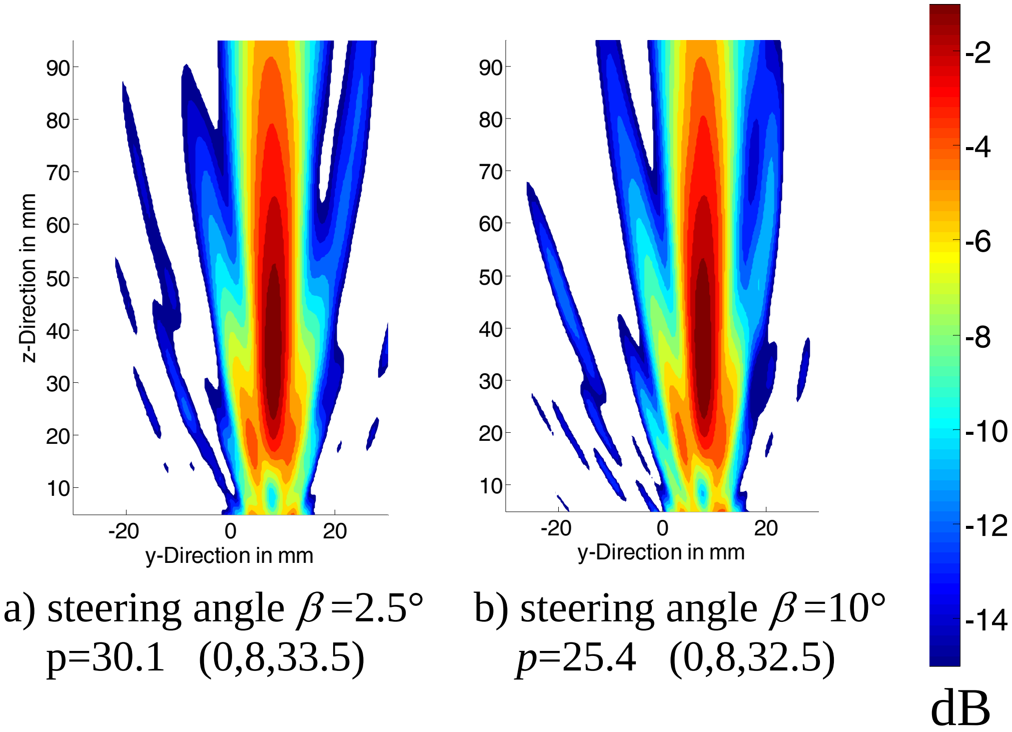
Transient
f_M=3MHz



a) 1 period p =51.7 (0,8,30)   b) 2 periods p = 59.4 (0,8,32.0)   c) 5 periods p =66.3 (0,8,31)

Fig.6: **Comparing time harmonic and transient sound fields in steel, β=10°**

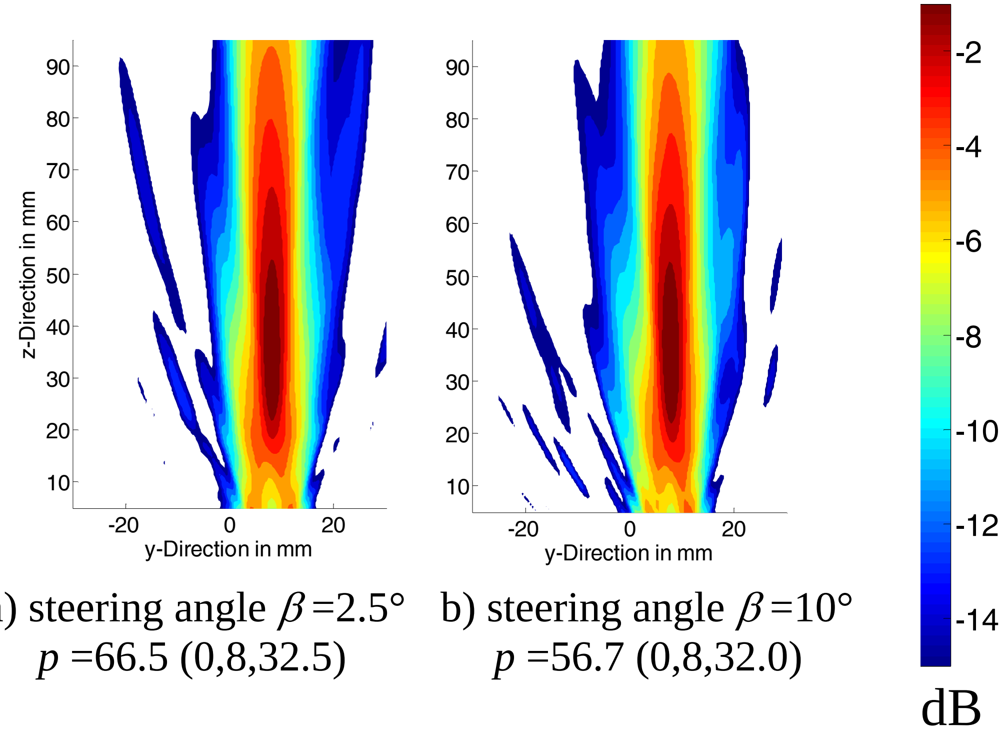
- Inspection of steel half-finished products; element width is $\lambda/2$ in steel



a) steering angle β=2.5° p=30.1 (0,8,33.5)

b) steering angle β=10° p=25.4 (0,8,32.5)

Fig.7: **Time harmonic sound fields of a plane array in steel** (16 elements, frequency: f= 3 MHz, distance of elements g=1mm**,** water delay 40 mm)



a) steering angle β=2.5° p =66.5 (0,8,32.5)

b) steering angle β=10° p =56.7 (0,8,32.0)

Fig.8: **Transient sound field in steel plane array** (16 elements, centre frequency: f_M= 3 MHz, excitation function: 3 periods, water delay 40 mm)

- No grating lobes
- Intensity loss of –3dB (71%) caused by the strong grating lobe in water for a steering of 10°

	p_1 β=2.5°	p_2 β=10°	p_2^2 / p_1^2
Harmonic (3 MHz)	10 061	8 459	0.707
Transient: 1 period	59 341	51 732	0.760
Transient: 2 periods	68 654	59 375	0.748
Transient: 3 periods	66 500	56 717	0.727
Transient: 5 periods	77 238	66 253	0.736

Comparing time harmonic and transient sound fields with respect to energy loss
plane array (16 elements, f=3MHz)

- Increasing steering angle β causes an increase of energy loss
- Harmonic: maximum for β=10° has a loss of intensity of –3dB (71%) in comparison to the maximum for β=2.5°
- Transient excitation: energy loss between 73% and 76%
- **Comparing time harmonic sound fields yields to a good approximation!**

Summary:

- The harmonic sound field at center frequency is a good approximation of the transient sound field, even for short signals.
  - the shape and extension of the field
  - the locations of maxima or focus
  - the incidence angle of the steered beam
  - the appearance of grating lobes
  - it predicts an energy loss caused by the appearing side lobe in water

↓

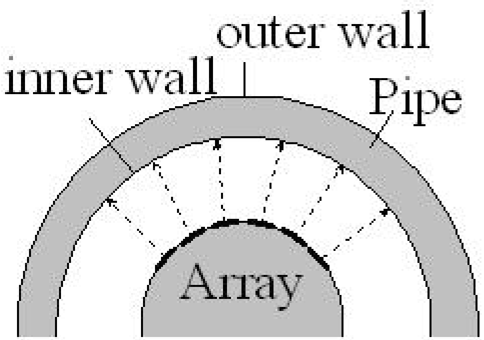
The time harmonic sound field is an efficient tool to optimize the aperture and the controlling mode for broadband arrays

- Since for immersion technique controlling takes place in the water delay, **the maximum possible steering angle in water and the grating lobes in water limit the steering angle and the strength of focusing.** Therefore the keeping of the $\lambda/2$-condition with respect to steel is not the best available approach. After a water delay, smaller elements also yield to a better controlling result in steel.

- $\lambda/2$ - conclusion should be kept! (larger steering angles, grating lobes)

Focusing with a convex curved array

a) pipe inspection

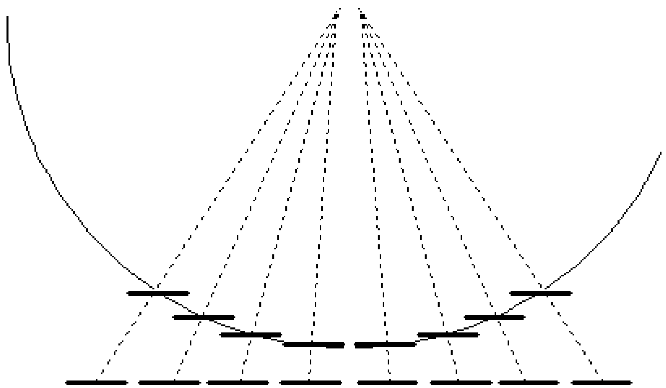


8 elements, f_M=10 MHz,

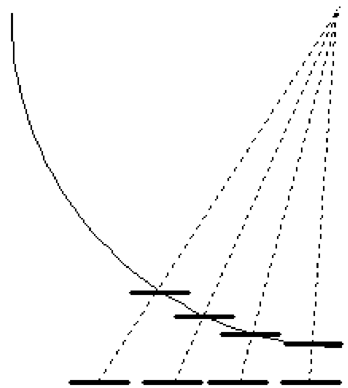
grating distance of 0.33 mm

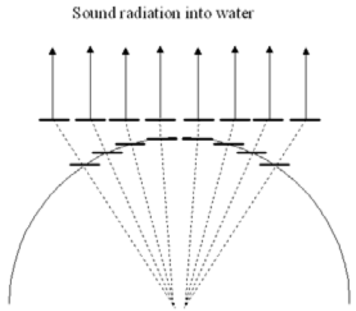
(λ/2 regarding to pipe wall, 2λ regarding to water).

b) Focusing with a plane array

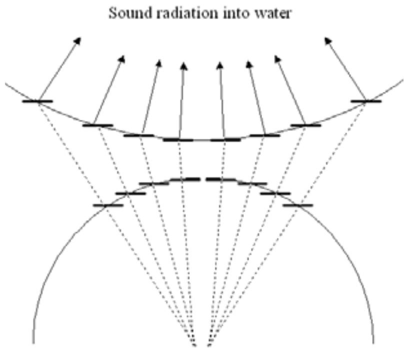


c) Focusing with a semi- array





a) geometric: Compensation of array curvature (centre of elements) - **Controlling C**



b) geometric: Compensation of array curvature and focusing at 15mm - **Controlling F15**

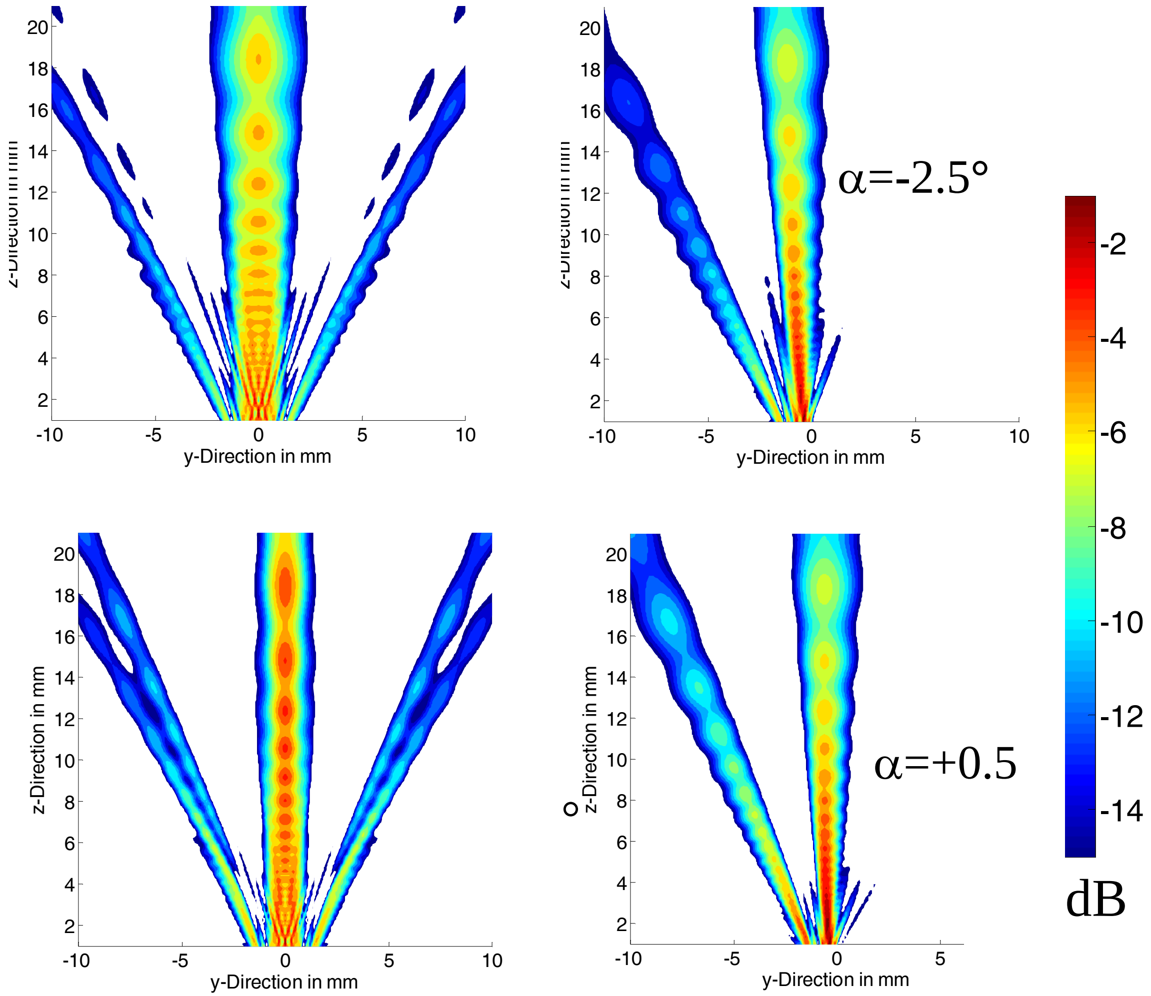
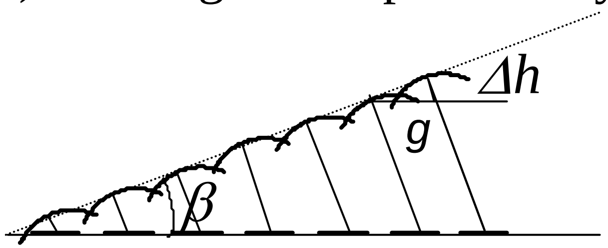


Fig.9: Time harmonic sound fields of a **curved array in water**
(8 elements, *f*= 10 MHz, element distance 2 λ with respect to water)

- **Limitation of steering angle → aimed focus is not reached**!

Geometrical calculation of delay times

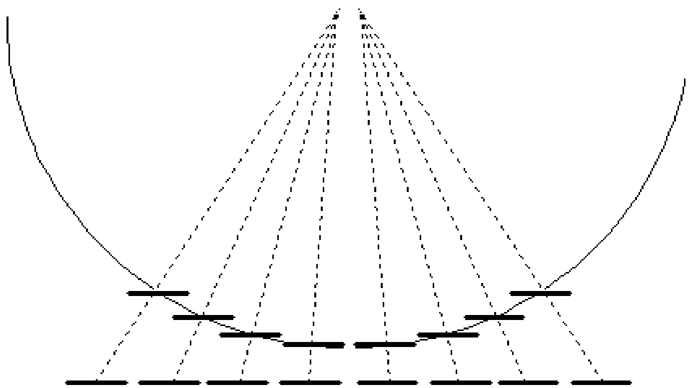
a) Steering with a plane array



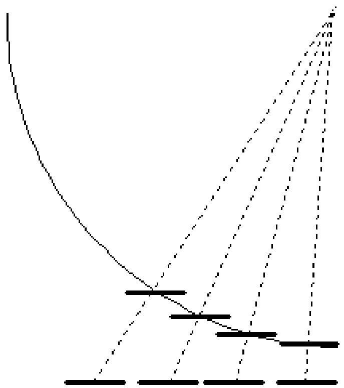
$$\sin\beta = \frac{\Delta h}{g}$$

$$\Delta t = \frac{\Delta h}{c} = \frac{g \cdot \sin\beta}{\lambda} \cdot T$$

b) Focusing with a plane array



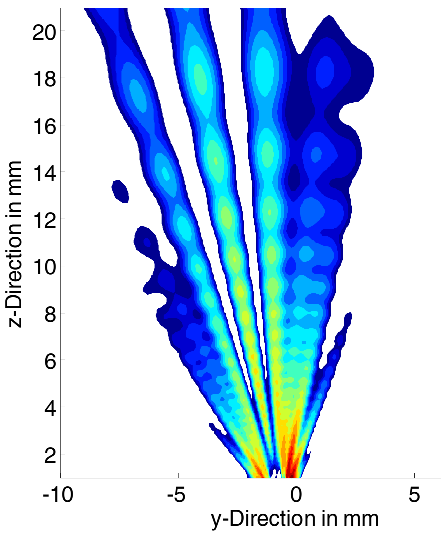
c) Focusing with a semi- array



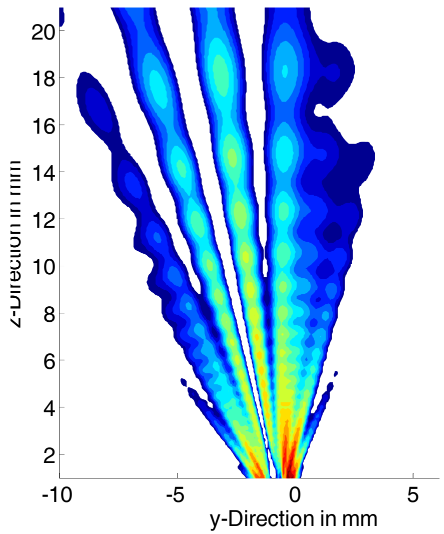
Keeping the λ/2 – condition

- to avoid grating lobes
- to meet the aimed steering angle/focus

3.2 Curved array for testing of a pipe wall with immersions technique
Focussing with a curved Array - Time harmonic fields in water (4)



$\Delta t = 0$



$\Delta t=1.35T$ α_m=-8.0°, $\alpha_{g,\ right}$=0.5°, $\alpha_{g\ left}$=-8.5°

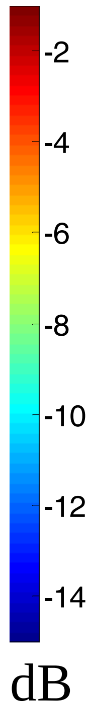
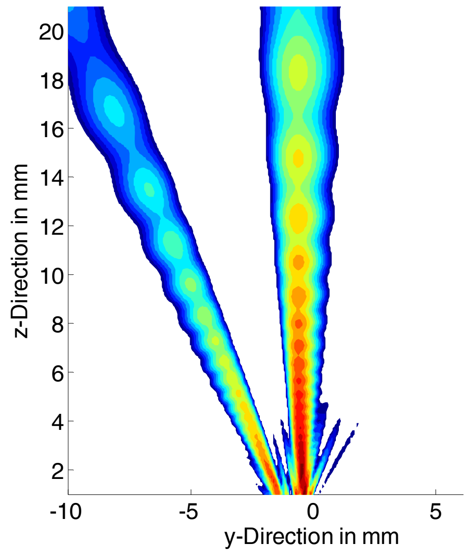


Fig.10: **Steering of the outer single elements** of the curved 8-element array, g=2λ (steering between 1. and 4. element)

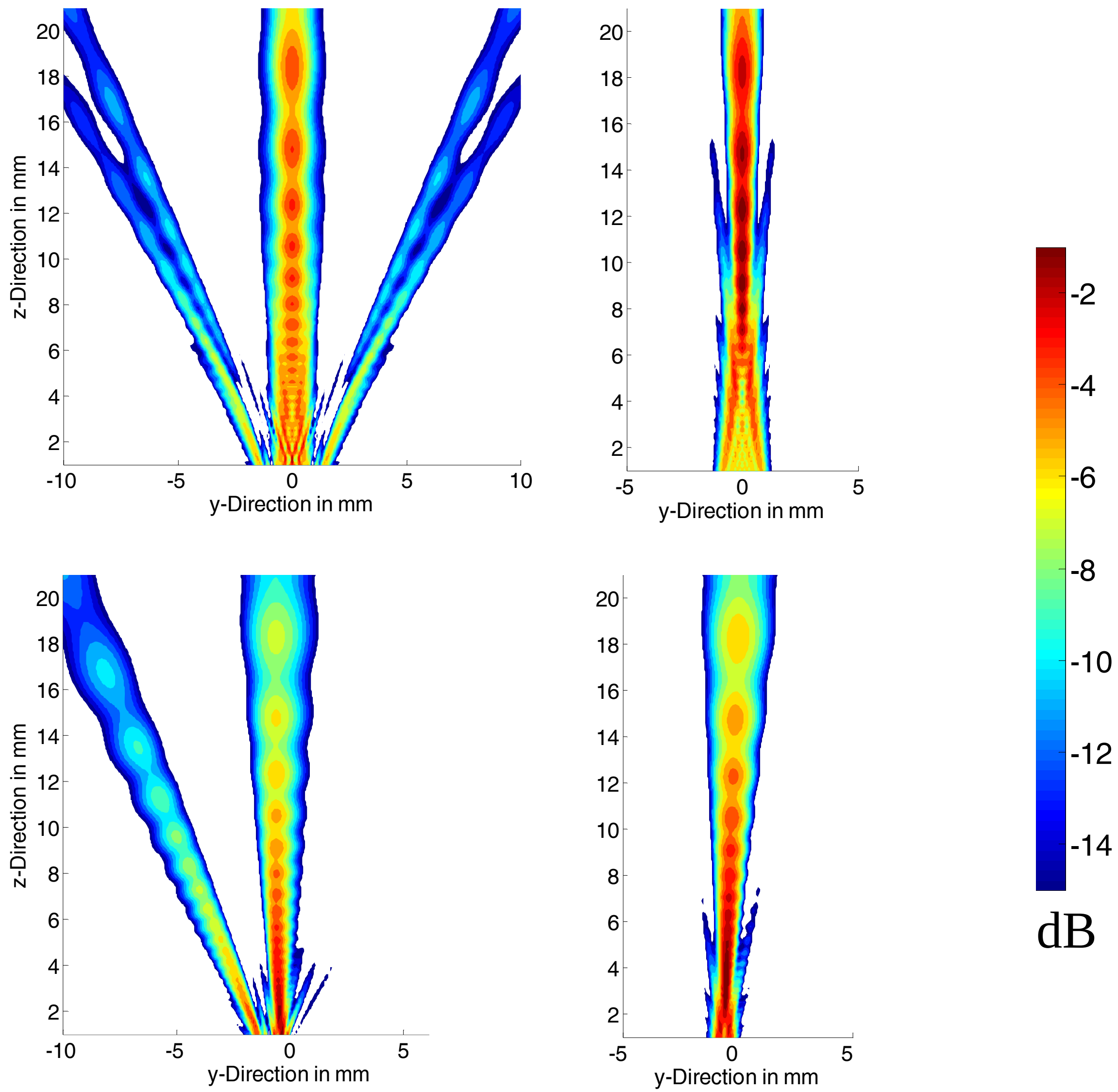
Δt= delay time times between 1. and 4. element

- Non-steered array: main structure is directed outwards
- Curved Array for F15: right grating lobe is directed normally to the surface of the pip wall
  - Semi-array beam is not directed inwards
  - Grating lobe could improve the main structure of semi-array beam
  - Main structure of 4.element could reduce side lobes?



Field in water for the **whole array**

Field in water for the **semi array** (first 4 elements)



a) **8-element-array** with g=0.33 mm

b)**32-element-array** with g=0.0825 mm

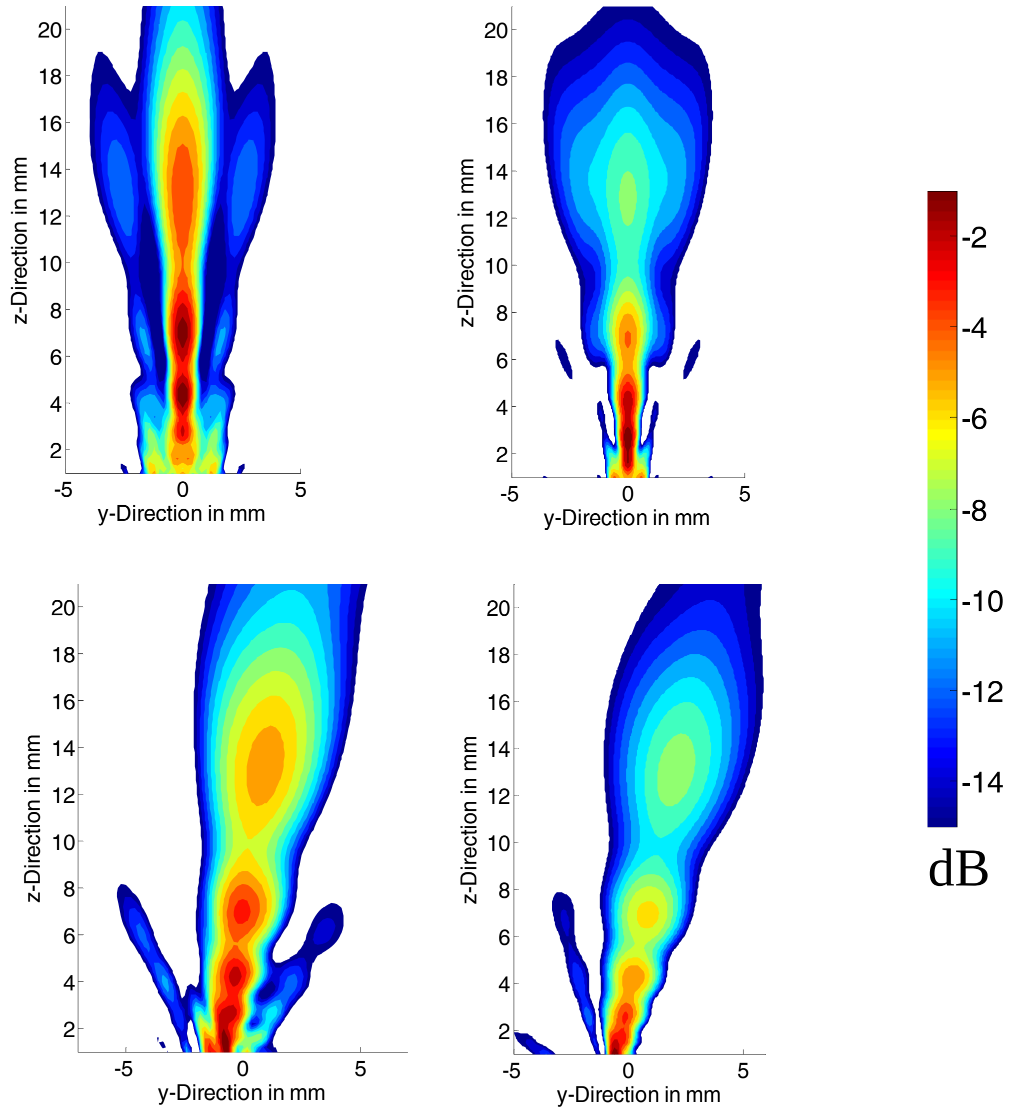
Fig.11: **Sound fields in water for Controlling F15**

Compensation of array curvature + focussing to 15mm

- For smaller elements a better focussing is possible

Field in the pipe wall for the
whole array

Field in the pipe wall for the
semi array (first 4 elements)



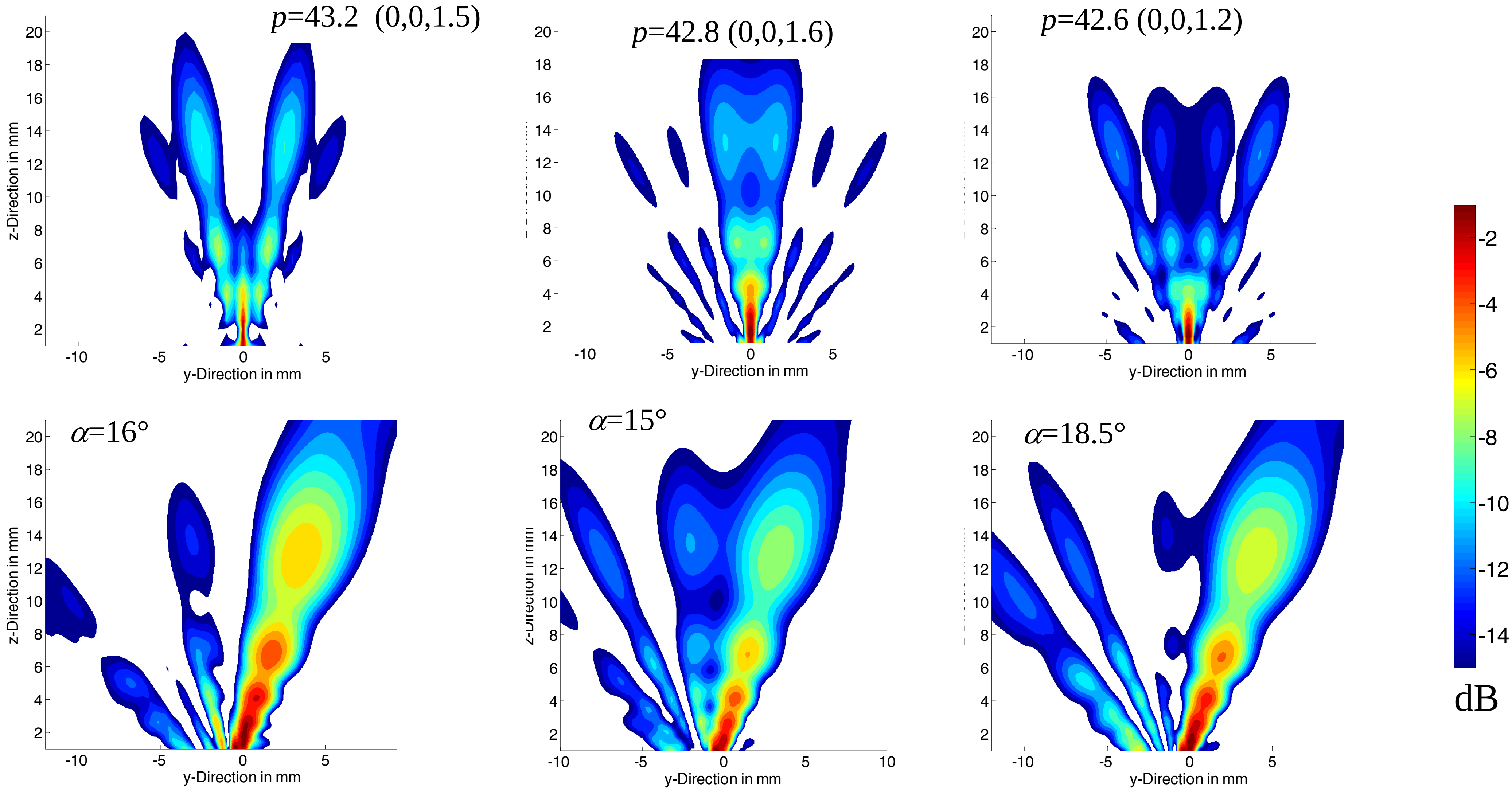
p=40.1 (0,0,4.4) α=9° *p*=45.3 (0,0,2.6) α=12°

10-element array **8-element array**

Fig.12 Sound field in the pipe wall at Controlling C for different number of elements

- application of 8 elements

Focussing with a curved Array in steel - Optimisation of the controlling mode



a) Compensation of the array curvature with respect to element edge - **Controlling CE**

b) Compensation of array curvature + focussing to 15mm **Controlling F15**

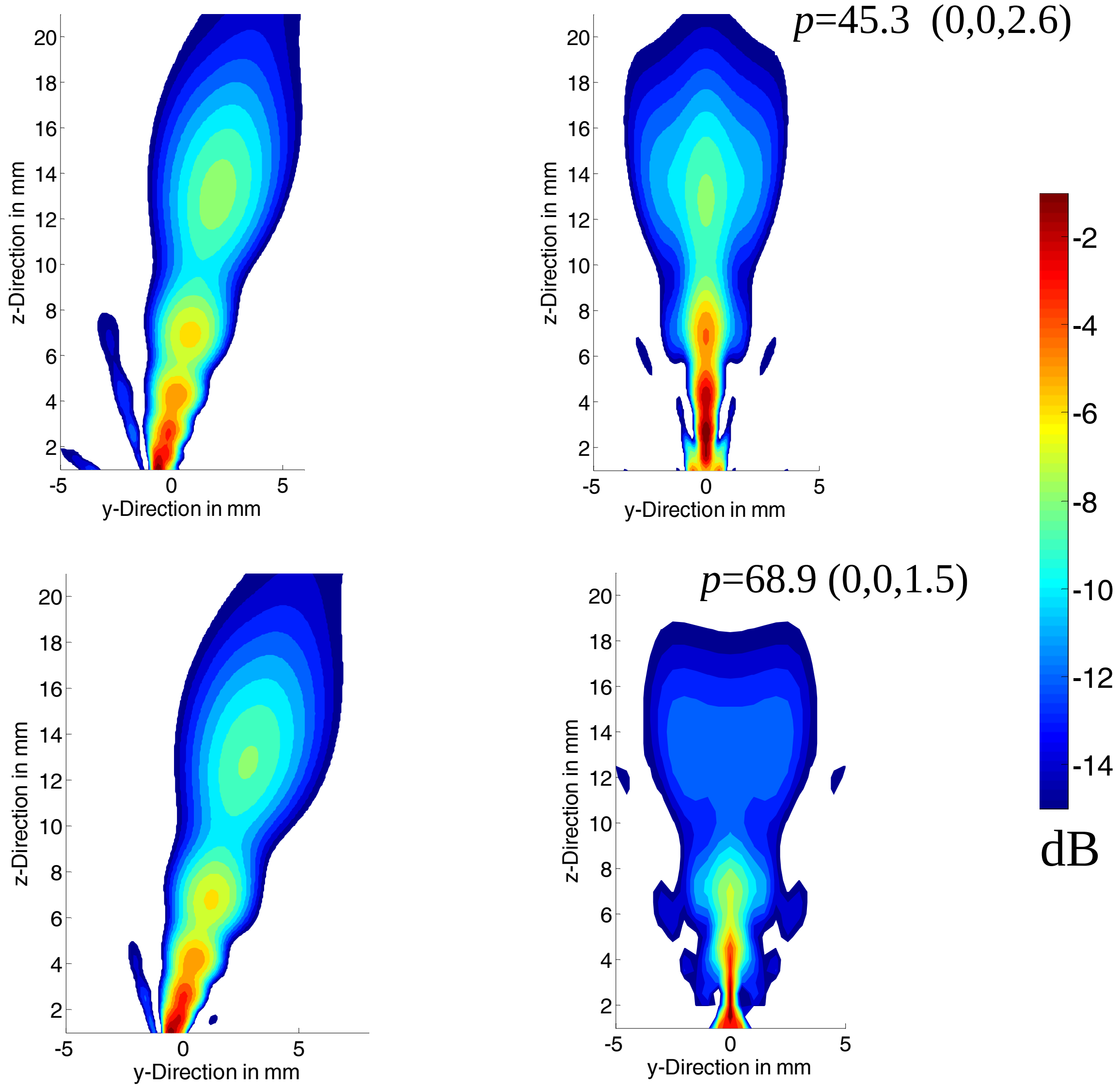
c) **Controlling F15*** with enlarged delay for peripheral elements

Fig.13: **Time harmonic sound fields of a curved array (8 elements) in the pipe wall**

3.2 Curved array for testing of a pipe wall with immersions technique
Focussing with a curved Array in steel- Improvement by applying smaller elements (9)

8-element array
($g=2\lambda$ regarding to water)

32-element array
($g=\lambda/2$ regarding to water)



aim focus at *z*=1mm to 1.5 mm

- for 32-element array: this is already reached for Controlling C
- improvement of intensity

Fig.15: **Comparison of the 8-element and of the 32-element array in the pipe wall**
for Controlling C (Compensation of the array curvature)

Focussing with a curved Array in steel- Improvement by applying smaller elements (10)

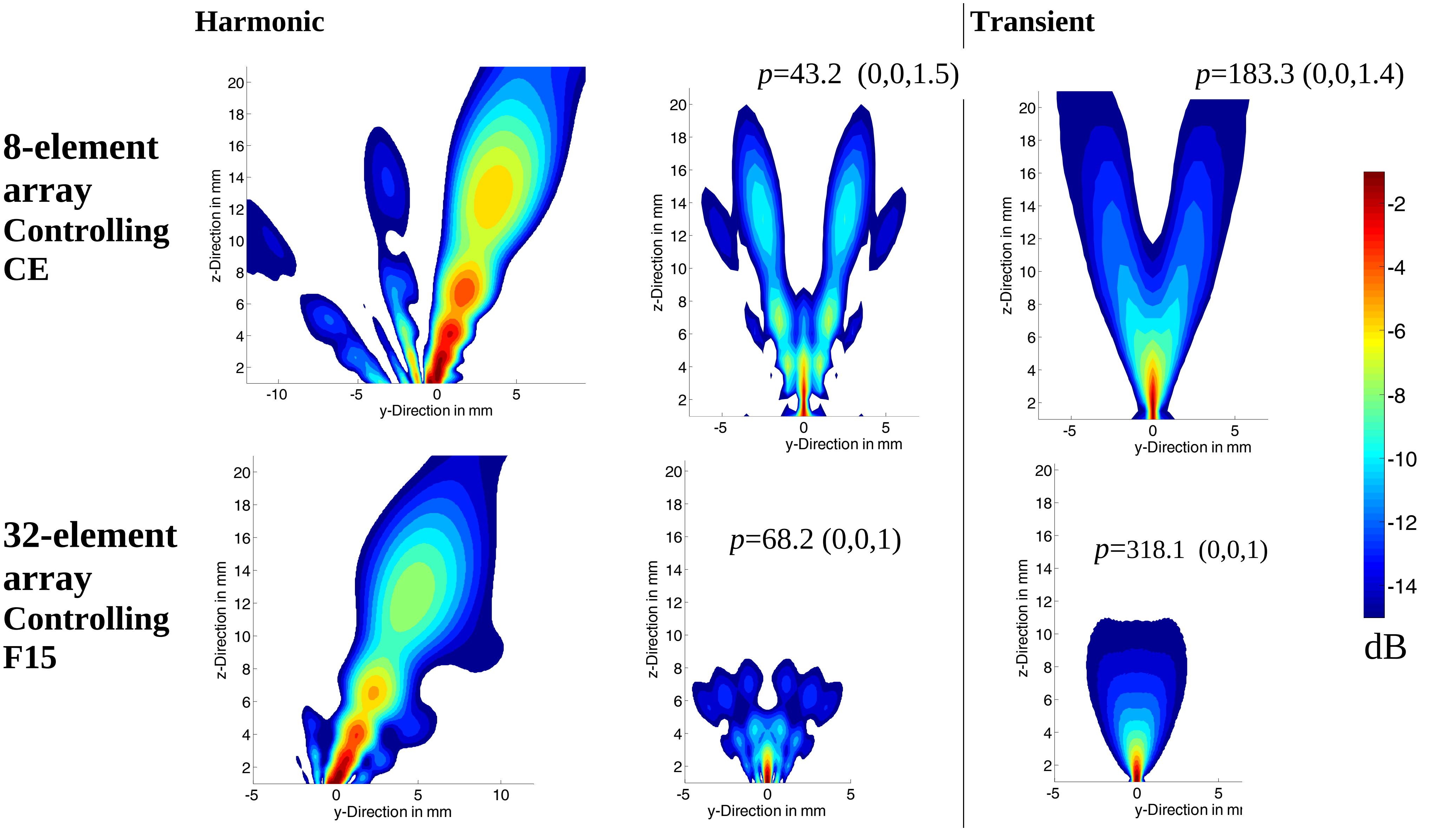
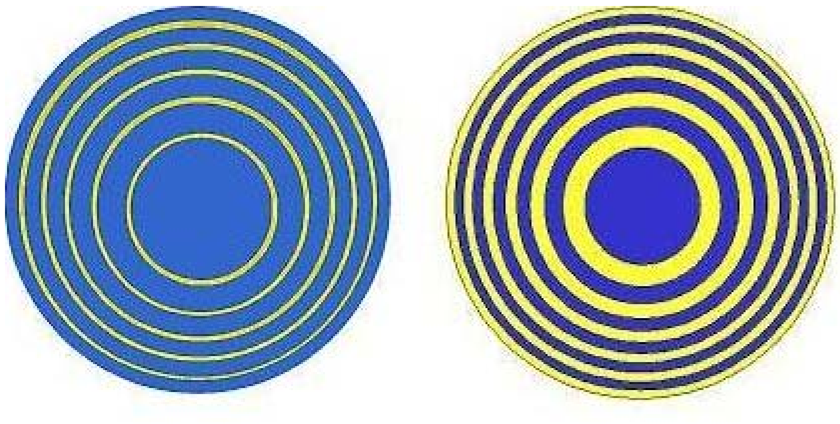


Fig.16:Comparison of the 8-element and of the 32-element array (*f*= 10 MHz) in pipe wall
left: semi array, harmonic middle: whole array, harmonic right: transient, 2 periods



Annular Arrays for High-Frequency Imaging:

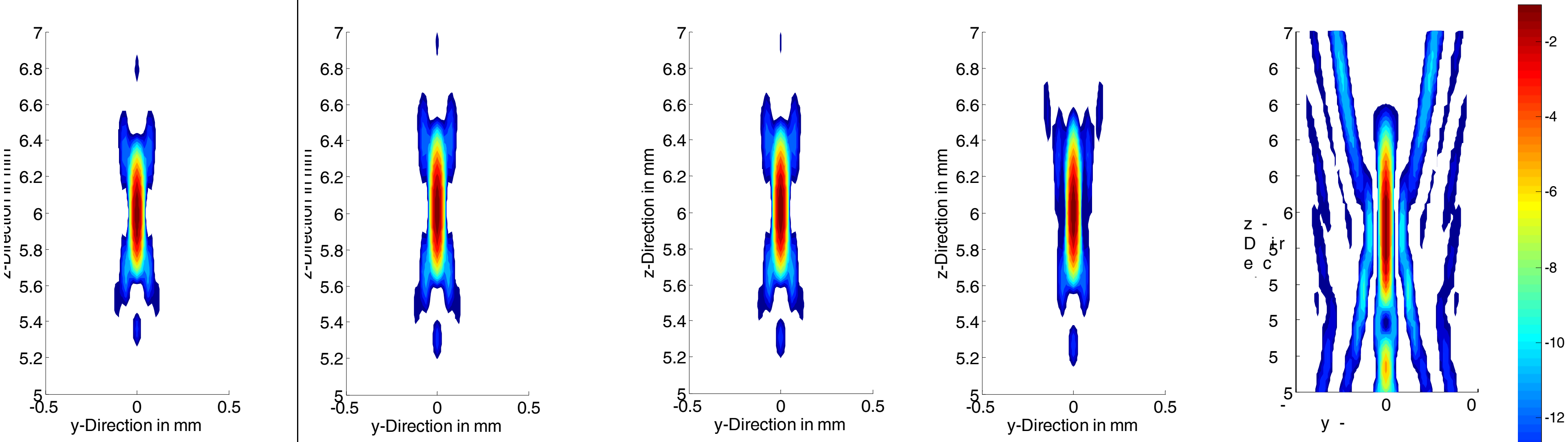
10-20 elements

aperture: *d*=5mm, frequency *f*=35 MHz

central element: ***d*=1.1mm**
comparison: **λ=0.043 mm**

- **Elements are much larger than λ/2**
- Delay time between neighbouring elements < T/2
- By a sparse array (dead space between the elements) with the same aperture as the full array, the number of elements decreases!

a) Focusing at 6mm in water – necessary element number



a) sphere *r*=6mm
a=0.08mm
p=32 408 (0,0,5.98)

b) *pl E*=80 S=0:
a=0.08mm
p=28 947 (0,0,6.02)

c) *pl E*=60 S=0:
a=0.08mm
p=28 (0,0,6.02)

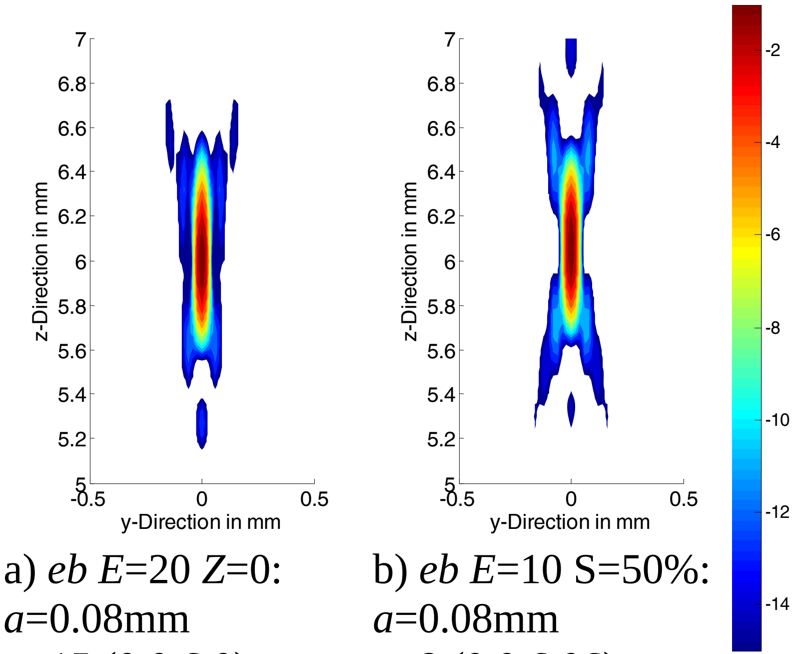
d) *pl E*=20 S=0:
a=0.08mm
p=15 (0,0,6.0)

e) *pl E*=10 *S*=0:
a=0.08mm
p=3 252 (0,0,5.9)

Fig.17: Sound fields in water for plane (pl) annular arrays of the same aperture (*d*=5mm) with a different number of elements E at a frequency *f*=35 MHz (*a* – lateral extension of the 6dB-zone, *S* – sparse between the elements)

- **20 elements yield to the same focussing as the sphere!**
- Focusing with 10 elements to 6mm – only with strong secondary structures!

b) Focusing at 6mm in water– Application of arrays with gap (sparse)



a) *eb E*=20 *Z*=0:
a=0.08mm
p=15 (0,0,6.0)

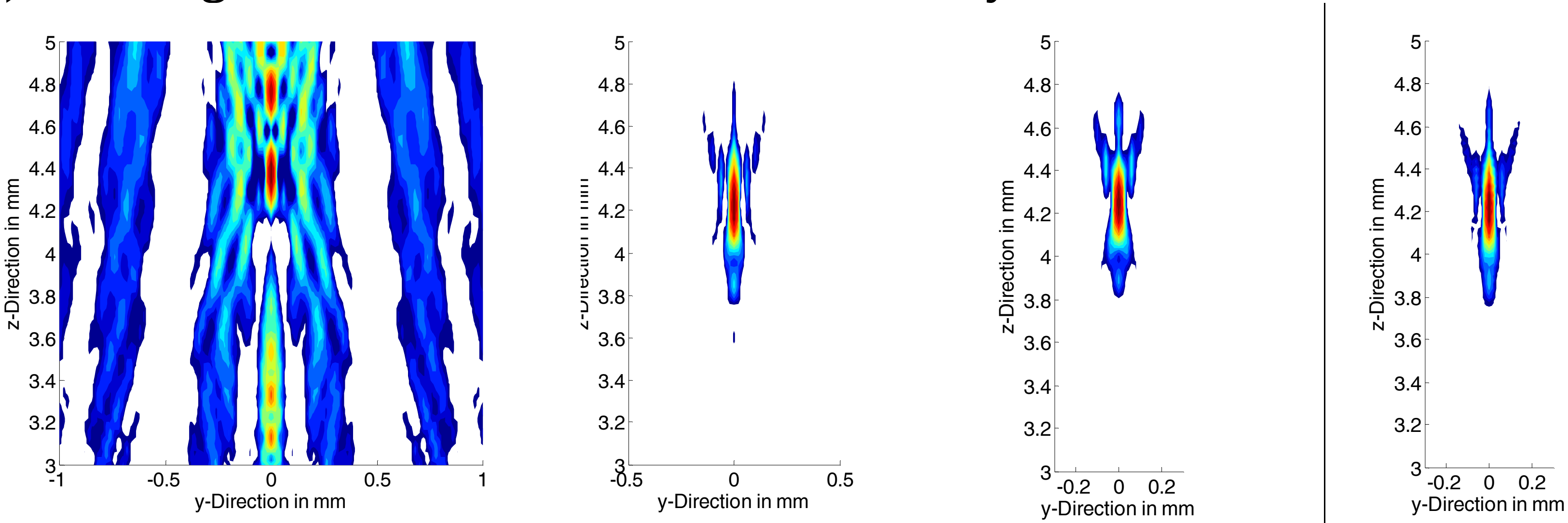
b) *eb E*=10 S=50%:
a=0.08mm
p=8 (0,0,6.06)

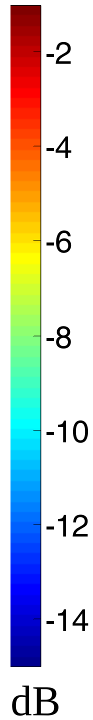
dB

Fig.18: Sound fields of plane (pl) annular arrays of the same aperture (*d*=5mm) with a different number of elements E in water at a frequency *f*=35 MHz
a) Full array of 20 elements without space b) sparse array with 10 elements
(*a* – lateral extension of the 6dB-zone, *S* – dead space between the elements)

- **Sparse array with 10 elements (50% active aperture) yields to the same focusing as a full array with 20 elements**

c) Focusing at 4mm in water with curved arrays





a) *cv E*=10 *S*=0:
p=3 600 (0,0,4.38)

b) *cv E*=20 *S*=0:
a=0.05mm
p=24 560 (0,0,4.22)

c) *cv E*=10 *S*=50%:
a=0.06mm
p=13 477 (0,0,4.24)

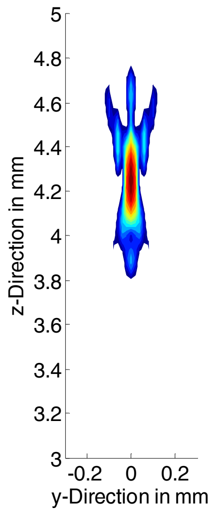
d) transient 2 periods
cv E=20 *S*=0:
a=0.05mm

Fig.19: Sound field of curved (cv) annular arrays (*f*=35 MHz, aperture *d*=5mm, curvature *r*=10mm) with a different number of elements E in water, focussing at *Foc*=4mm (*a* – lateral extension of the 6dB-zone, *S* – dead space between the elements)

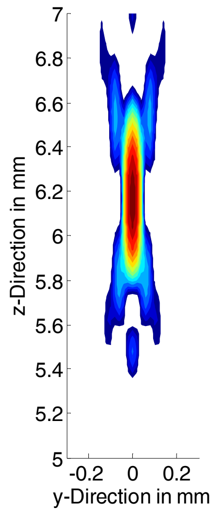
In water:

- **Decreasing of focus depth by pre-focusing!**
- **Sparse array works as a full array but needs only half the number of elements!**

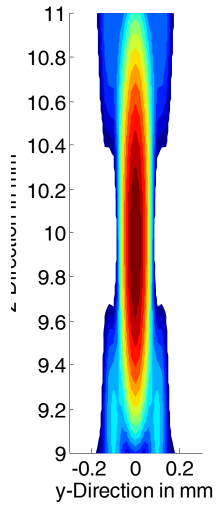
d) Focusing range in water with concavely curved sparse array



Foc=4mm
p=13 477 (0,0,4.24)
0.06 x 0.36



Foc=6mm
p=14 468 (0,0,6.16)
0.08 x 0.66



Foc=10 mm
p=10 051 (0,0,9.94)
0.12 x 1.65

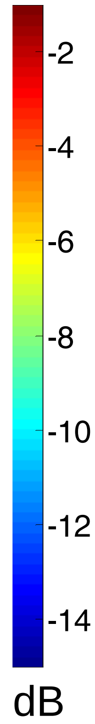
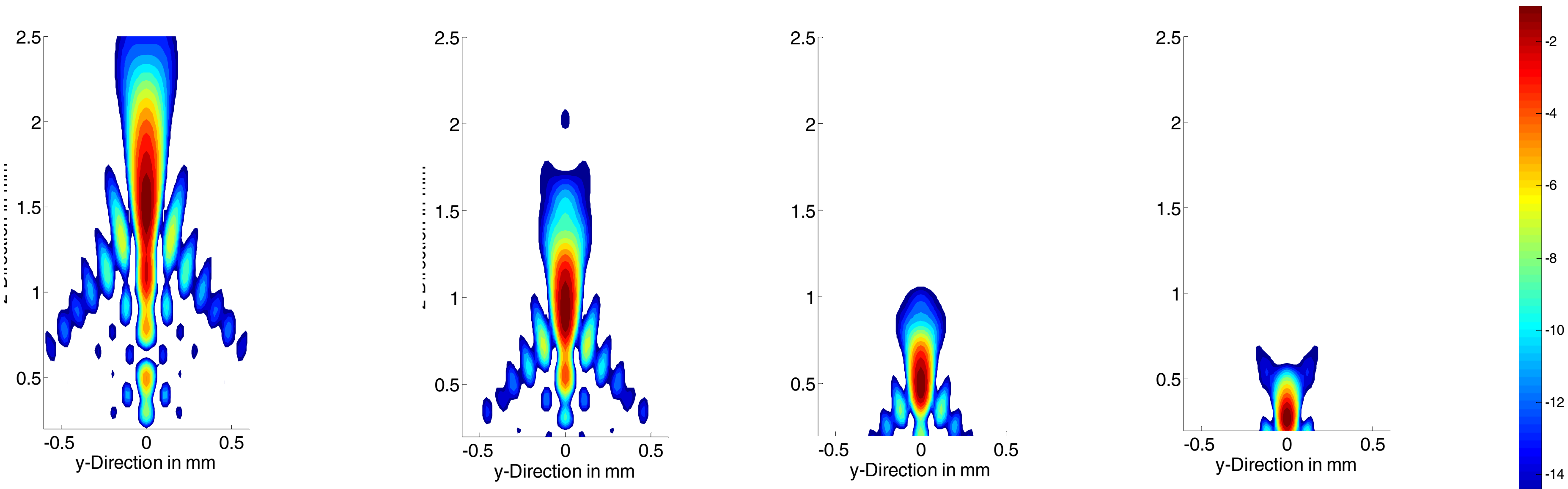


Fig. 4_20: Focusing range of a pre-focused sparse array
(10 elements 50% space, curvature *r*=10mm, *d*=5mm, *f*=35 MHz)

e) Array for solid application after a water delay

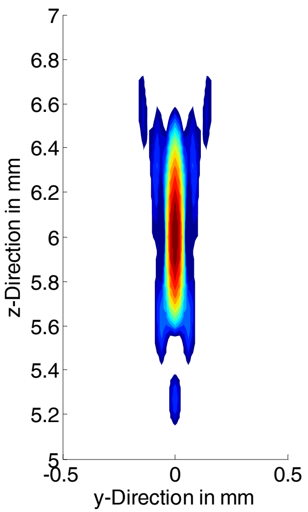


Foc=10	*Foc*=7mm	*Foc*=5mm	*Foc*=4mm
p=192 643 (0,0,1.5)	*p*=196 015 (0,0,0.90)	*p*=183 897 (0,0,0.48)	*p*=152 130 (0,0,0.26)
a=0.16 mm	*a*=0,15mm	*a*=0,13 mm	*a*=0,11mm

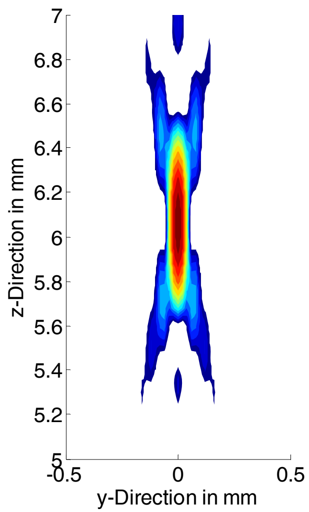
Fig.21: Sound field of a curved annular array (20 elements, *f*=35 MHz, aperture *d*=5mm, pre-focused) in steel after a water delay of 2mm (*a* – lateral extension of the 6dB-zone)

- **Using a 20-element full array, the sound field has the doubled extension of that in water**
- For testing a solid in immersion technique, a 50% reduction of the number of elements does not always work.

Water / plane

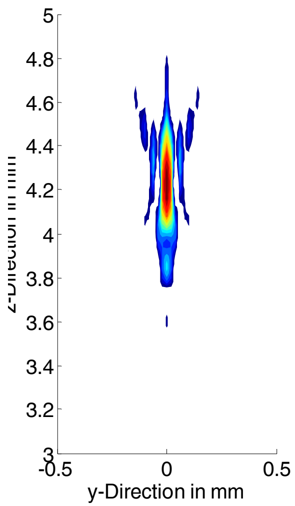


a) *pl E*=20 S=0:
a=0.08mm
p=15 (0,0,6.0)

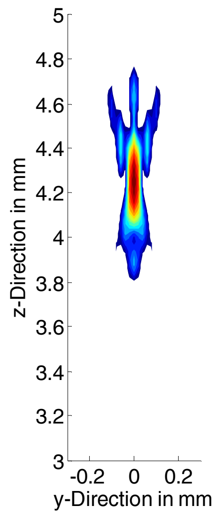


b) *pl E*=10 S=50%:
a=0.08mm
p=8 (0,0,6.06)

Water / curved

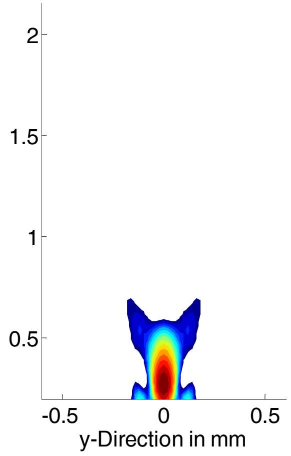


c) *cv E*=20 *S*=0:
a=0.05mm
p=24 (0,0,4.22)

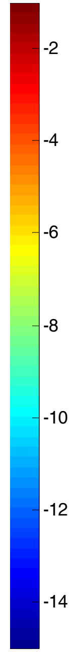


d) *cv E*=10 *S*=50%:
a=0.06mm
p=13 (0,0,4.24)

Steel / curved



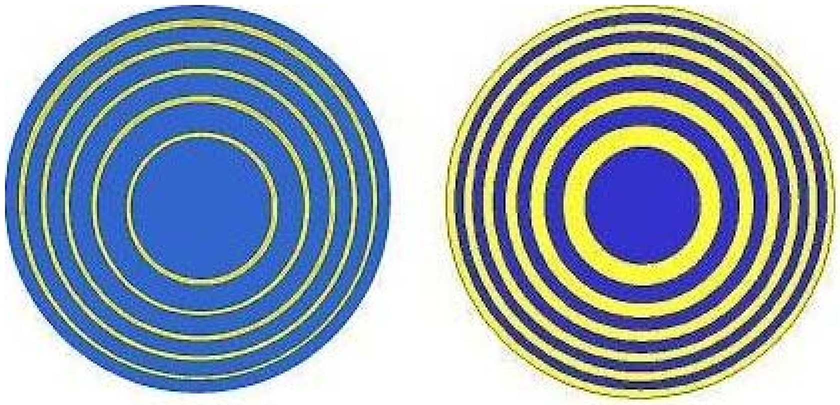
cv E=20 *S*=0
a=0,11mm
focusing at 4mm



dB

Fig.22: Sound fields of plane (*pl*) and curved (*cv*) annular arrays with the same aperture (*d*=5mm) with different element number *E* at *f*=35 MHz
(*a* – lateral extension of the 6dB-zone, *S* – space between the elements)

- **Water:** 10-element sparse array works as a full array and reaches the same focus point
- **Water and steel:** pre-focusing enables a stronger focusing and a better resolution



Annular Arrays for High-Frequency Imaging:

10-20 elements

aperture: *d*=5mm, frequency *f*=35 MHz

central element: ***d*=1.1mm**
comparison: **λ=0.043 mm**

- In water: 10-element sparse array = same focusing as a twenty element full array
  → number of elements can be reduced
- curved array = shorter focal distance + higher lateral resolution → pre-focusing
- In steel: -6dB zone with a width of 110µm for a 20-element array
  → curved annular arrays with only few elements for testing solid state bodies with immersion technique.
- Unlike linear arrays, annular array have strong benefits - **Small number of elements connected with the possibility of strong focusing.**
- A good example of use is the application in a scanning ultrasound microscope.

References:

- E. Kühnicke: Plane arrays - Fundamental investigations for correct steering by means of sound field calculations, *WAVE MOTION* **44** (2007) 248–261.
- E. Kühnicke: Curved arrays for pipe wall inspection – Fundamentals of electronic focusing for curved and plane arrays, *WAVE MOTION* **46** (2009) 221–236.
- E. Kühnicke: Design of Curved Annular Arrays for High - Frequency Imaging, In: D. O. Thompson and D. E. Chimenti (eds.): Review of Progress in Quantitative Nondestructive Evaluation, Vol.28, Melville, New York, 2009, AIP Conference Proceedings, Volume 1096, pp. 816-823.