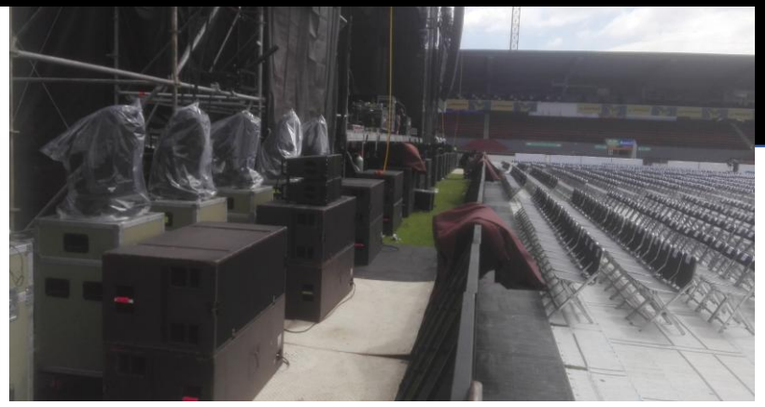
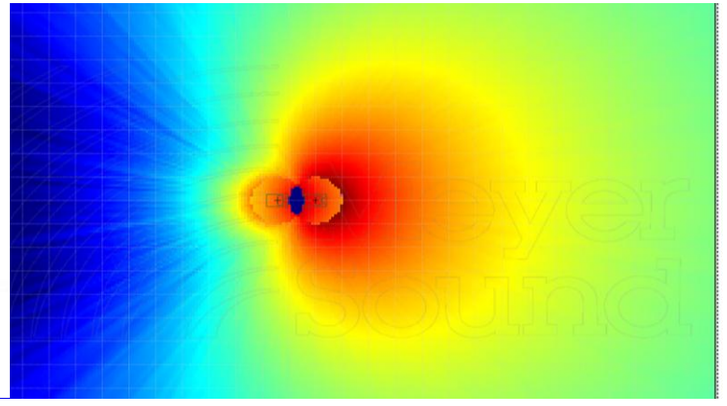










Never without my subs…

Coupling and directivity control.

AI-assisted translation from the original French course. We apologise for any inaccuracies. The French version remains the reference. Please report corrections at www.silemio.com/contact. Original sources and credits are retained.

Introduction



This course covers the coupling and directivity control of low-frequency loudspeakers (subwoofers).

The mechanical and electrical aspects of subwoofers could be a course in their own right and are largely outside the scope of this course.



Contents

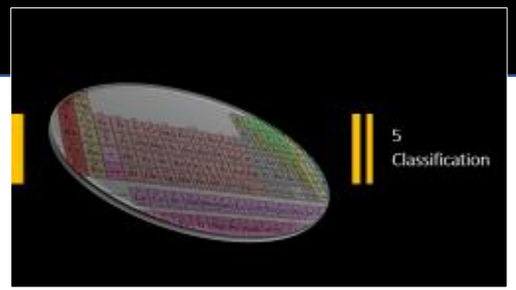








1. Fundamentals
2. Steering effect
3. Forward and vertical steering
4. Special configurations
5. Classification
6. Simulations
7. Examples
8. Appendices





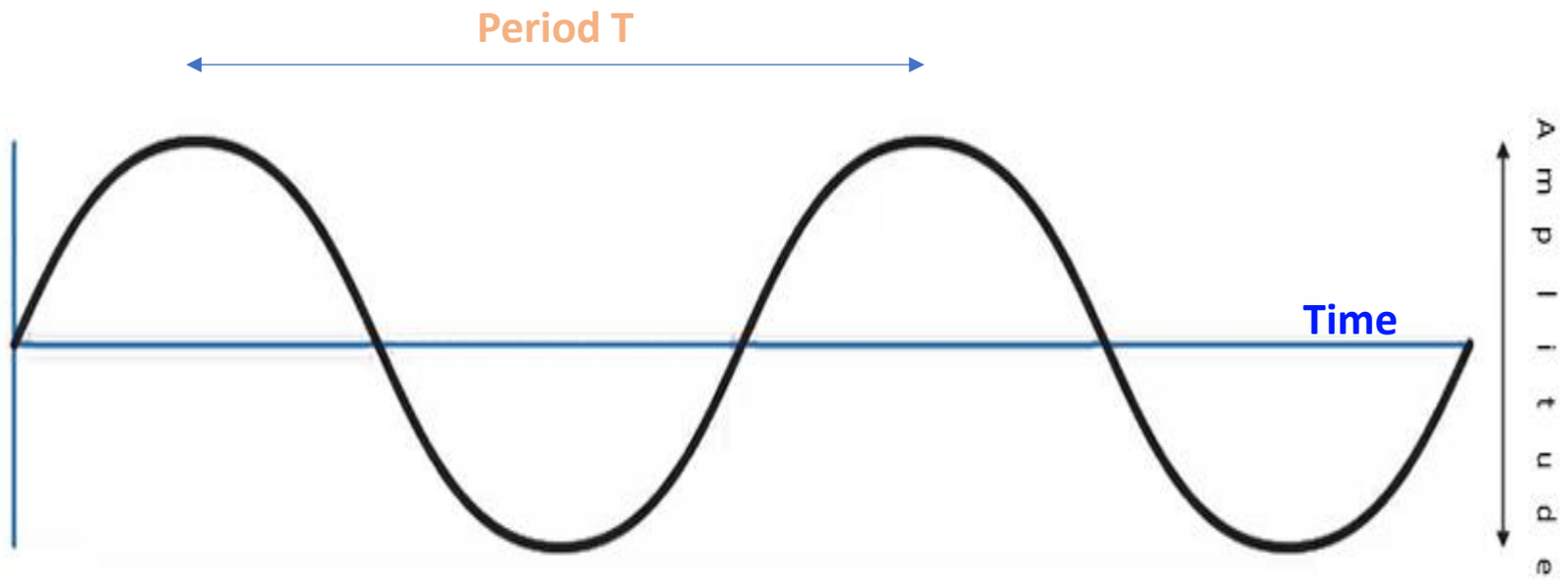






1 Fundamentals

Frequency (f), wavelength (λ) and period (T)

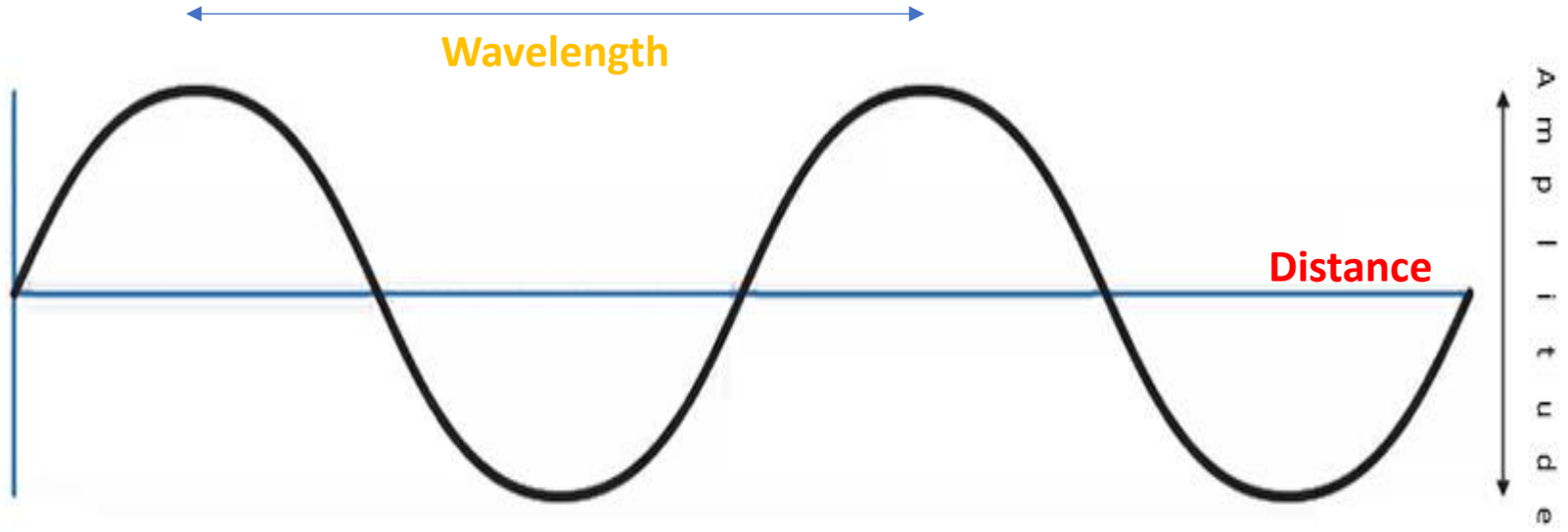


Period T =
The time interval between two successive identical states of an oscillation.

Frequency f =
The number of cycles per unit of time.
For hertz, the unit of time is the second.

$$F = 1/T$$

Frequency (f), wavelength (λ) and period (T)



To simplify the following examples, we assume a speed of sound in air of 340 m·s−1.

Reconsider this value whenever the conditions require it.

Period T =

The time interval between two successive identical states of an oscillation.

Frequency f =

The number of cycles per unit of time.

For hertz, the unit of time is the second.

$$F = 1/T$$

Wavelength λ =

The distance travelled during one period T.

$$\lambda = c/f$$

where c is the wave propagation speed.

Waves on a large scale

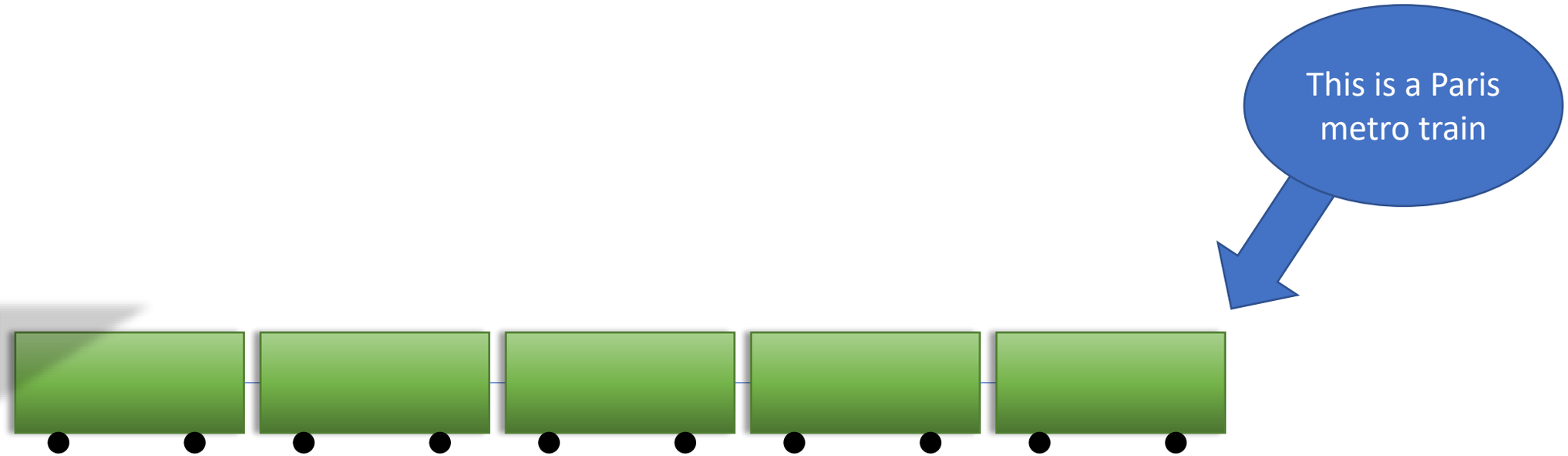


f	λ
20 Hz	17 m
25 Hz	13,6 m
31,5 Hz	10,79 m
45 Hz	7,56 m
50 Hz	6,8 m
60 Hz	5,67 m
80 Hz	4,25 m
100 Hz	3,40 m
125 Hz	2,72 m



Waves on a large scale

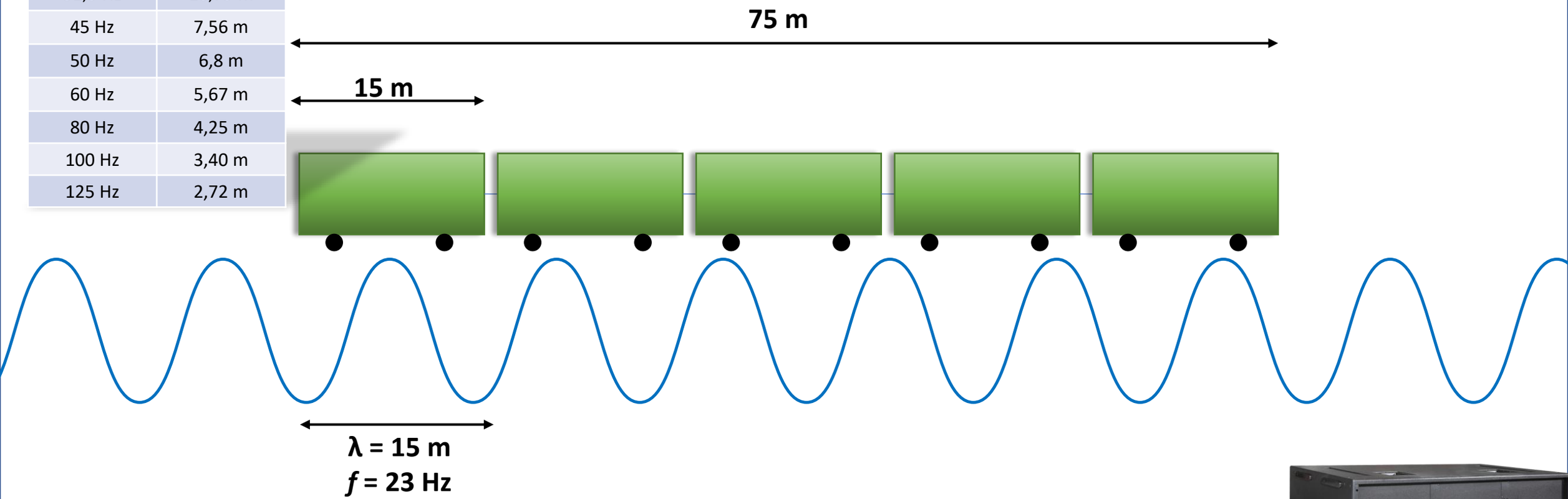
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Waves on a large scale

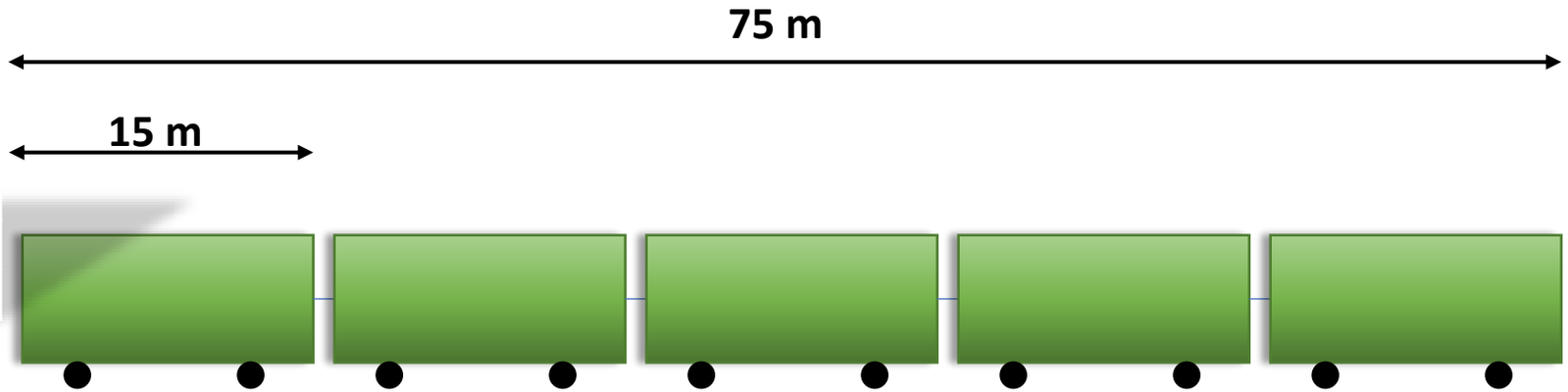
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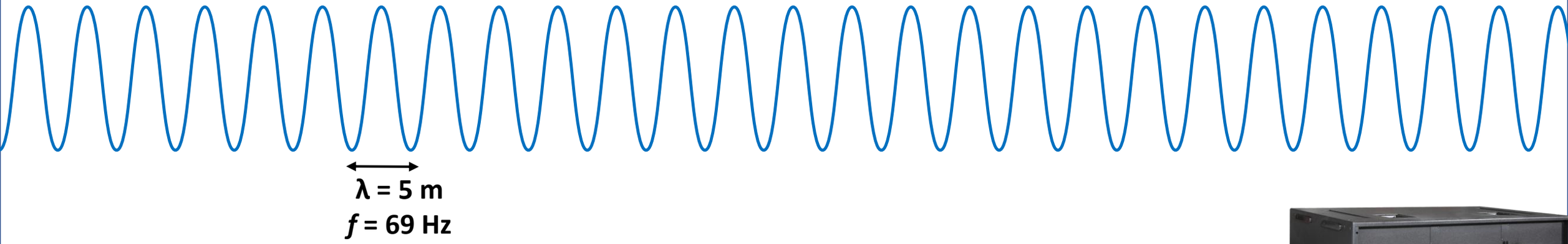




Waves on a large scale

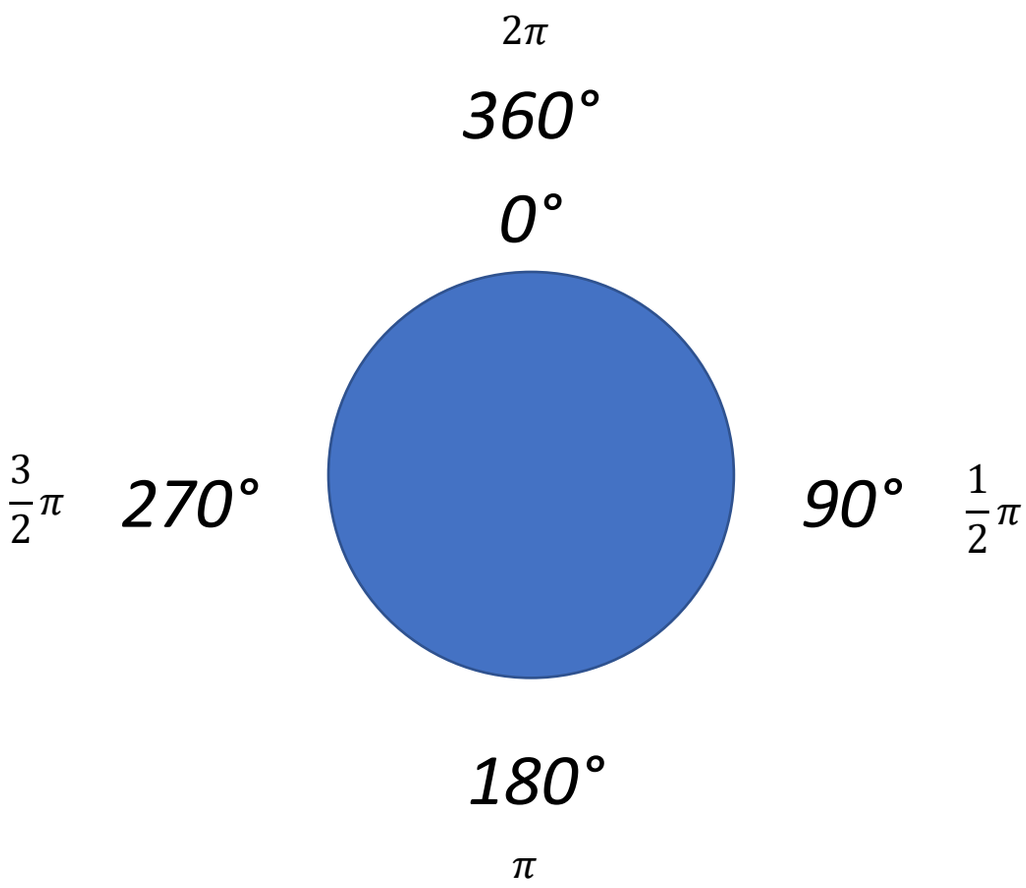
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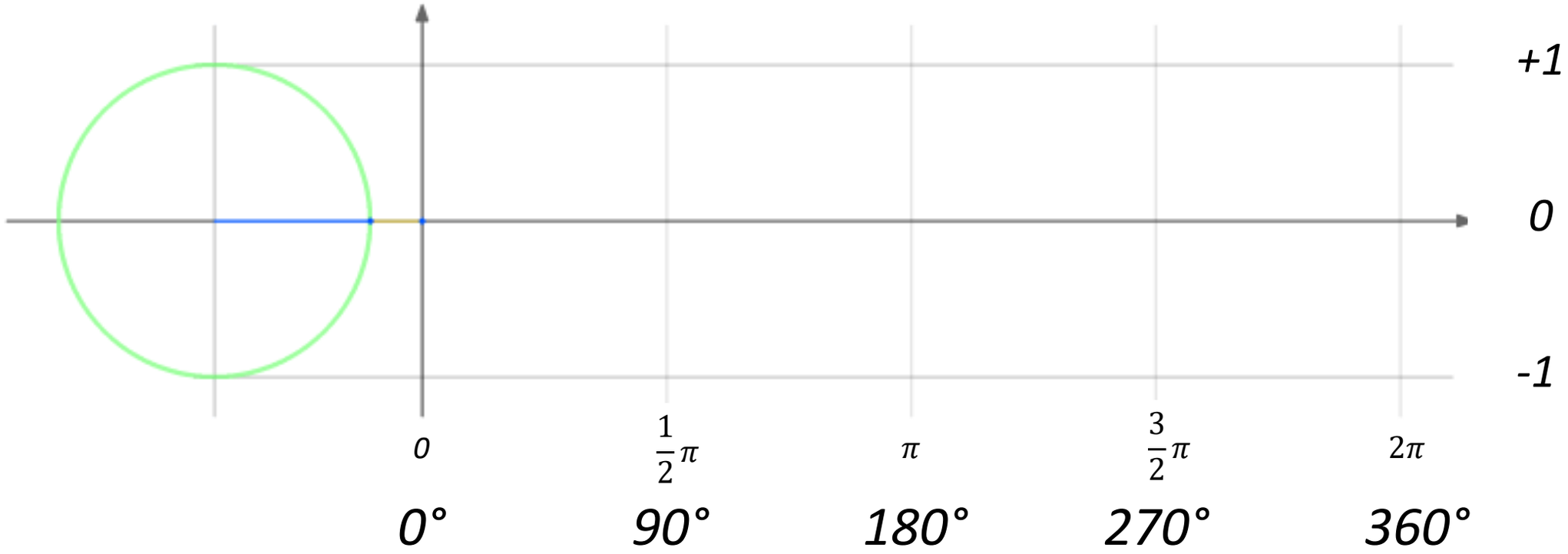




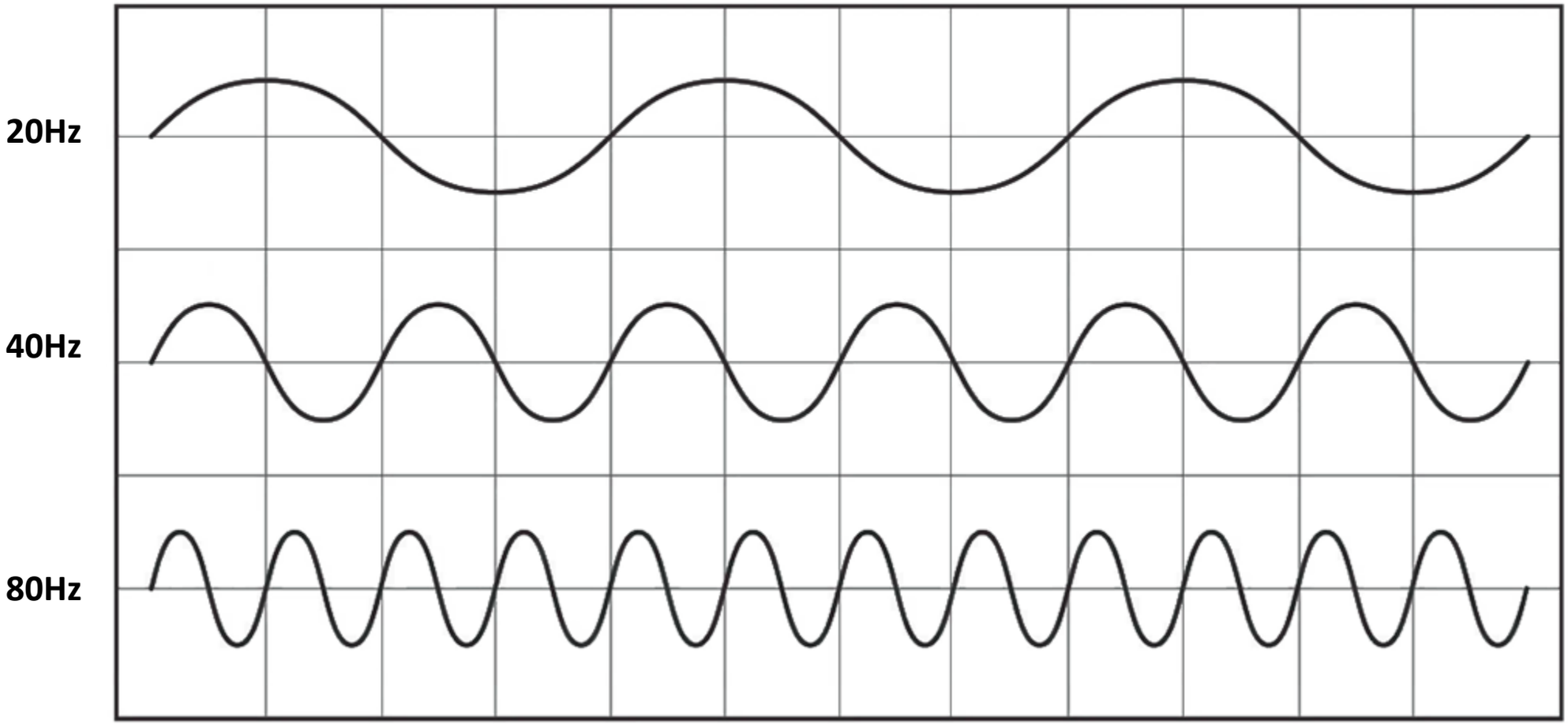
Phase (φ) and frequency (f)



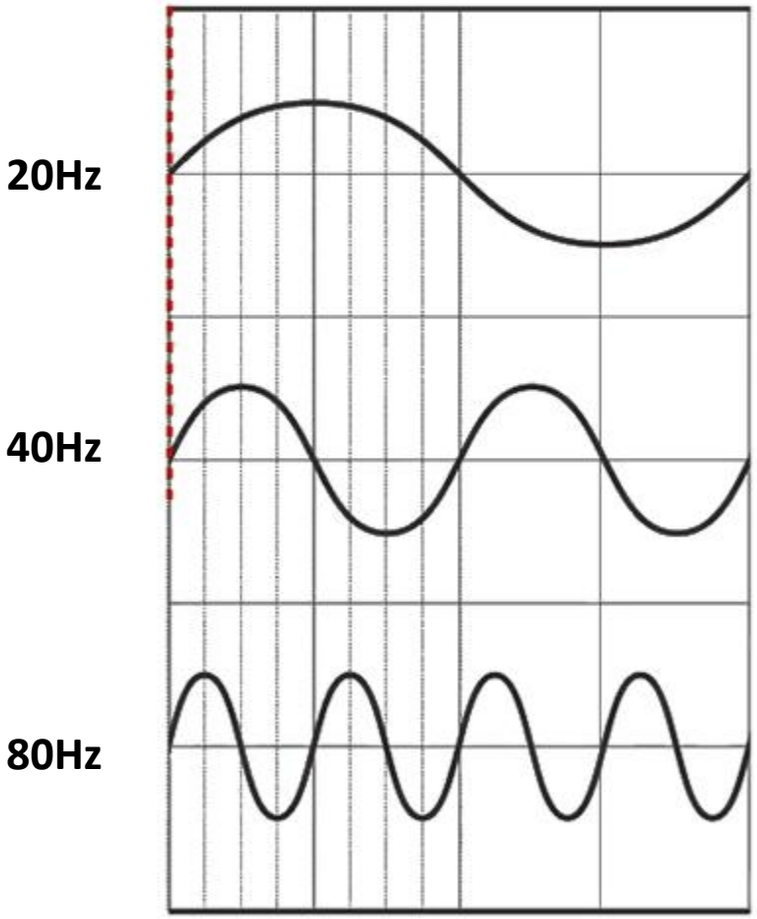
Phase (φ) and frequency (f)



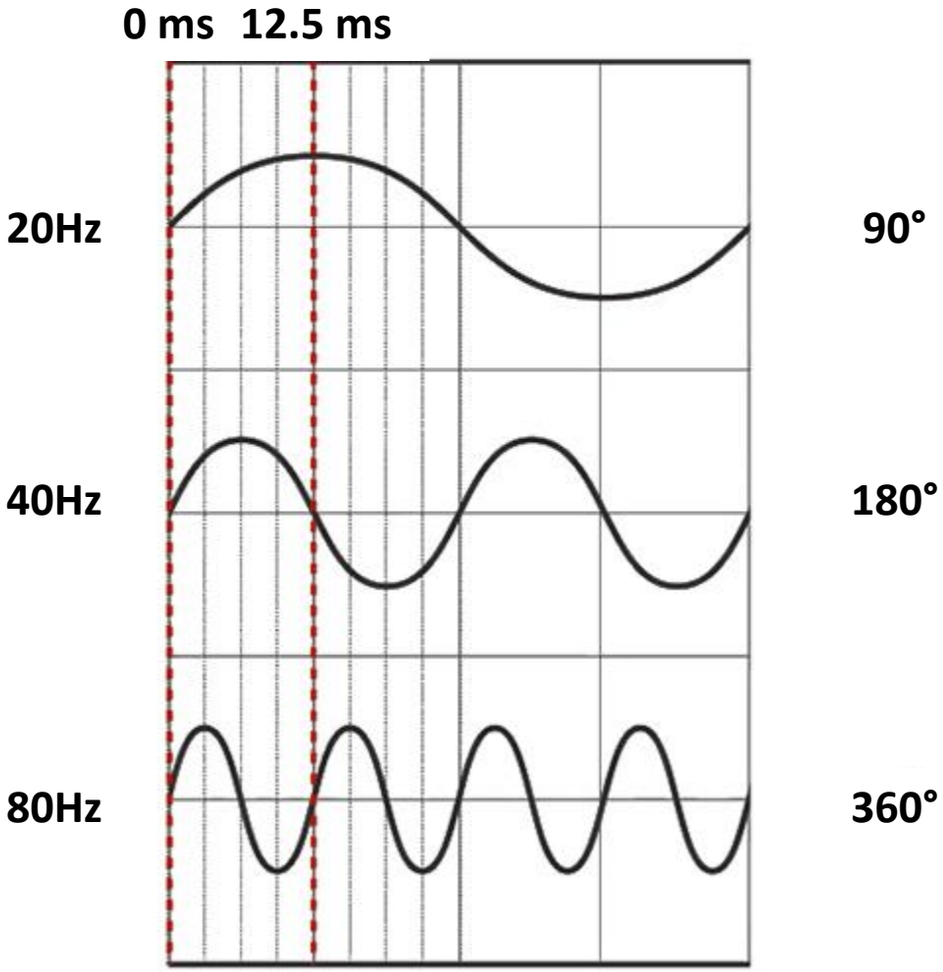
Phase (φ) and frequency (f)



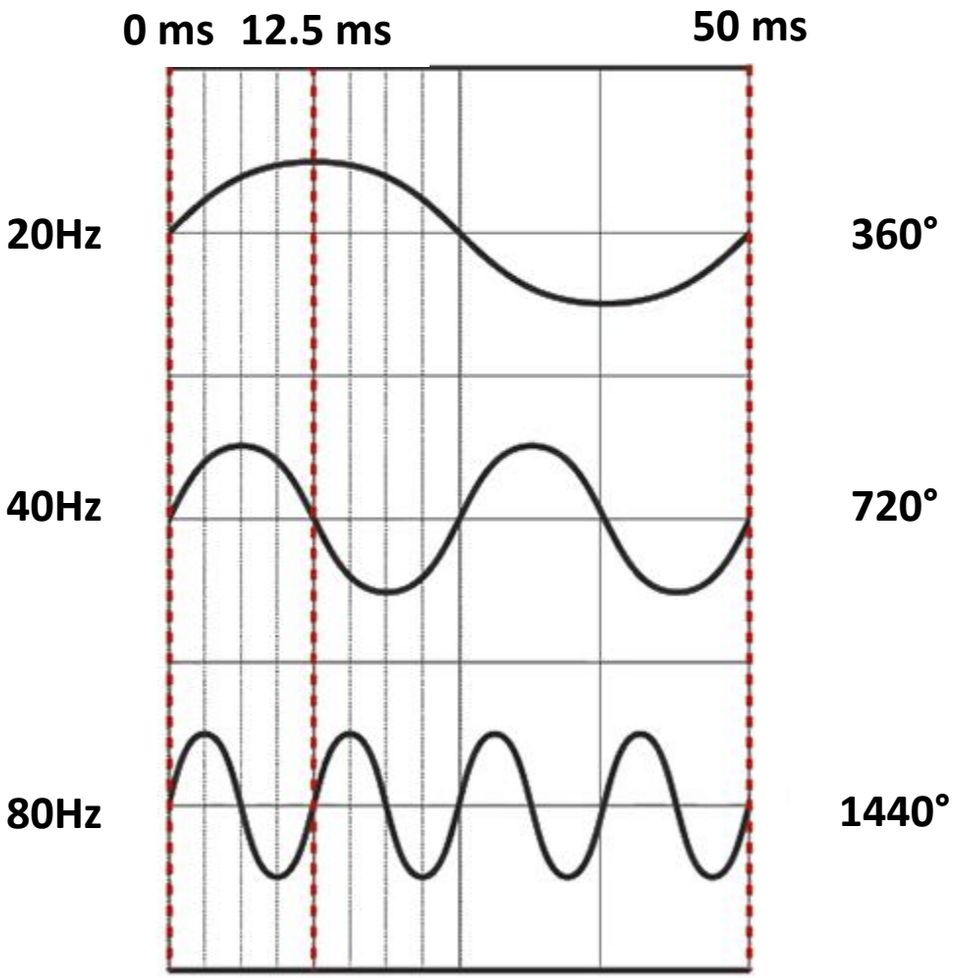
Phase (φ) and frequency (f)



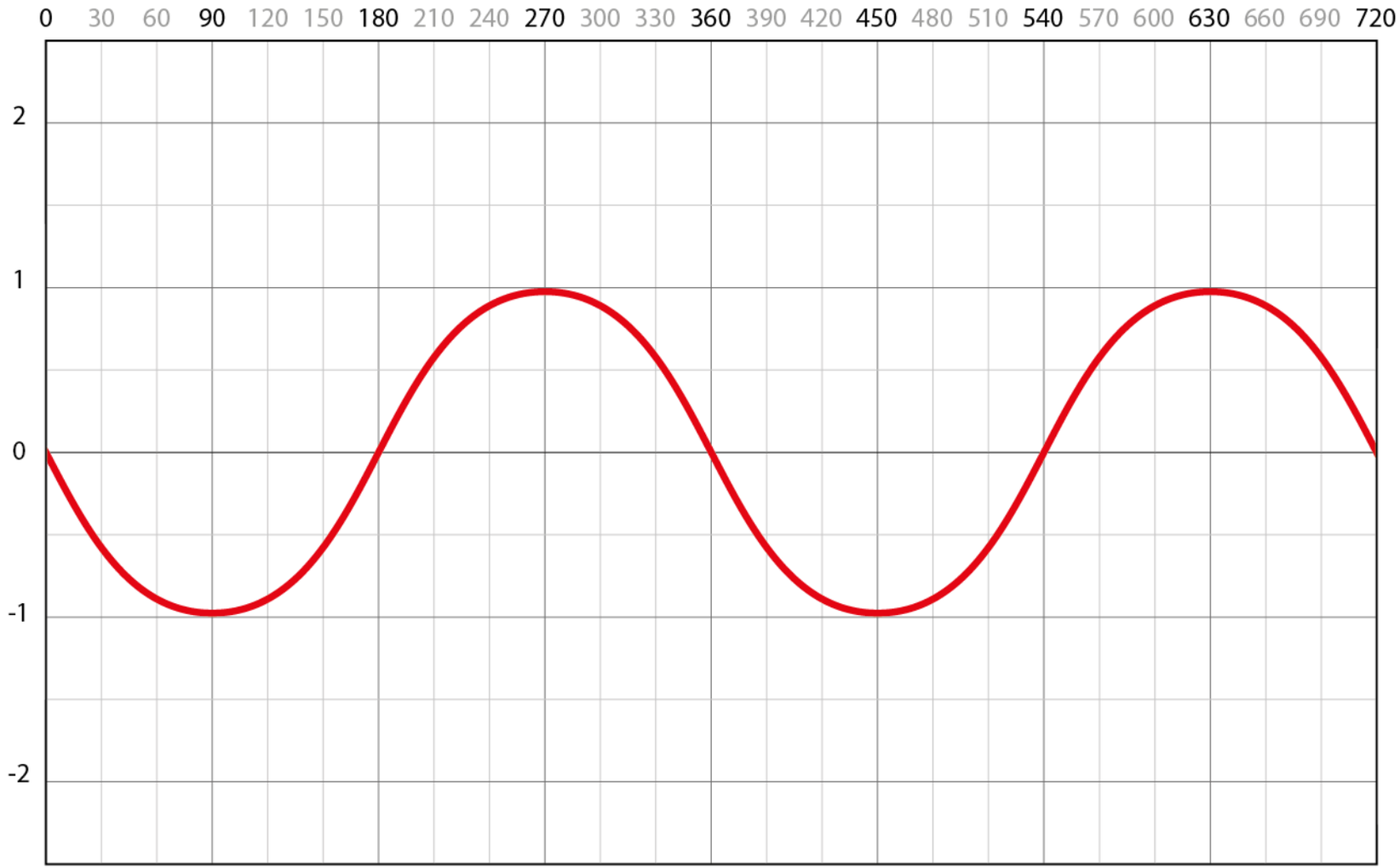
Phase (φ) and frequency (f)



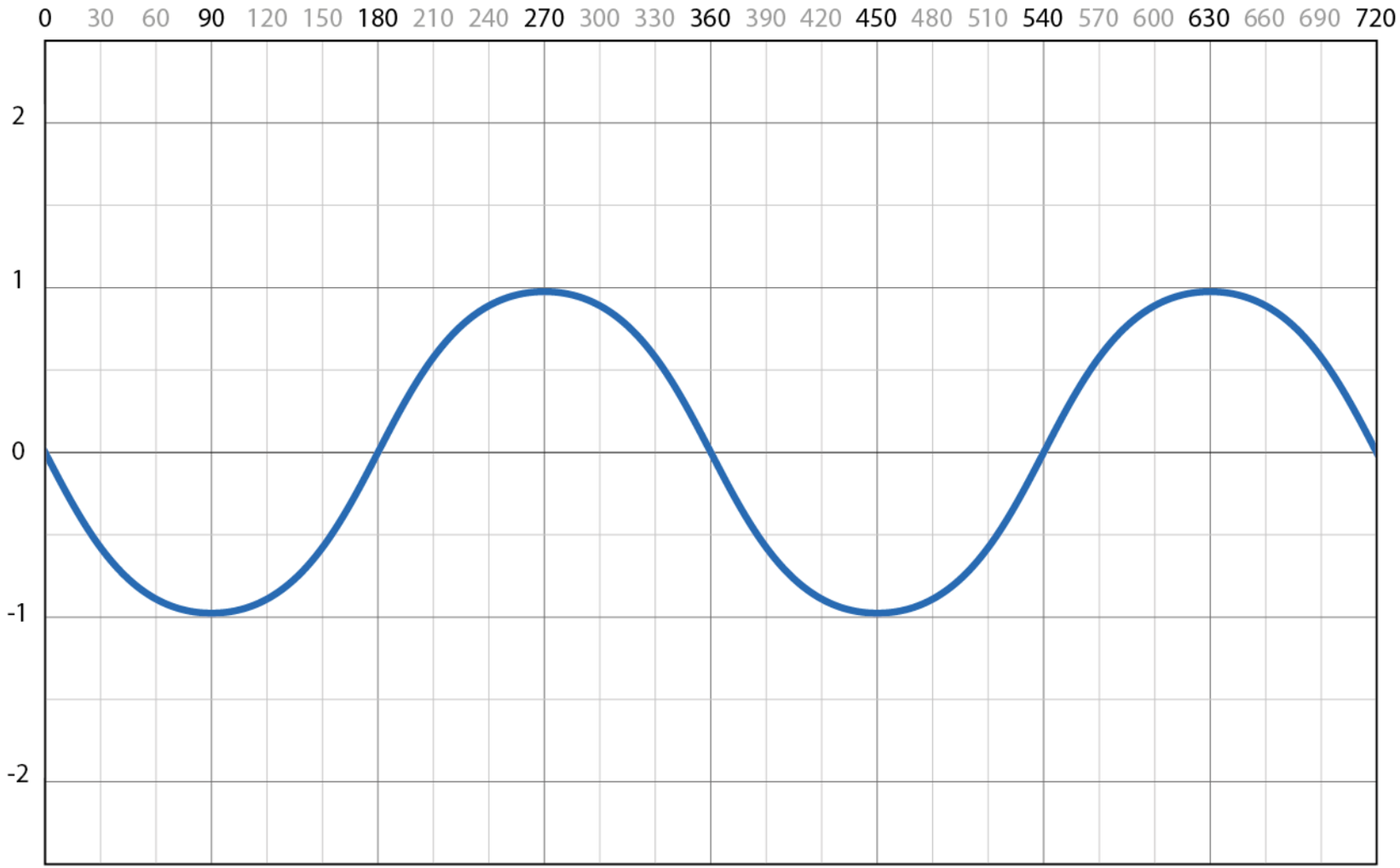
Phase (φ) and frequency (f)



Phase difference (Δϕ) — summation and attenuation

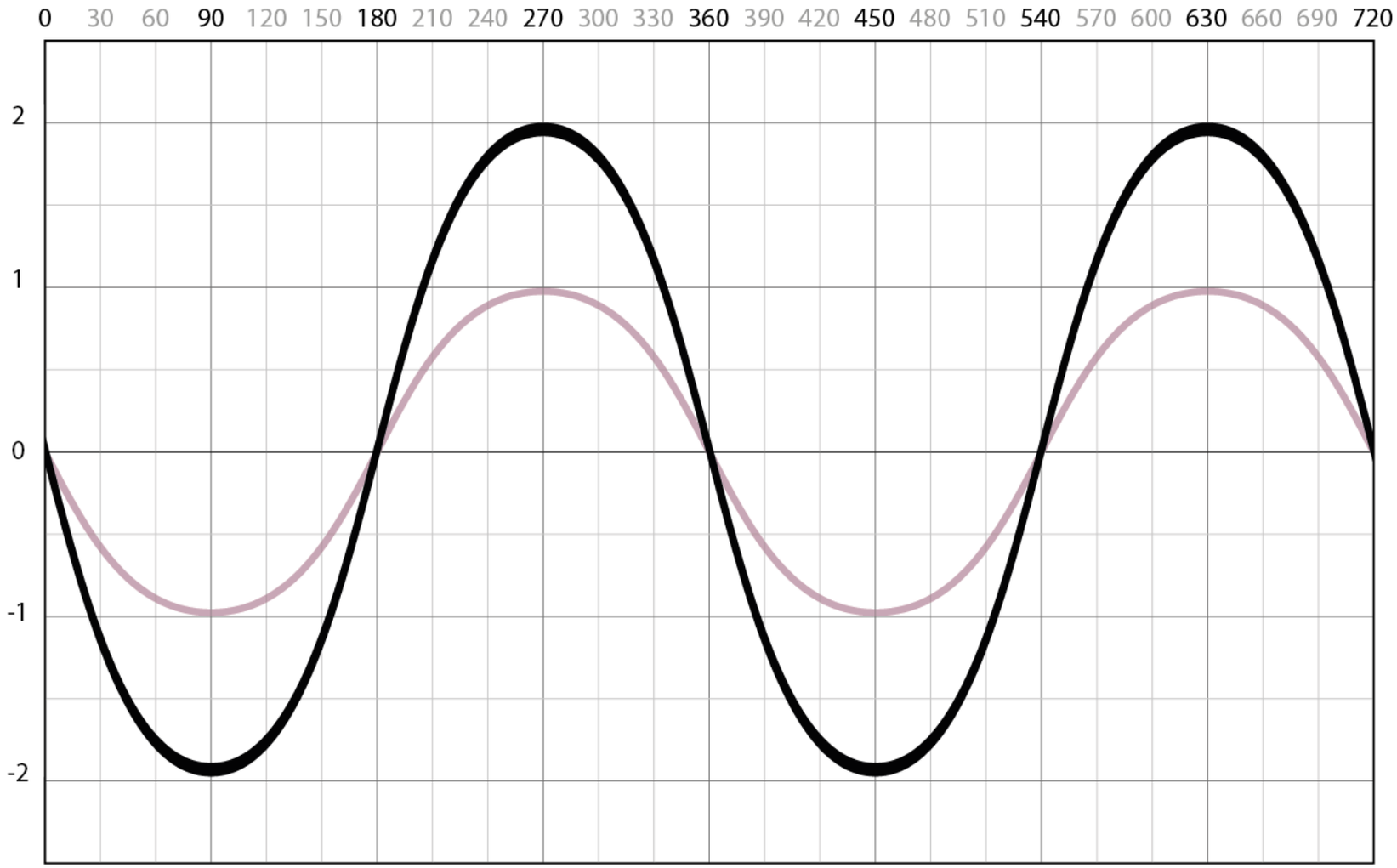


Phase difference (Δϕ) — summation and attenuation



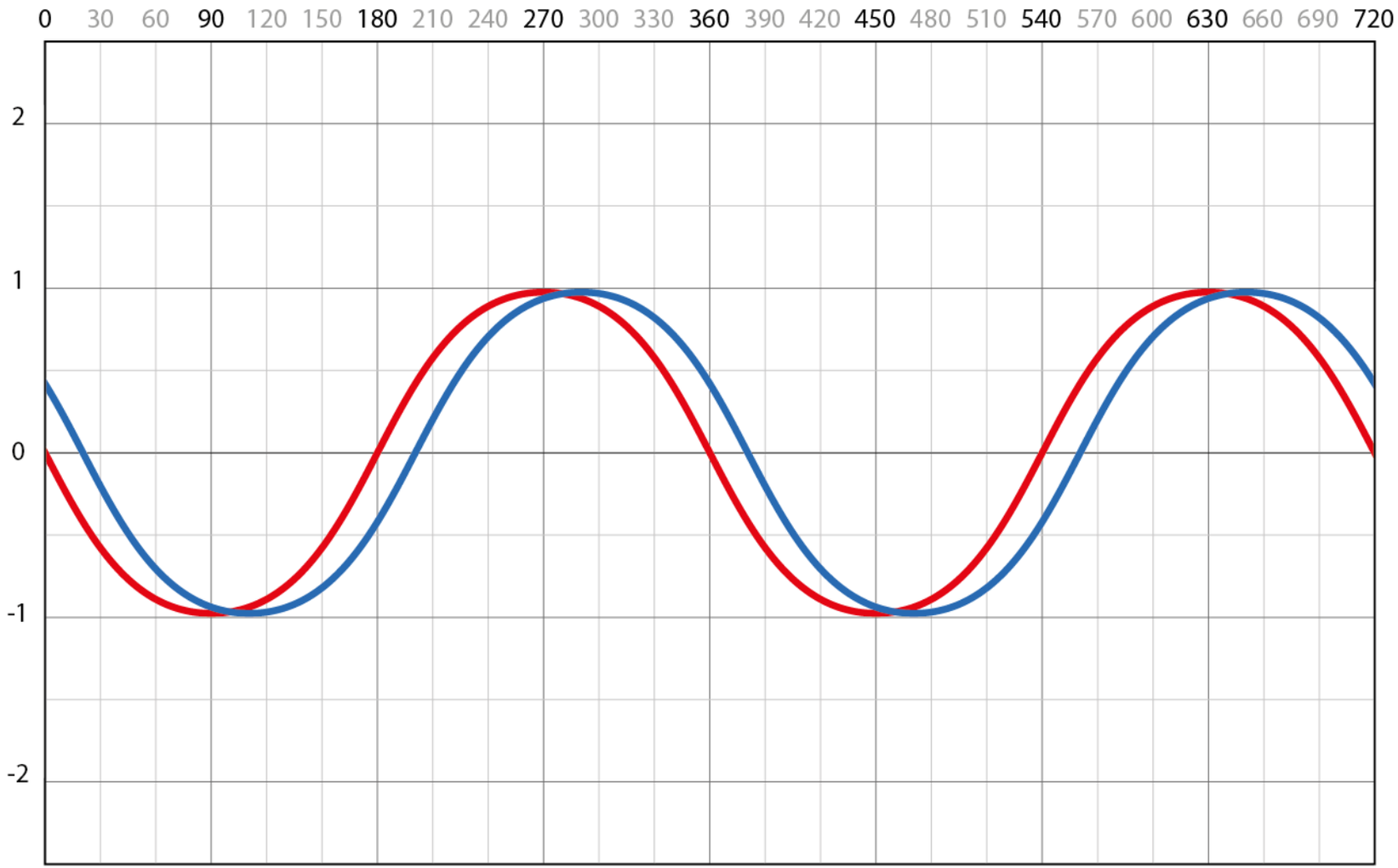
Phase difference = 0°

Phase difference (Δϕ) — summation and attenuation



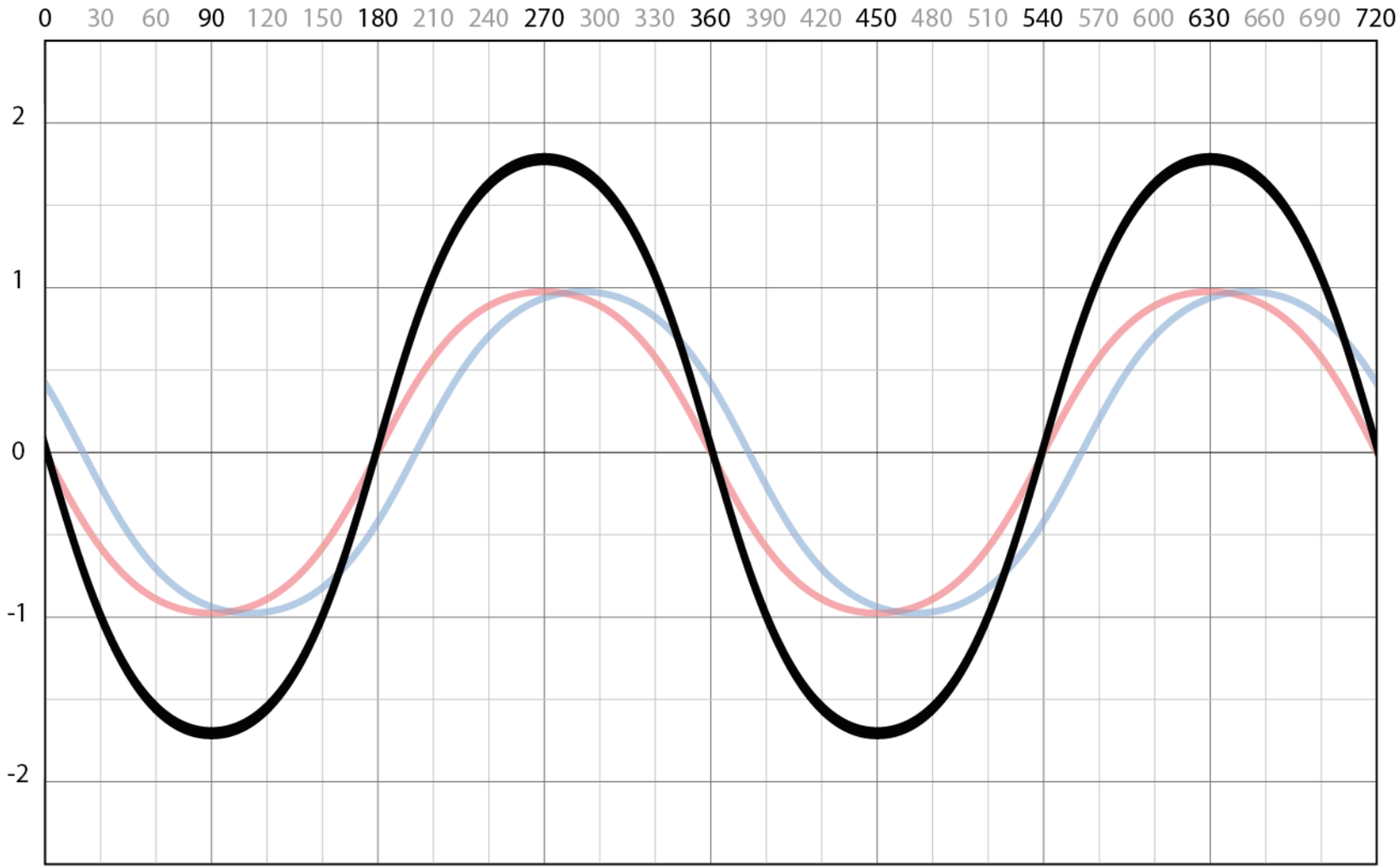
Phase difference = 0°
= + 6 dB

Phase difference (Δϕ) — summation and attenuation



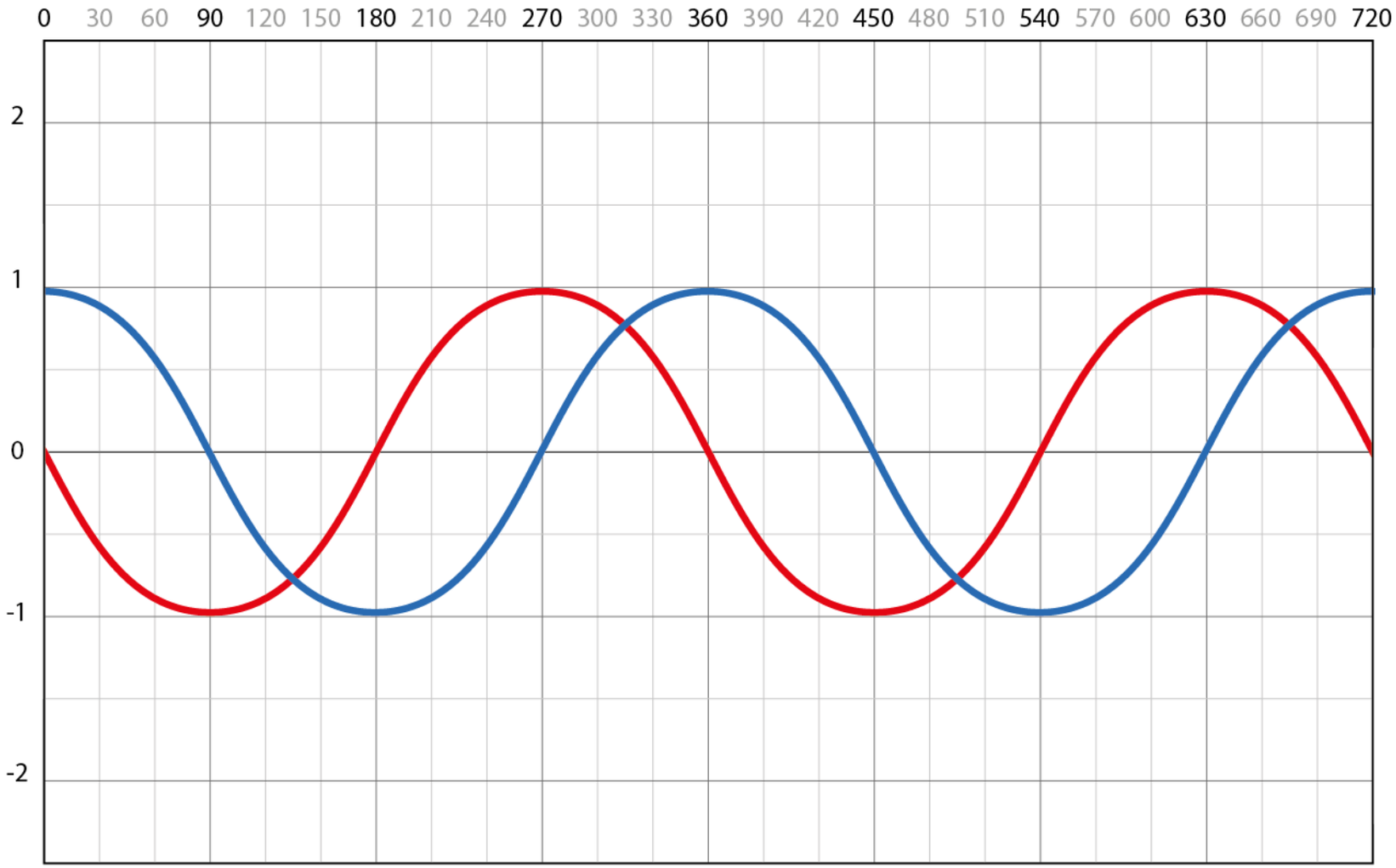
Phase difference = 20°

Phase difference (Δϕ) — summation and attenuation



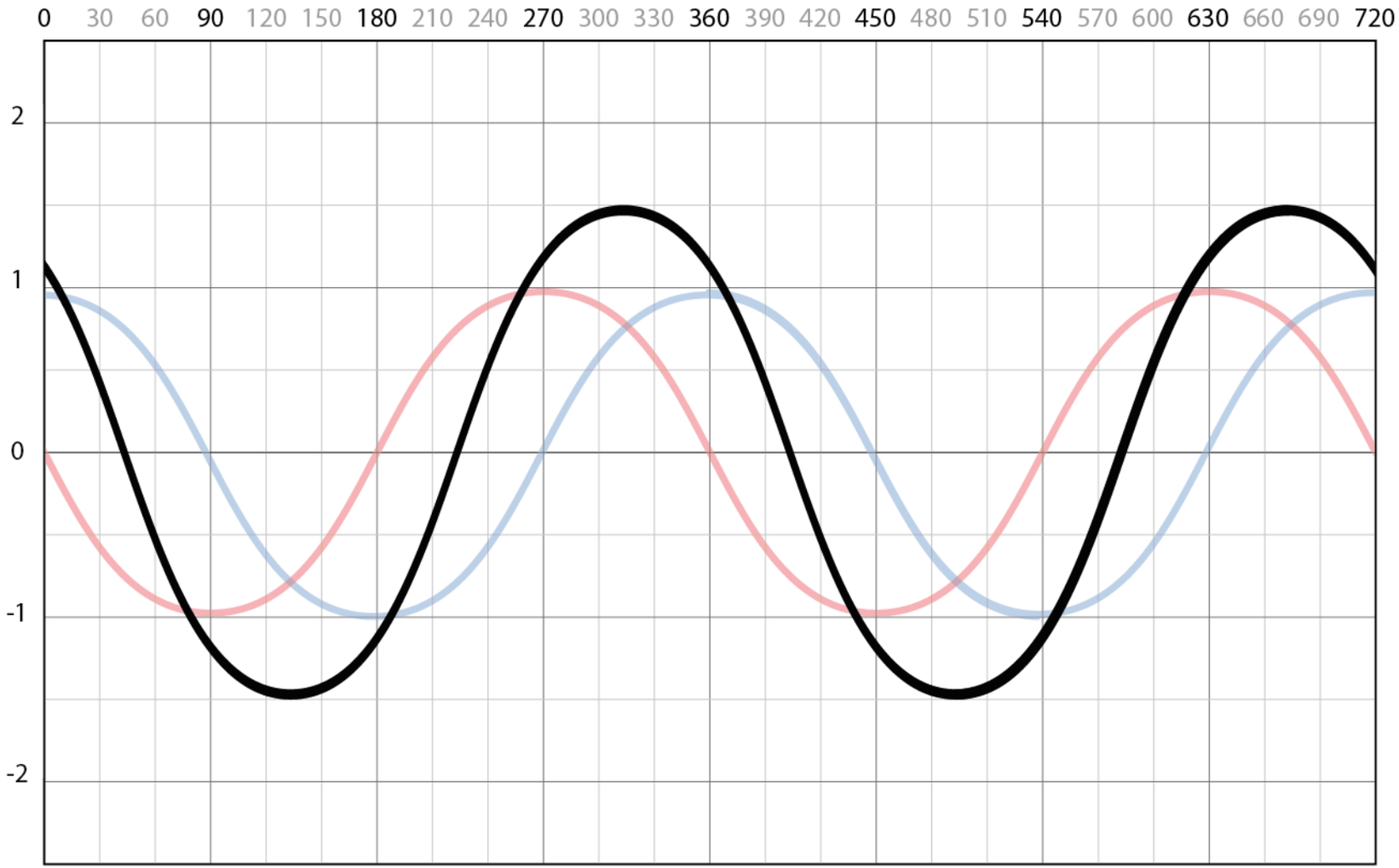
Phase difference = 20°
< 6 dB

Phase difference (Δϕ) — summation and attenuation



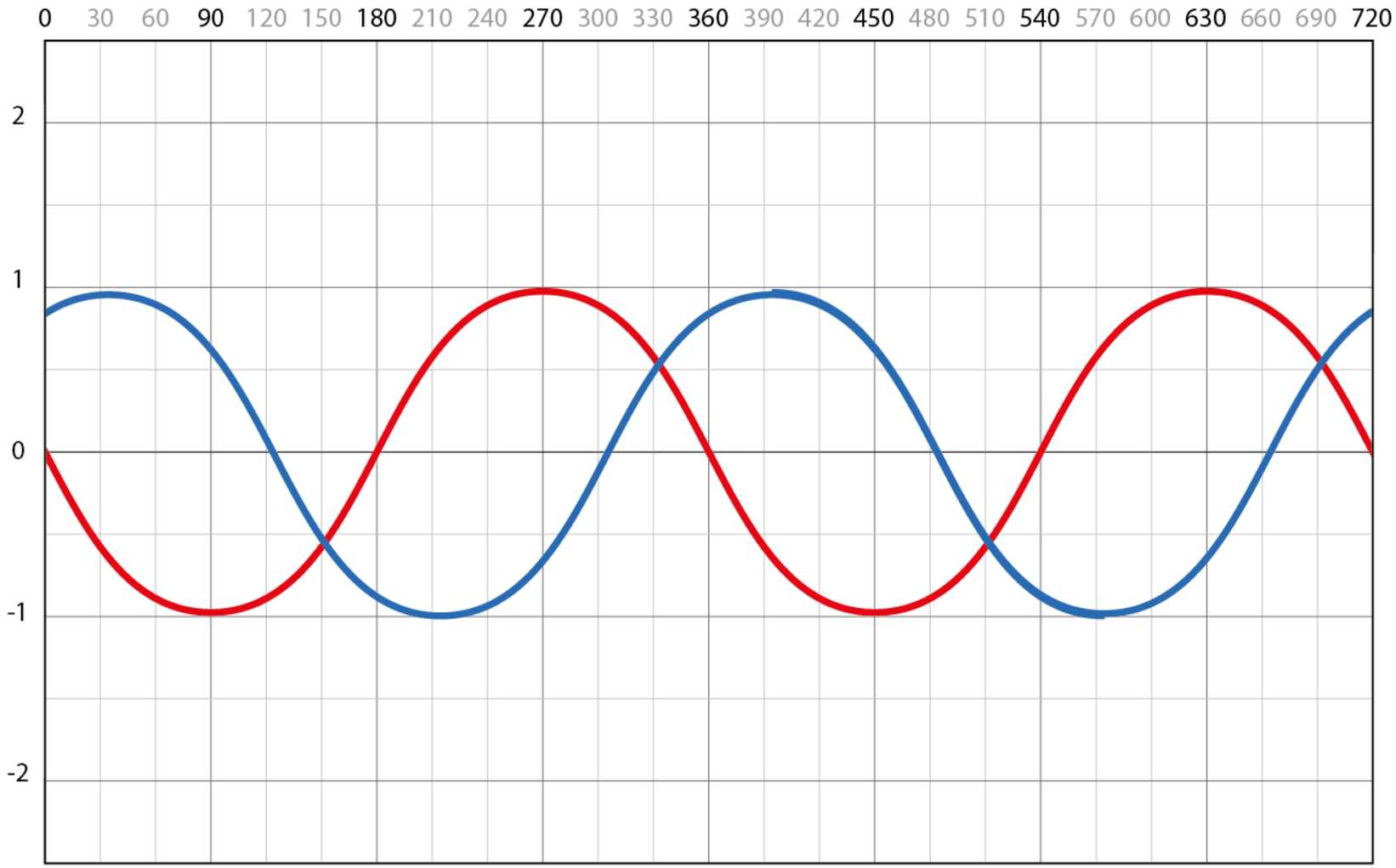
Phase difference = 90°

Phase difference (Δϕ) — summation and attenuation



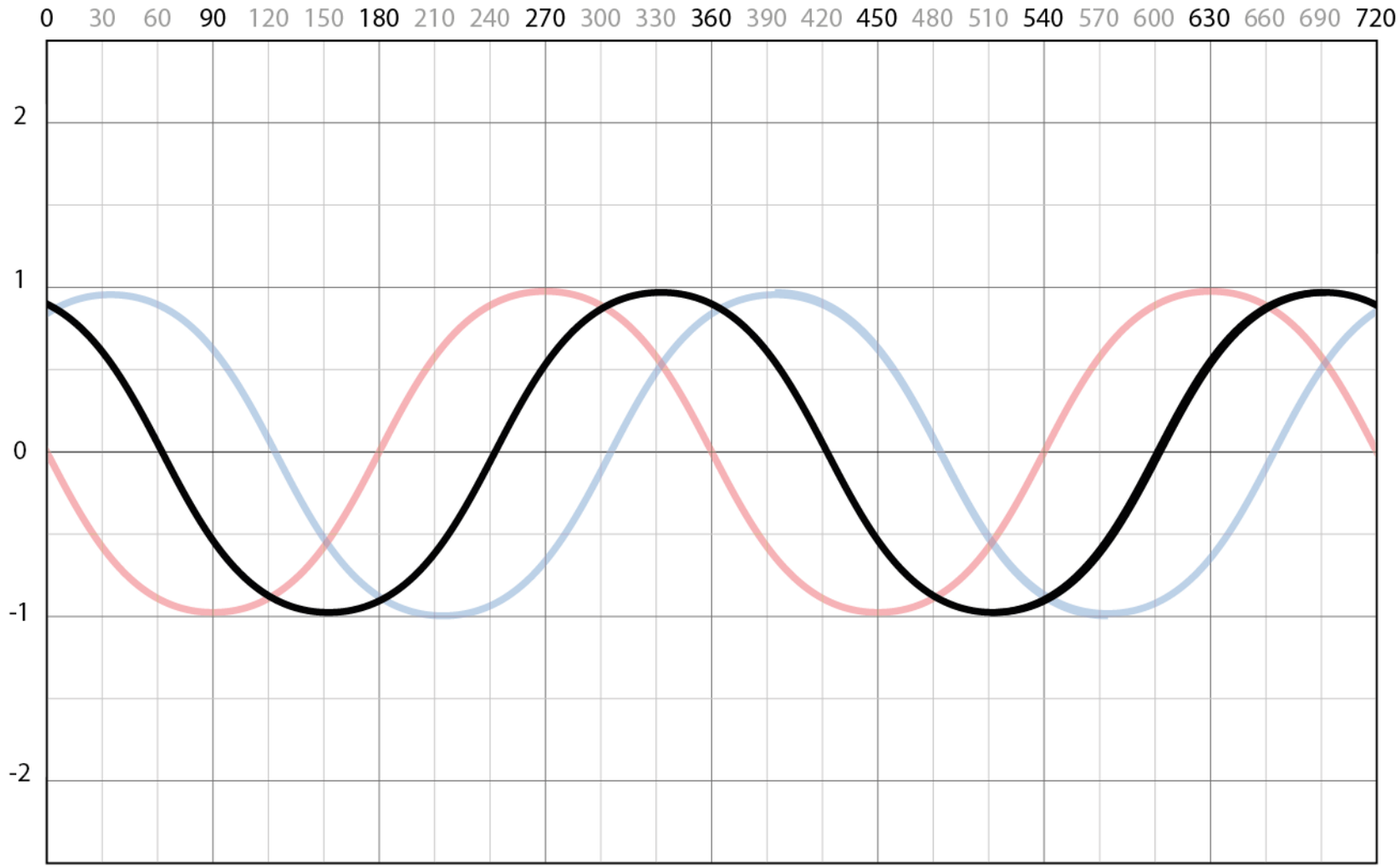
Phase difference = 90°
≈ 3 dB

Phase difference (Δϕ) — summation and attenuation



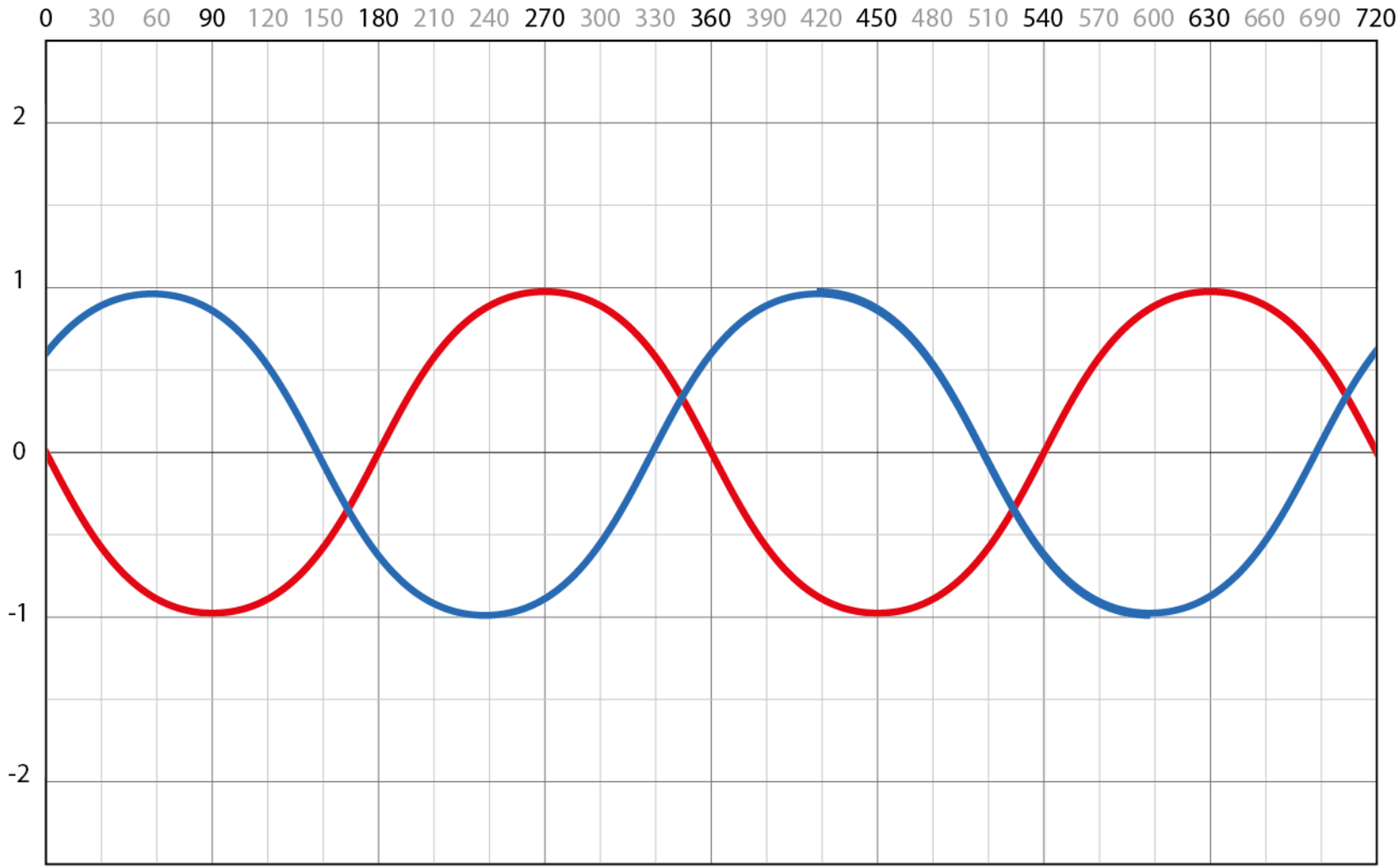
Phase difference = 120°

Phase difference (Δϕ) — summation and attenuation



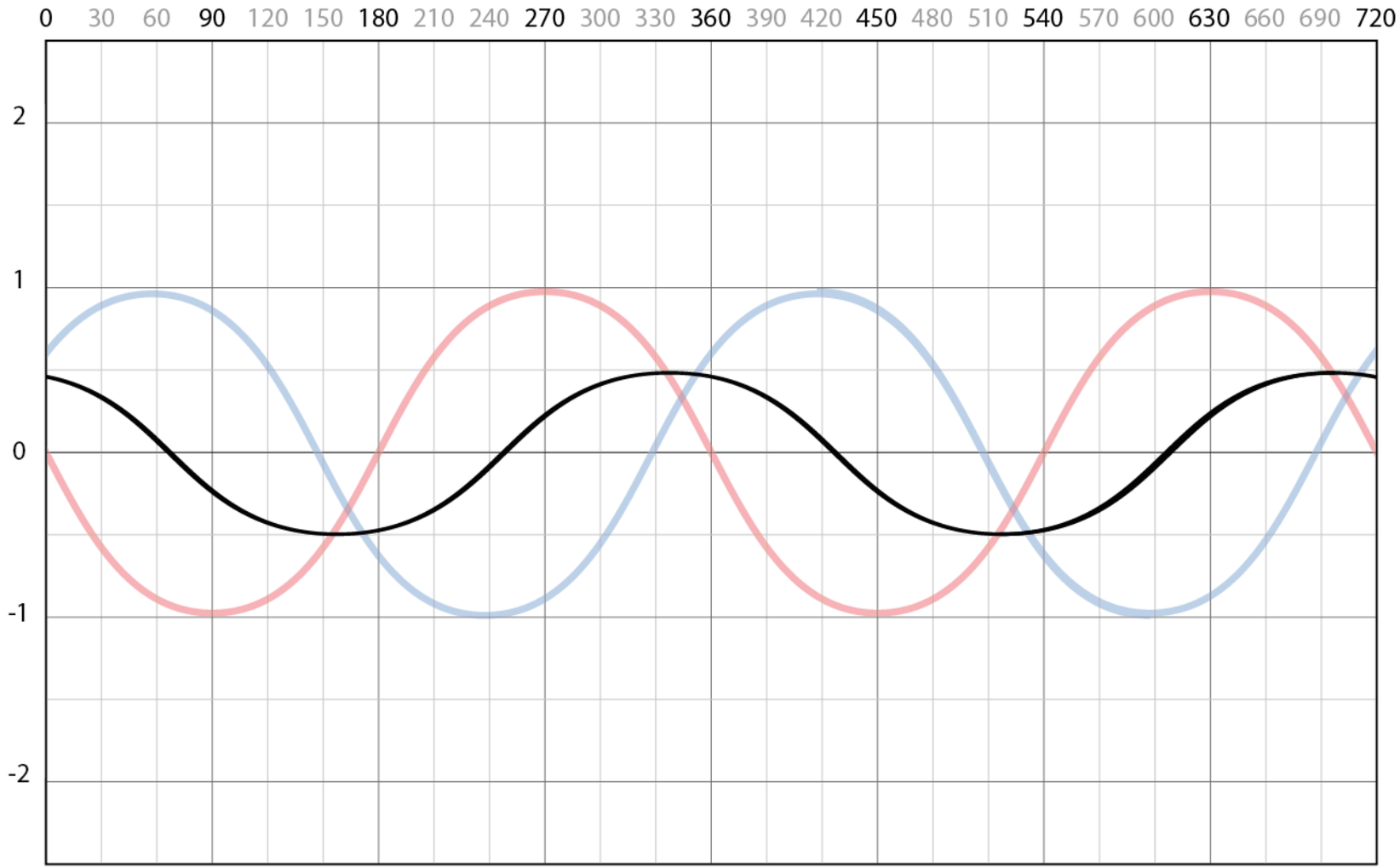
Phase difference = 120°
± 0 dB

Phase difference (Δϕ) — summation and attenuation



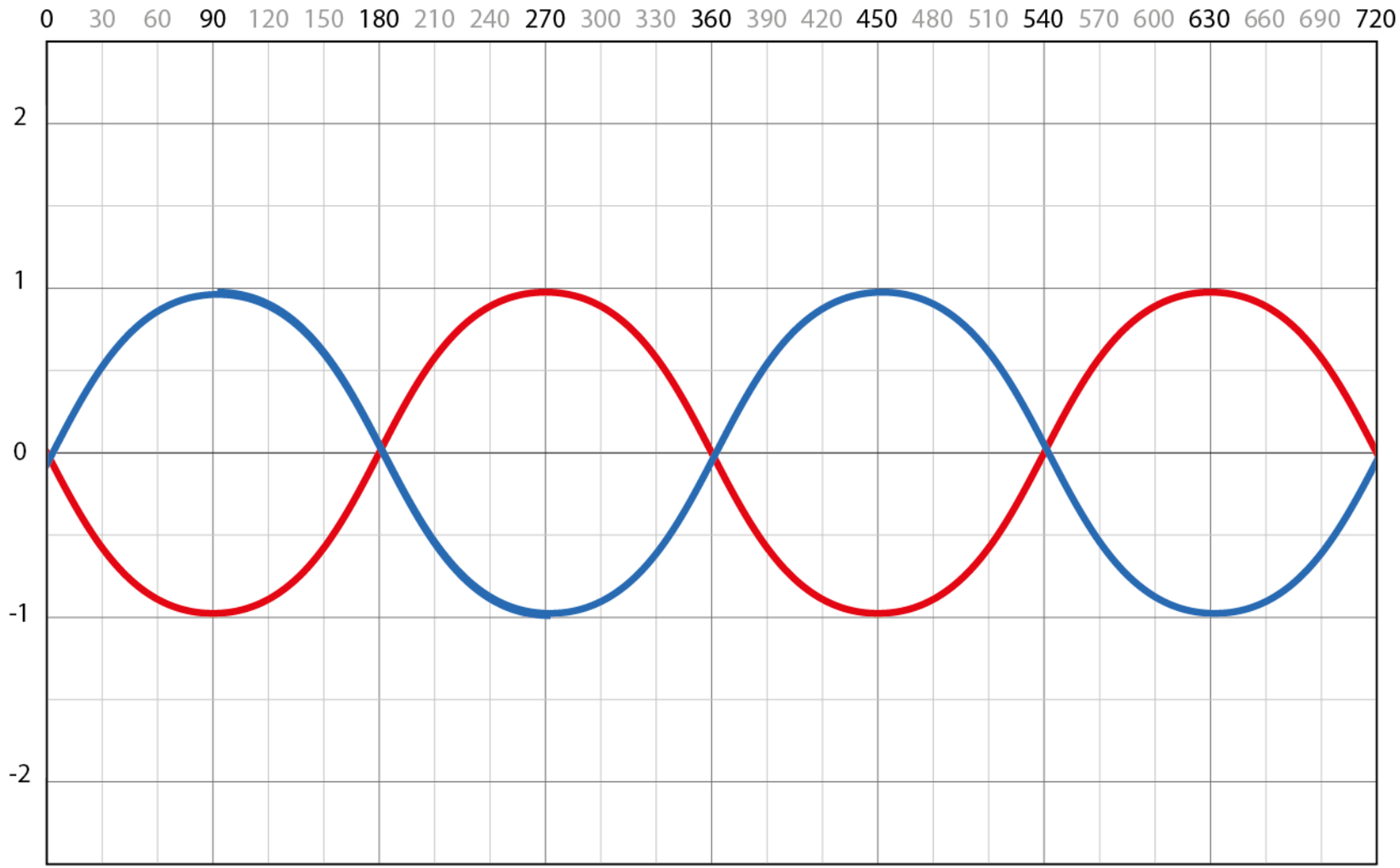
Phase difference = 150°

Phase difference (Δϕ) — summation and attenuation



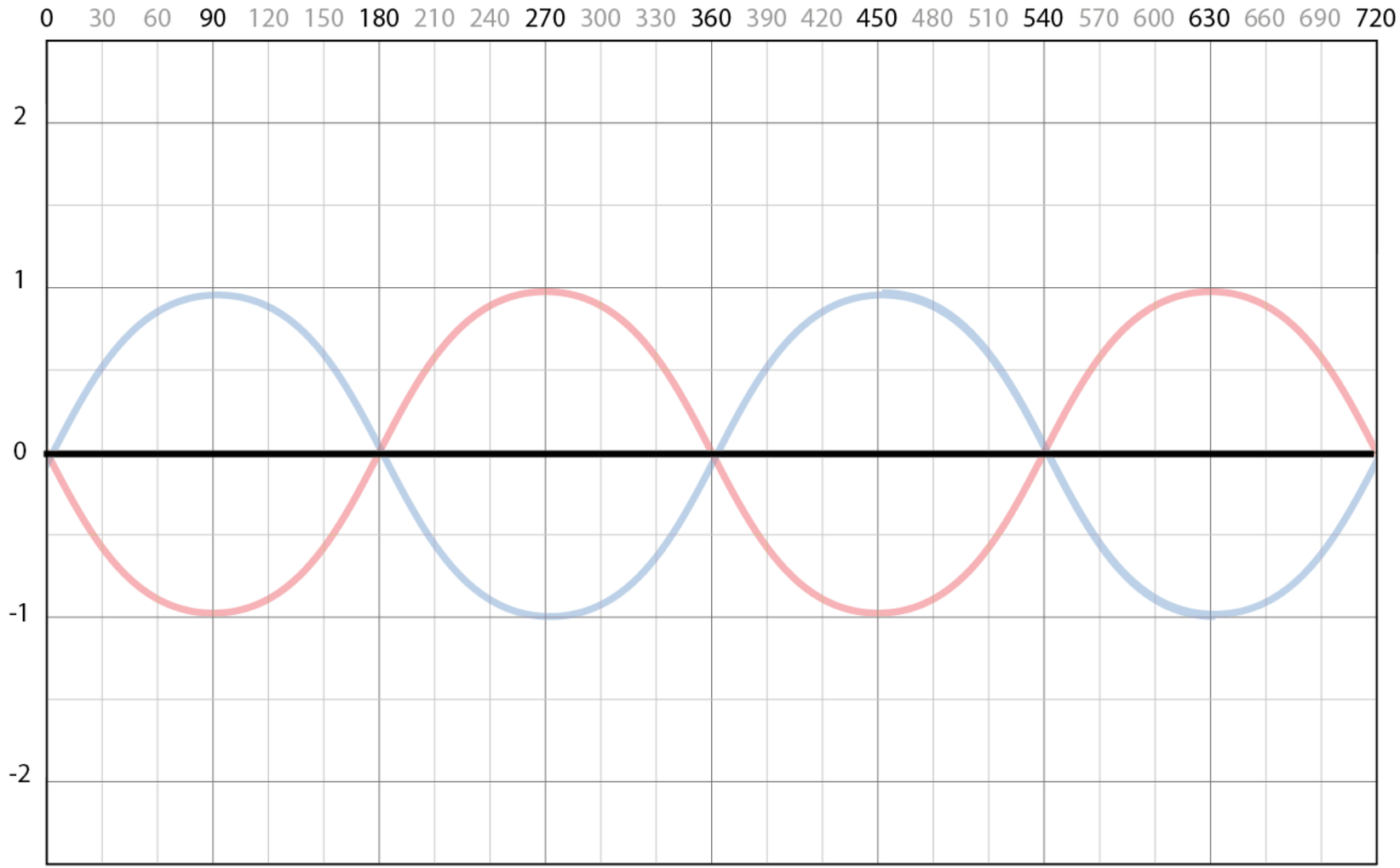
Phase difference = 150°
≤ -3 dB

Phase difference (Δϕ) — summation and attenuation



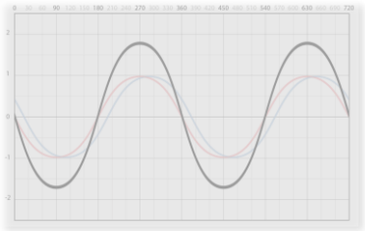
Phase difference = 180°

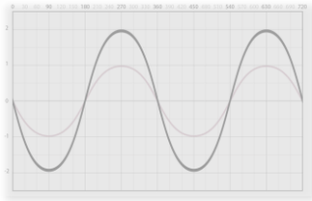
Phase difference (Δϕ) — summation and attenuation

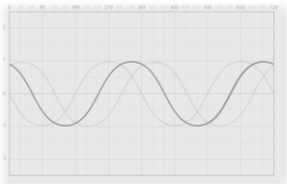


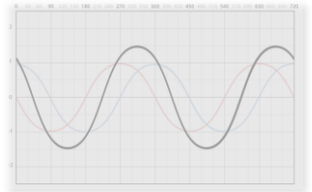
Phase difference = 180°
≈ Cancellation

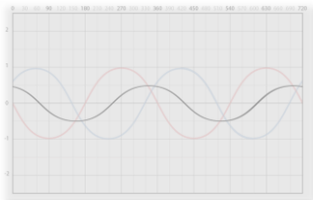
Phase difference (Δϕ) — the magic circle!











360° - 1 Cycle
2π
(0° - 0 Cycle)

322°

38°

270° - 3/4 Cycle
3/2π

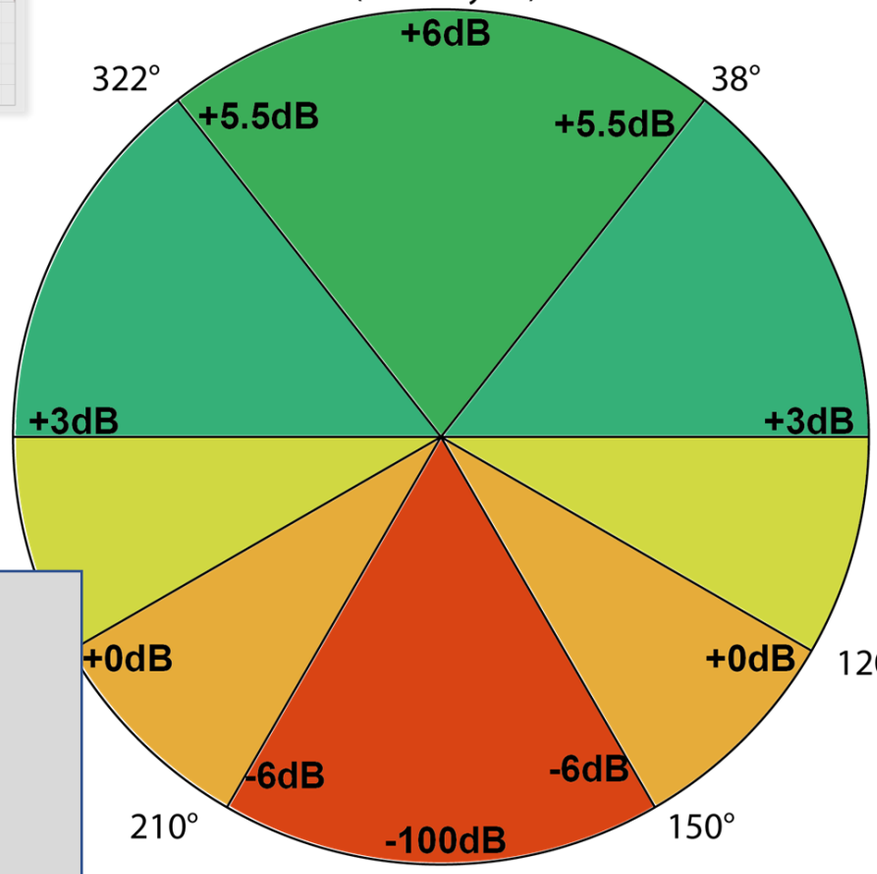
90° - 1/4 Cycle
1/2π

120° - 1/3 Cycle
1/6π

210°

150°

180° - 1/2 Cycle
π

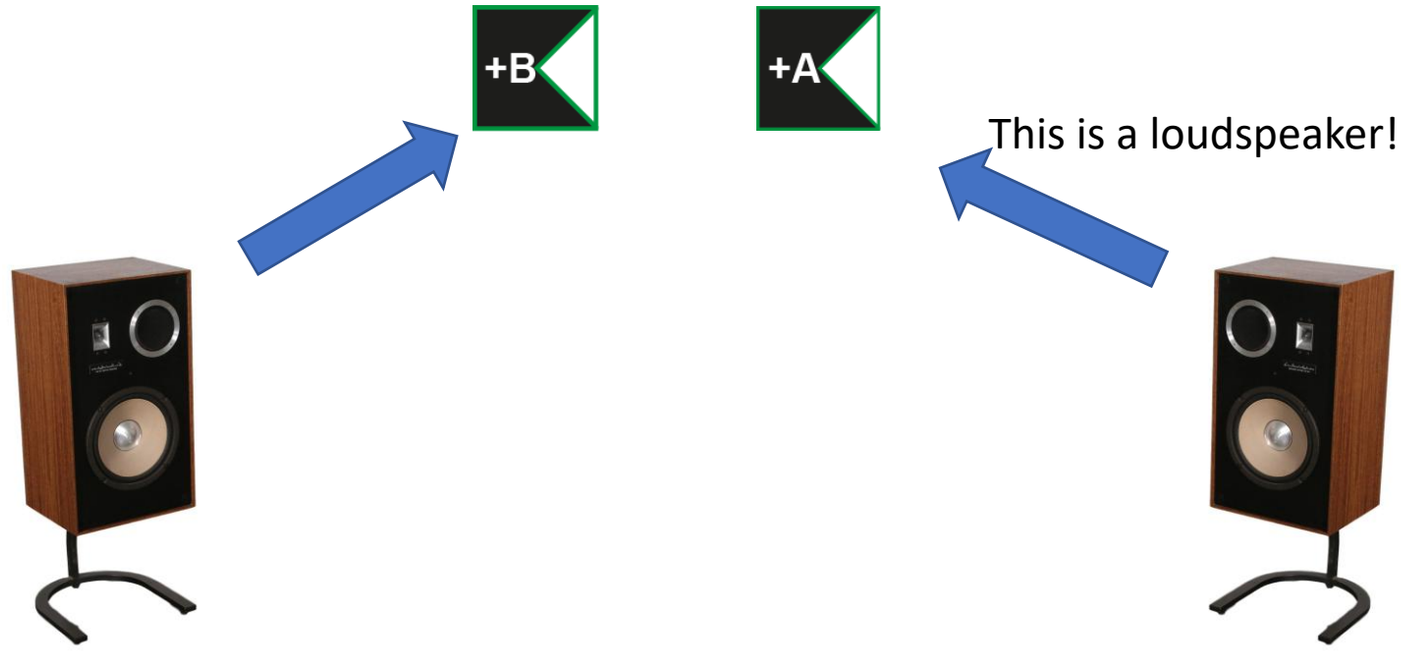


$$\Delta_{\varphi} = \frac{\Delta_d . f . 360}{c}$$

- *where:*
- *f = frequency*
- *λ = wavelength*
- *C = speed of sound*
- *Δd = path-length difference*

Source: Van Veen M., 2008

Path-length difference (Δd)



Path-length difference (Δd)

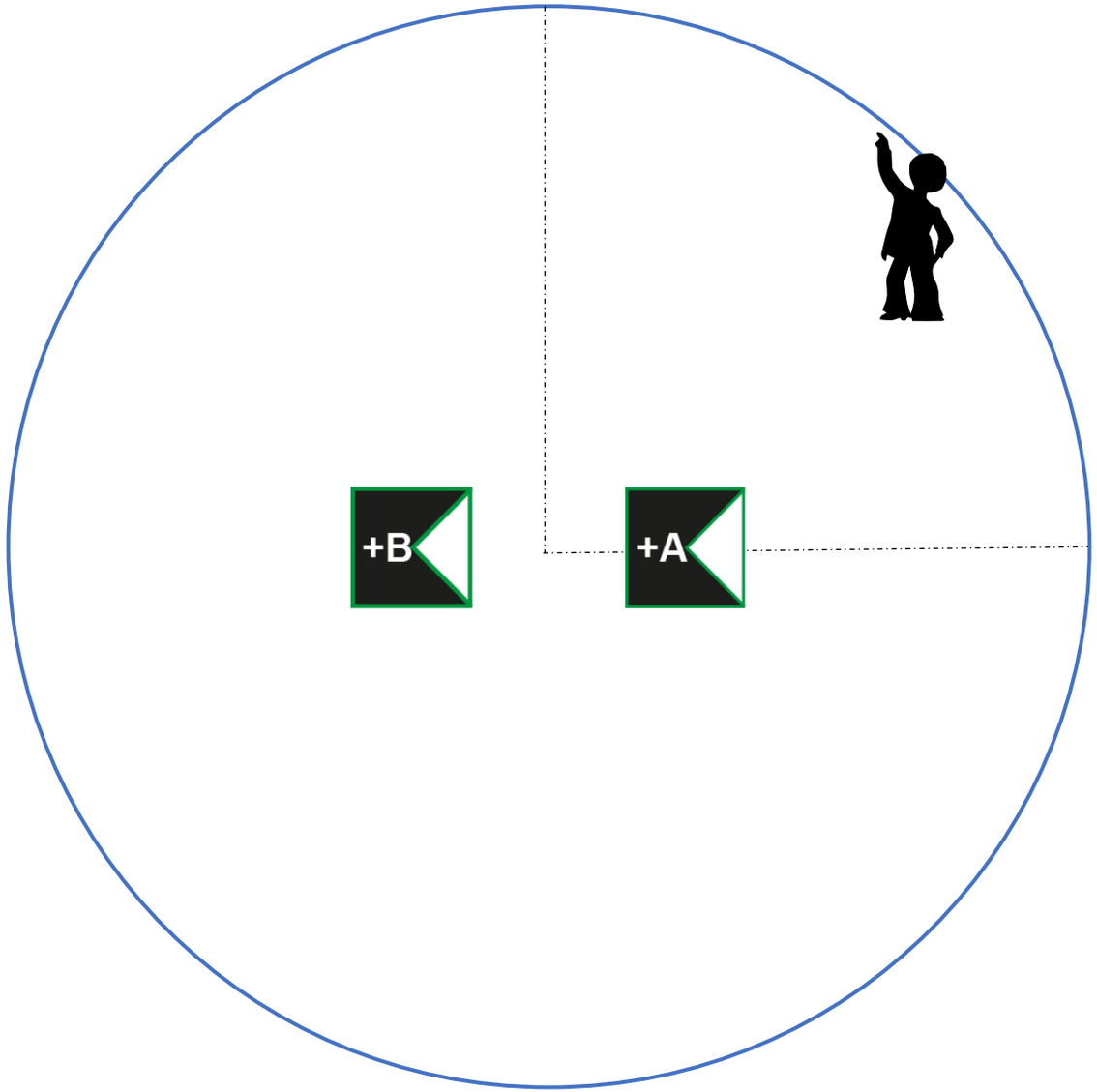


This is you!

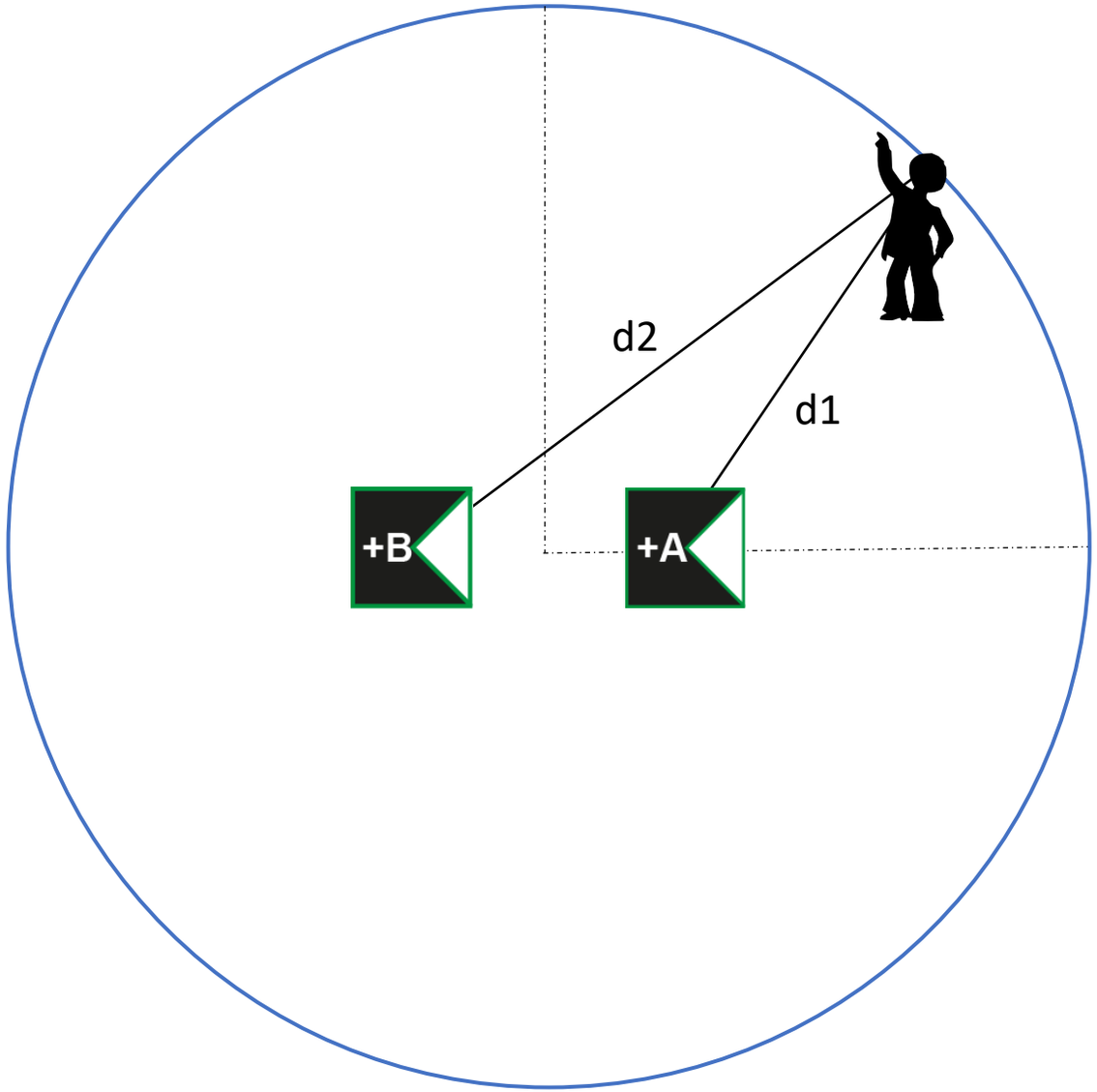




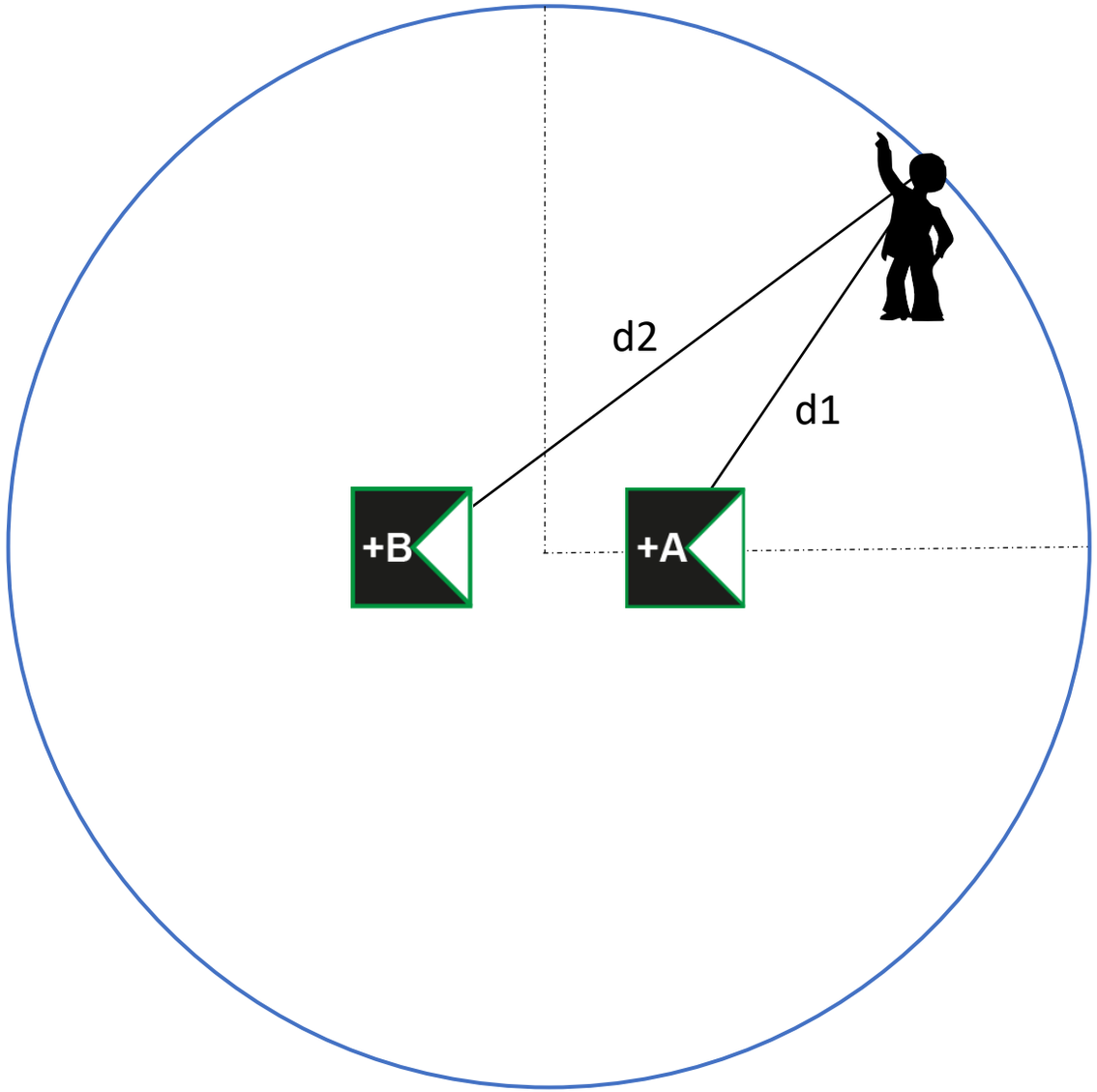
Path-length difference (Δd)



Path-length difference (Δd)

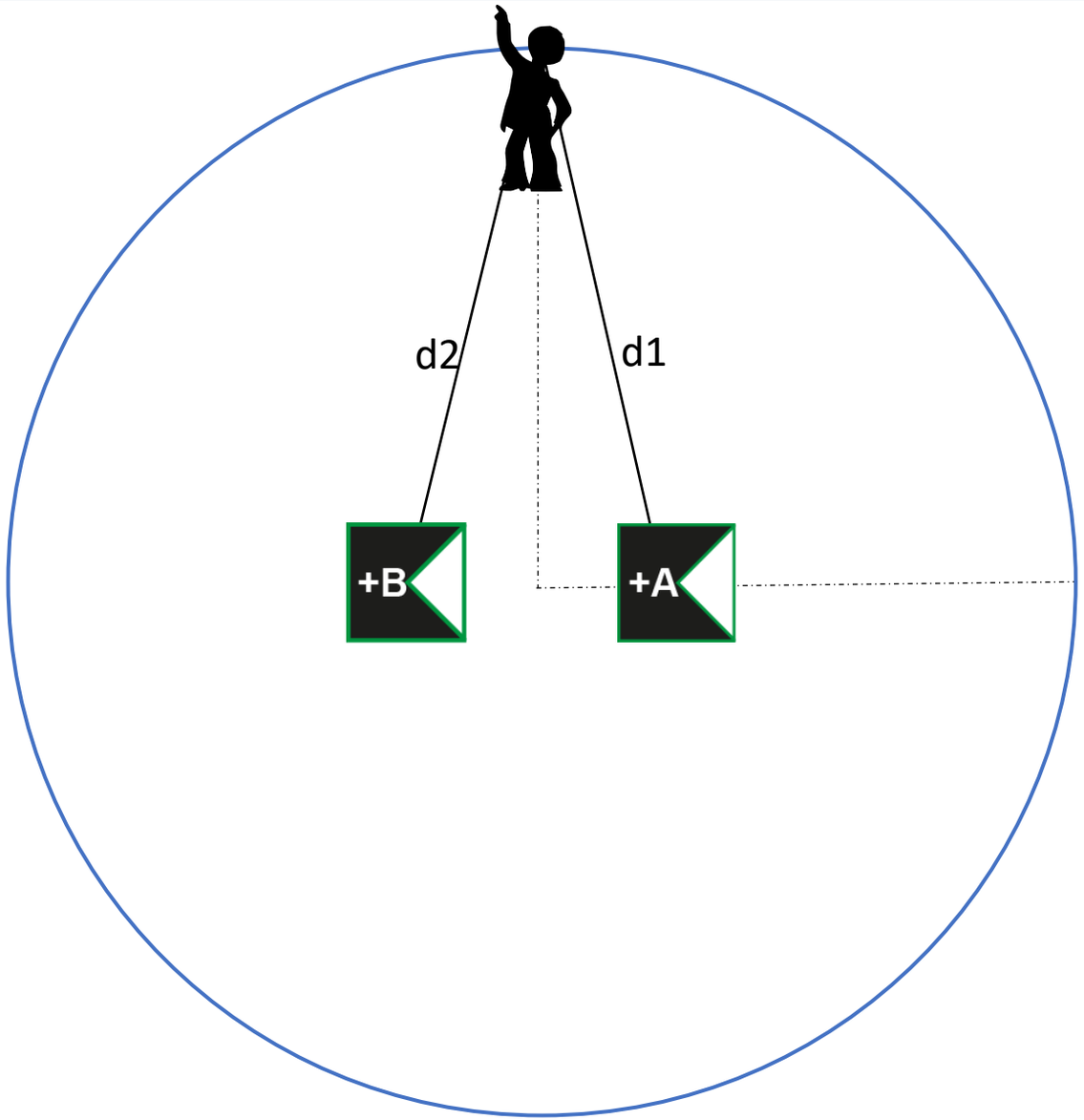


Path-length difference (Δd)



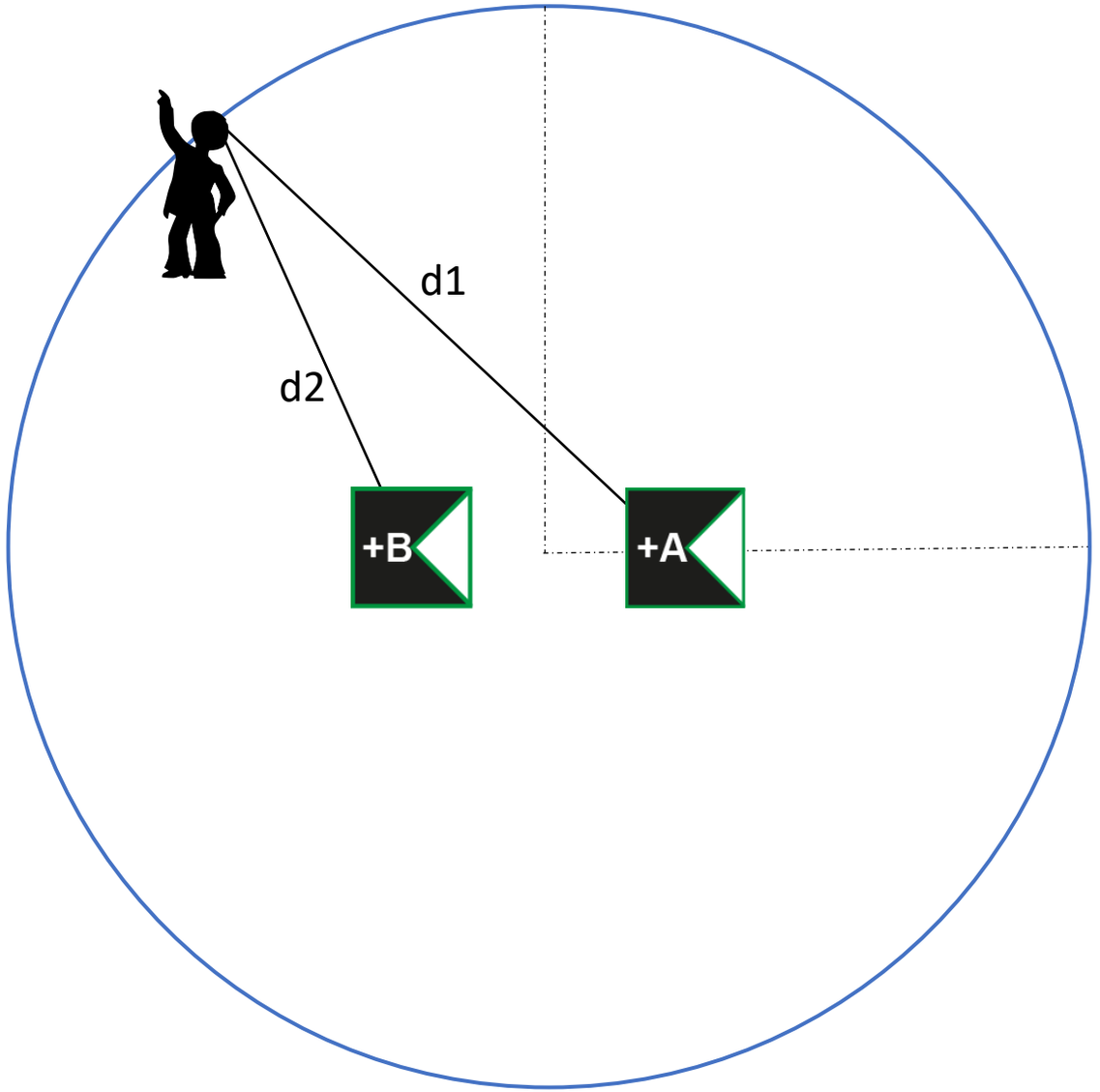
- Δ_d = d1-d2 < 0

Path-length difference (Δd)



- Δ_d = d1-d2 = 0

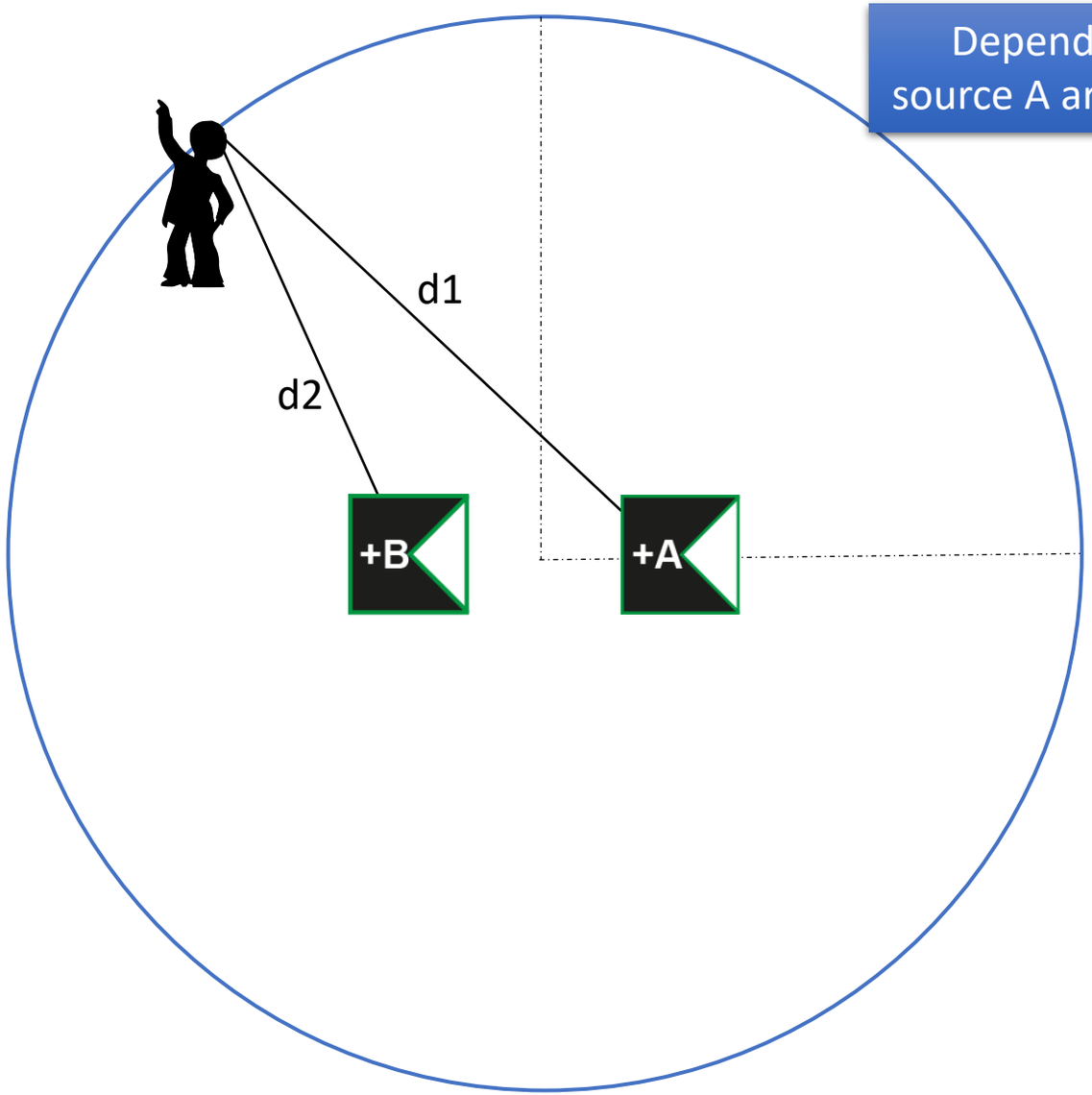
Path-length difference (Δd)



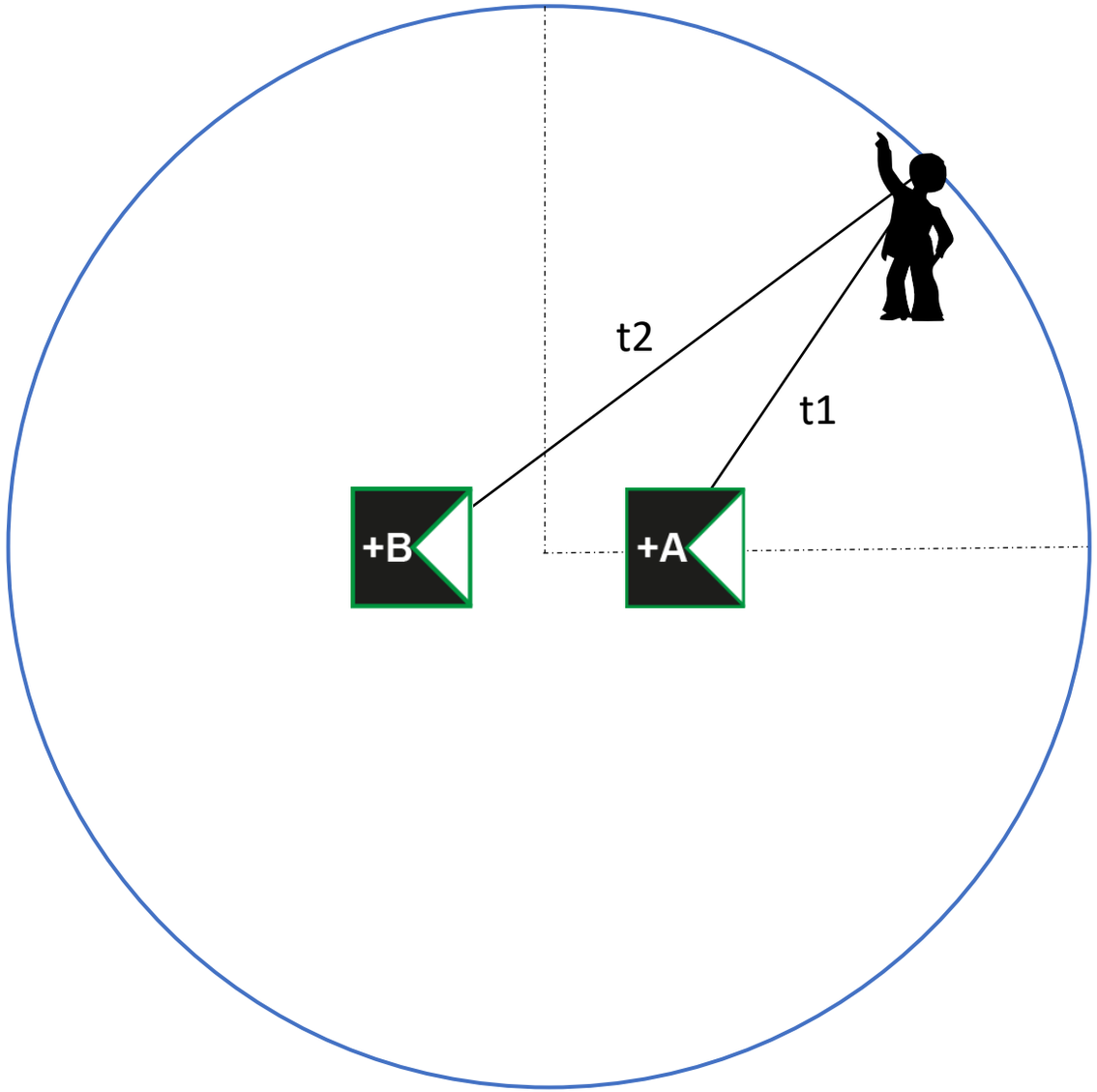
- Δ_d = d1-d2 > 0

Path-length difference (Δd)

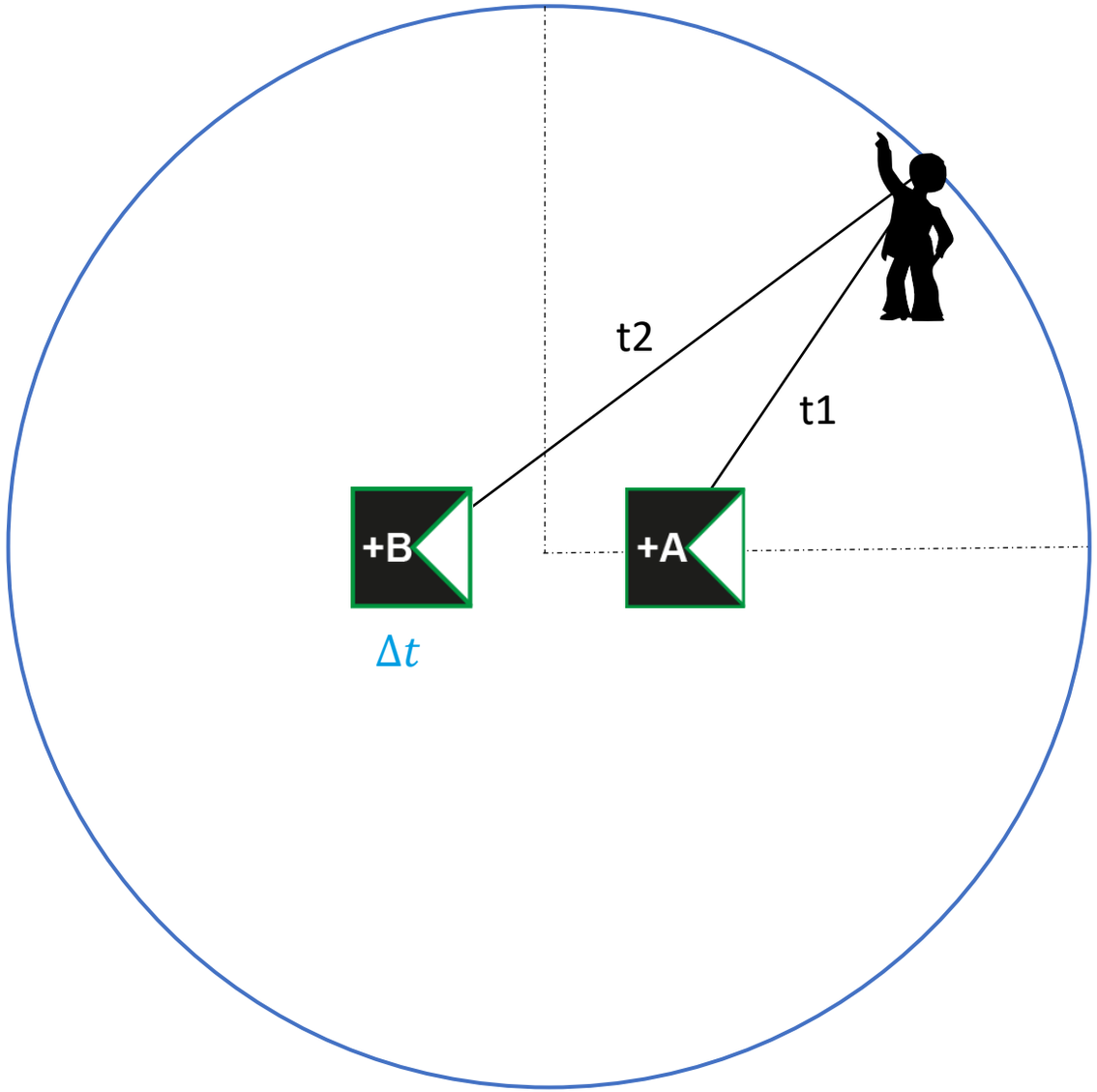
Depending on the listener's position, source A arrives earlier or later than source B.



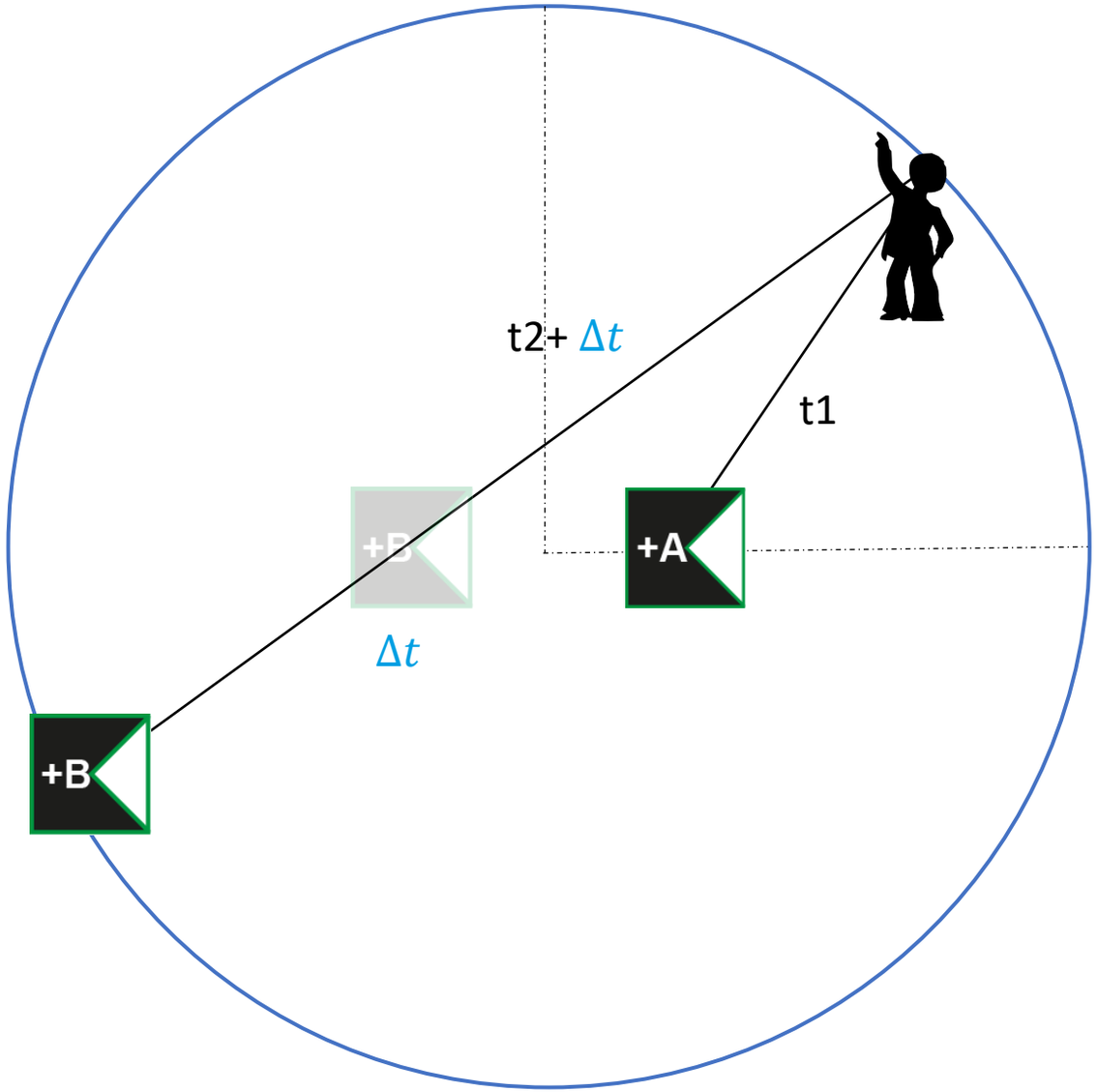
Time difference (Δt)



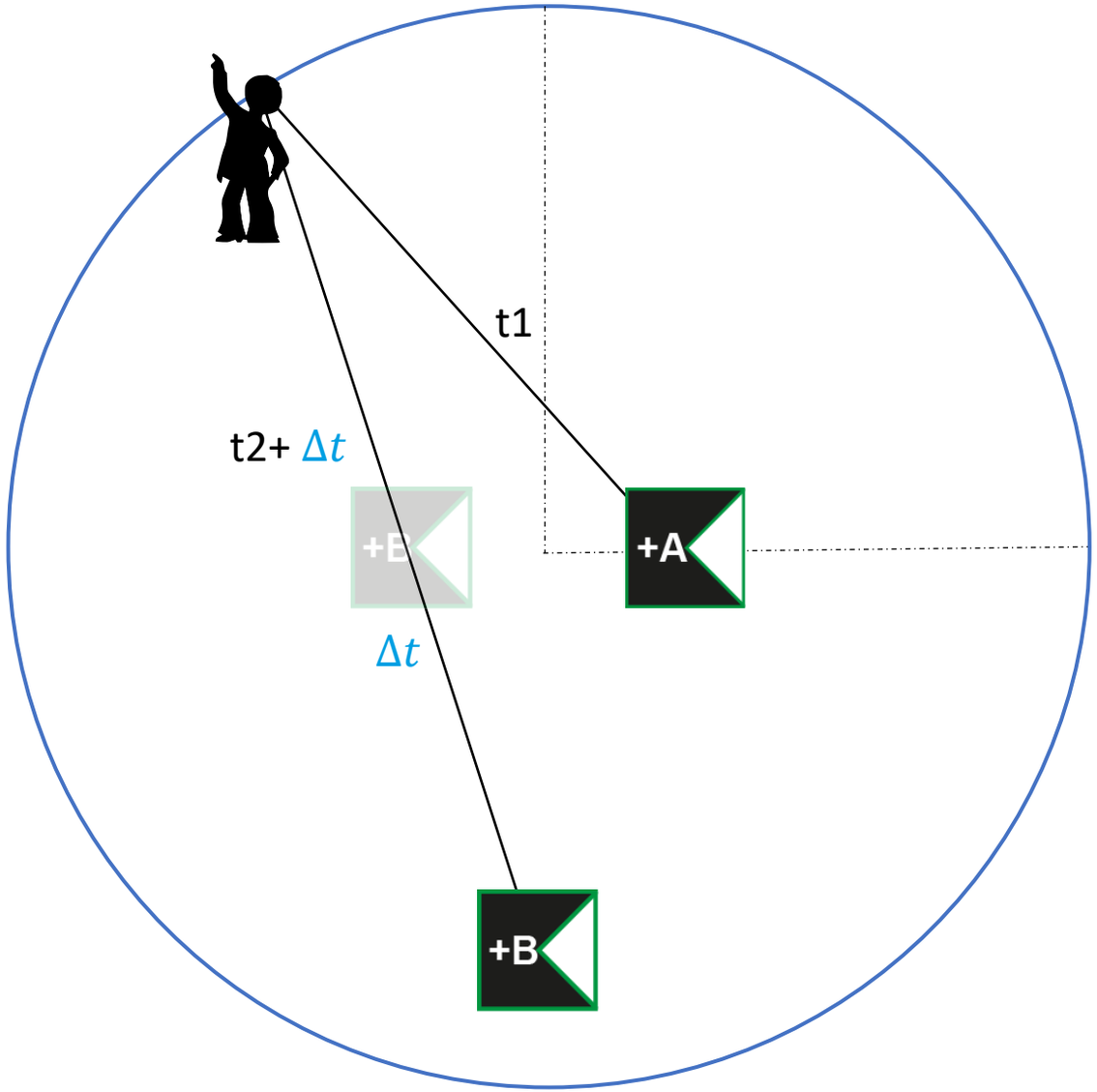
Time difference (Δt)



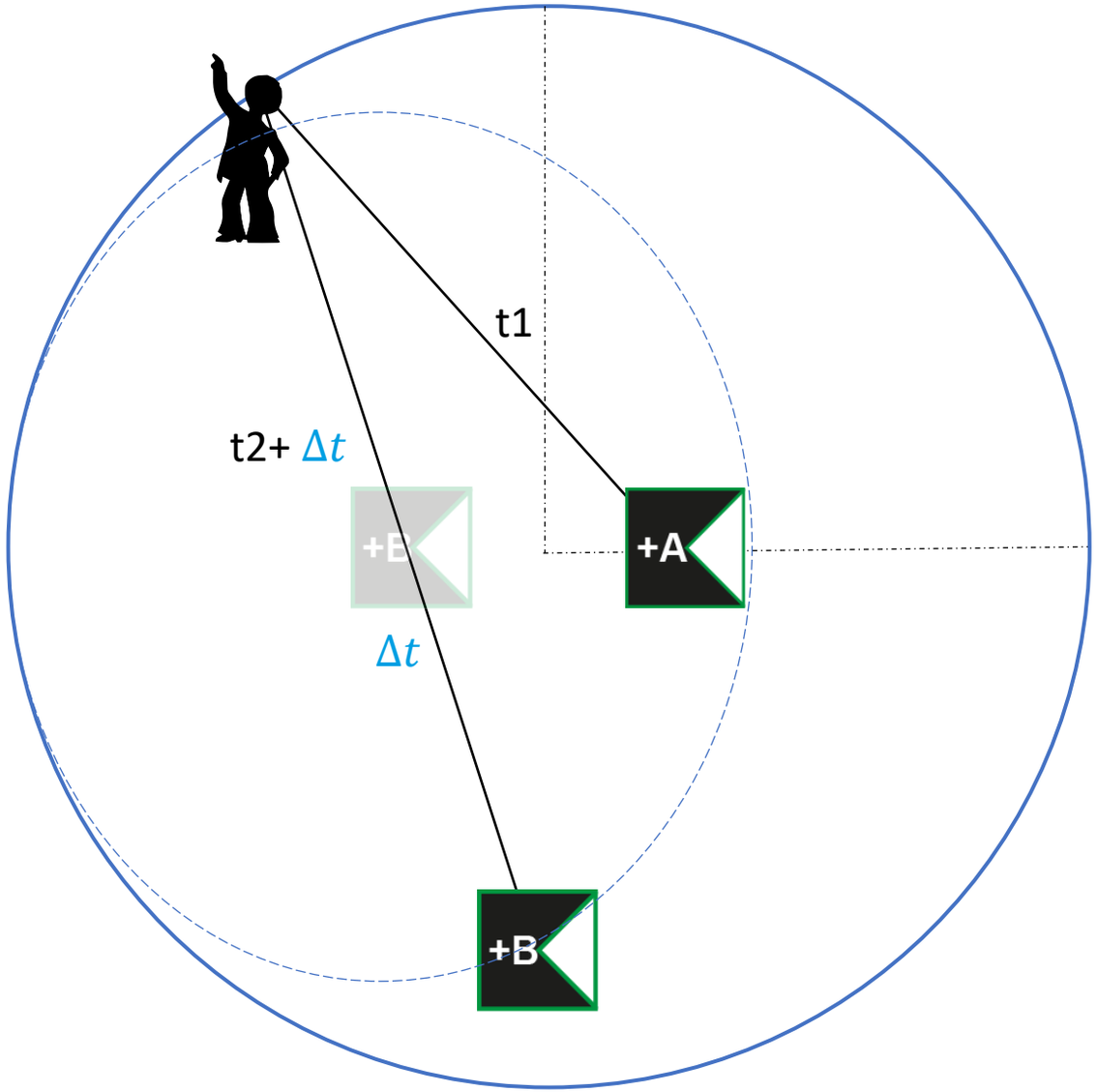
Time difference (Δt)



Time difference (Δt)



Time difference (Δt)

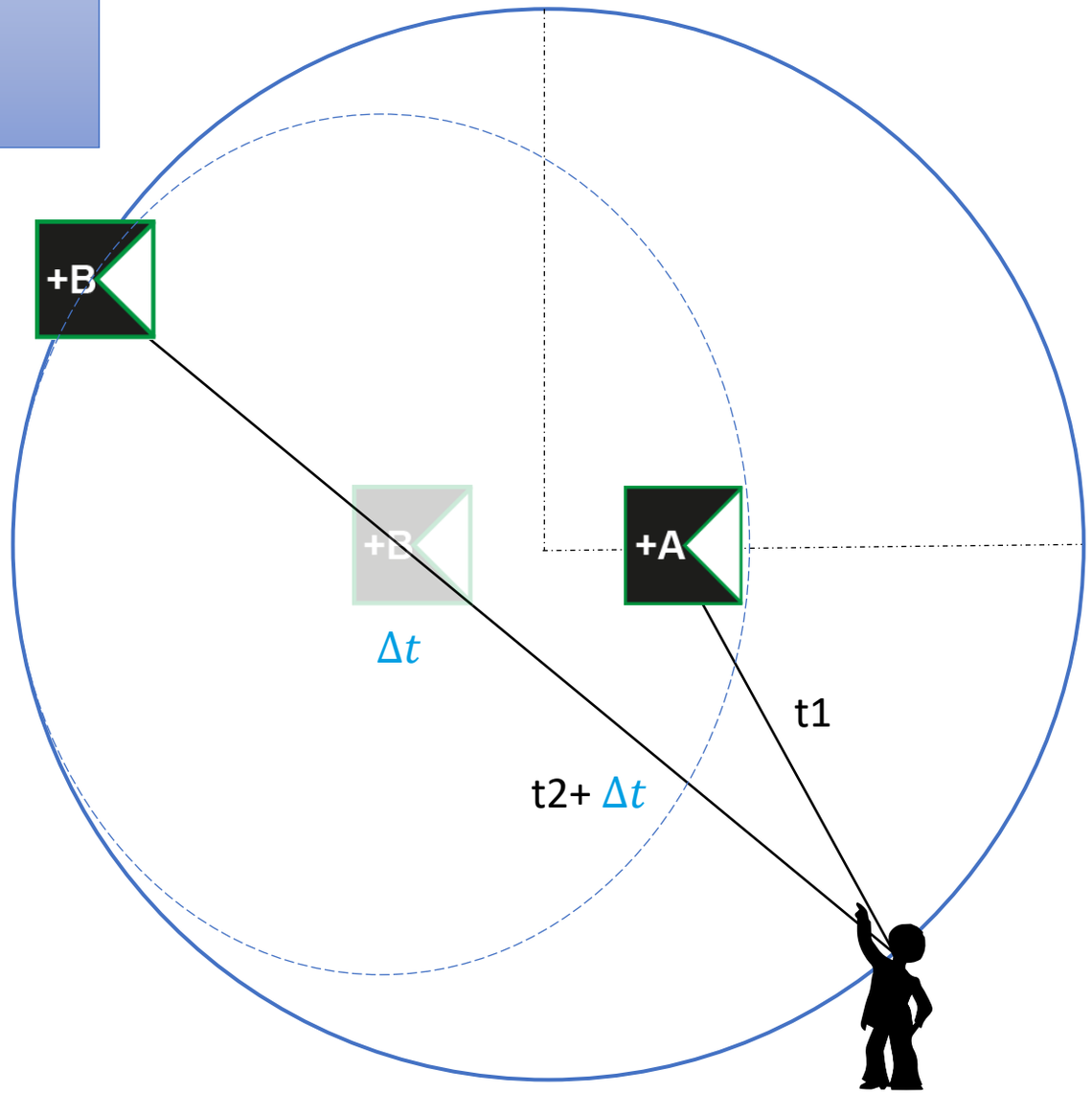


Time difference (Δt)

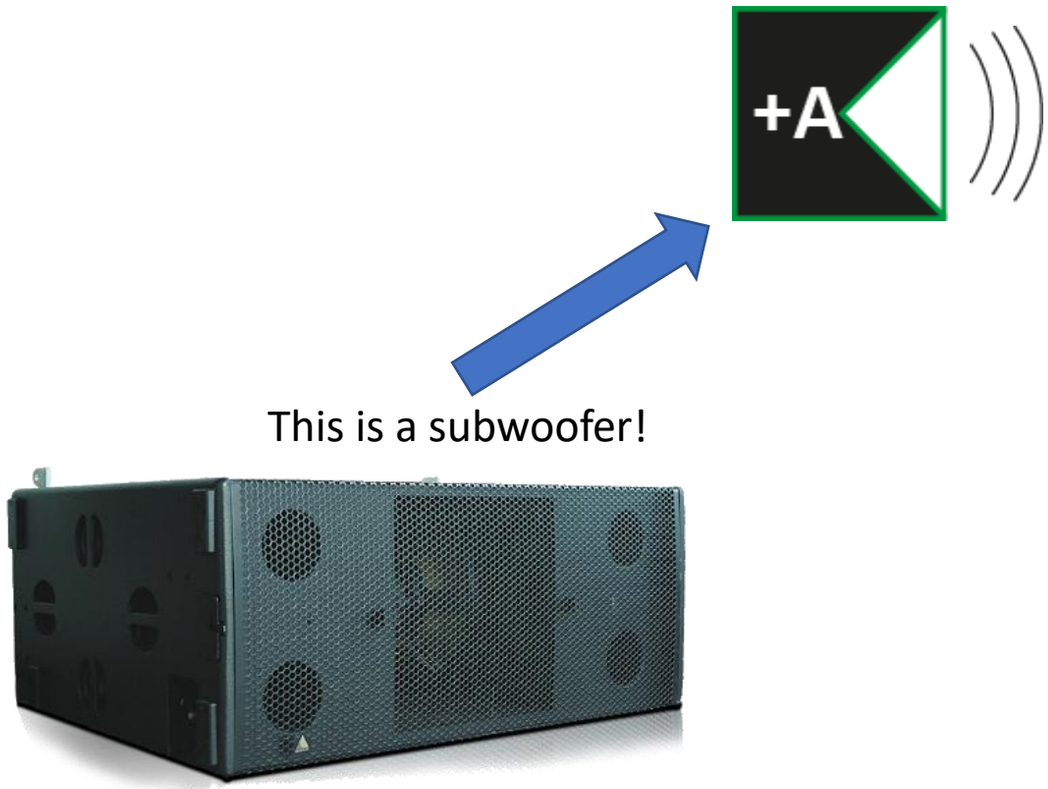
Calculating phase difference ($\Delta\varphi$)

$$\Delta_{\varphi} = \frac{\Delta_d . f . 360}{c}$$

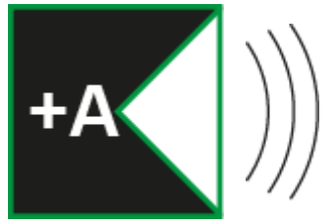
- *where:*
- *f = frequency*
- *λ = wavelength*
- *C = speed of sound*
- *Δd = path-length difference*



The suction myth



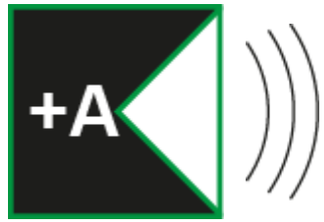
The suction myth



Or an array of subwoofers!

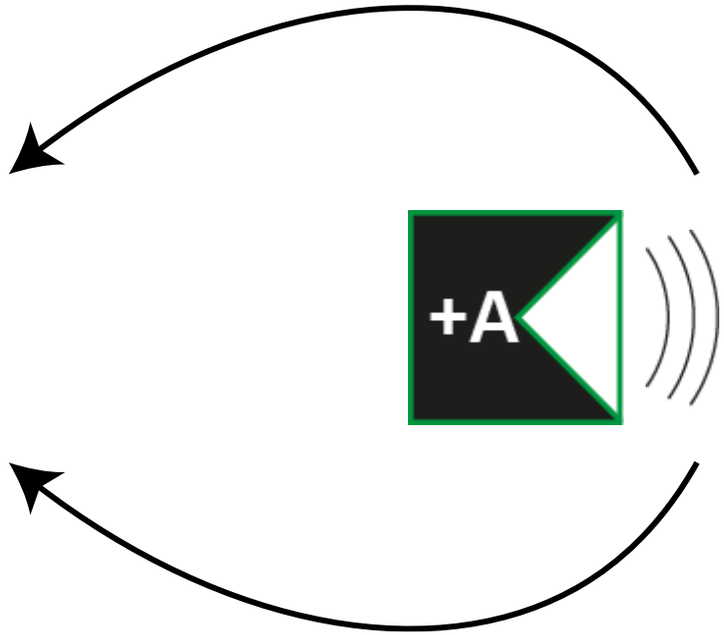


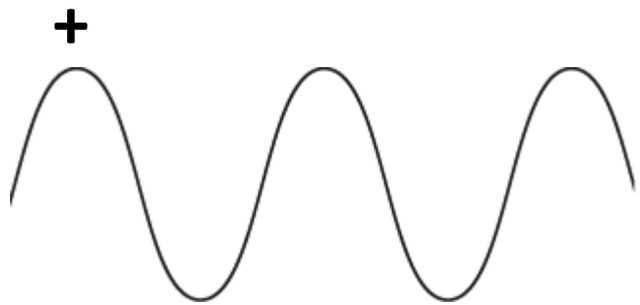
The suction myth



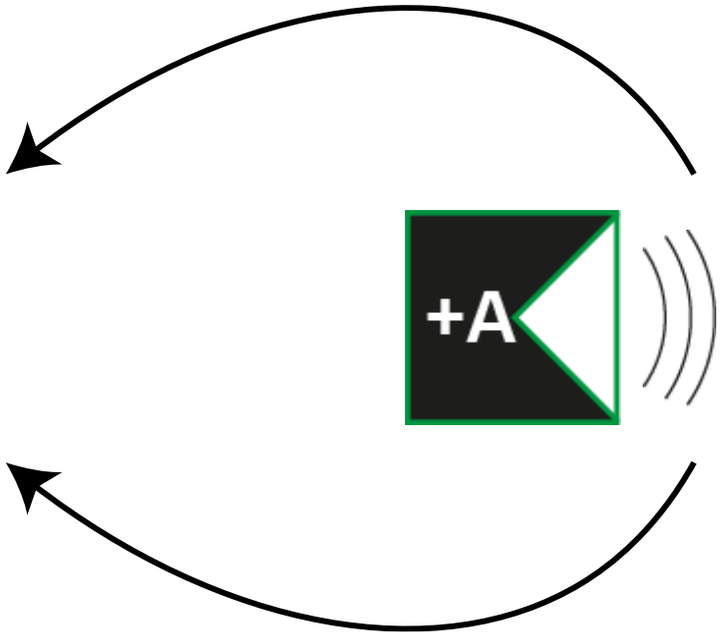


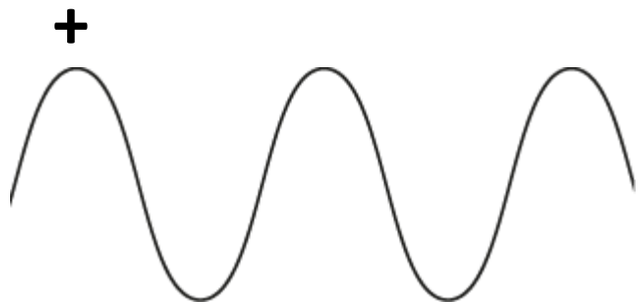
The suction myth

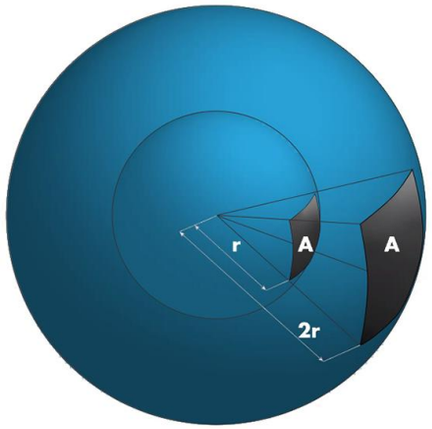




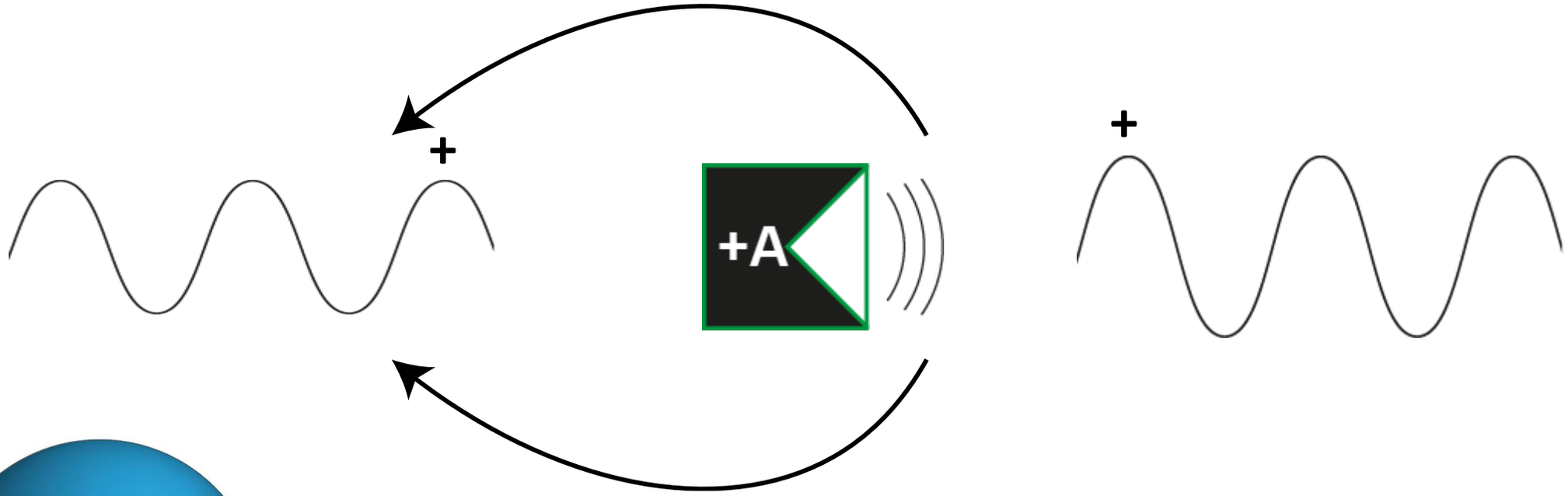
The suction myth

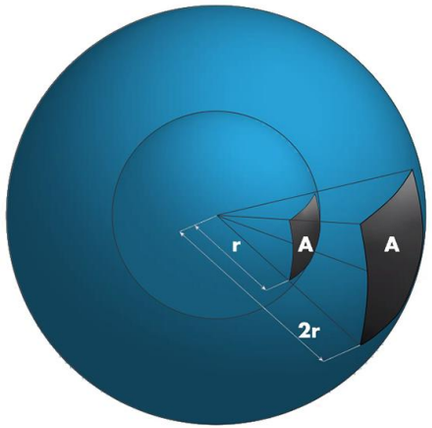




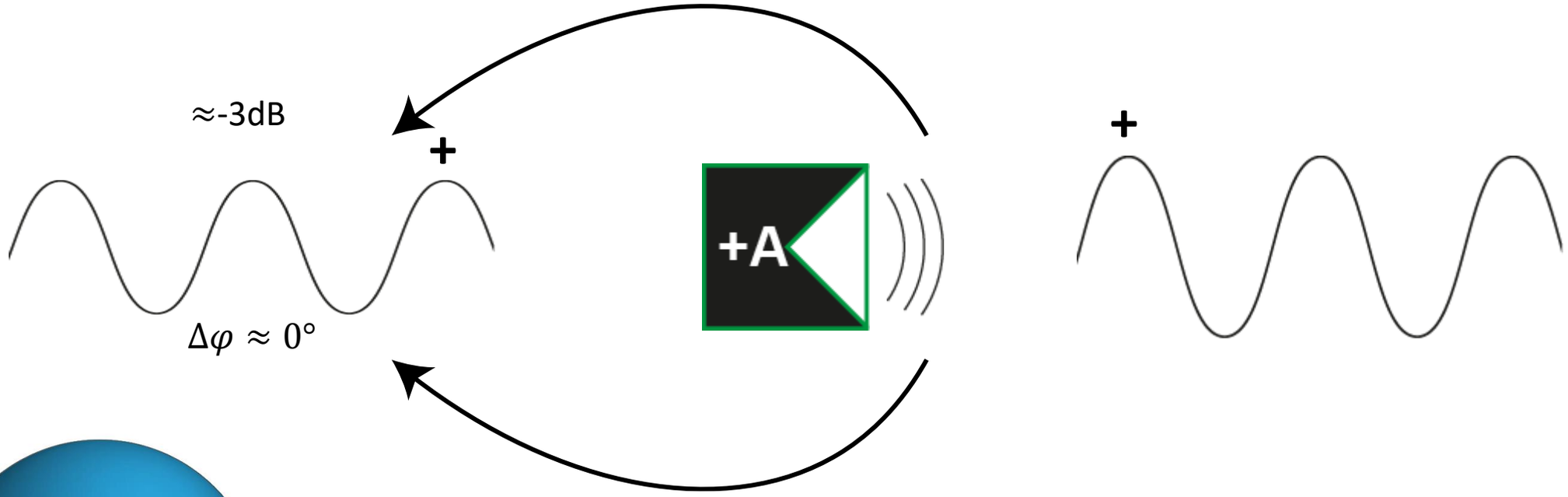


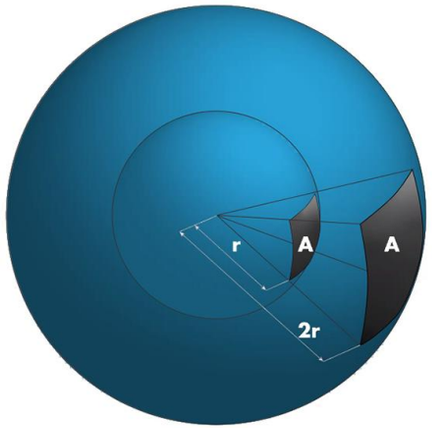
The suction myth



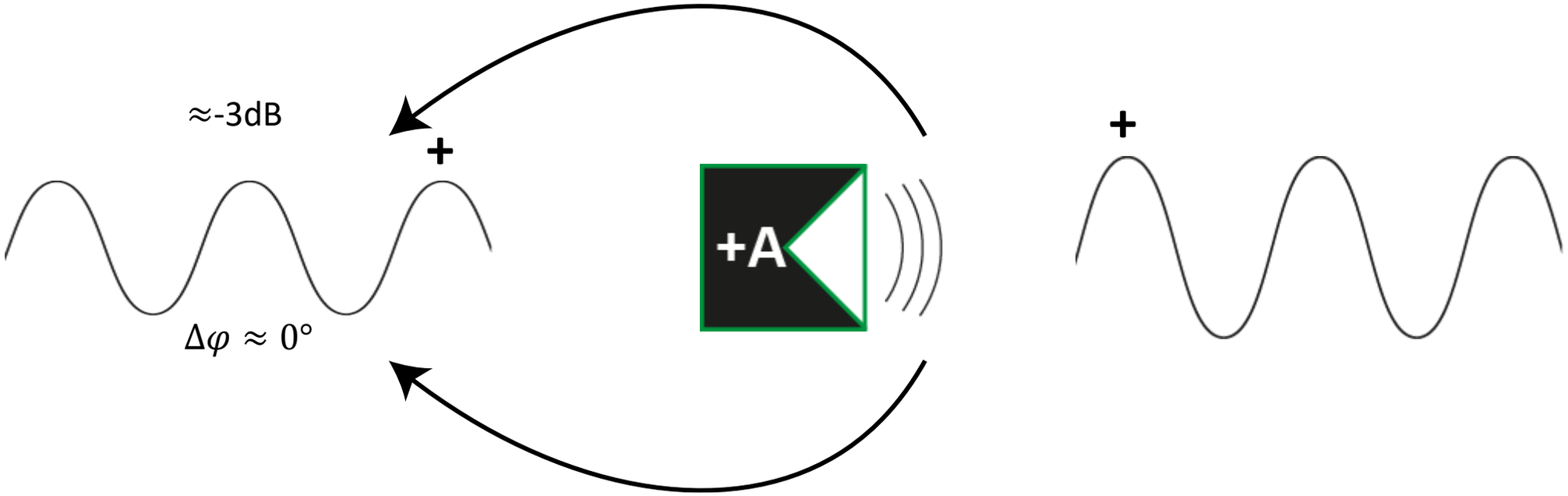


The suction myth



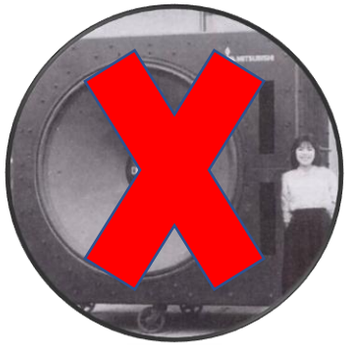


The suction myth

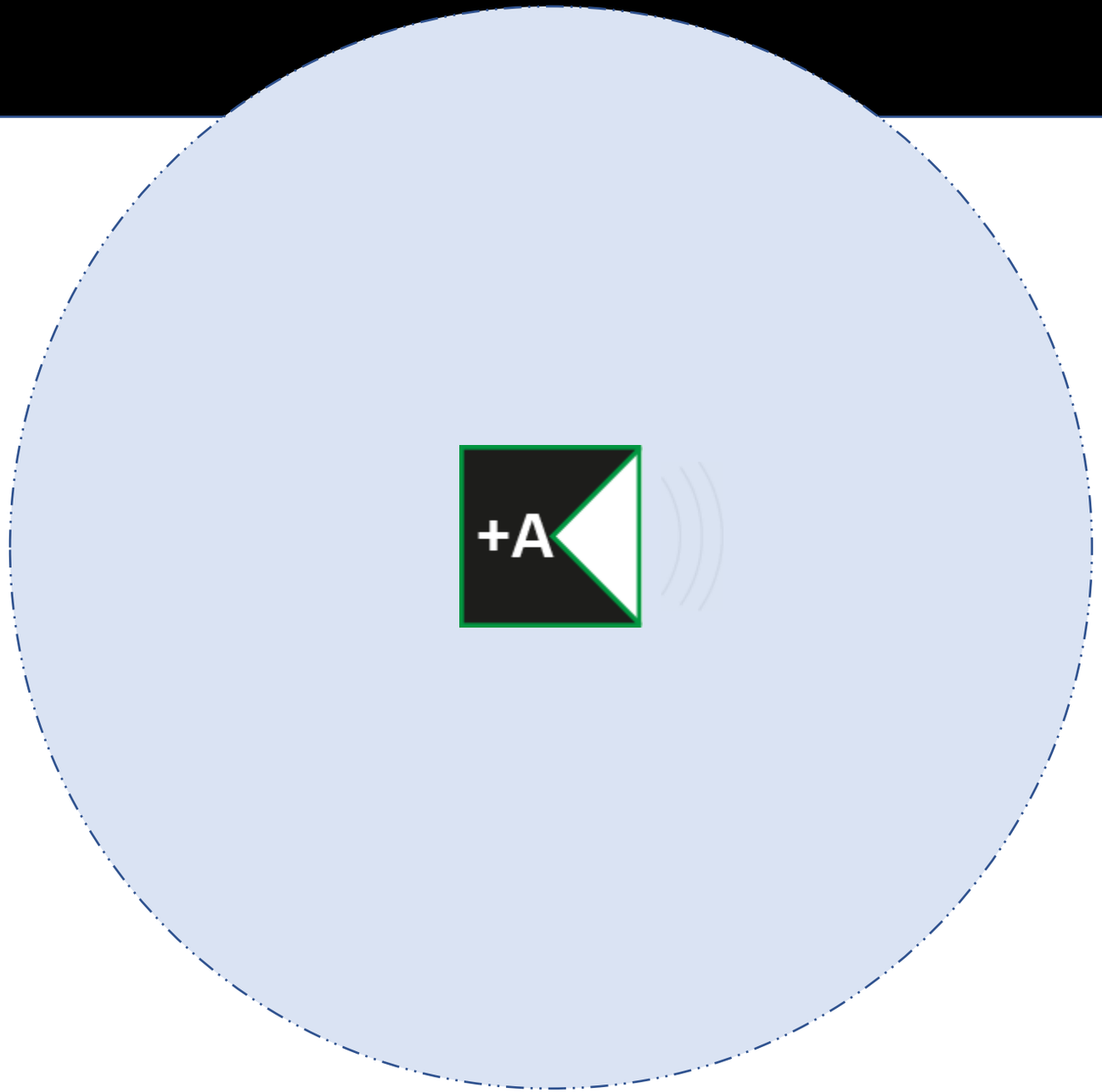




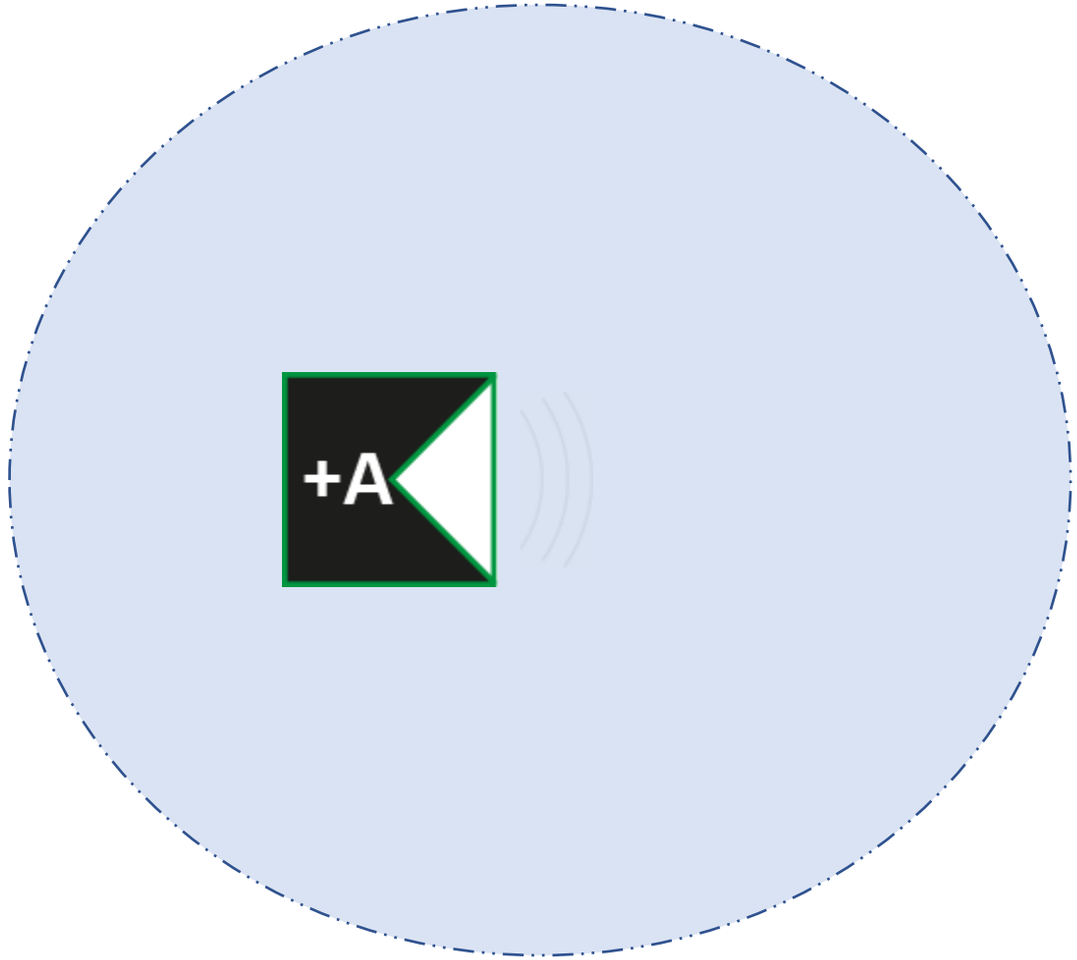
This is only true for a conventional subwoofer!



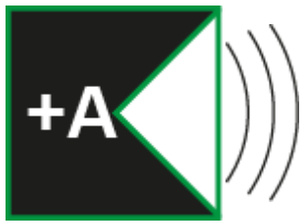
An imperfect omni



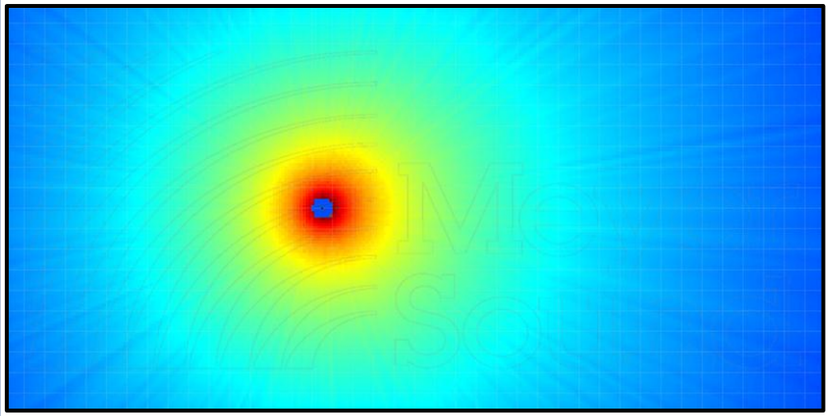
An imperfect omni



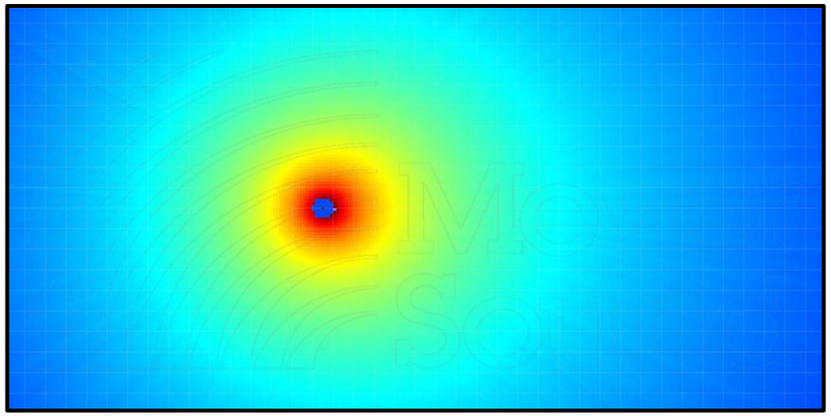
An imperfect omni



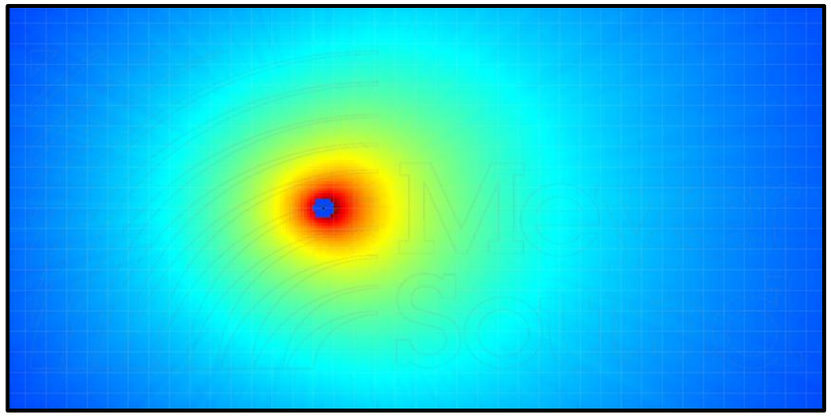
Does this look omnidirectional to you?



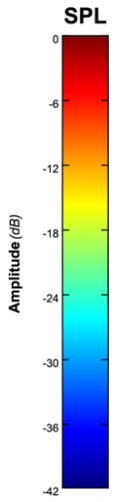
31,5 Hz



63 Hz



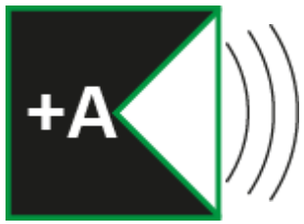
125 Hz

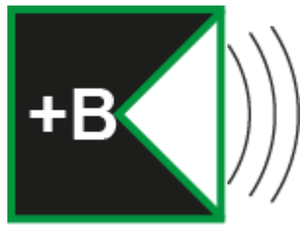


Air Attenuation On
Temperature = 15,0°C
Pressure = 101,33 kPa
Relative Humidity = 50,0 %

Relative Bandwidth = 1 octave

An imperfect omni





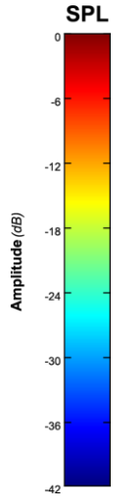
Air Attenuation On

Temperature = 15,0°C

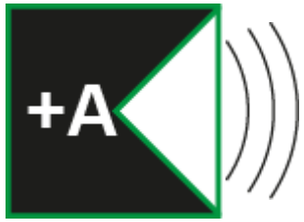
Pressure = 101,33 kPa

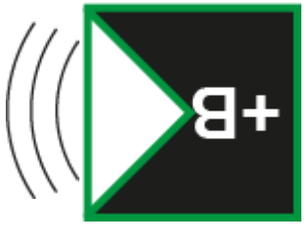
Relative Humidity = 50,0 %

Relative Bandwidth = 1 octave



An imperfect omni





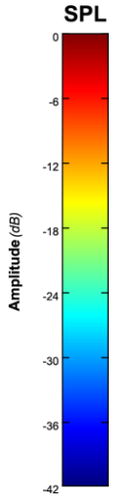
Air Attenuation On

Temperature = 15,0°C

Pressure = 101,33 kPa

Relative Humidity = 50,0 %

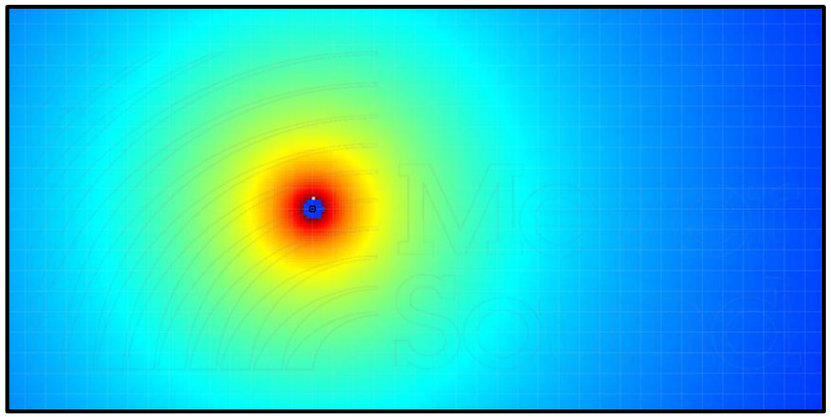
Relative Bandwidth = 1 octave



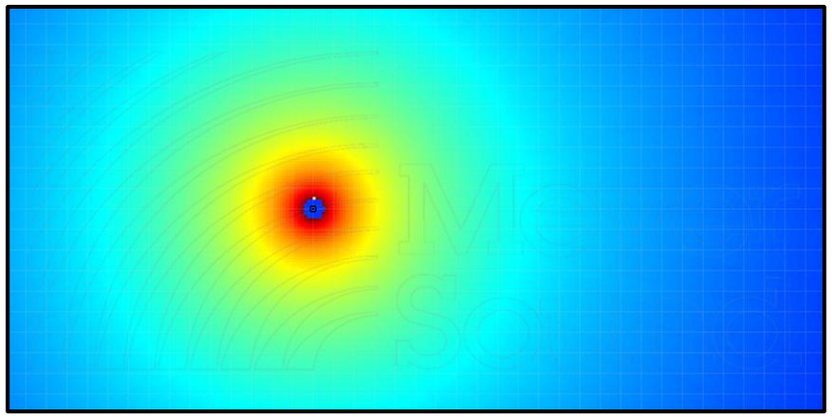
A perfect virtual omni

At a single point

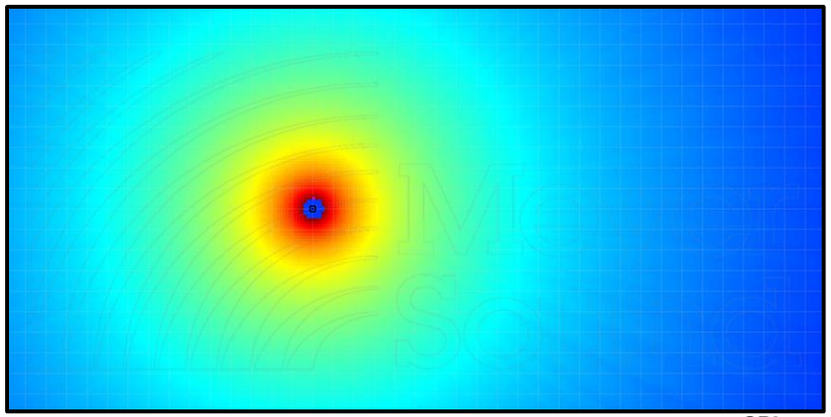




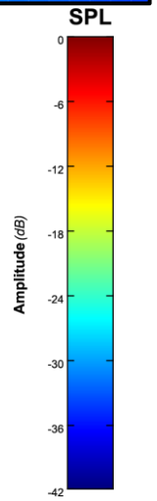
31,5 Hz



63 Hz



125 Hz



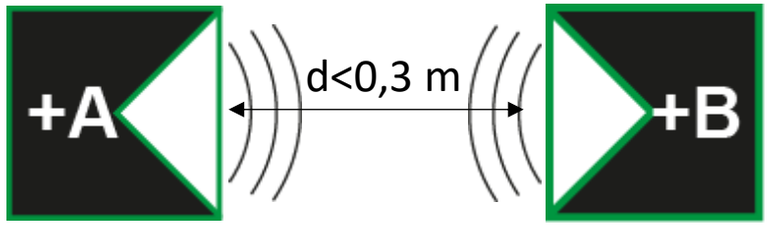
Air Attenuation On
Temperature = 15,0°C
Pressure = 101,33 kPa
Relative Humidity = 50,0 %

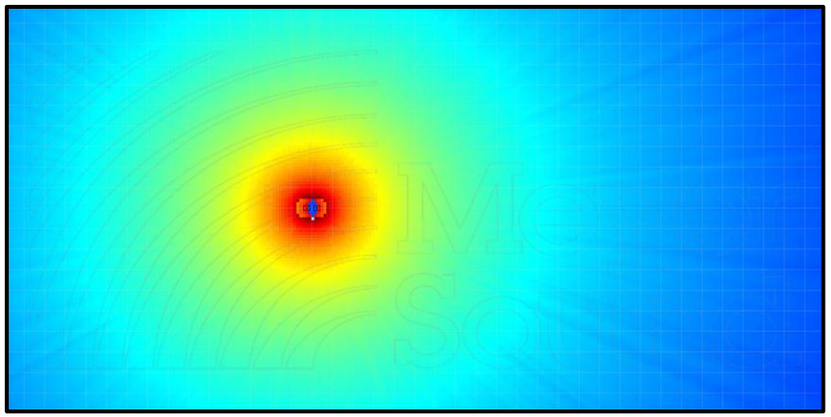
Relative Bandwidth = 1 octave

Very convenient for simulation software!

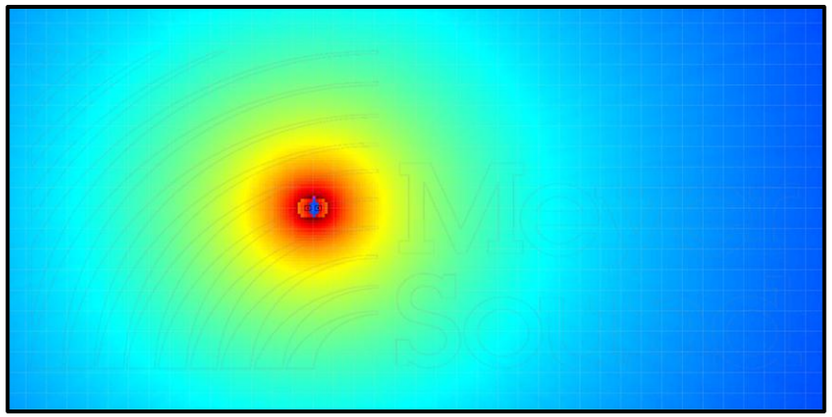
A perfect real-world omni

Front to front

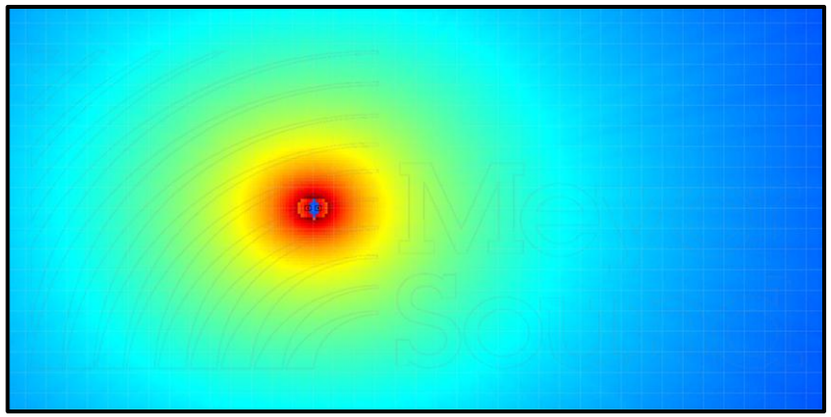




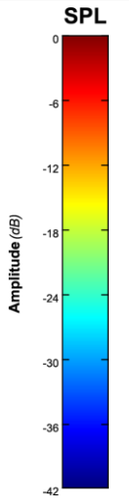
31,5 Hz



63 Hz



125 Hz



Air Attenuation On

Temperature = 15,0°C

Pressure = 101,33 kPa

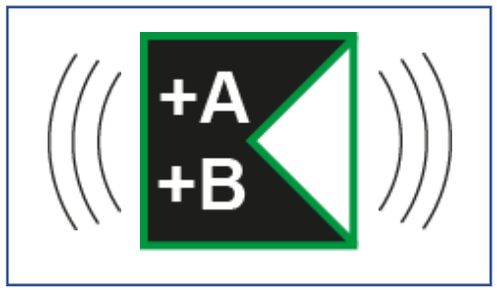
Relative Humidity = 50,0 %

Relative Bandwidth = 1 octave

A perfect omni

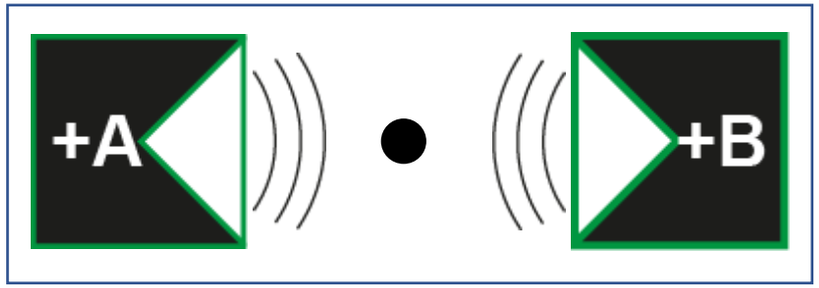
Many of the following configurations assume that the subwoofers are fully omnidirectional.

This is not the case in practice. However, you can use this type of arrangement to improve future configurations, calculating from the resulting acoustic centres.



=
A fully omnidirectional sub, +6 dB, with the same acoustic centre

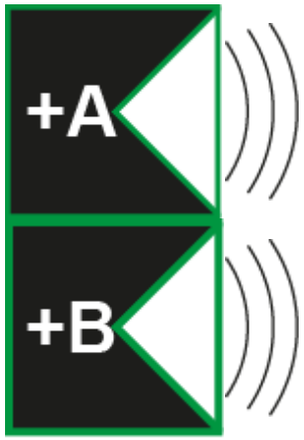
This is called a point source.



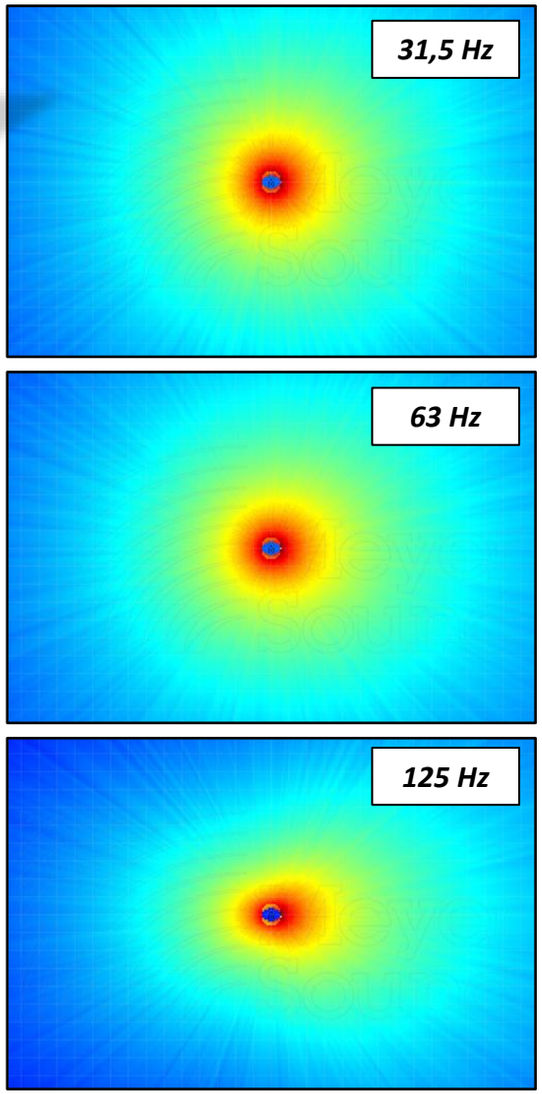
=
A fully omnidirectional sub, ≈ +6 dB, with a virtual acoustic centre at the midpoint

Delay and polarity
Our first summations

f	T	T/2	T/4
31 Hz	32 ms	16 ms	8 ms
63Hz	16 ms	8 ms	4 ms
125 Hz	8ms	4 ms	2 ms

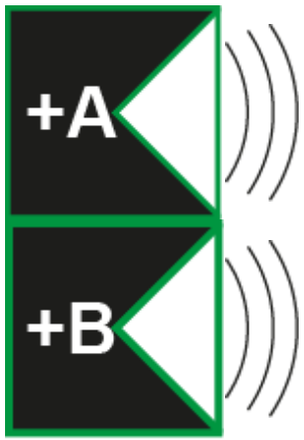


2 subs — same polarity

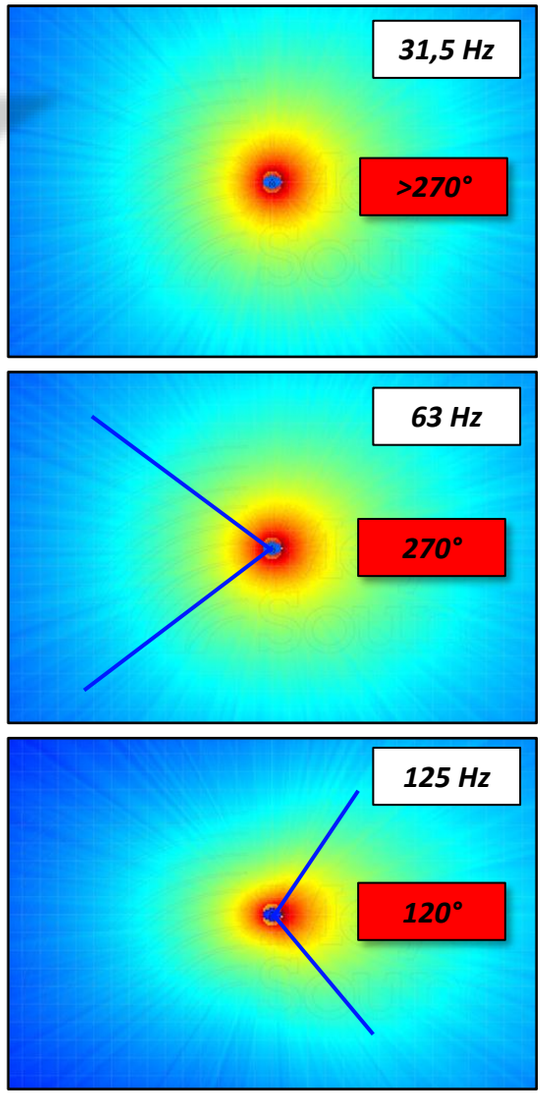


Delay and polarity
Our first summations

f	T	T/2	T/4
31 Hz	32 ms	16 ms	8 ms
63Hz	16 ms	8 ms	4 ms
125 Hz	8ms	4 ms	2 ms



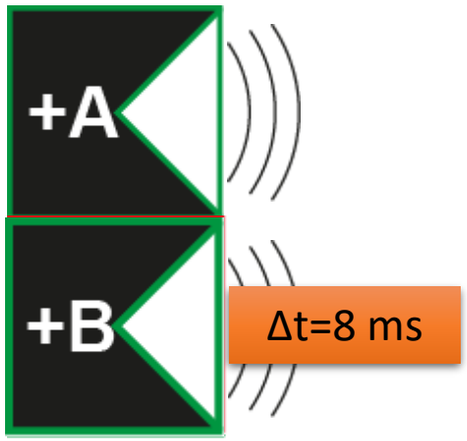
2 subs — same polarity

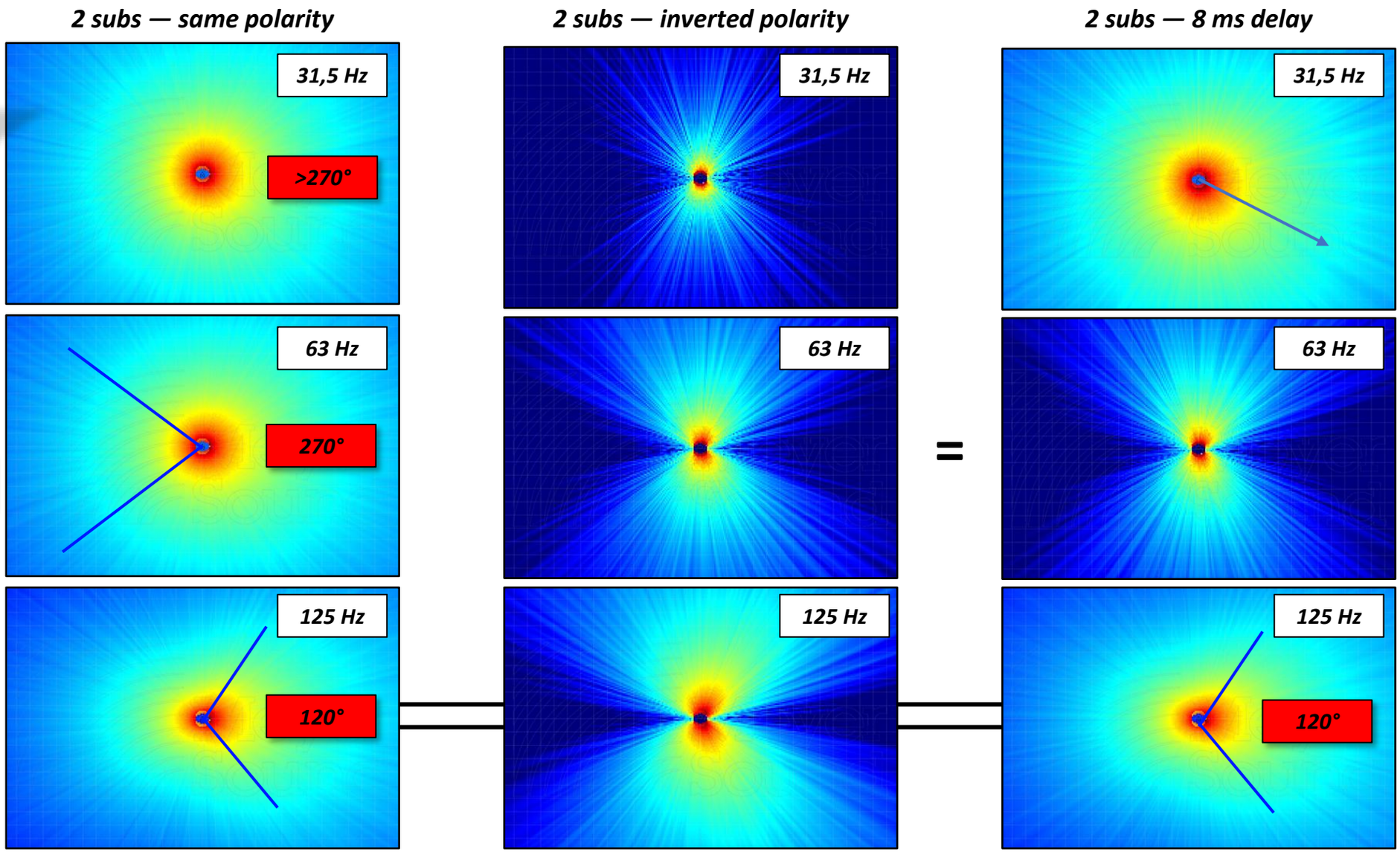


Coverage narrows as frequency increases

Delay and polarity
Our first summations

f	T	T/2	T/4
31 Hz	32 ms	16 ms	8 ms
63Hz	16 ms	8 ms	4 ms
125 Hz	8ms	4 ms	2 ms





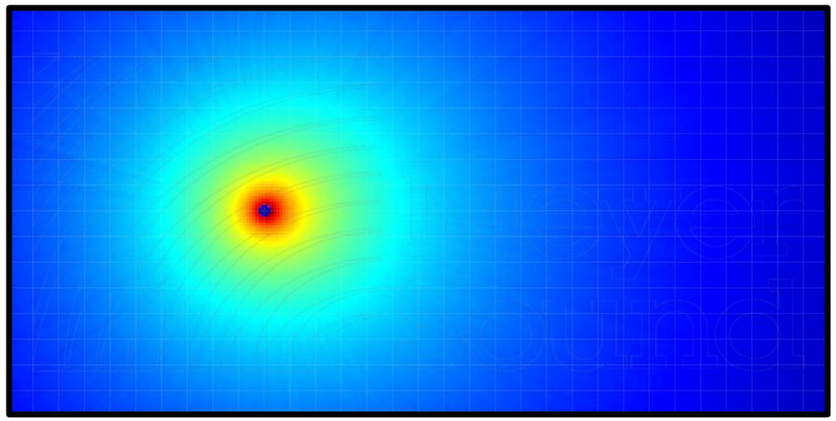
?

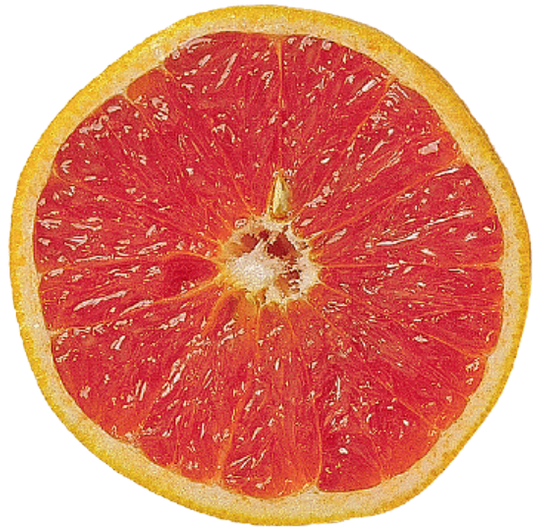


2
Steering effect

Steering effect

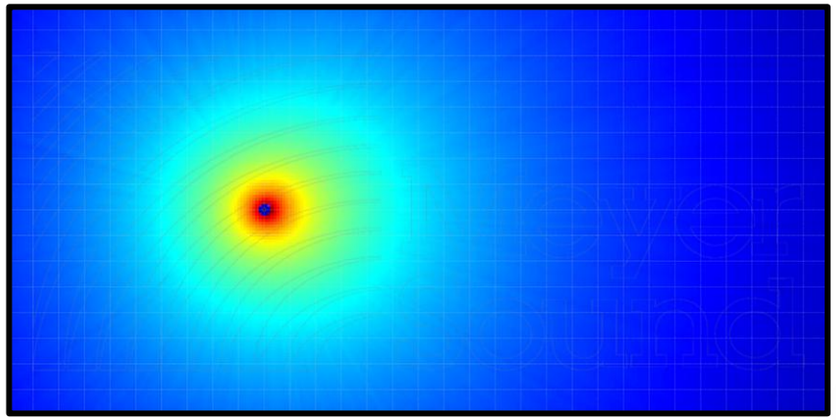
1 Sub



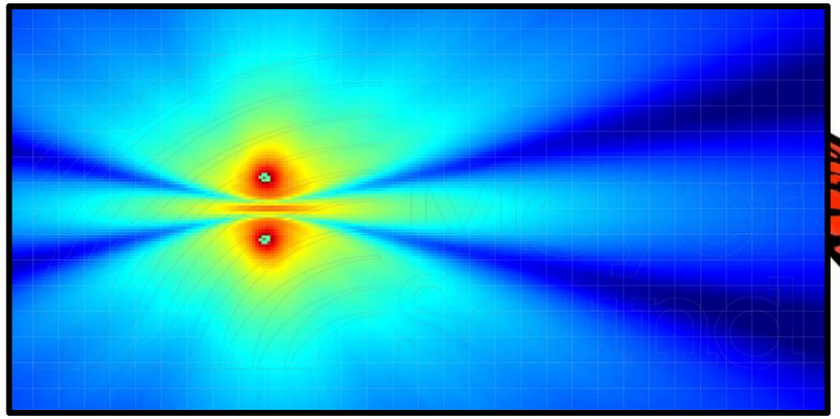


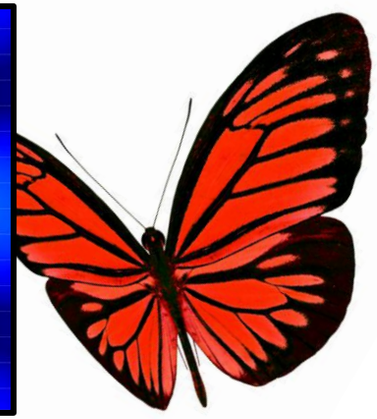
Steering effect

1 Sub



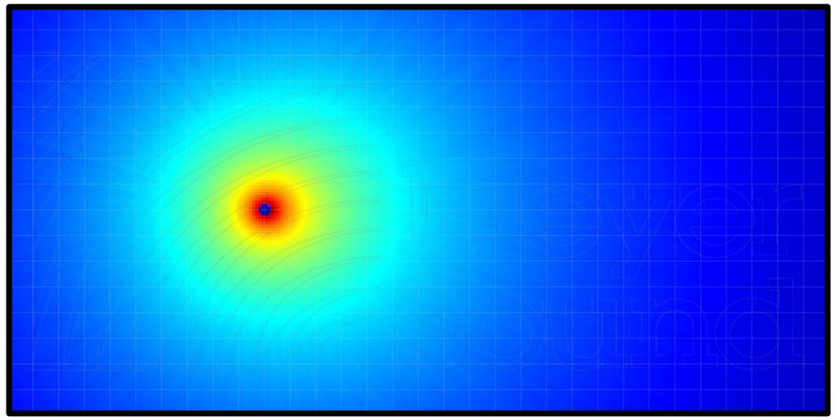
2 subs — 12 metres



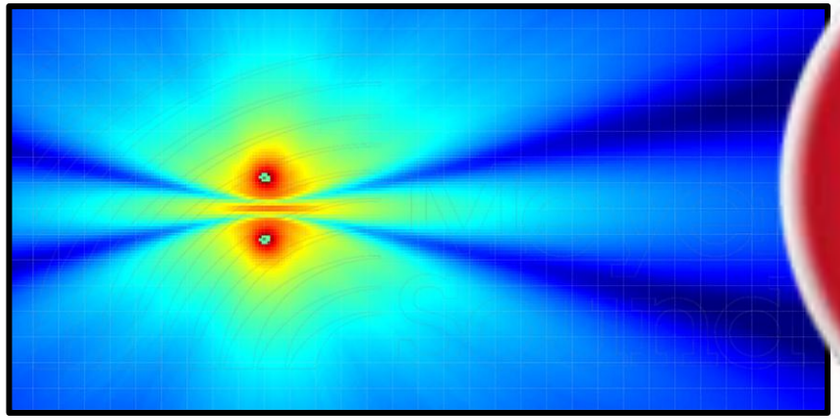


Steering effect

1 Sub



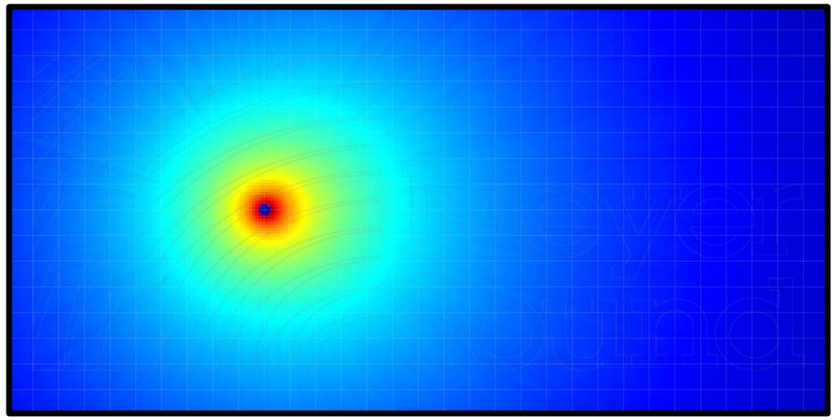
2 subs — 12 metres



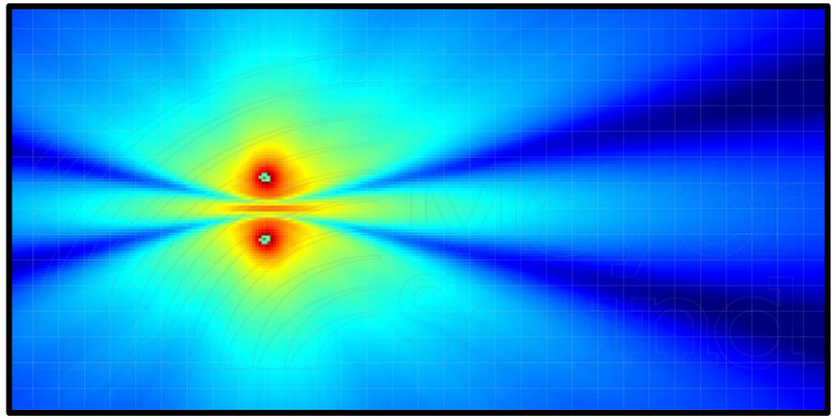


Steering effect

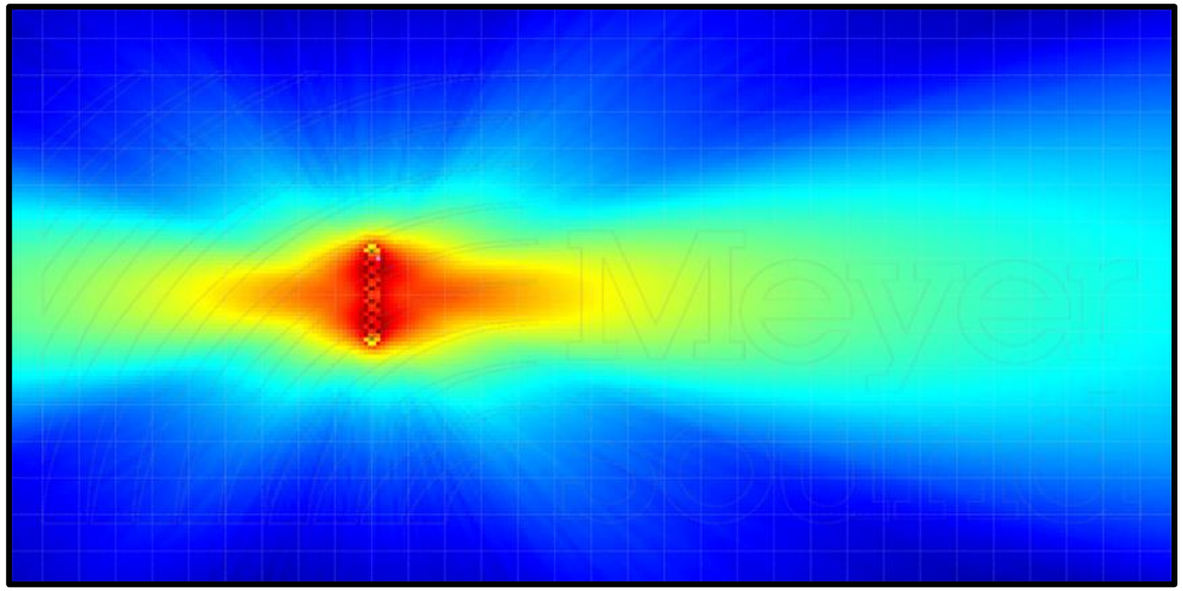
1 Sub



2 subs — 12 metres

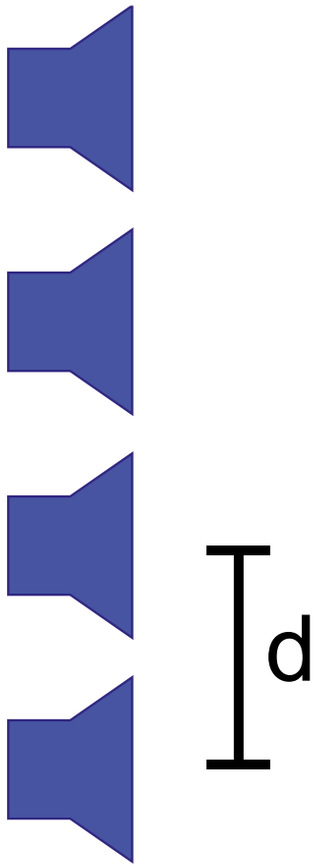


8 subs — 12 metres

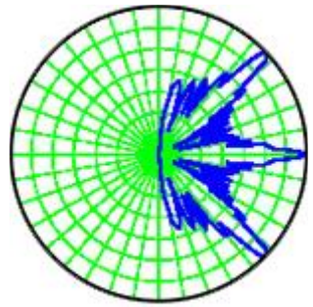




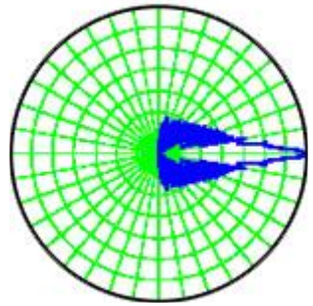
Steering effect
Maximum spacing



d > λ/2



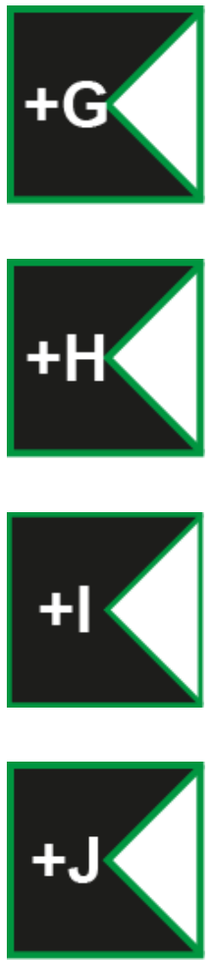
d < λ/2



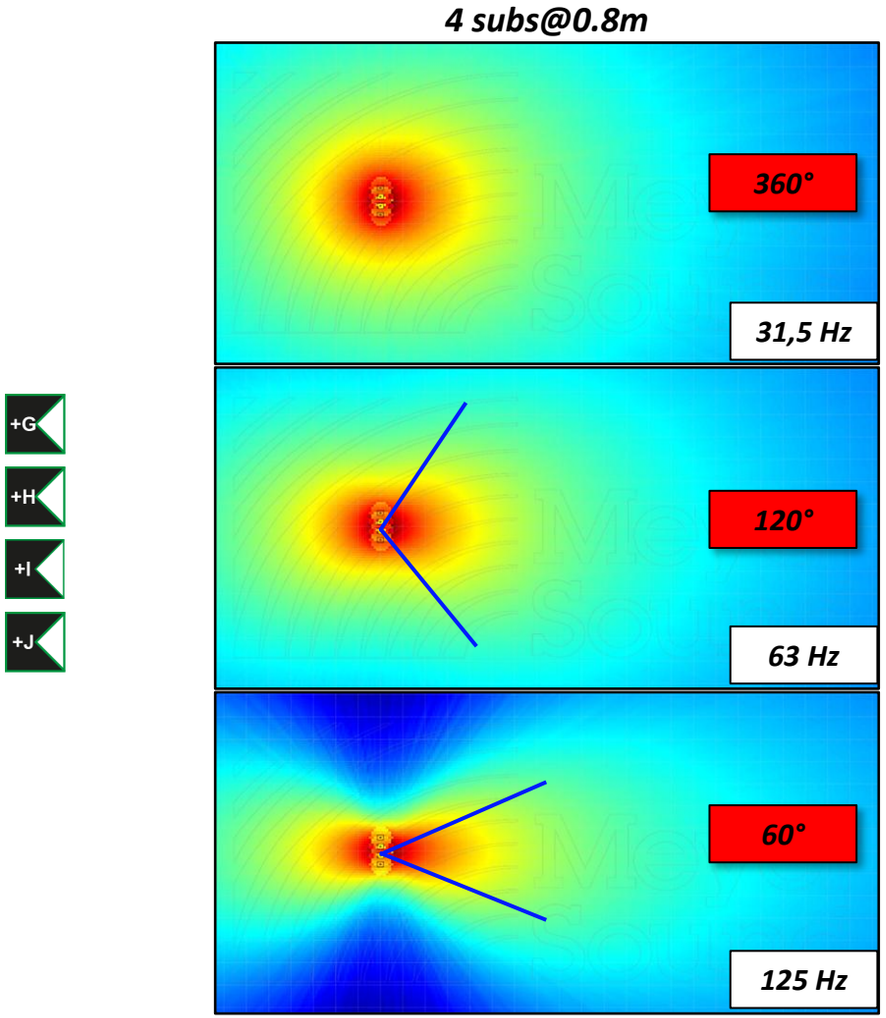
f	λ	λ/2
25 Hz	13.6 m	6.80 m
31,5 Hz	10.79 m	5.40 m
40 Hz	8.5 m	4.25 m
50 Hz	6.8 m	3.40 m
63 Hz	5.4 m	2.70 m
80 Hz	4.25 m	2.12 m
100 Hz	3.4 m	1.70 m
125 Hz	2.72 m	1.36 m

d = distance between source centres

Steering effect
Quantity

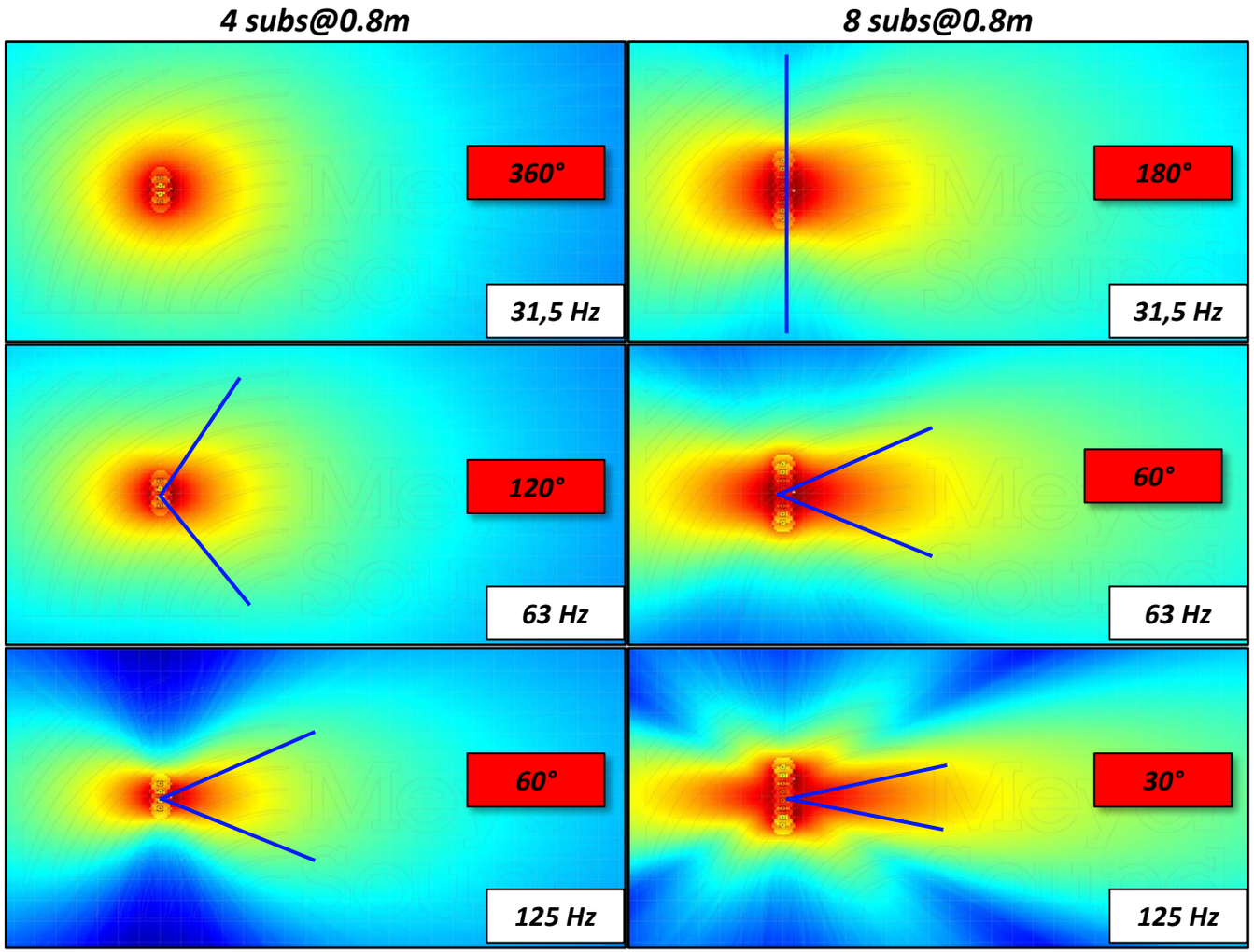


Steering effect
Quantity

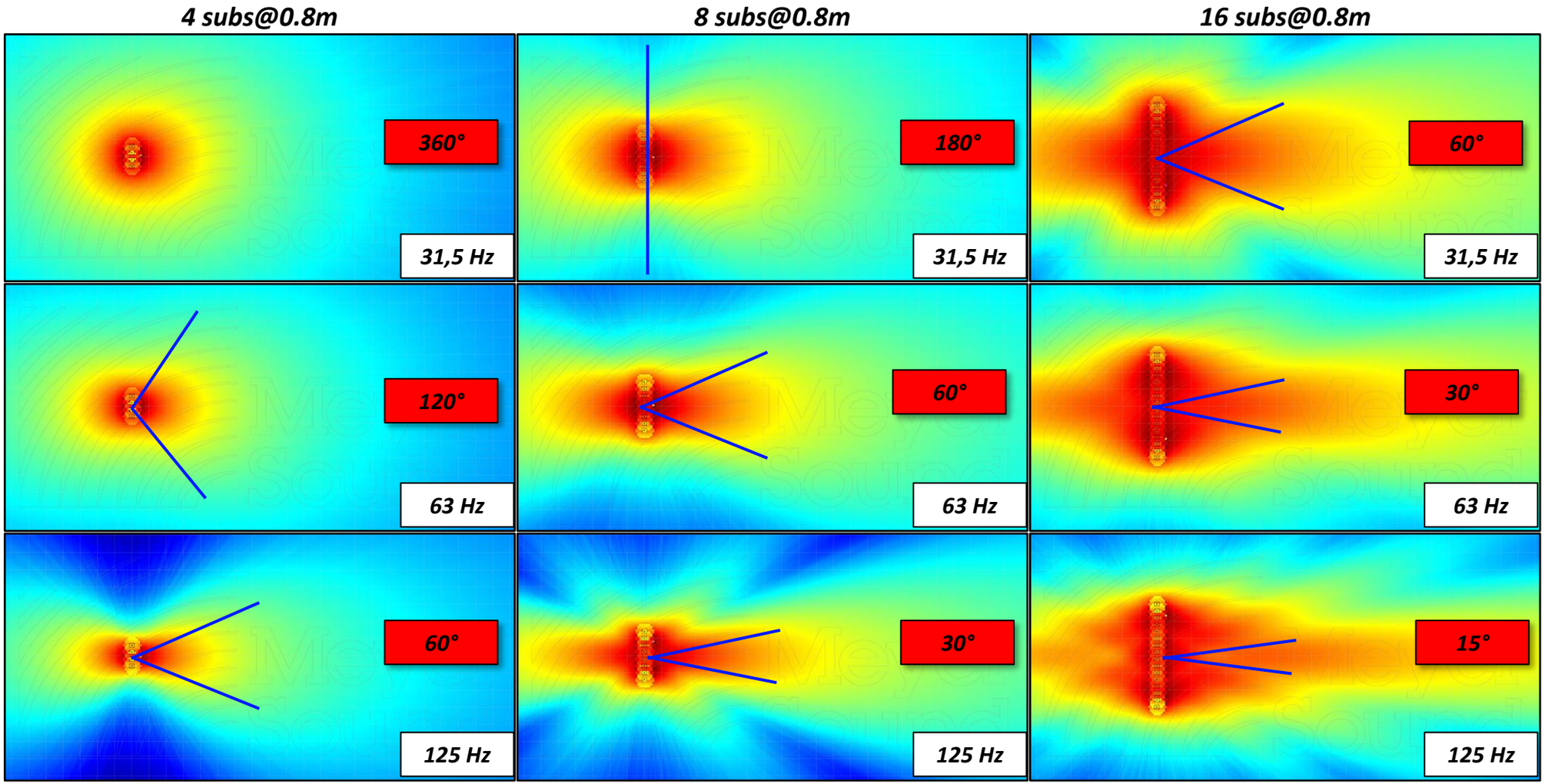


Steering effect
Quantity

+E
+F
+G
+H
+I
+J
+K
+L

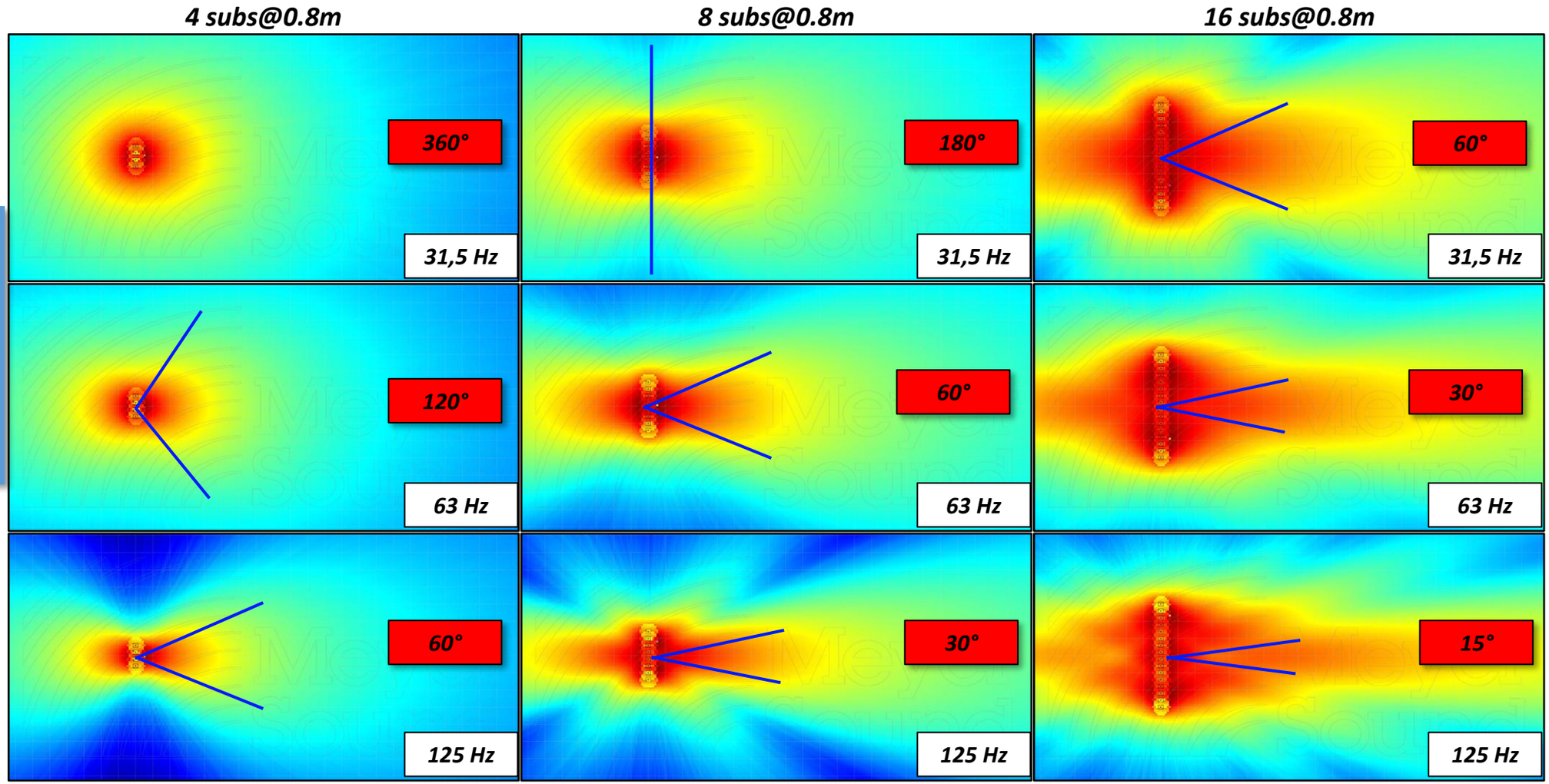


Steering effect
Quantity



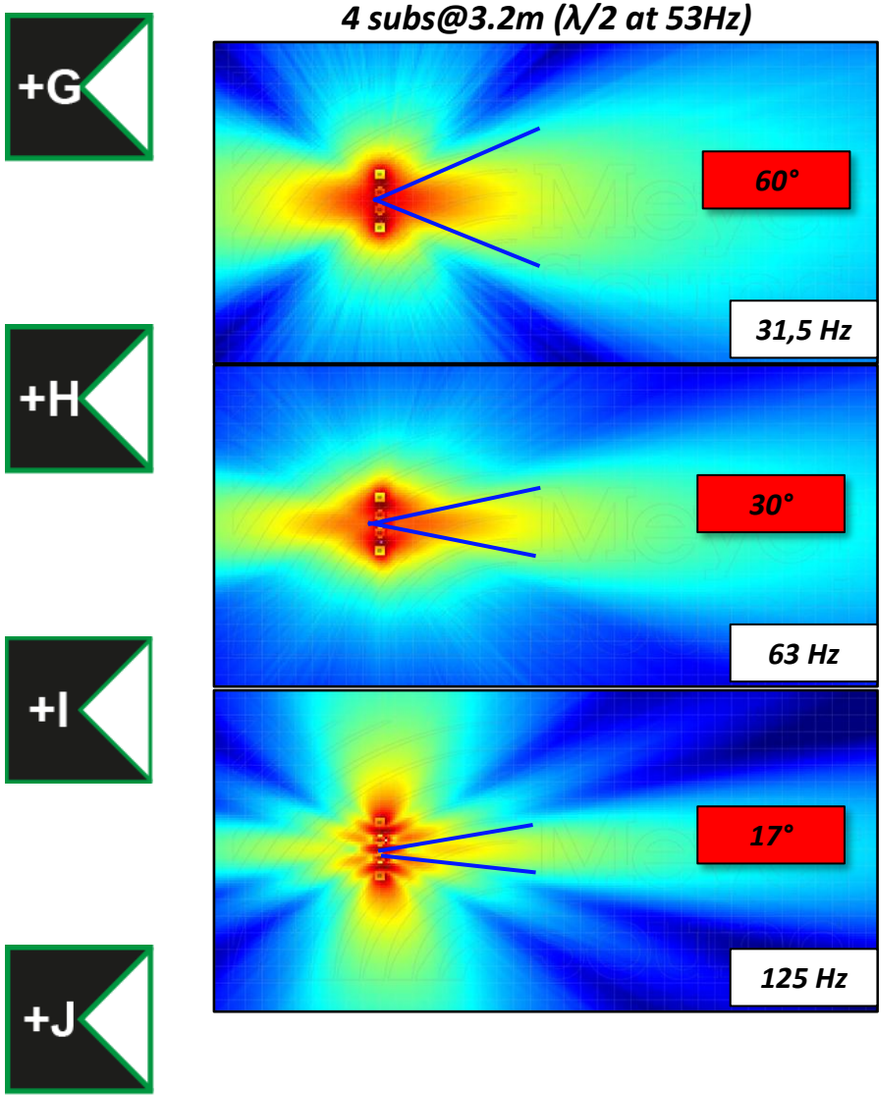
Steering effect
Quantity

As frequency increases, coverage narrows.



As the number of subwoofers increases, coverage narrows.

Steering effect
Position



Steering effect
Position

+E

+F

+G

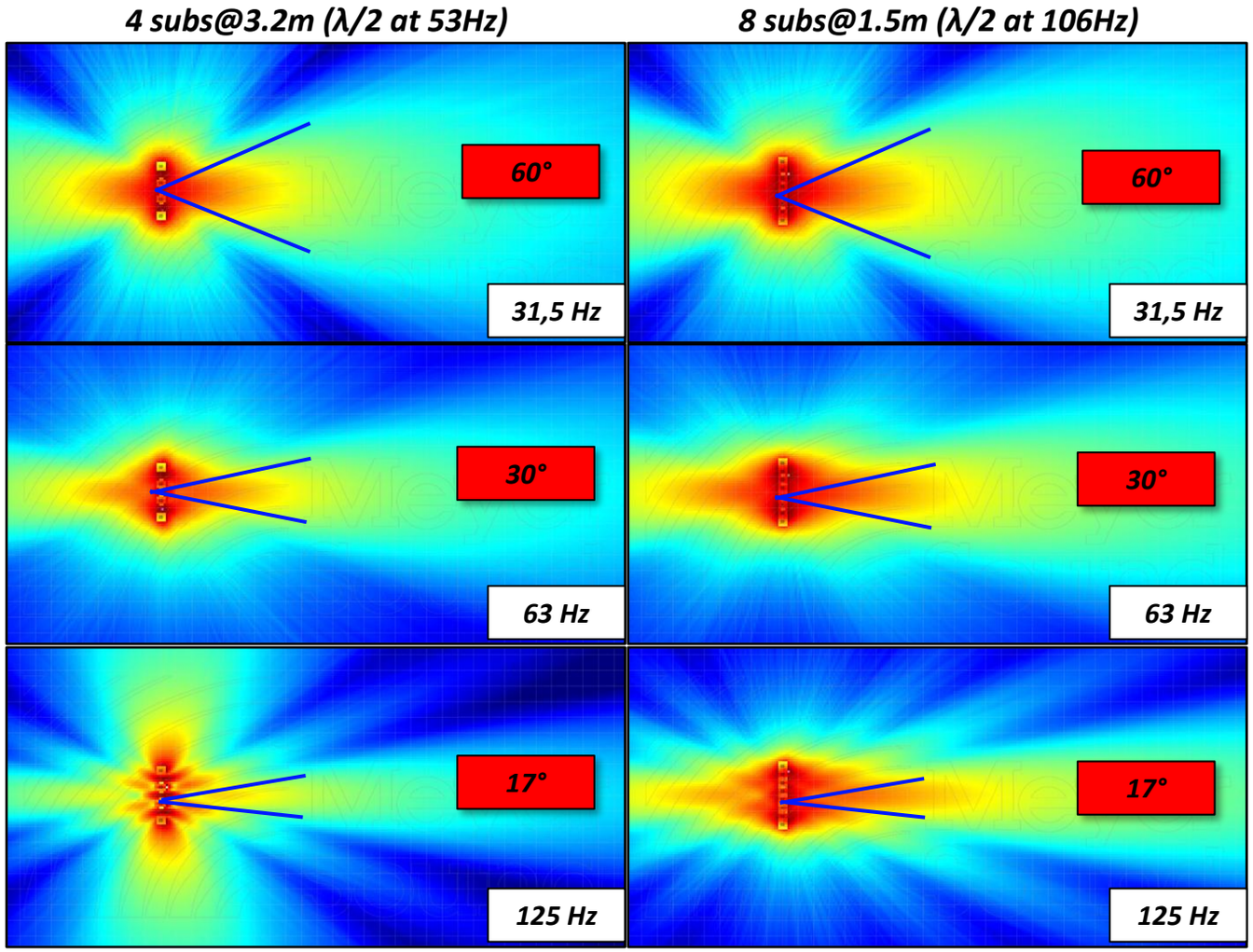
+H

+I

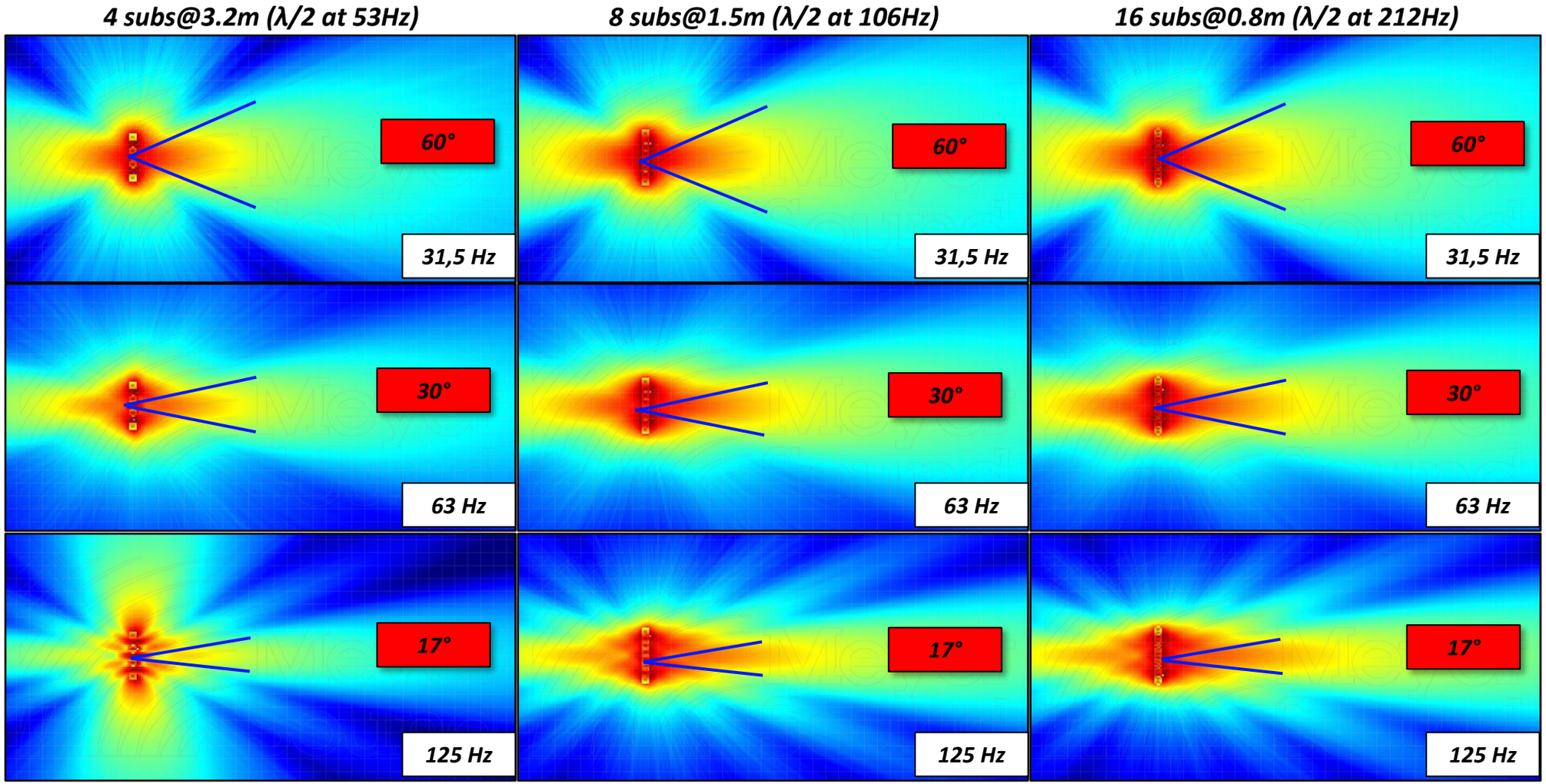
+J

+K

+L

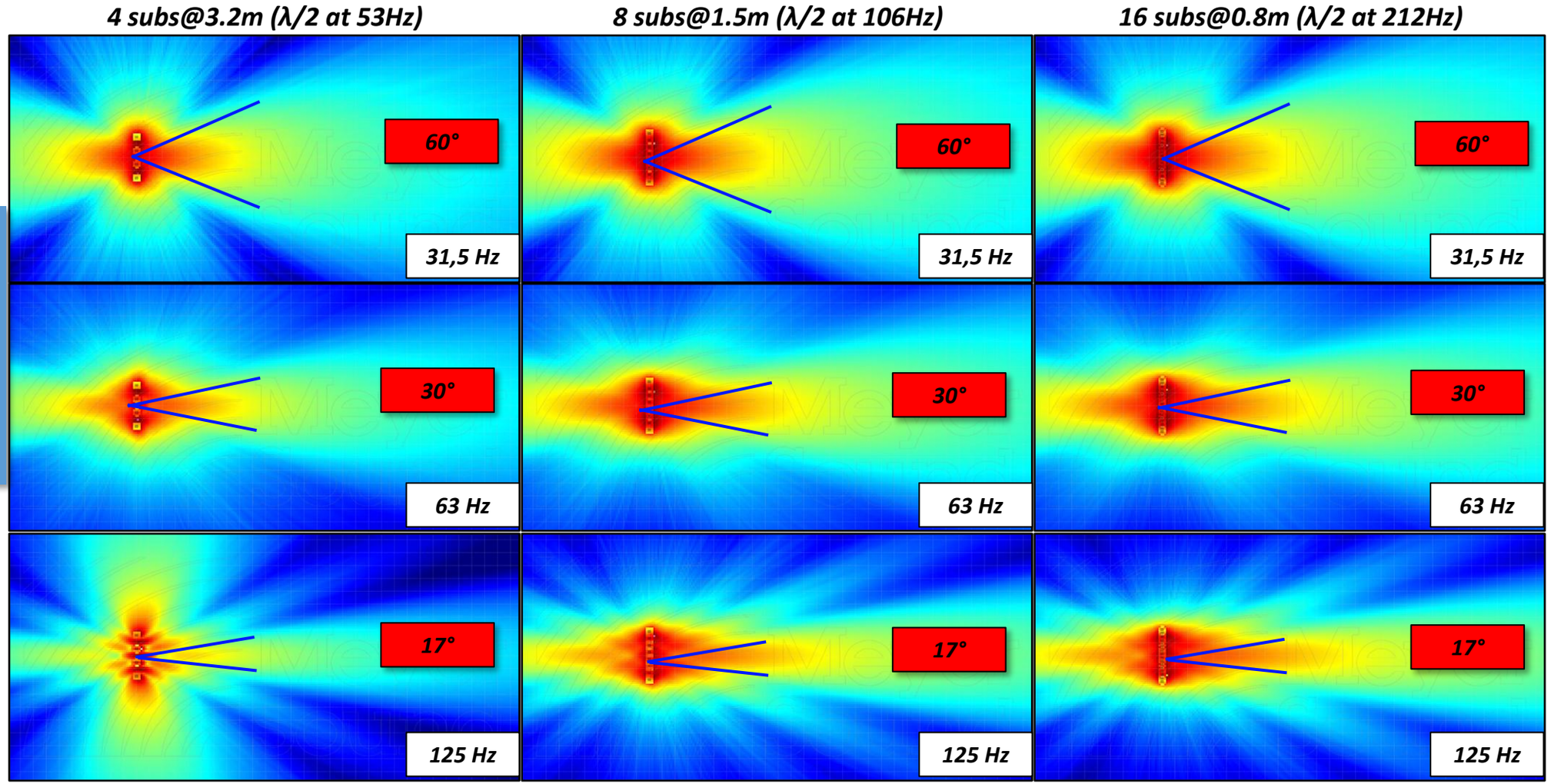


Steering effect
Position



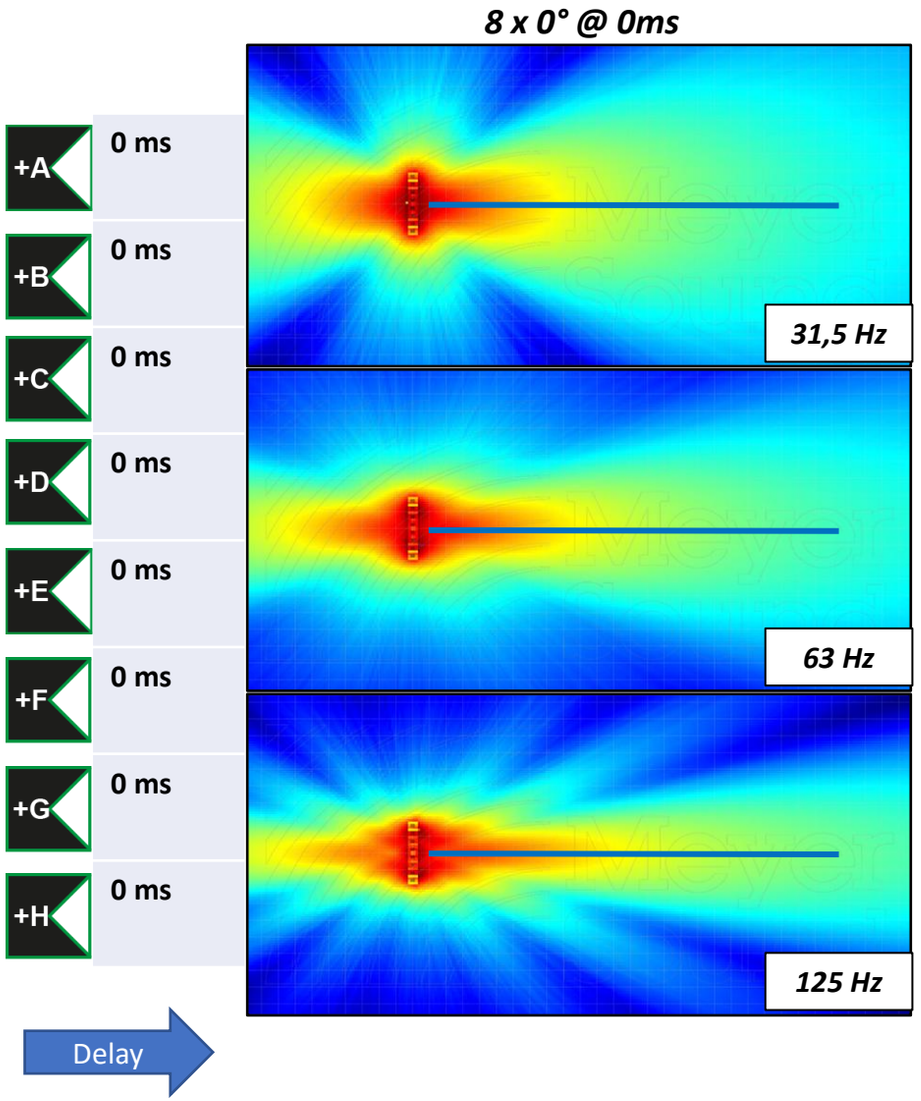
Steering effect
Position

As frequency increases, coverage narrows.

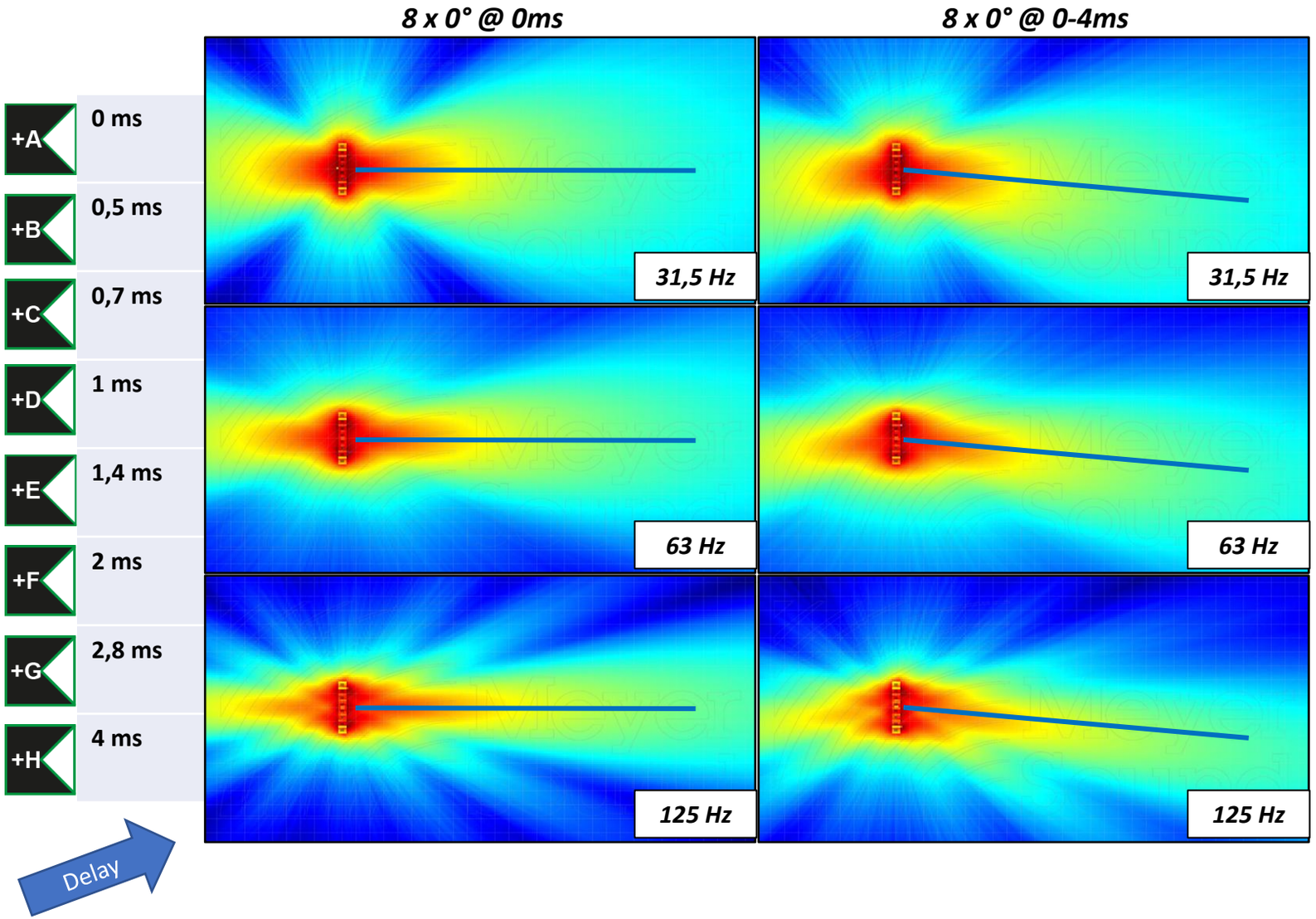


When the number of subwoofers increases, coverage stays the same.

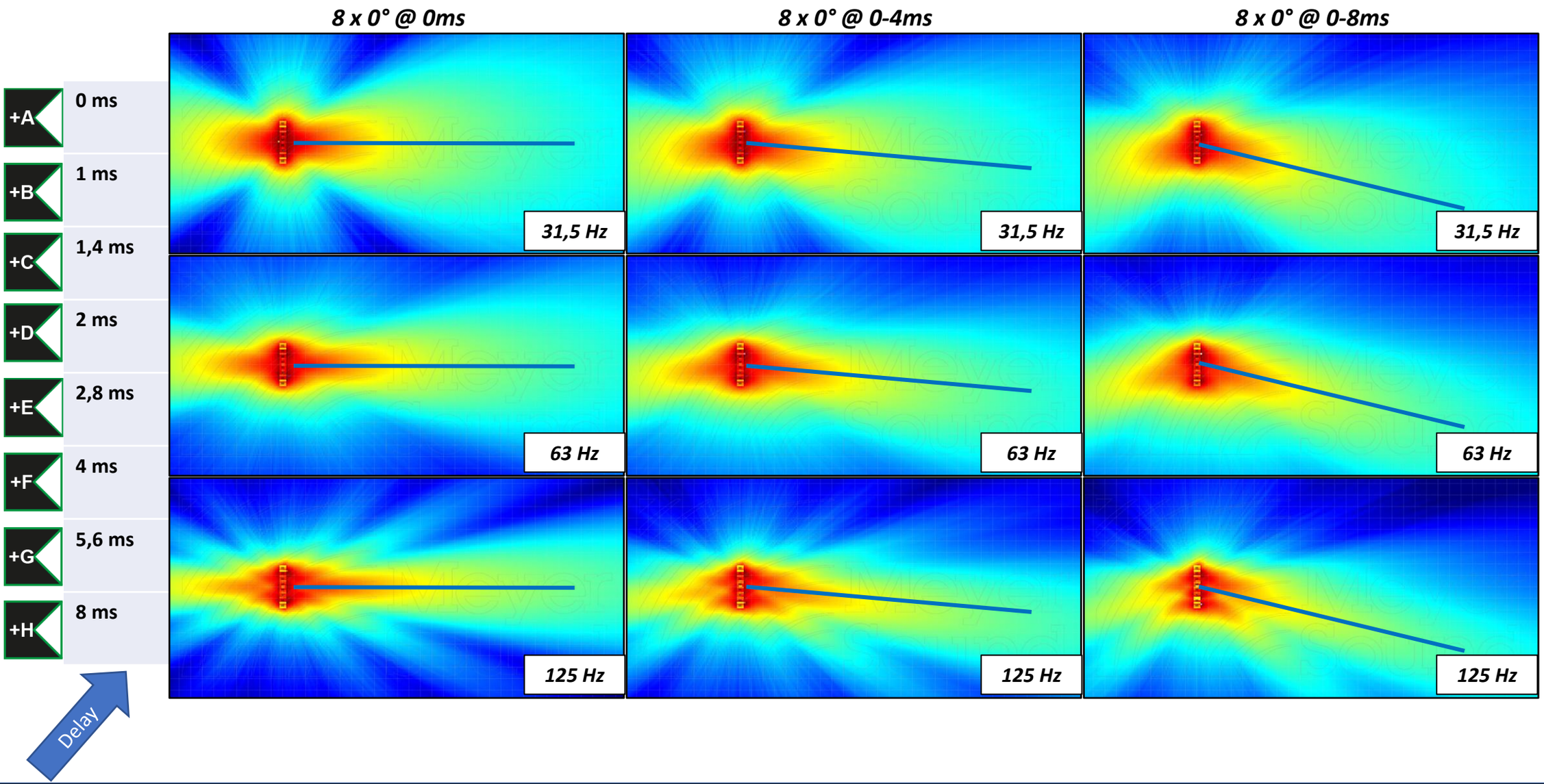
Steering effect
Lateral



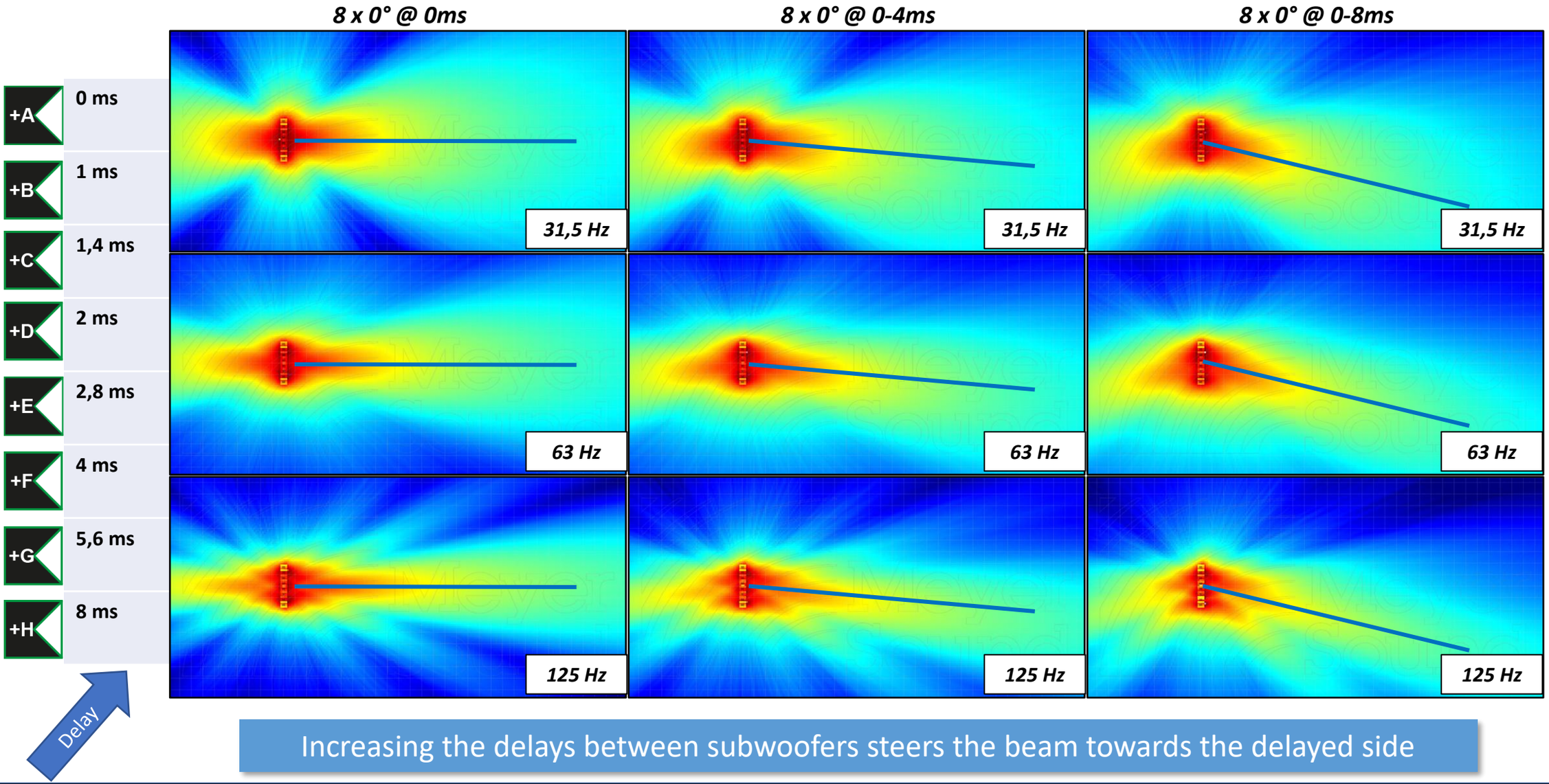
Steering effect
Lateral



Steering effect
Lateral



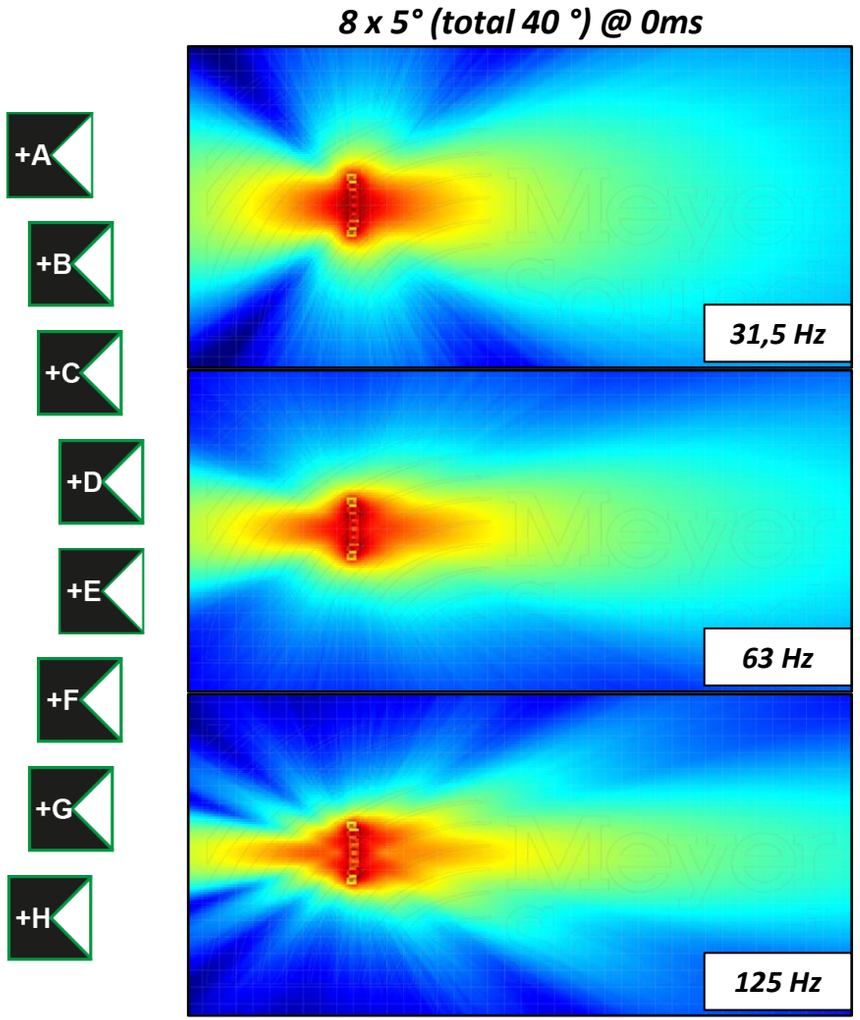
Steering effect
Lateral



Increasing the delays between subwoofers steers the beam towards the delayed side

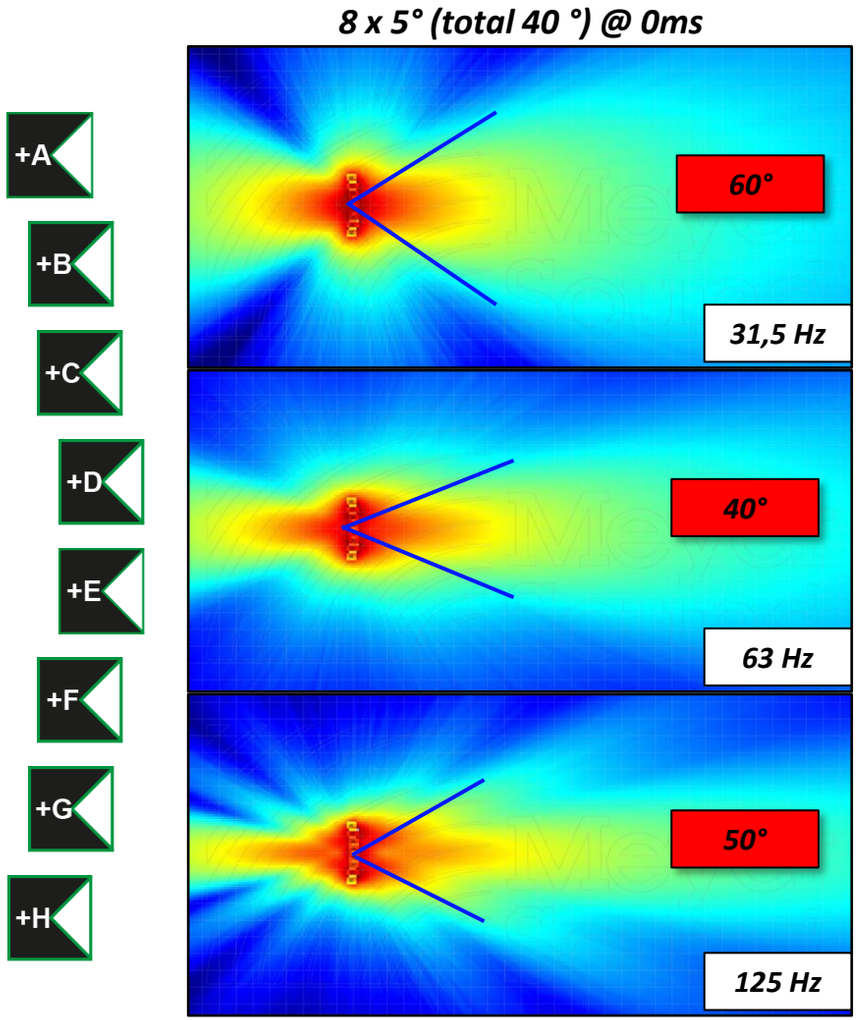
Steering effect

Radial — physical subwoofer arc



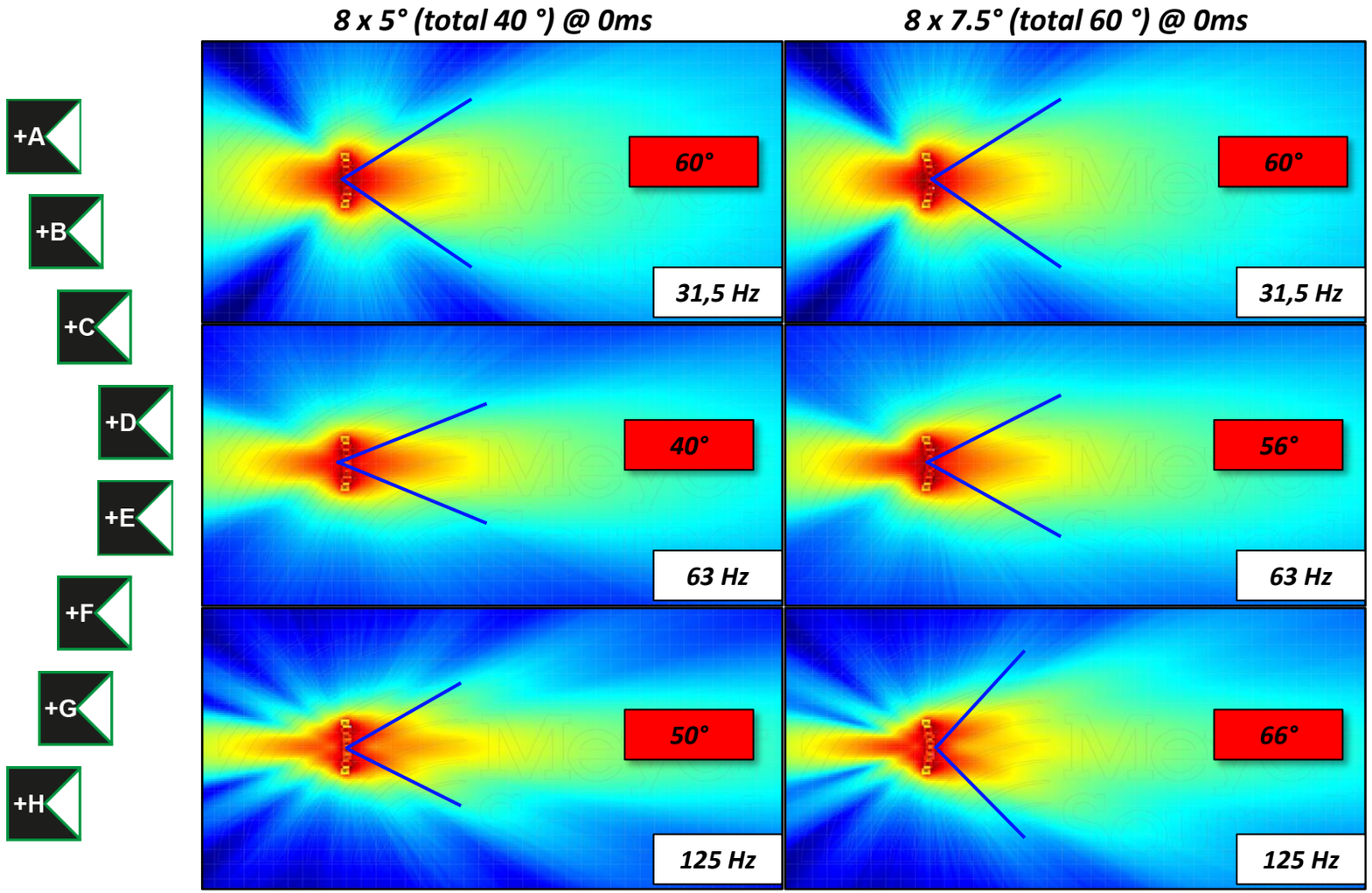
Steering effect

Radial — physical subwoofer arc



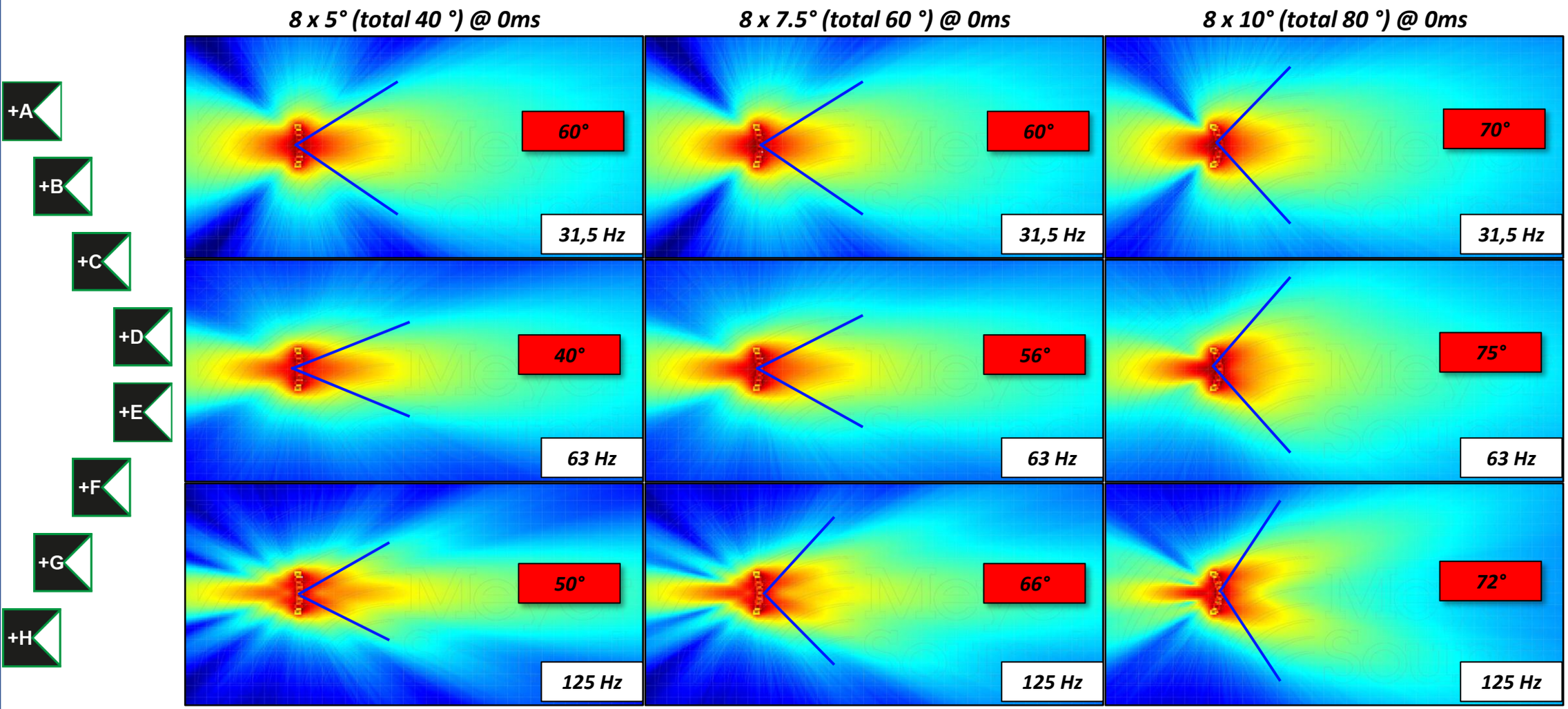
Steering effect

Radial — physical subwoofer arc



Steering effect

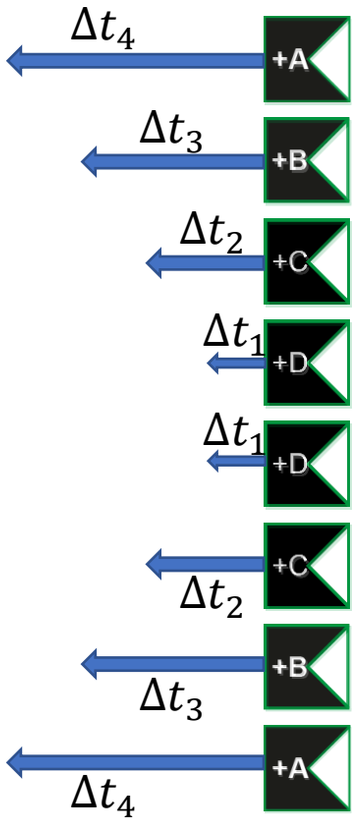
Radial — physical subwoofer arc



Increasing the curvature of the arc widens the coverage.

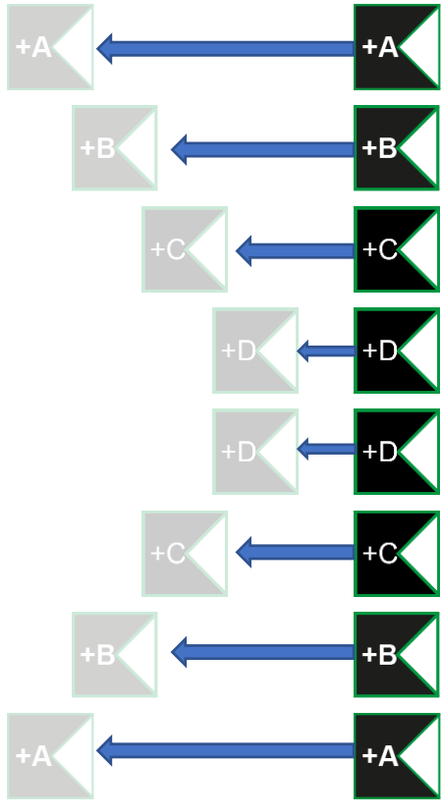
Steering effect

Radial — virtual subwoofer arc



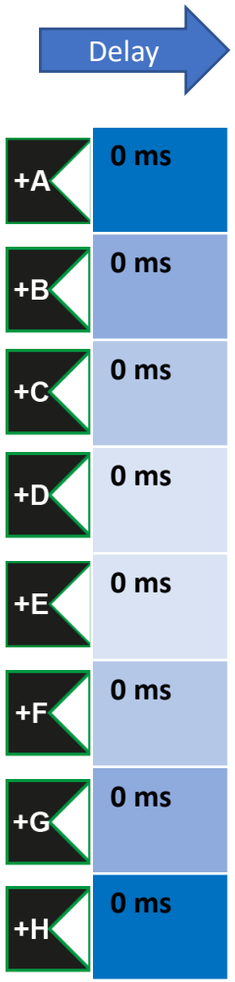
Steering effect

Radial — virtual subwoofer arc



Steering effect

Radial — virtual subwoofer arc



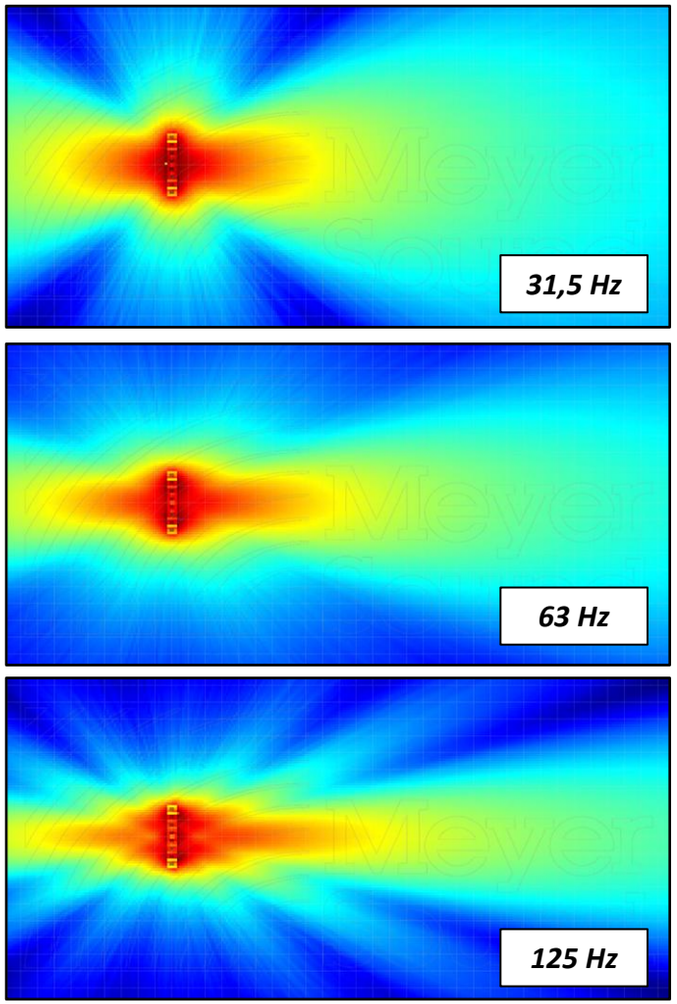
Steering effect

Radial — virtual subwoofer arc

Delay

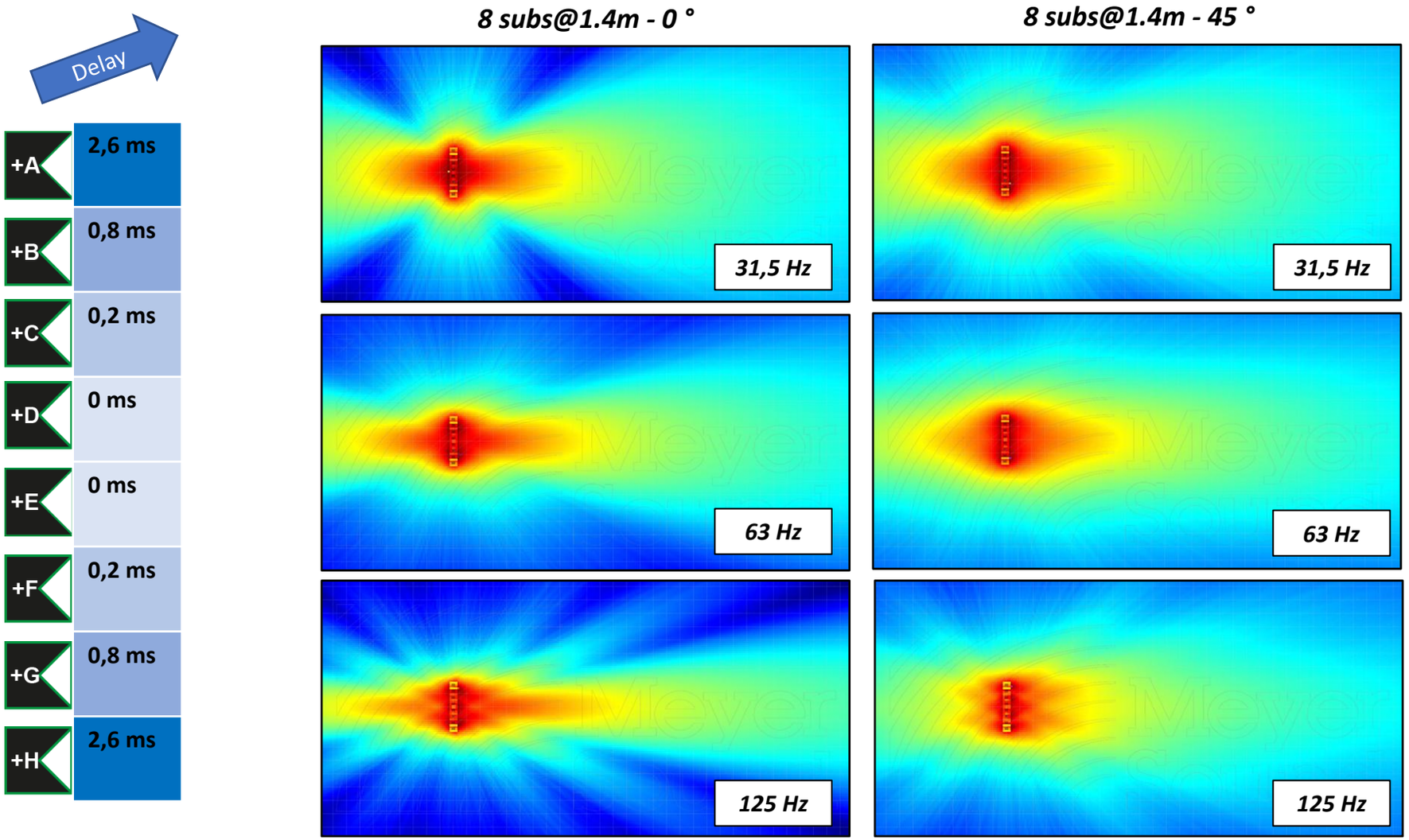
+A	0 ms
+B	0 ms
+C	0 ms
+D	0 ms
+E	0 ms
+F	0 ms
+G	0 ms
+H	0 ms

8 subs@1.4m - 0 °



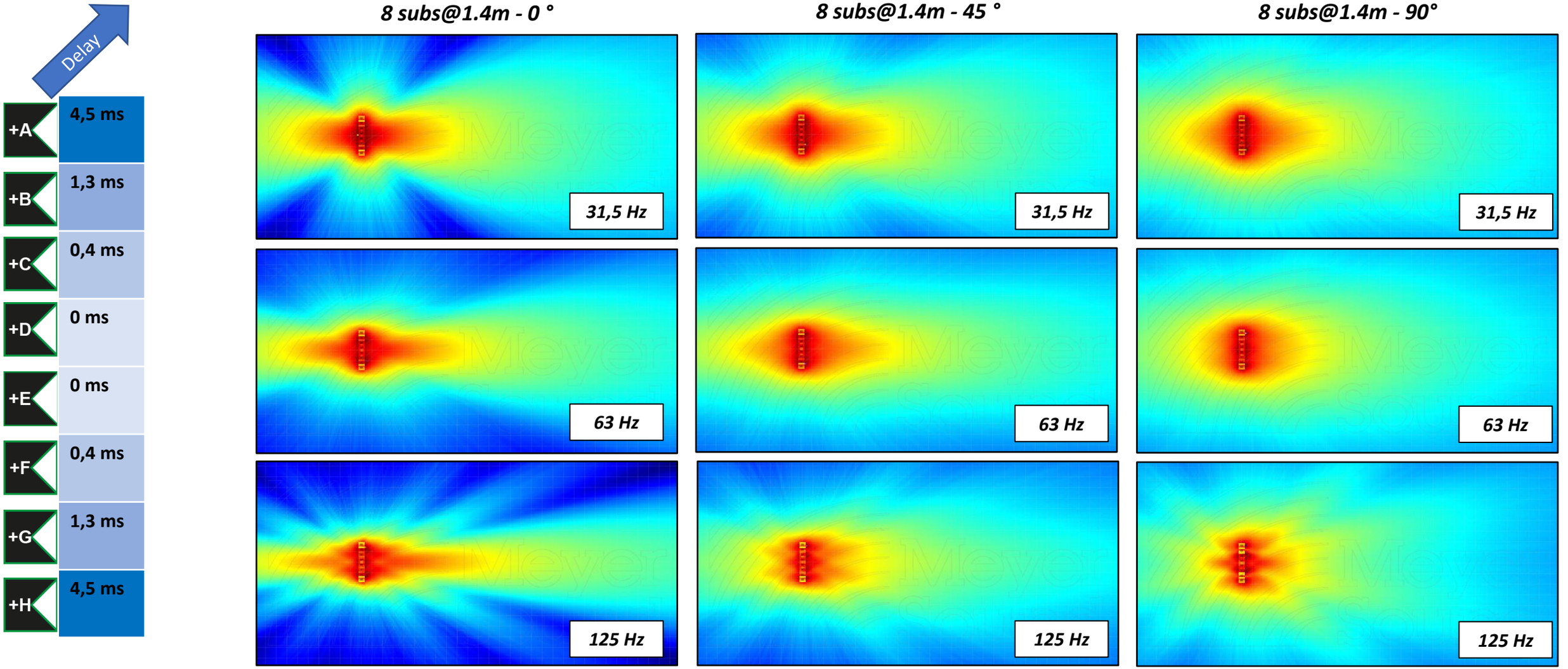
Steering effect

Radial — virtual subwoofer arc



Steering effect

Radial — virtual subwoofer arc



Increasing the arc delays widens the coverage.

?



3
Forward Steering

"Cardioid" configurations

Directivity

There are two main methods for making subwoofer arrays directional.

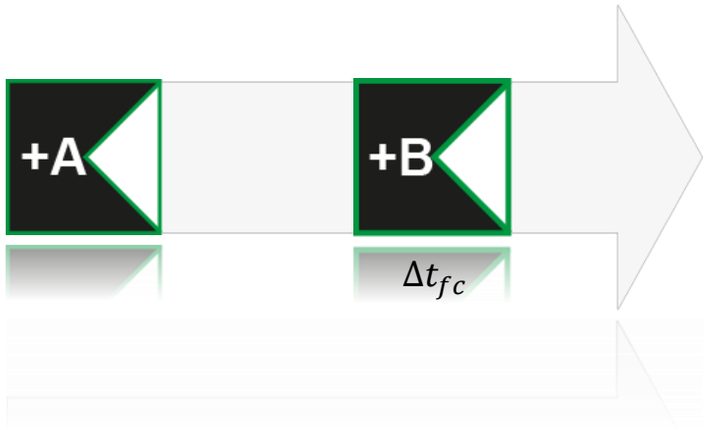
Directivity

There are two main methods for making subwoofer arrays directional.
These arrays are often simply described as “cardioid”.

Directivity

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“Native” configurations

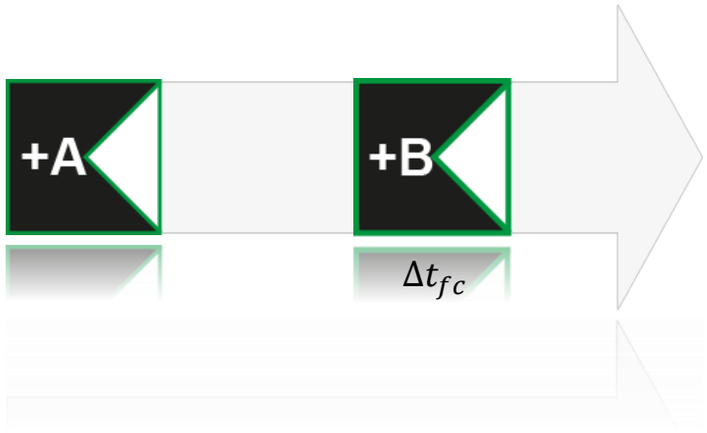


Configurations using “pressure gradient”

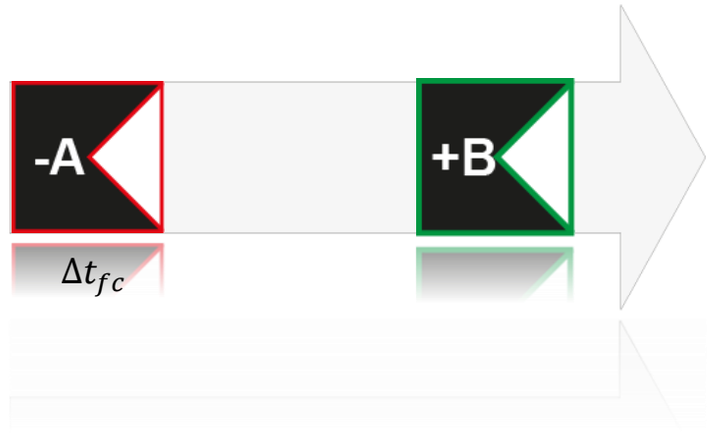
Directivity

There are two main methods for making subwoofer arrays directional.
These arrays are often simply described as “cardioid”.

“Native” configurations



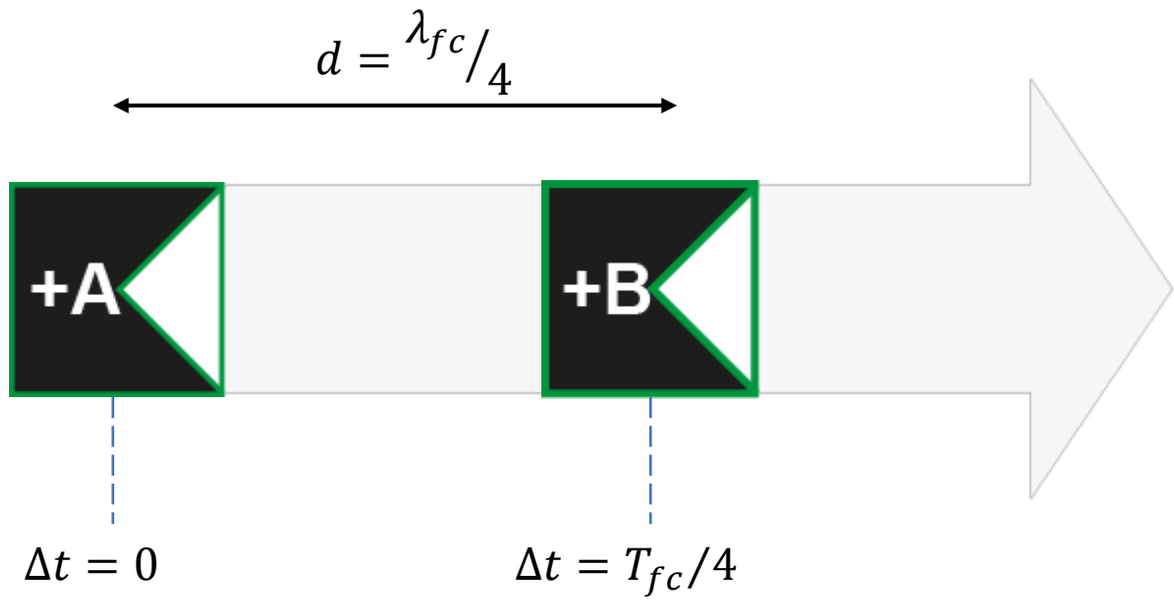
Configurations using “pressure gradient”



“Native” configurations

Parameters	
fc =	$\boldsymbol{fc}$
λ =	$\boldsymbol{\lambda_{fc}}$
T =	$\boldsymbol{T_{fc}}$

- ***fc** = centre frequency*
- ***λfc** = wavelength at the centre frequency*
- ***Tfc** = period at the centre frequency*



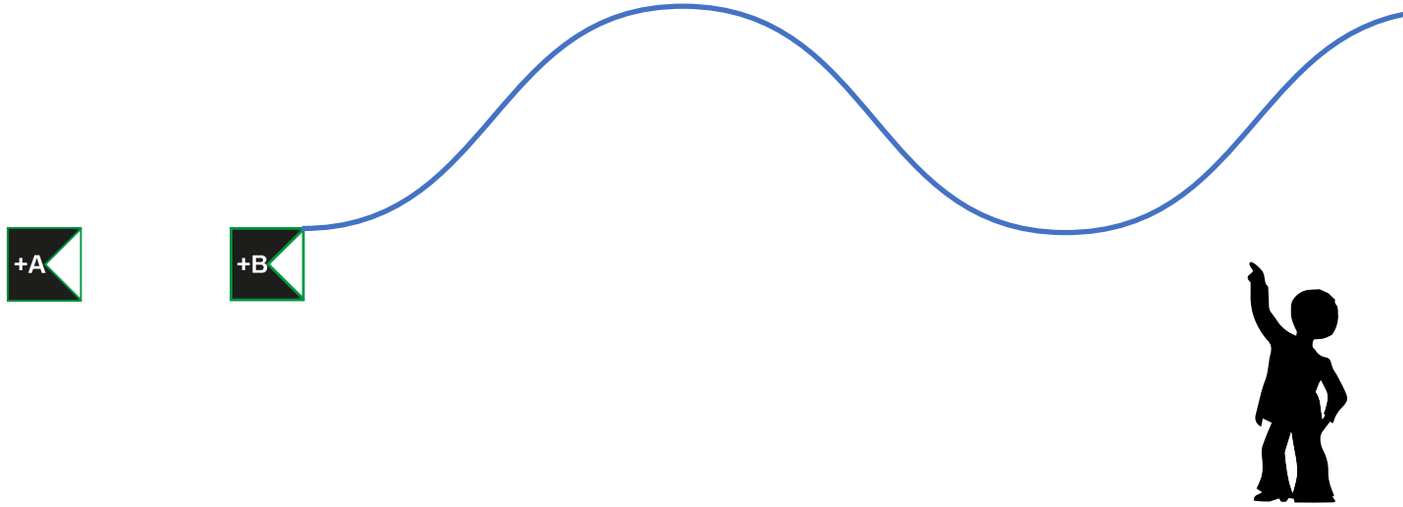
“Native” configurations
Wave visualisation





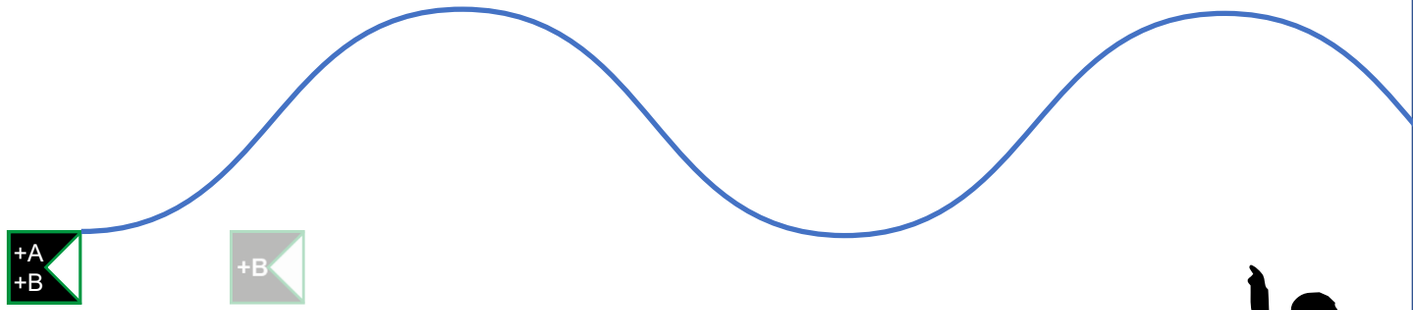
“Native” configurations
Wave visualisation

Front view



“Native” configurations
Wave visualisation

Front view

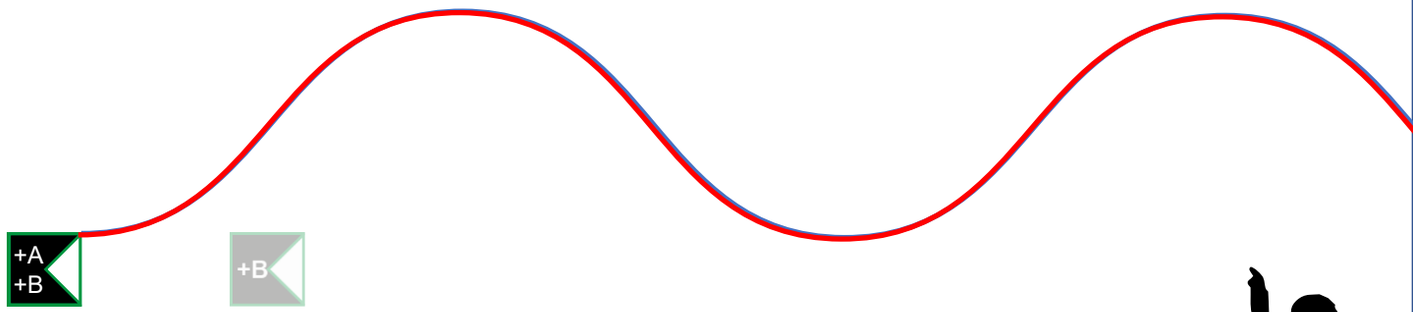


$$\Delta t = T_{fc}/4$$



“Native” configurations
Wave visualisation

Front view

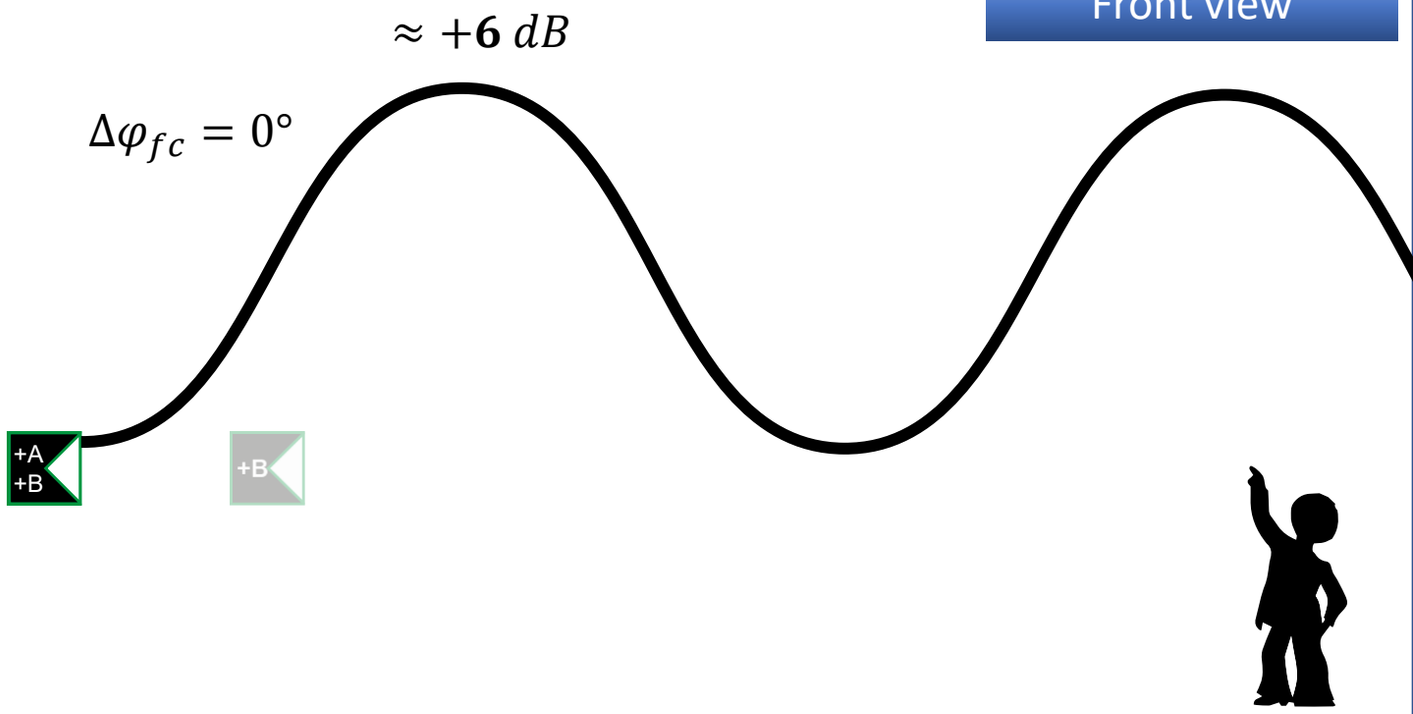


$$\Delta t = T_{fc}/4$$



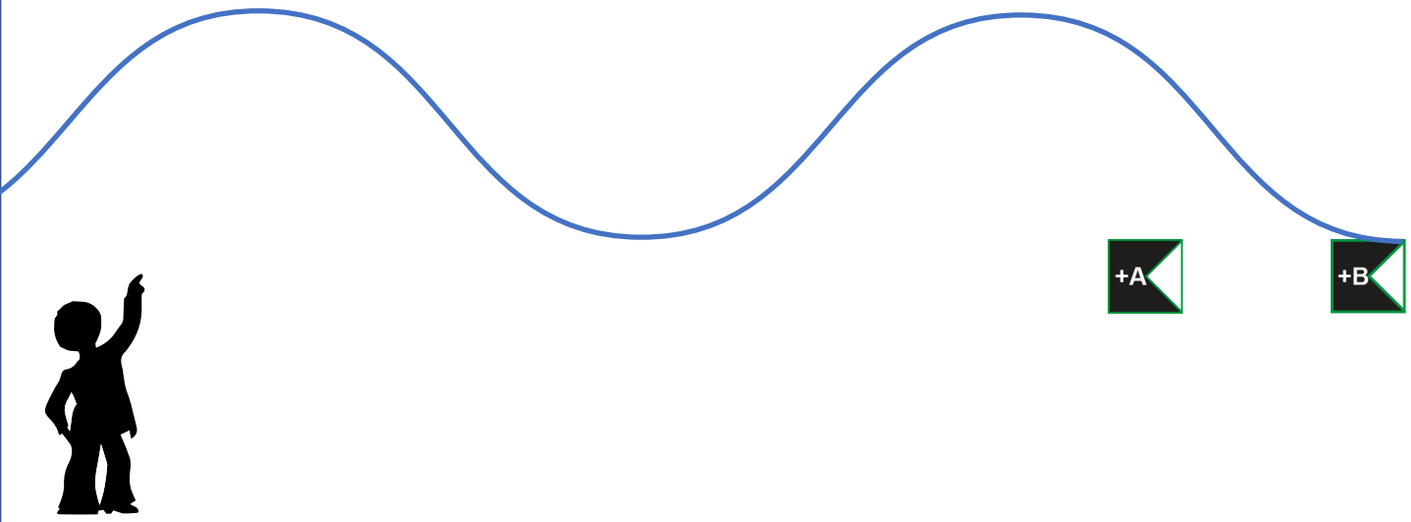
“Native” configurations
Wave visualisation

Front view



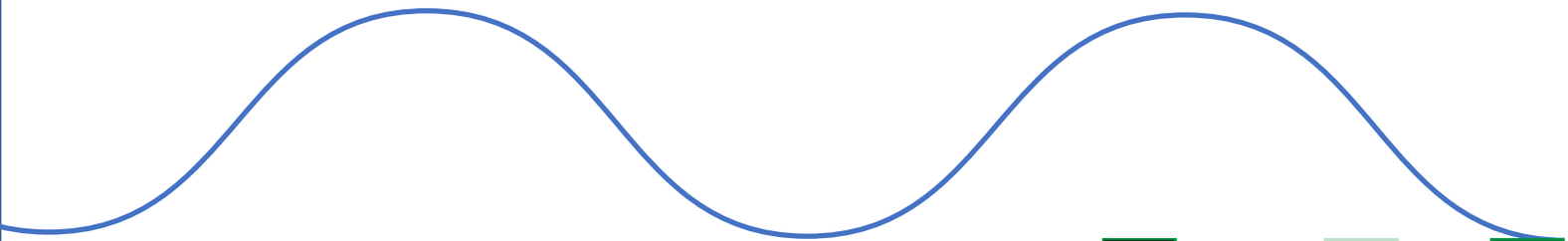
“Native” configurations
Wave visualisation

Rear view



“Native” configurations
Wave visualisation

Rear view

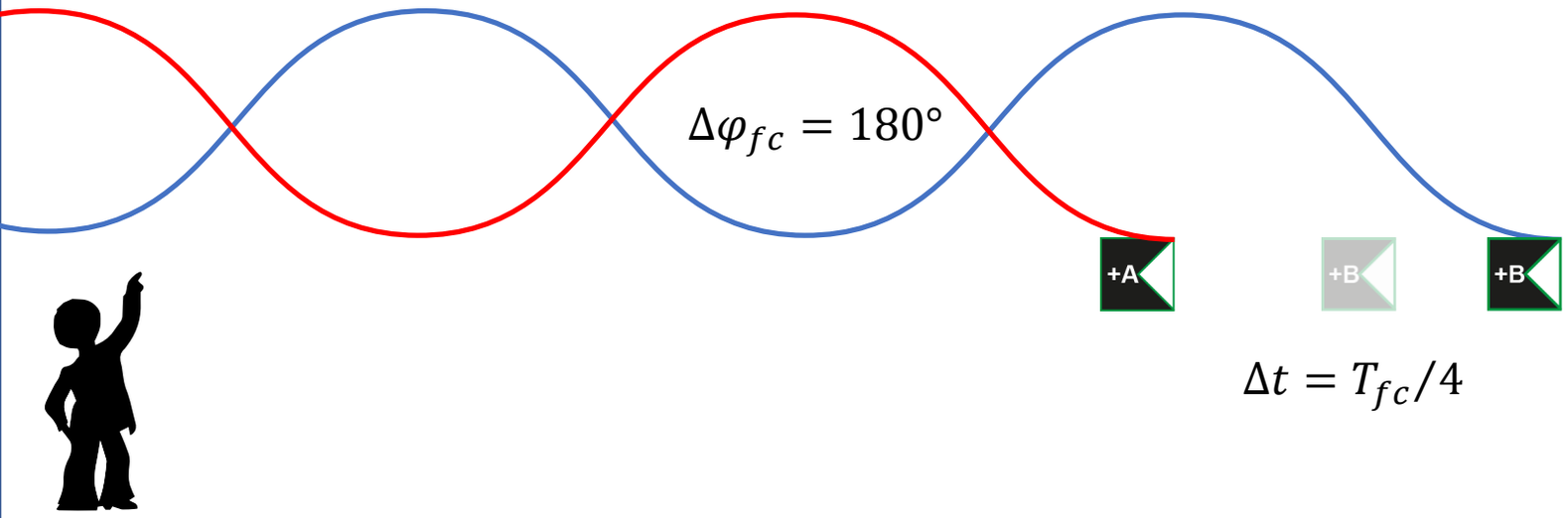




$$\Delta t = T_{fc}/4$$

“Native” configurations
Wave visualisation

Rear view



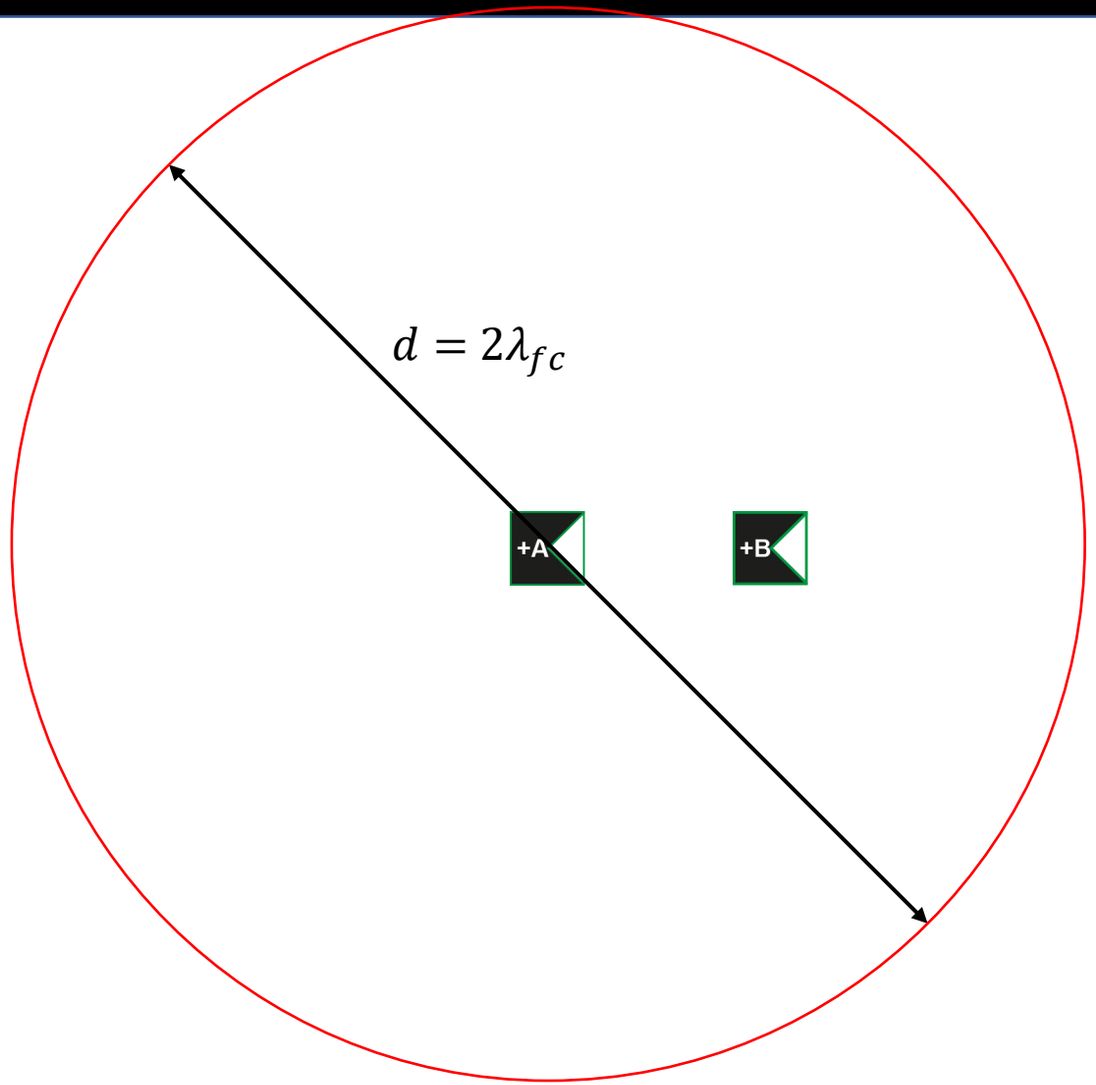
“Native” configurations
Wave visualisation

$$\Delta\varphi_{fc} = 180°$$



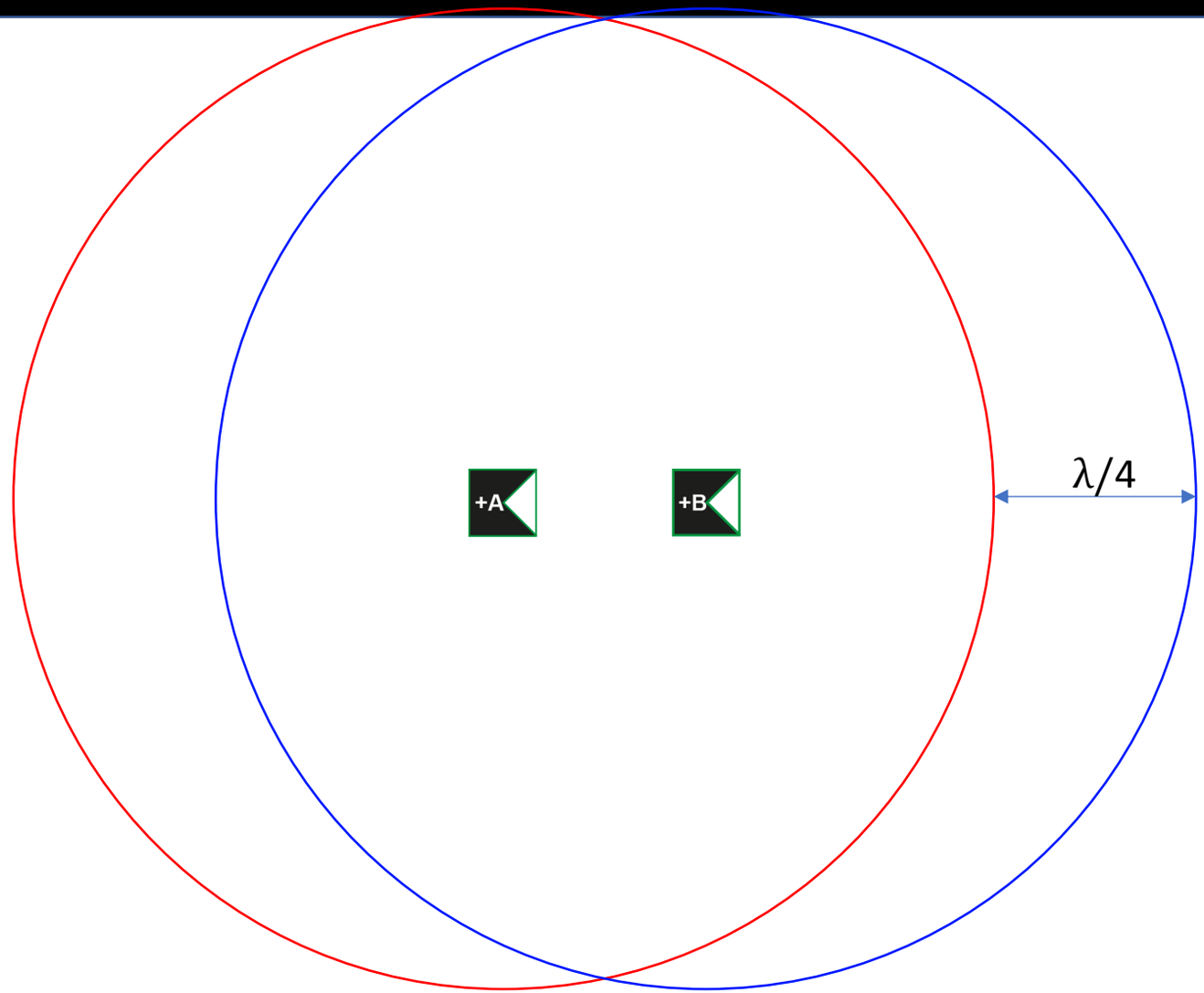
$$\Delta t = T_{fc}/4$$

“Native” configurations
Circular visualisation



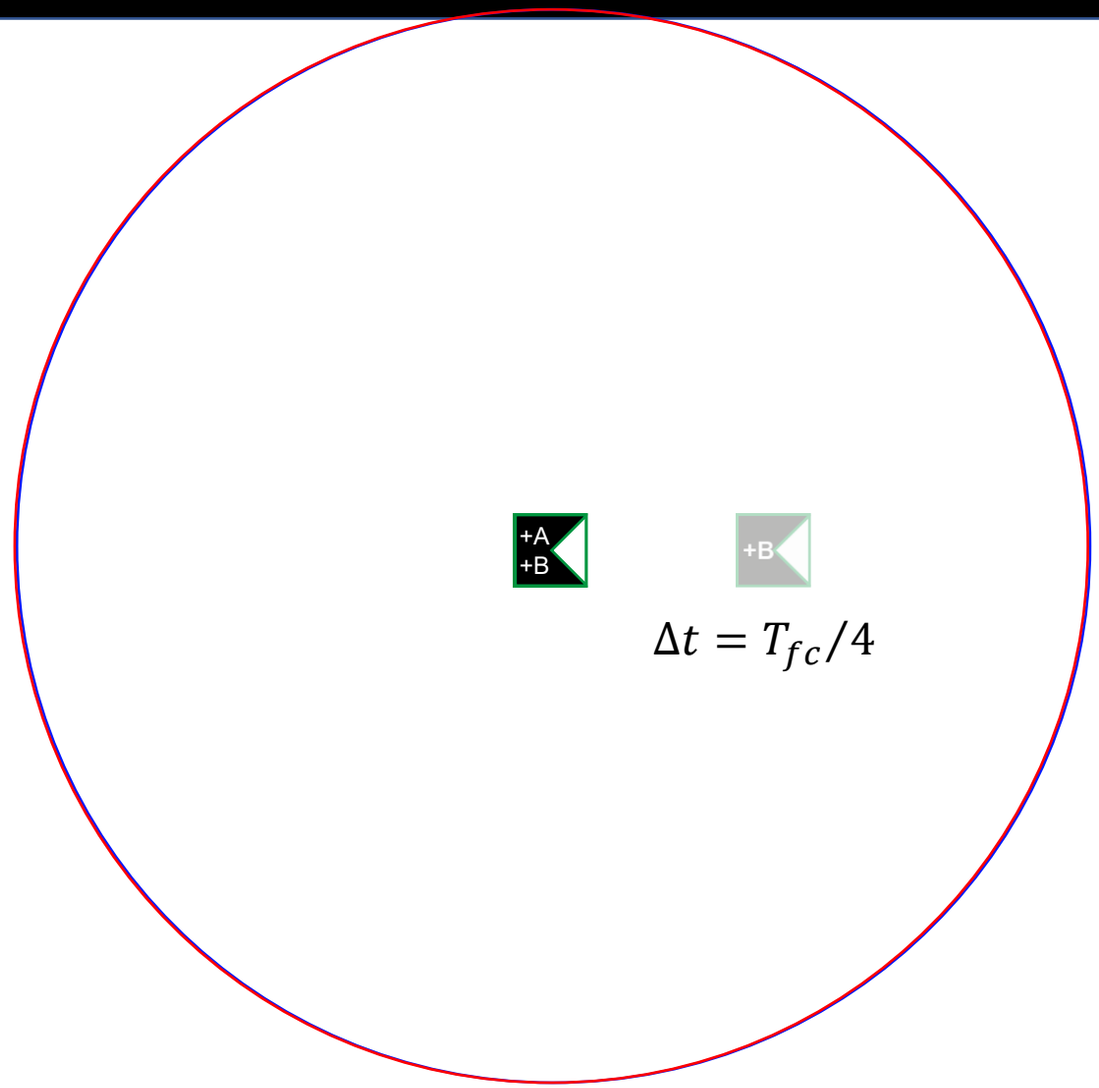
“Native” configurations

Circular visualisation



“Native” configurations
Circular visualisation

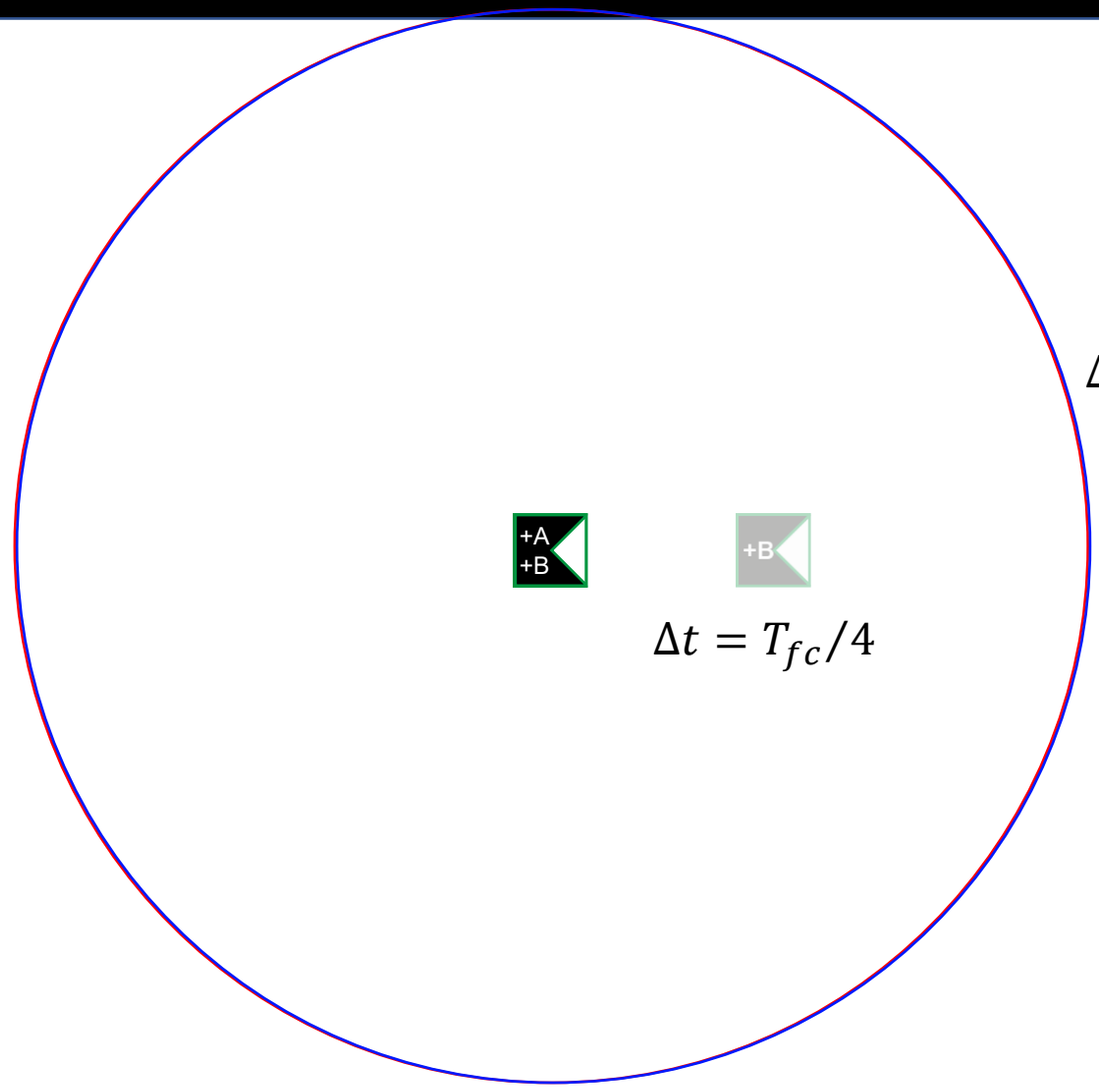
Front view





“Native” configurations
Circular visualisation

Front view



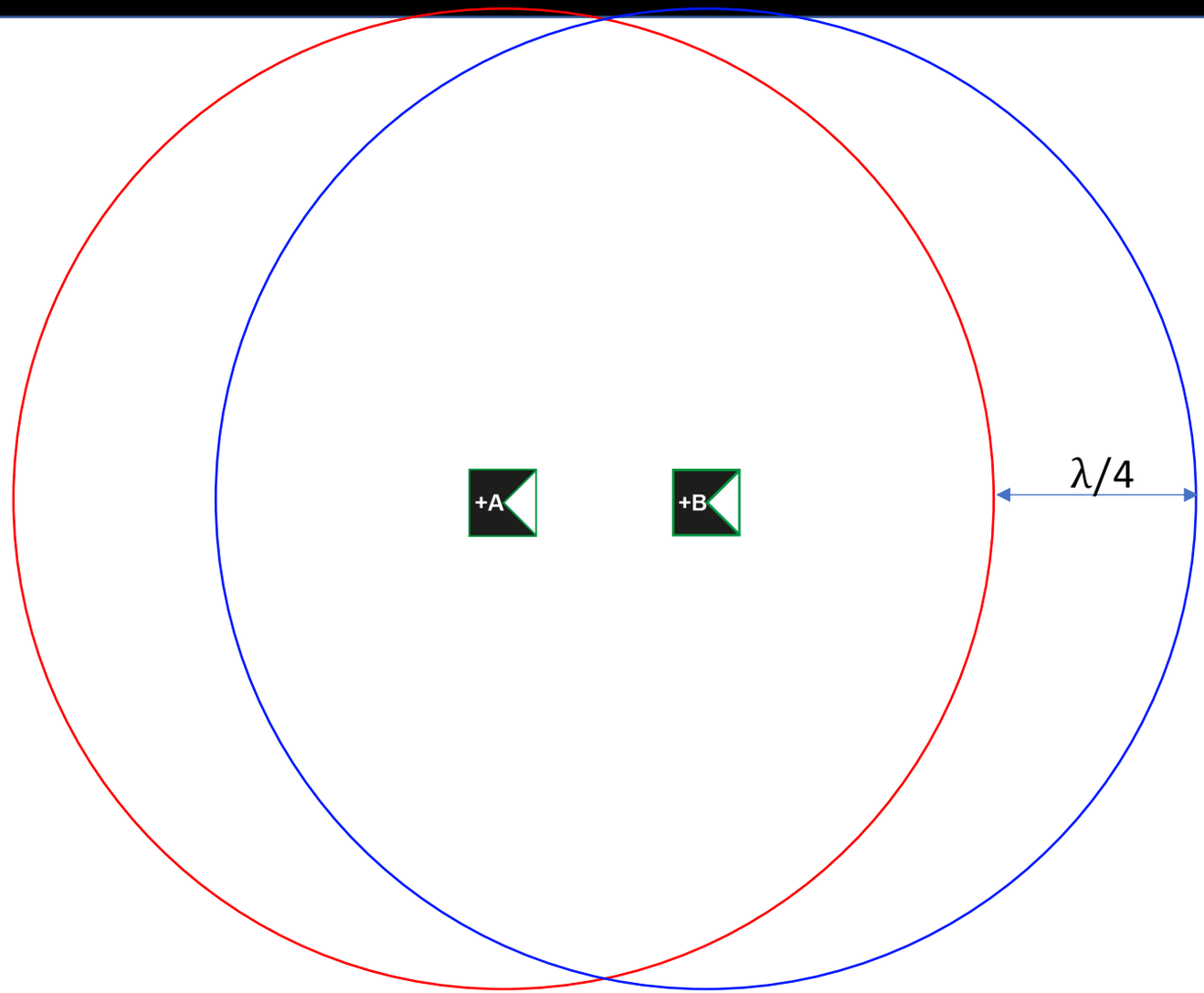
$\Delta\varphi_{fc} = 0°$

$\Delta t = T_{fc}/4$



“Native” configurations

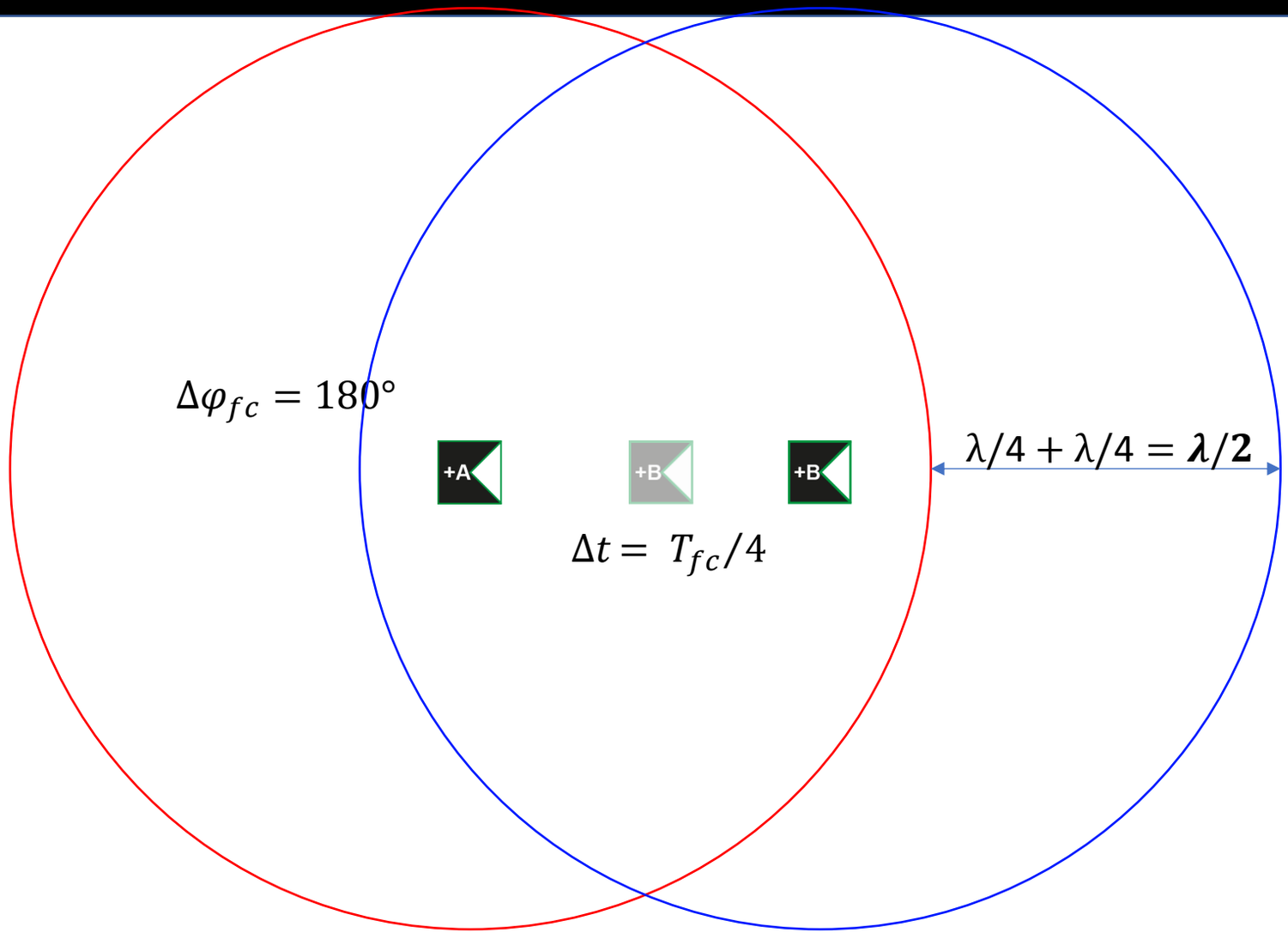
Circular visualisation



“Native” configurations
Circular visualisation

Rear view

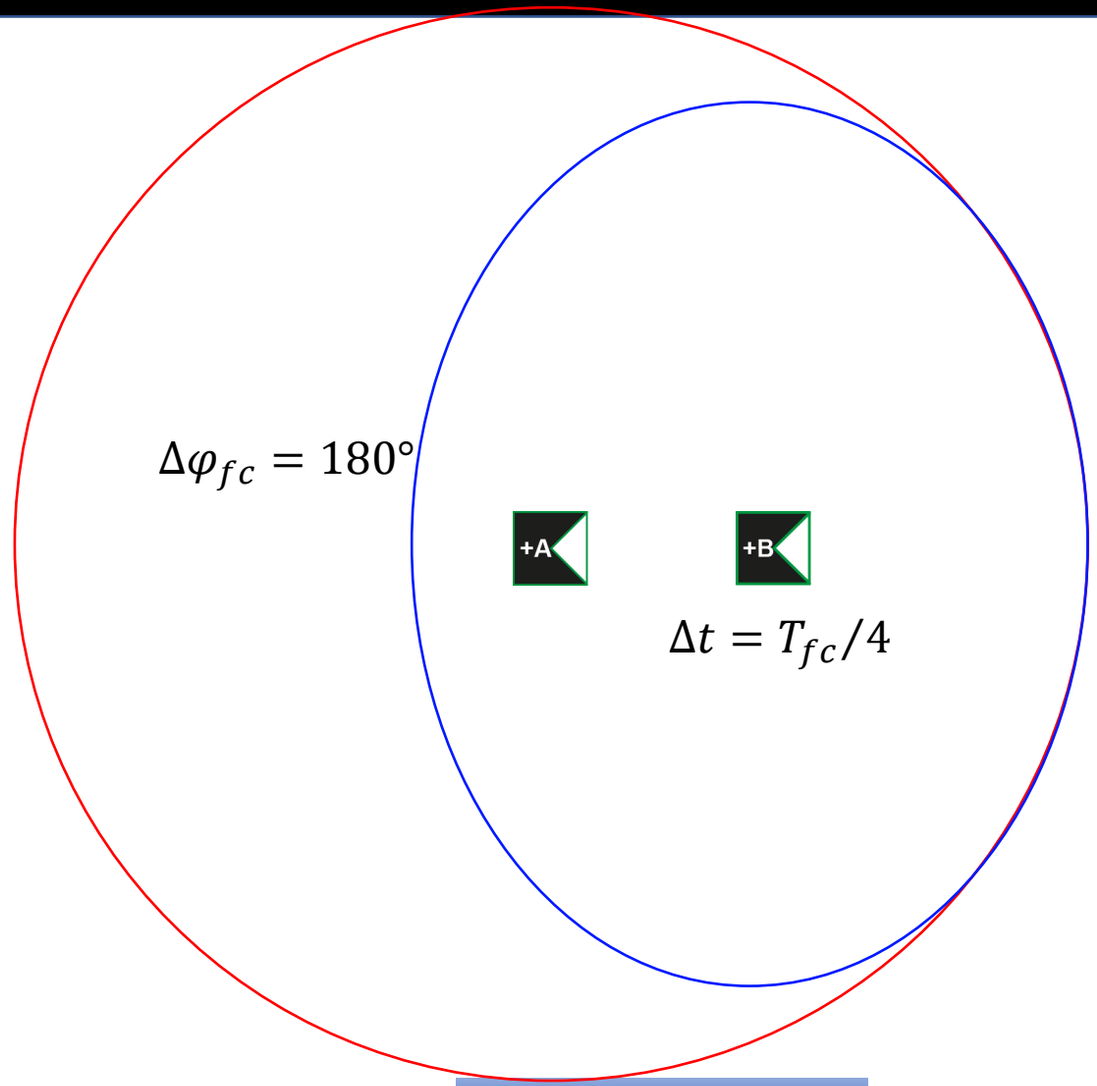




“Native” configurations
Circular visualisation



$\Delta\varphi_{fc} = 180°$



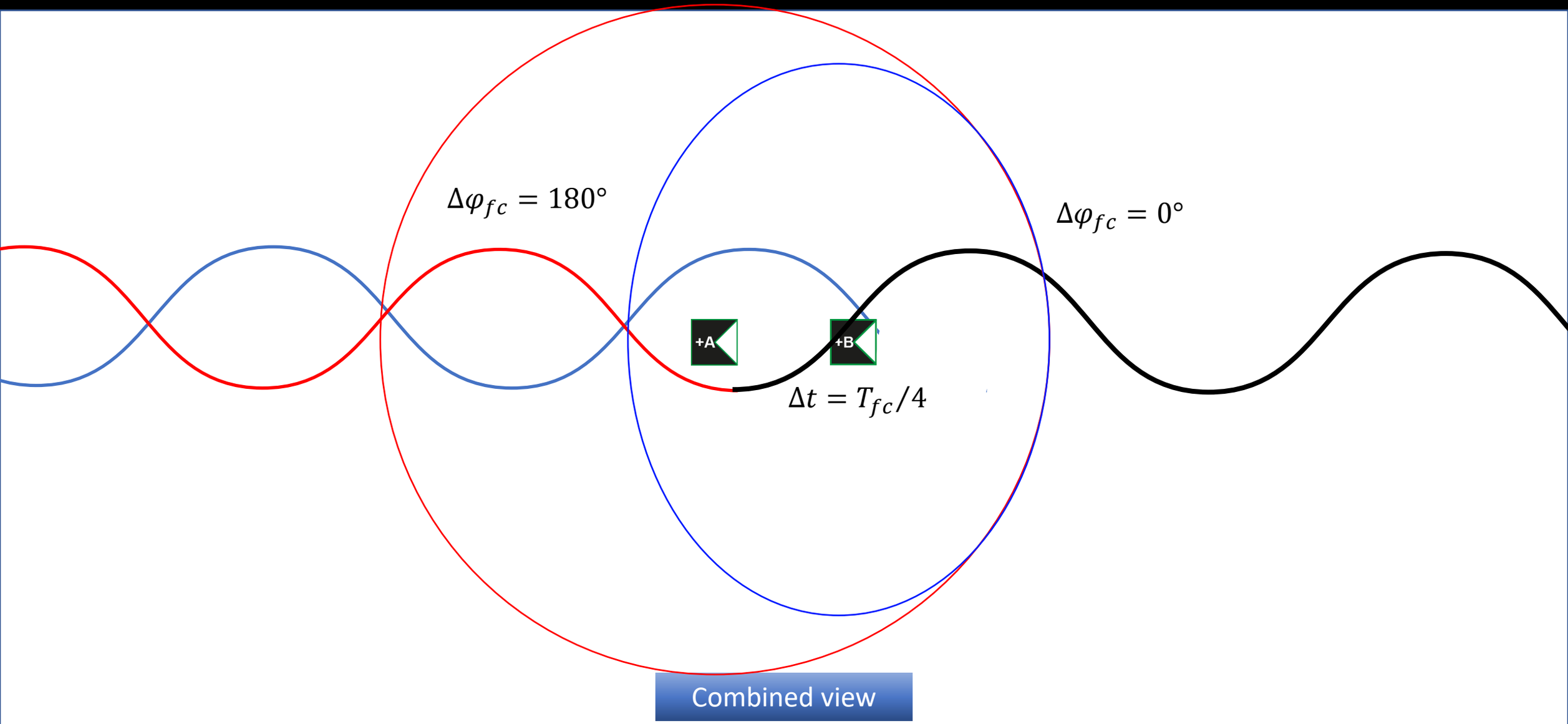
$\Delta t = T_{fc}/4$

$\Delta\varphi_{fc} = 0°$



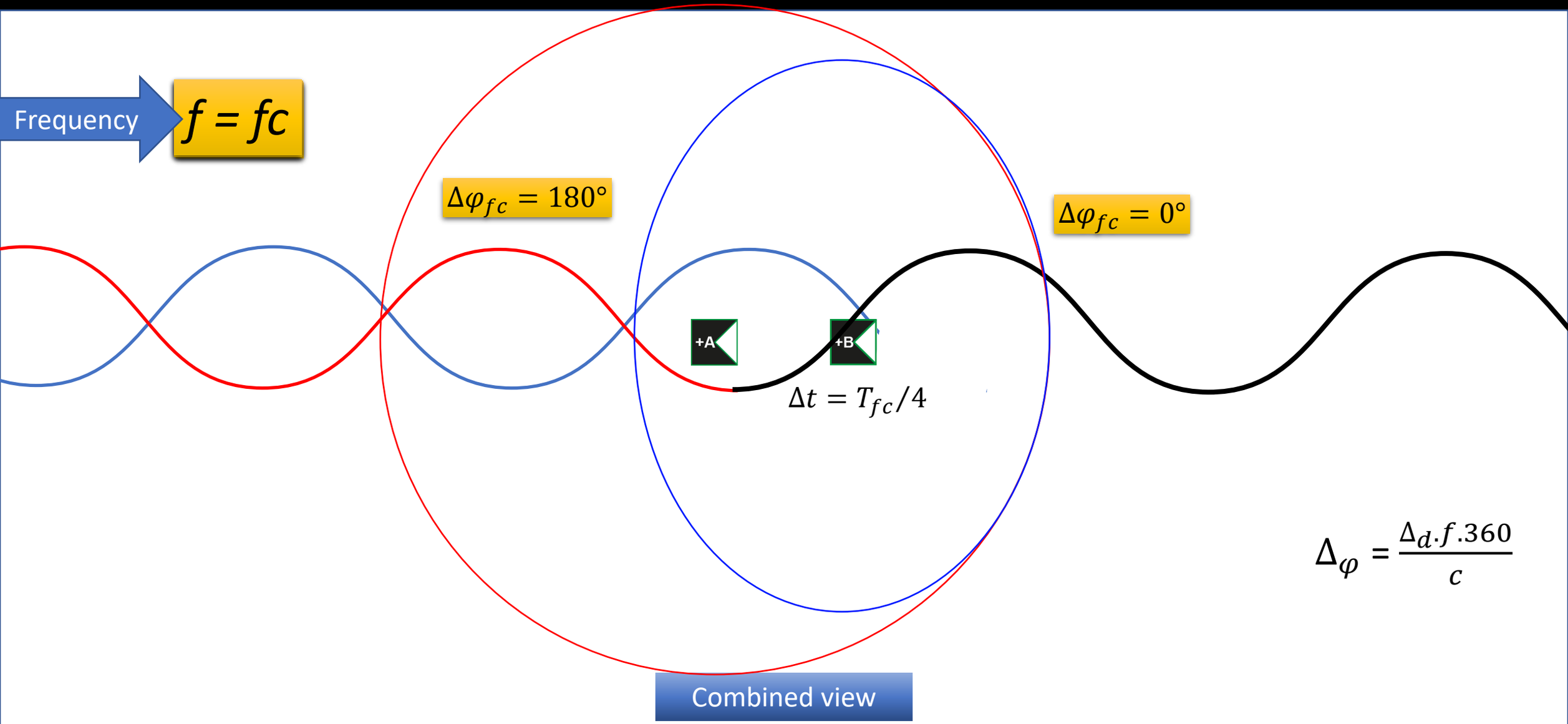
Combined view

“Native” configurations
Overall visualisation



“Native” configurations

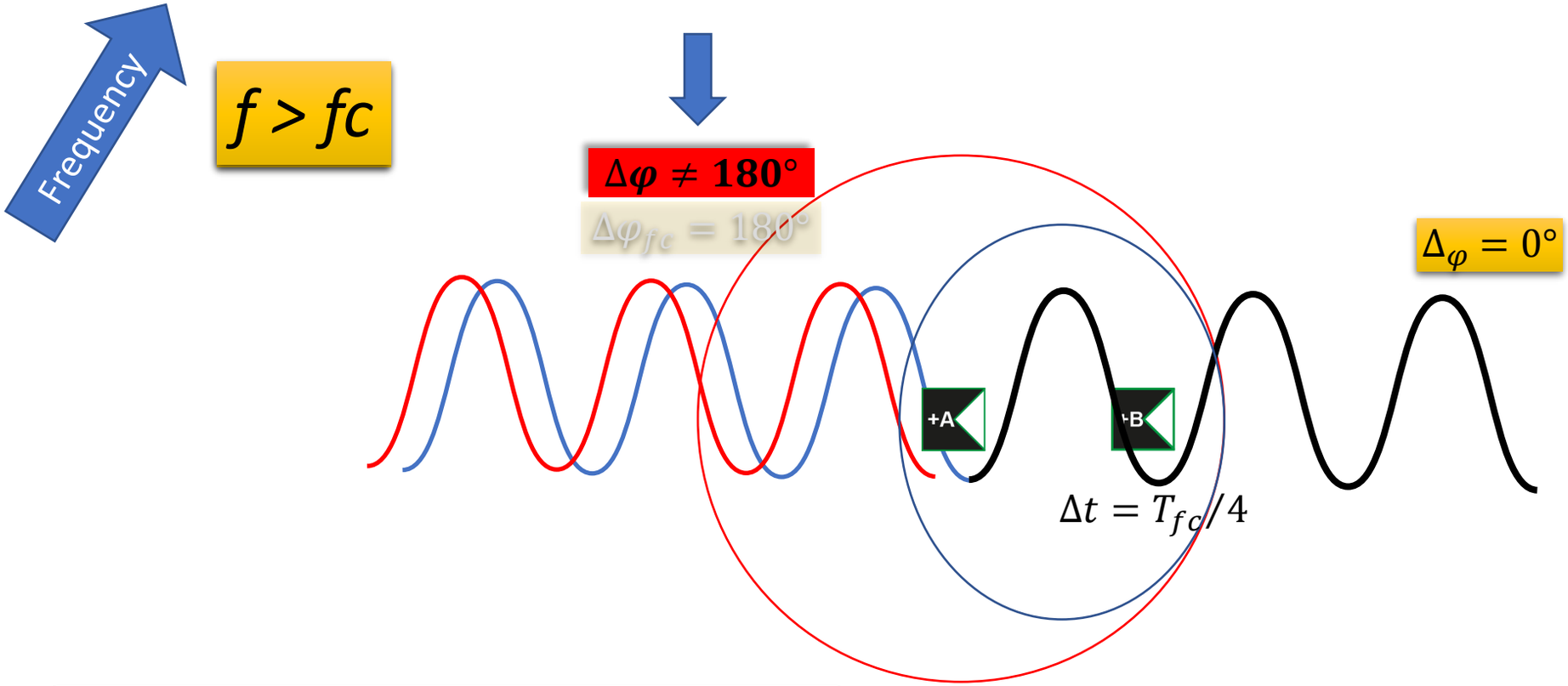
Frequency changes = rear phase changes



$$\Delta_{\varphi} = \frac{\Delta_d . f . 360}{c}$$

“Native” configurations

Frequency changes = rear phase changes

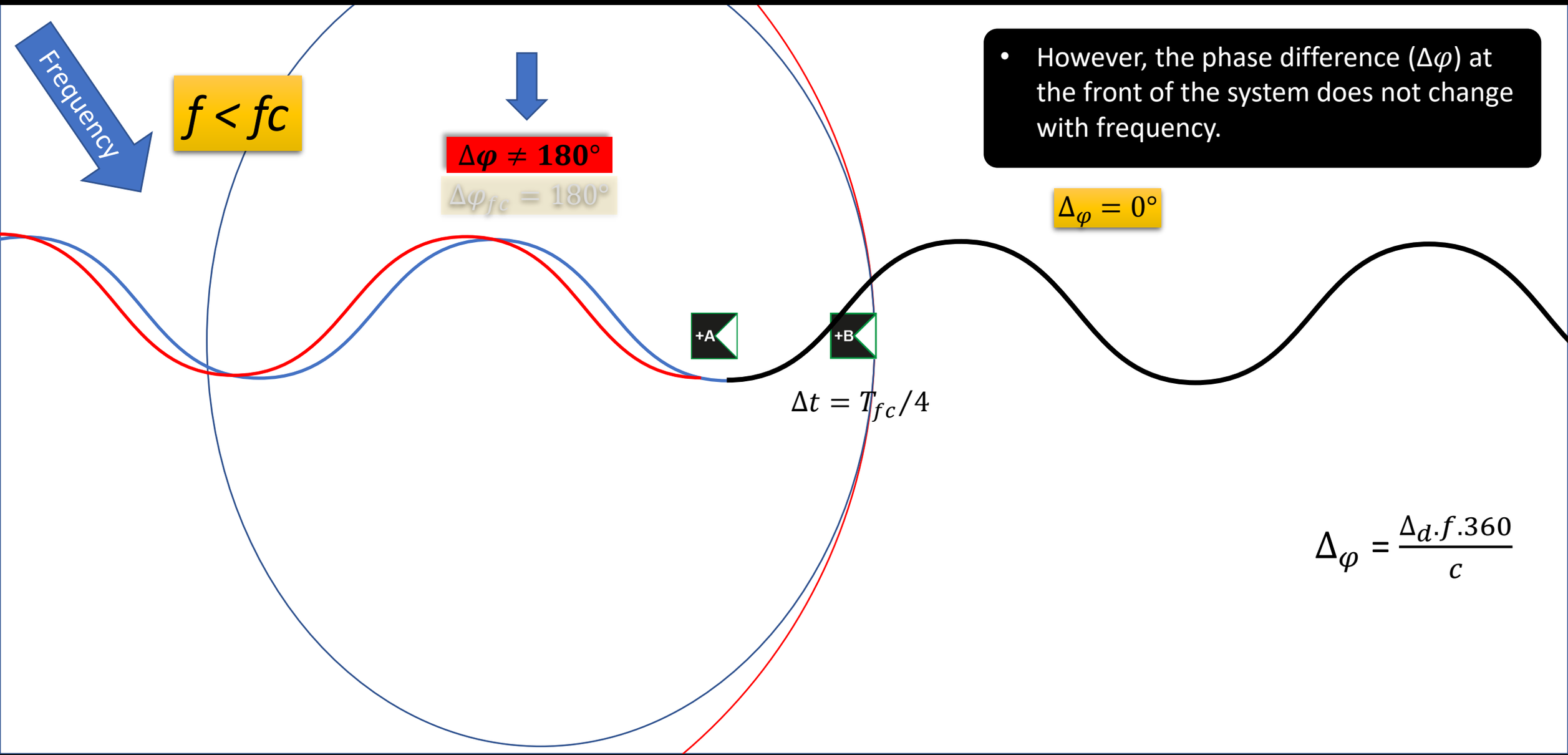


- The phase difference ($\Delta\varphi$) at the rear of the system varies with frequency.

$$\Delta_\varphi = \frac{\Delta_d . f . 360}{c}$$

“Native” configurations

Frequency changes = rear phase changes



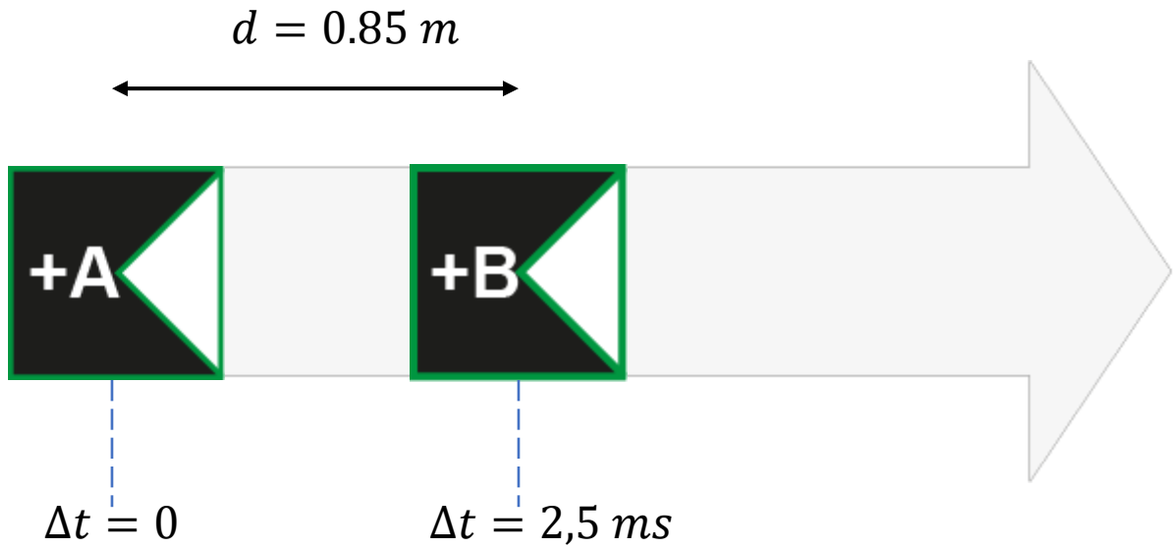
- However, the phase difference ($\Delta\varphi$) at the front of the system does not change with frequency.

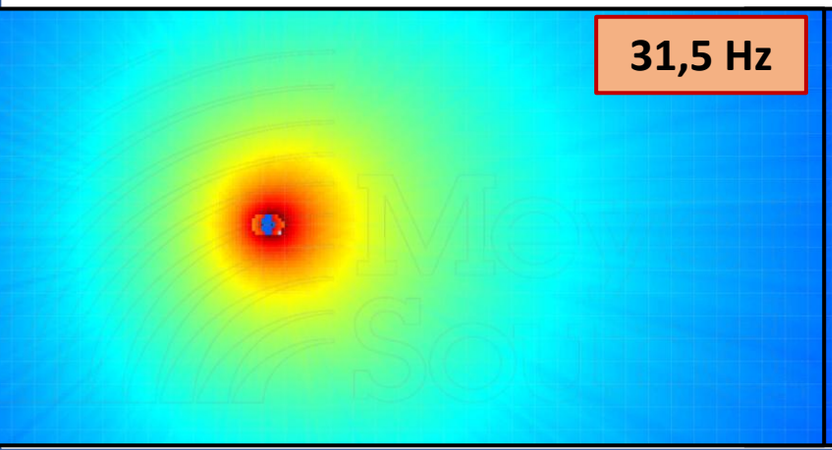
$$\Delta_\varphi = \frac{\Delta_d . f . 360}{c}$$

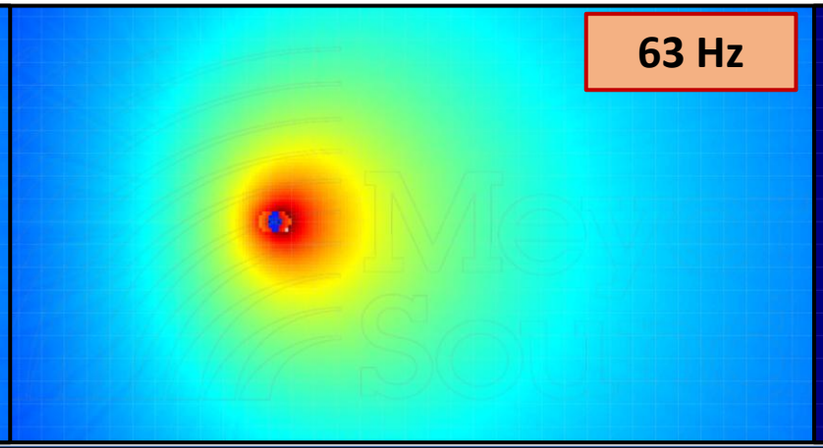
“Native” configurations

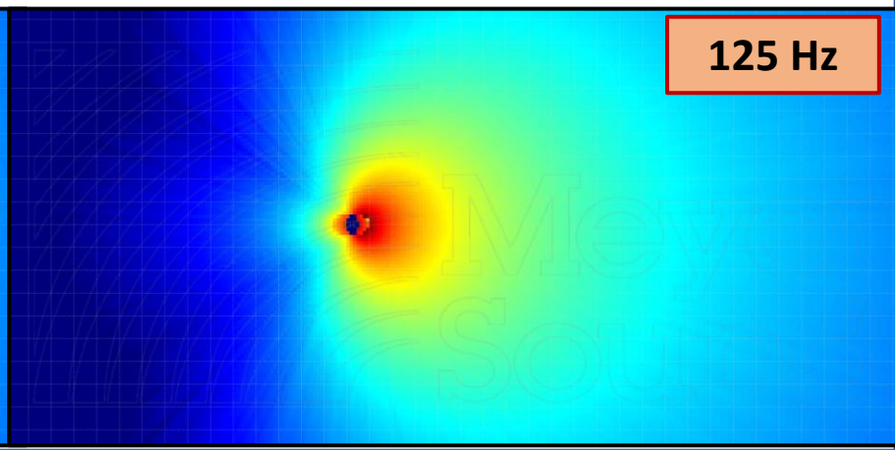
Example 0.85 m

Parameters	
fc =	**100 Hz**
λ =	**3.4 m**
T =	**10 ms**





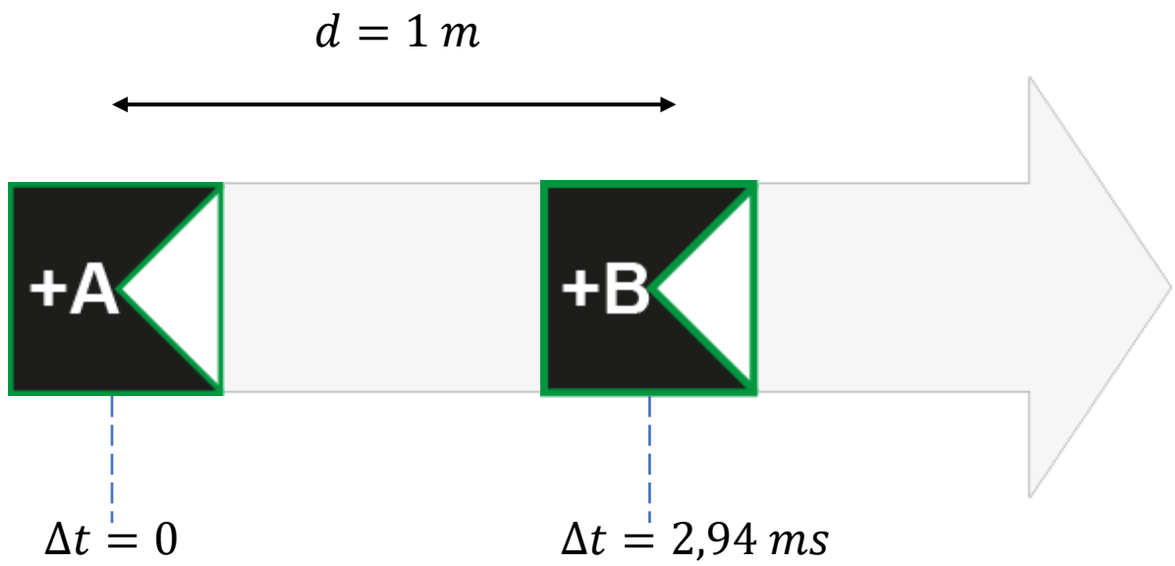


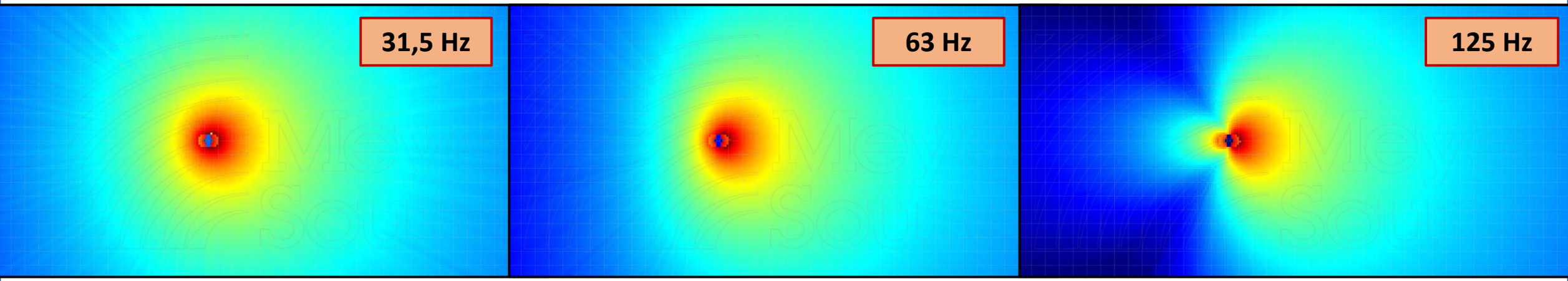


“Native” configurations

Example 1m

Parameters	
fc =	**85 Hz**
λ =	**4 m**
T =	**11.66 ms**

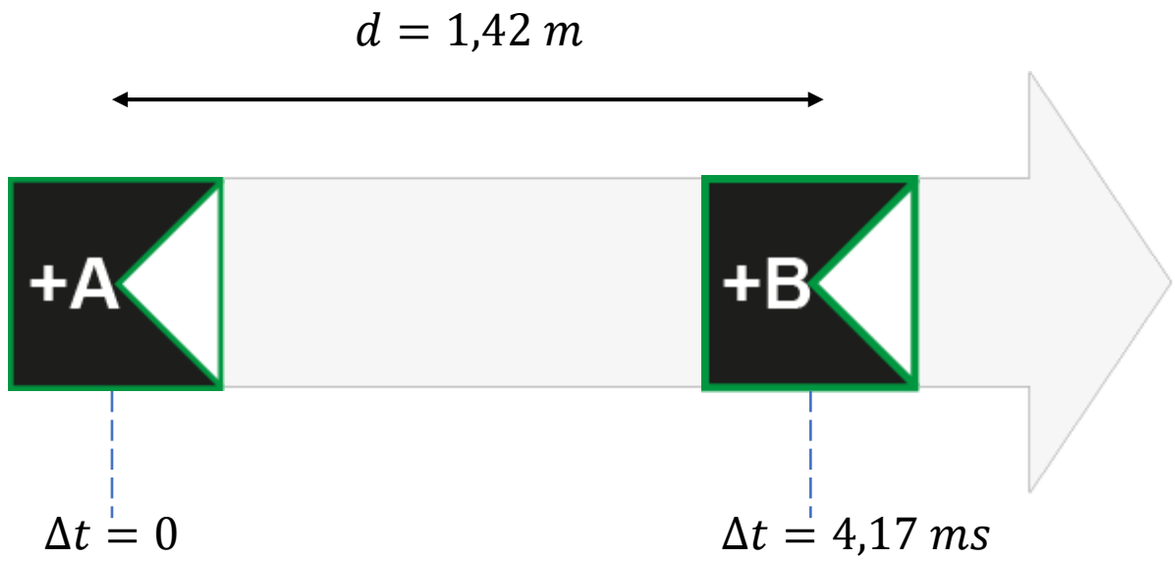


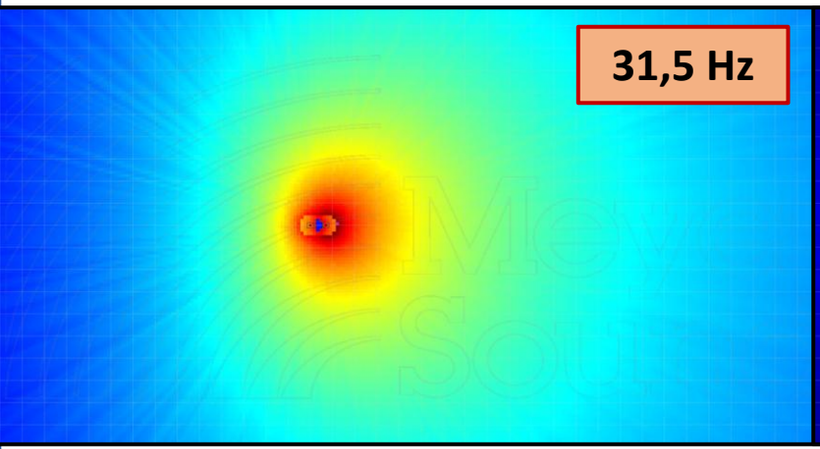


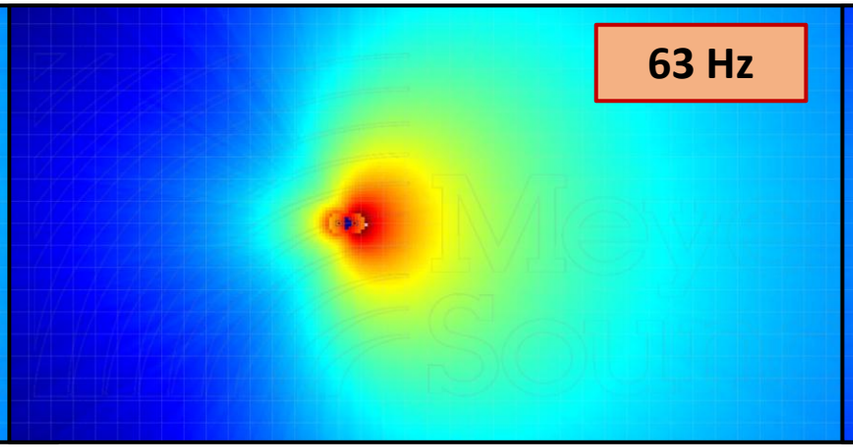
“Native” configurations

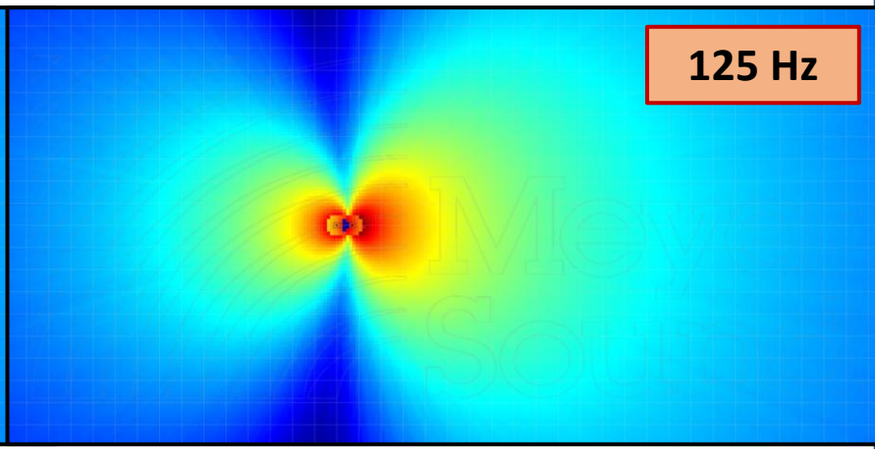
Example 1.42 m

Parameters	
fc =	**60 Hz**
λ =	**5.67 m**
T =	**16.67 ms**



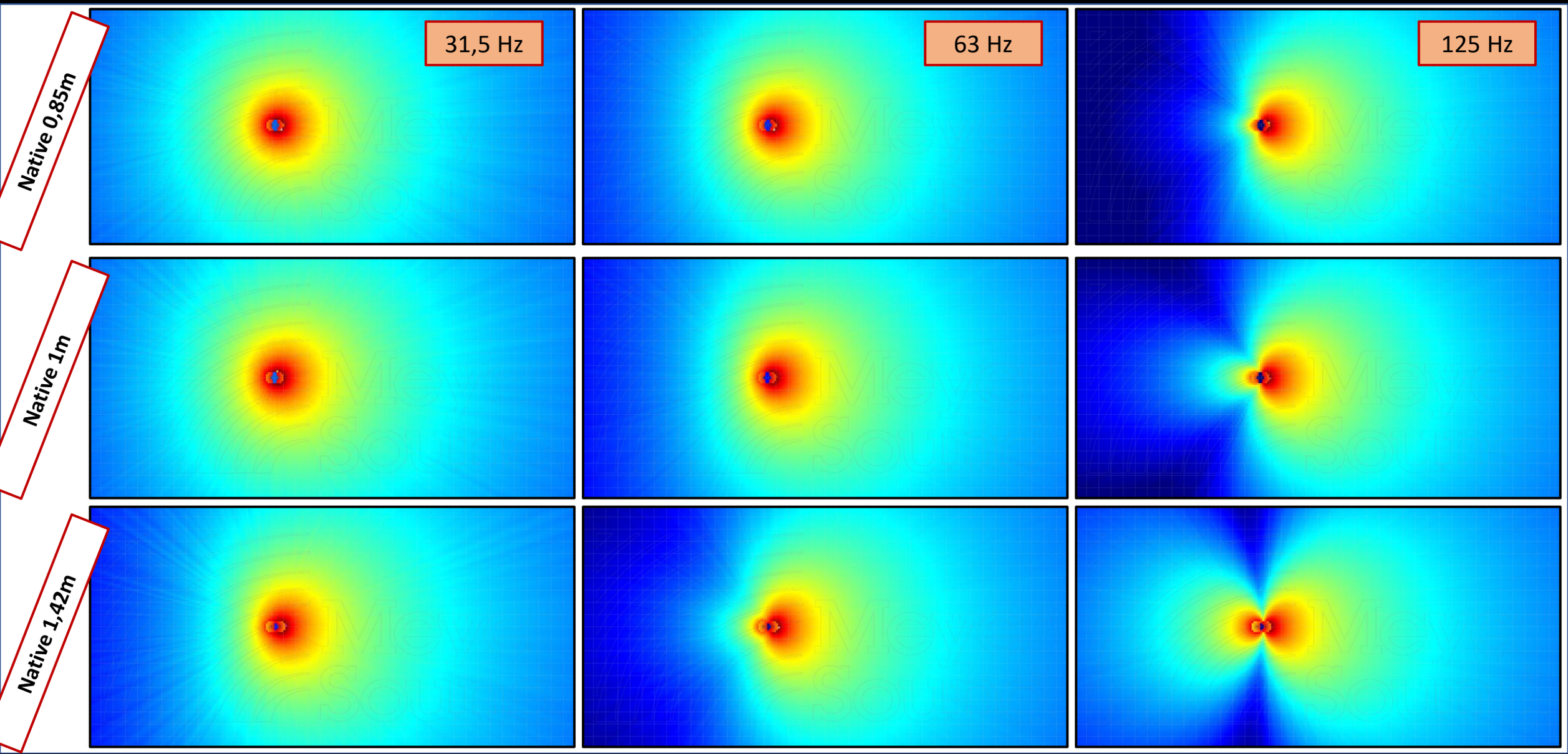




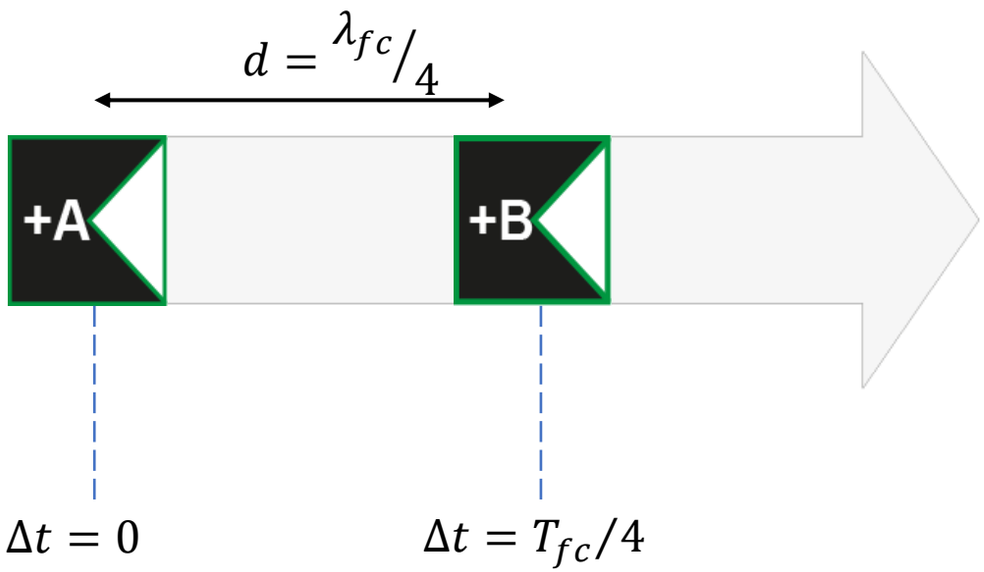


“Native” configurations

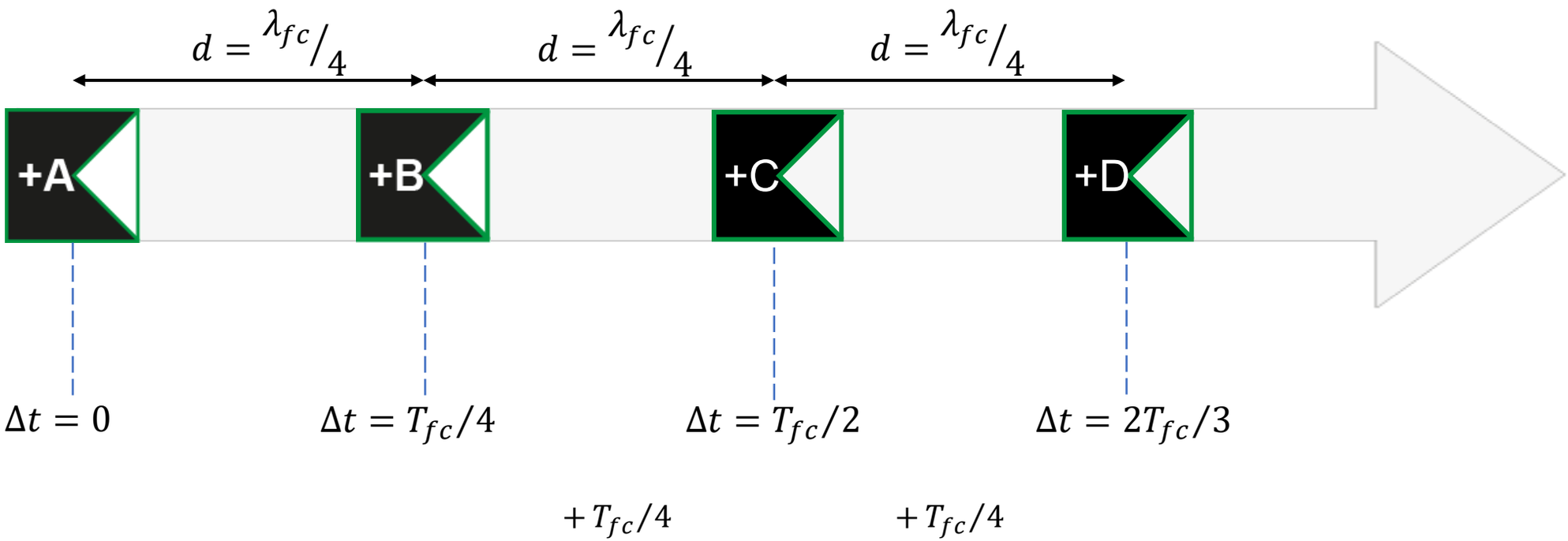
Comparison



End Fire - Standard



End Fire - Standard



End Fire - Standard



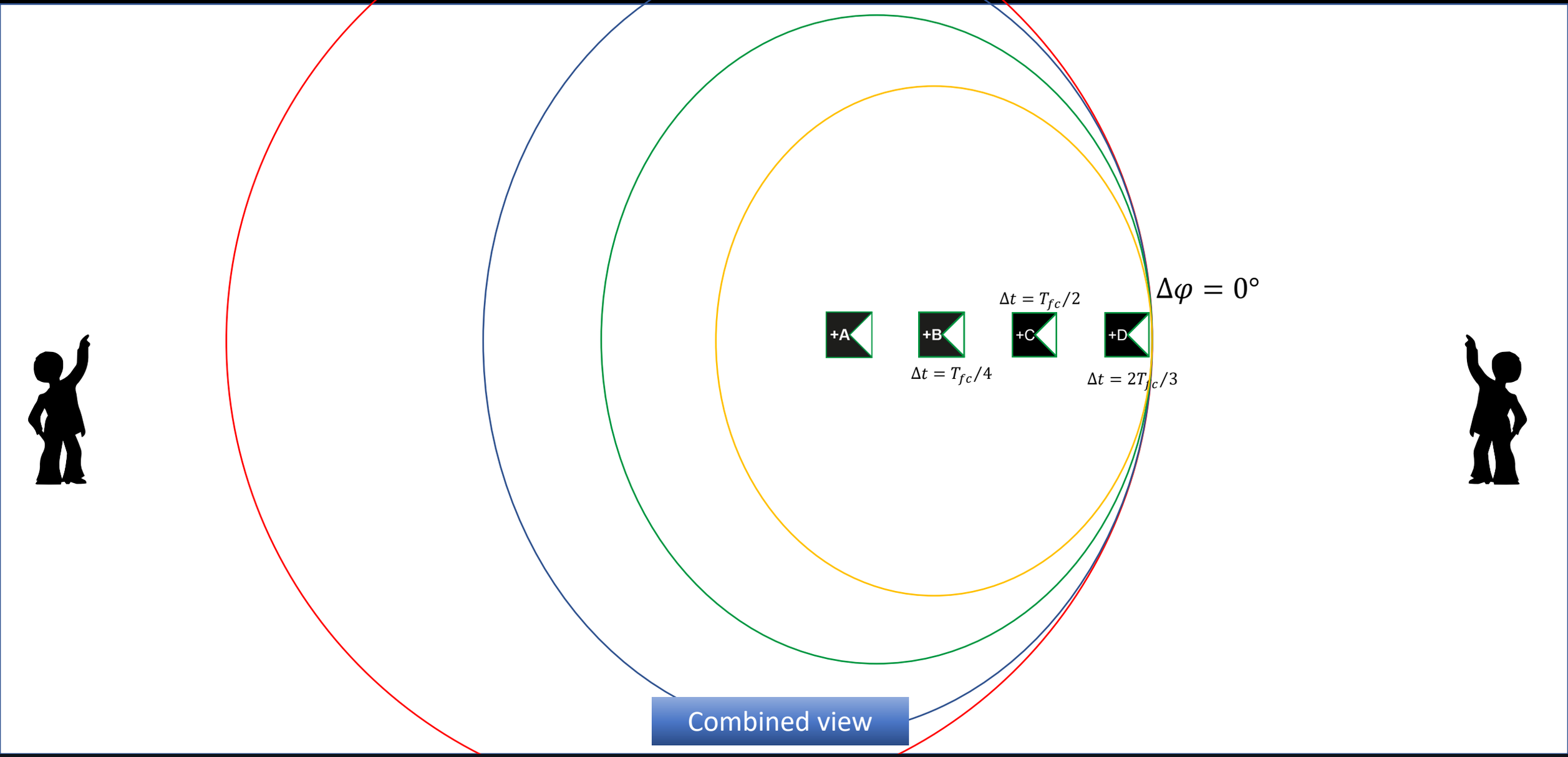




Combined view

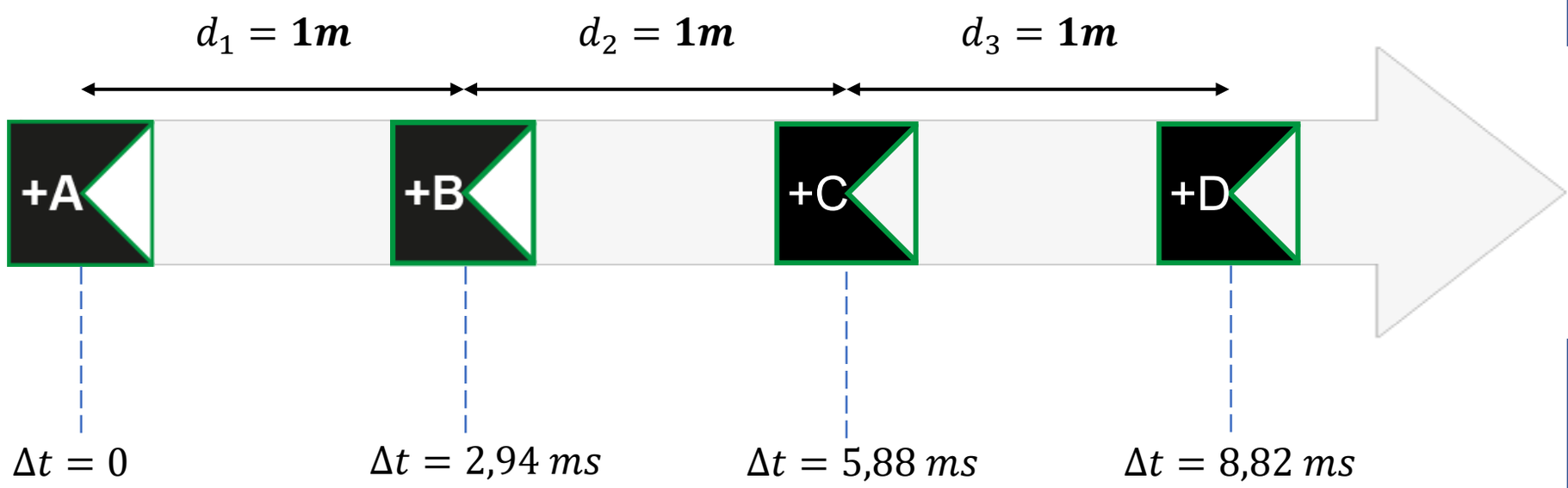
End Fire - Standard

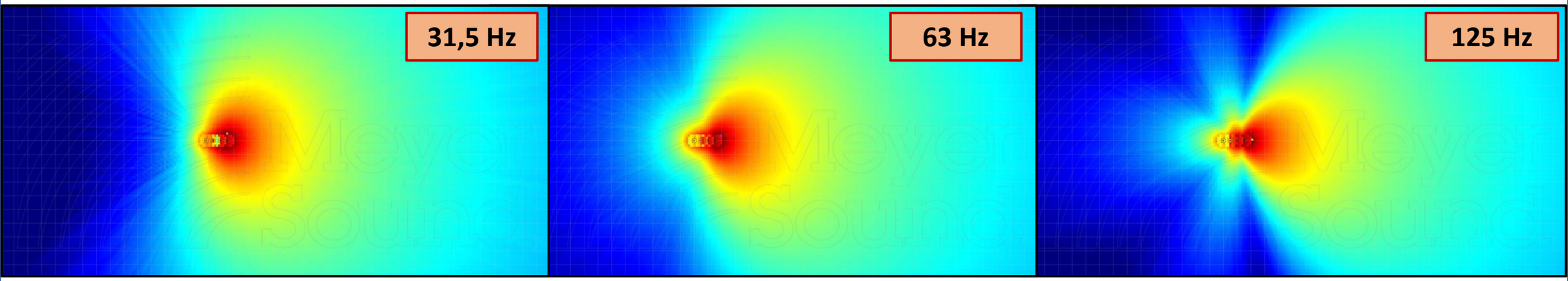
Circular visualisation



End Fire - Standard

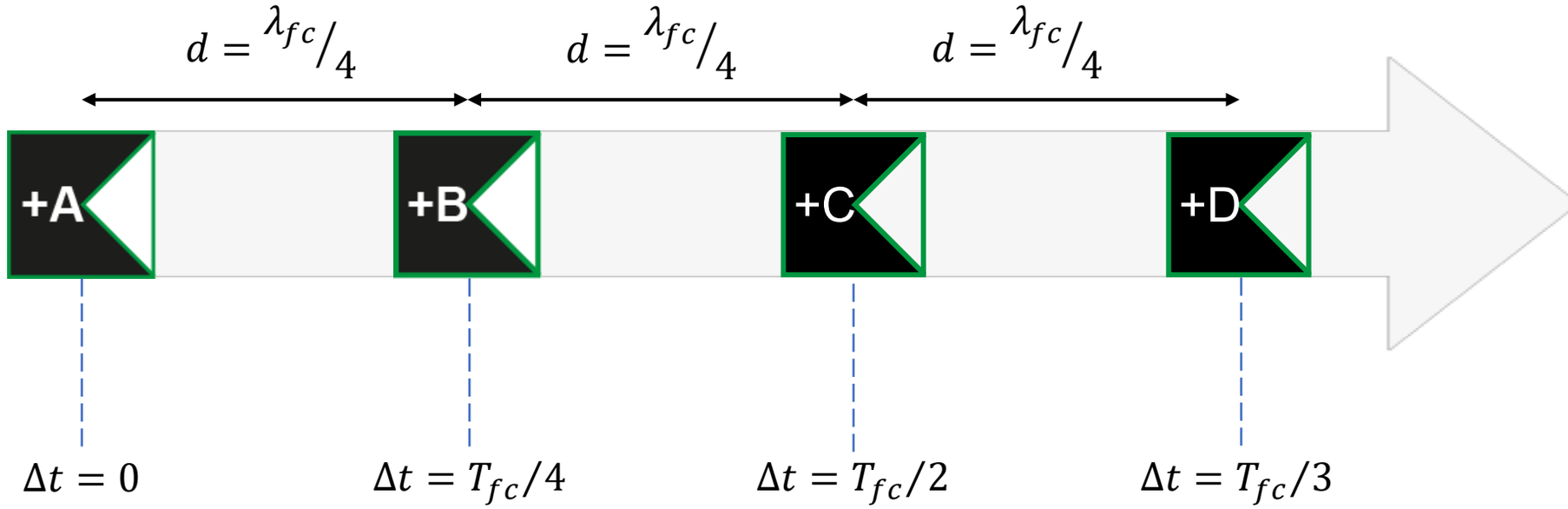
Parameters	
fc =	85 Hz
λ =	4 m
T =	11.66 ms





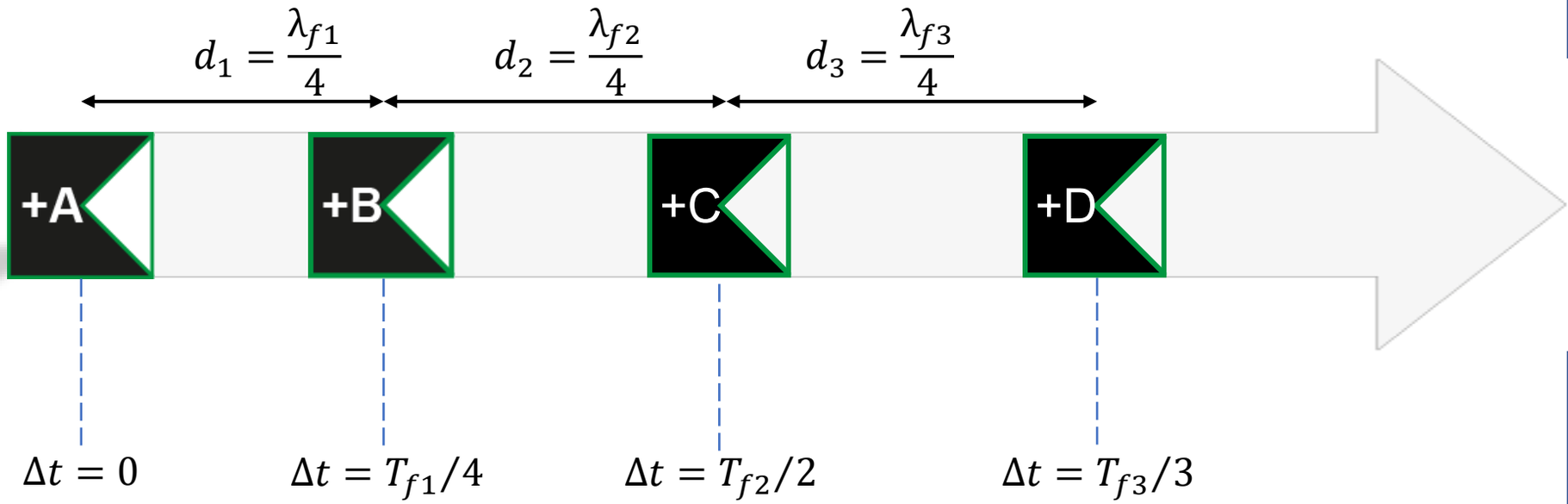
End Fire - Standard

Parameters	
$fc =$	fc
$\lambda =$	T_{fc}
$T =$	λ_{fc}



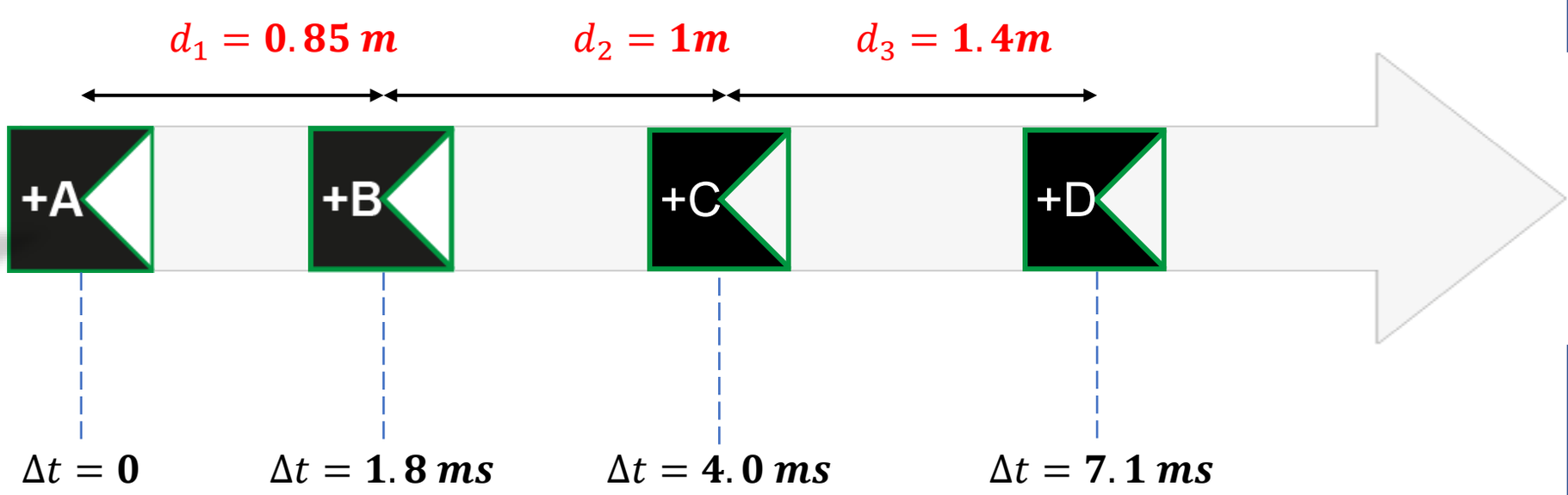
End Fire – Log. 1

Parameters	
fc =	*f1 / f2 / f3*
λ =	λ_{f1} / λ_{f2} / λ_{f3}
T =	T_{f2} / T_{f2} / T_{f3}



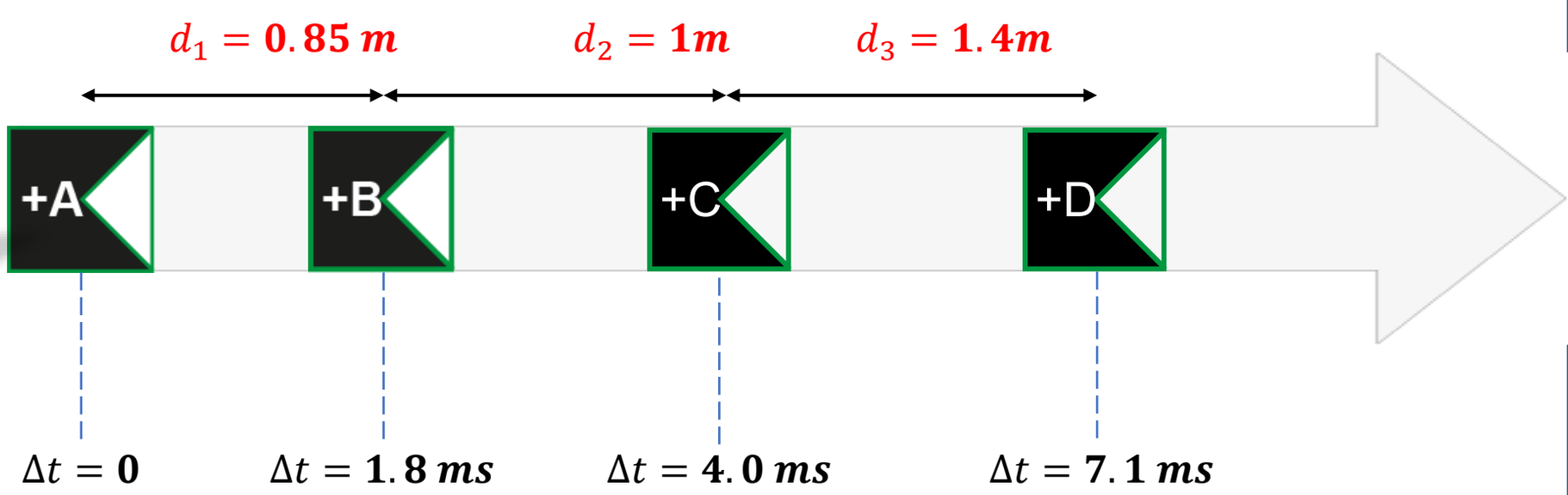
End Fire – Log. 1

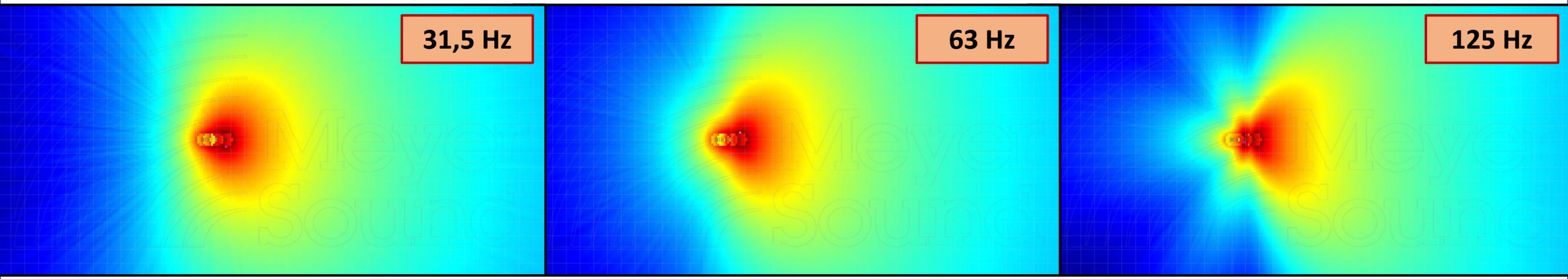
Parameters	
fc =	100 / 85 / 60 Hz
λ =	3.4 / 4 / 5.67 m
T =	10 / 11.76/ 16.67 ms



End Fire – Log. 1

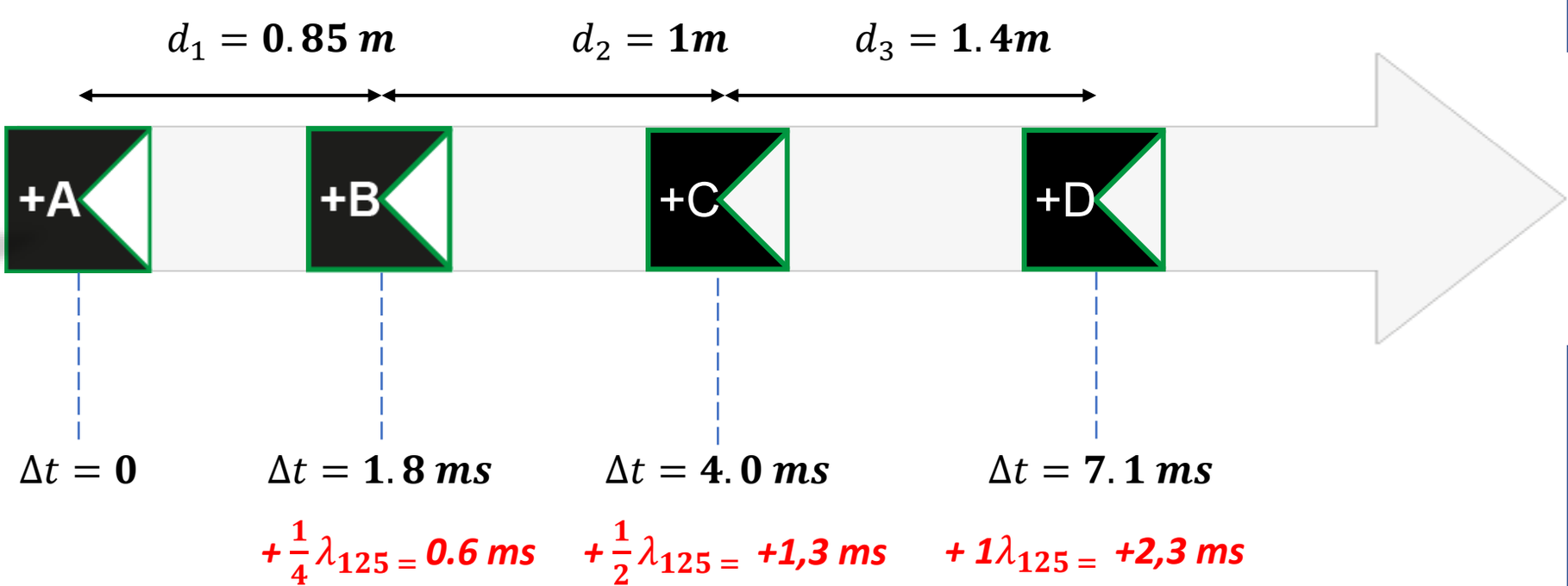
Parameters	
fc =	100 / 85 / 60 Hz
λ =	3.4 / 4 / 5.67 m
T =	10 / 11.76/ 16.67 ms





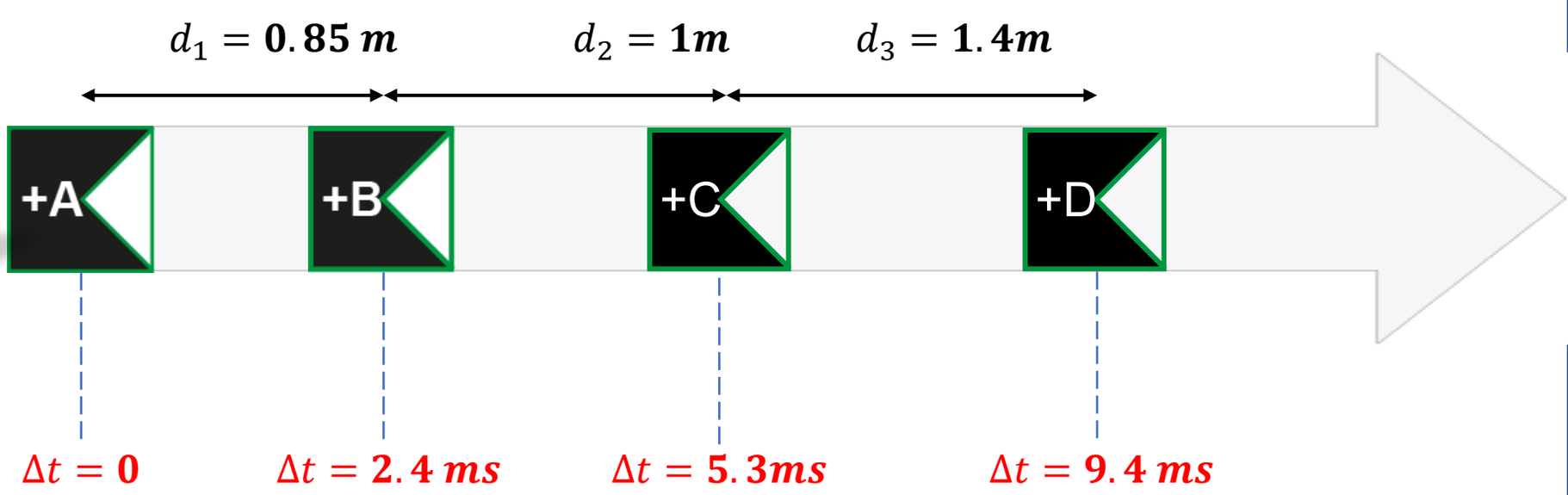
End Fire – Log. 2
(90° rotation at 125 Hz)

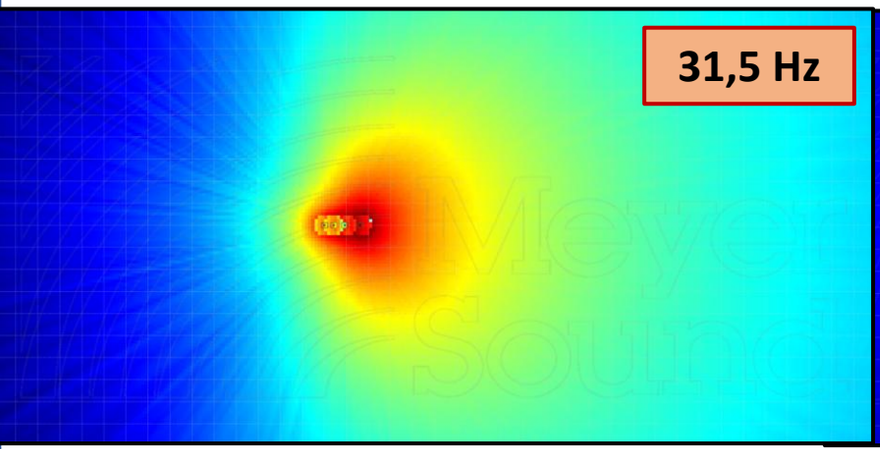
Parameters	
fc =	100 / 85 / 60 Hz
λ =	3.4 / 4 / 5.67 m
T =	10 / 11.76/ 16.67 ms

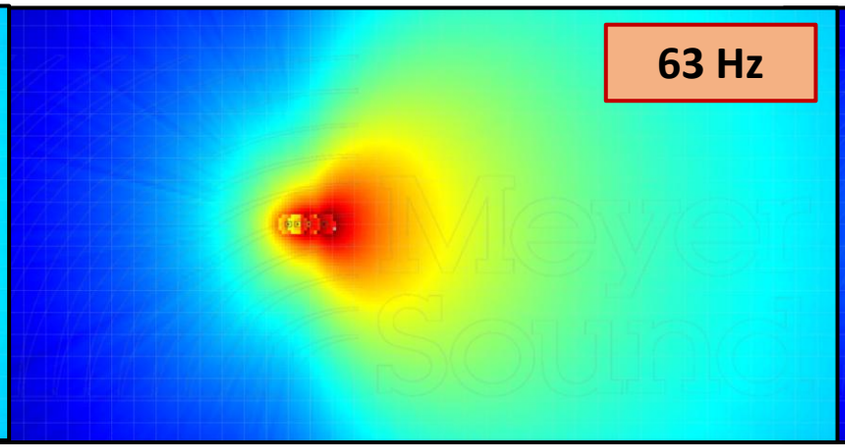


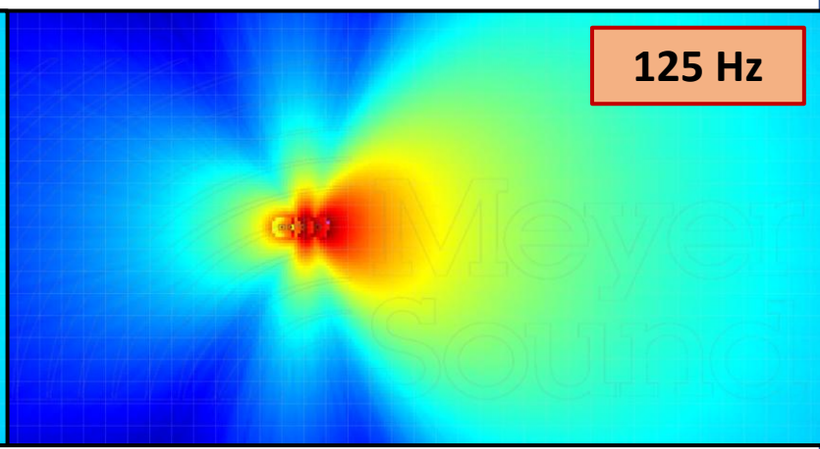
End Fire – Log. 2
(90° rotation at 125 Hz)

Parameters	
fc =	100 / 85 / 60 Hz
λ =	3.4 / 4 / 5.67 m
T =	10 / 11.76/ 16.67 ms







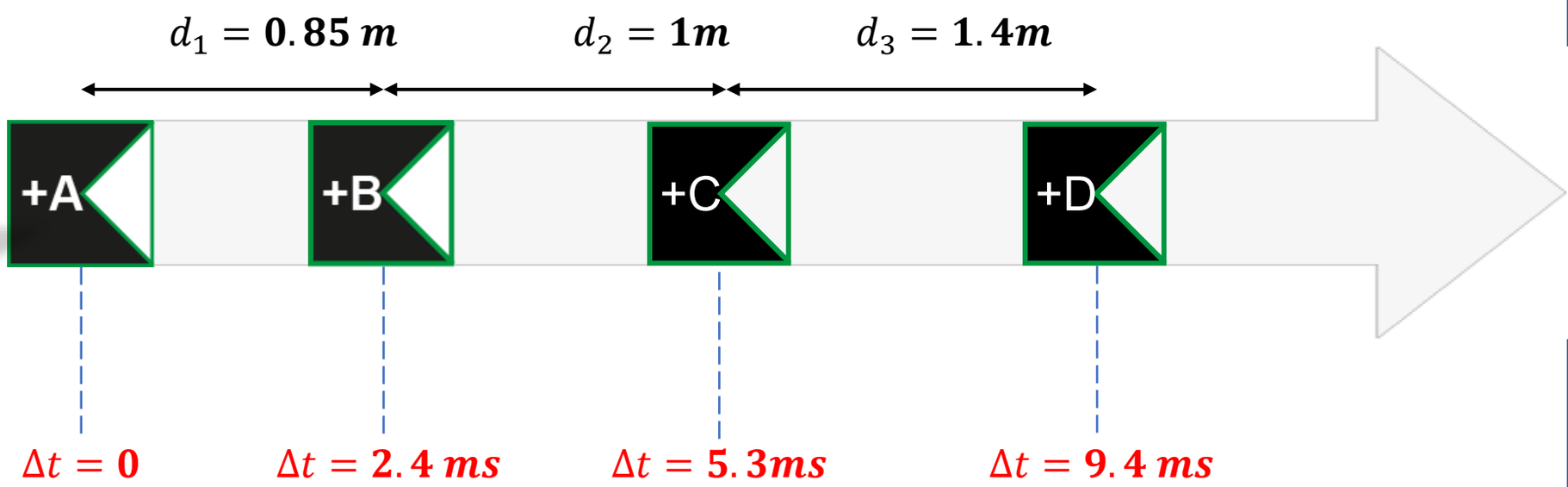


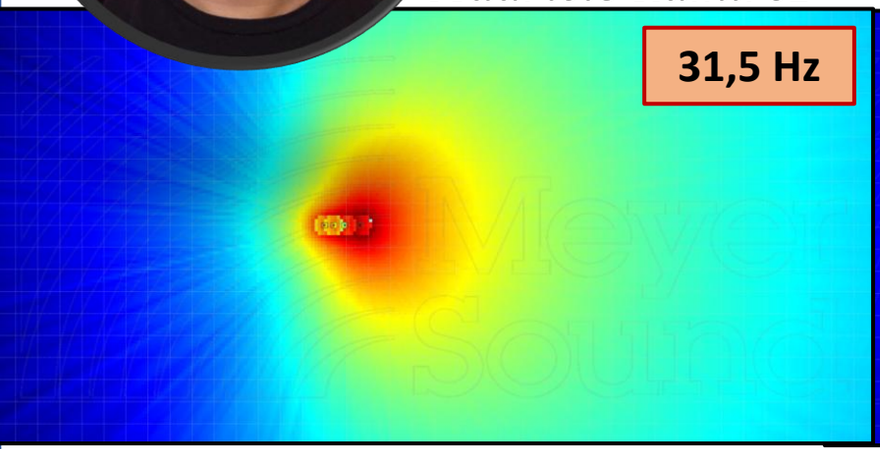
End Fire – Log. 2
(90° rotation at 125 Hz)

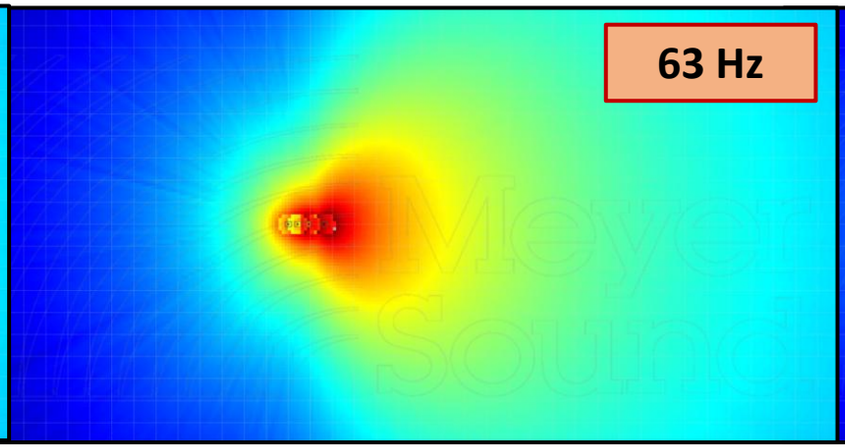
Parameters	
fc =	100 / 85 / 60 Hz
λ =	3.4 / 4 / 5.67 m
T =	10 / 11.76/ 16.67 ms

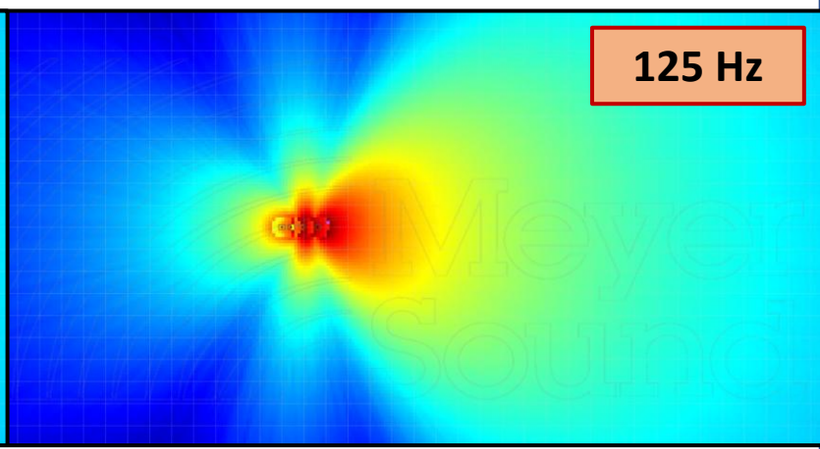


Mauricio Ramirez

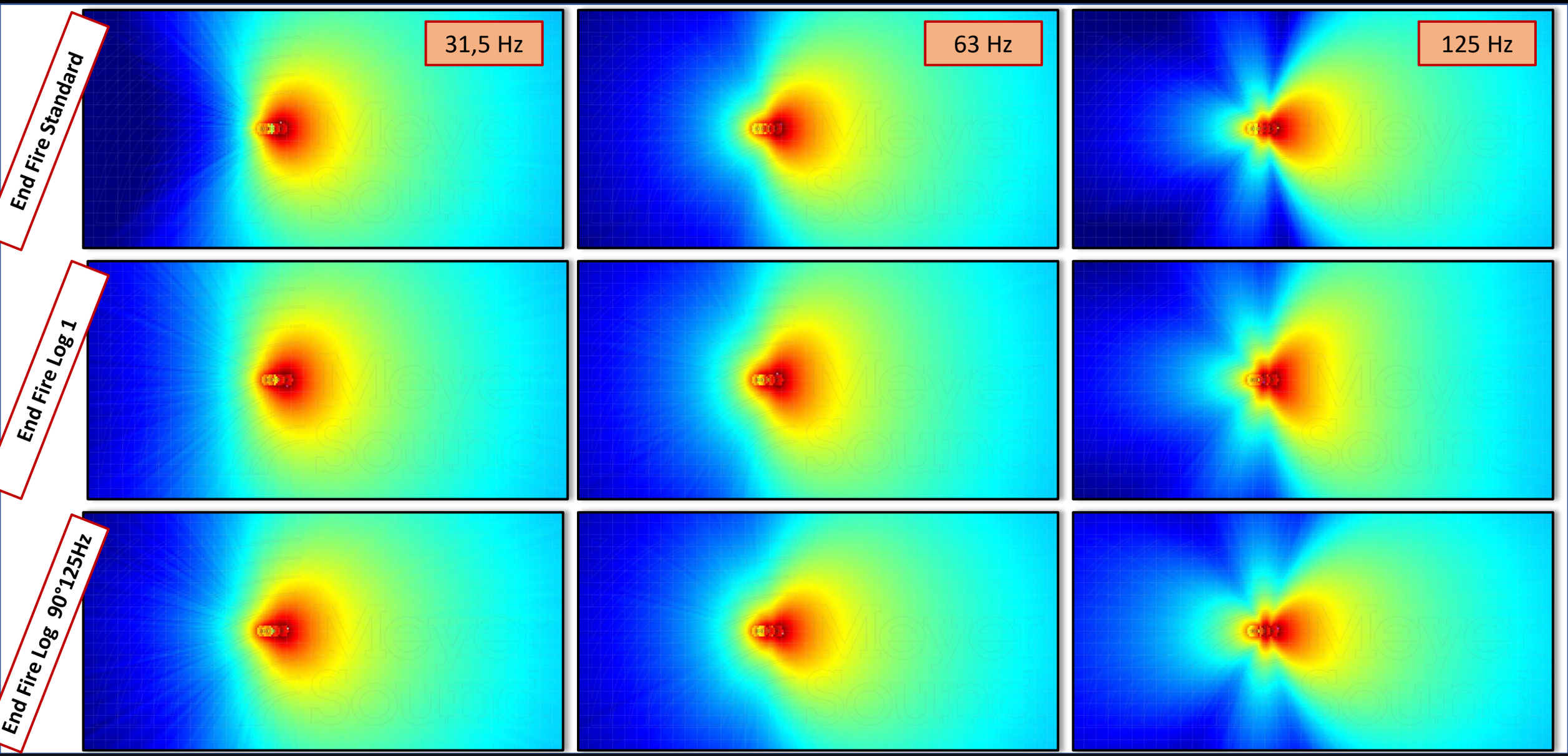








End-fire — comparison

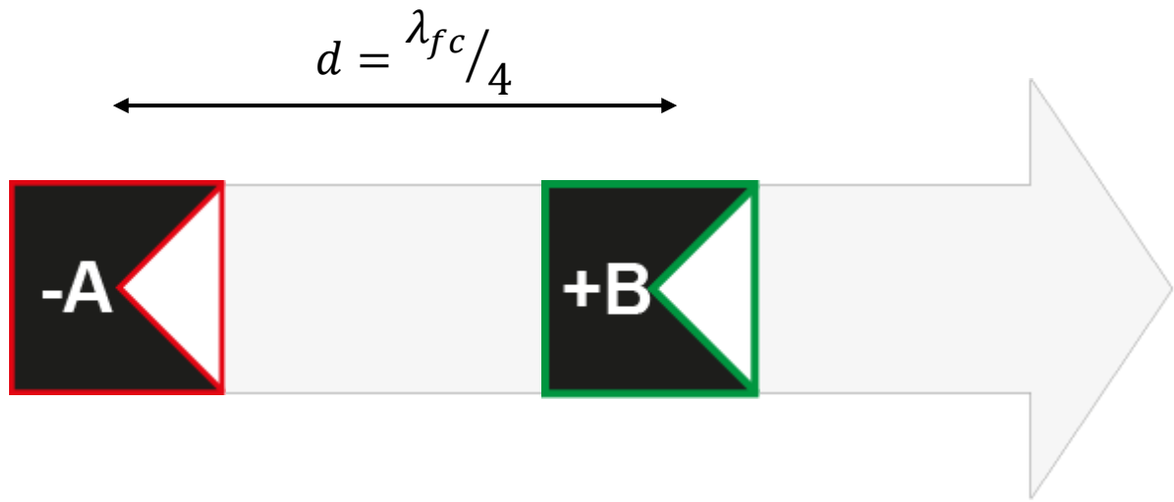


?

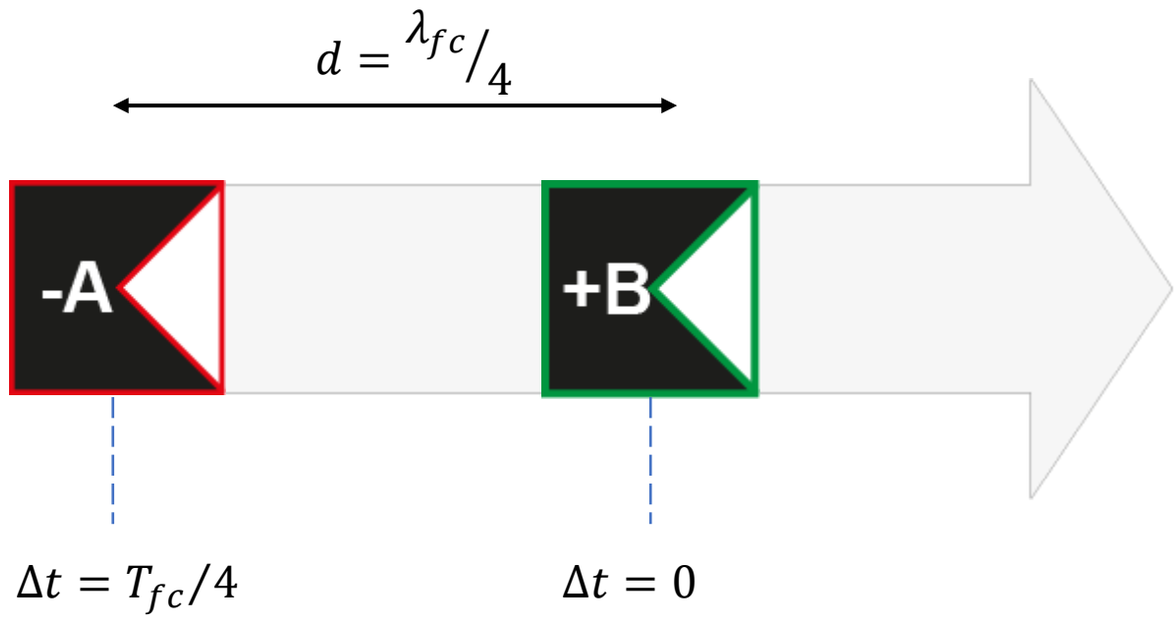
Pressure-gradient configuration



Pressure-gradient configuration



Pressure-gradient configuration



Pressure-gradient configuration

Wave visualisation

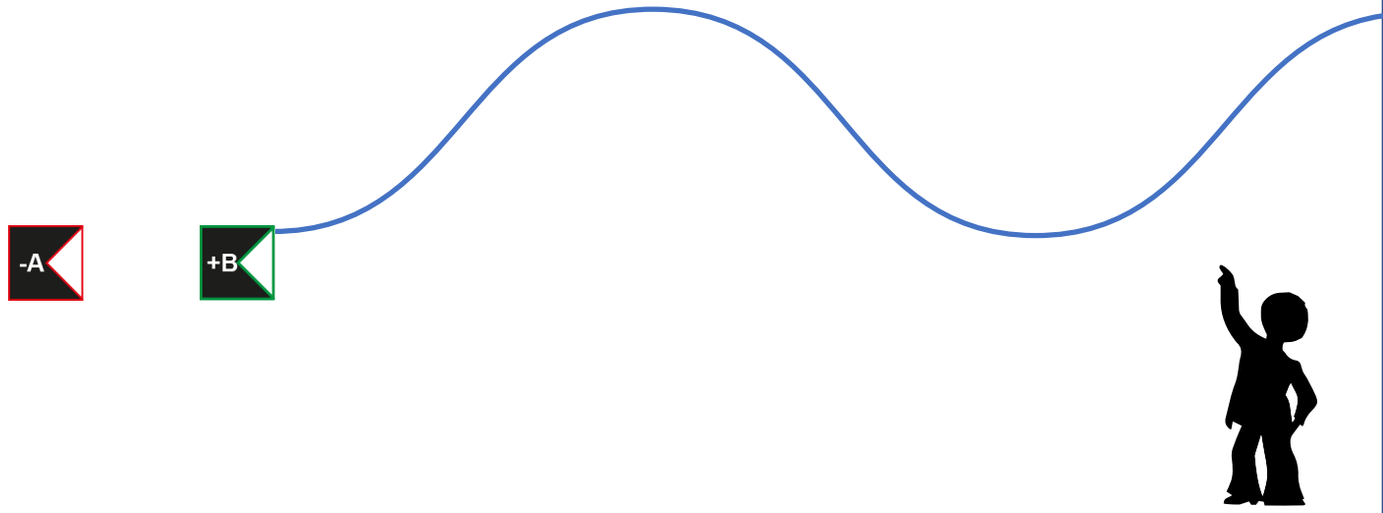




Pressure-gradient configuration

Wave visualisation

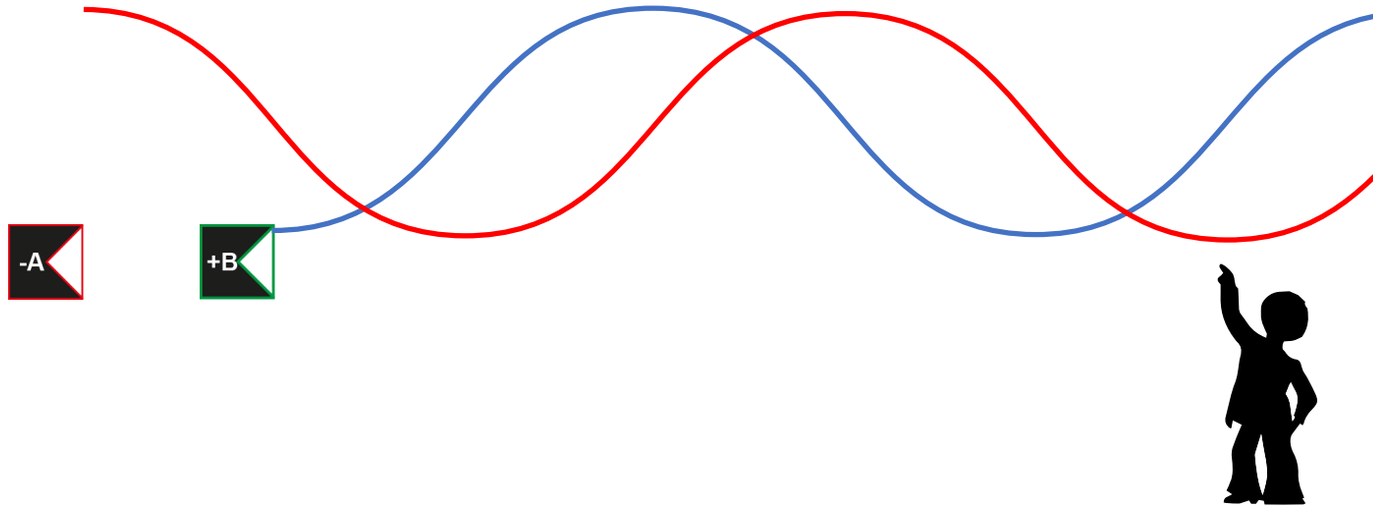
Front view



Pressure-gradient configuration

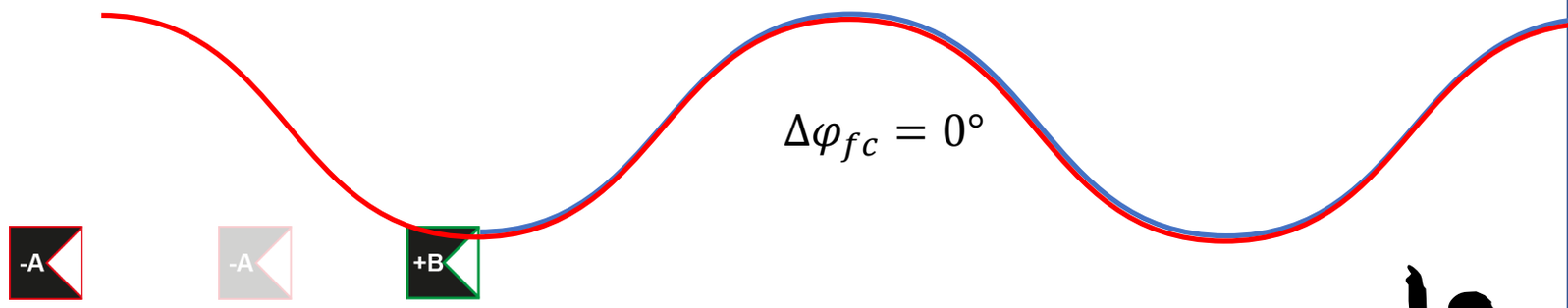
Wave visualisation

Front view



Pressure-gradient configuration
Wave visualisation

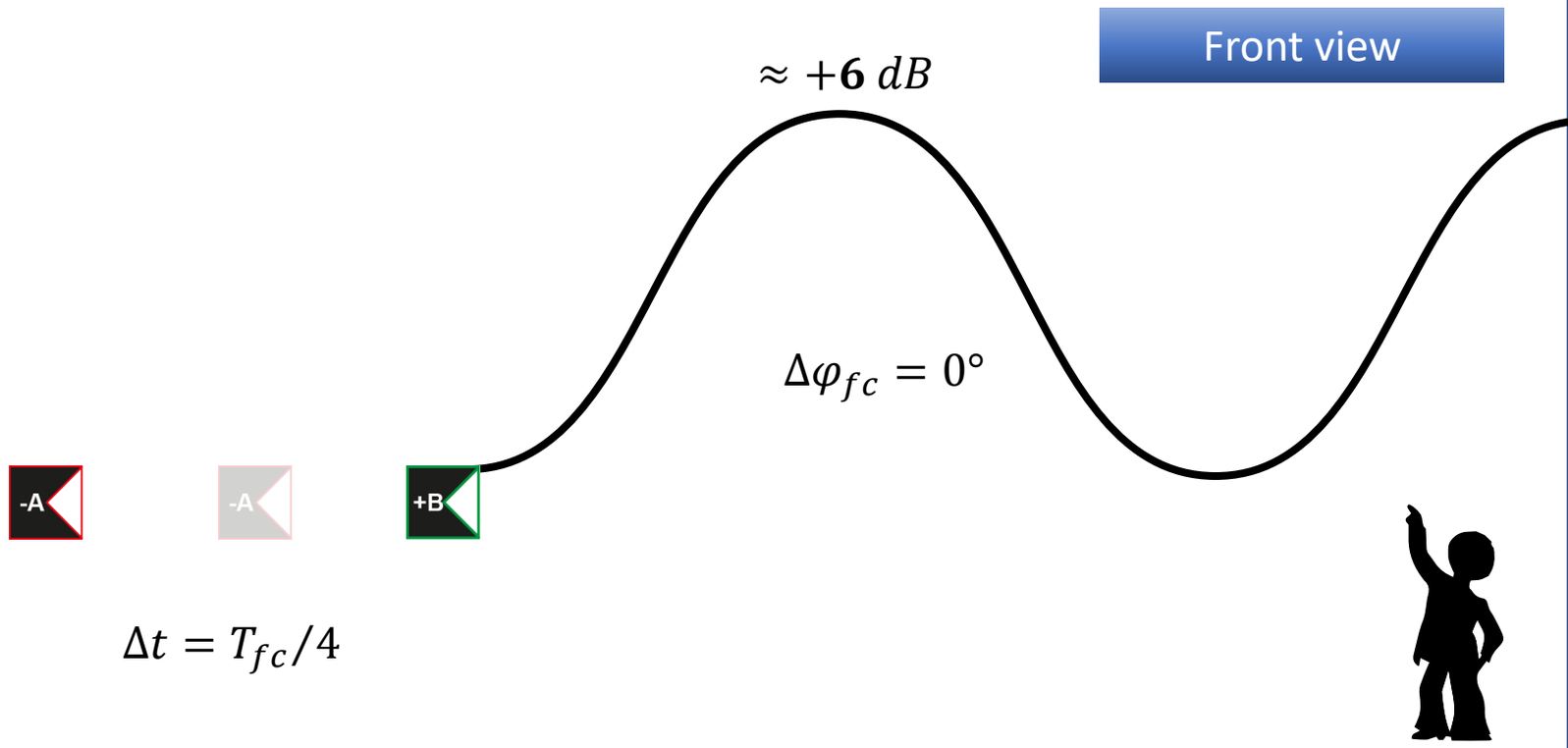
Front view



$$\Delta t = T_{fc}/4$$



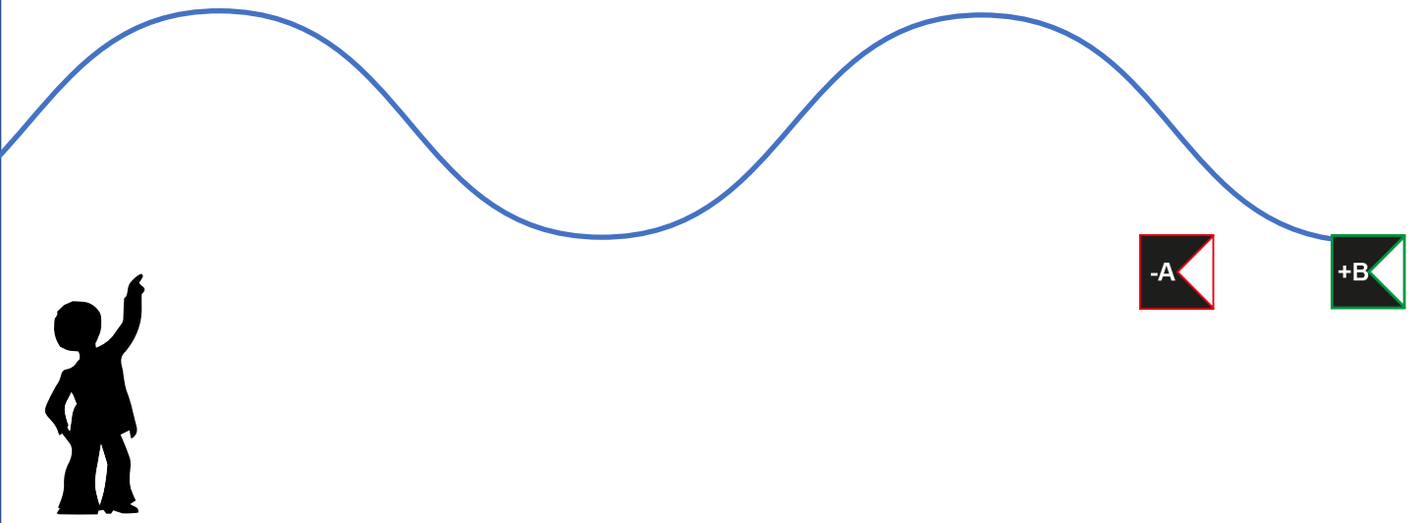
Pressure-gradient configuration
Wave visualisation



Pressure-gradient configuration

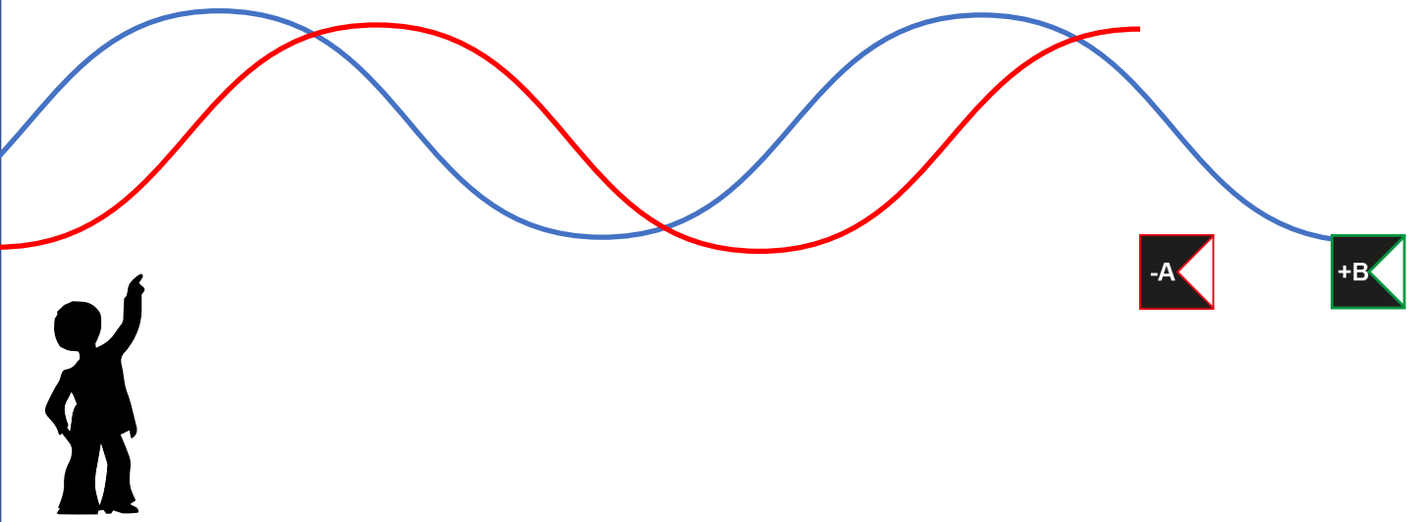
Wave visualisation

Rear view



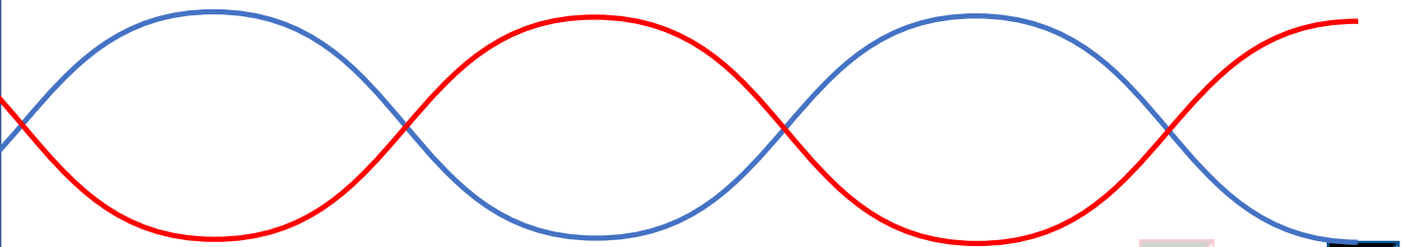
Pressure-gradient configuration
Wave visualisation

Rear view



Pressure-gradient configuration
Wave visualisation

Rear view



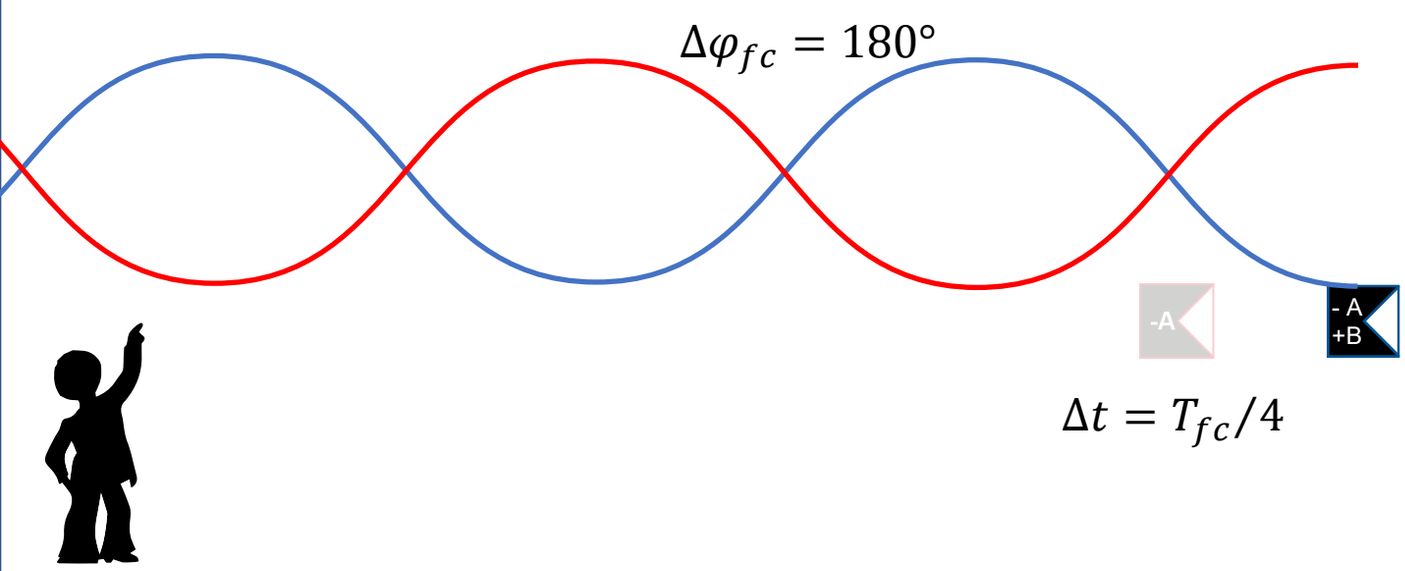




$$\Delta t = T_{fc}/4$$

Pressure-gradient configuration
Wave visualisation

Rear view



Pressure-gradient configuration
Wave visualisation

Rear view

$$\Delta\varphi_{fc} = 180°$$

$$-\infty\ dB$$





$$\Delta t = T_{fc}/4$$

Pressure-gradient configuration

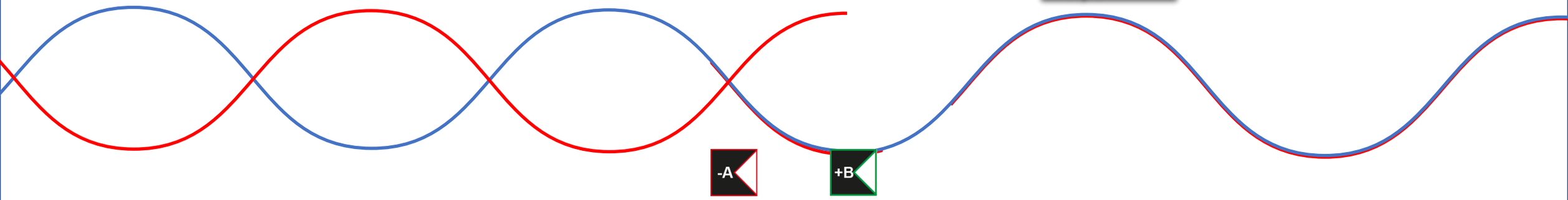
Frequency changes = front phase changes

Frequency

$f = fc$

$\Delta\varphi_{fc} = 180°$

$\Delta\varphi_{fc} = 0°$



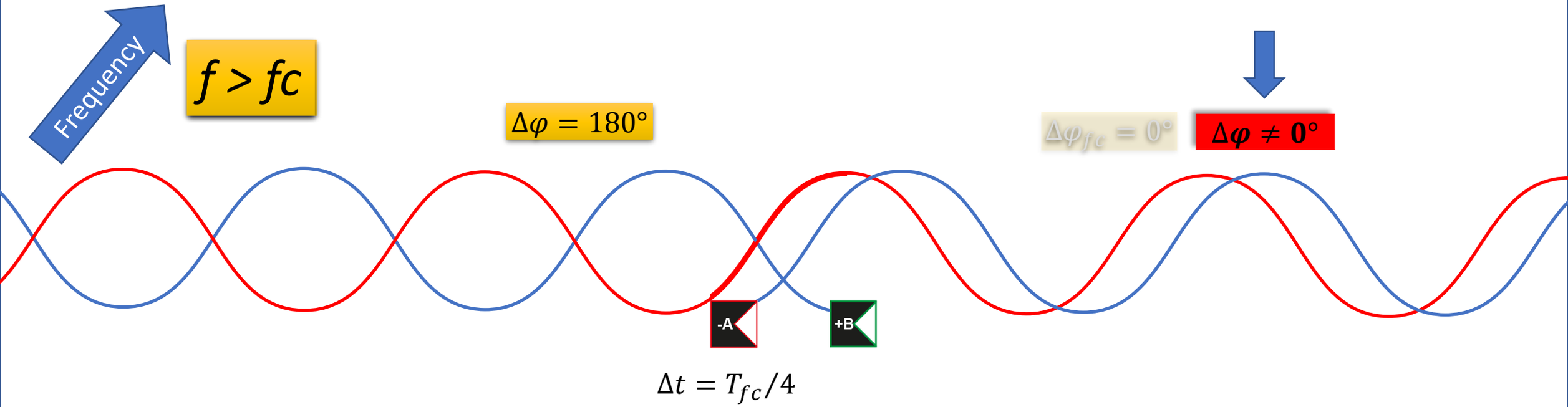
$$\Delta t = T_{fc}/4$$

Combined view

$$\Delta_{\varphi} = \frac{\Delta_d . f . 360}{c}$$

Pressure-gradient configuration

Frequency changes = front phase changes



$$\Delta t = T_{fc}/4$$

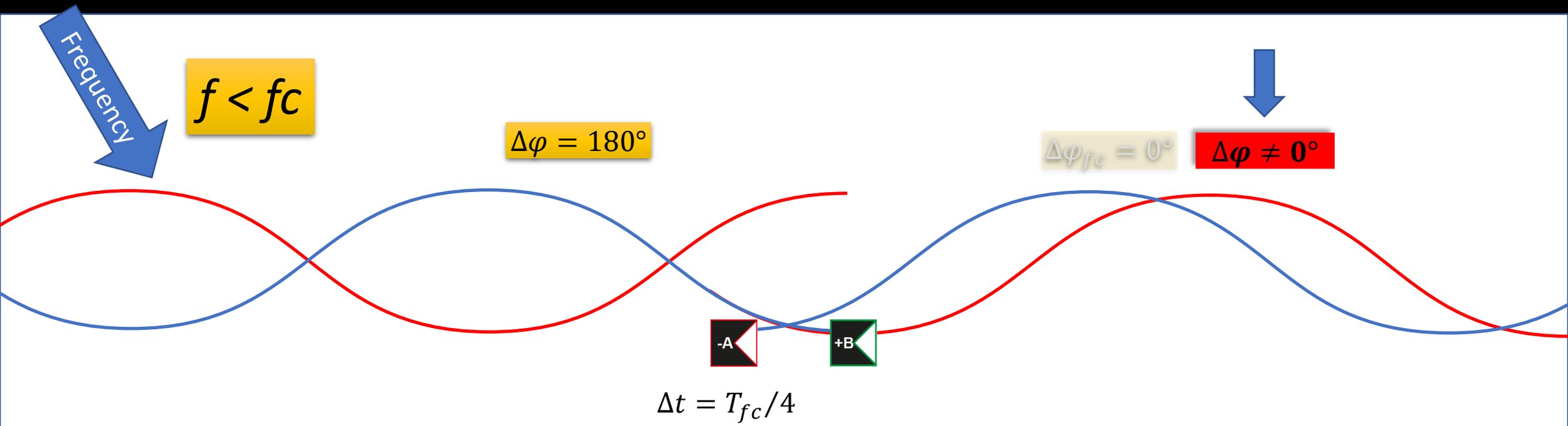
The phase difference ($\Delta\varphi$) at the rear of the system does not change with frequency.

Combined view

$$\Delta_{\varphi} = \frac{\Delta_d . f . 360}{c}$$

Pressure-gradient configuration

Frequency changes = front phase changes



$$\Delta t = T_{fc}/4$$

However, the phase difference ($\Delta\varphi$) at the front of the system changes with frequency

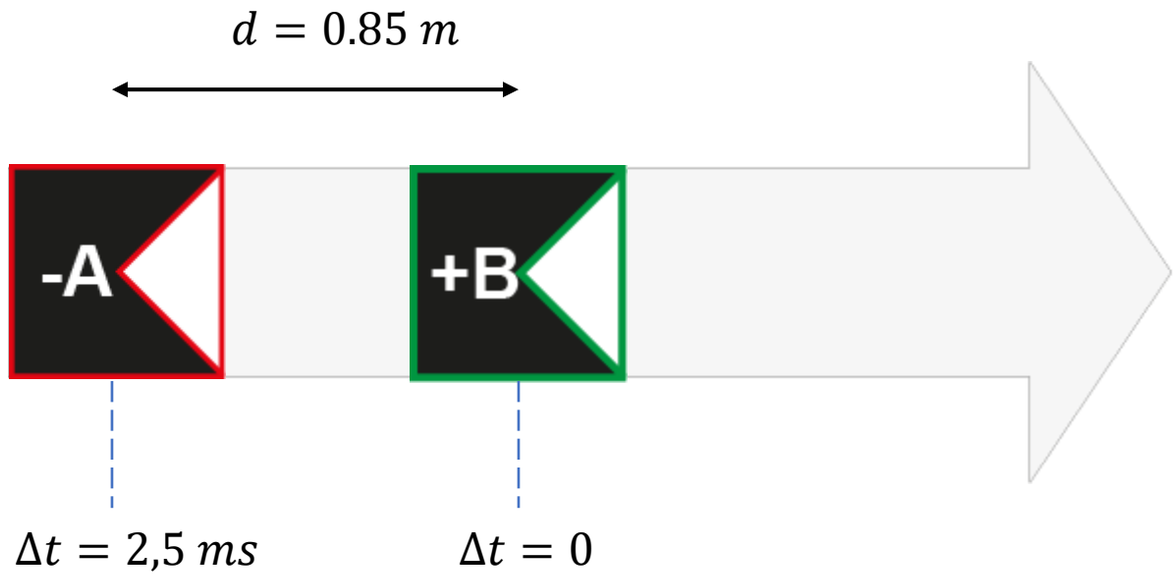
Combined view

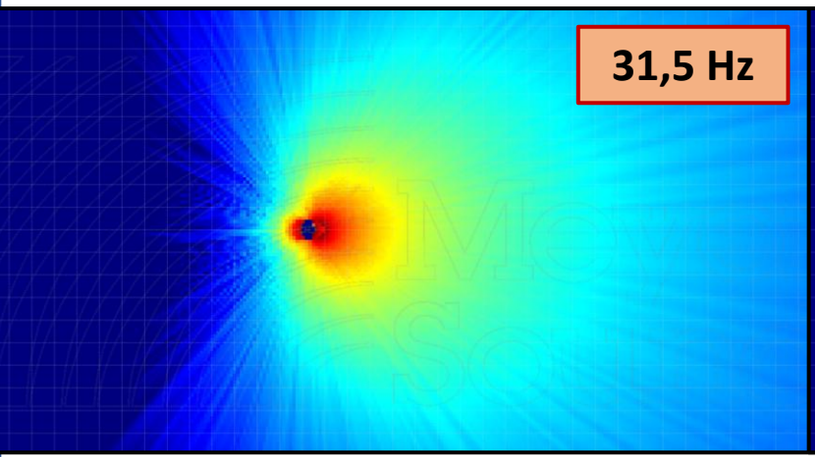
$$\Delta_\varphi = \frac{\Delta_d . f . 360}{c}$$

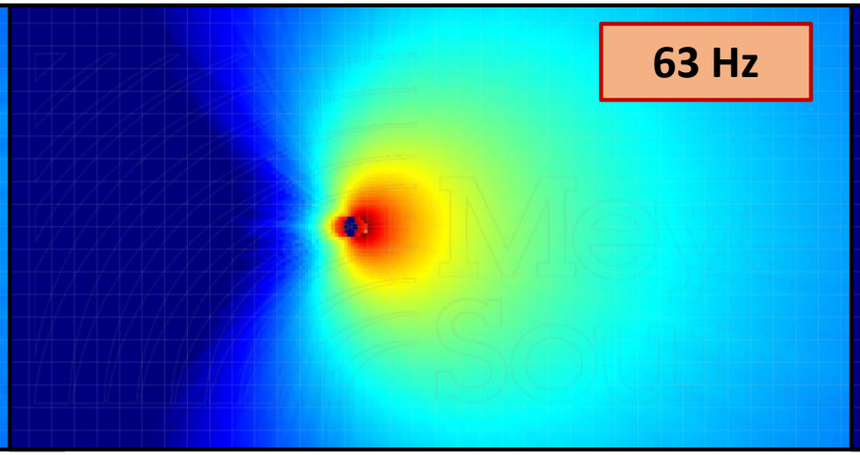
Pressure-gradient configuration

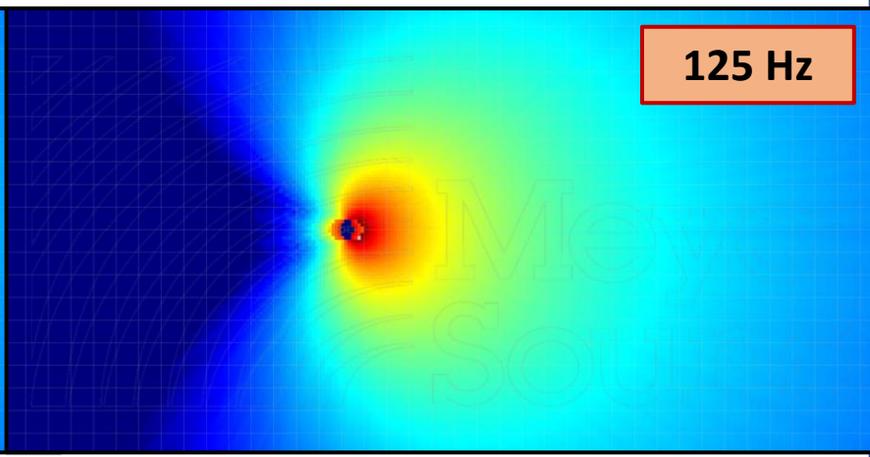
Example 0.85 m

Parameters	
fc =	**100 Hz**
λ =	**3.4 m**
T =	**10 ms**





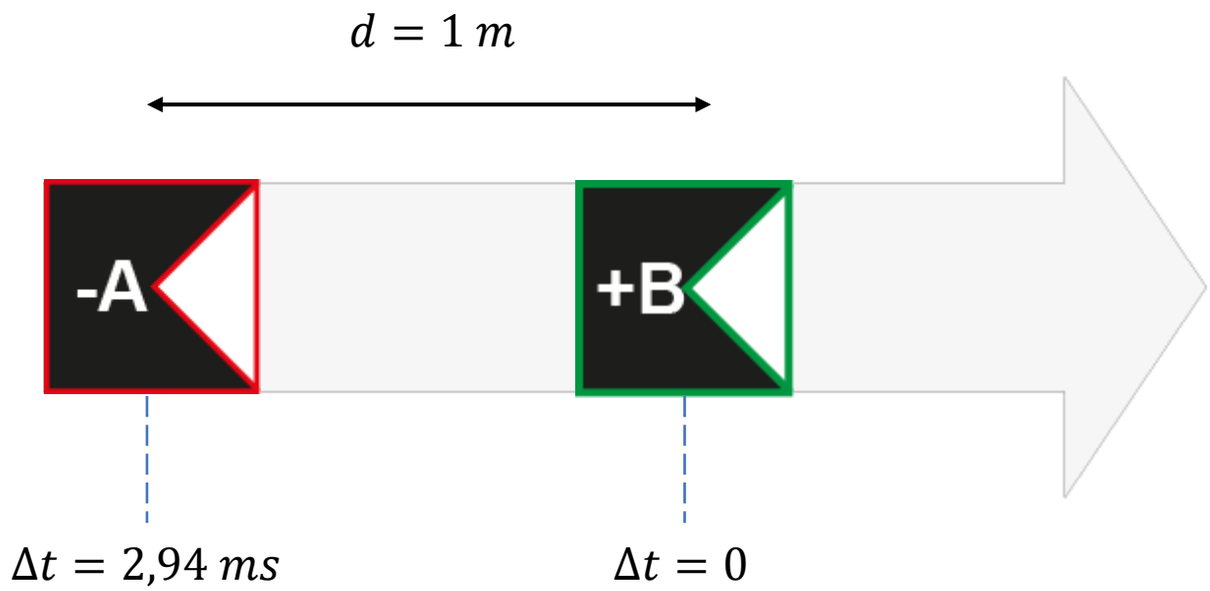


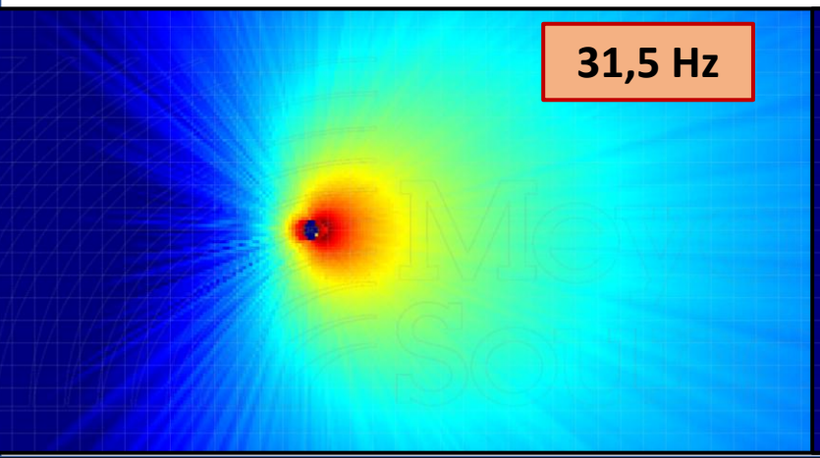


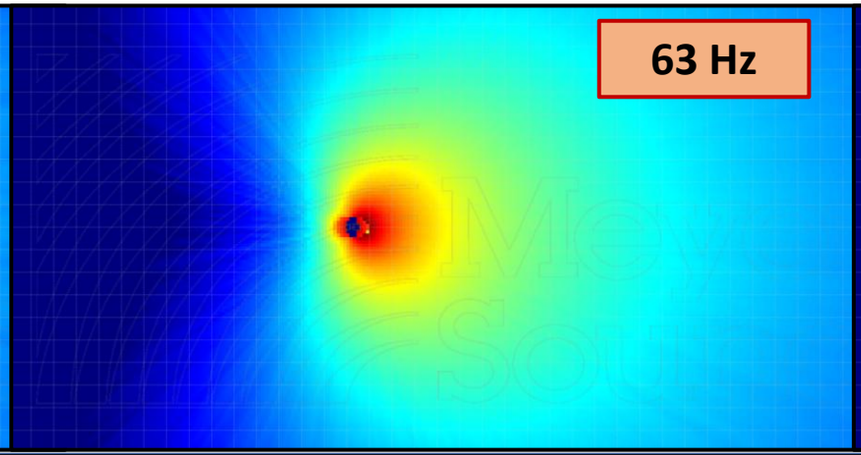
Pressure-gradient configuration

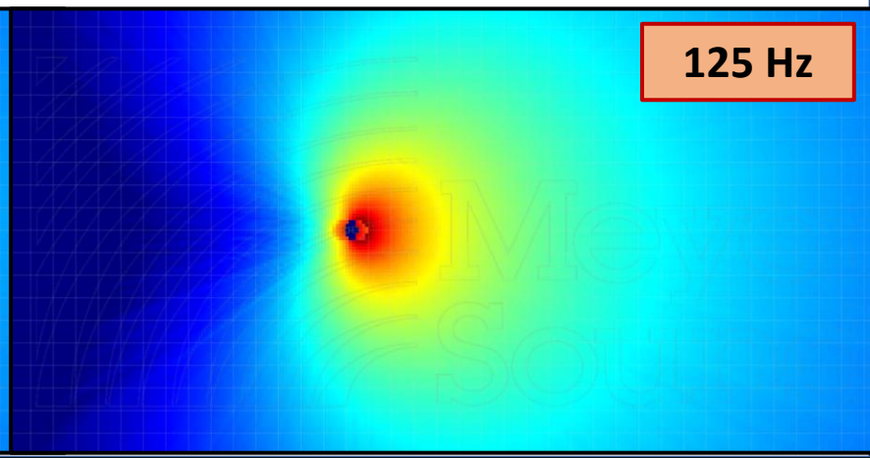
Example 1m

Parameters	
fc =	**85 Hz**
λ =	**4 m**
T =	**11.66 ms**





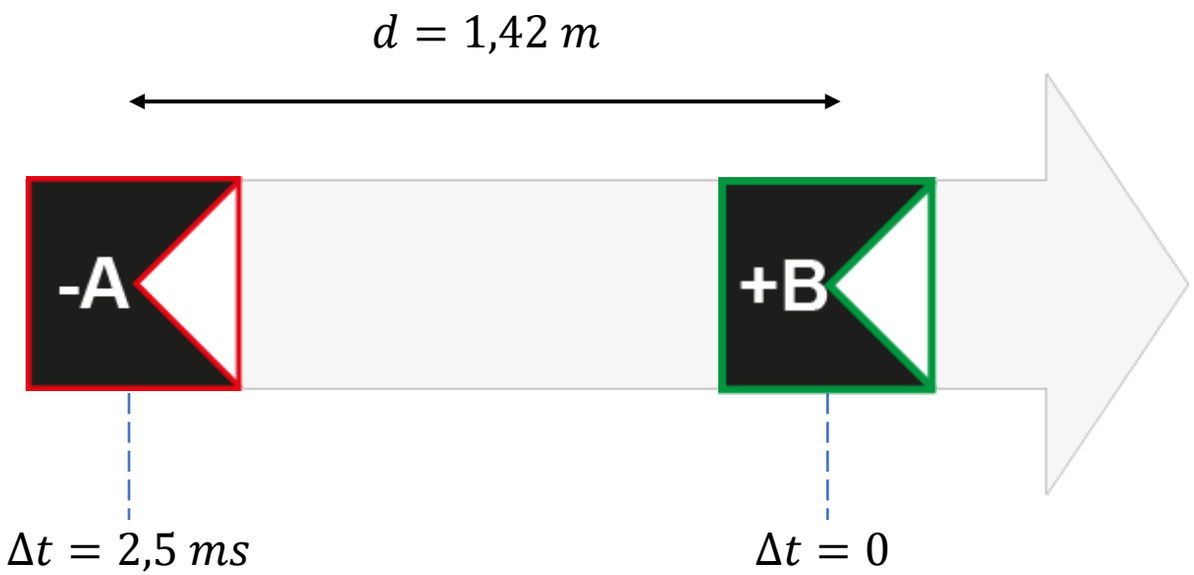


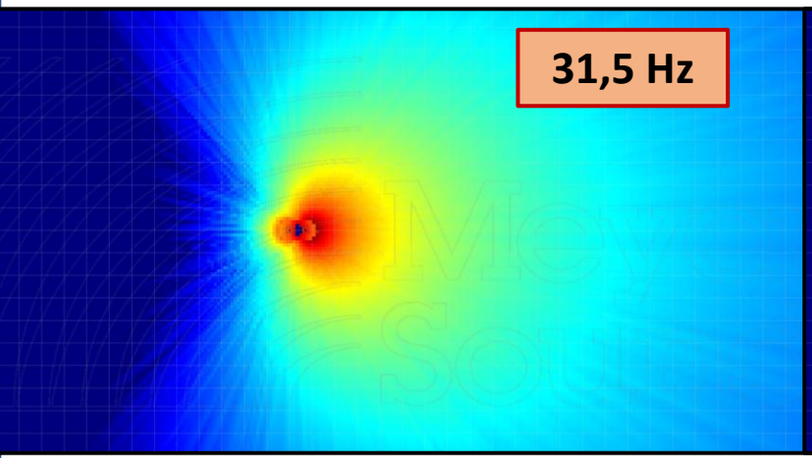


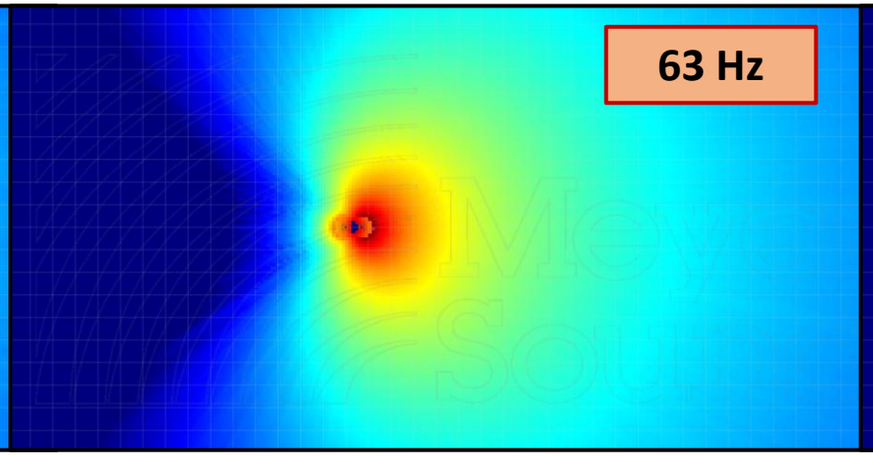
Pressure-gradient configuration

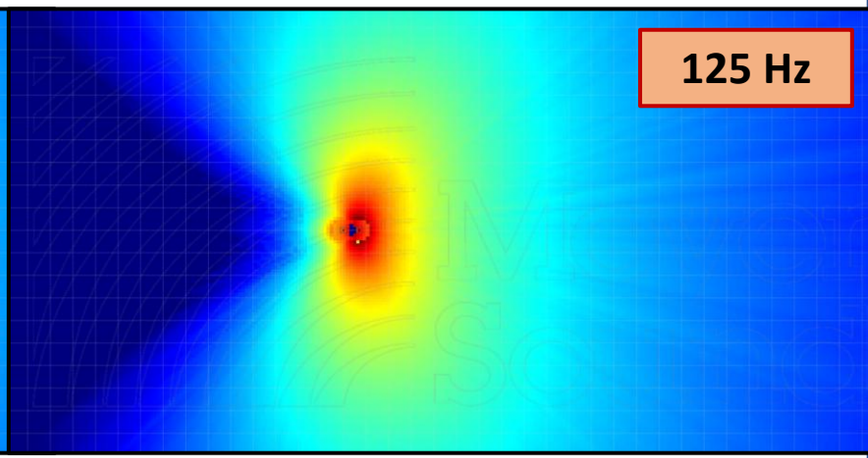
Example 1.42 m

Parameters	
fc =	**60 Hz**
λ =	**5.67 m**
T =	**16.67 ms**



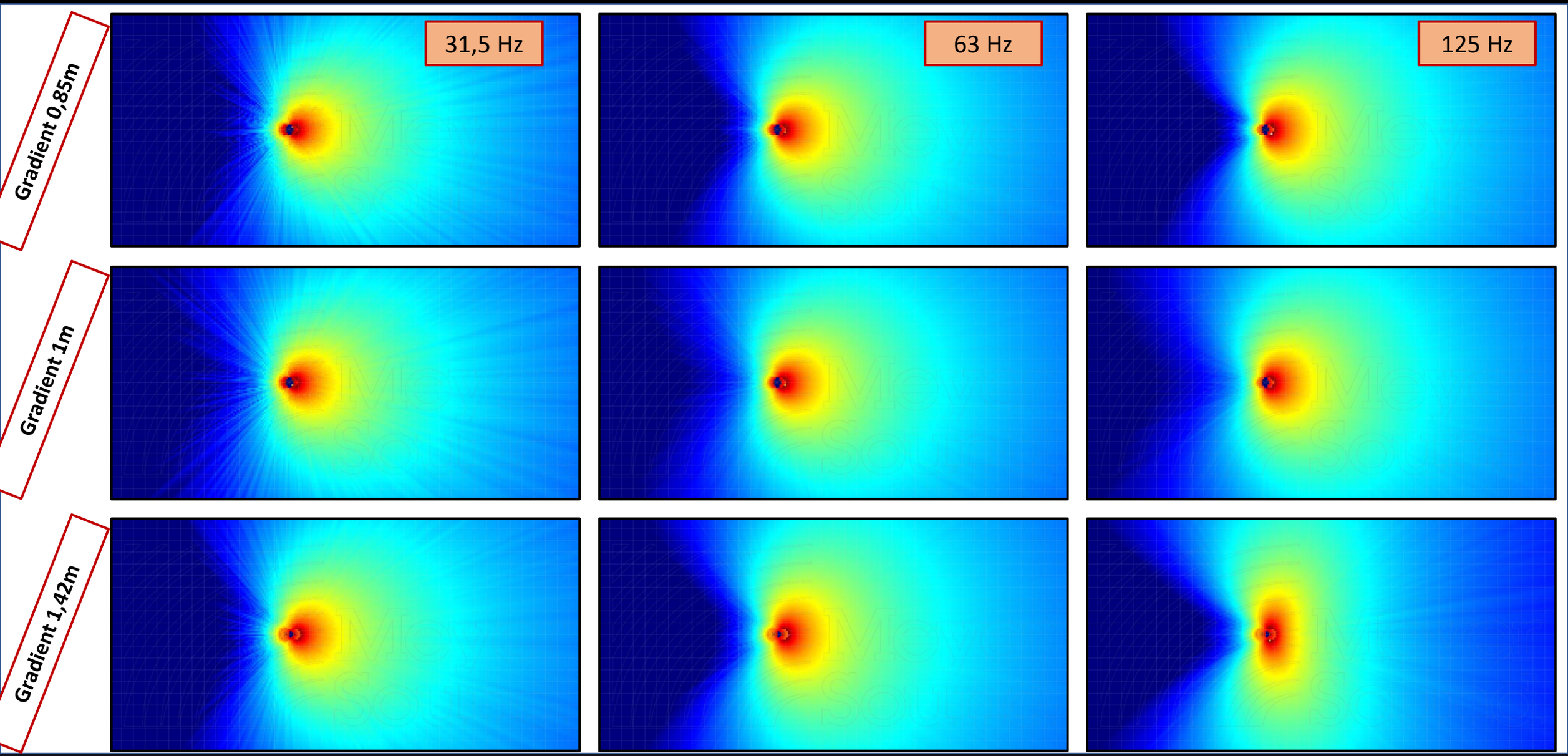






Pressure-gradient configuration

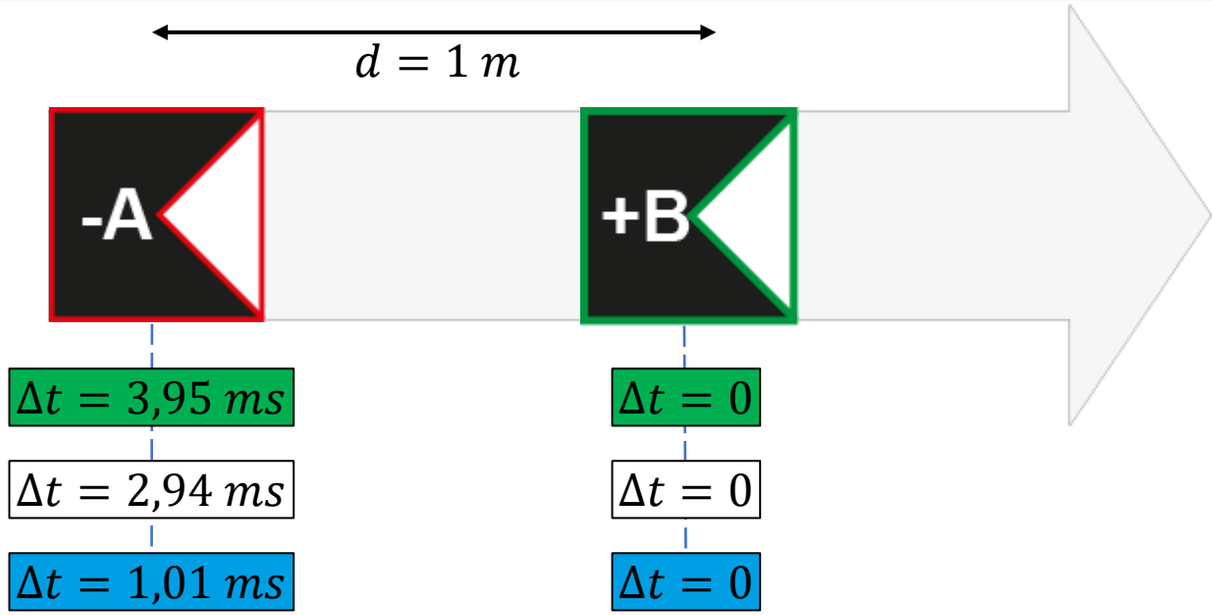
Comparison

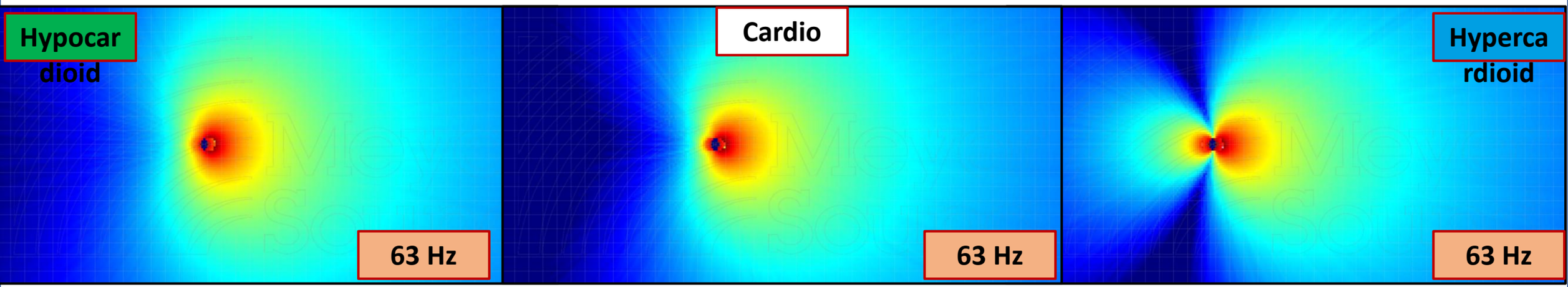


Pressure-gradient configuration

Hypocardioid — hypercardioid

Parameters	
fc =	85 Hz
λ =	4 m
T =	11.66 ms



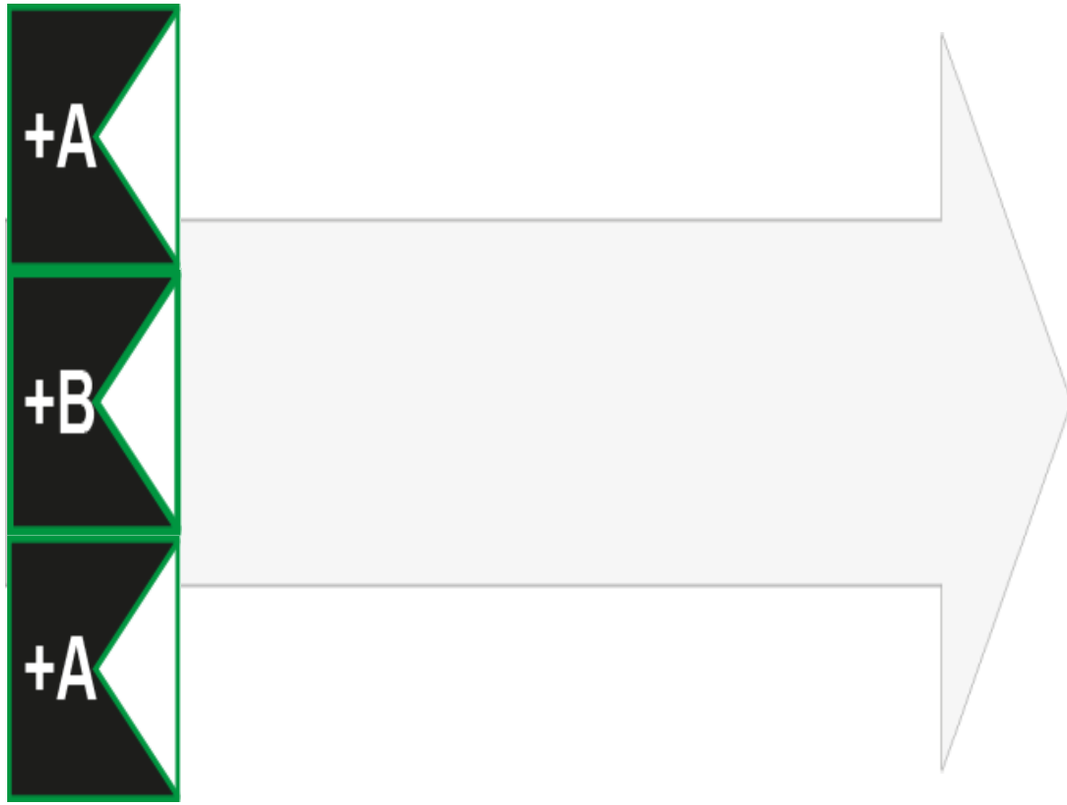


A good-looking gradient array

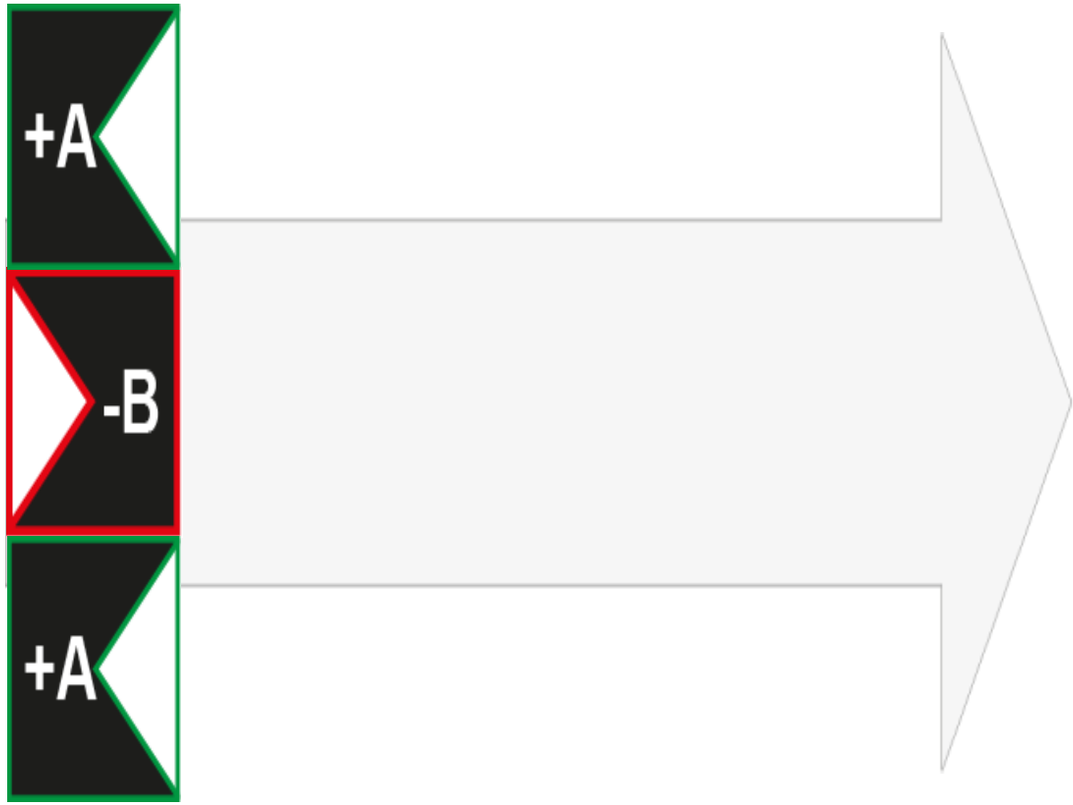


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Stacks
Horizontal inverted gradient stack

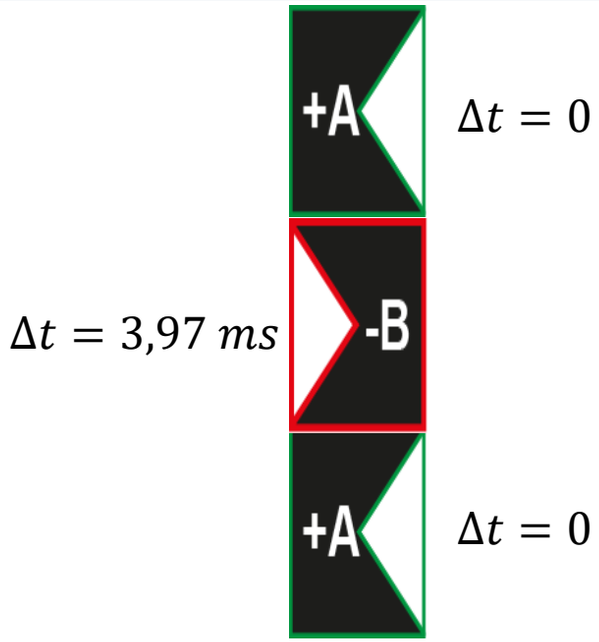


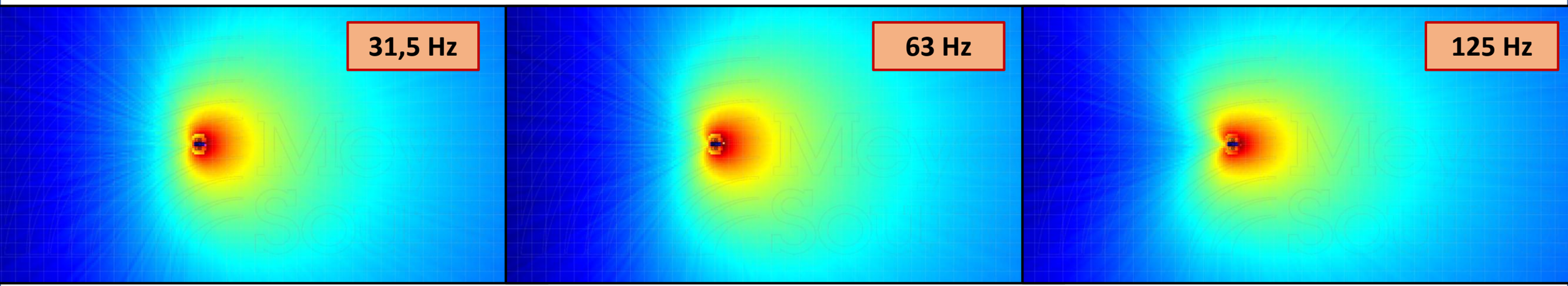
Stacks
Horizontal inverted gradient stack



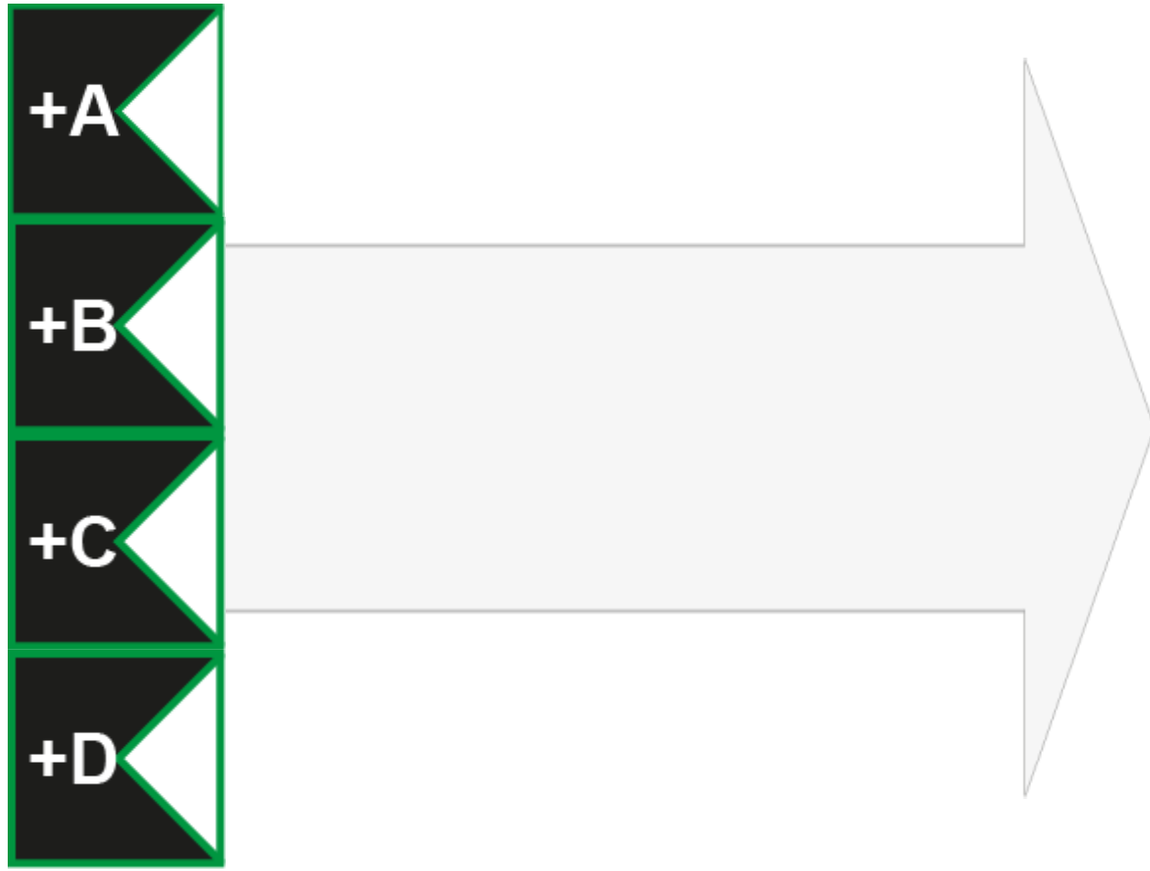
Stacks
Horizontal inverted gradient stack

Parameters	
fc =	≈ 85 Hz
λ =	5.4 m
T =	15.87 ms

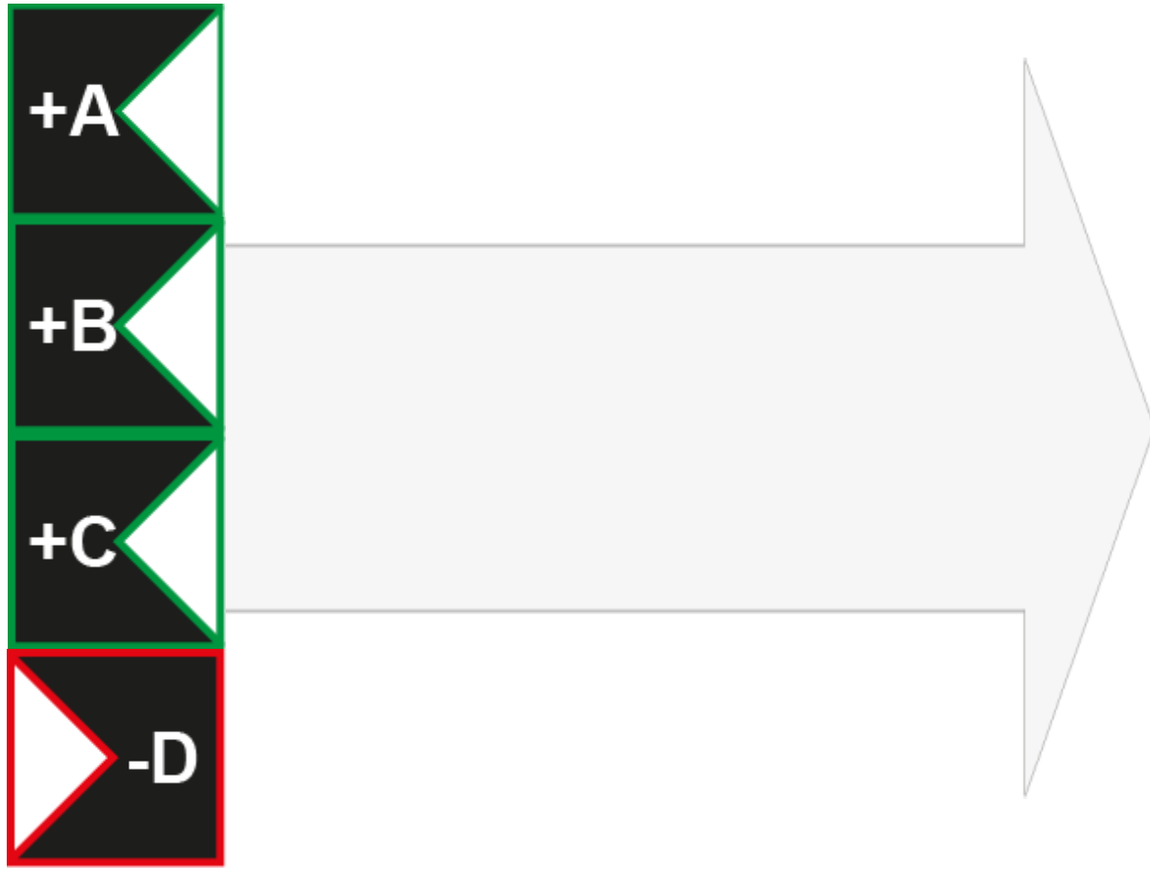




Stacks
Vertical inverted gradient stack

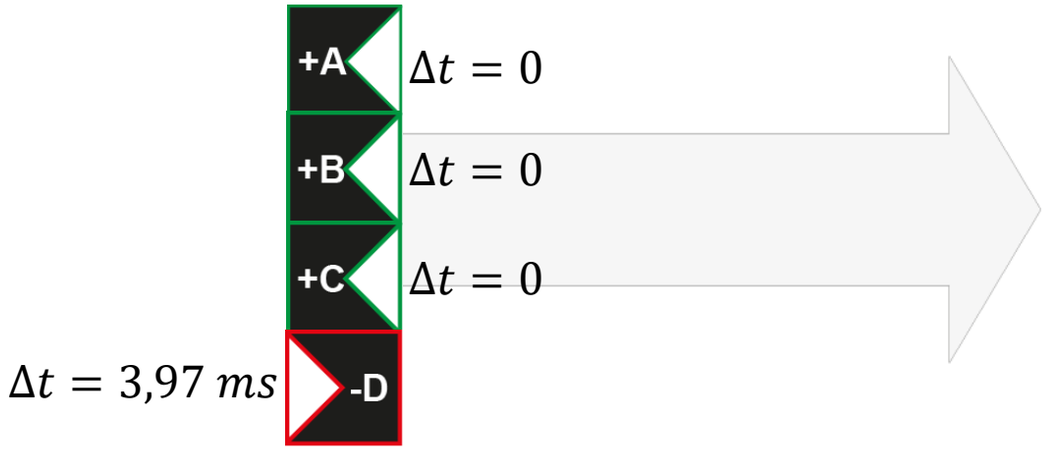


Stacks
Vertical inverted gradient stack

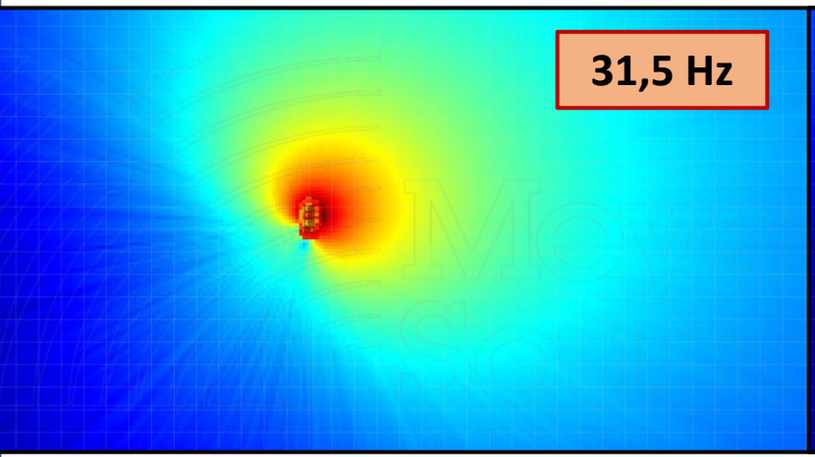


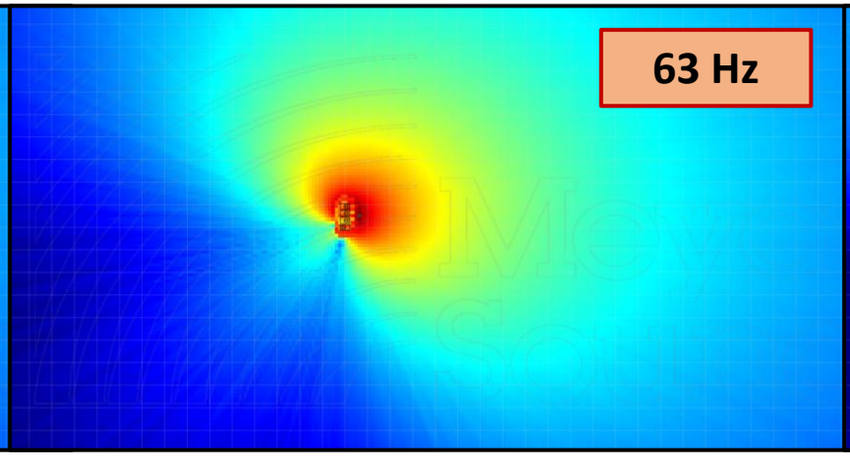
Stacks
Vertical inverted gradient stack

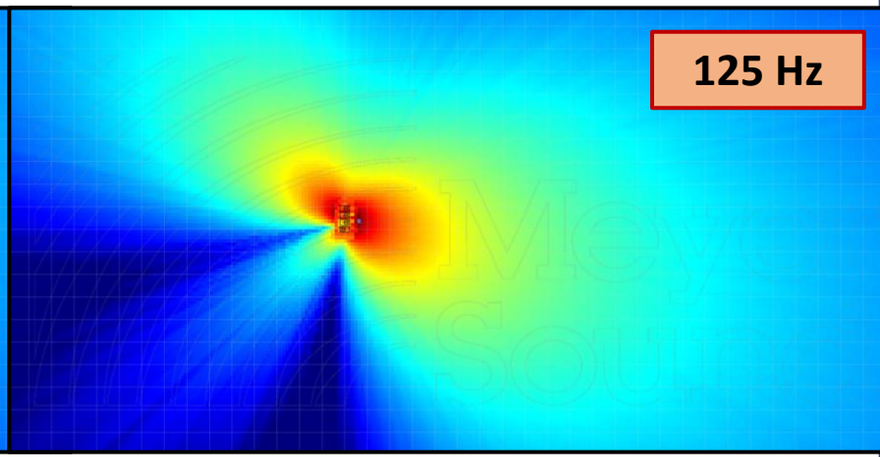
Parameters	
fc =	≈ 85 Hz
λ =	5.4 m
T =	15.87 ms



- The radiation pattern steers towards the earlier-arrival side.



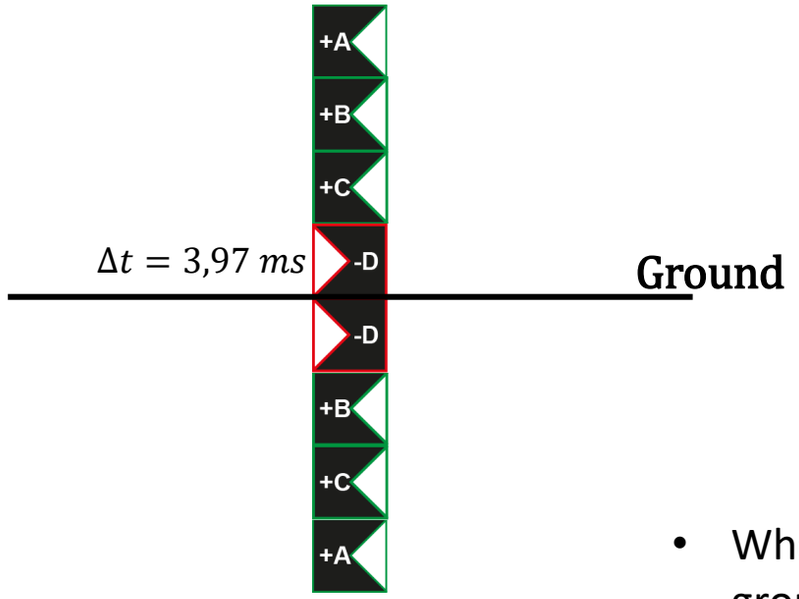




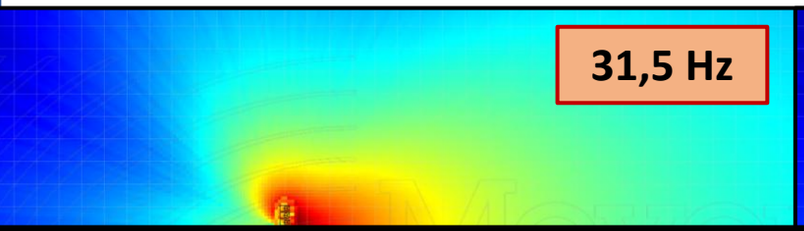
Vertical inverted gradient stack

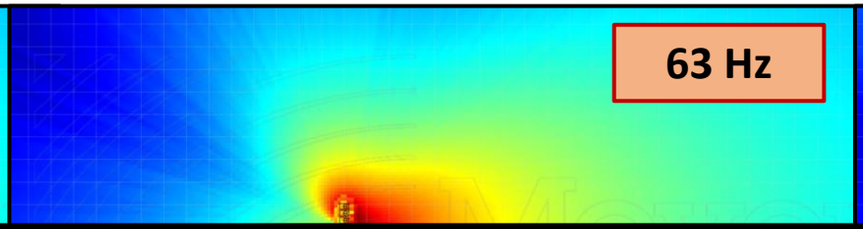
Mirror effect

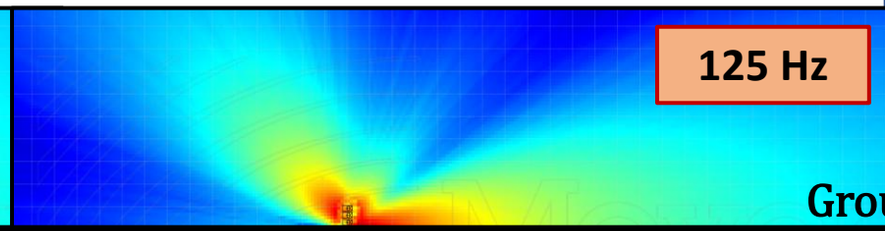
Parameters	
fc =	≈ 85 Hz
λ =	5.4 m
T =	15.87 ms



- When placed on the ground, ground coupling changes the radiation pattern.





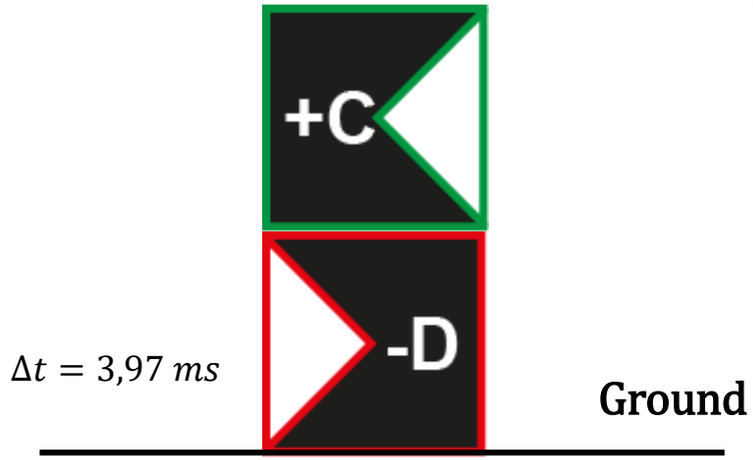


Vertical inverted gradient stack

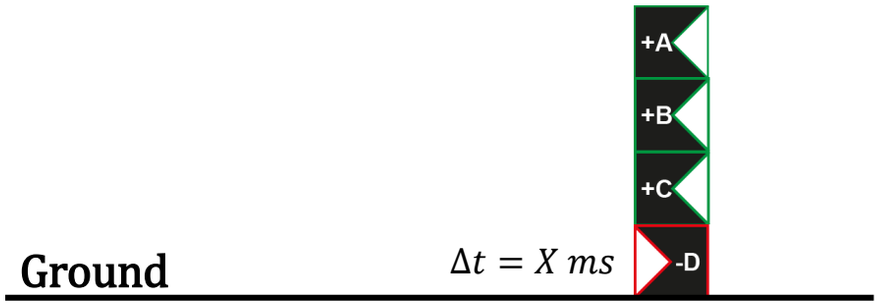
Mirror effect

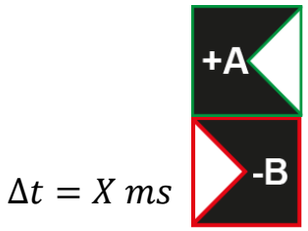




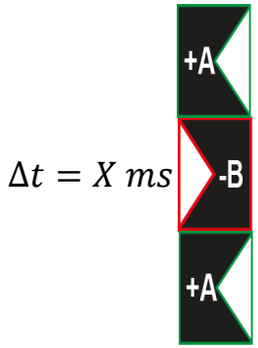


Gradient Inverted Stack
Manufacturer configurations









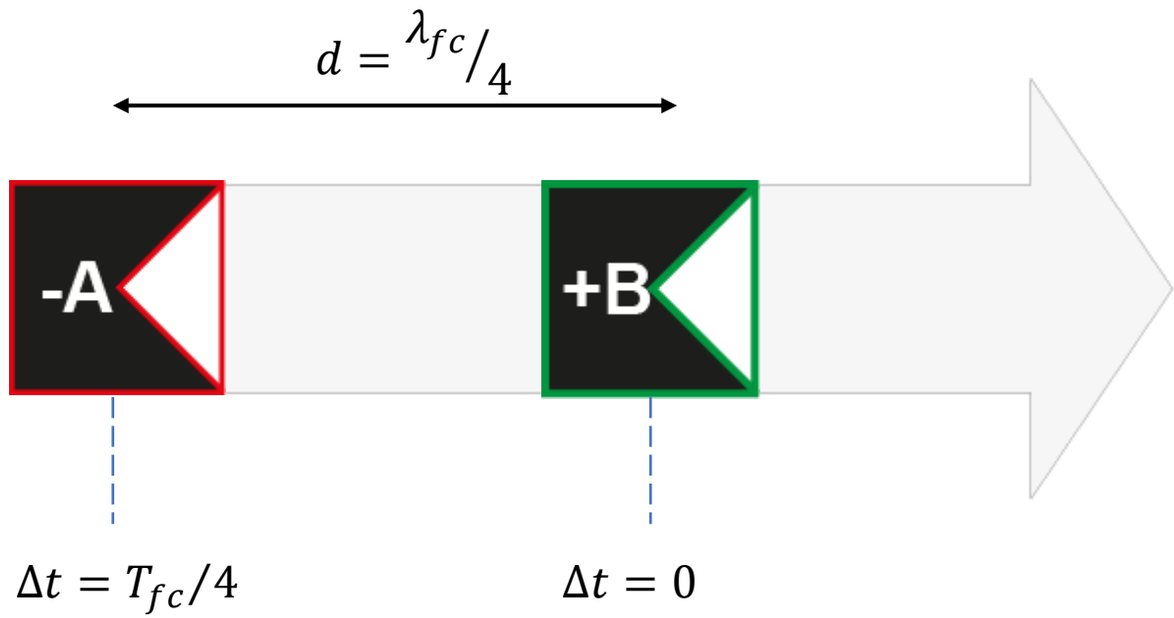
- Most manufacturers offer presets of this type.
- Each uses its own parameters.
- FIR filters can control directivity over a wide frequency range.
- Always read the manuals!

lake

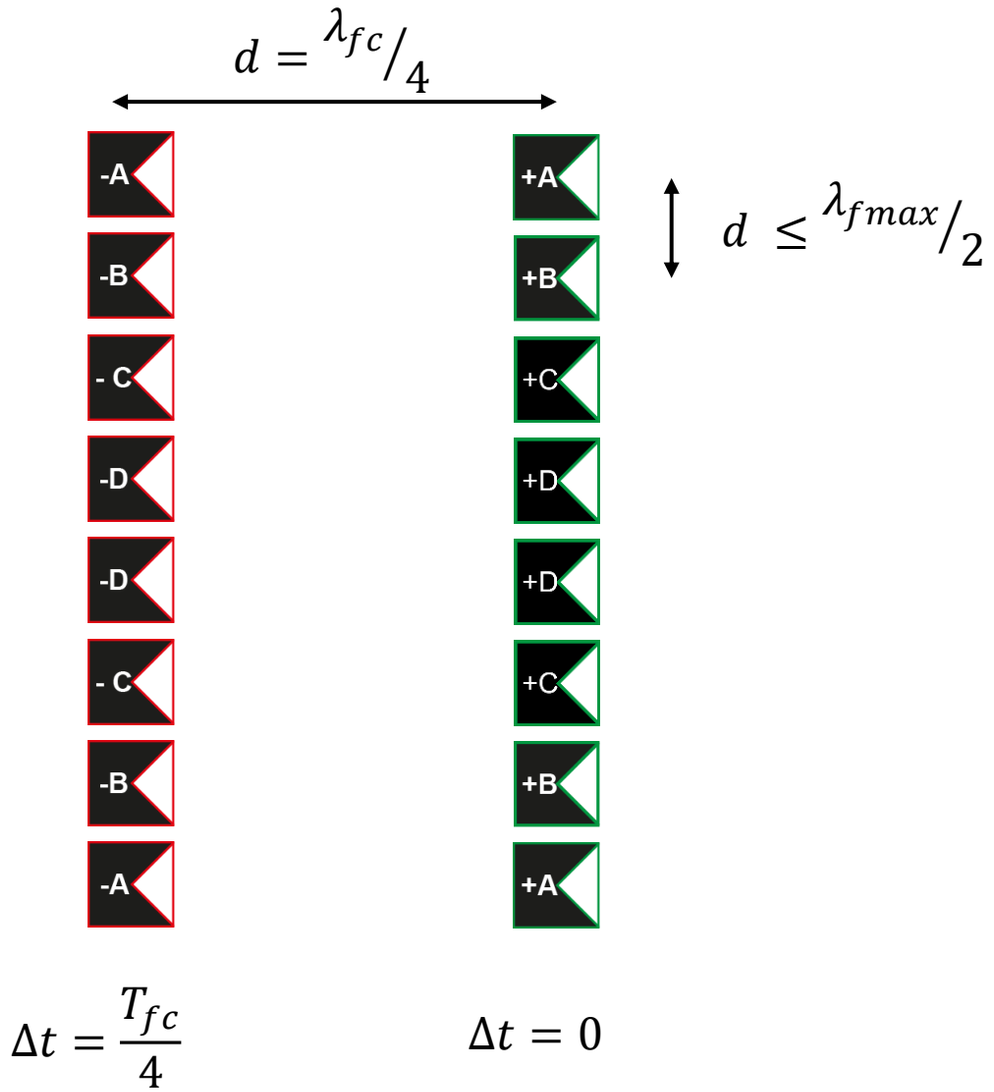
JBL ADAMSON NEXO L-ACOUSTICS Meyer Sound

?

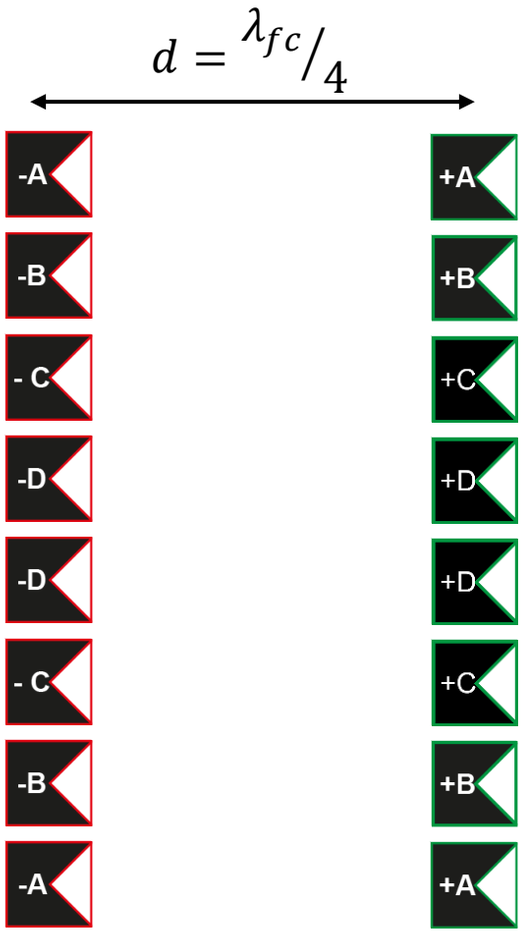
Cardioid subwoofer arc — gradient



Cardioid subwoofer arc — gradient

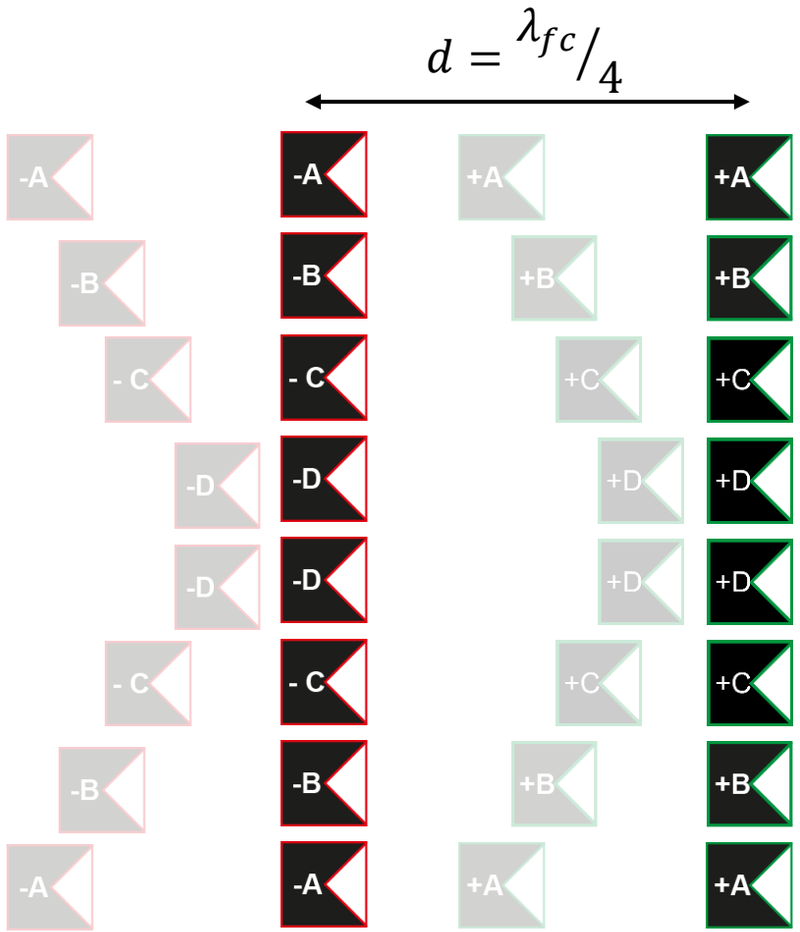


Cardioid subwoofer arc — gradient



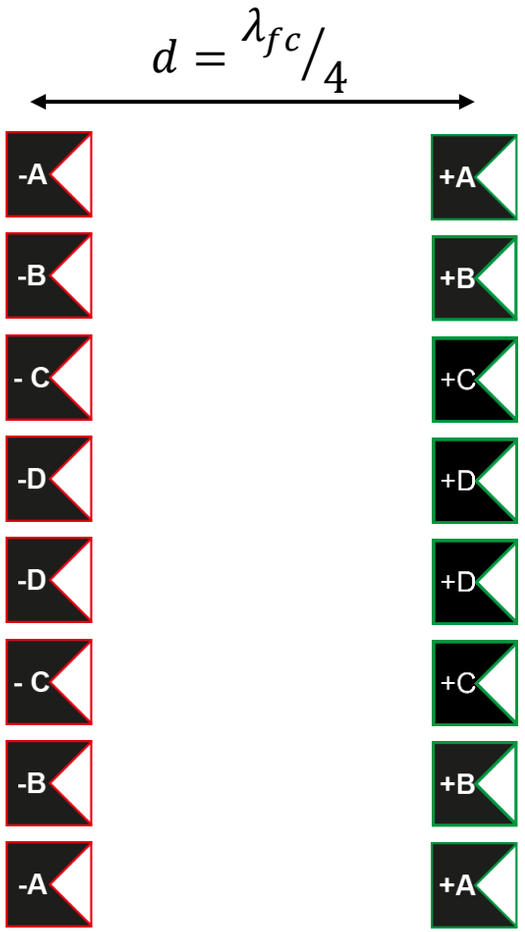
$$\Delta t = \frac{T_{fc}}{4} + \Delta t_{disp} \qquad \Delta t = 0 + \Delta t_{disp}$$

Cardioid subwoofer arc — gradient



$$\Delta t = \frac{T_{fc}}{4} + \Delta t_{disp} \qquad \Delta t = 0 + \Delta t_{disp}$$

Cardioid subwoofer arc — gradient

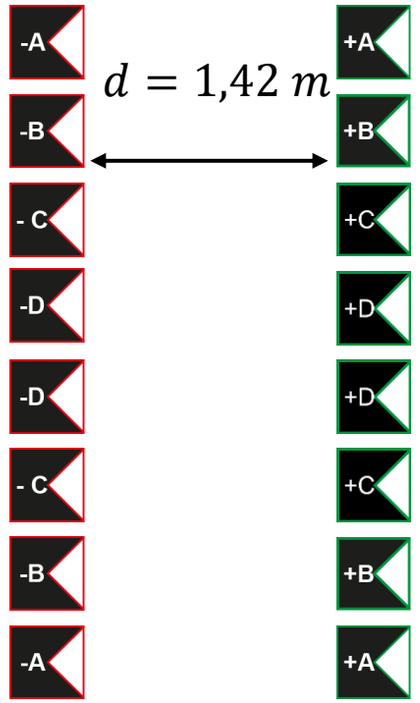


$$\Delta t = \frac{T_{fc}}{4} + \Delta t_{disp} \qquad \Delta t = 0 + \Delta t_{disp}$$

Cardioid subwoofer arc — gradient

Parameters	
$fc =$	60 Hz
$\lambda =$	5.67 m
$T =$	16.67 ms
$disp =$	90°

$\Delta t = 4{,}2 + \Delta t_{disp}$

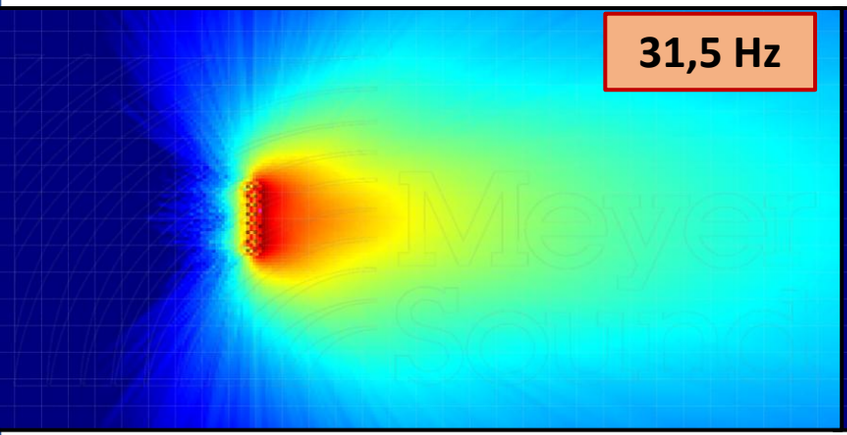


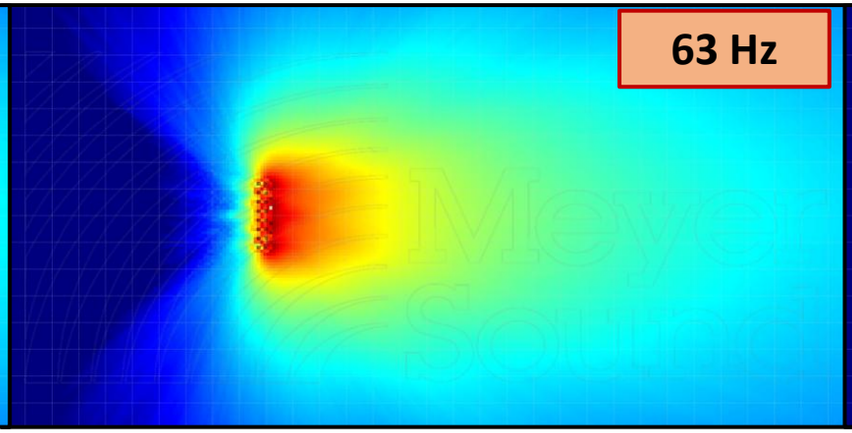
$d = 1{,}42\ m$

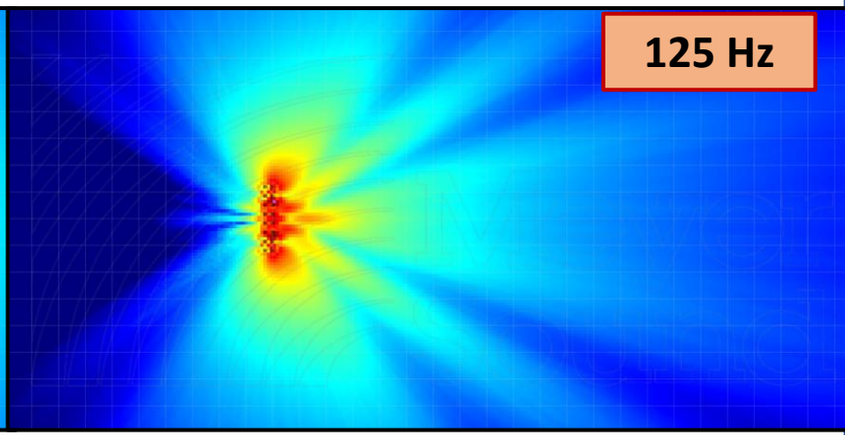
$d \leq 1{,}42\ m$

$\Delta t = \Delta t_{disp}$

One of my favourite configurations!

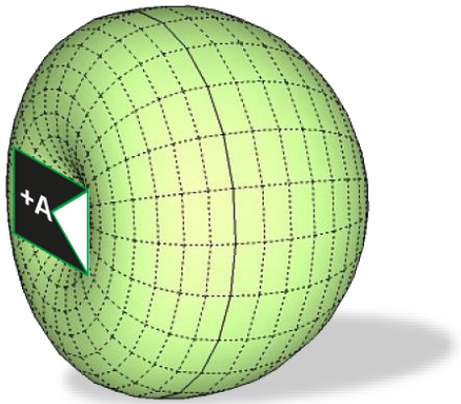






Manufacturer cardioid subwoofers

- Manufacturers do not only make omnidirectional subwoofers.
- Some also make subwoofers with varying degrees of cardioid directivity!

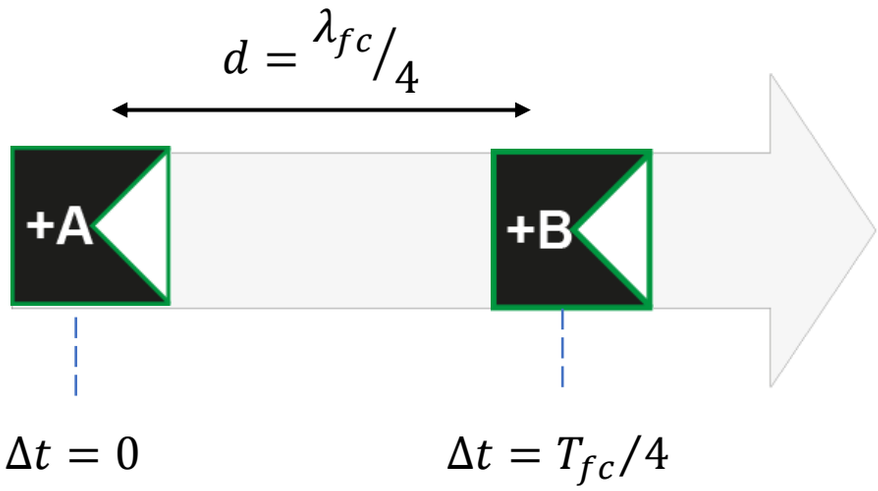




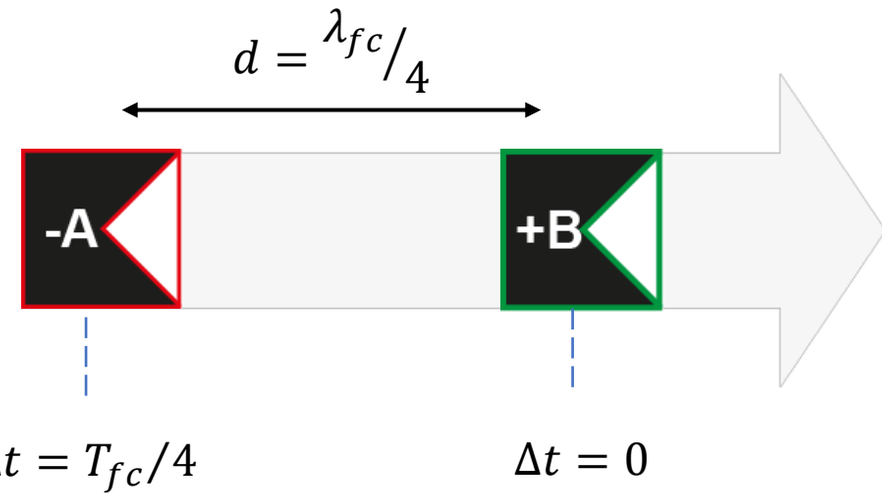


Native vs gradient

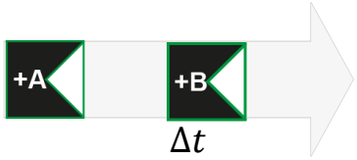
Native



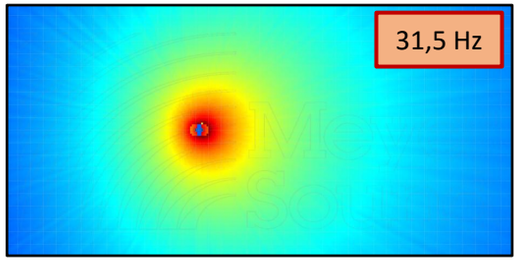
Gradient

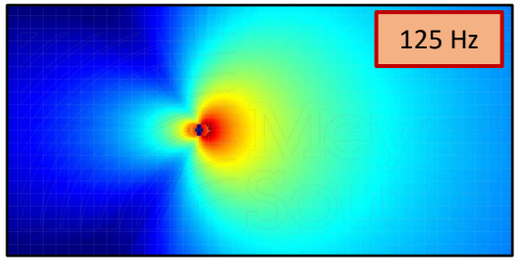


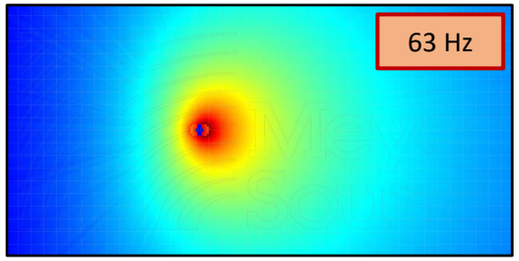
Native vs gradient



Native



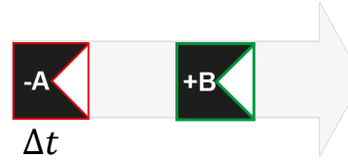


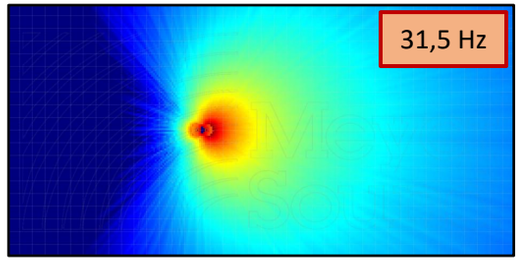


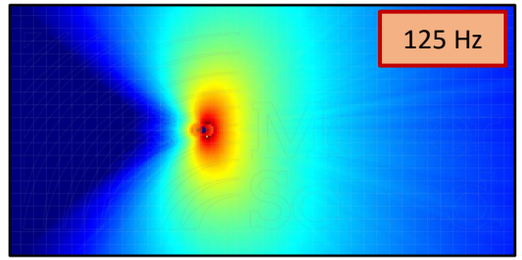
- *φ stable at the front of the system*
- *φ variable at the rear*

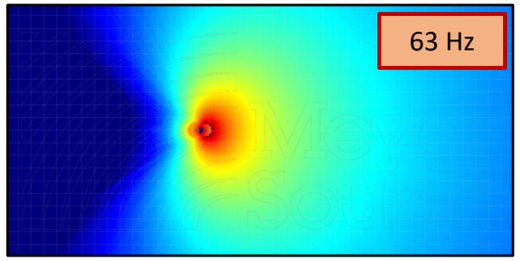
- Moderate rejection

Gradient









- *φ variable at the front of the system*
- *φ stable at the rear*

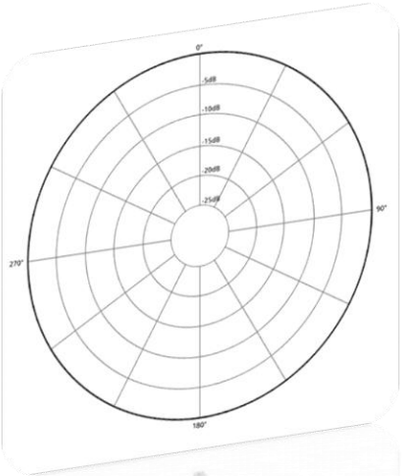
- Strong rejection

Omni vs cardioid

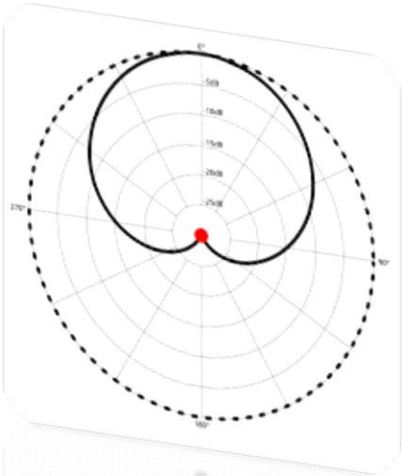
- Most subwoofers are designed to operate almost omnidirectionally.

- Changing directivity through coupling alters the original impulse response.

- These changes affect the definition of the configuration.
- This produces a less pronounced sense of “impact”.



- However, this slight loss is offset by more precise coverage.



?

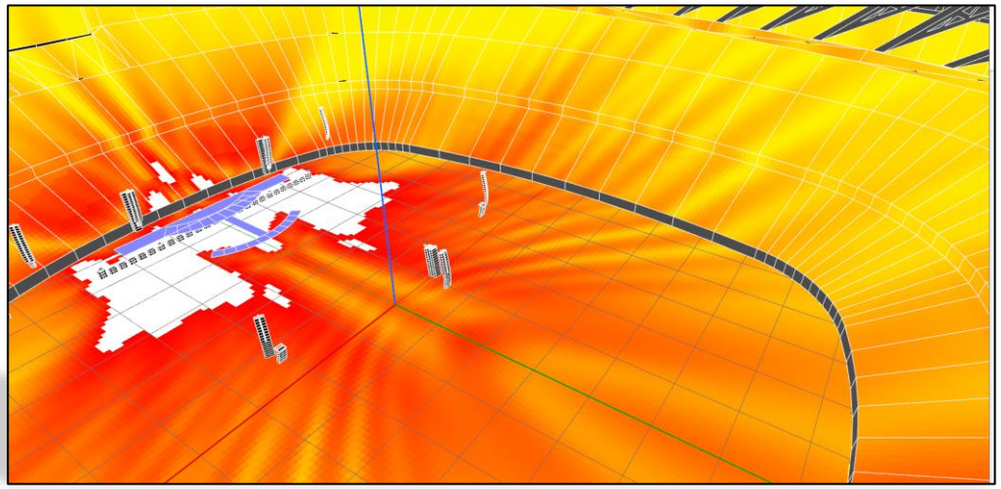
4
Special configurations

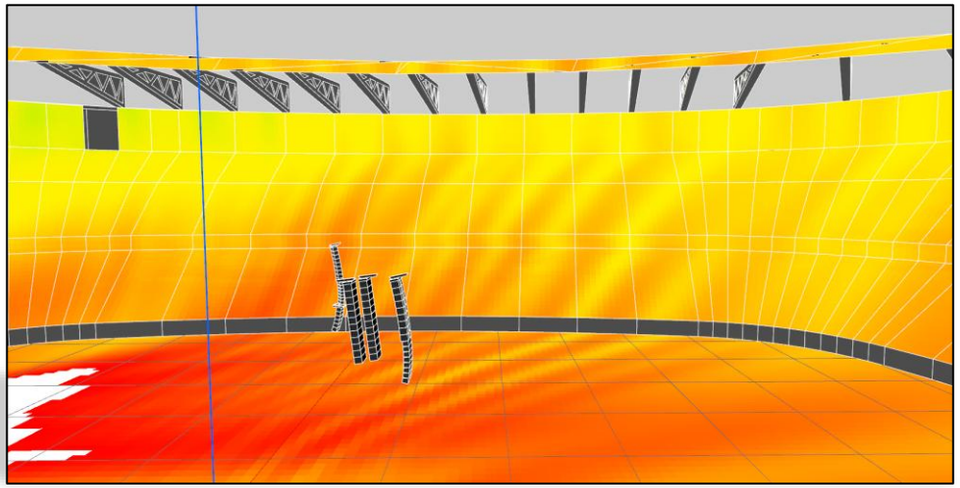


Subwoofer fills

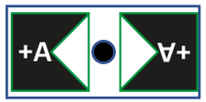
The frequencies reproduced by subwoofers are often poorly represented in official A-weighted level measurements (dBA).

To avoid exposing the front rows to excessive levels, additional fill subwoofers may be necessary.

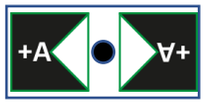




Subwoofer fills



Omni x2

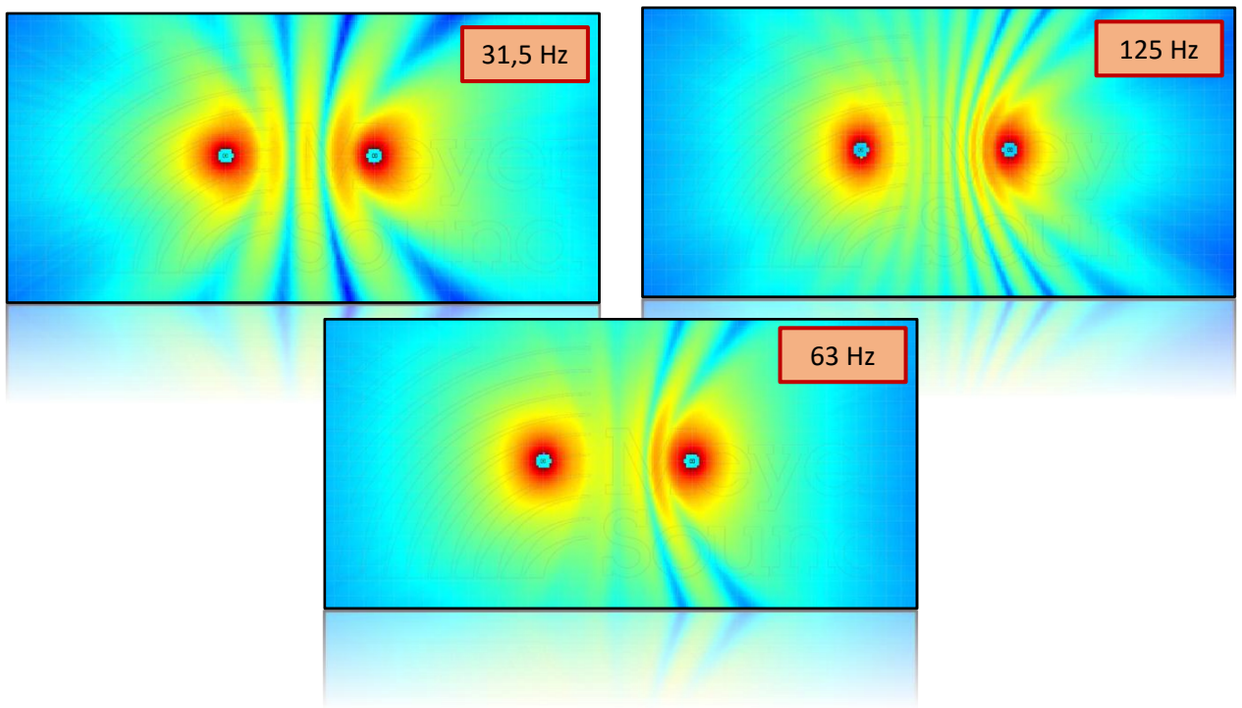


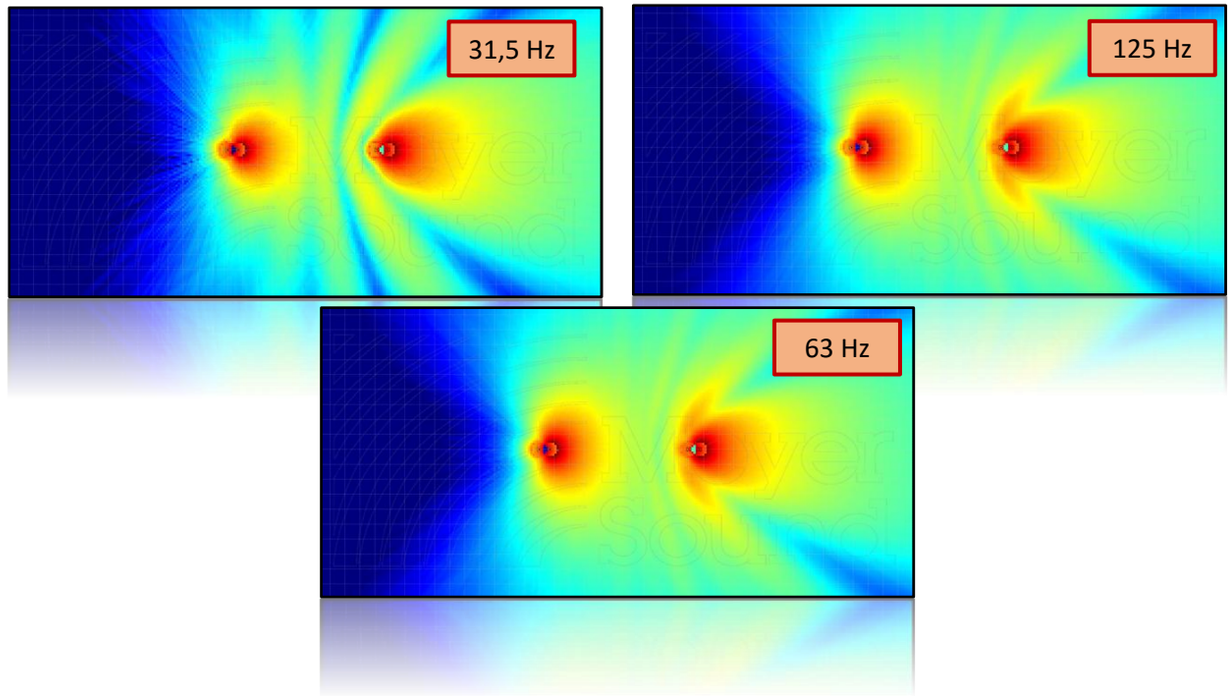


Gradient x2

1m42 – 60Hz

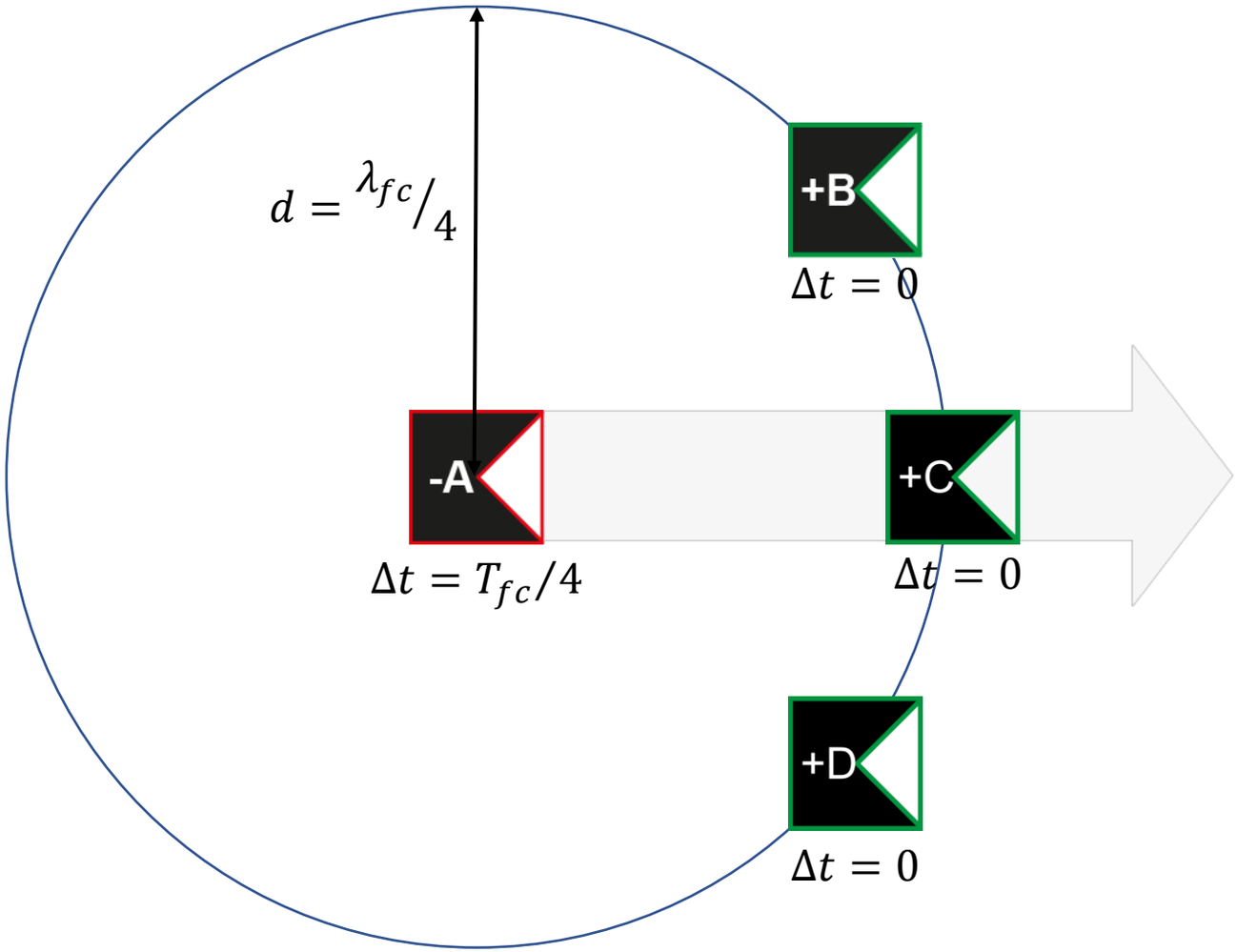




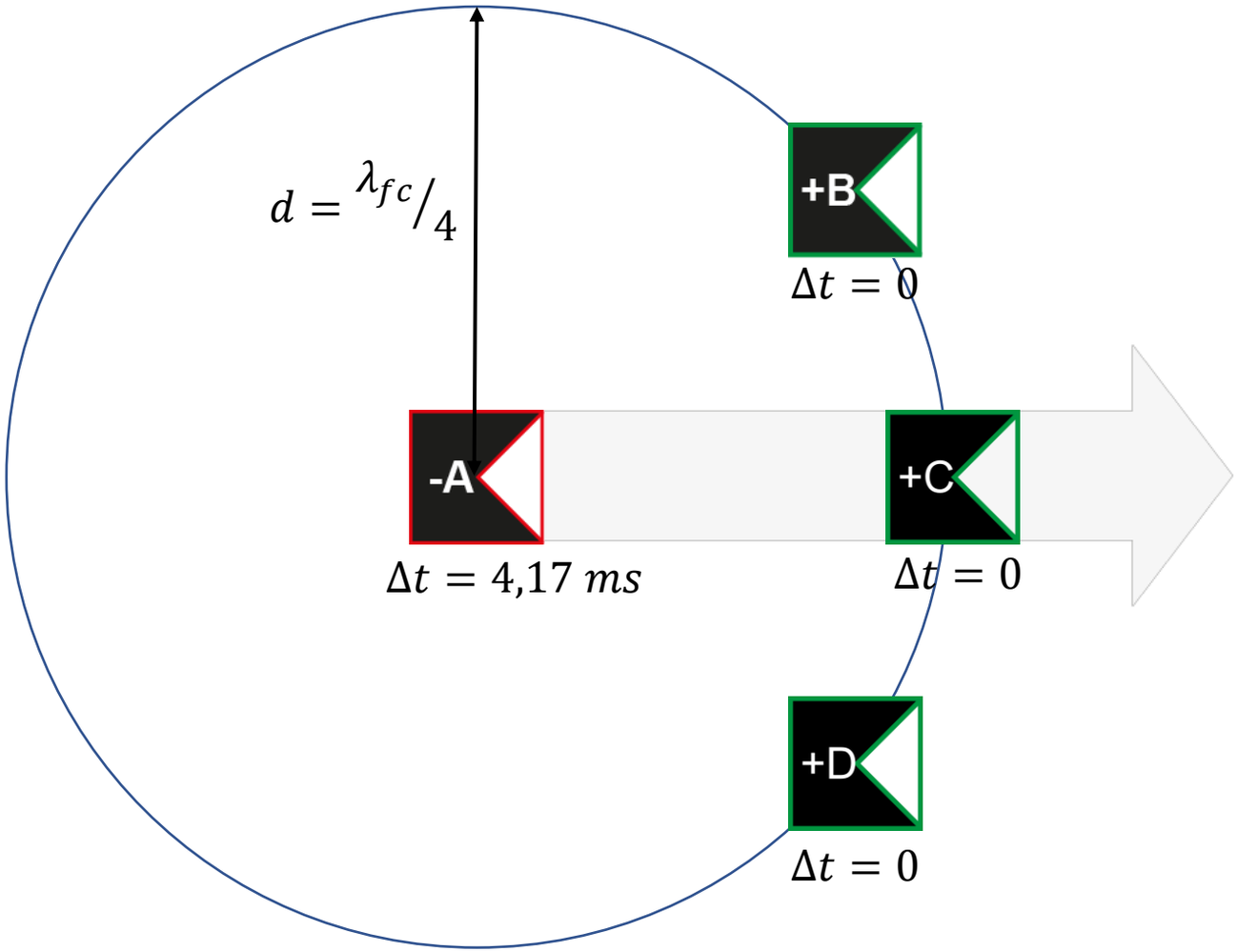


- Cardioid subwoofers are recommended for fills.

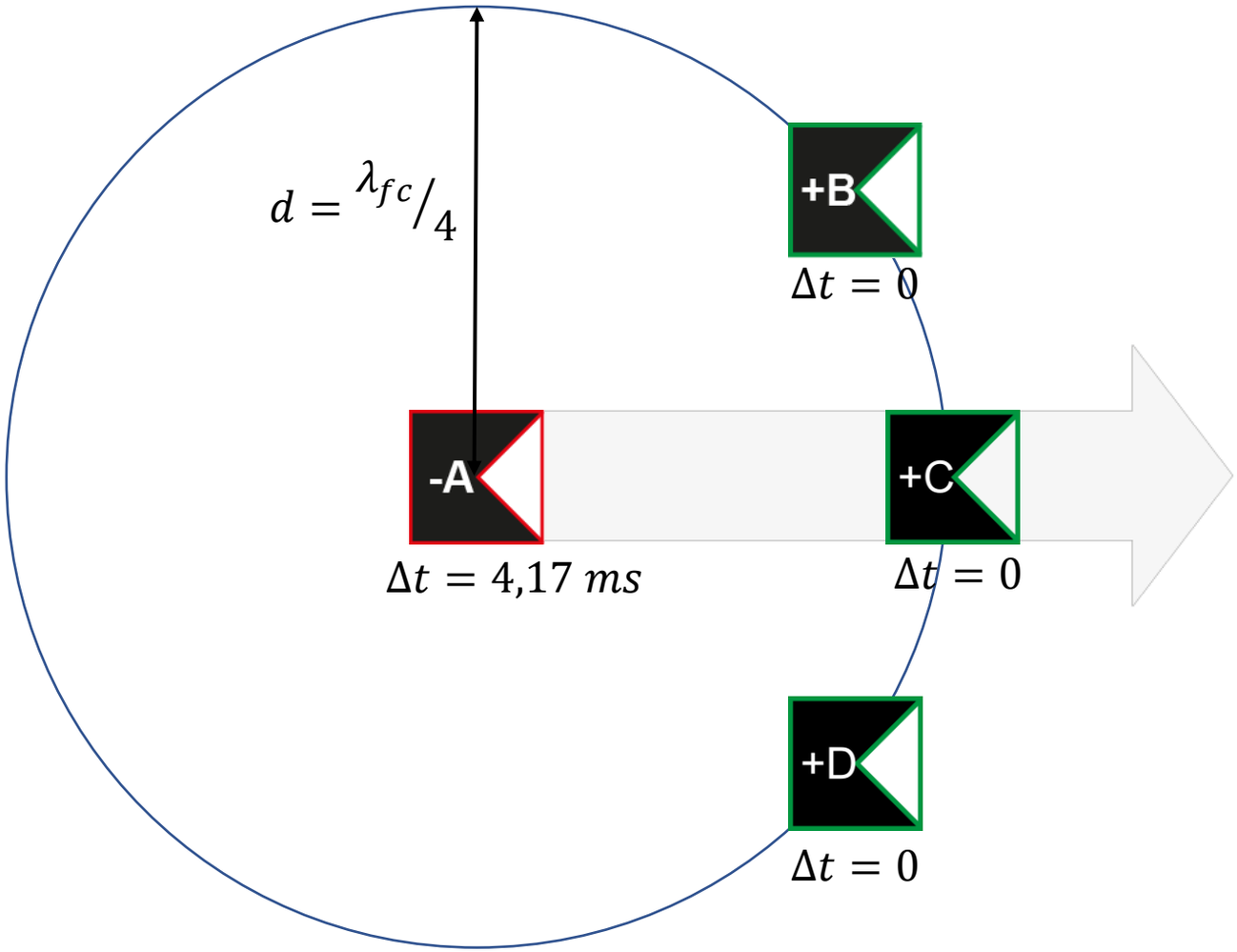
Flower Fire

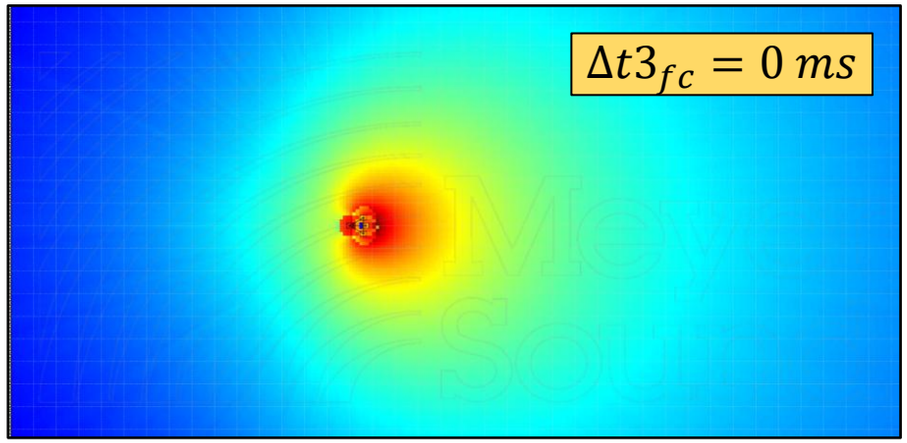


Flower Fire
60 Hz

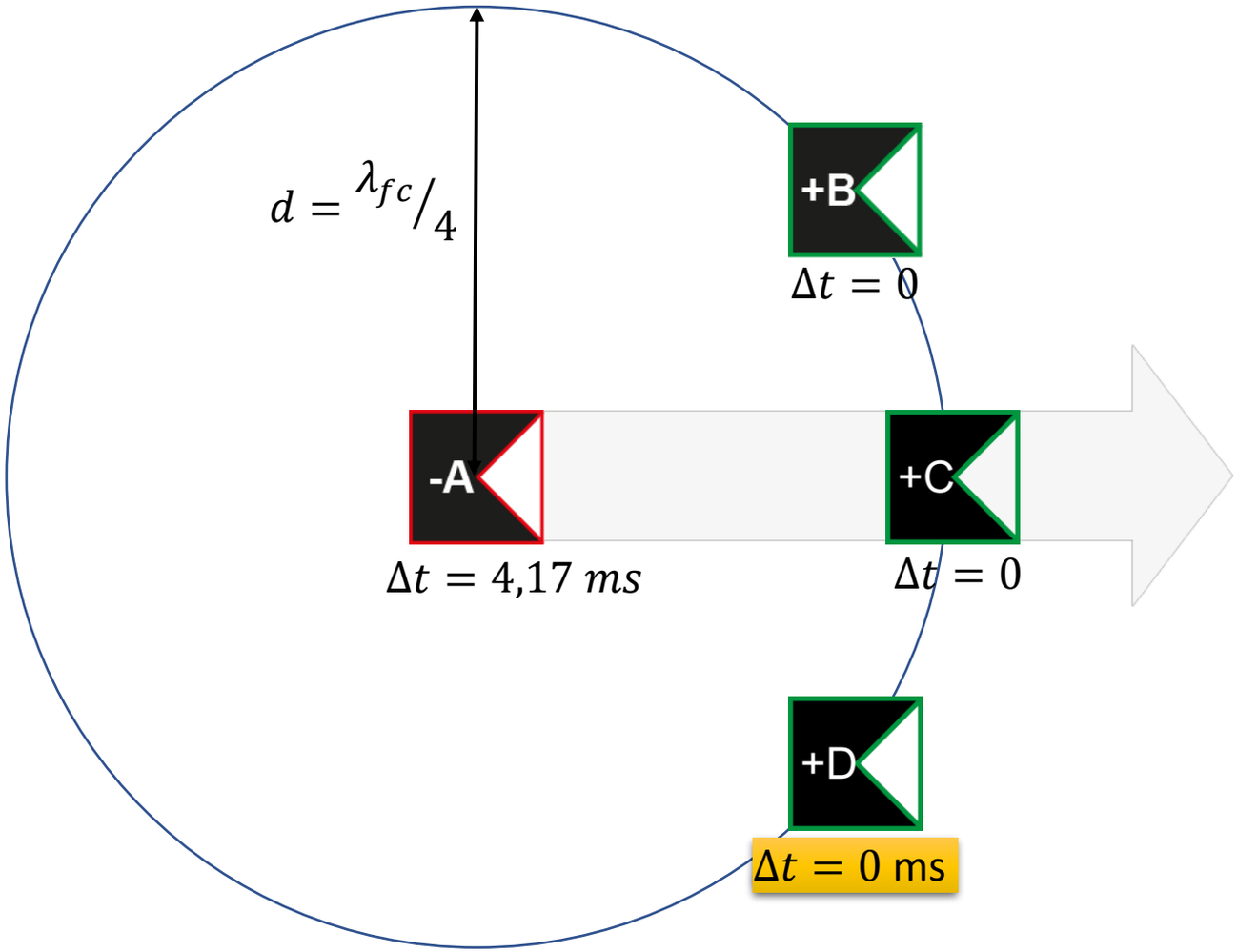


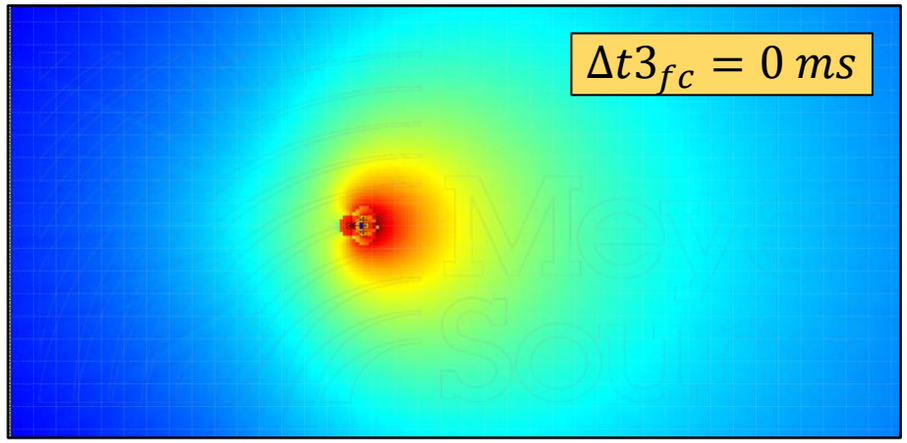
Flower Fire
60 Hz



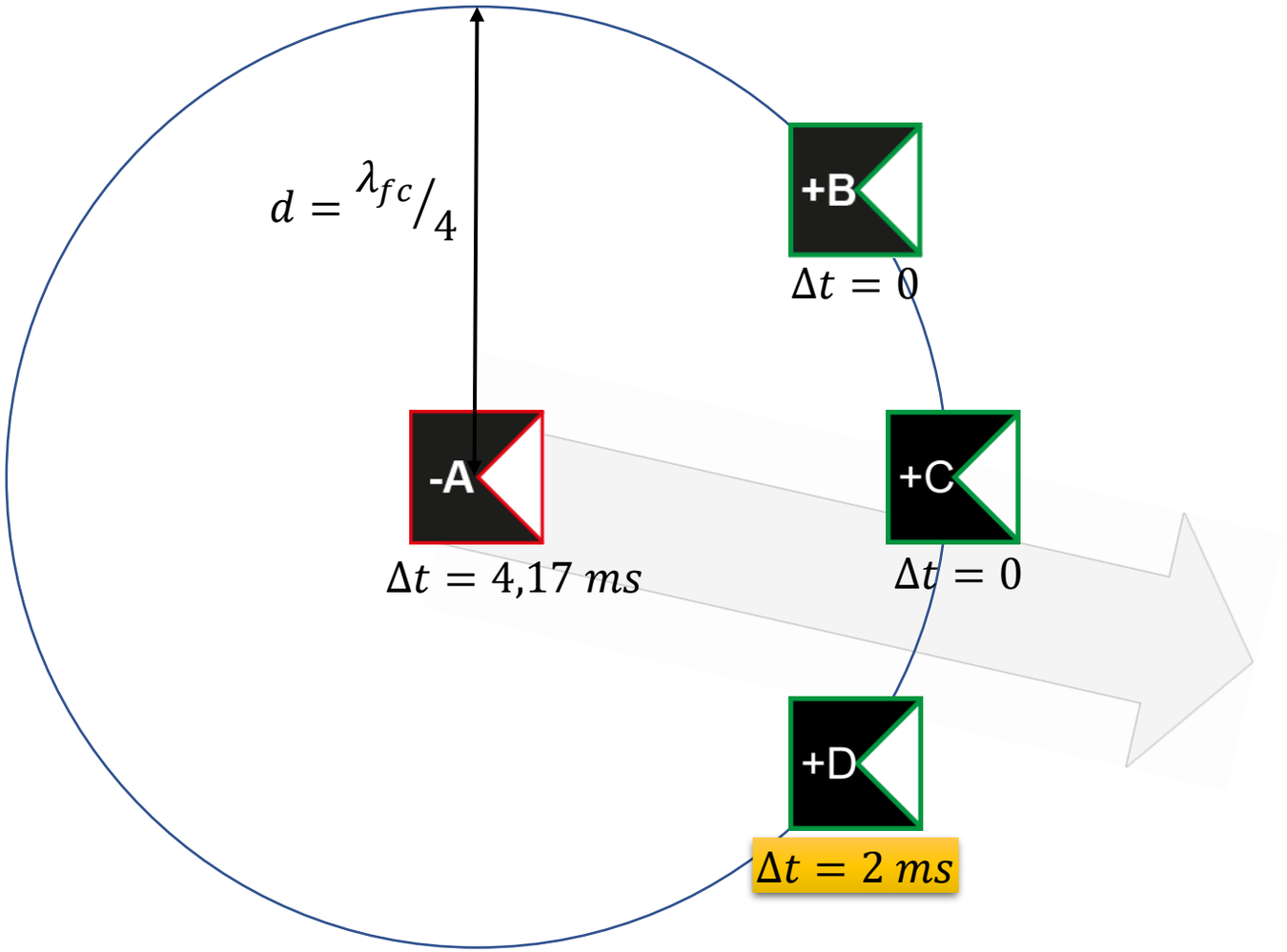


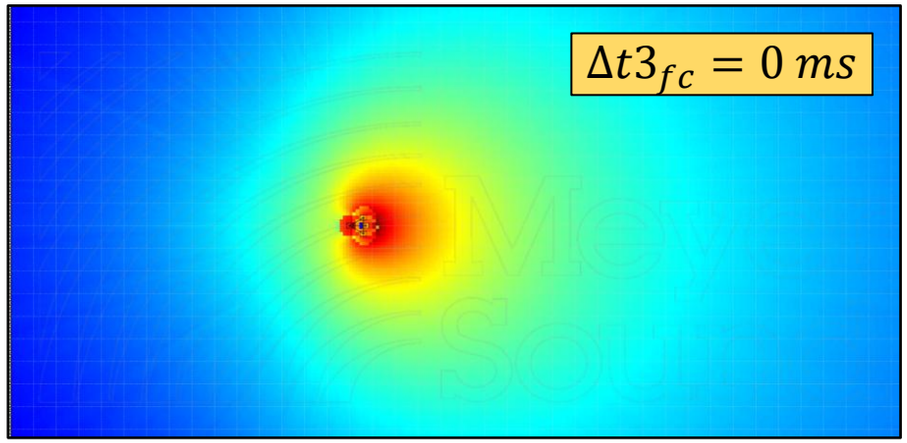
Flower Fire
60 Hz

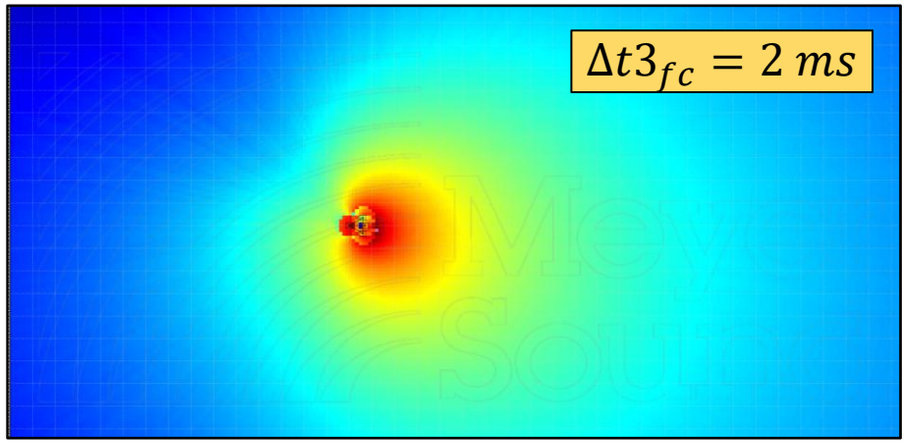




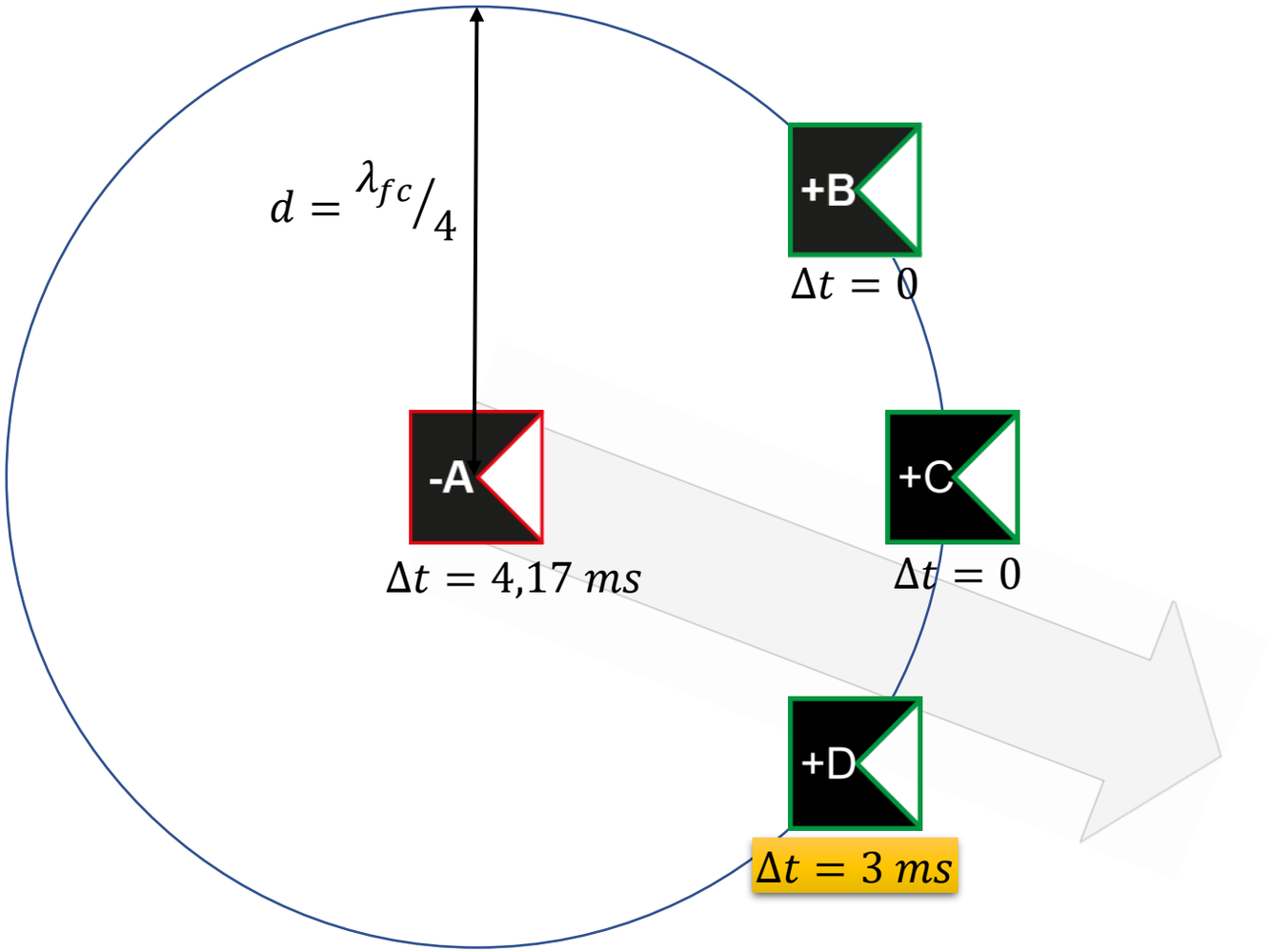
Flower Fire
60 Hz

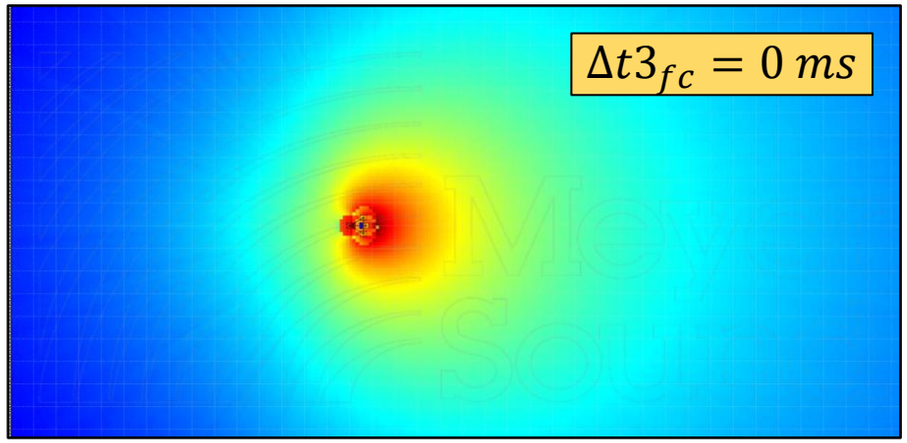


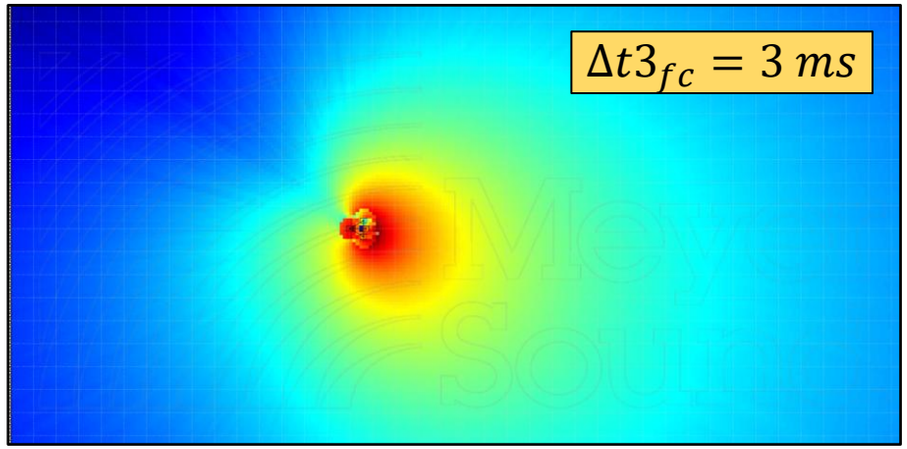




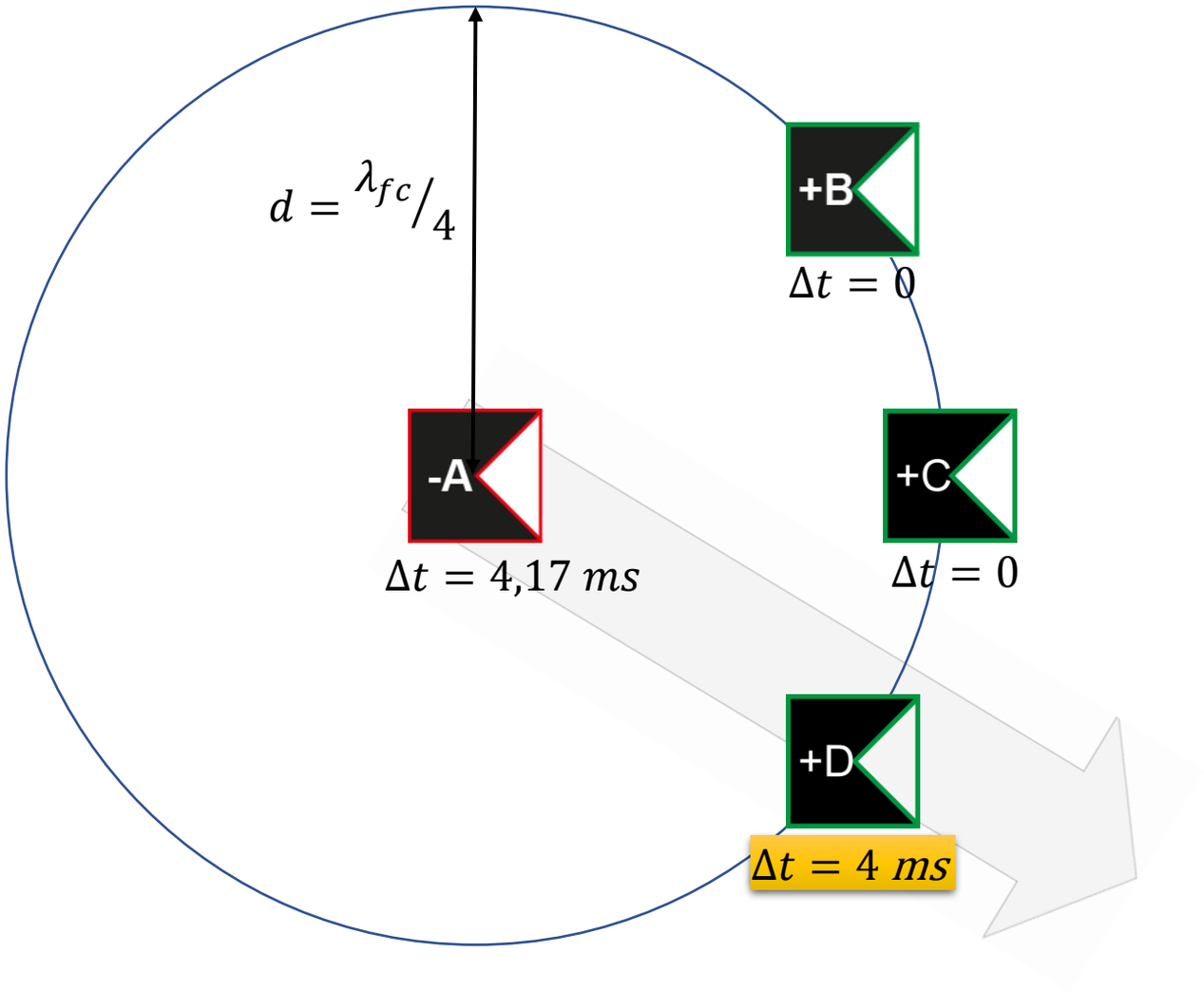
Flower Fire
60 Hz

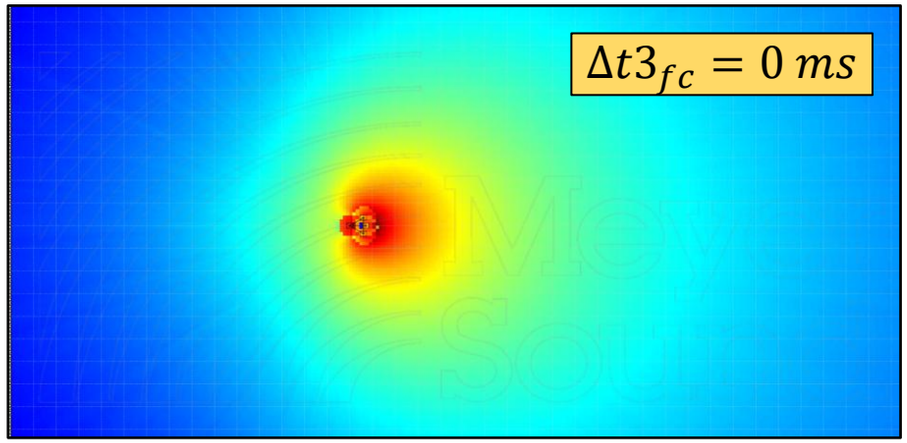


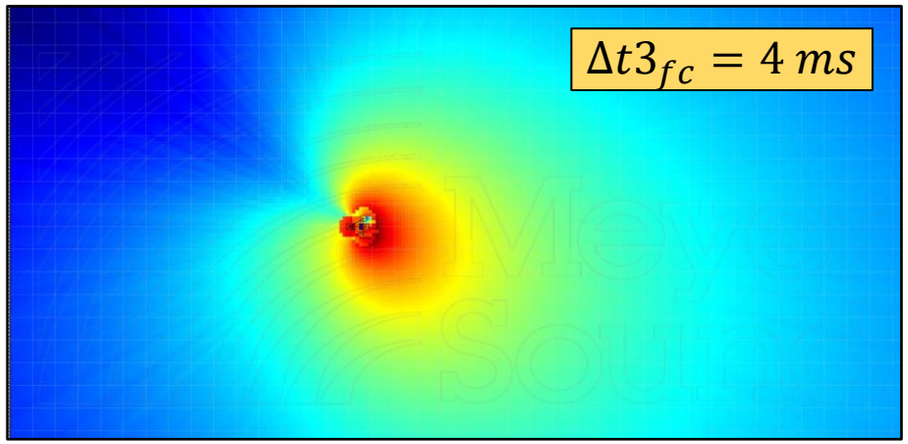




Flower Fire
60 Hz







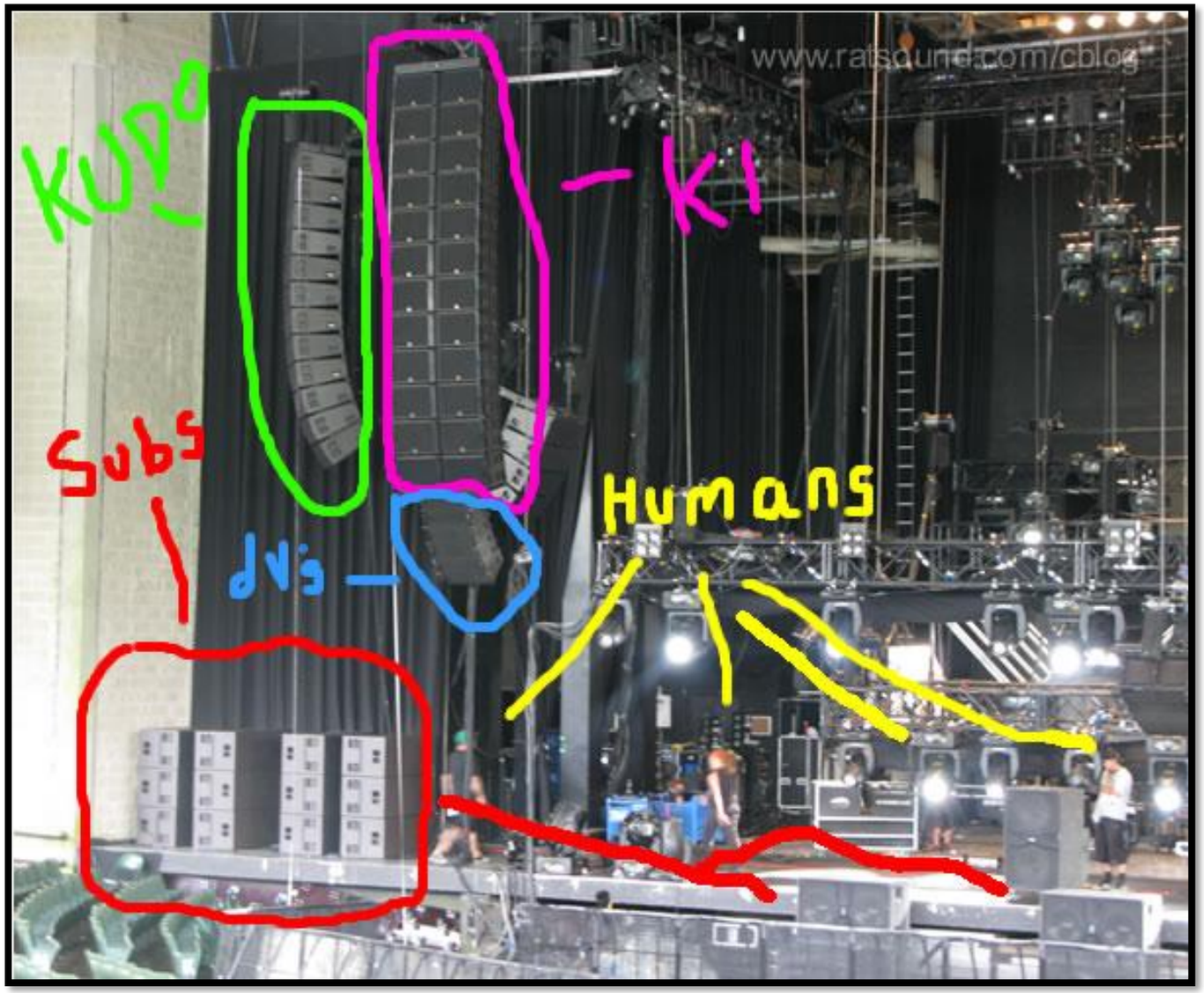
Dave Rat



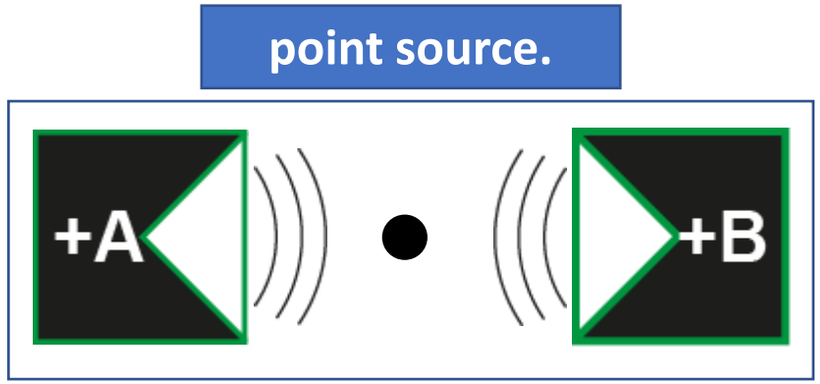


Slot fire

Dave Rat



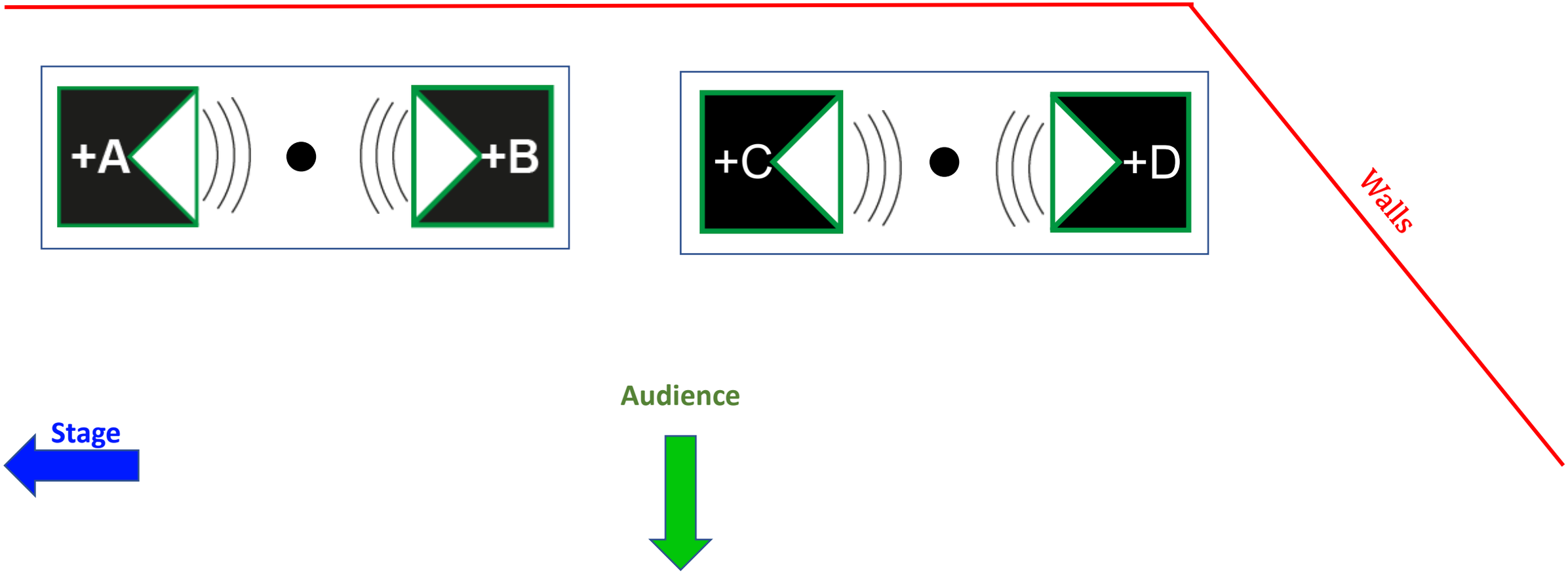




A fully omnidirectional sub with a virtual acoustic centre at the midpoint

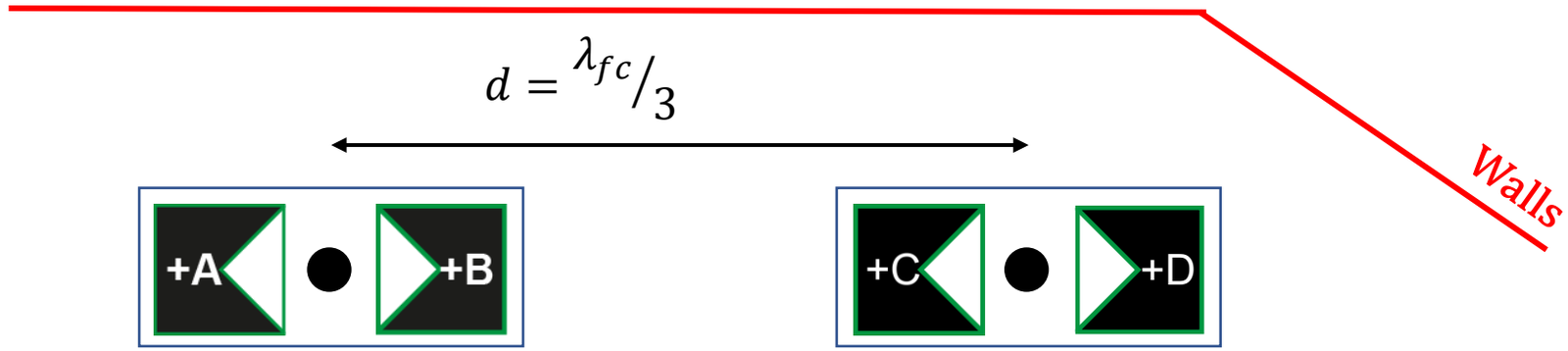
Slot fire

Dave Rat



Slot fire

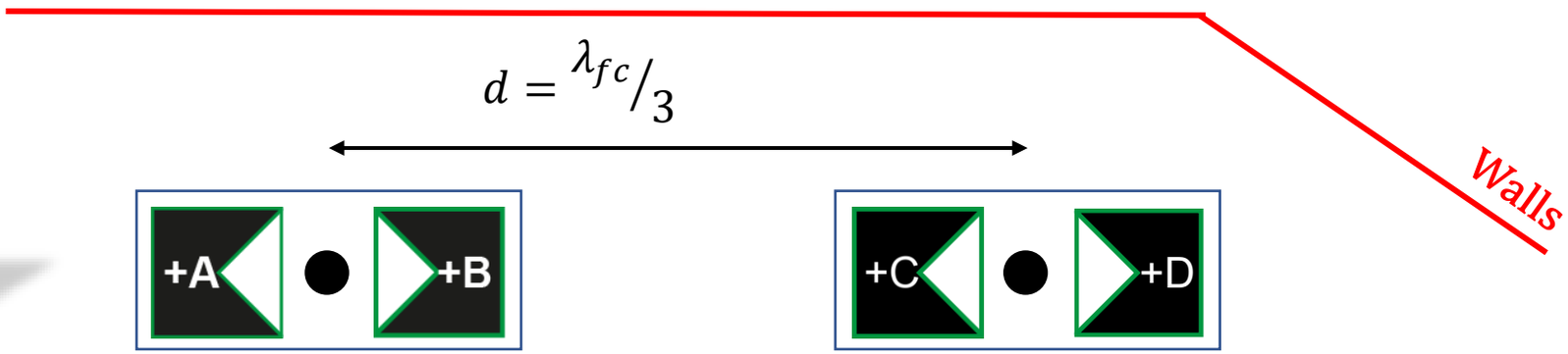
Dave Rat



Slot fire

Example 45 Hz

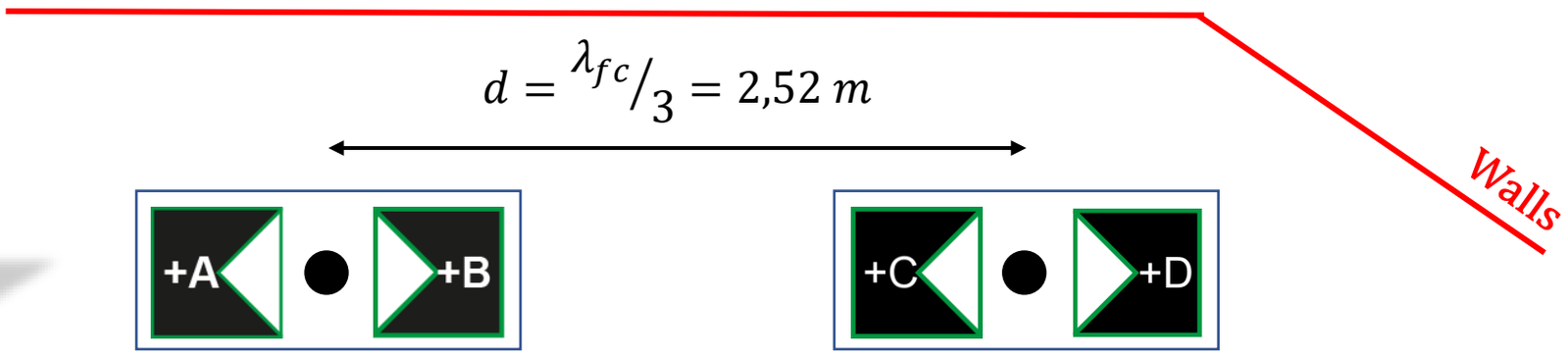
Parameters	
fc =	**45 Hz**
λ =	**7.56 m**
T =	**22.22 ms**



Slot Fire

Example 45 Hz

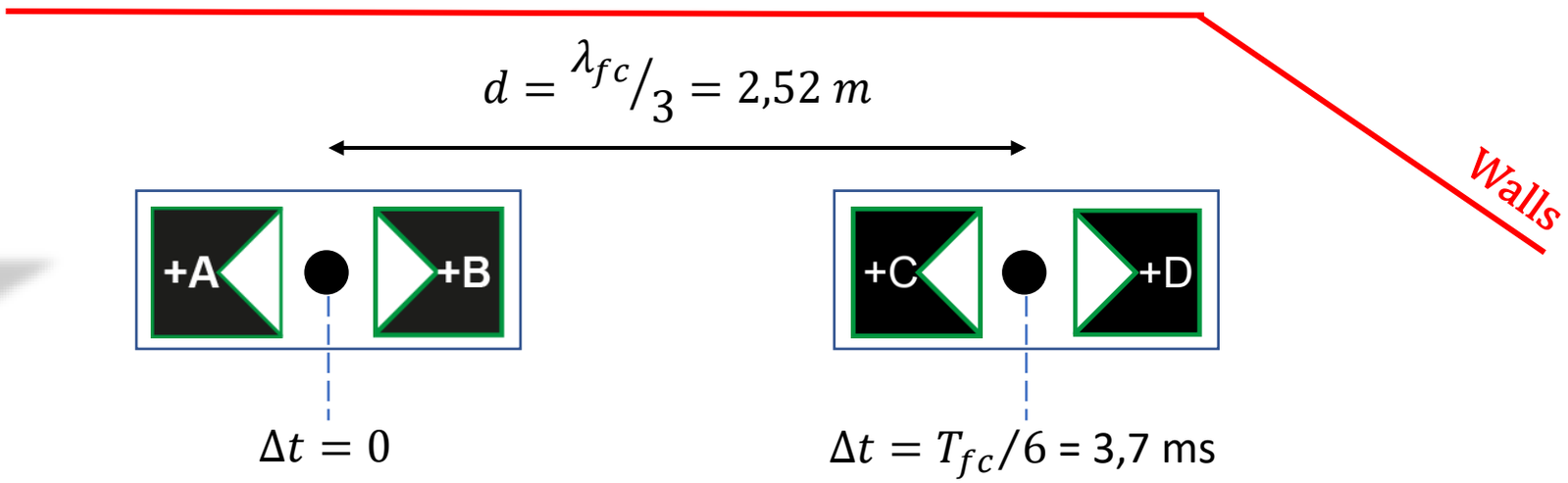
Parameters	
fc =	**45 Hz**
λ =	**7.56 m**
T =	**22.22 ms**



Slot Fire

Example 45 Hz

Parameters	
fc =	**45 Hz**
λ =	**7.56 m**
T =	**22.22 ms**

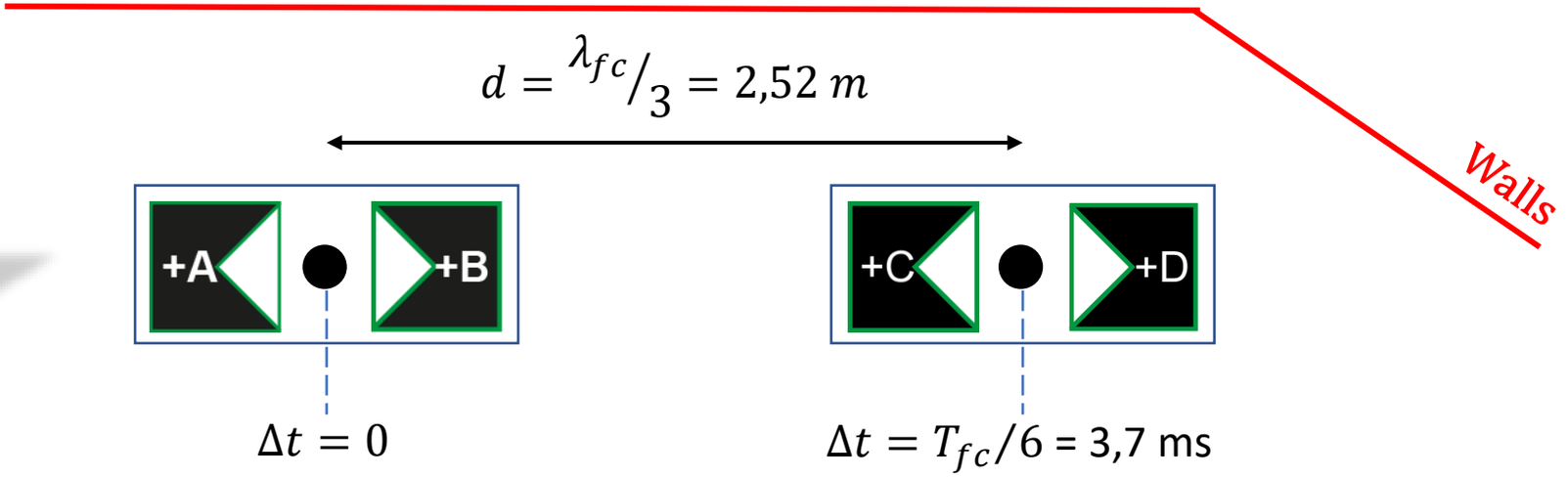


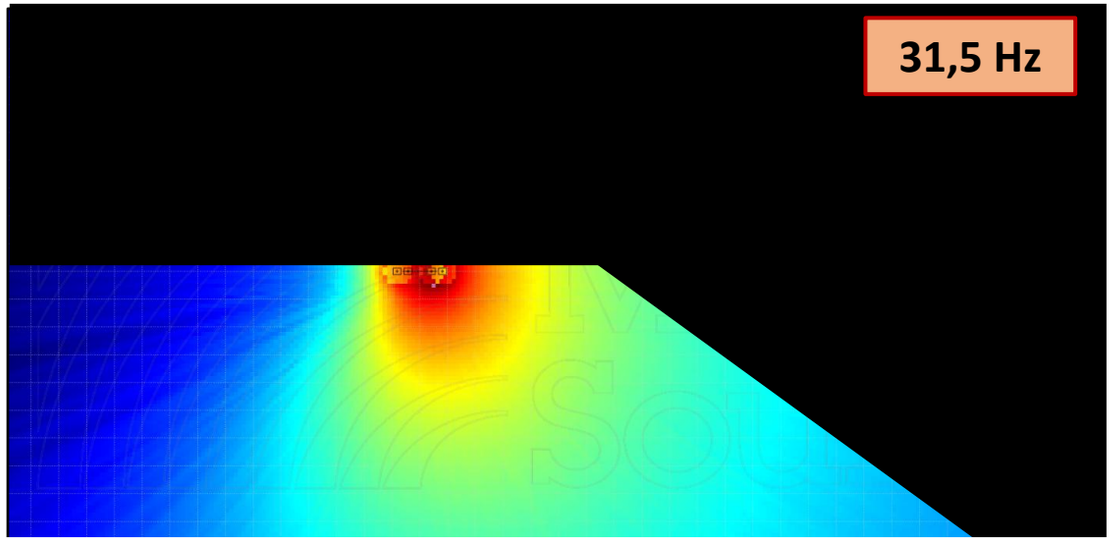
$$\frac{1}{3} + \frac{1}{6} = \frac{1}{2}$$

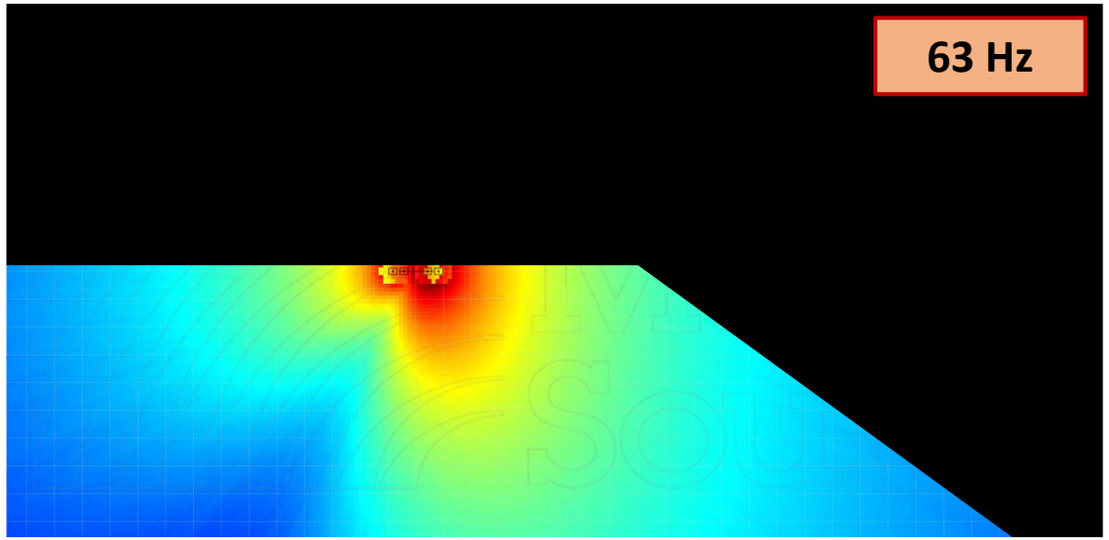
Slot Fire

Example 45 Hz

Parameters	
fc =	**45 Hz**
λ =	**7.56 m**
T =	**22.22 ms**



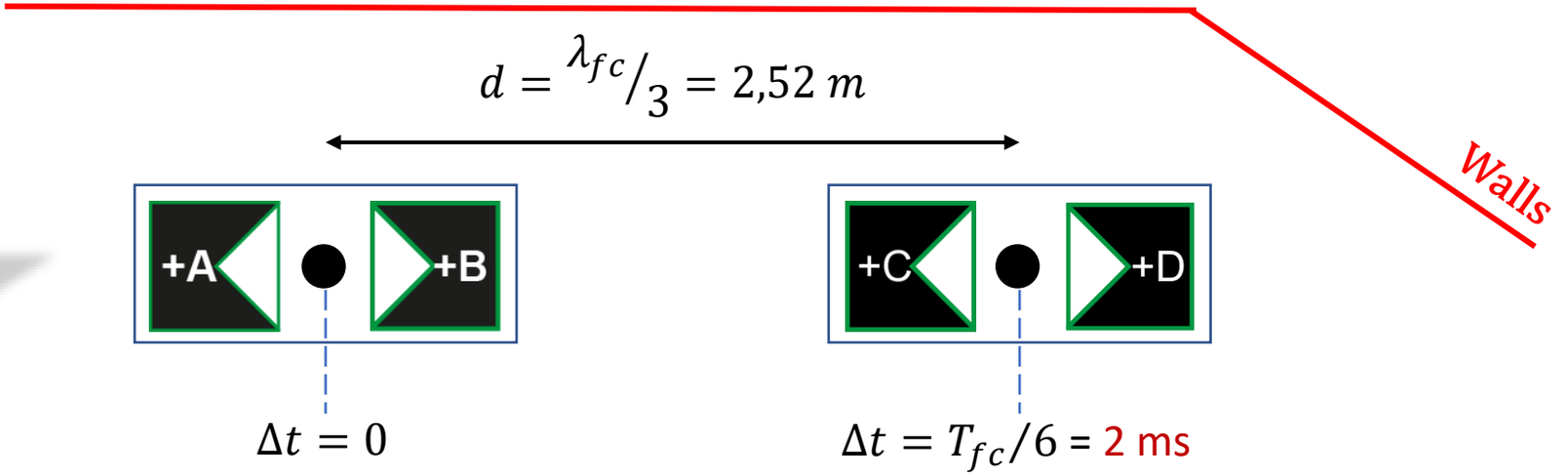


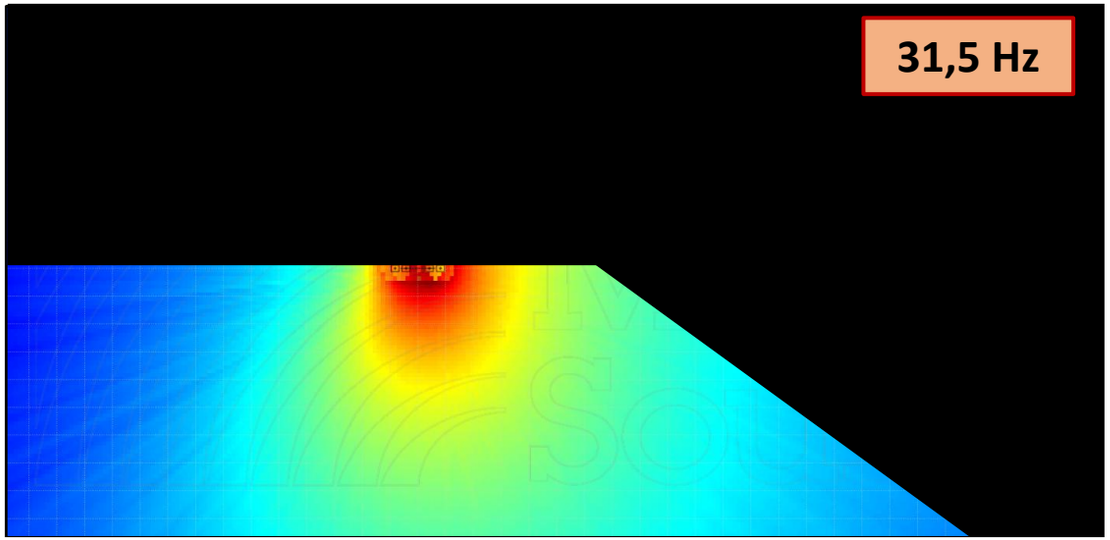


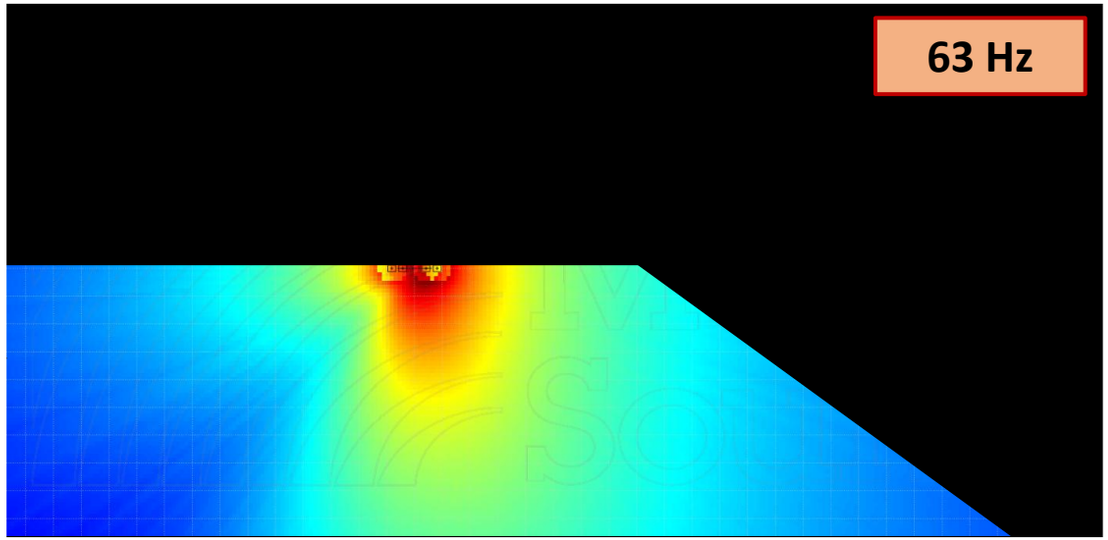
Slot Fire

Example 45 Hz

Parameters	
fc =	**45 Hz**
λ =	**7.56 m**
T =	**22.22 ms**







Slot Fire

Example 45 Hz

Parameters	
fc =	**45 Hz**
λ =	**7.56 m**
T =	**22.22 ms**



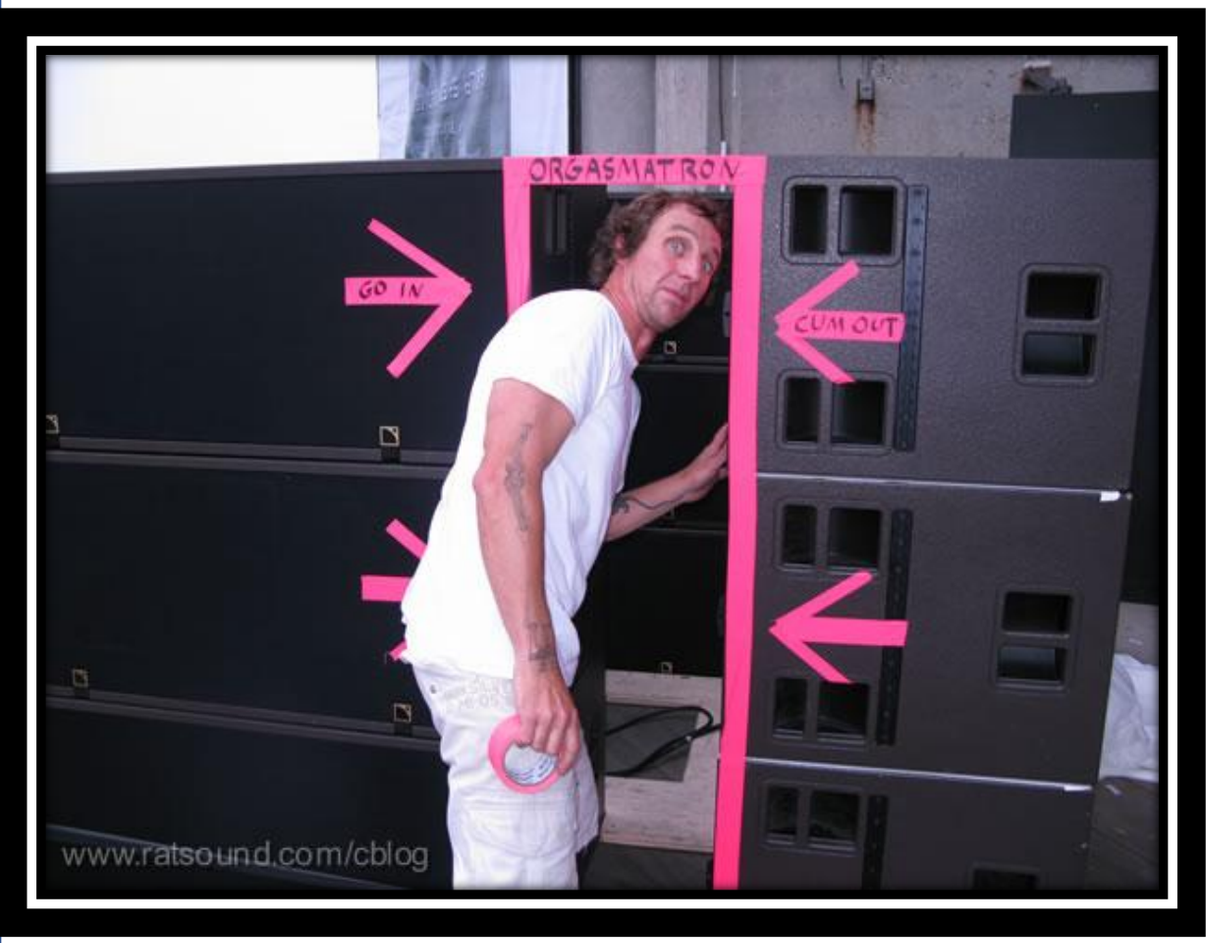
Vortex - Orgasmotron

Dave Rat



Vortex - Orgasmotron

Dave Rat

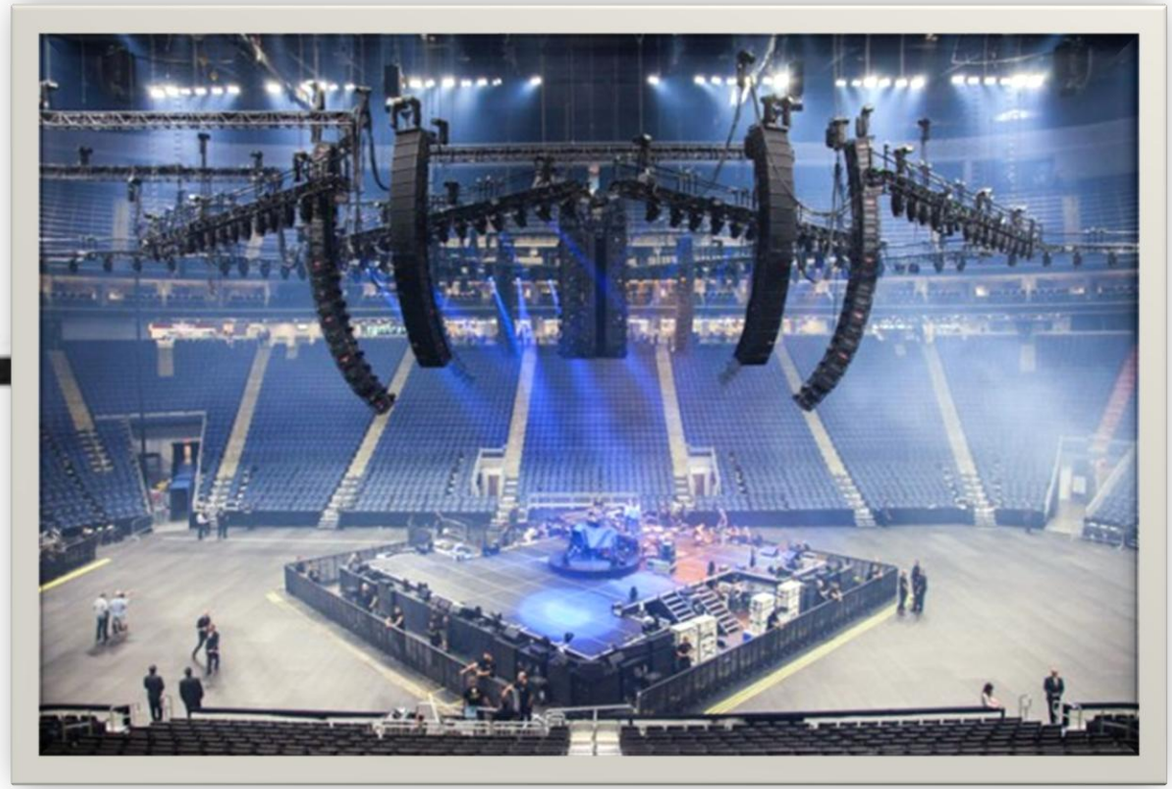


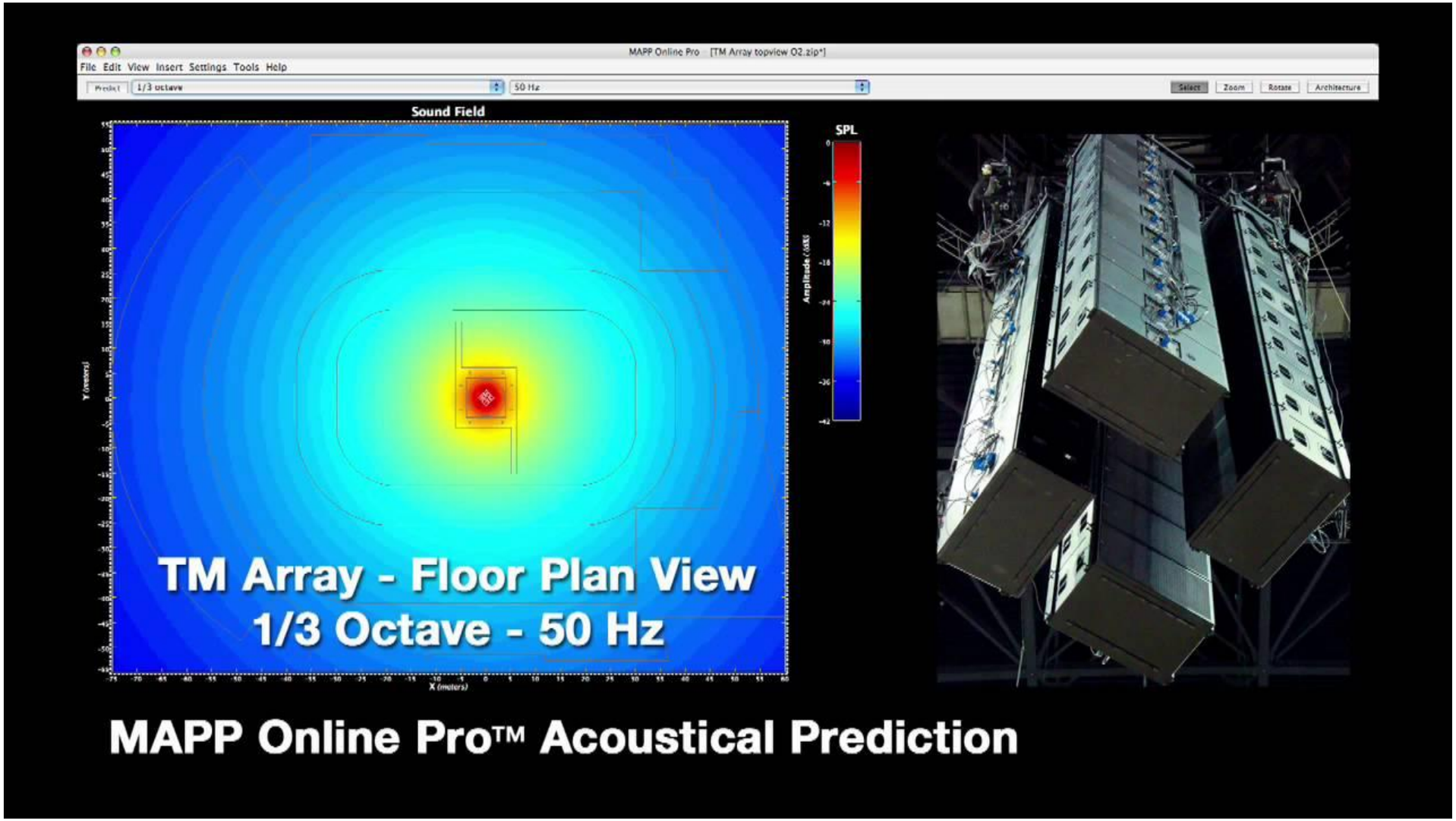


TM Array
Thomas Mundorf

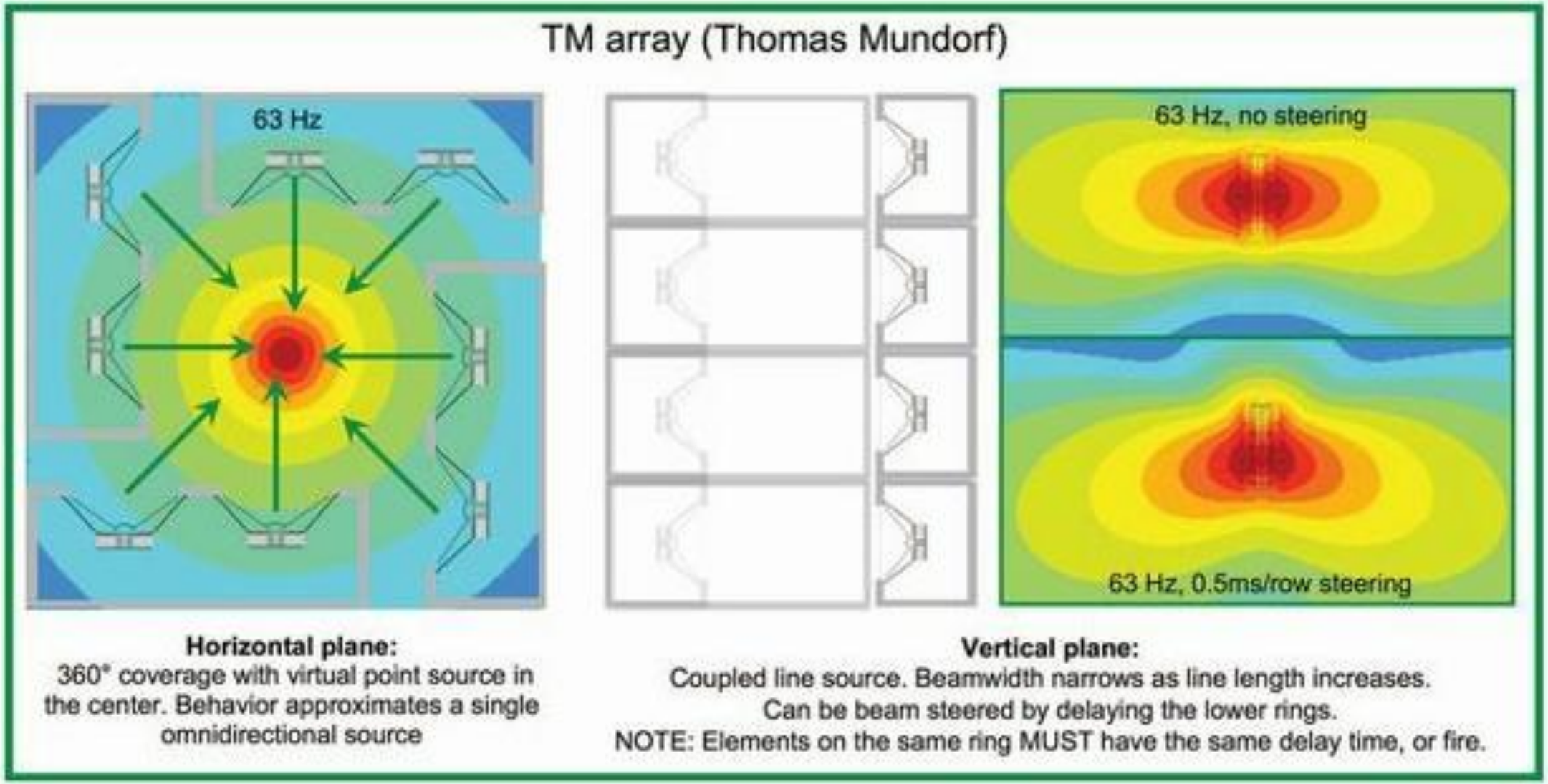


METAL

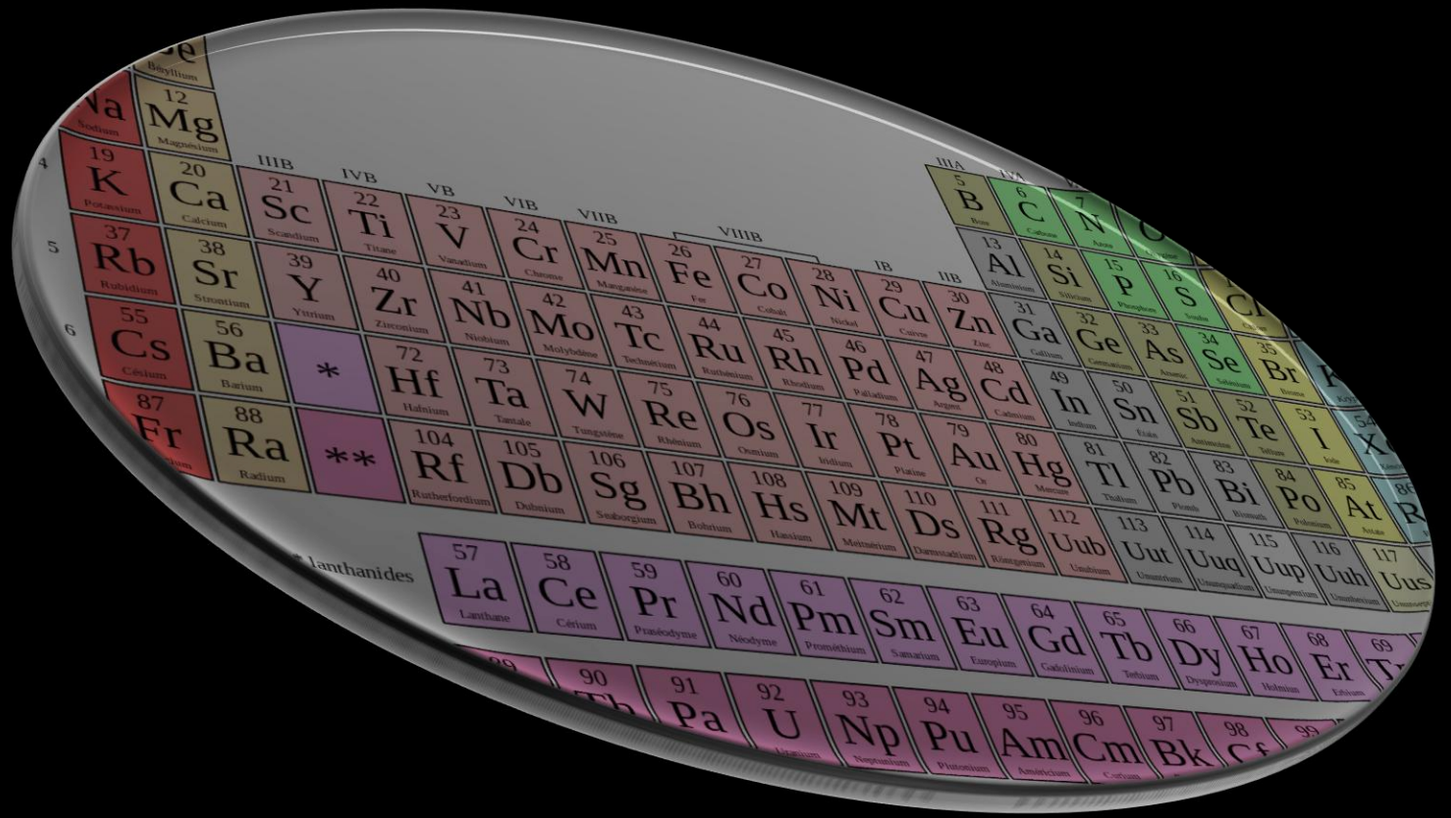



MAPP Online Pro [TM Array topview 02.zip*]
File Edit View Insert Settings Tools Help
Sound Field
SPL
TM Array - Floor Plan View
1/3 Octave - 50 Hz
MAPP Online Pro™ Acoustical Prediction

TM Array
Thomas Mundorf



Source: Bob McCarthy — Sound Systems: Design and Optimization, third edition



5 Classification

Classification

Types	Native				Gradient				
Models	**Native 2**	**End Fire**	**Slot Fire**	**Tm Array**	**Subwoofer arc Cardio**	**Gradient 2**	**Stacks**	**Flowers**	**Vortex**
Maximum spacing	1/4λ		1/3λ	≅ 1.20 m	1/4λ	1/4λ	1/4λ + 1/3λ	1/4λ	
Rejection	++	++	++	++	++	++++	++++	+++	+	++
Radiation-pattern stability	+++	+++	++	+++	+++	++	++	++	++	++
Encombrement	+	+++	+++	++++++	++++++	++++++	+	-	++	+++

6 Simulations

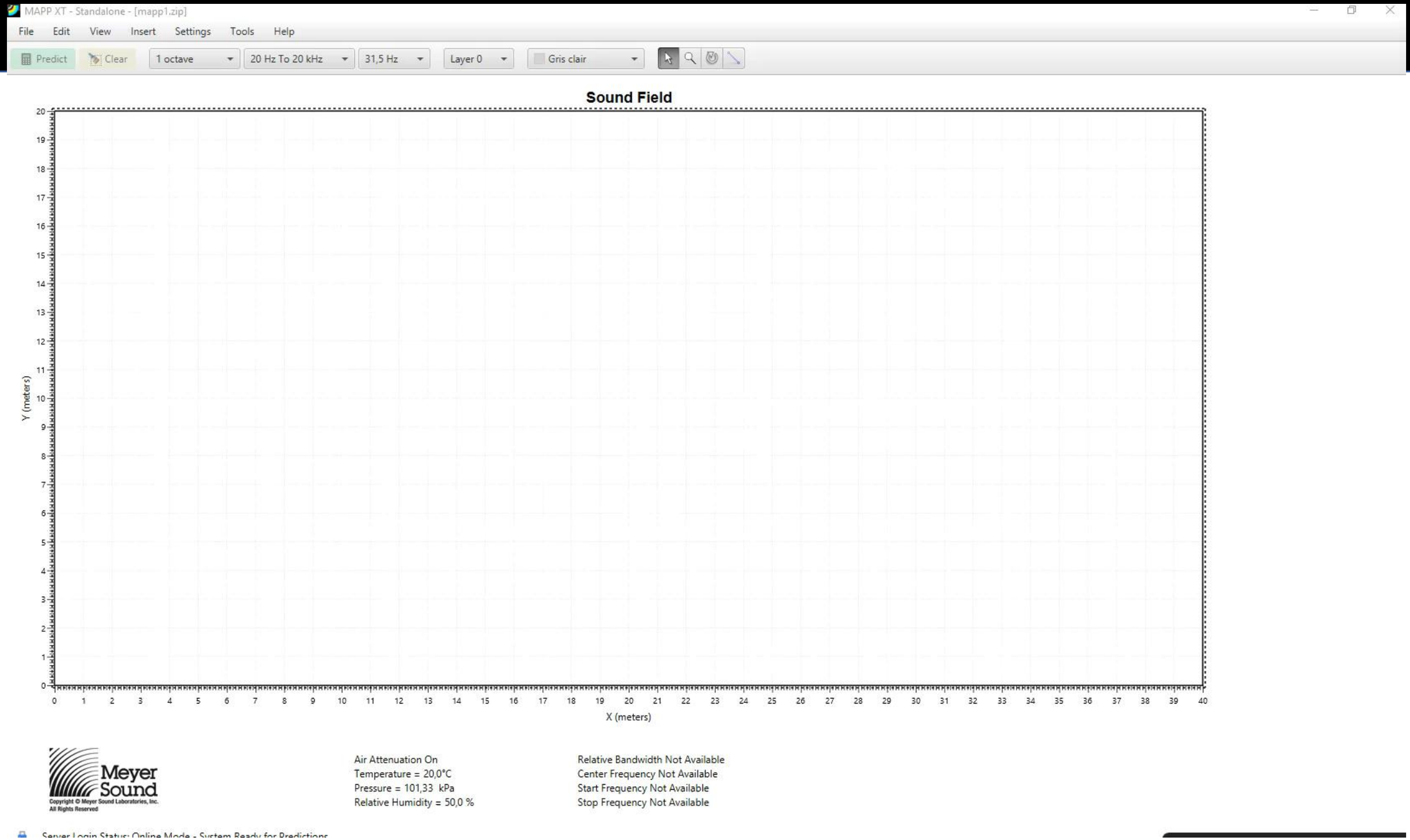


Excel

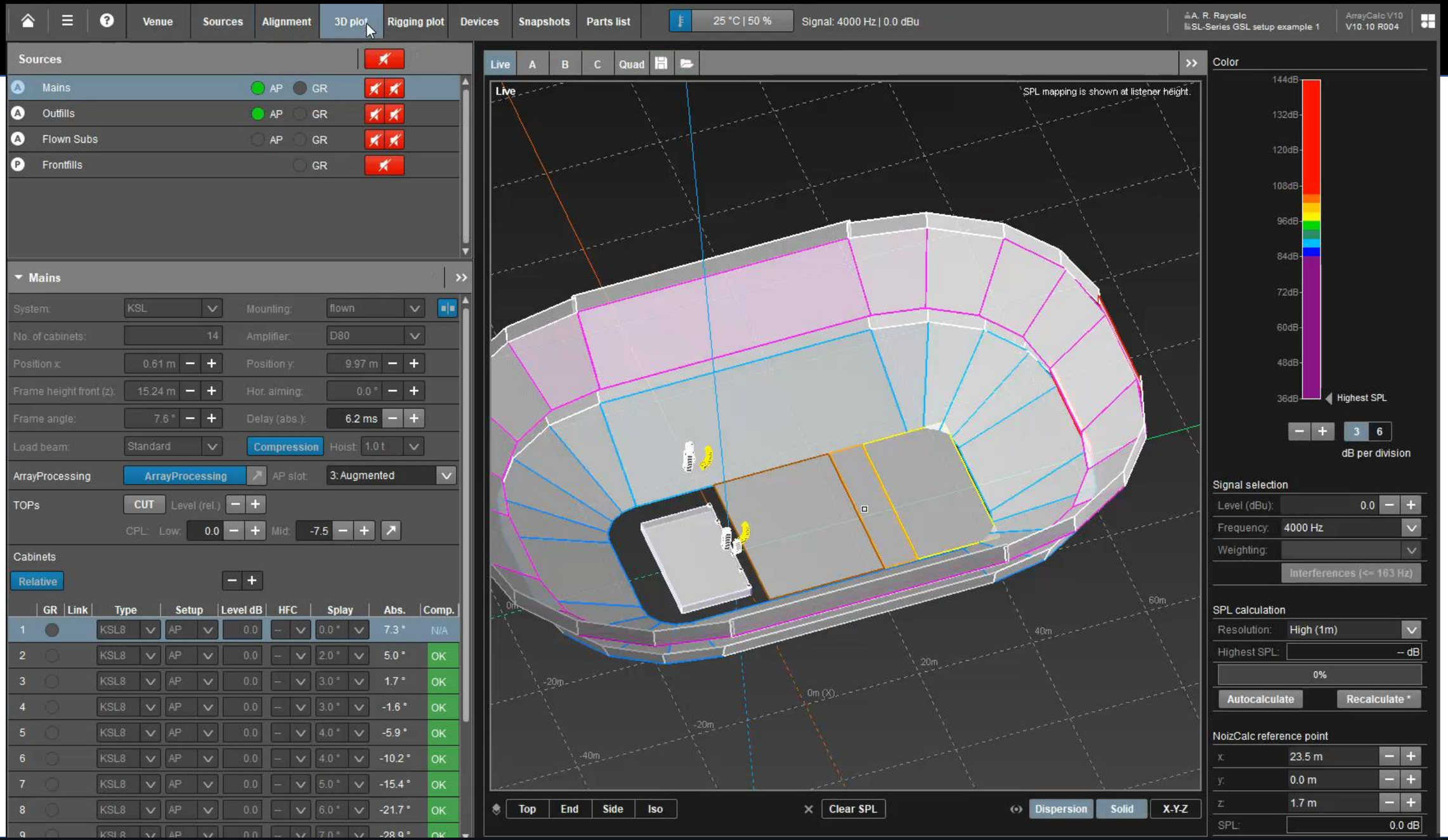
B2 =20.05*RACINE((B1+273.15))

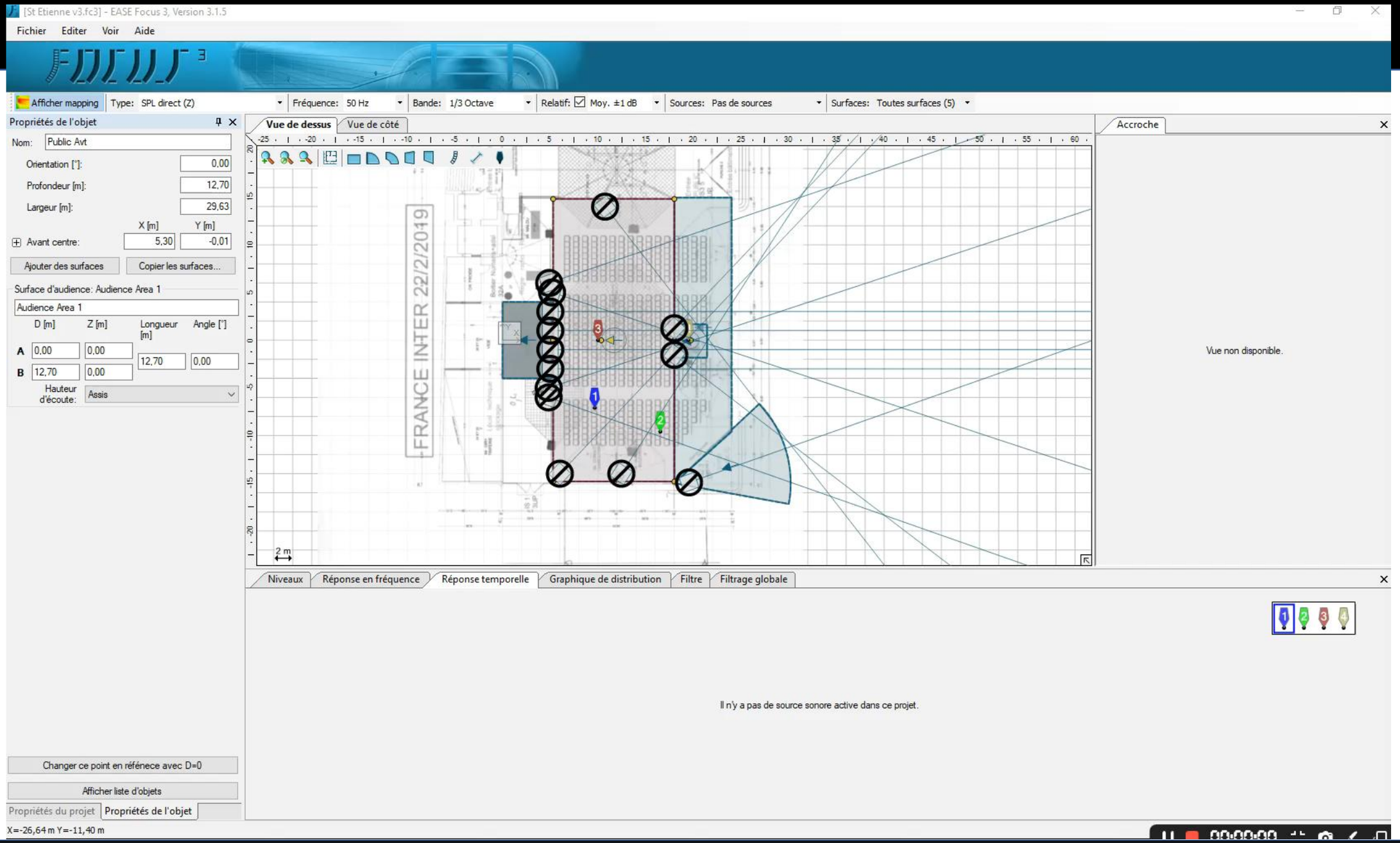
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Température (°)	14.41			Cardio				Espace max						
2	Célérité (M/s)	340.00		λ/4 90° +3dB		λ/2 180° -100dB		λ/3 120° +0dB		λ/10 36° +6dB		λ/6 60° +4dB		3λ/4270° + 3dB	
3	Freq (Hz)	Periode T (ms)	λ (m)	ms	Métres	ms	Métres	ms	Métres	ms	Métres	ms	Métres	ms	Métres
4	20	50.00	17.00	12.50	4.25	25.00	8.50	16.67	5.67	5.00	1.70	8.33	2.83	37.50	12.75
5	25	40.00	13.60	10.00	3.40	20.00	6.80	13.33	4.53	4.00	1.36	6.67	2.27	30.00	10.20
6	31.5	31.75	10.79	7.94	2.70	15.87	5.40	10.58	3.60	3.17	1.08	5.29	1.80	23.81	8.10
7	40	25.00	8.50	6.25	2.12	12.50	4.25	8.33	2.83	2.50	0.85	4.17	1.42	18.75	6.37
8	50	20.00	6.80	5.00	1.70	10.00	3.40	6.67	2.27	2.00	0.68	3.33	1.13	15.00	5.10
9	60	16.67	5.67	4.17	1.42	8.33	2.83	5.56	1.89	1.67	0.57	2.78	0.94	12.50	4.25
10	80	12.50	4.25	3.13	1.06	6.25	2.12	4.17	1.42	1.25	0.42	2.08	0.71	9.38	3.19
11	100	10.00	3.40	2.50	0.85	5.00	1.70	3.33	1.13	1.00	0.34	1.67	0.57	7.50	2.55
12	125	8.00	2.72	2.00	0.68	4.00	1.36	2.67	0.91	0.80	0.27	1.33	0.45	6.00	2.04
13	160	6.25	2.12	1.56	0.53	3.13	1.06	2.08	0.71	0.63	0.21	1.04	0.35	4.69	1.59
14	200	5.00	1.70	1.25	0.42	2.50	0.85	1.67	0.57	0.50	0.17	0.83	0.28	3.75	1.27
15	250	4.00	1.36	1.00	0.34	2.00	0.68	1.33	0.45	0.40	0.14	0.67	0.23	3.00	1.02
16	315	3.17	1.08	0.79	0.27	1.59	0.54	1.06	0.36	0.32	0.11	0.53	0.18	2.38	0.81
17	400	2.50	0.85	0.63	0.21	1.25	0.42	0.83	0.28	0.25	0.08	0.42	0.14	1.88	0.64
18	500	2.00	0.68	0.50	0.17	1.00	0.34	0.67	0.23	0.20	0.07	0.33	0.11	1.50	0.51
19	630	1.59	0.54	0.40	0.13	0.79	0.27	0.53	0.18	0.16	0.05	0.26	0.09	1.19	0.40
20	800	1.25	0.42	0.31	0.11	0.63	0.21	0.42	0.14	0.13	0.04	0.21	0.07	0.94	0.32
21	1000	1.00	0.34	0.25	0.08	0.50	0.17	0.33	0.11	0.10	0.03	0.17	0.06	0.75	0.25
22	1250	0.80	0.27	0.20	0.07	0.40	0.14	0.27	0.09	0.08	0.03	0.13	0.05	0.60	0.20
23	1600	0.63	0.21	0.16	0.05	0.31	0.11	0.21	0.07	0.06	0.02	0.10	0.04	0.47	0.16
24	2000	0.50	0.17	0.13	0.04	0.25	0.08	0.17	0.06	0.05	0.02	0.08	0.03	0.38	0.13
25	2500	0.40	0.14	0.10	0.03	0.20	0.07	0.13	0.05	0.04	0.01	0.07	0.02	0.30	0.10
26	3150	0.32	0.11	0.08	0.03	0.16	0.05	0.11	0.04	0.03	0.01	0.05	0.02	0.24	0.08
27	4000	0.25	0.08	0.06	0.02	0.13	0.04	0.08	0.03	0.03	0.01	0.04	0.01	0.19	0.06
28	5000	0.20	0.07	0.05	0.02	0.10	0.03	0.07	0.02	0.02	0.01	0.03	0.01	0.15	0.05
29	6300	0.16	0.05	0.04	0.01	0.08	0.03	0.05	0.02	0.02	0.01	0.03	0.01	0.12	0.04
30	8000	0.13	0.04	0.03	0.01	0.06	0.02	0.04	0.01	0.01	0.00	0.02	0.01	0.09	0.03
31	10000	0.10	0.03	0.03	0.01	0.05	0.02	0.03	0.01	0.01	0.00	0.02	0.01	0.08	0.03
32	12500	0.08	0.03	0.02	0.01	0.04	0.01	0.03	0.01	0.01	0.00	0.01	0.00	0.06	0.02
33	16000	0.06	0.02	0.02	0.01	0.03	0.01	0.02	0.01	0.01	0.00	0.01	0.00	0.05	0.02
34	20000	0.05	0.02	0.01	0.00	0.03	0.01	0.02	0.01	0.01	0.00	0.01	0.00	0.04	0.01
35															
36															

F - Long -- Période | Natif | End fire 2 | End Fire 4 | Gradient 2 | Gradient EF 2 Dfixe | Native 2 Dfixe | Slotfire 2 λ3 | Slotfire 2 λ6 | Slotfire 2 λ12 | Slc ...


MAPP XT - Standalone - [mapp1.zip]
File
Edit
View
Insert
Settings
Tools
Help
Predict
Clear
1 octave
20 Hz To 20 kHz
31,5 Hz
Layer 0
Gris clair
Sound Field
Y (meters)
X (meters)
Meyer Sound
Copyright © Meyer Sound Laboratories, Inc.
All Rights Reserved
Air Attenuation On
Temperature = 20,0°C
Pressure = 101,33 kPa
Relative Humidity = 50,0 %
Relative Bandwidth Not Available
Center Frequency Not Available
Start Frequency Not Available
Stop Frequency Not Available

ArrayCalc


Venue
Sources
Alignment
3D plot
Rigging plot
Devices
Snapshots
Parts list
25 °C | 50 %
Signal: 4000 Hz | 0.0 dBu
A. R. Raycalc
SL-Series GSL setup example 1
ArrayCalc V10
V10.10 R004
Sources
Mains
Outfills
Flown Subs
Frontfills
AP
GR
Mains
System: KSL
Mounting: flown
No. of cabinets: 14
Amplifier: D80
Position x: 0.61 m
Position y: 9.97 m
Frame height front (z): 15.24 m
Hor. aiming: 0.0 °
Frame angle: 7.6 °
Delay (abs.): 6.2 ms
Load beam: Standard
Compression
Hoist: 1.0 t
ArrayProcessing
AP slot: 3: Augmented
TOPs
CUT
Level (rel.)
CPL: Low: 0.0 Mid: -7.5
Cabinets
Relative
GR Link Type Setup Level dB HFC Splay Abs. Comp.
1 KSL8 AP 0.0 0.0 ° 7.3 ° N/A
2 KSL8 AP 0.0 2.0 ° 5.0 ° OK
3 KSL8 AP 0.0 3.0 ° 1.7 ° OK
4 KSL8 AP 0.0 3.0 ° -1.6 ° OK
5 KSL8 AP 0.0 4.0 ° -5.9 ° OK
6 KSL8 AP 0.0 4.0 ° -10.2 ° OK
7 KSL8 AP 0.0 5.0 ° -15.4 ° OK
8 KSL8 AP 0.0 6.0 ° -21.7 ° OK
Live
A
B
C
Quad
Live
SPL mapping is shown at listener height.
Top
End
Side
Iso
Clear SPL
Dispersion
Solid
X-Y-Z
Color
144dB
132dB
120dB
108dB
96dB
84dB
72dB
60dB
48dB
36dB
Highest SPL
3
6
dB per division
Signal selection
Level (dBu): 0.0
Frequency: 4000 Hz
Weighting:
Interferences (<= 163 Hz)
SPL calculation
Resolution: High (1m)
Highest SPL: -- dB
0%
Autocalculate
Recalculate *
NoizCalc reference point
x: 23.5 m
y: 0.0 m
z: 1.7 m
SPL: 0.0 dB


[St Etienne v3.fc3] - EASE Focus 3, Version 3.1.5
Fichier Editer Voir Aide
Afficher mapping
Type: SPL direct (Z)
Fréquence: 50 Hz
Bande: 1/3 Octave
Relatif: Moy. ±1 dB
Sources: Pas de sources
Surfaces: Toutes surfaces (5)
Propriétés de l'objet
Nom: Public Avt
Orientation [°]: 0,00
Profondeur [m]: 12,70
Largeur [m]: 29,63
X [m] Y [m]
Avant centre: 5,30 -0,01
Ajouter des surfaces
Copier les surfaces...
Surface d'audience: Audience Area 1
Audience Area 1
D [m] Z [m] Longueur [m] Angle [°]
A 0,00 0,00 12,70 0,00
B 12,70 0,00
Hauteur d'écoute: Assis
Changer ce point en référence avec D=0
Afficher liste d'objets
Propriétés du projet
Propriétés de l'objet
Vue de dessus
Vue de côté
FRANCE INTER 22/2/2019
2 m
Accroche
Vue non disponible.
Niveaux
Réponse en fréquence
Réponse temporelle
Graphique de distribution
Filtre
Filtrage globale
Il n'y a pas de source sonore active dans ce projet.
X=-26,64 m Y=-11,40 m

Limitations of simulations



Simulation software is never perfect.
Few tools account for the acoustic characteristics of the venue.

Depending on the configuration, each tool’s strengths and your working habits, using more than one simulation tool can be useful.



Always verify on site and compare measurements with predictions.

?

Conclusion



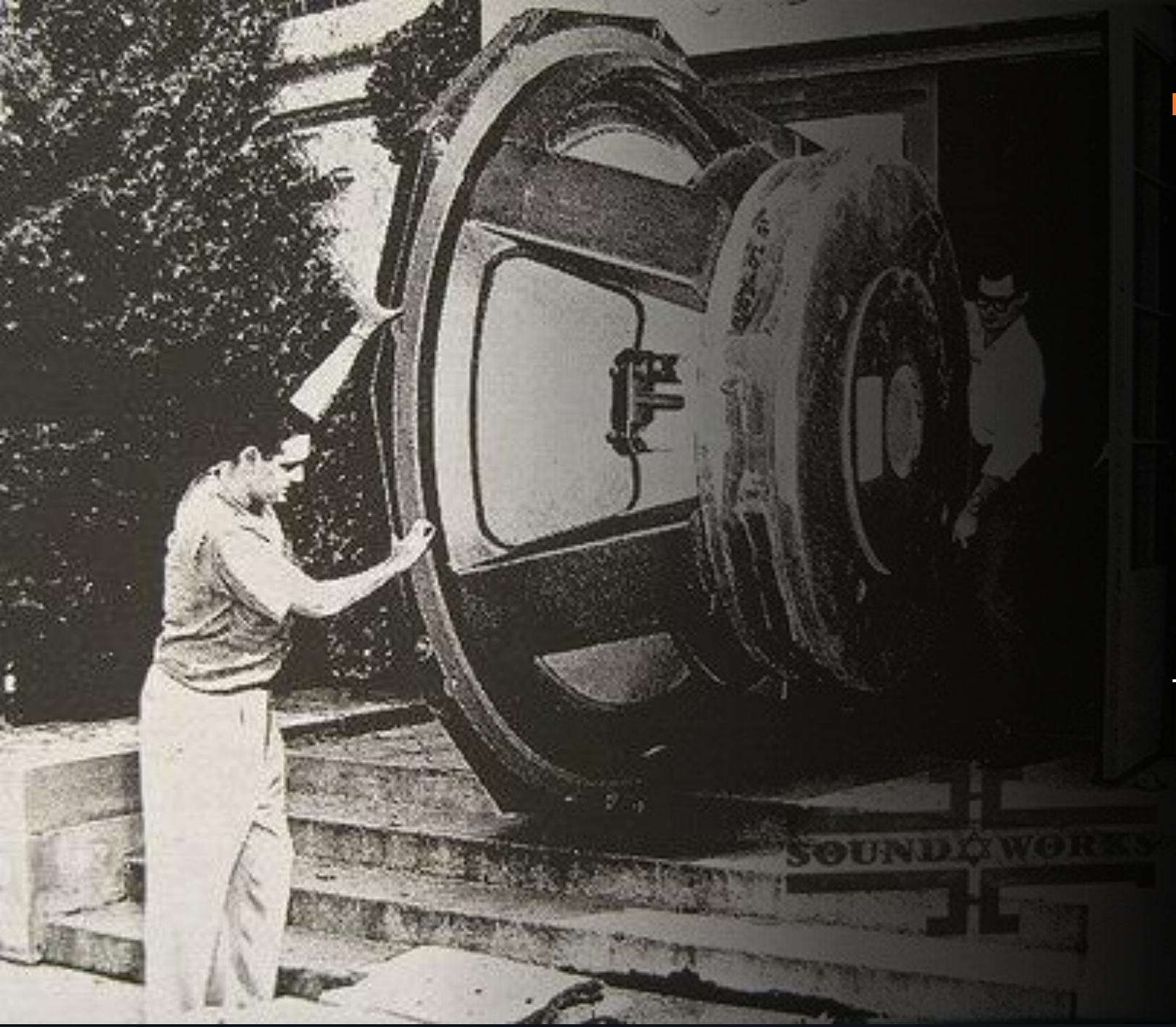
- Understanding and controlling subwoofer directivity is essential for coherent coverage and fewer acoustic problems.
- Simulation software provides valuable assistance.
- Although largely outside the scope of this course, relative level management and electrical system design are essential.
- As so often in audio, the answer is:

  “It depends…”



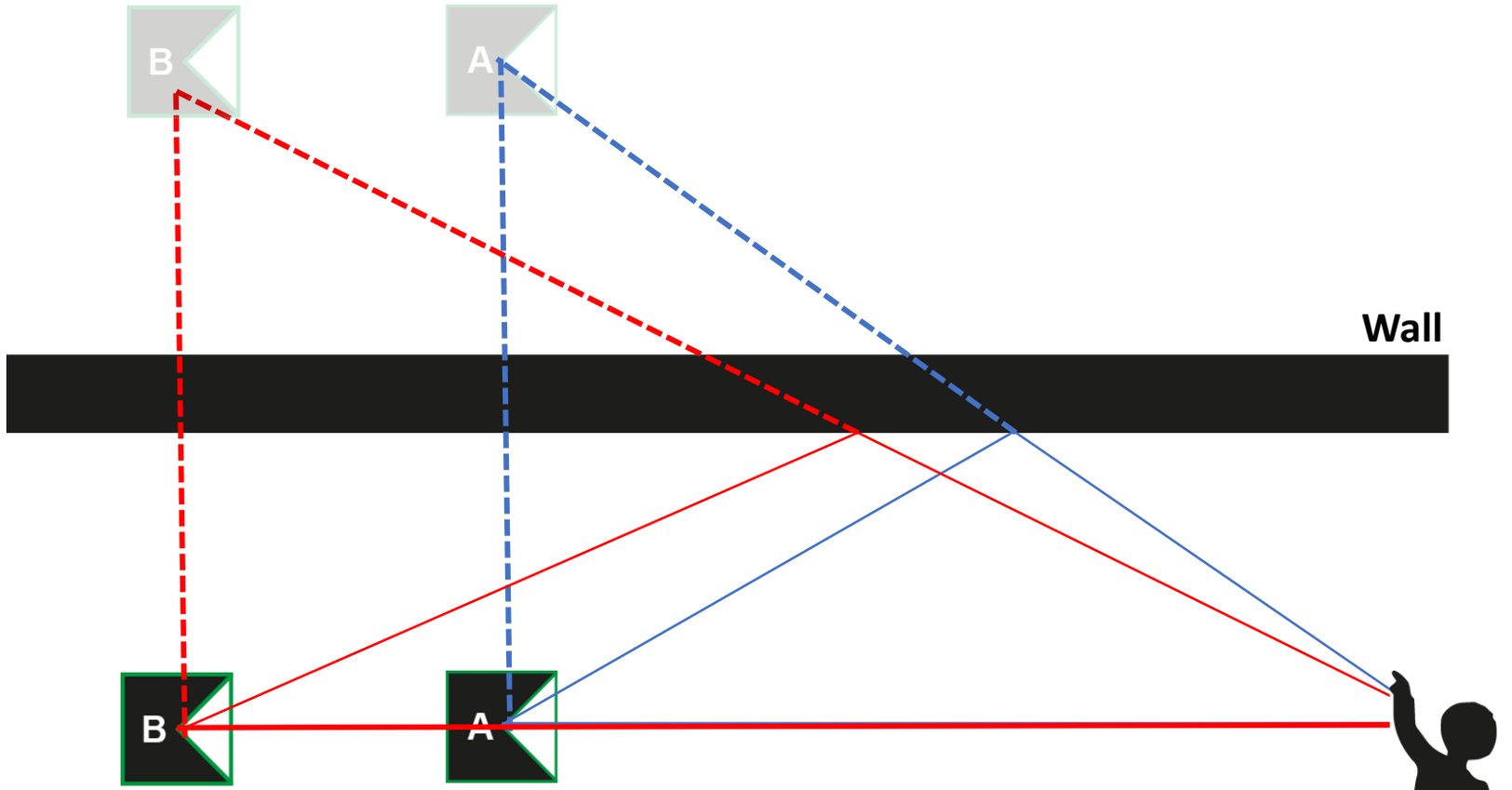


7
Examples



8 Appendices

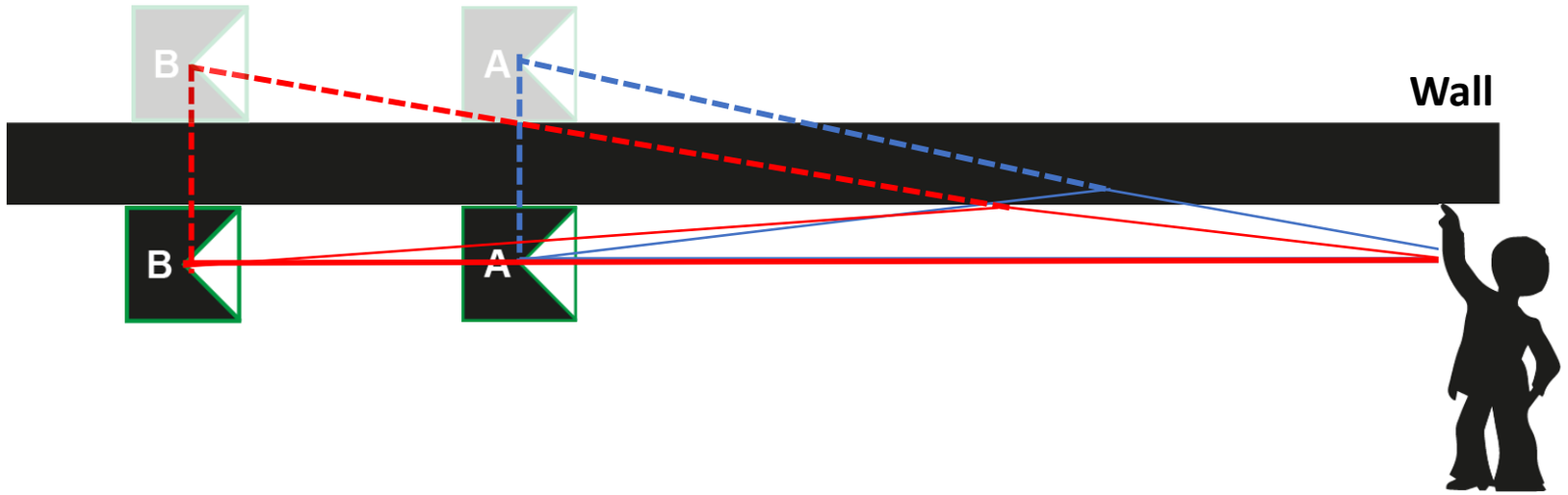
Virtual sources



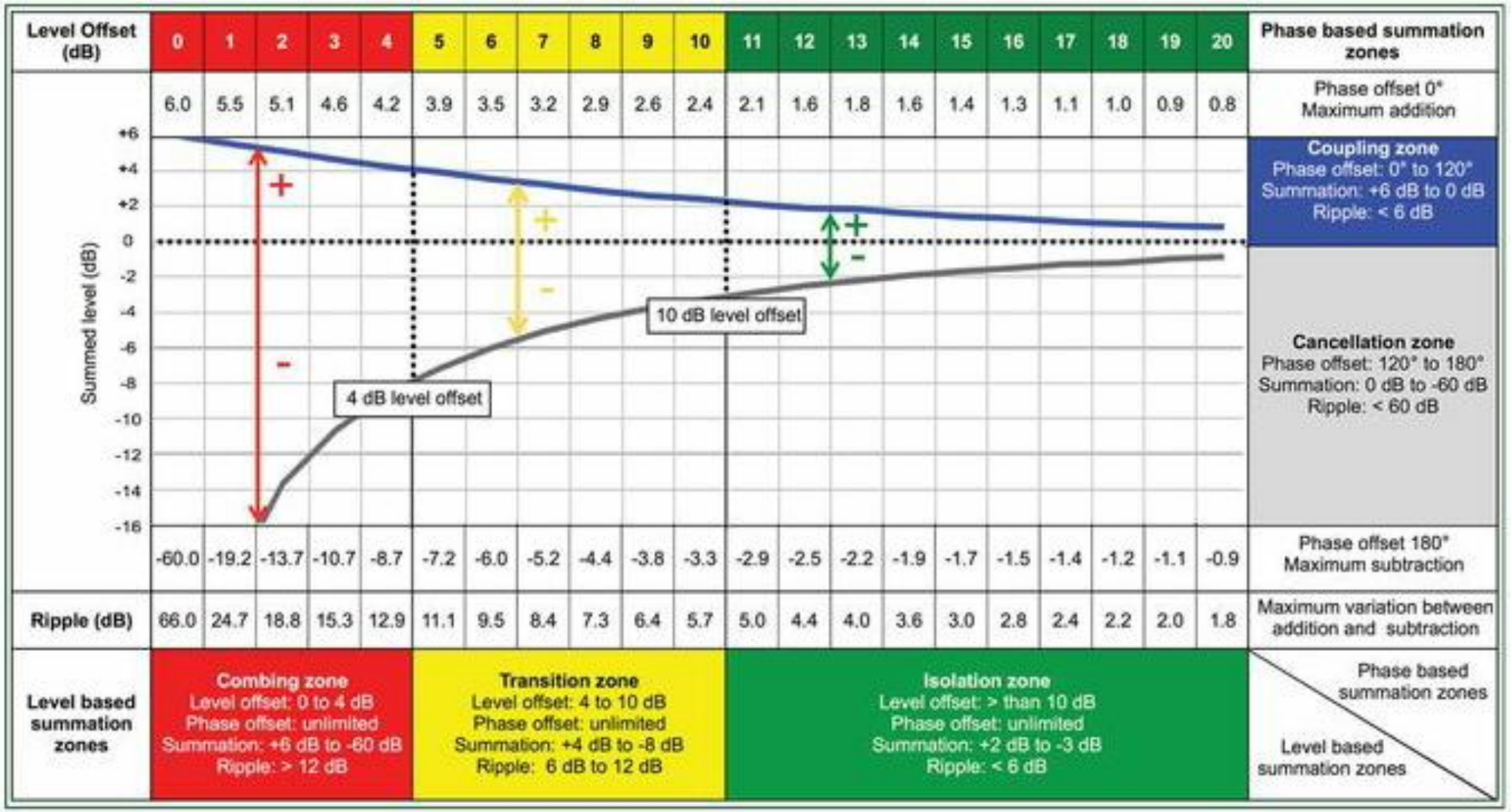
It is important to account for acoustic reflections.

The directivity and impulse response will change.

Virtual sources



Summation: relative levels and phases



Level Offset (dB)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Phase based summation zones
	6.0	5.5	5.1	4.6	4.2	3.9	3.5	3.2	2.9	2.6	2.4	2.1	1.6	1.8	1.6	1.4	1.3	1.1	1.0	0.9	0.8	Phase offset 0° Maximum addition
																						Coupling zone Phase offset: 0° to 120° Summation: +6 dB to 0 dB Ripple: < 6 dB
																						Cancellation zone Phase offset: 120° to 180° Summation: 0 dB to -60 dB Ripple: < 60 dB
	-60.0	-19.2	-13.7	-10.7	-8.7	-7.2	-6.0	-5.2	-4.4	-3.8	-3.3	-2.9	-2.5	-2.2	-1.9	-1.7	-1.5	-1.4	-1.2	-1.1	-0.9	Phase offset 180° Maximum subtraction
Ripple (dB)	66.0	24.7	18.8	15.3	12.9	11.1	9.5	8.4	7.3	6.4	5.7	5.0	4.4	4.0	3.6	3.0	2.8	2.4	2.2	2.0	1.8	Maximum variation between addition and subtraction
Level based summation zones	**Combing zone** Level offset: 0 to 4 dB Phase offset: unlimited Summation: +6 dB to -60 dB Ripple: > 12 dB					**Transition zone** Level offset: 4 to 10 dB Phase offset: unlimited Summation: +4 dB to -8 dB Ripple: 6 dB to 12 dB						**Isolation zone** Level offset: > than 10 dB Phase offset: unlimited Summation: +2 dB to -3 dB Ripple: < 6 dB										Phase based summation zones / Level based summation zones

Source: Bob McCarthy — Sound Systems: Design and Optimization, third edition

Speed of sound

Temperature

θ en °C	c en m·s^{-1}	ρ in kg·m^{-3}	Ƶ en N·s·m^{-3}
- 10	**325,4**	1,341	436,5
- 5	**328,4**	1,316	432,4
0	**331,5**	1,293	428,3
+ 5	**334,5**	1,269	424,5
+ 10	**337,5**	1,247	420,7
+ 15	**340,5**	1,225	417,0
+ 20	**343,4**	1,204	413,5
+ 25	**346,3**	1,184	410,0
+ 30	**349,2**	1,164	406,6

- θ = *temperature*
- c = *speed of sound*
- ρ = *density*
- Ƶ = *acoustic impedance*

$$c \approx 20,05\sqrt{T_k}$$

Or

$$c \approx 331,5 + 0.607.\theta$$

- c = *Vitesse du son*
- T_k = *temperature in kelvin*
- θ = *temperature*

$T_c = T_k$ - *273,15*

Or

$T_k = T_c$ + *273,15*

Altitude

Altitude in m	θ en °C	P *in kPa*	c en m·s^{-1}	ρ en kg·m^{-3}
0	15,00	101,33	**340,3**	1,225
200	13,70	98,95	**339,5**	1,202
400	12,40	96,61	**338,8**	1,179
600	11,10	94,32	**338,0**	1,156
800	9,80	92,08	**337,2**	1,134
1 000	8,50	89,88	**336,4**	1,112
2 000	2,00	79,50	**332,5**	1,007
3 000	-4,49	70,12	**328,6**	0,909
4 000	-10,98	61,66	**324,6**	0,819
6 000	-24,0	47,22	**316,5**	0,660
8 000	-36,9	35,65	**308,1**	0,526
10 000	-49,9	26,50	**299,5**	0,414
12 000	-62,9	19,40	**295,1**	0,312

- θ = *temperature*
- P = *pressure*
- c = *speed of sound*
- ρ = *density*

Calculating phase difference ($\Delta\varphi$)

$$\Delta_\varphi = \frac{\Delta_d . f . 360}{c} = \frac{\Delta_d . 360}{\lambda}$$

- *where:*
- *f = frequency*
- *λ = wavelength*
- *C = speed of sound*
- *Δd = path-length difference*

Calculating phase difference ($\Delta\varphi$)

$$\Delta_{\varphi} = \frac{\Delta_d . f . 360}{c} = \frac{\Delta_d . 360}{\lambda}$$

- *where:*
- *f = frequency*
- *λ = wavelength*
- *C = speed of sound*
- *Δd = path-length difference*

Calculating phase difference ($\Delta\varphi$)

Example

$$\Delta_\varphi = \frac{\Delta_d . f . 360}{c} = \frac{\Delta_d . 360}{\lambda}$$

- *If:*
- $f = 100\ Hz$
- $\lambda = 3{,}4\ m$
- $C = 340\ m/s$
- $\Delta_d = 1{,}03\ m$

$$\Delta_\varphi = \frac{1{,}03 \times 100 \times 360}{340} = \frac{1{,}03 \times 360}{3{,}4}$$

$$\Delta_\varphi = 110°$$

Further reading

- **Bob McCarthy — Sound Systems: Design and optimization**
- **D&B** – TI330
- **Dave Rat** – Roadies in the Midst : https://www.ratsound.com/cblog/
- **Zest du savoir** :
  - https://zestedesavoir.com/tutoriels/2451/les-signaux-sinusoidaux-en-physique/dephasage-et-retard/#1-dephasage-et-retard-entre-deux-signaux-sinusoidaux
- **Techniques du son** : http://www.techniquesduson.com/sub.html
- **TM Array :**
  - http://www.audiomeasurements.com/?p=5943
  - https://www.youtube.com/watch?v=uoLE8AvsHD0
- **Bob McCarthy** : https://bobmccarthy.wordpress.com/2010/04/15/phase-wavelengths-the-end-fire-cardioid-array-made-visible/