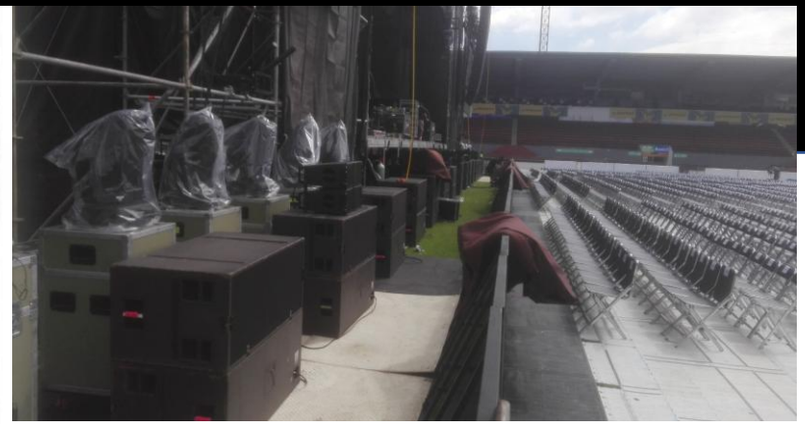
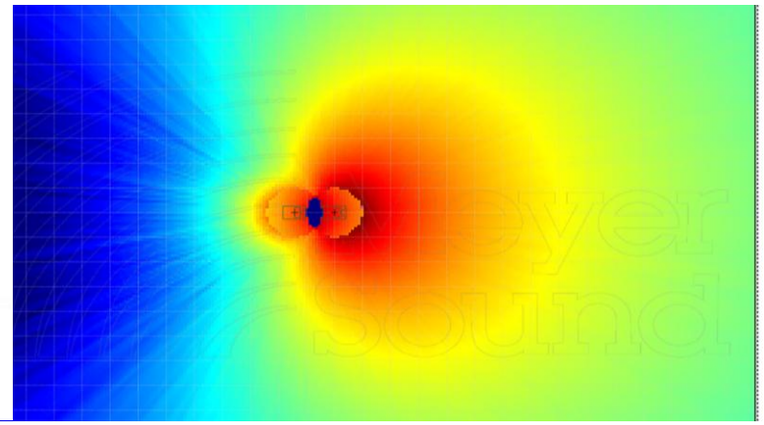










Jamais sans mes subs...

Couplages et contrôle de directivité.

Avant-Propos



Le propos de ce cours concerne les couplages et le contrôle de la directivité des enceintes de graves (subs).

Les parties mécaniques et électriques de ces machines pourraient en elles-mêmes faire l'objet d'un cours et ne seront presque pas traitées ici.



Plan

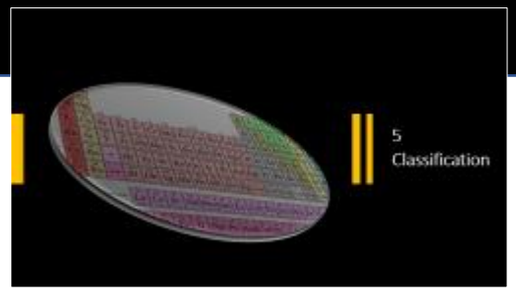








1. Notions fondamentales
2. Steering effect
3. Foward et vertical Steering
4. Configurations spéciales
5. Classification
6. Simulations
7. Exemples
8. Annexes





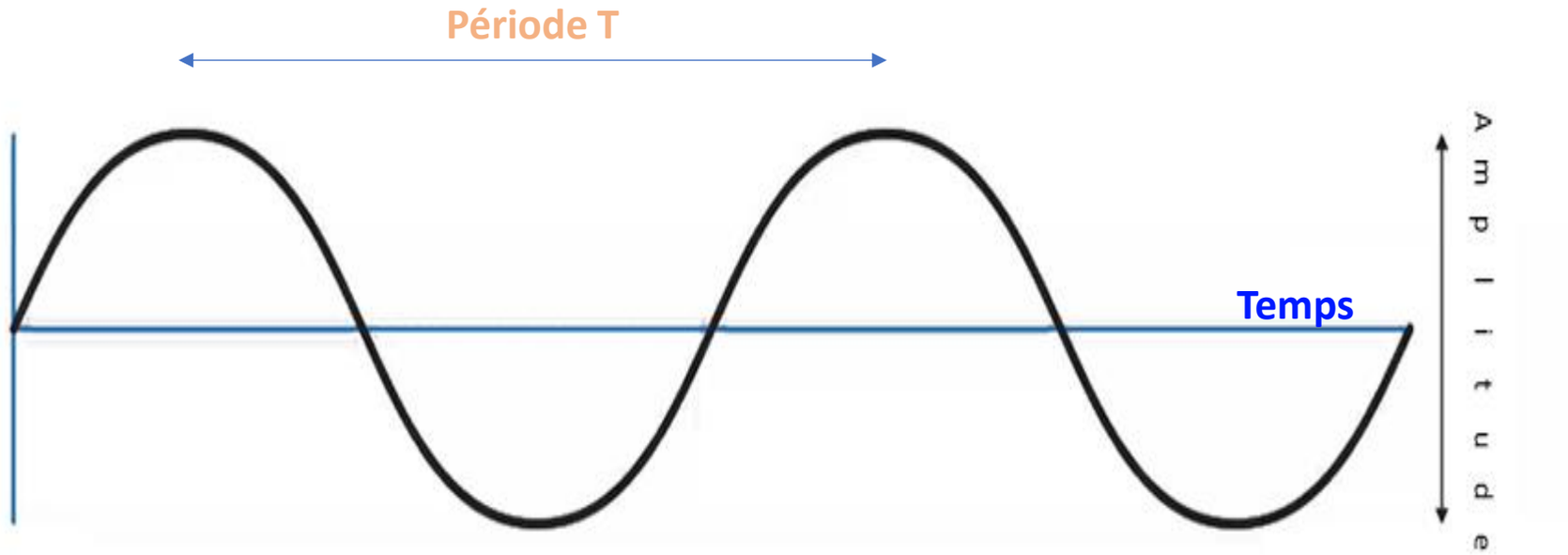






1 Notions fondamentales

Fréquence (*f*), longueur d'onde (**λ**) et Période (**T**)

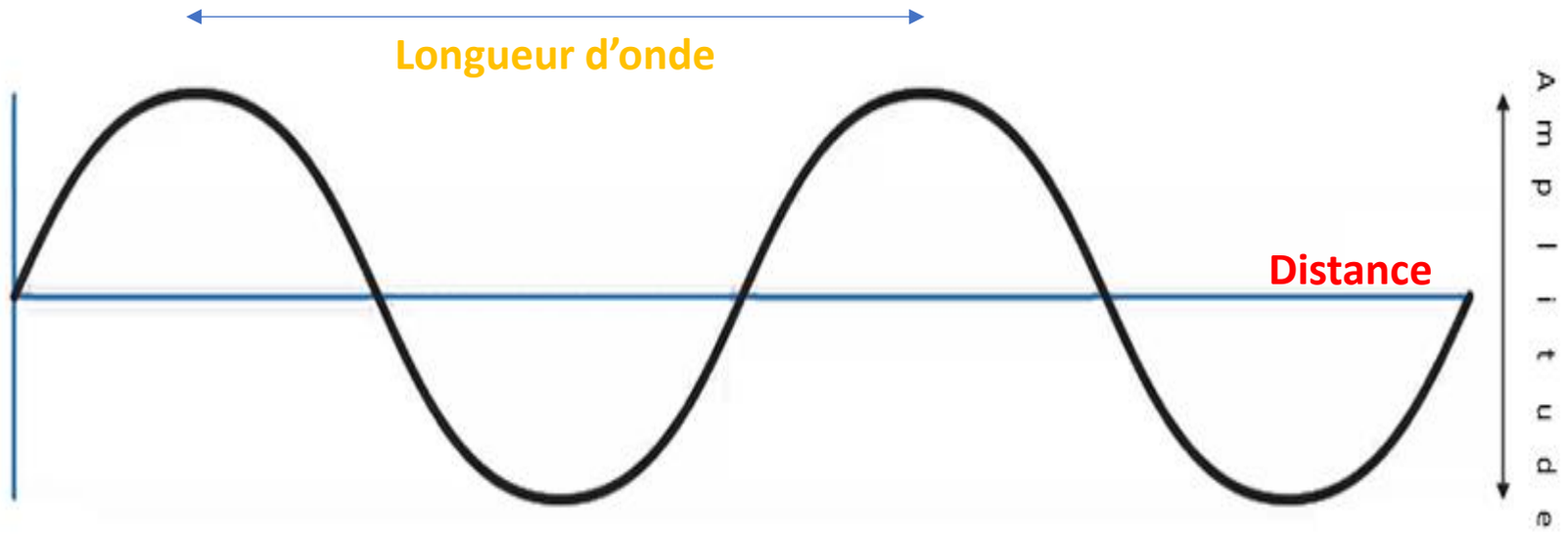


Période T =
Intervalle de temps séparant deux états vibratoires identiques et successifs.

Fréquence *f* =
Nombre de période par unité de temps.
En Hertz, l'unité de temps est la seconde.

$$F = 1/T$$

Fréquence (*f*), longueur d'onde (λ) et Période (T)



Afin de simplifier les exemples qui vont suivre, nous allons considérer que le son se propage dans l'air à $340 m \cdot s^{-1}$.

Il est quand même important de reconsidérer cette valeur si besoin.

Période T =
Intervalle de temps séparant deux états vibratoires identiques et successifs.

Fréquence *f* =
Nombre de période par unité de temps.
En Hertz, l'unité de temps est la seconde.

$$F = 1/T$$

Longueur d'onde λ =
Distance parcourue pendant une Période T.

$$\lambda = c/f$$

Avec c la célérité de l'onde.

Des ondes macroscopiques

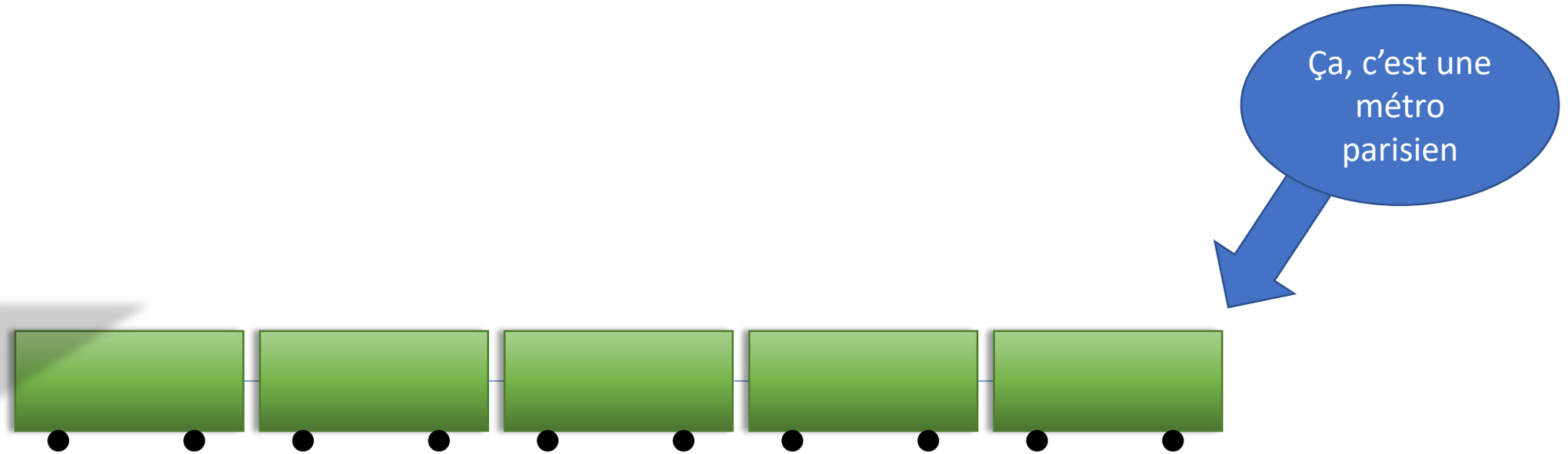


f	λ
20 Hz	17 m
25 Hz	13,6 m
31,5 Hz	10,79 m
45 Hz	7,56 m
50 Hz	6,8 m
60 Hz	5,67 m
80 Hz	4,25 m
100 Hz	3,40 m
125 Hz	2,72 m



Des ondes macroscopiques

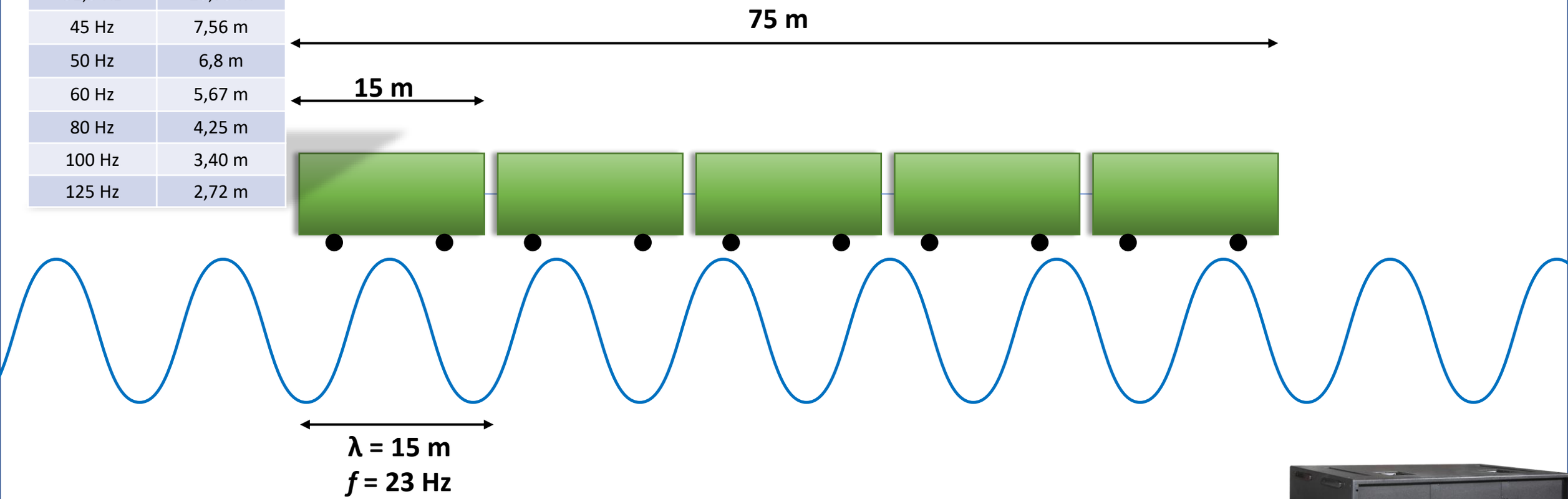
f	λ
20 Hz	17 m
25 Hz	13,6 m
31,5 Hz	10,79 m
45 Hz	7,56 m
50 Hz	6,8 m
60 Hz	5,67 m
80 Hz	4,25 m
100 Hz	3,40 m
125 Hz	2,72 m





Des ondes macroscopiques

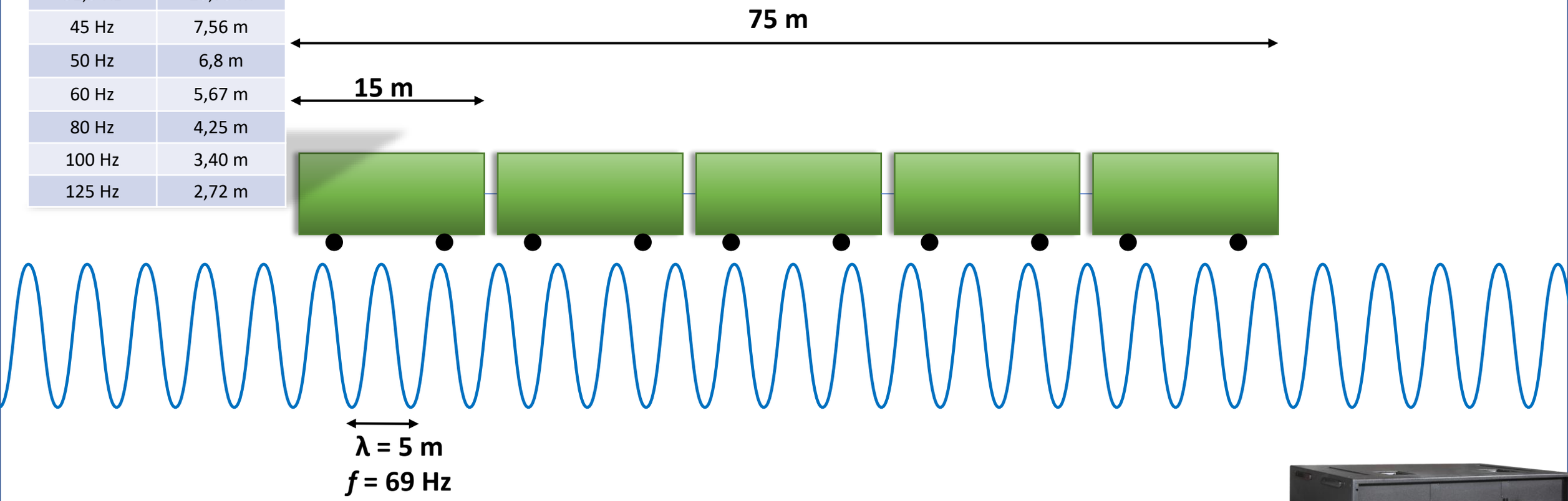
f	λ
20 Hz	17 m
25 Hz	13,6 m
31,5 Hz	10,79 m
45 Hz	7,56 m
50 Hz	6,8 m
60 Hz	5,67 m
80 Hz	4,25 m
100 Hz	3,40 m
125 Hz	2,72 m





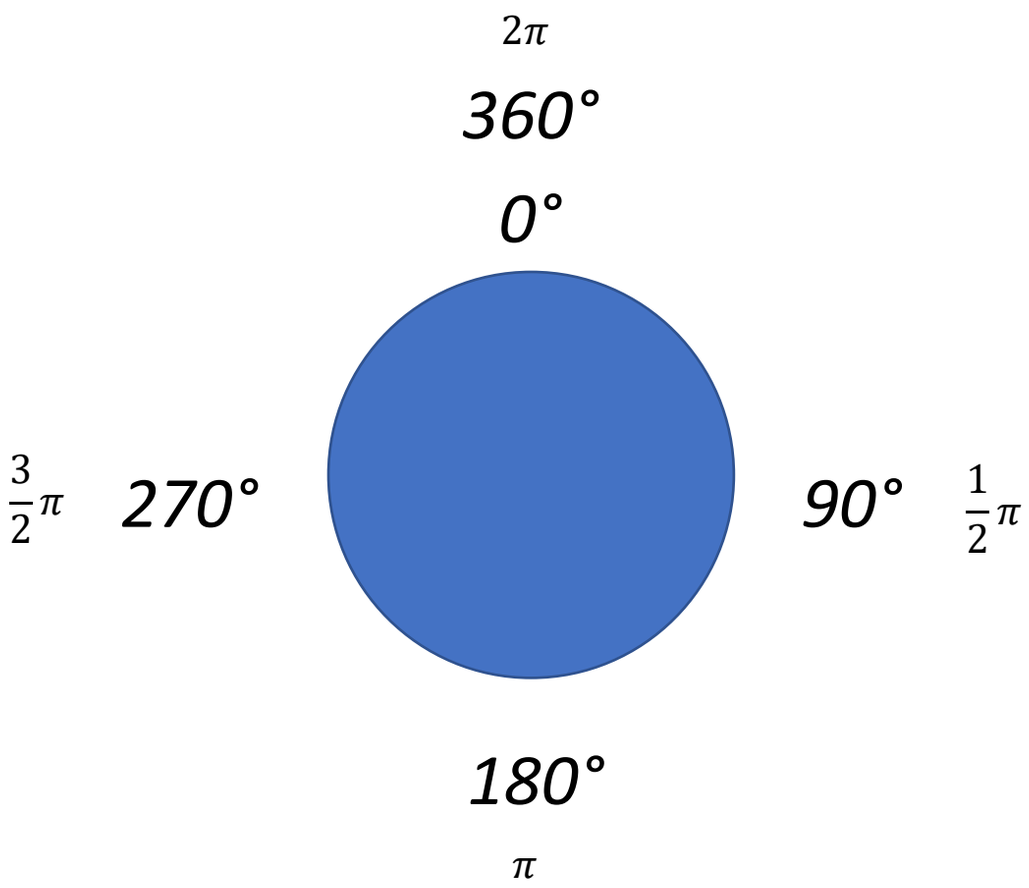
Des ondes macroscopiques

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

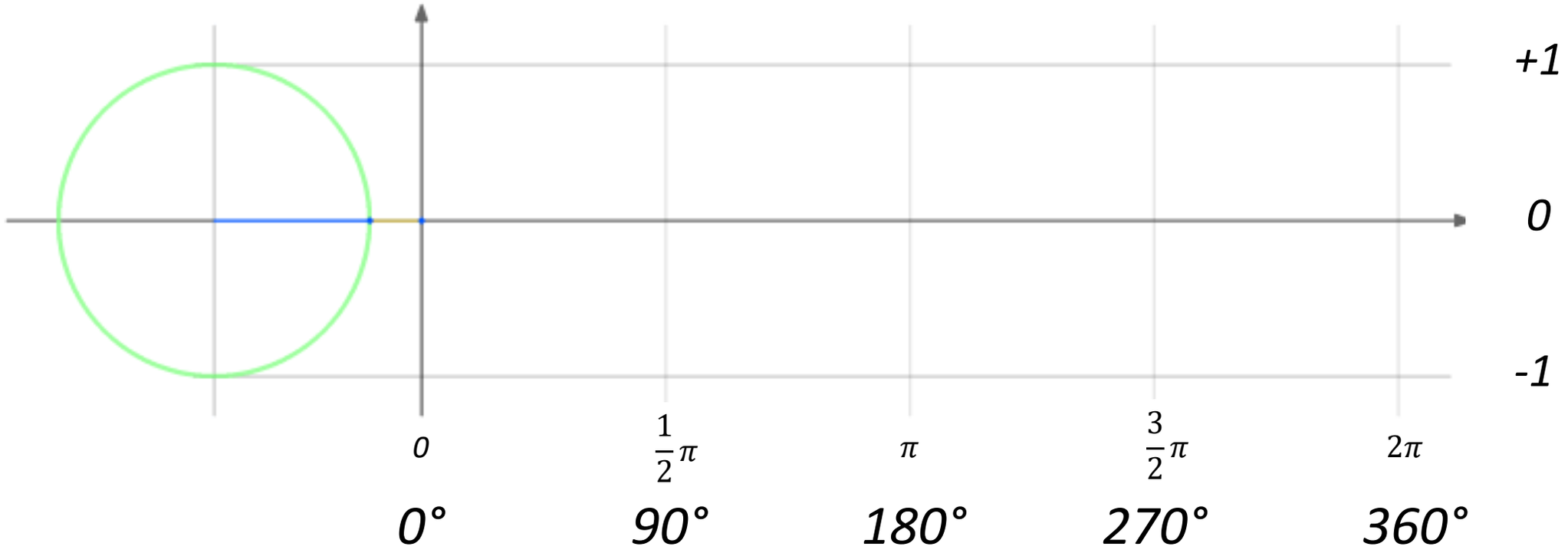




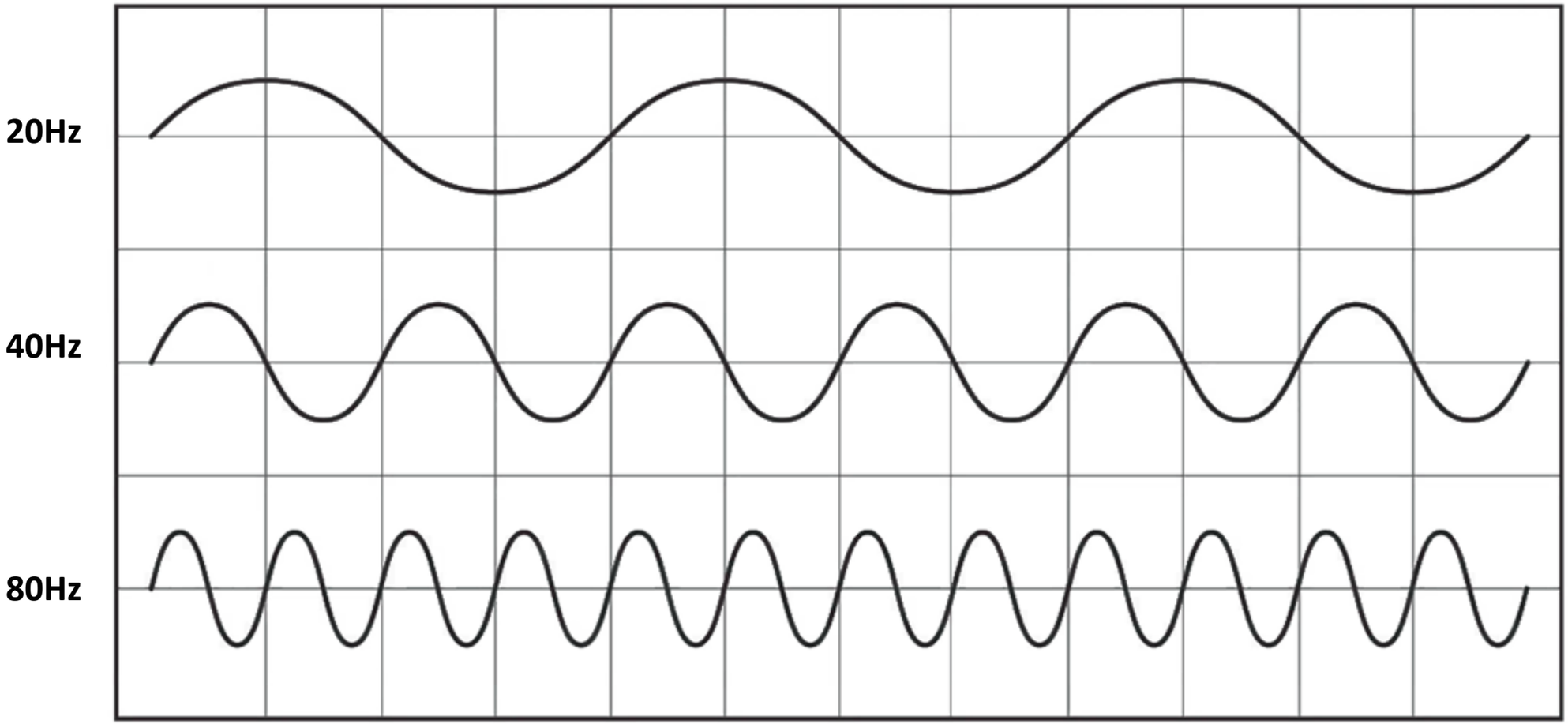
Phase (φ) et fréquence (f)



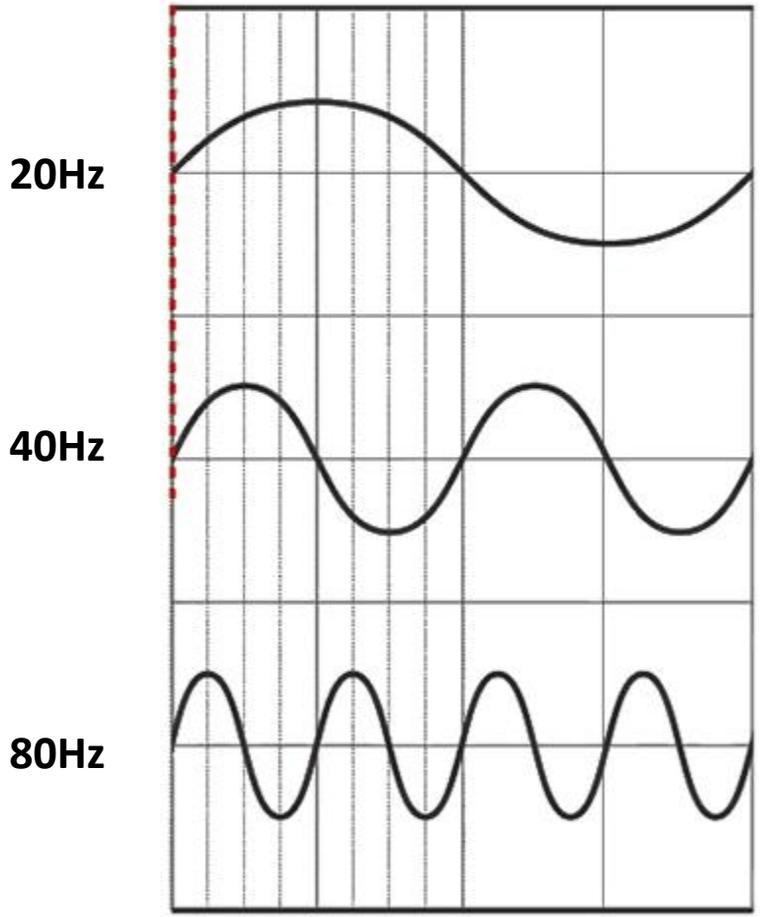
Phase (φ) et fréquence (f)



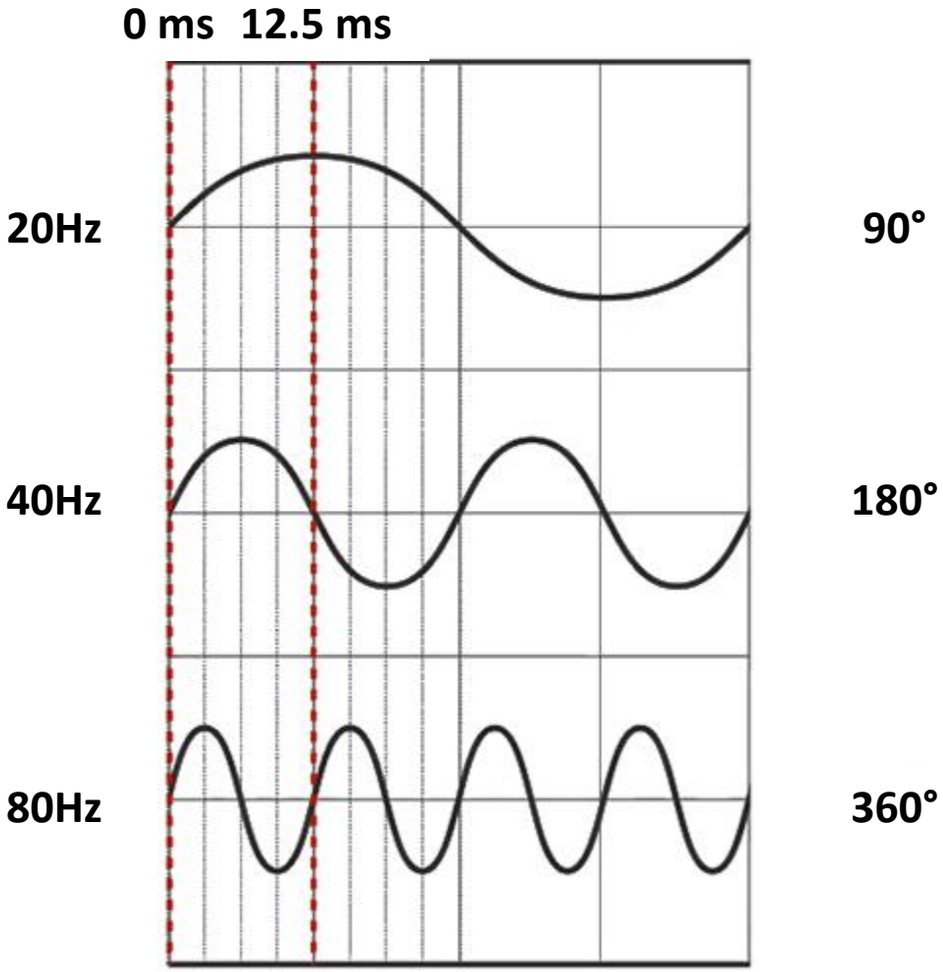
Phase (φ) et fréquence (f)



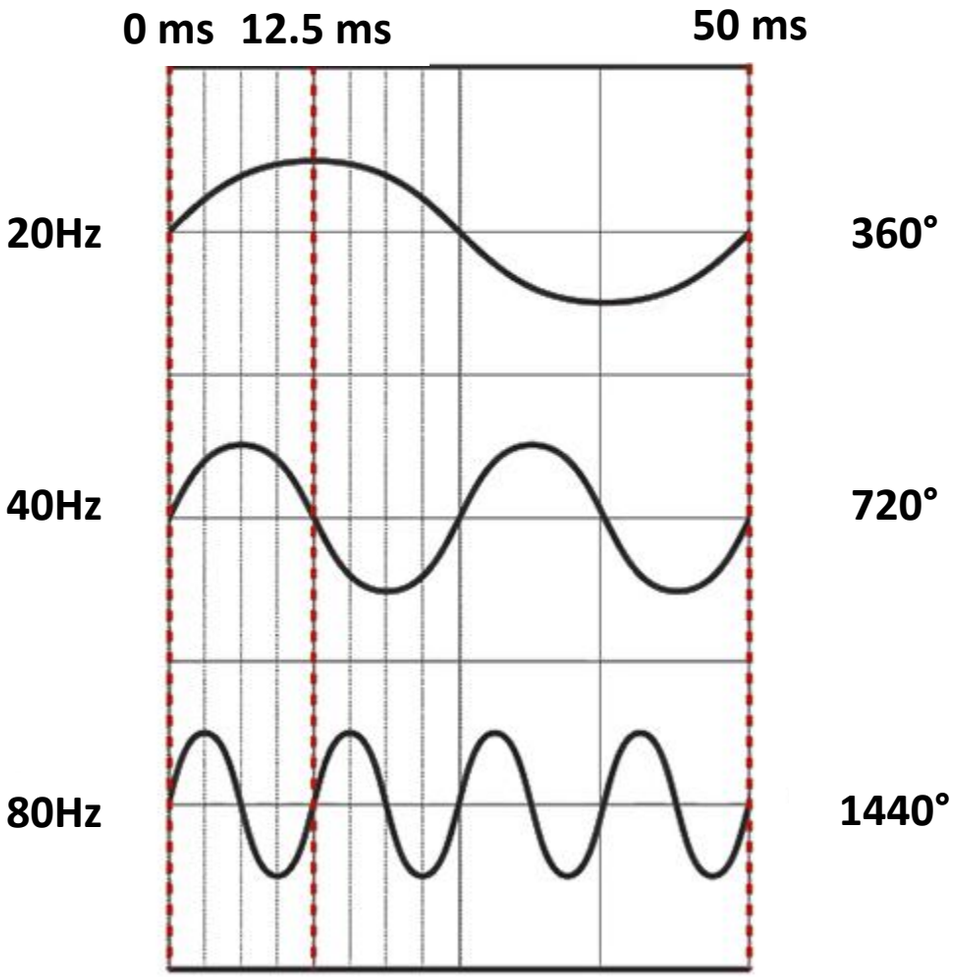
Phase (φ) et fréquence (f)



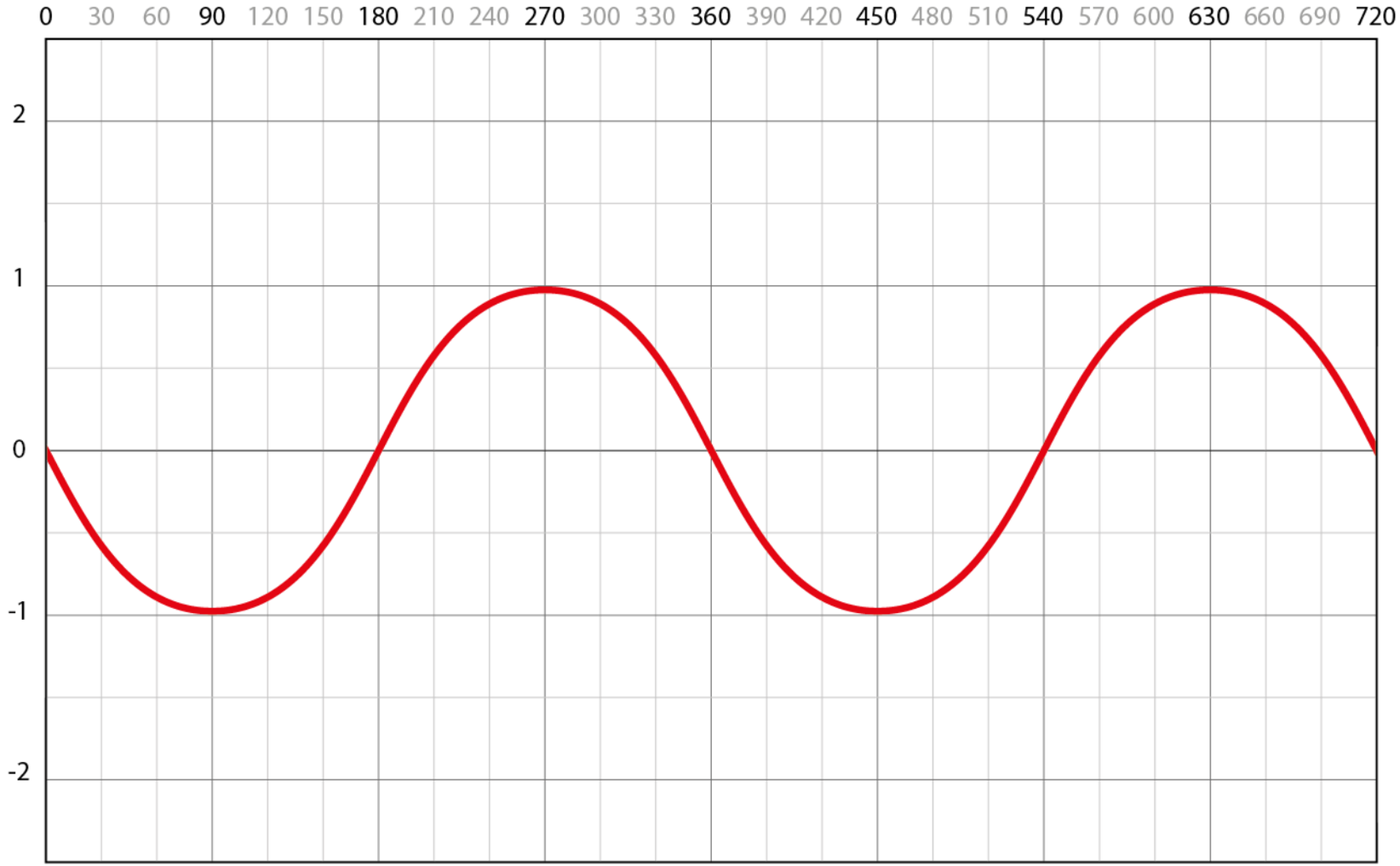
Phase (φ) et fréquence (f)



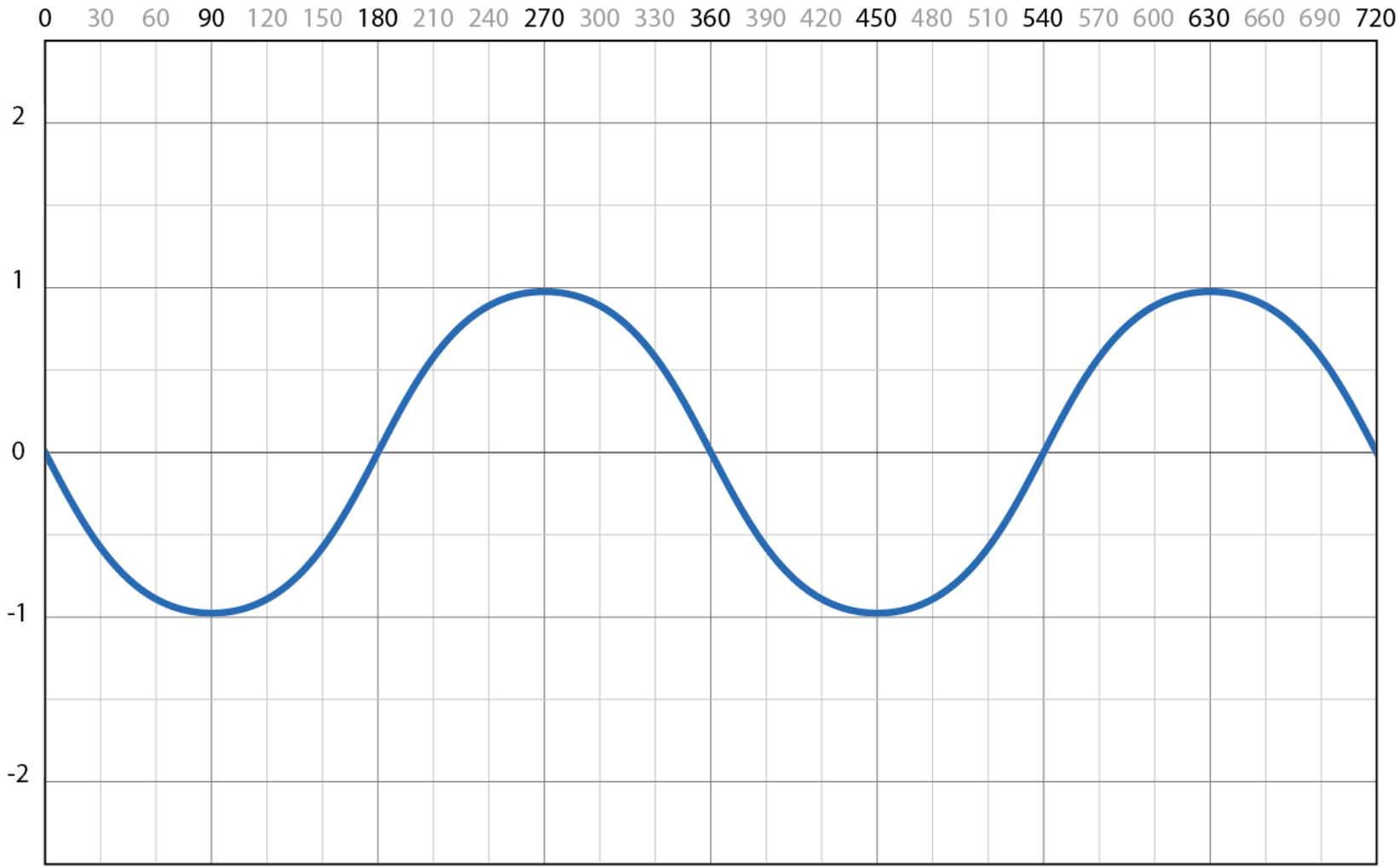
Phase (φ) et fréquence (f)



Déviation de phases (Δϕ) - Sommations et atténuations

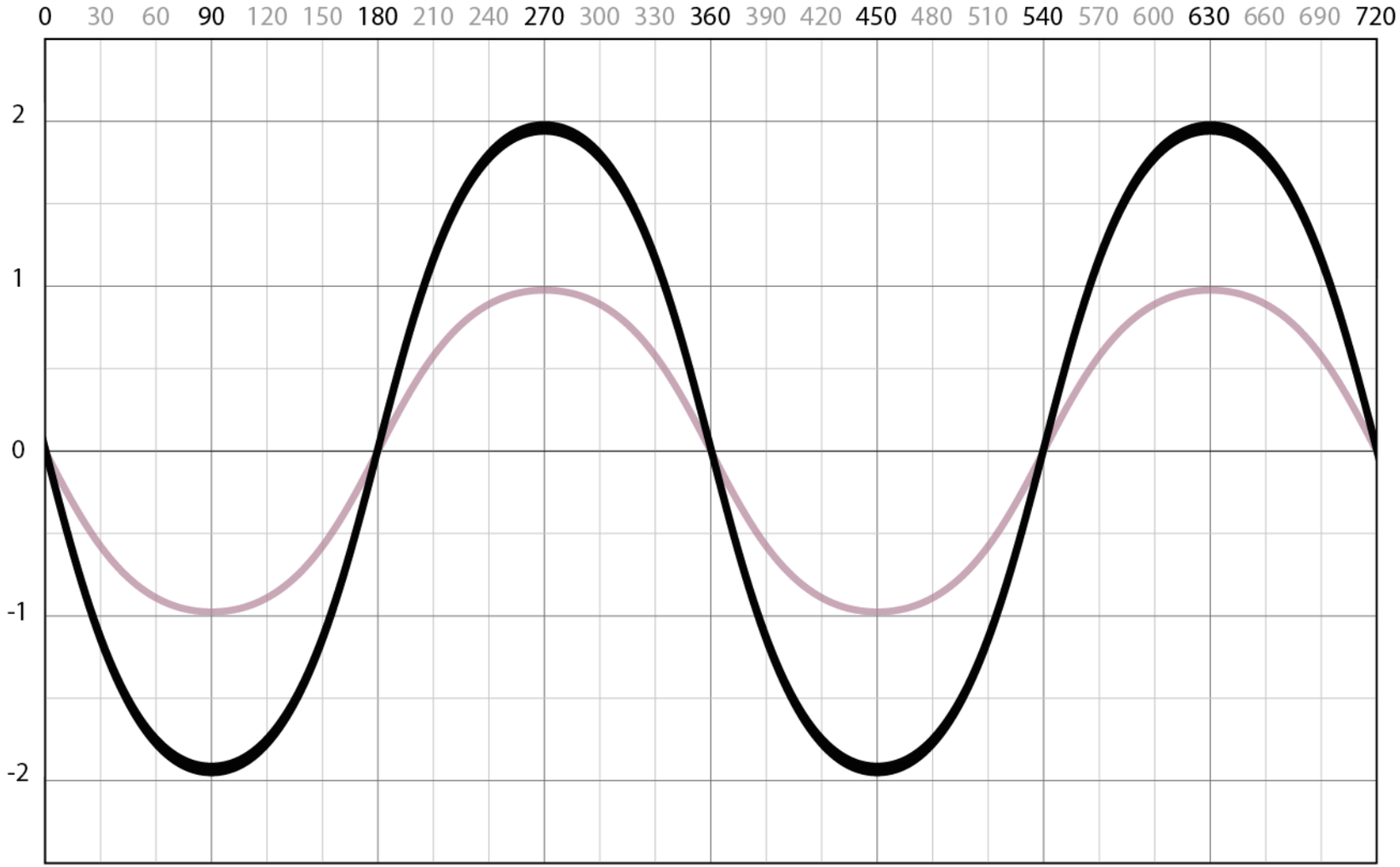


Déviation de phases (Δϕ) - Sommations et atténuations



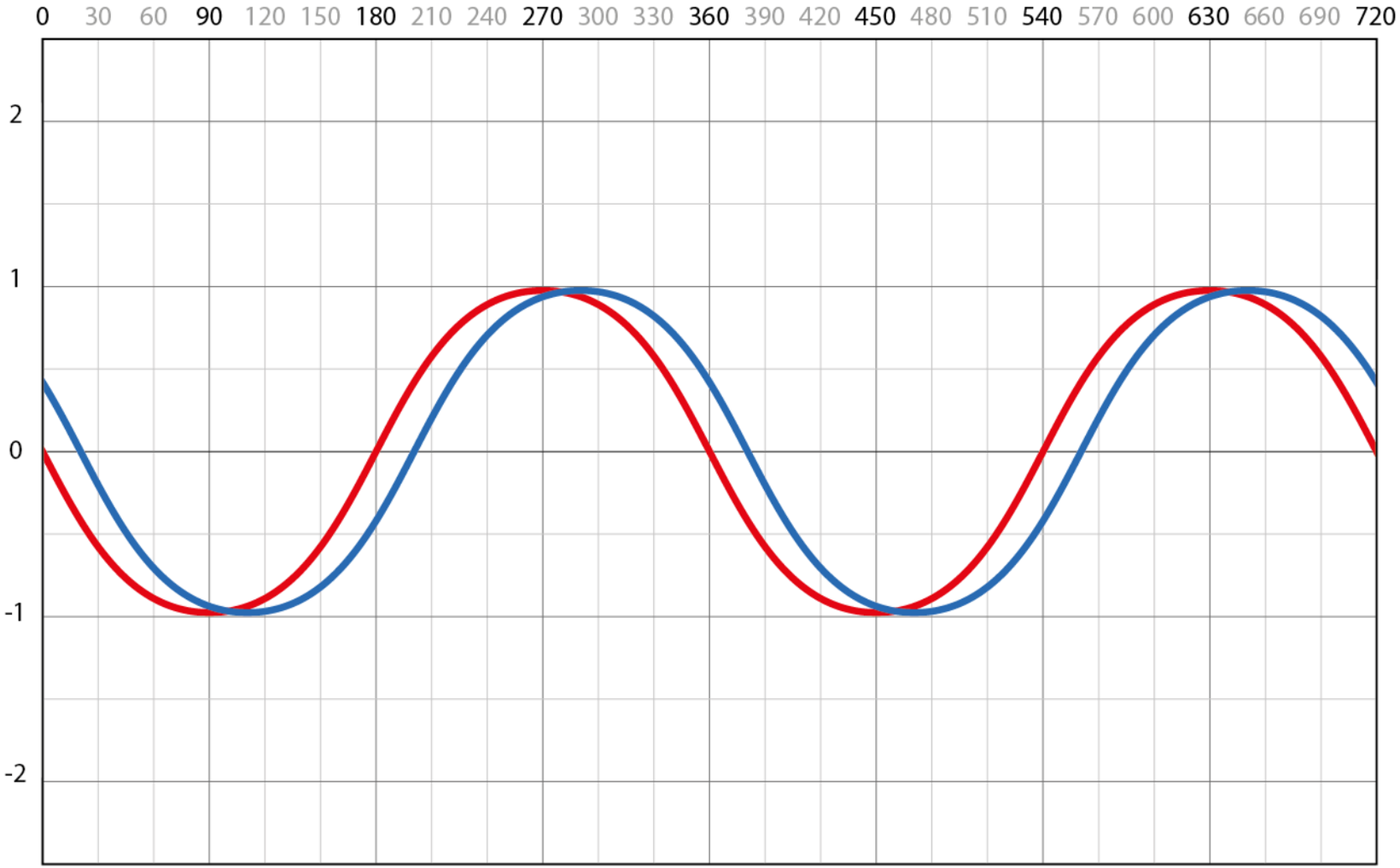
Déviation de phase = 0°

Déviation de phases (Δϕ) - Sommations et atténuations



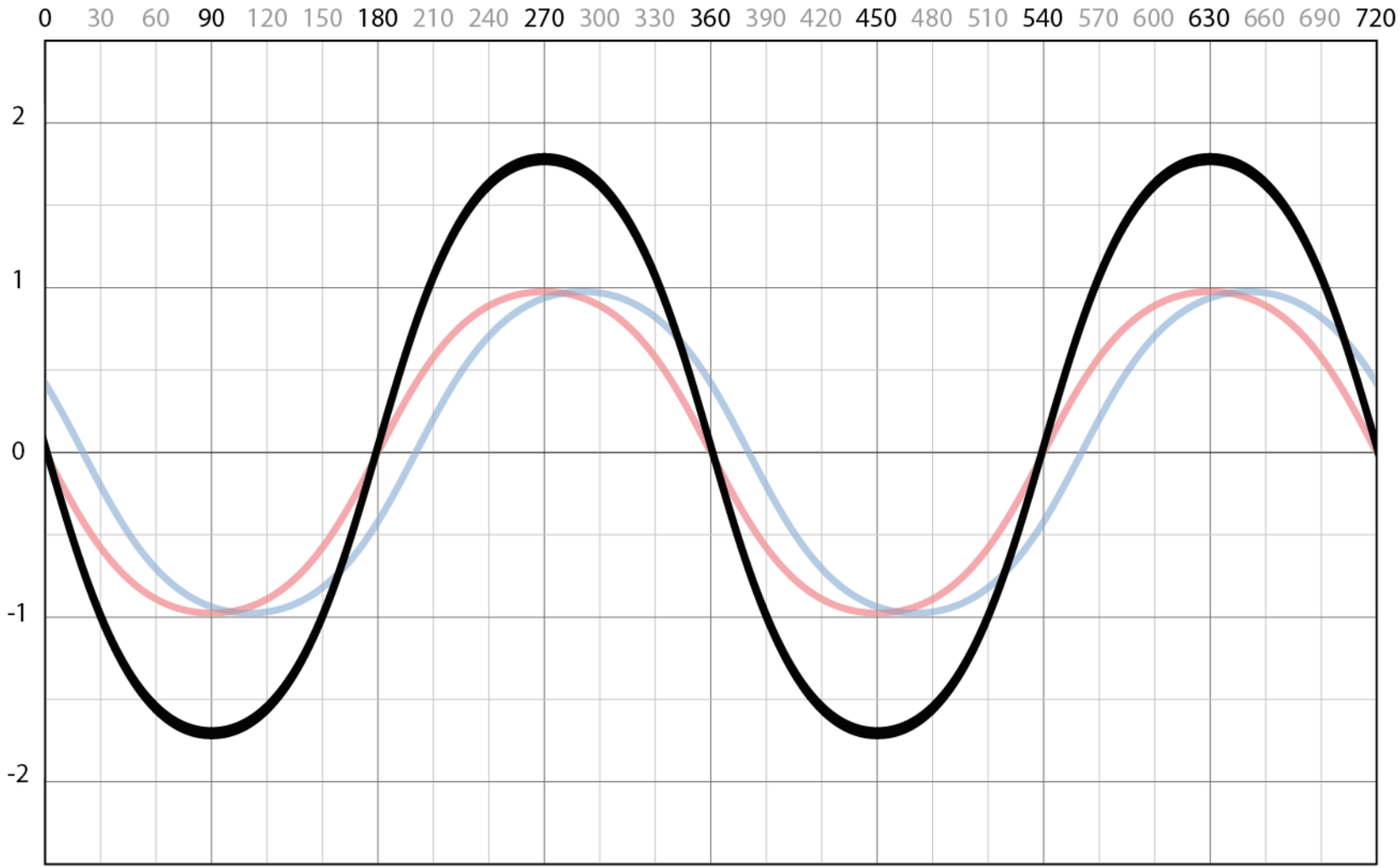
Déviation de phase = 0°
= + 6 dB

Déviation de phases (Δϕ) - Sommations et atténuations



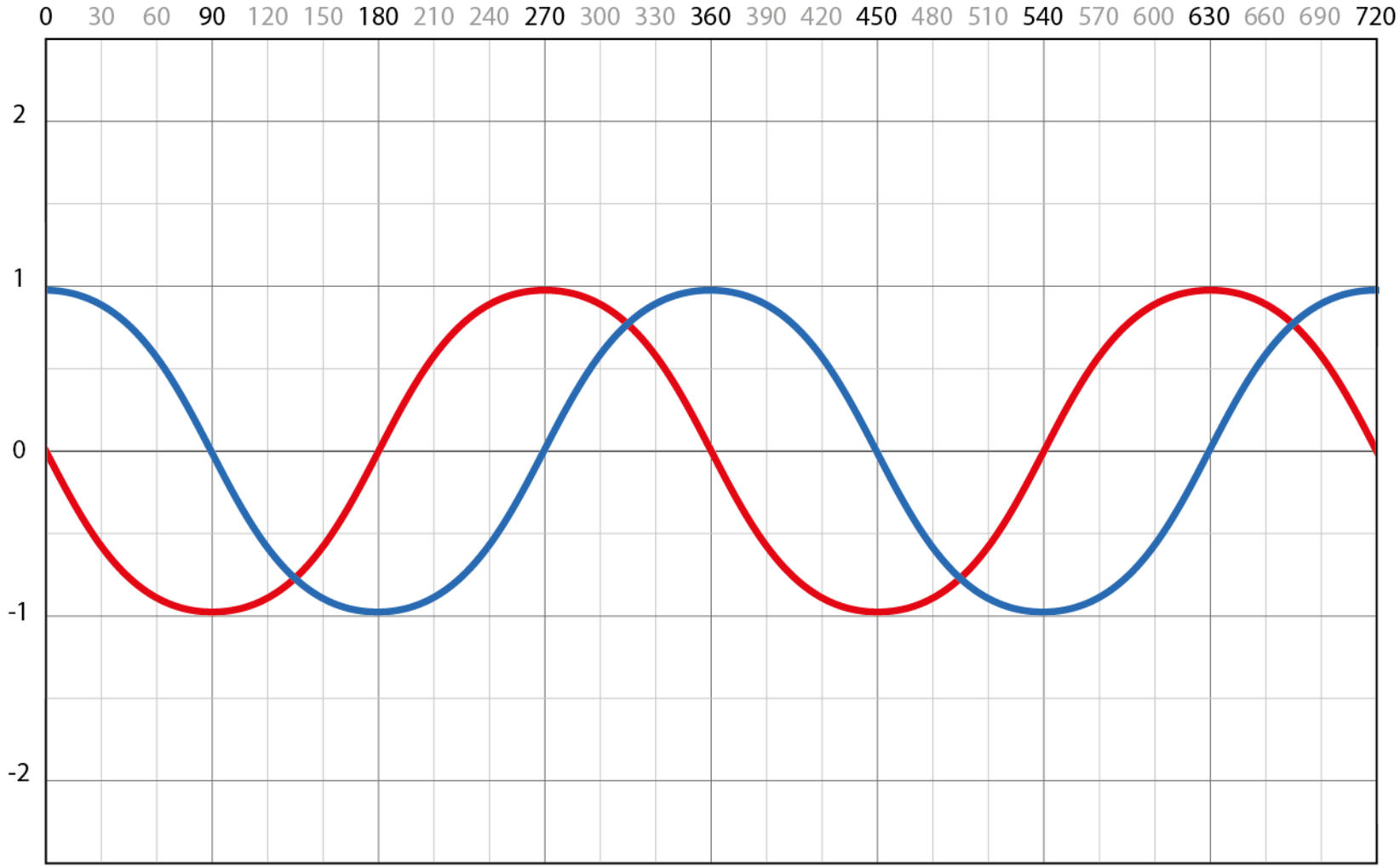
Déviation de phase = 20°

Déviation de phases (Δϕ) - Sommations et atténuations



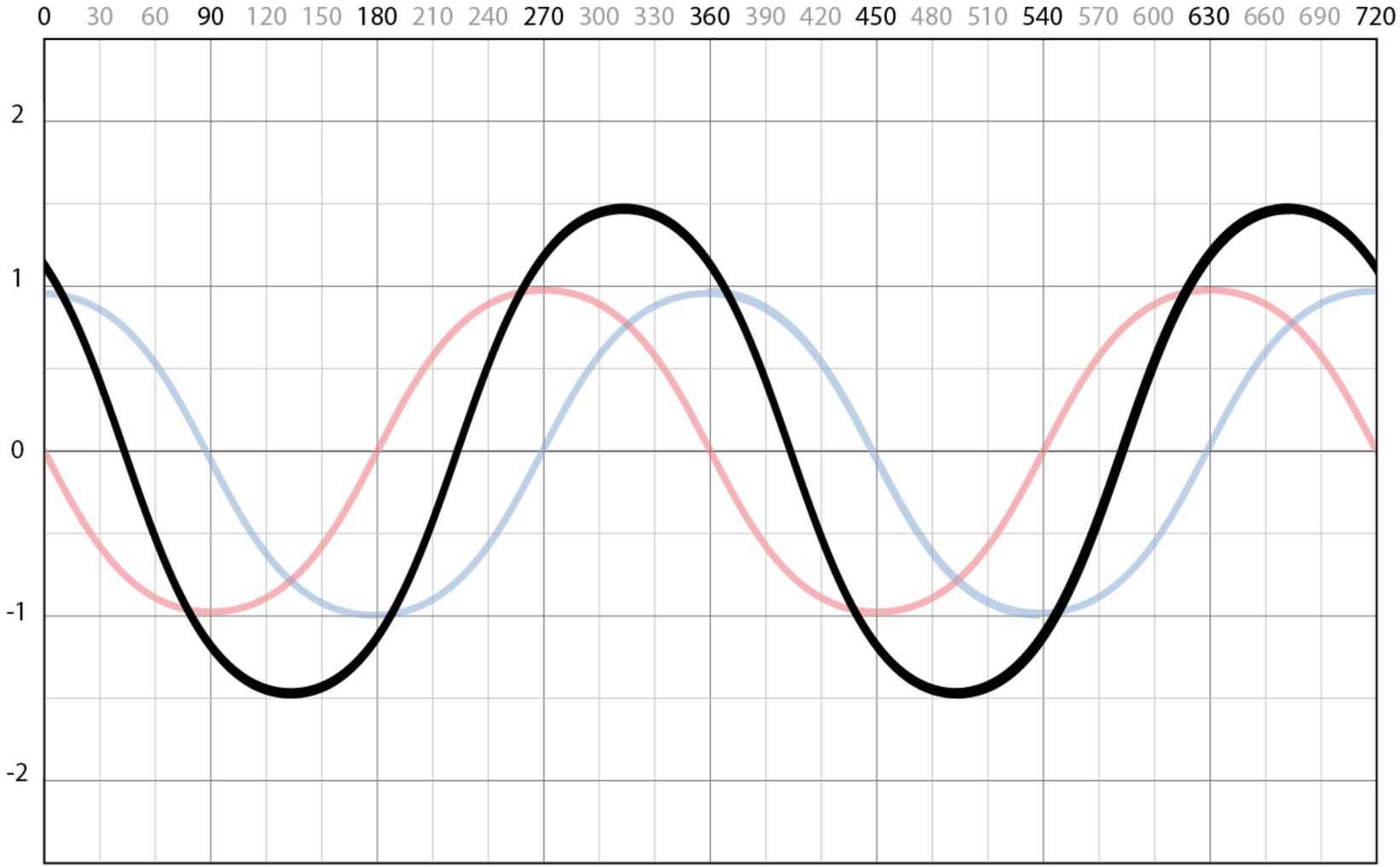
Déviation de phase = 20°
< 6 dB

Déviation de phases (Δϕ) - Sommations et atténuations



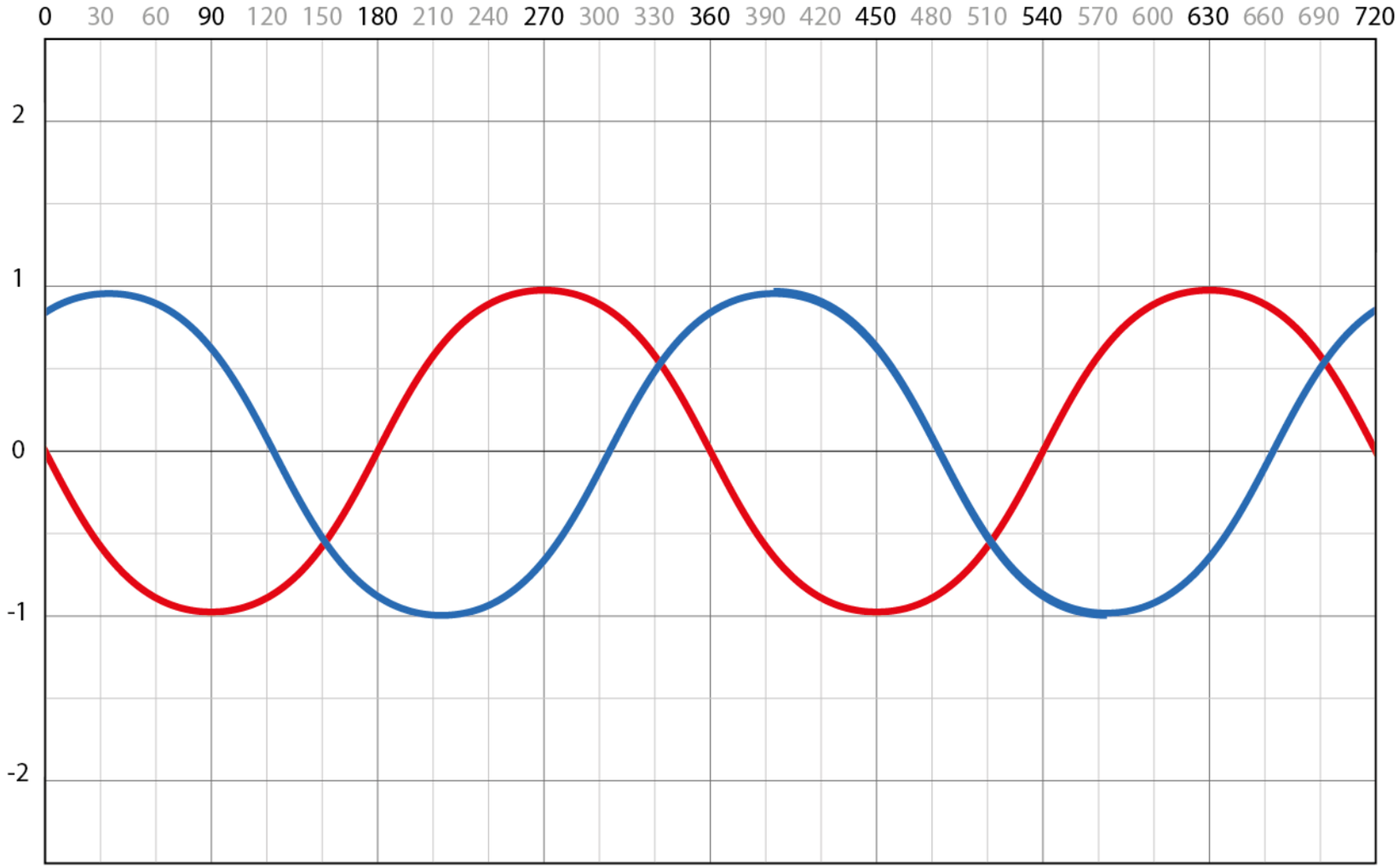
Déviation de phase = 90°

Déviation de phases (Δϕ) - Sommations et atténuations



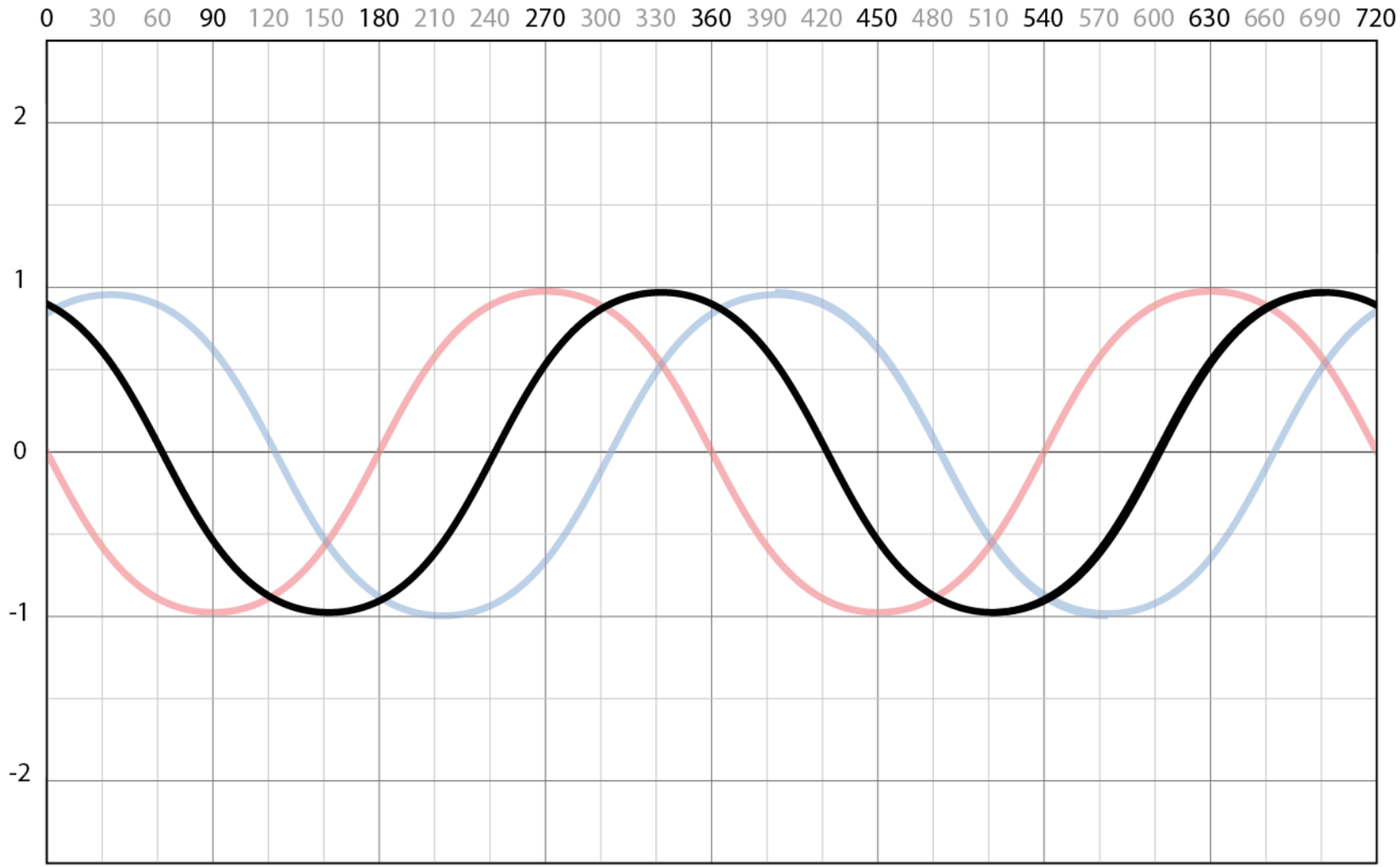
Déviation de phase = 90°
≈ 3 dB

Déviation de phases (Δϕ) - Sommations et atténuations



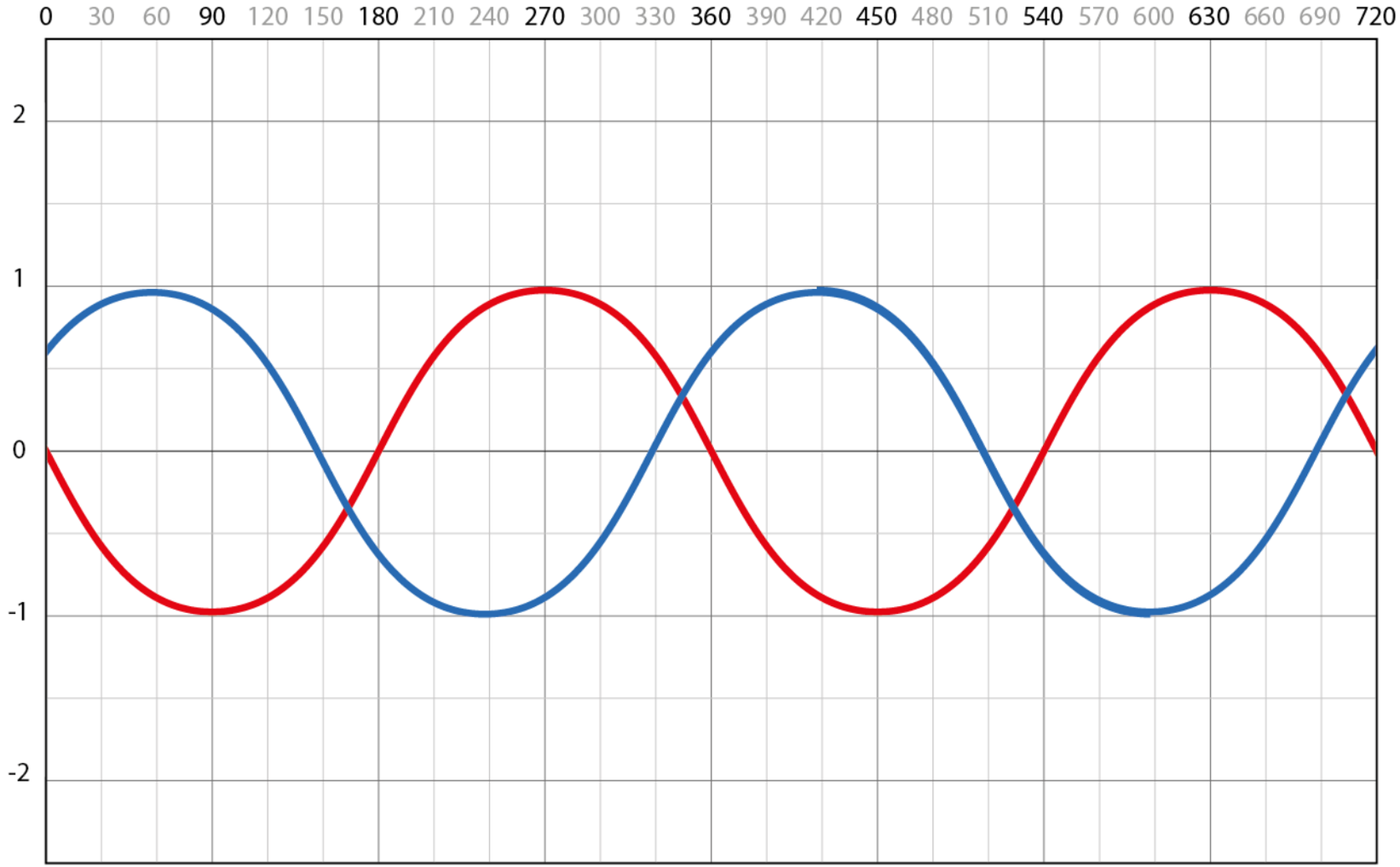
Déviation de phase = 120°

Déviation de phases (Δϕ) - Sommations et atténuations



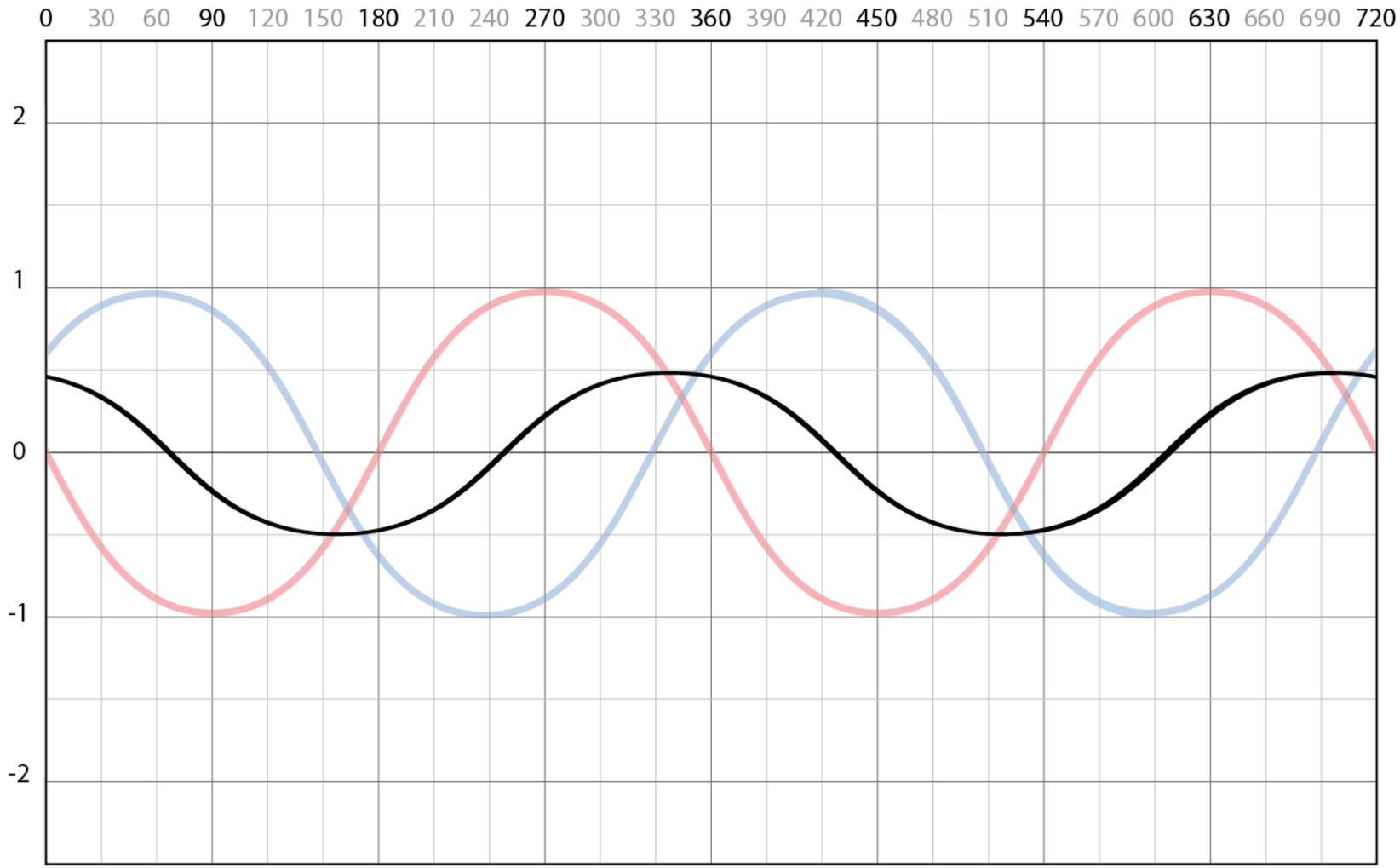
Déviation de phase = 120°
± 0 dB

Déviation de phases (Δϕ) - Sommations et atténuations



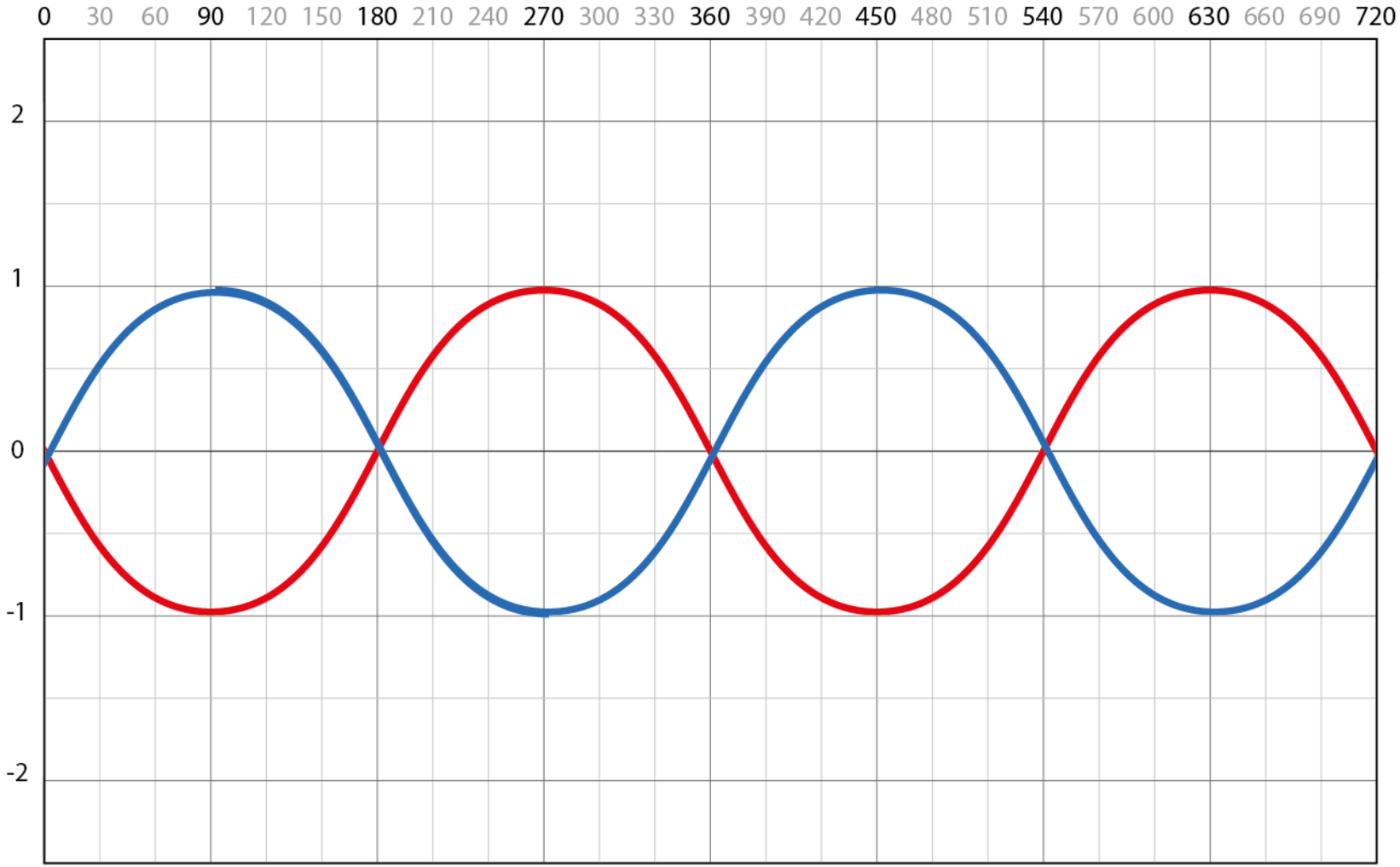
Déviation de phase = 150°

Déviation de phases (Δϕ) - Sommations et atténuations



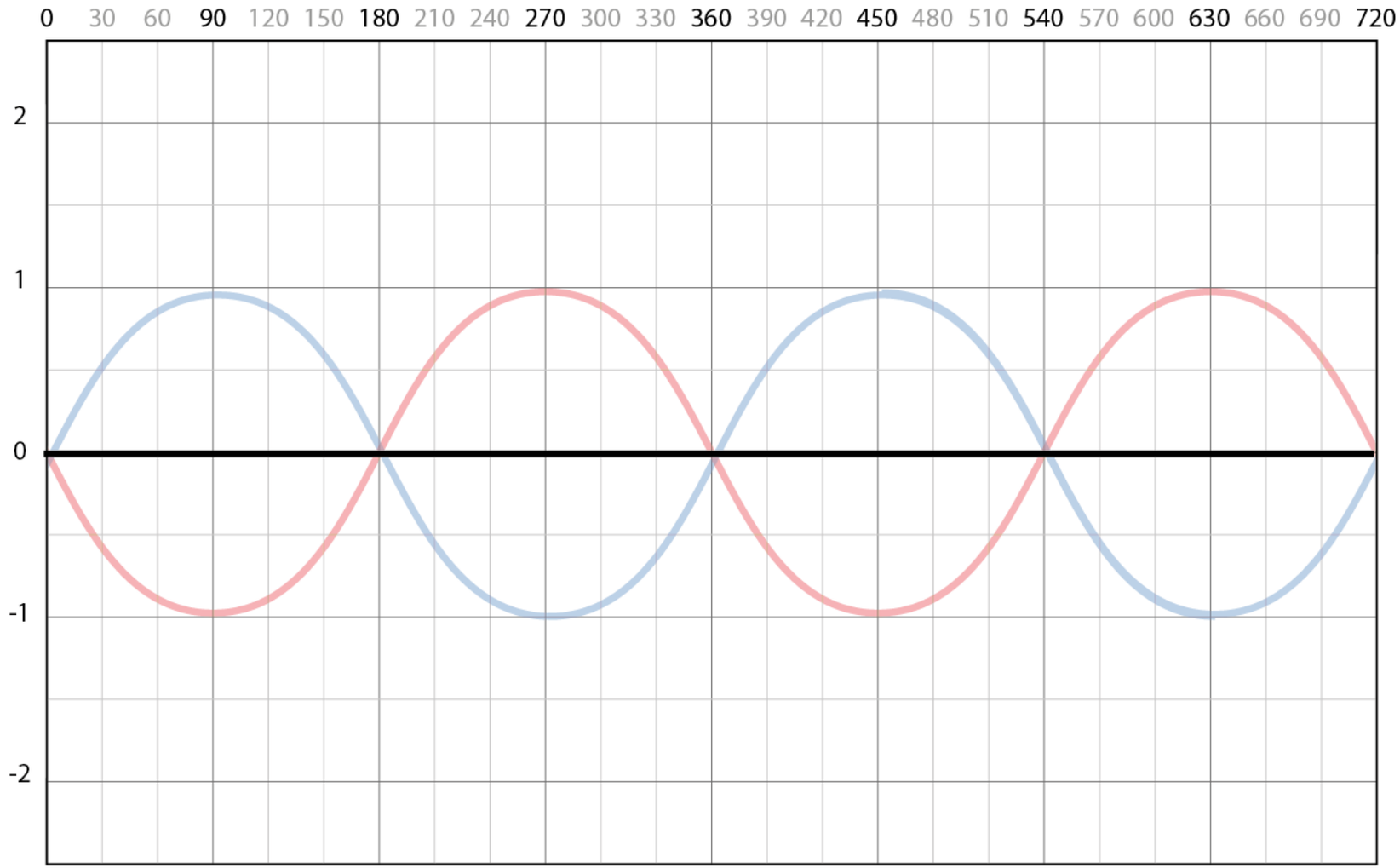
Déviation de phase = 150°
≤ -3 dB

Déviation de phases (Δϕ) - Sommations et atténuations



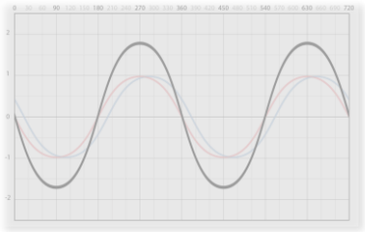
Déviation de phase = 180°

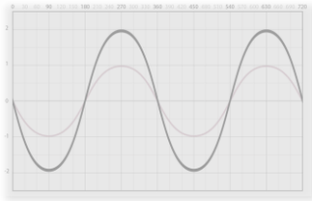
Déviation de phases (Δϕ) - Sommations et atténuations

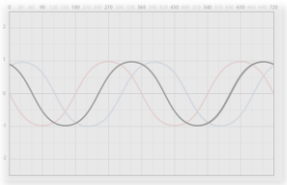


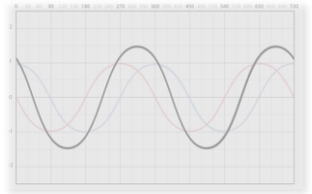
Déviation de phase = 180°
≈ Annulation

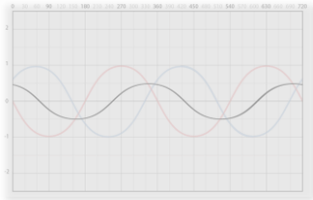
Déviation de phases (Δϕ) - Le cercle magique !

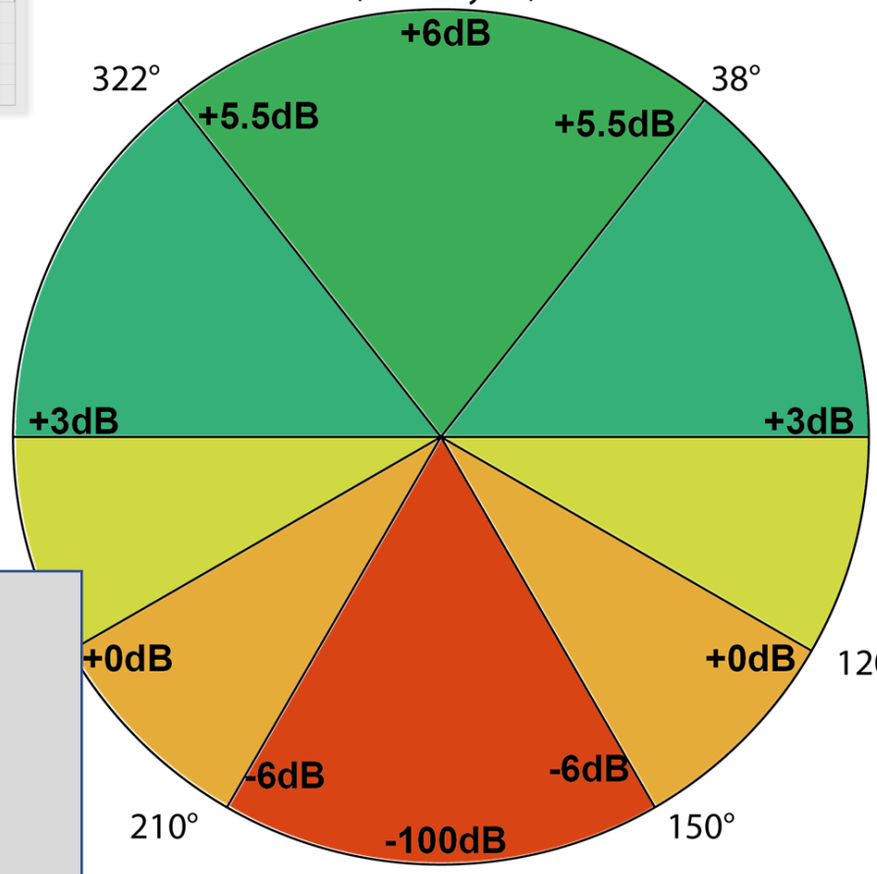










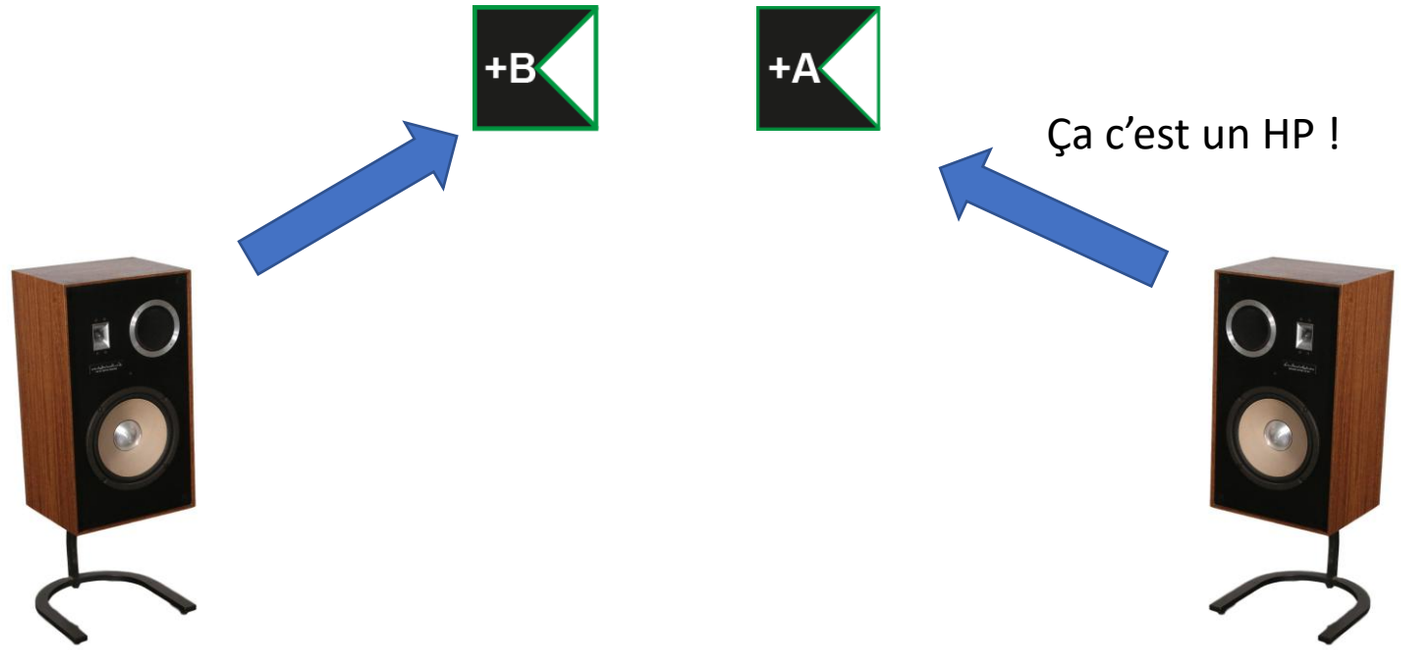


$$\Delta_{\varphi} = \frac{\Delta_d . f . 360}{c}$$

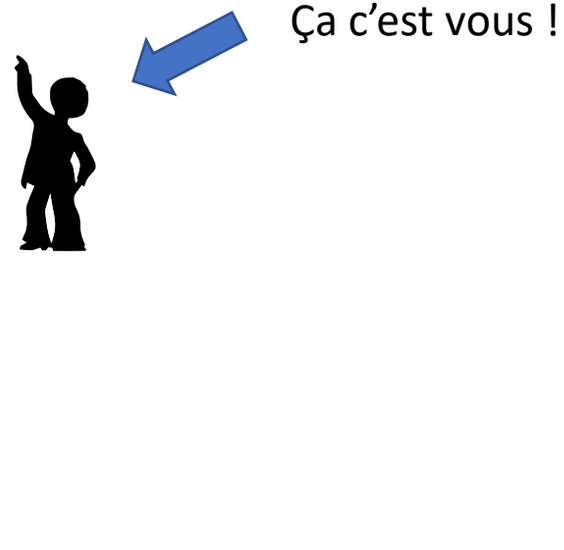
- *avec :*
- f *= fréquence*
- λ *= longueur d'onde*
- C *= Célérité*
- Δ_d *= Différence de distance*

Source : Van Veen M., 2008

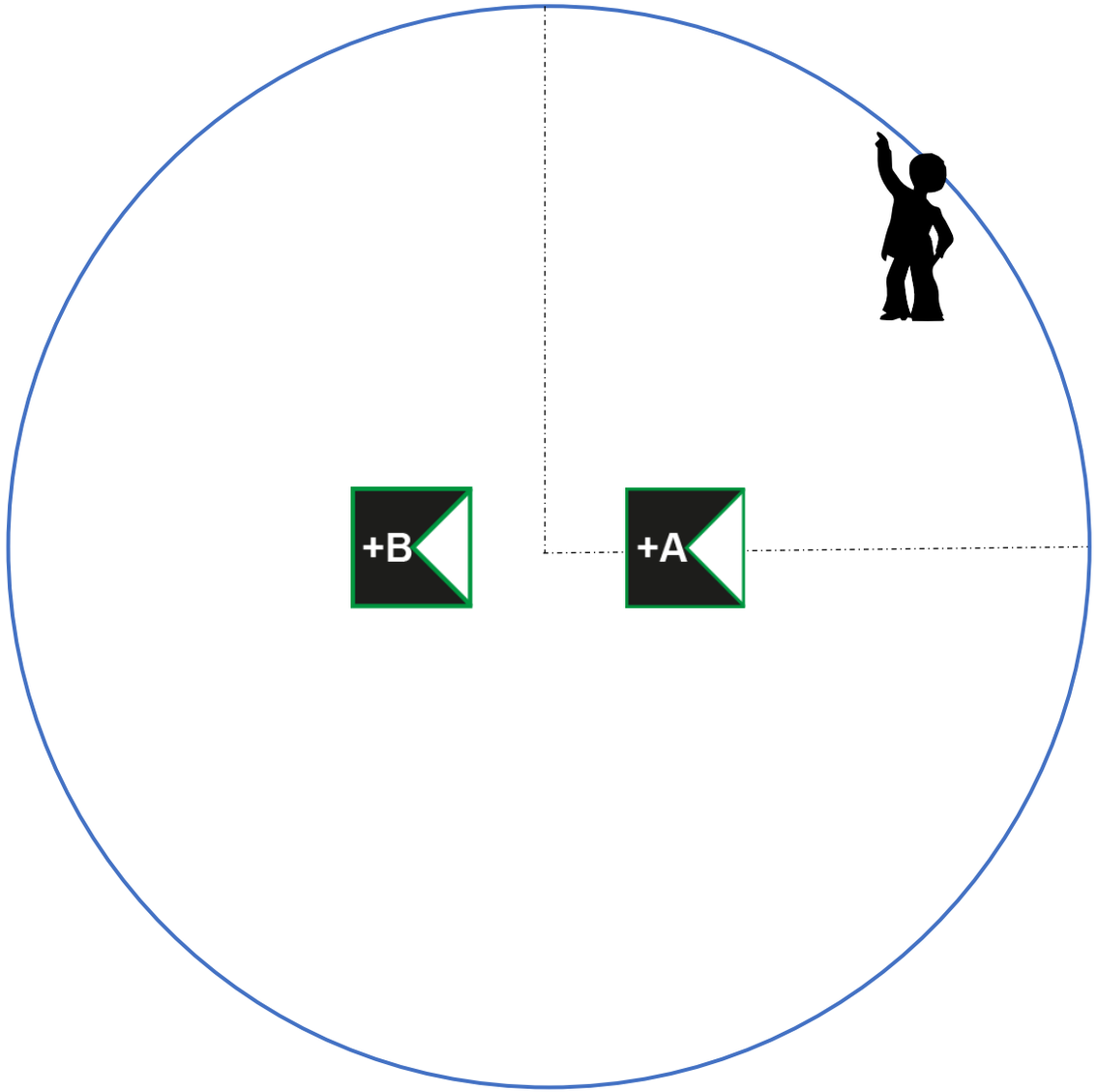
Différence spatiale (Δ_d)



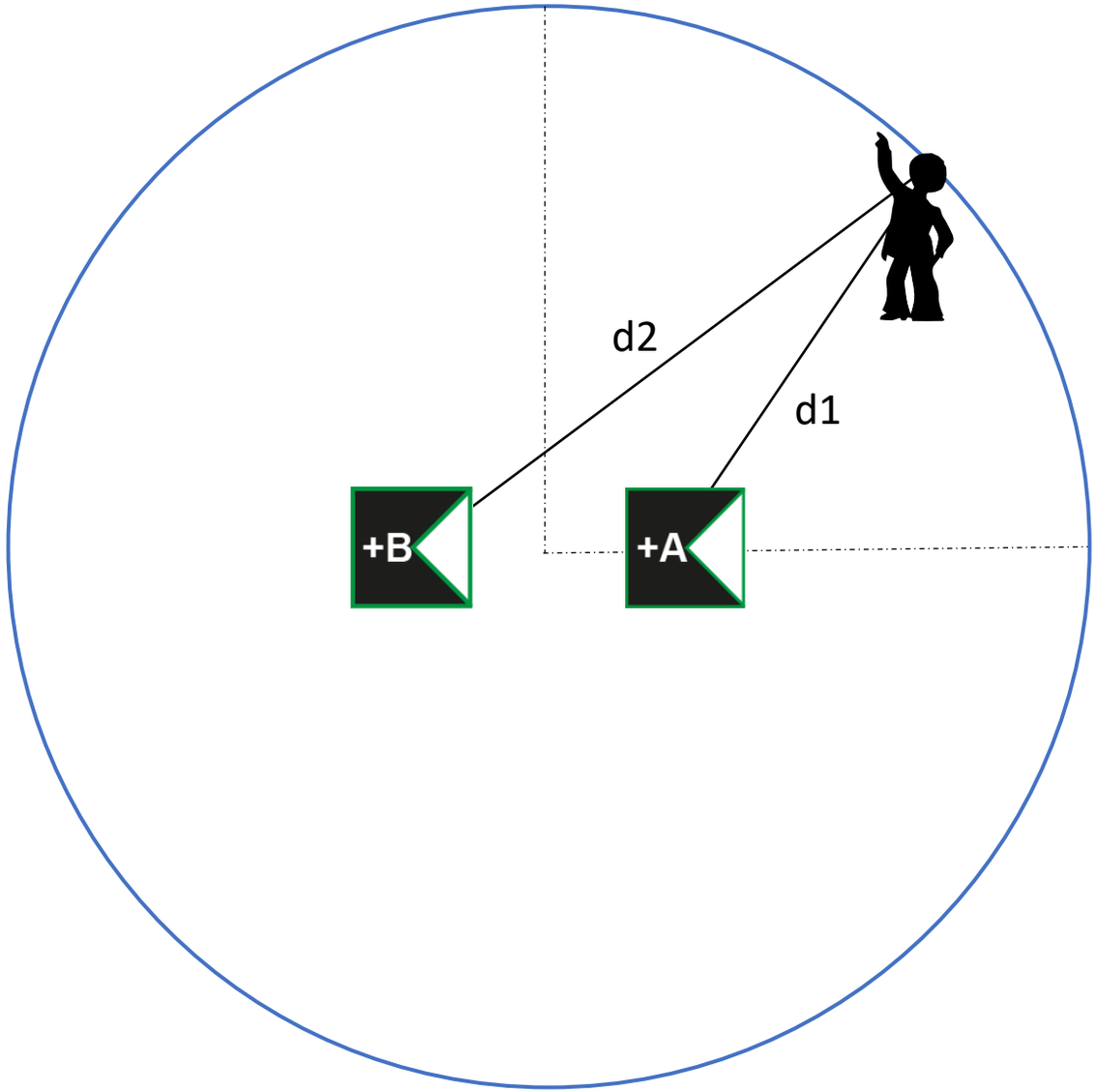
Différence spatiale (Δ_d)



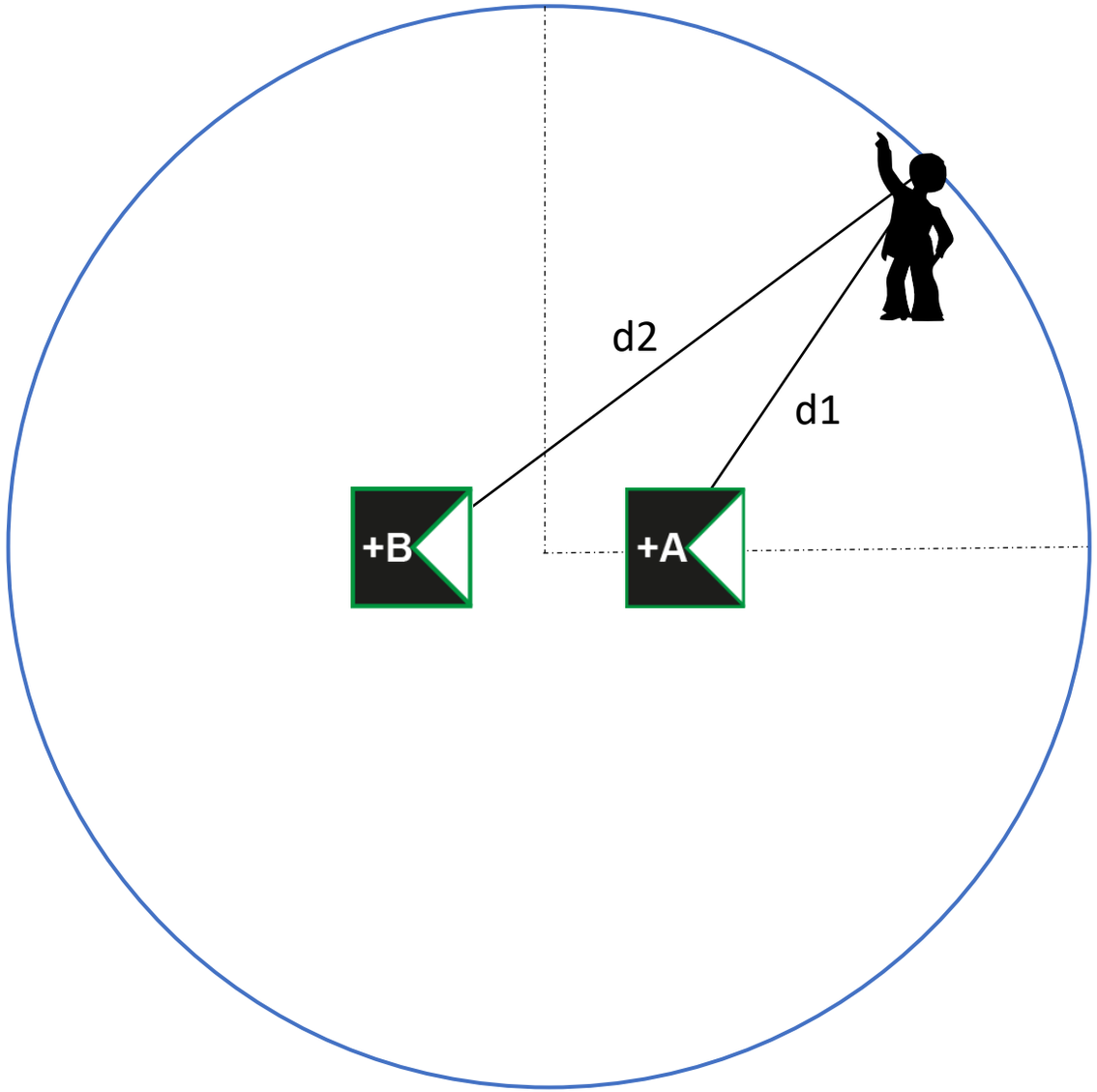
Différence spatiale (Δ_d)



Différence spatiale (Δ_d)

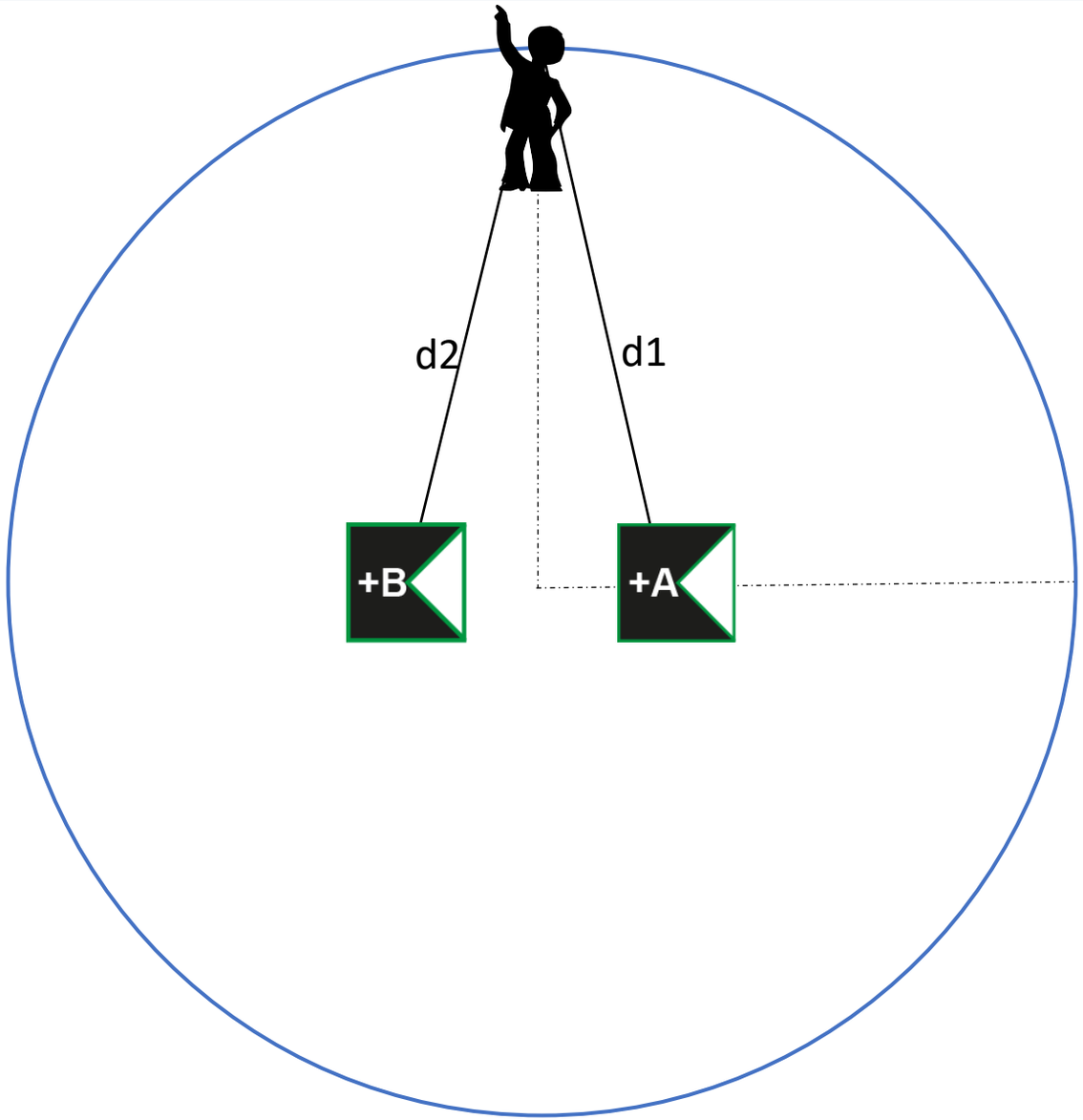


Différence spatiale (Δ_d)



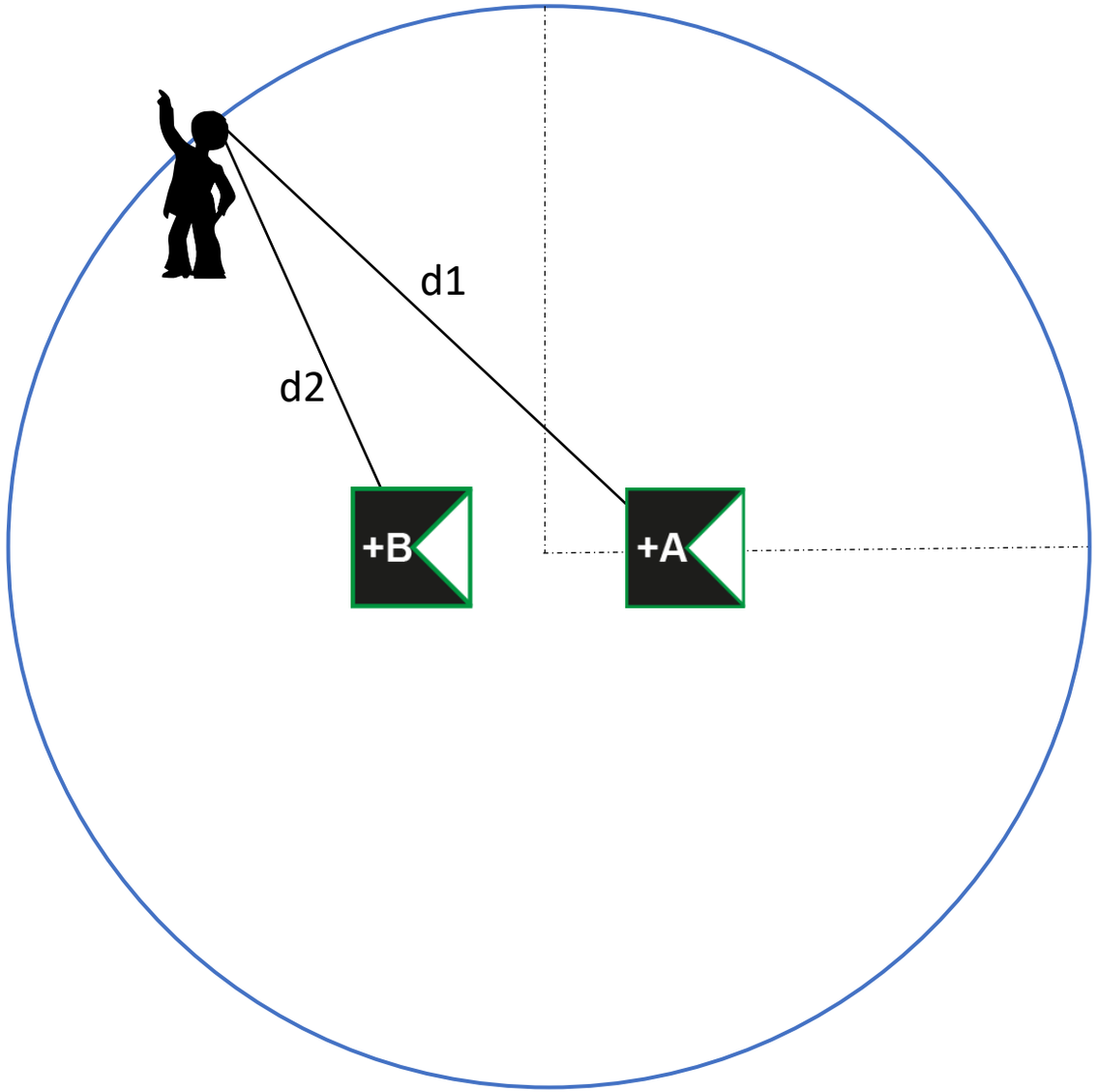
- Δ_d = d1-d2 < 0

Différence spatiale (Δ_d)



- Δ_d = d1-d2 = 0

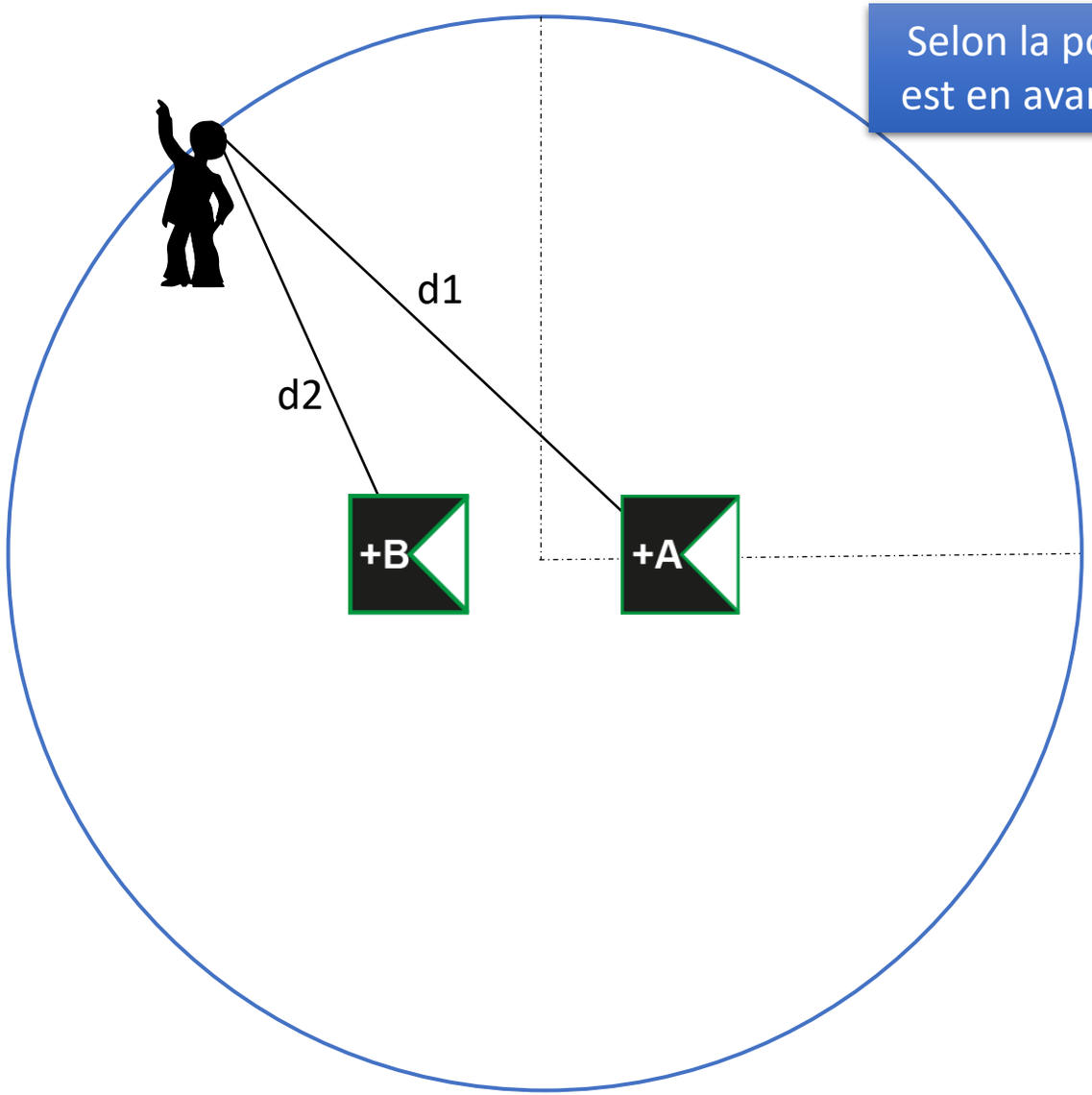
Différence spatiale (Δ_d)



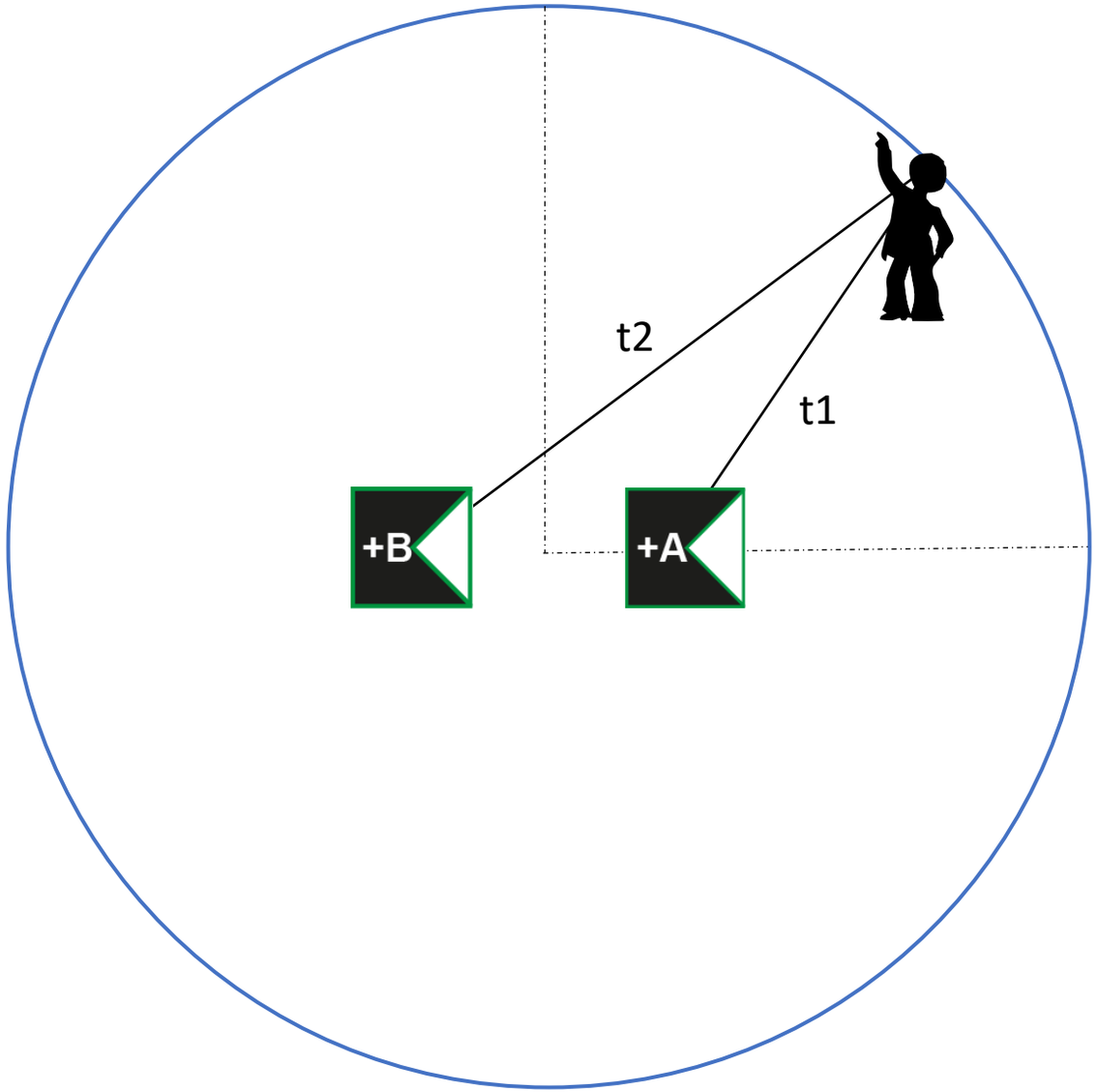
- Δ_d = d1-d2 > 0

Différence spatiale (Δ_d)

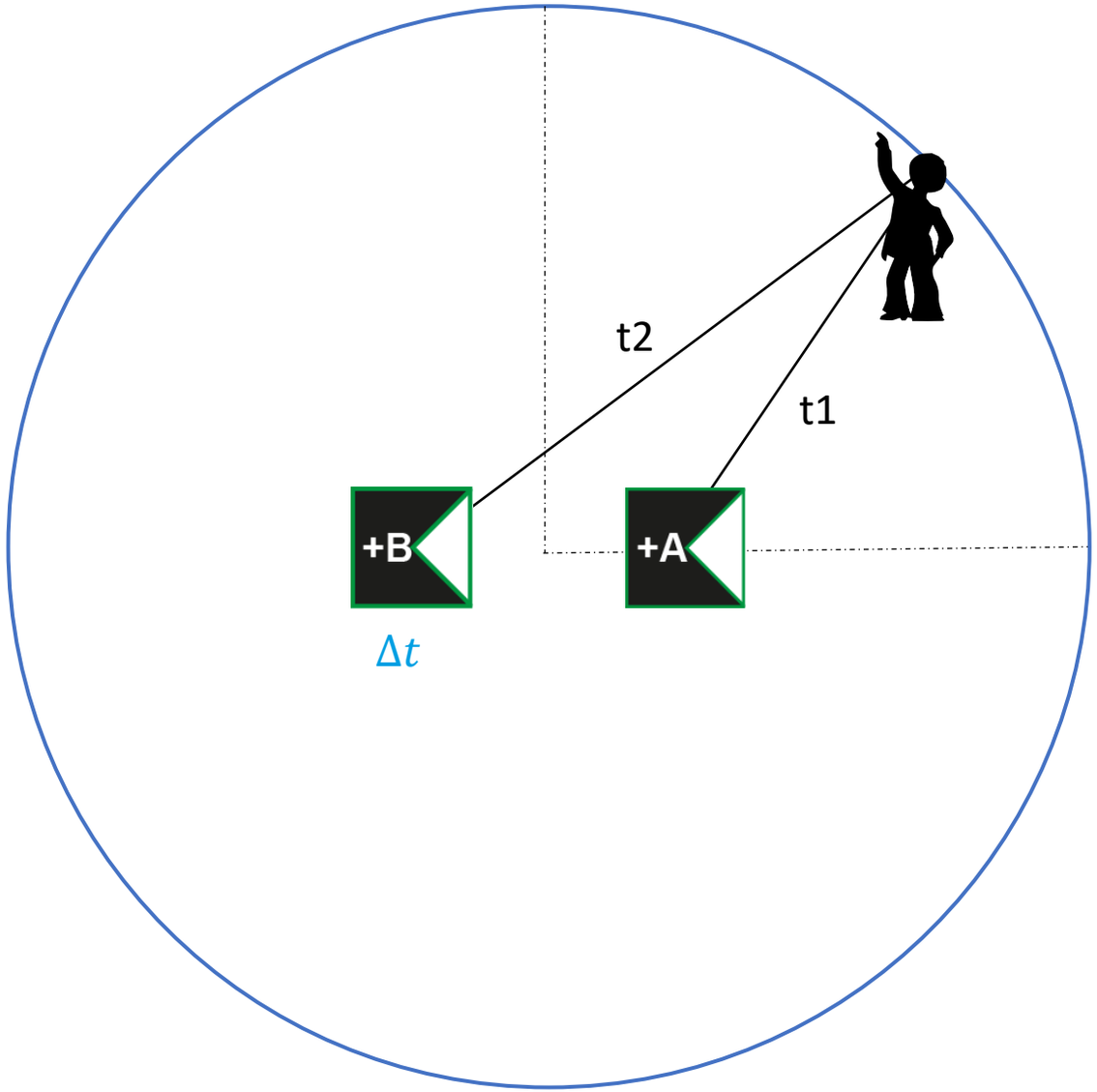
Selon la position de l'auditeur, la source A est en avance ou en retard sur la source B.



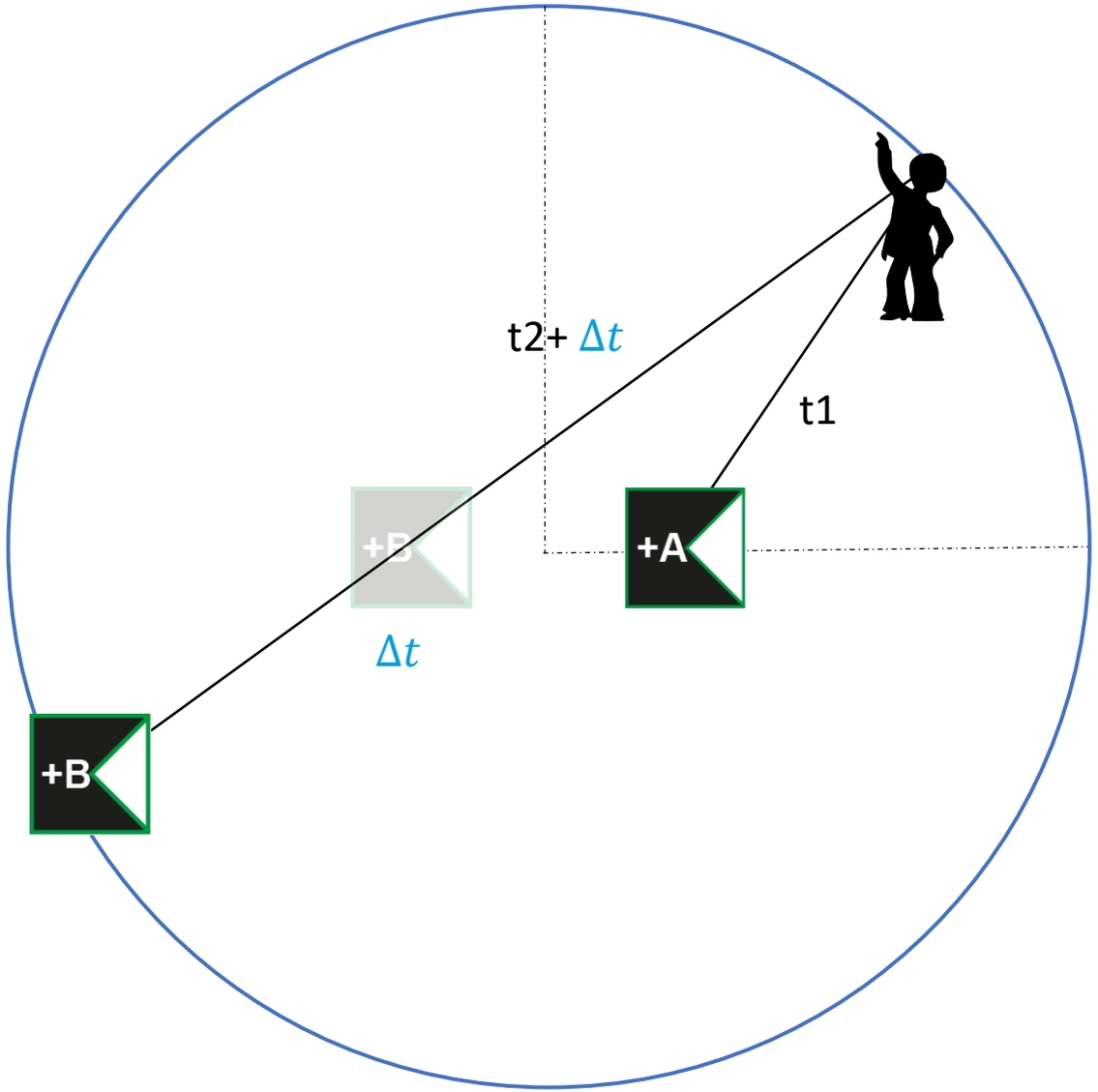
Différence temporelle (Δ_t)



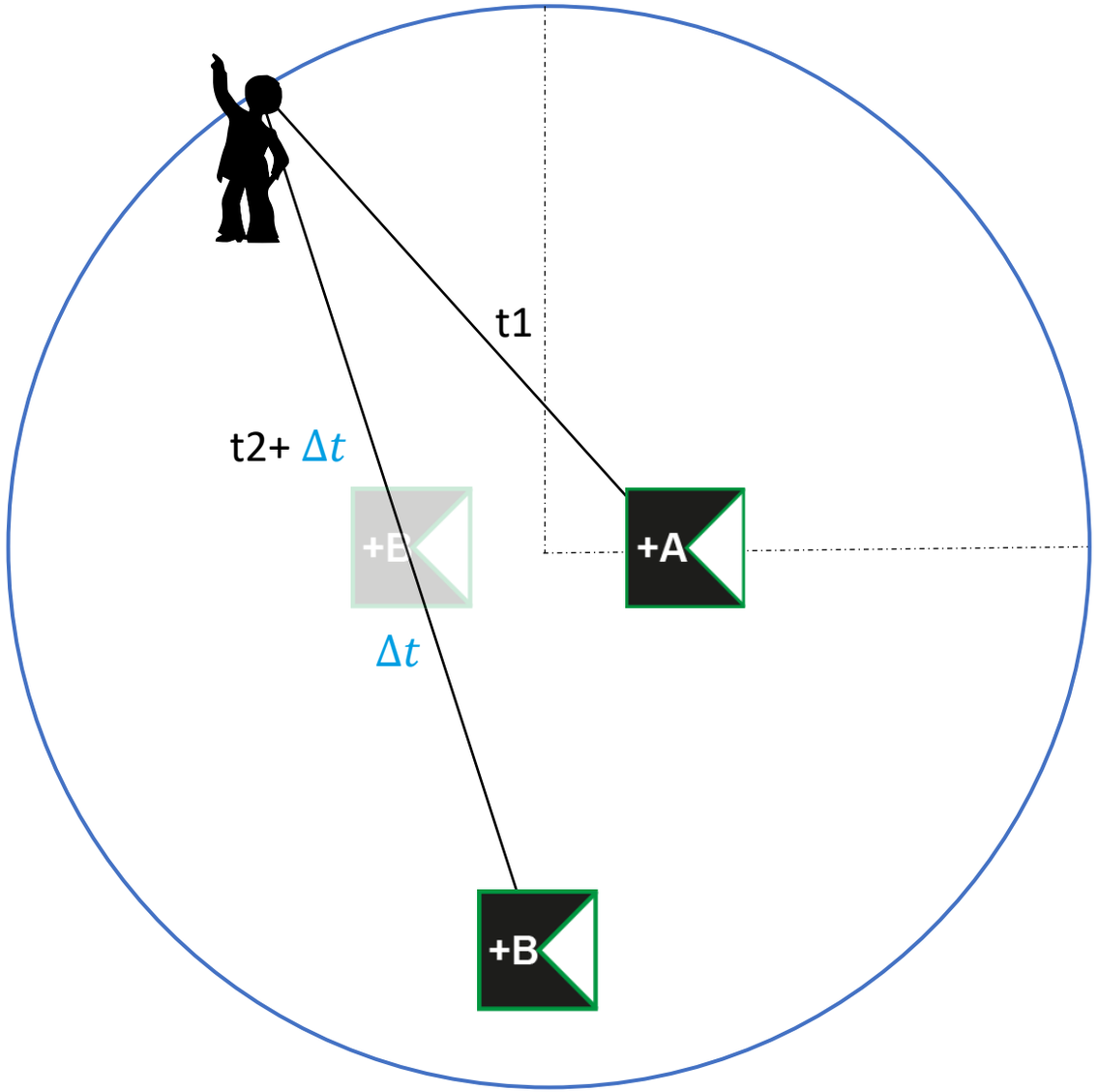
Différence temporelle (Δ_t)



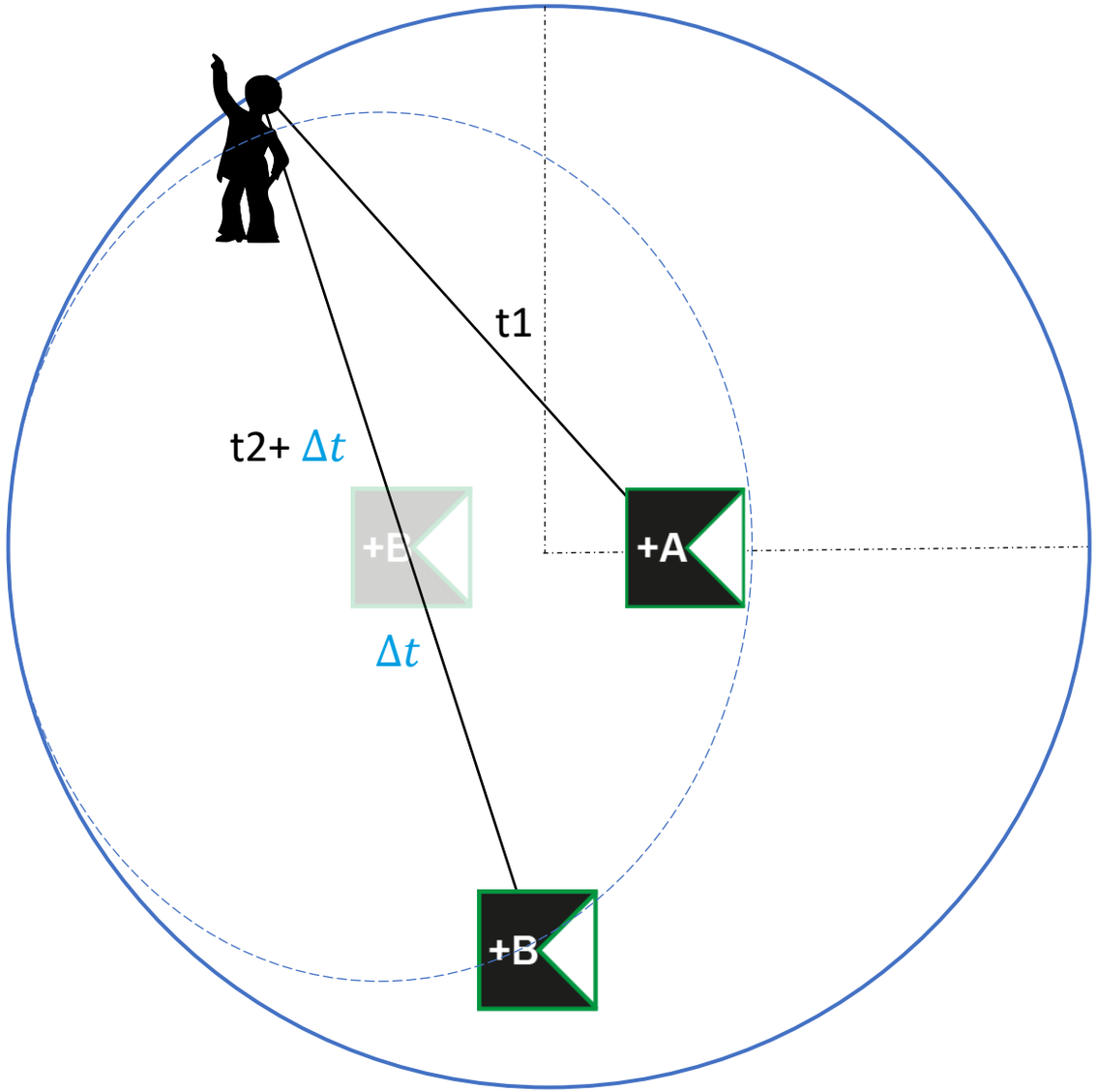
Différence temporelle (Δ_t)



Différence temporelle (Δ_t)



Différence temporelle (Δ_t)

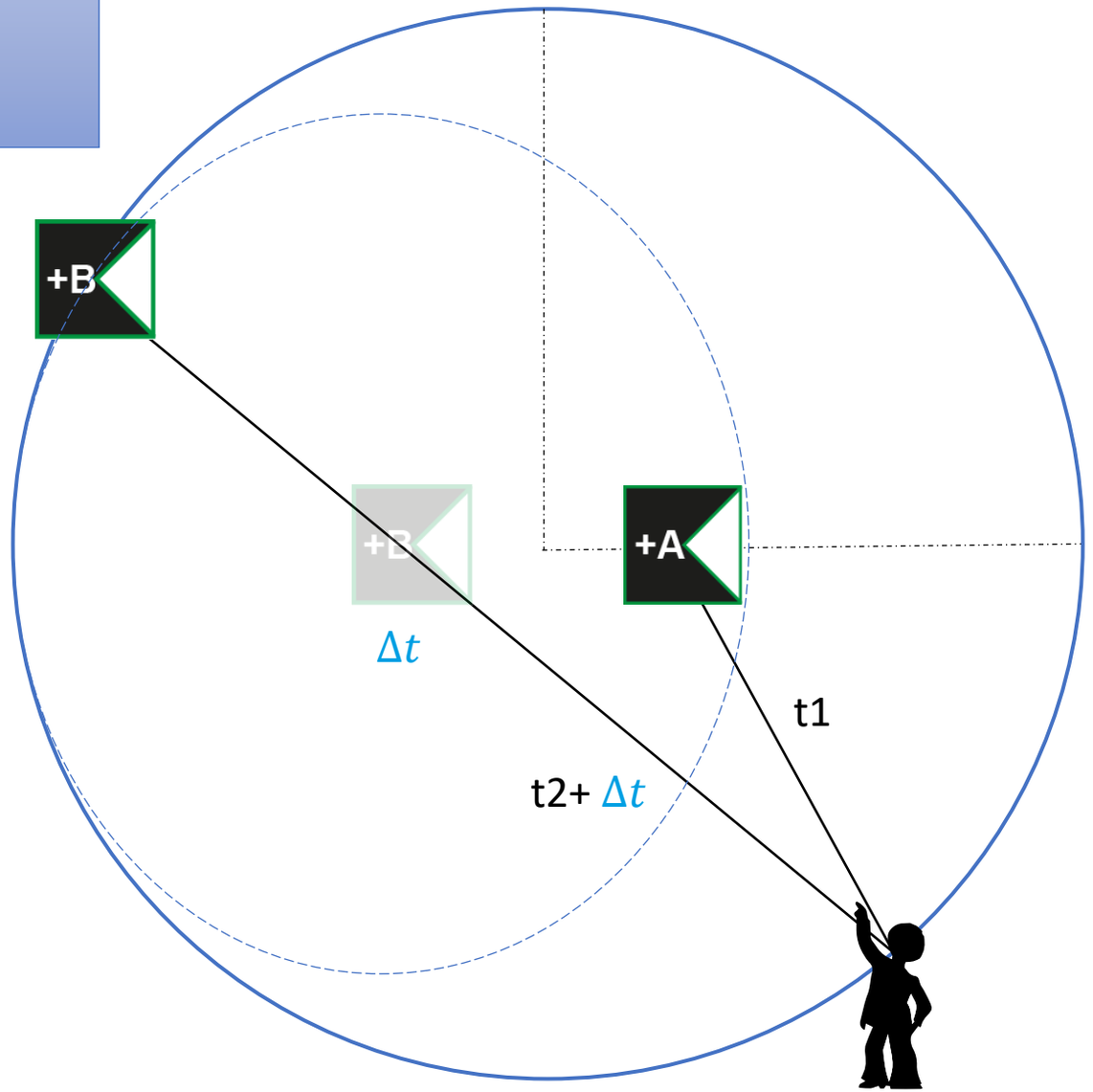


Différence temporelle (Δ_t)

Calcul différence de phase (Δ_φ)

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

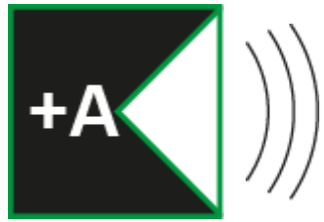
- *avec :*
- *f = fréquence*
- *λ = longueur d'onde*
- *C = Célérité*
- *Δ_d = Différence de distance*



Le mythe de la dépression



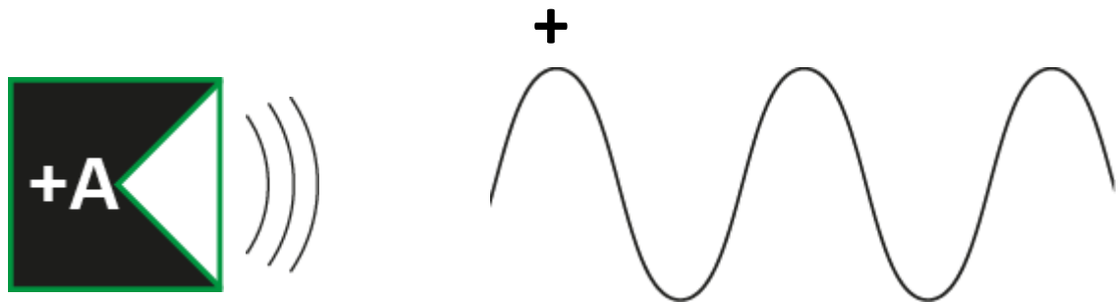
Le mythe de la dépression



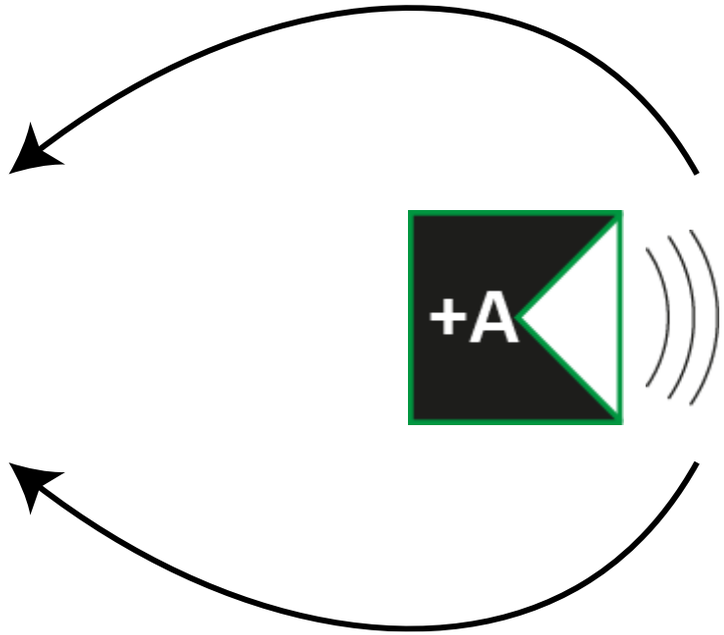
Ou un ensemble de Subs !

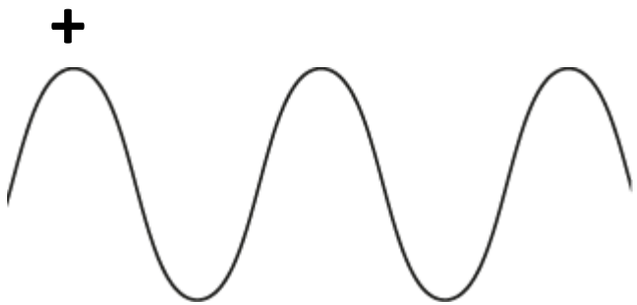


Le mythe de la dépression

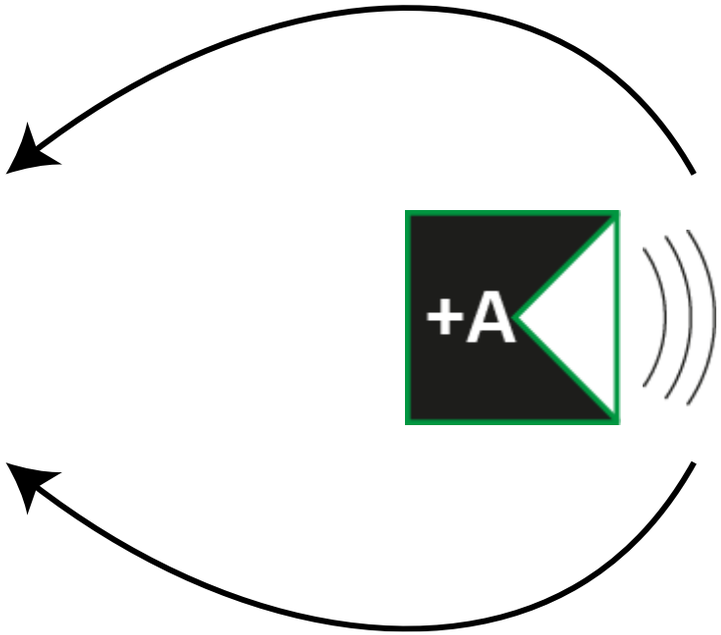


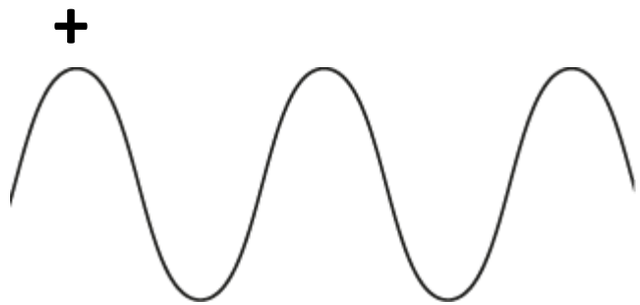
Le mythe de la dépression

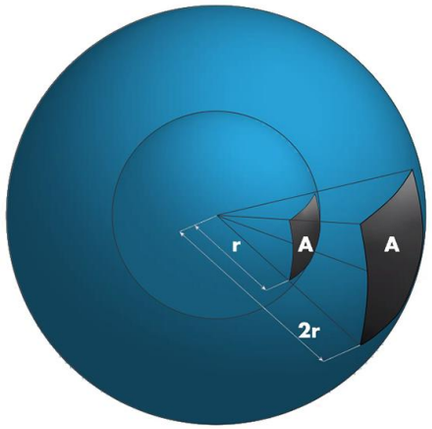




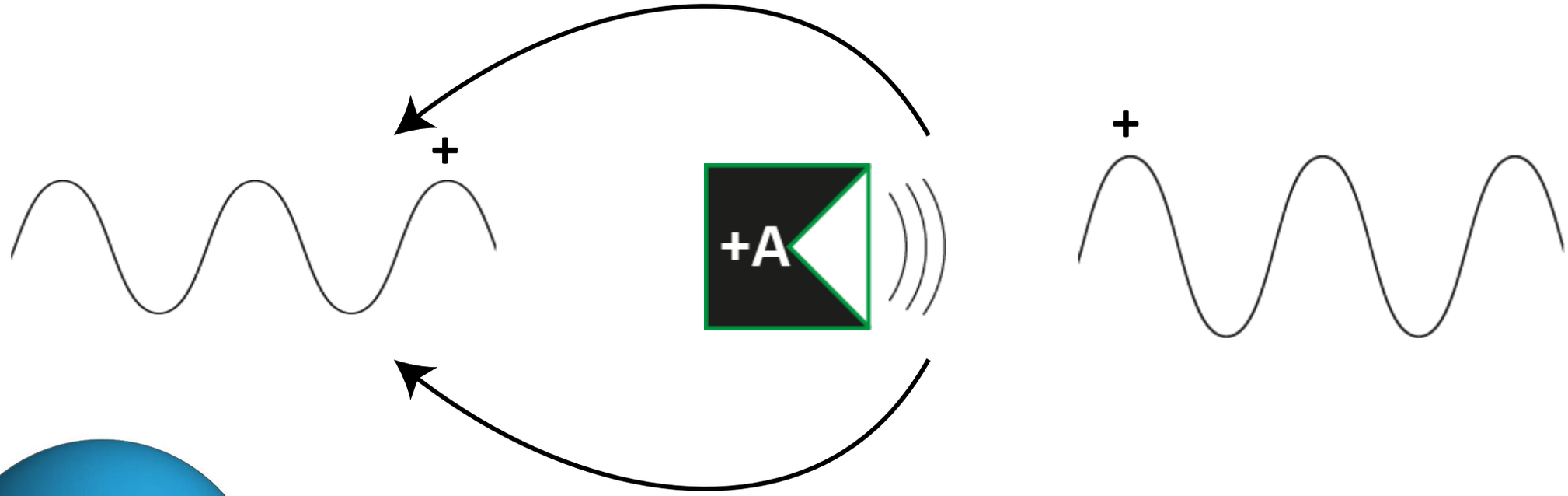
Le mythe de la dépression

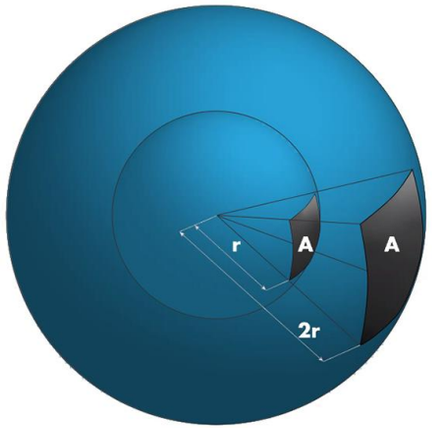




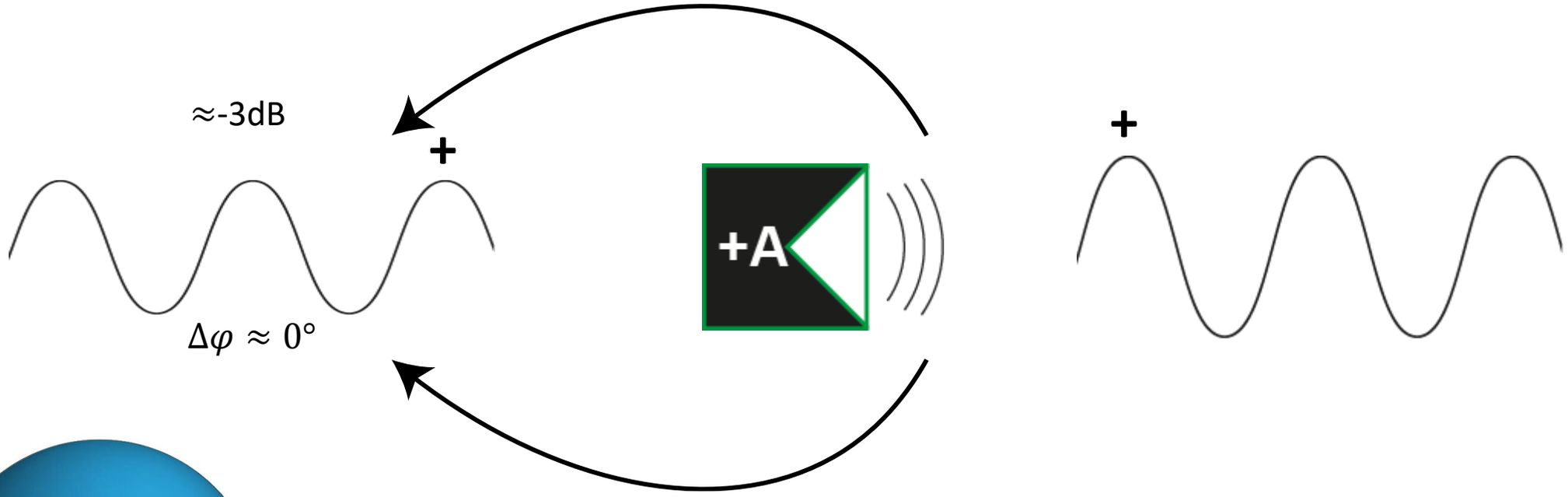


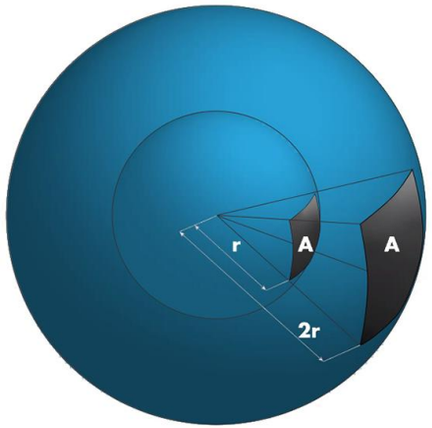
Le mythe de la dépression



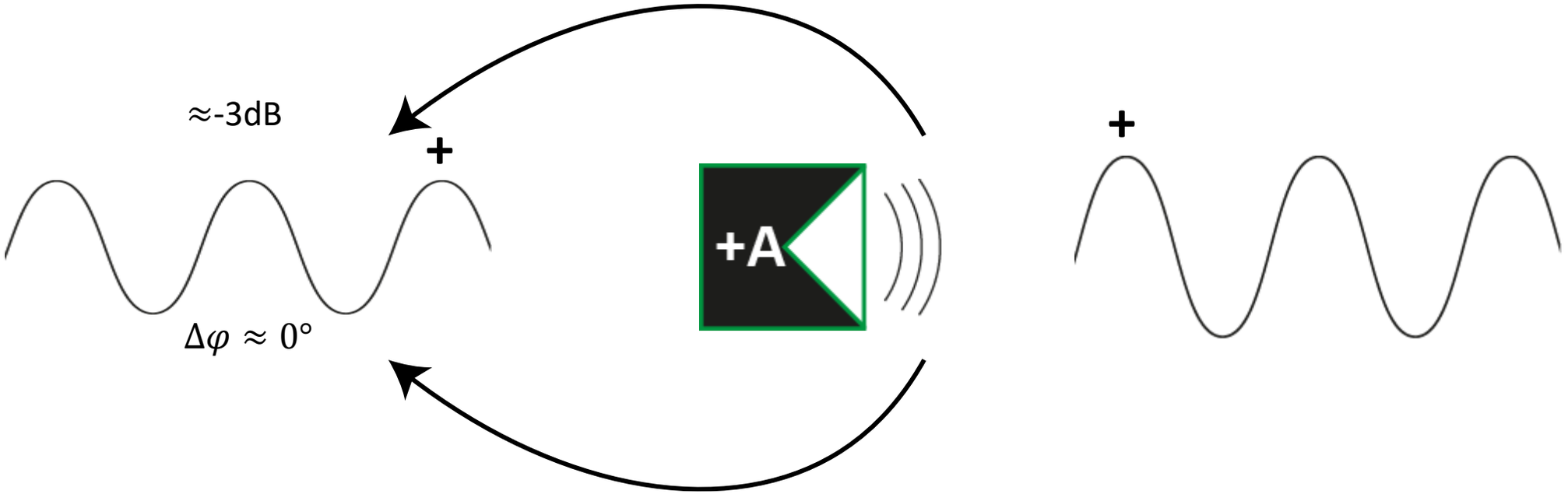


Le mythe de la dépression



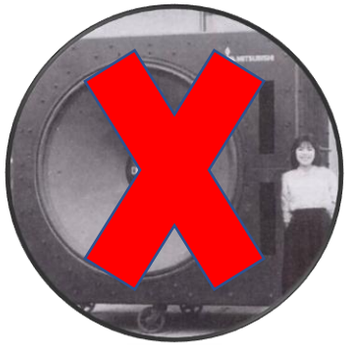


Le mythe de la dépression

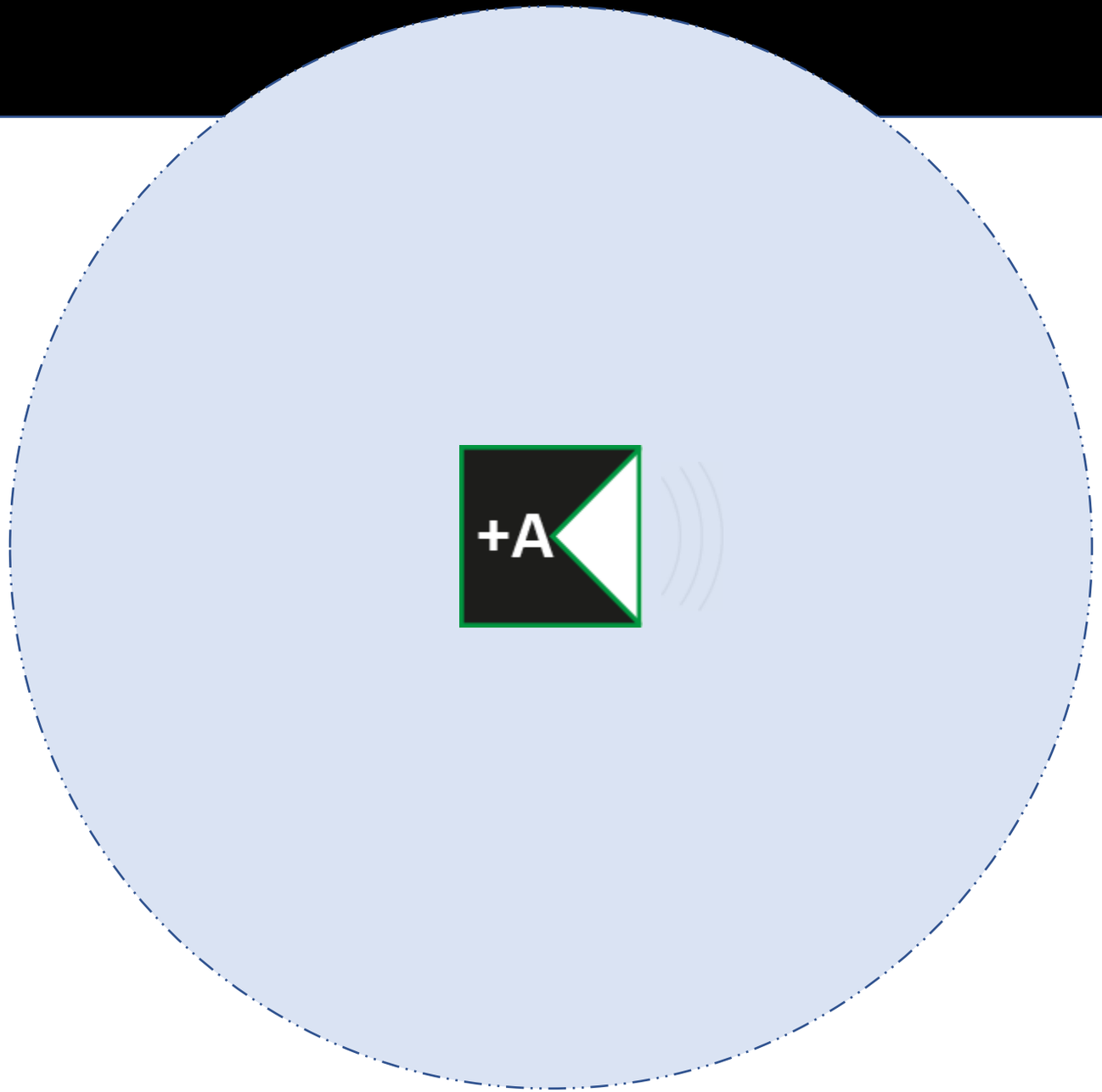




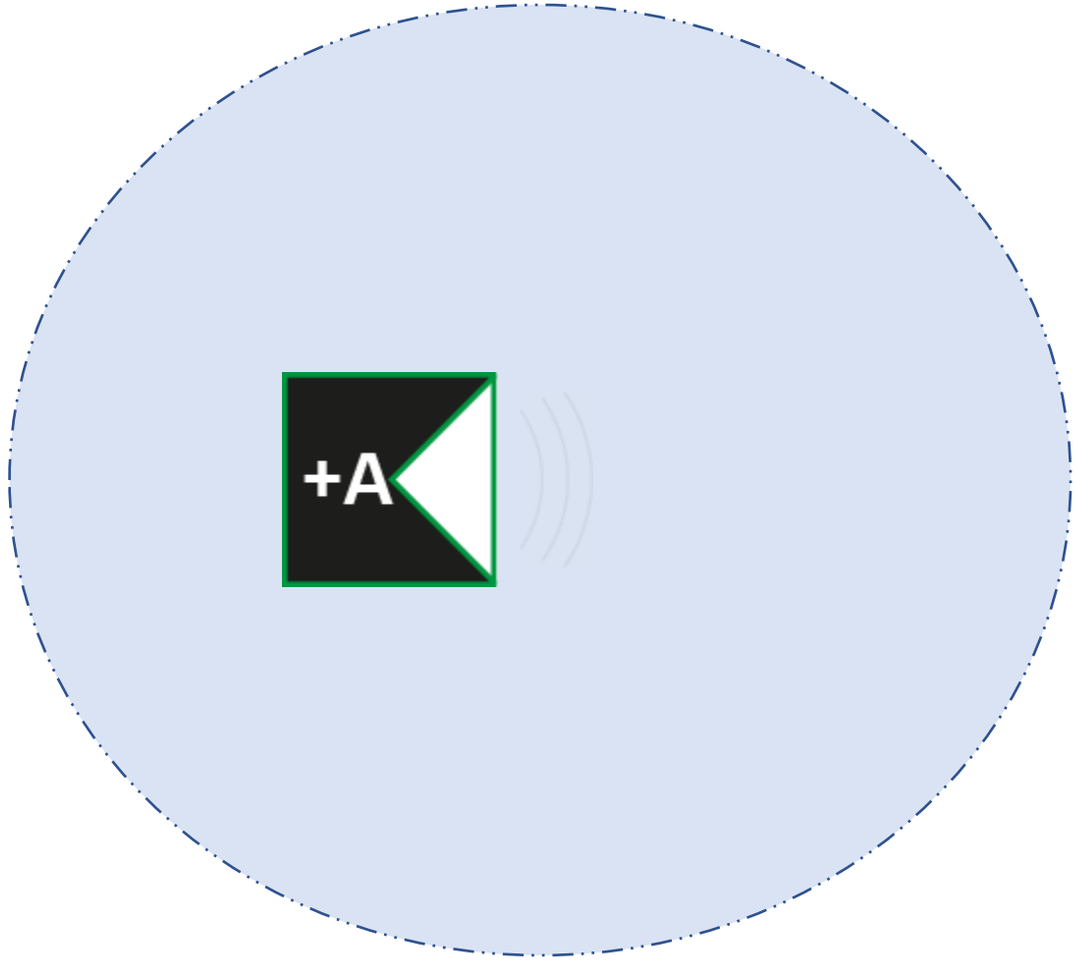
Ceci n’est vrai que pour un Sub conventionnel !



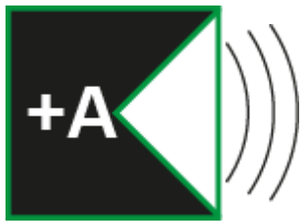
Un omni imparfait



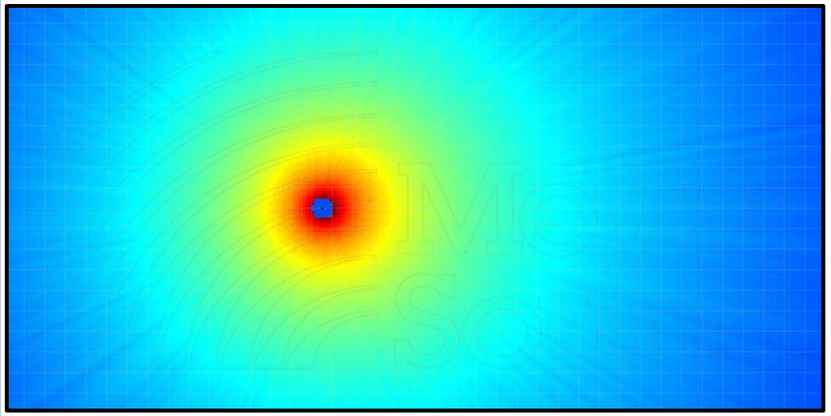
Un omni imparfait



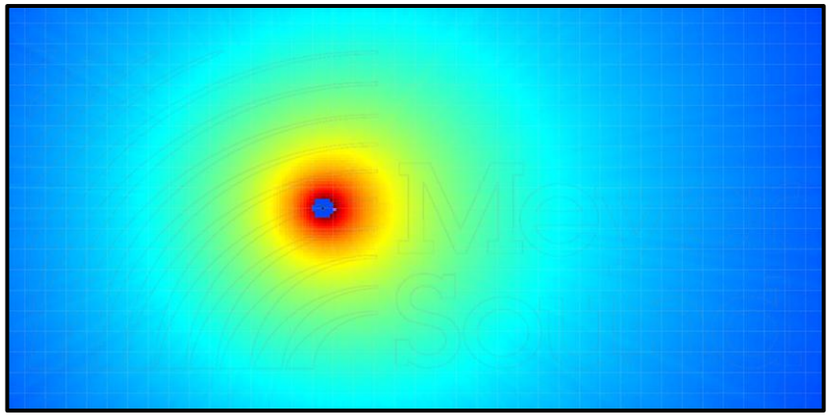
Un omni imparfait



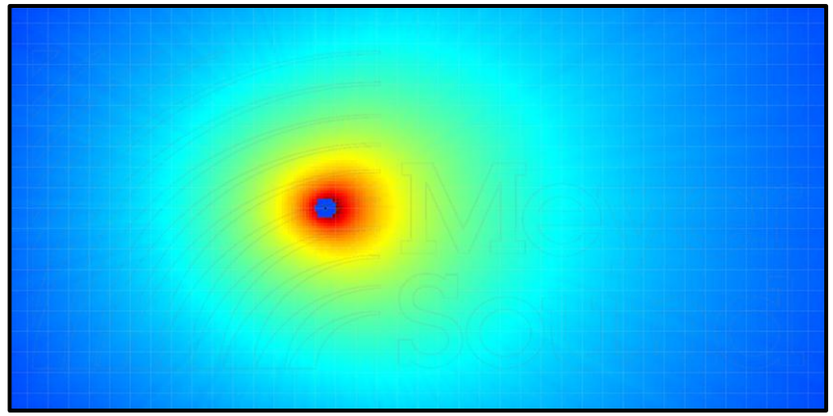
Cela vous semble omni ?



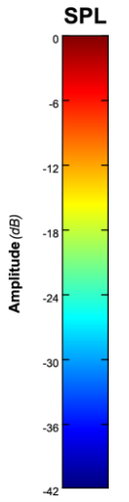
31,5 Hz



63 Hz



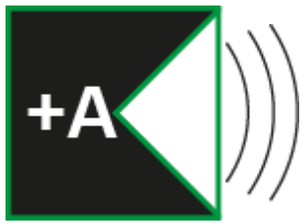
125 Hz

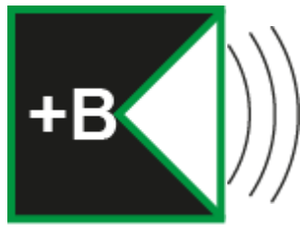


Air Attenuation On
Temperature = 15,0°C
Pressure = 101,33 kPa
Relative Humidity = 50,0 %

Relative Bandwidth = 1 octave

Un omni imparfait





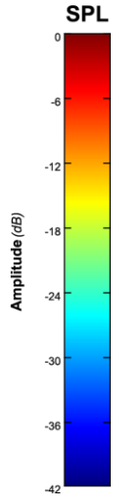
Air Attenuation On

Temperature = 15,0°C

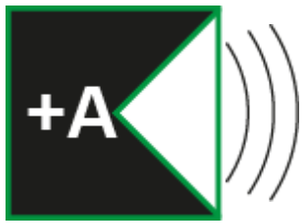
Pressure = 101,33 kPa

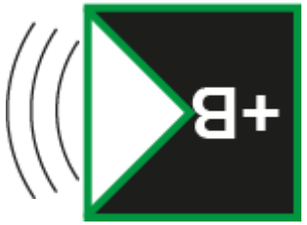
Relative Humidity = 50,0 %

Relative Bandwidth = 1 octave



Un omni imparfait





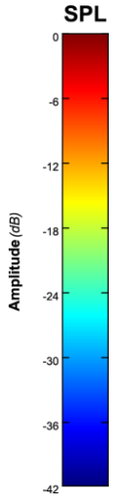
Air Attenuation On

Temperature = 15,0°C

Pressure = 101,33 kPa

Relative Humidity = 50,0 %

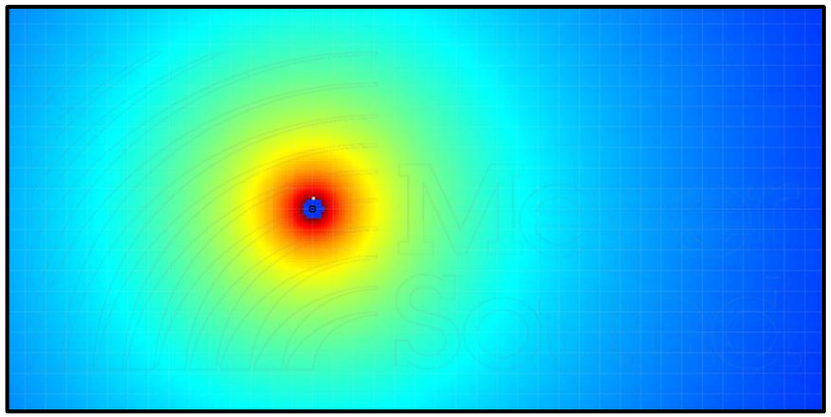
Relative Bandwidth = 1 octave



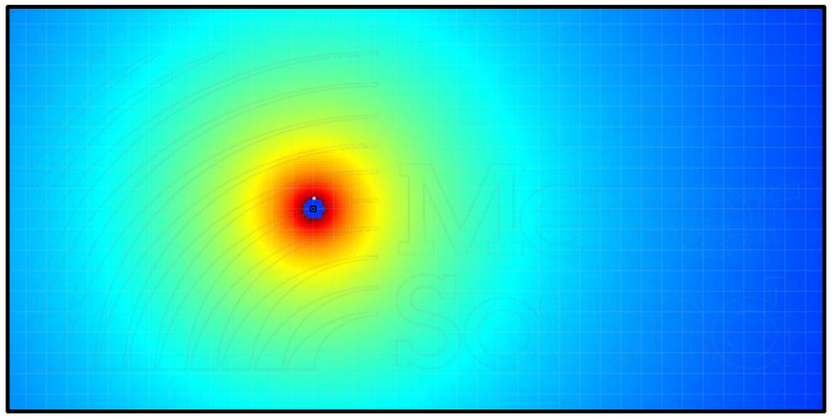
Un omni parfait virtuel

En un point

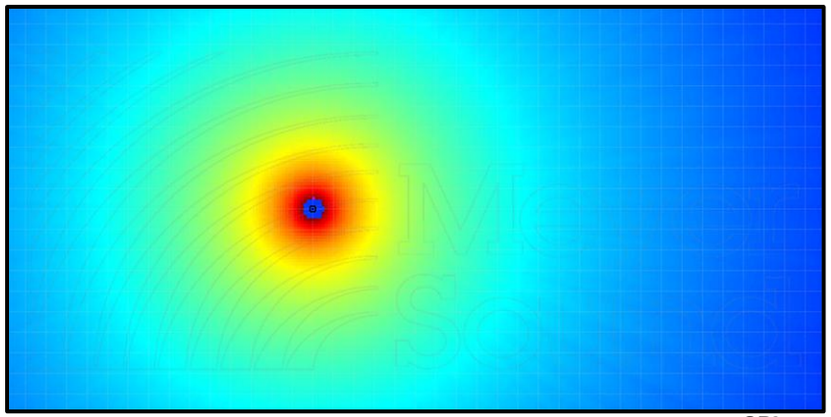




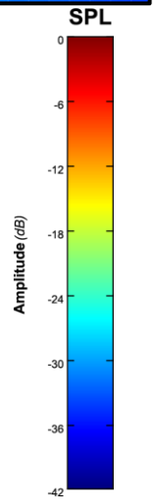
31,5 Hz



63 Hz



125 Hz



Air Attenuation On

Temperature = 15,0°C

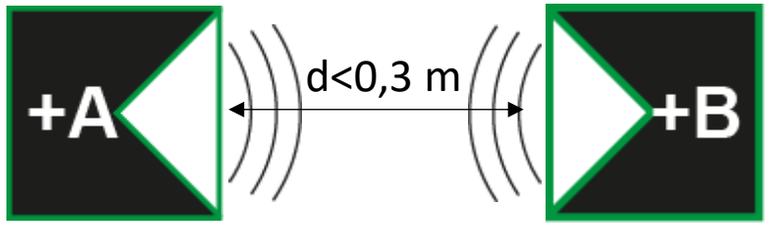
Pressure = 101,33 kPa

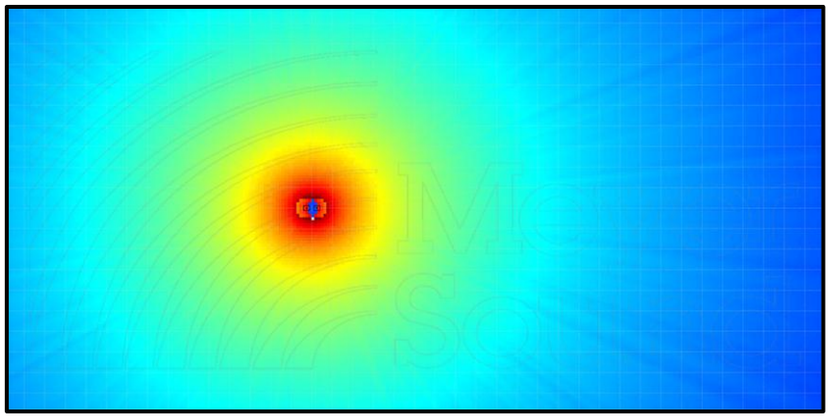
Relative Humidity = 50,0 %

Relative Bandwidth = 1 octave

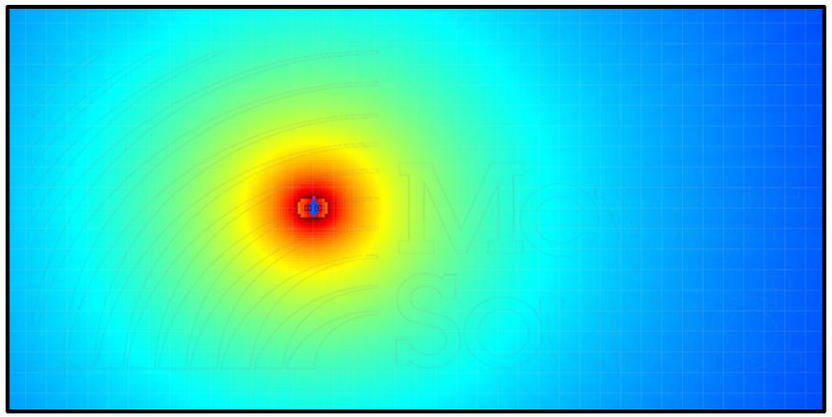
Bien pratique pour les logiciels !

Un omni parfait réel
Front to front

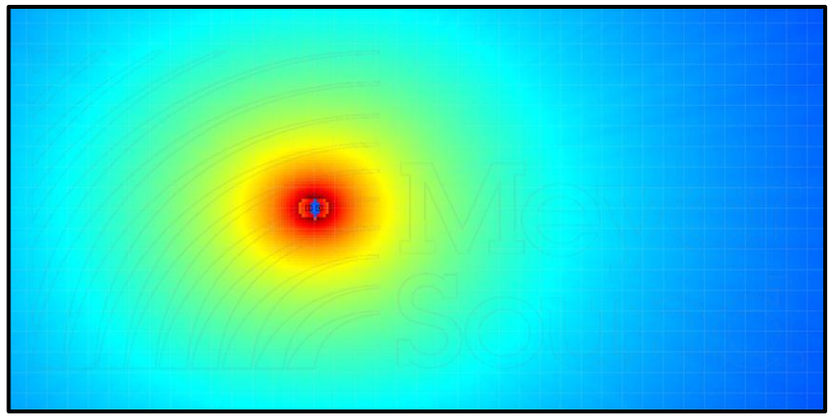




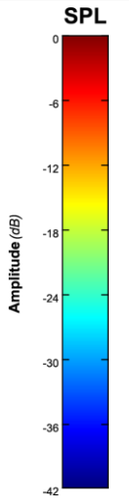
31,5 Hz



63 Hz



125 Hz



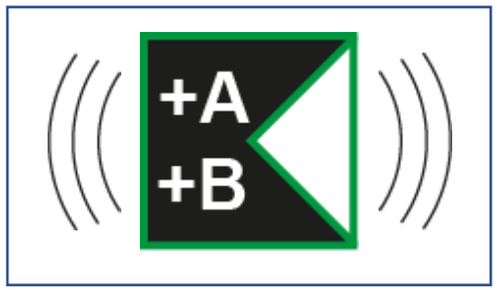
Air Attenuation On
Temperature = 15,0°C
Pressure = 101,33 kPa
Relative Humidity = 50,0 %

Relative Bandwidth = 1 octave

Un omni parfait

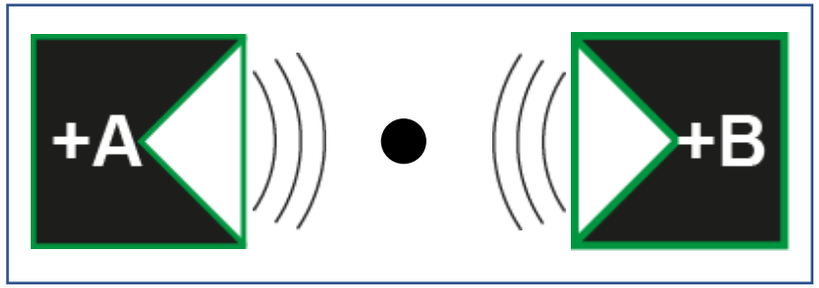
Dans la plupart des configurations que vous allez voir, beaucoup partent du principe que les subs sont totalement omni.

Dans le réel ce n'est pas le cas, mais rien ne vous empêche d'améliorer vos futures configurations en utilisant ce type de montage, et de calculer en fonction des nouveaux centres acoustiques.



=
Un sub 100% omni +6dB avec le même centre acoustique

On nomme cela un point source.

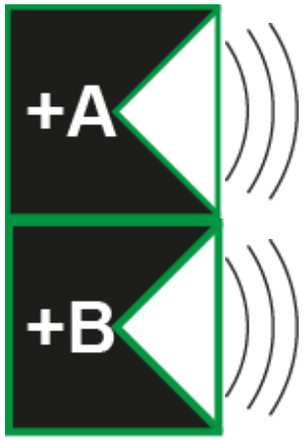


=
Un sub 100% omni ≈+6dB avec un centre acoustique virtuel au centre

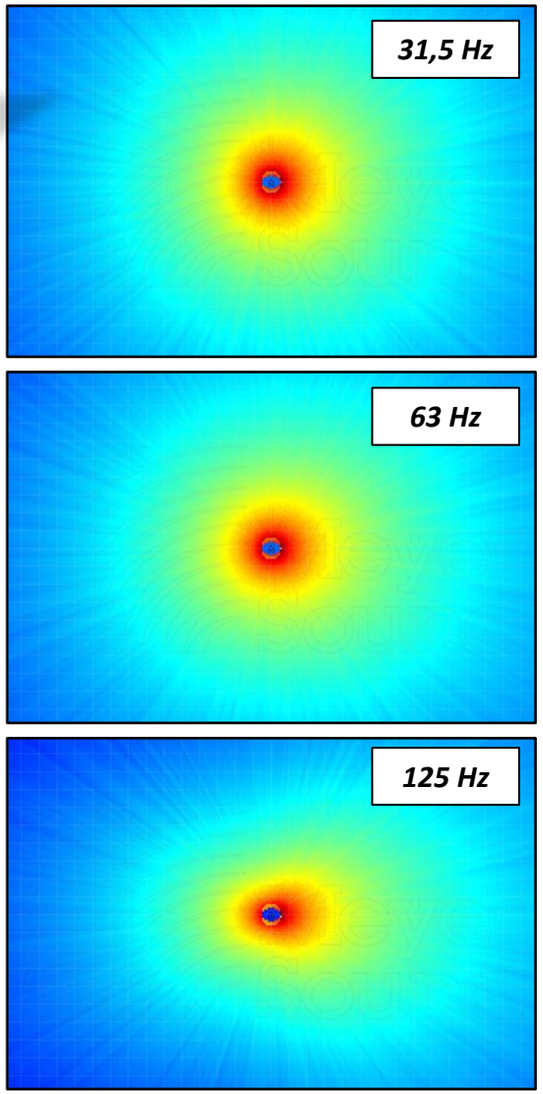
Délai et polarité

Nos premières additions

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



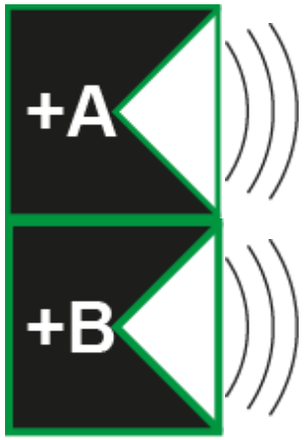
2 subs – même polarité



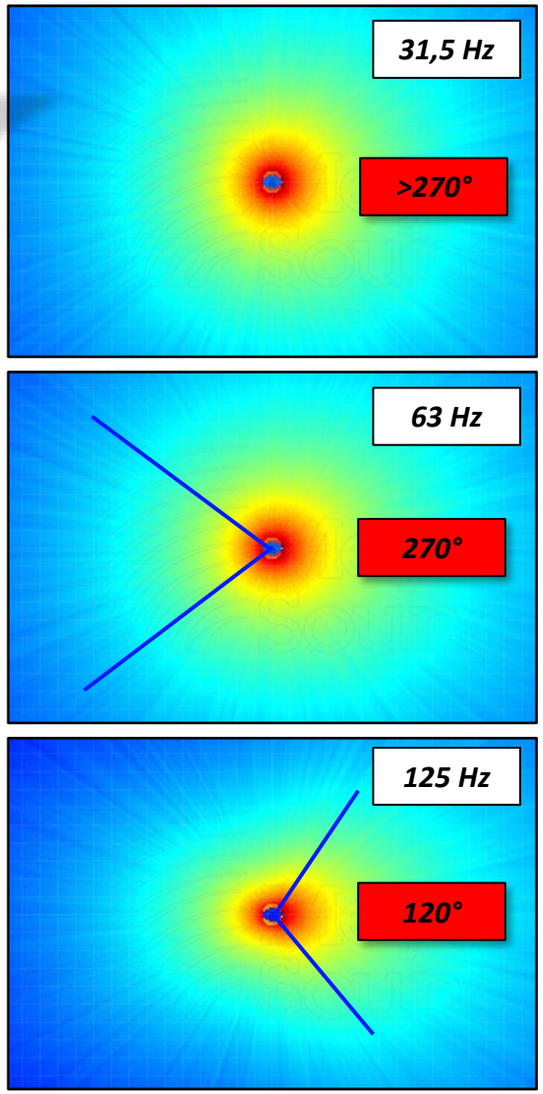
Délai et polarité

Nos premières additions

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



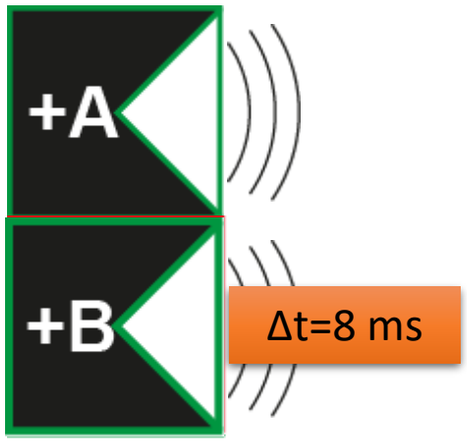
2 subs – même polarité

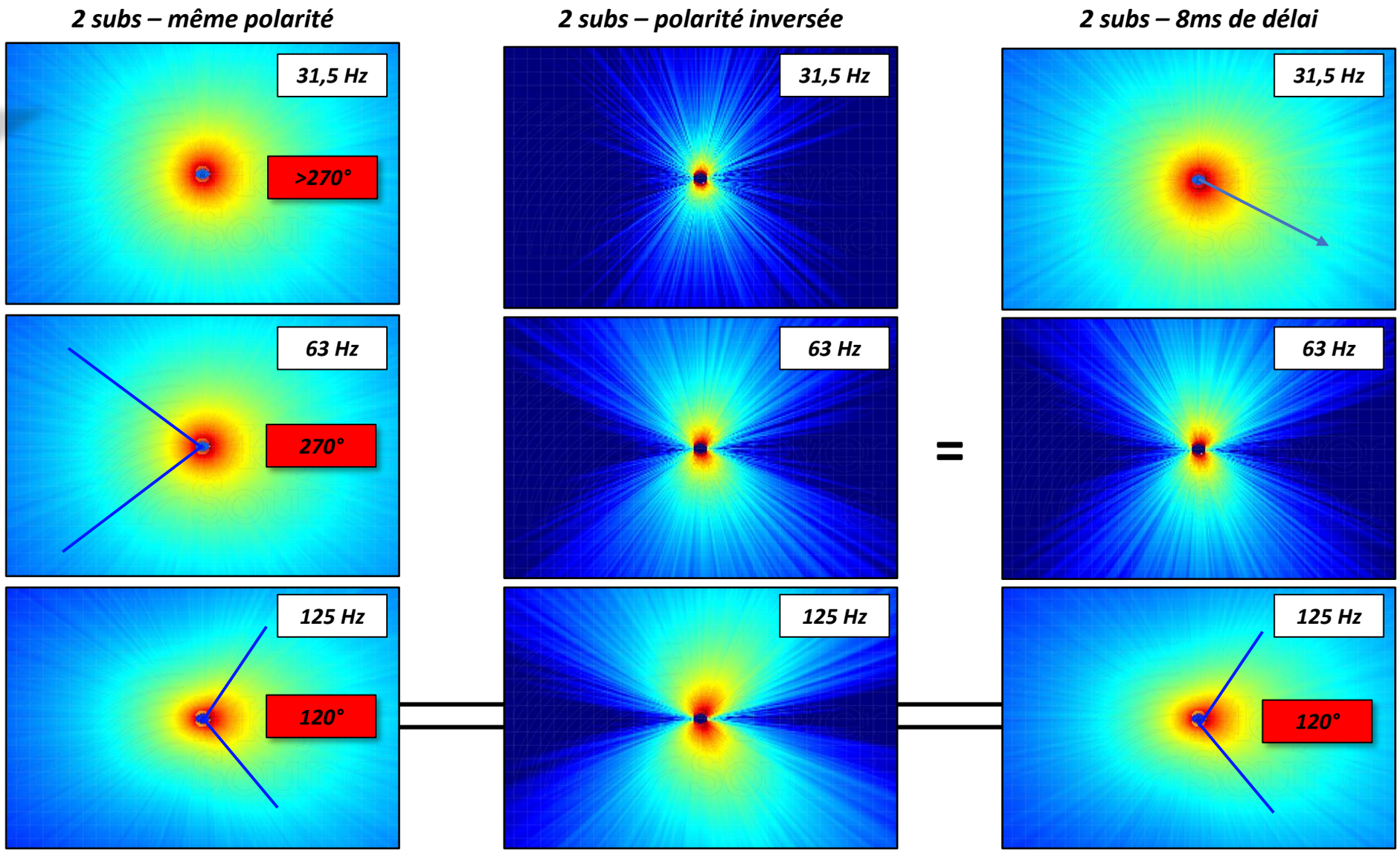


La couverture se resserre avec la fréquence

Délai et polarité
Nos premières additions

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





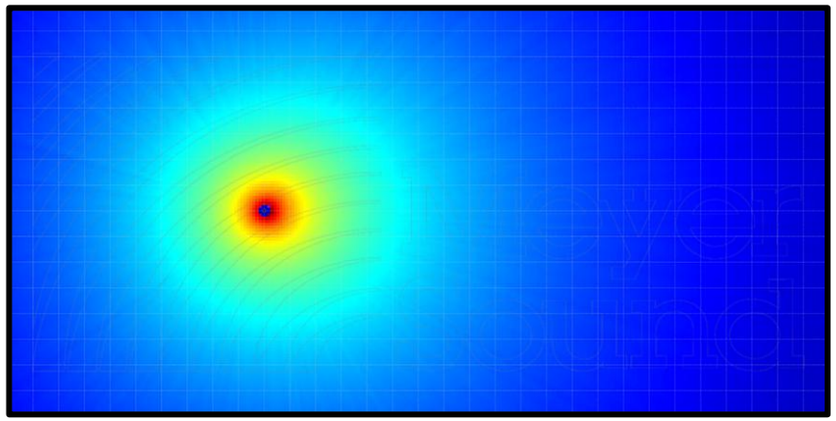
?

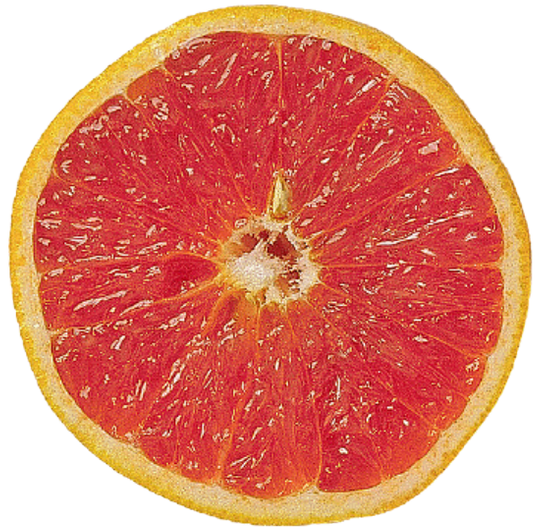


2
Steering effect

Steering effect

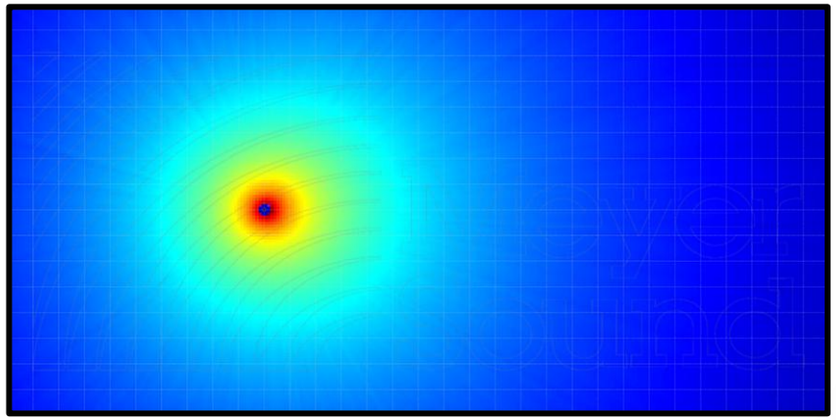
1 Sub



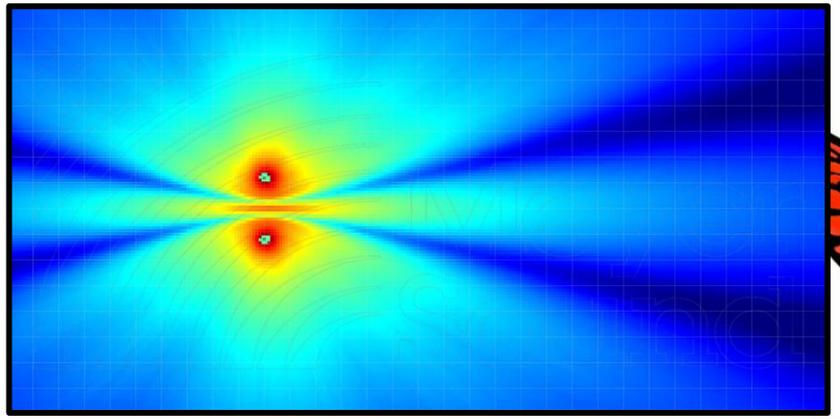


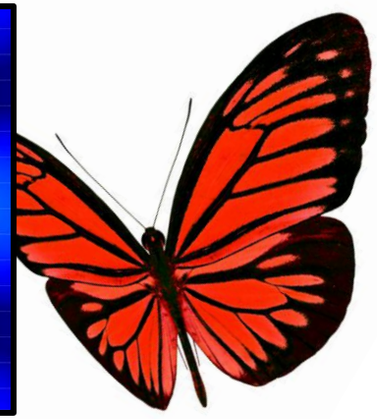
Steering effect

1 Sub



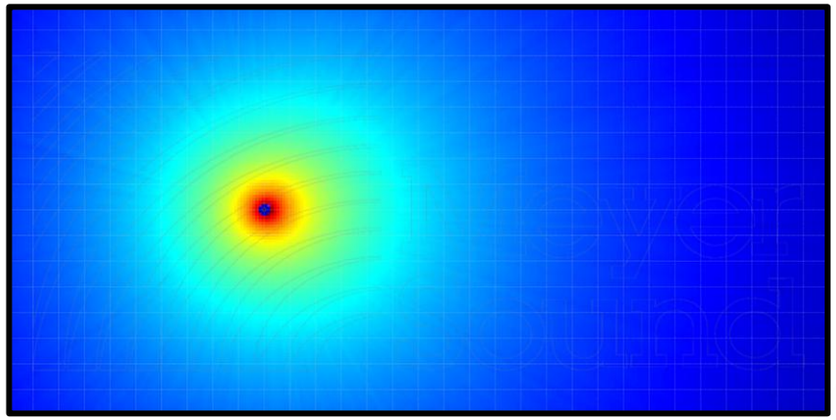
2 Subs – 12 mètres



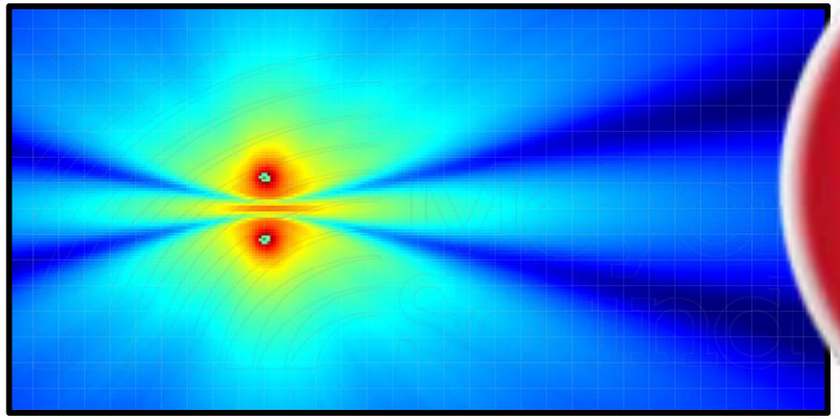


Steering effect

1 Sub



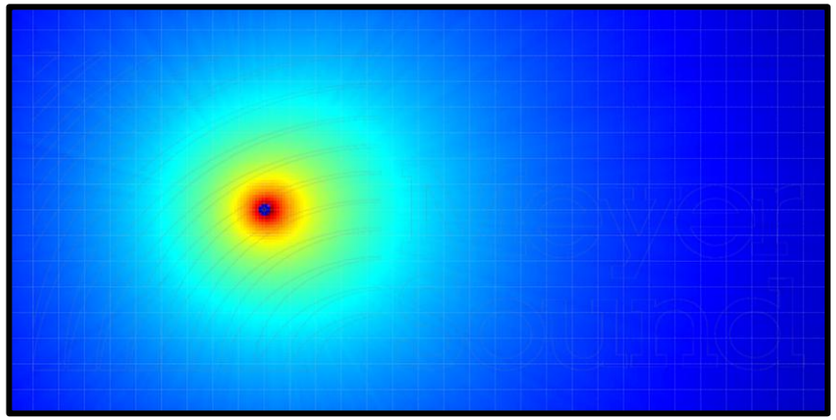
2 Subs – 12 mètres



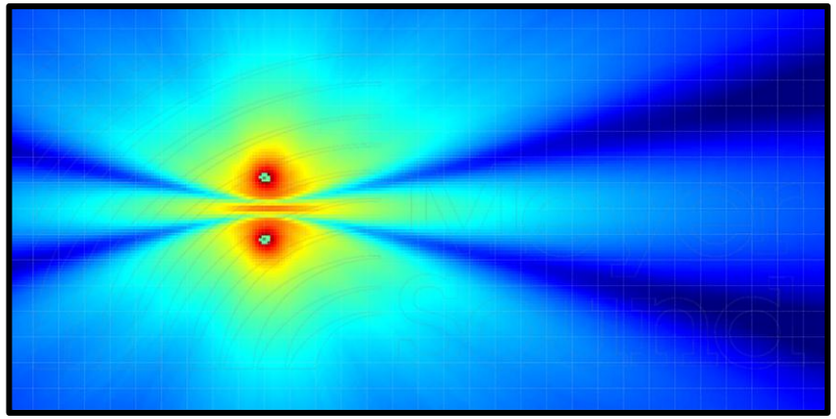


Steering effect

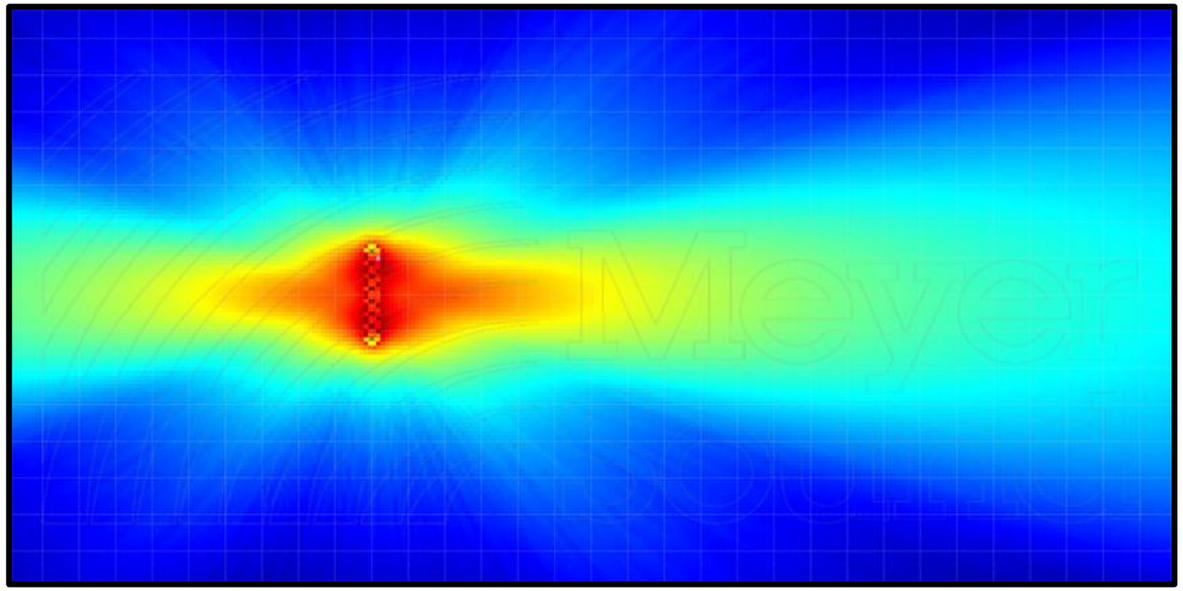
1 Sub



2 Subs – 12 mètres

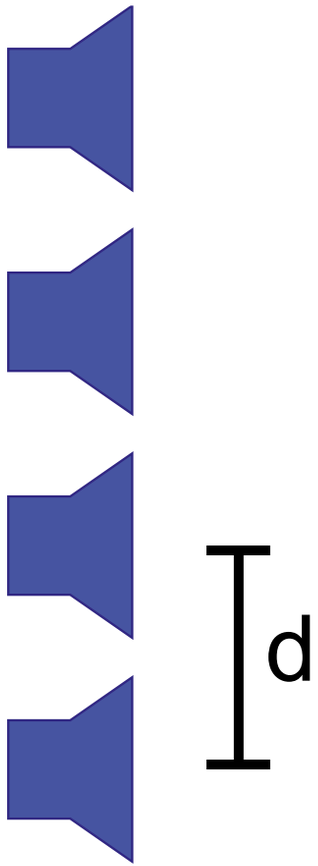


8 Subs – 12 mètres

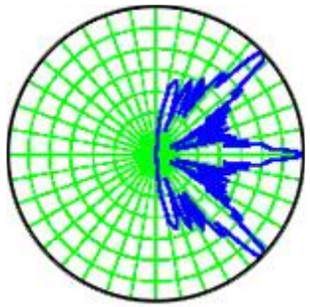




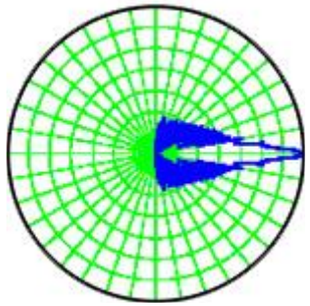
Steering effect
Écart maximum



d > λ/2



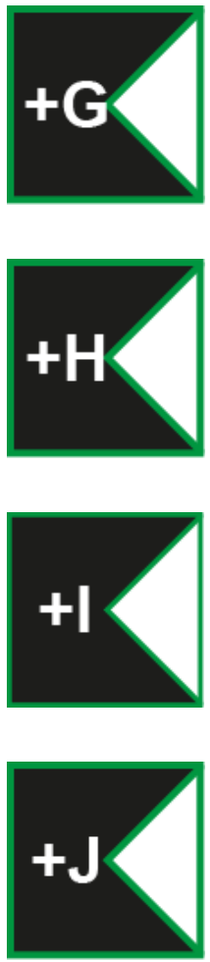
d < λ/2



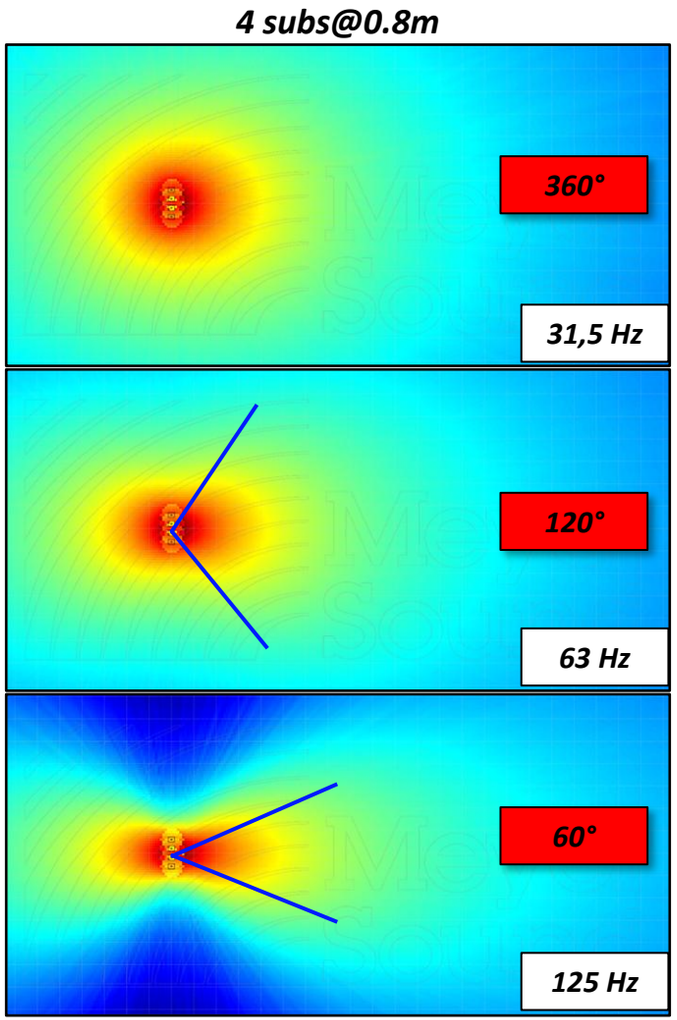
f	λ	λ/2
25 Hz	13.6 m	6.80 m
31,5 Hz	10.79 m	5.40 m
40 Hz	8.5 m	4.25 m
50 Hz	6.8 m	3.40 m
63 Hz	5.4 m	2.70 m
80 Hz	4.25 m	2.12 m
100 Hz	3.4 m	1.70 m
125 Hz	2.72 m	1.36 m

d = *Distance entre les centres des sources*

Steering effect
Quantité

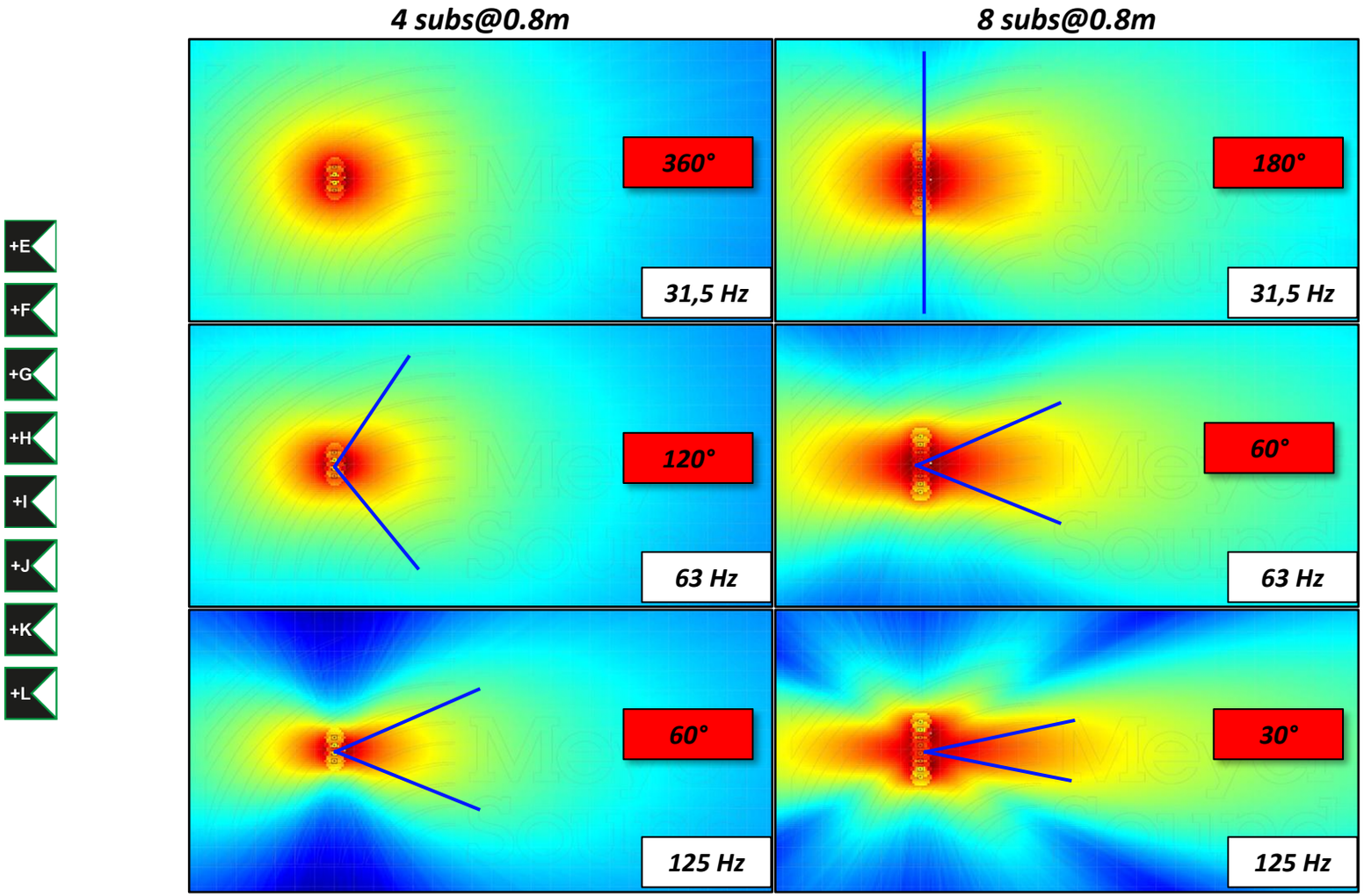


Steering effect
Quantité

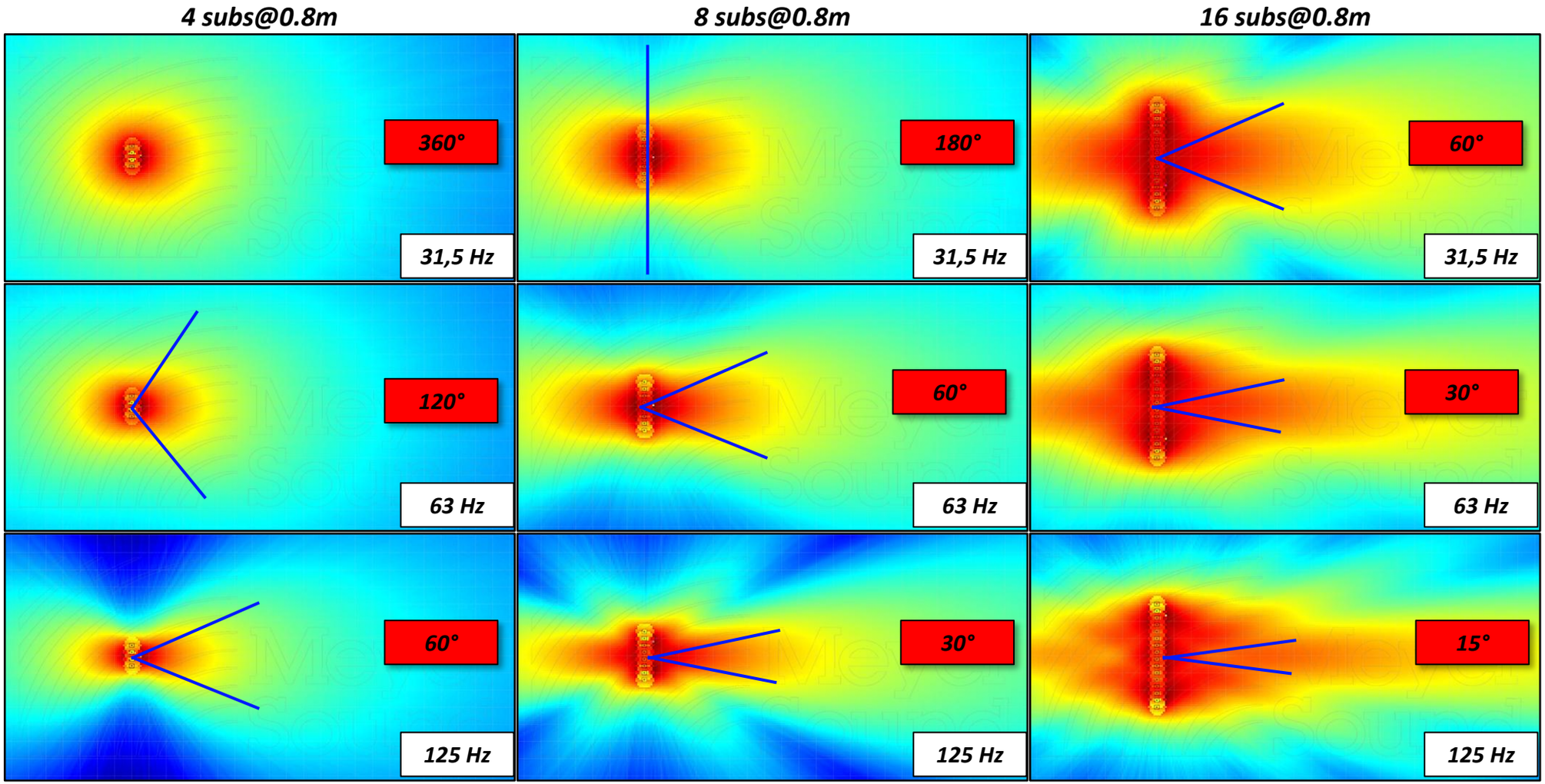


+G
+H
+I
+J

Steering effect
Quantité

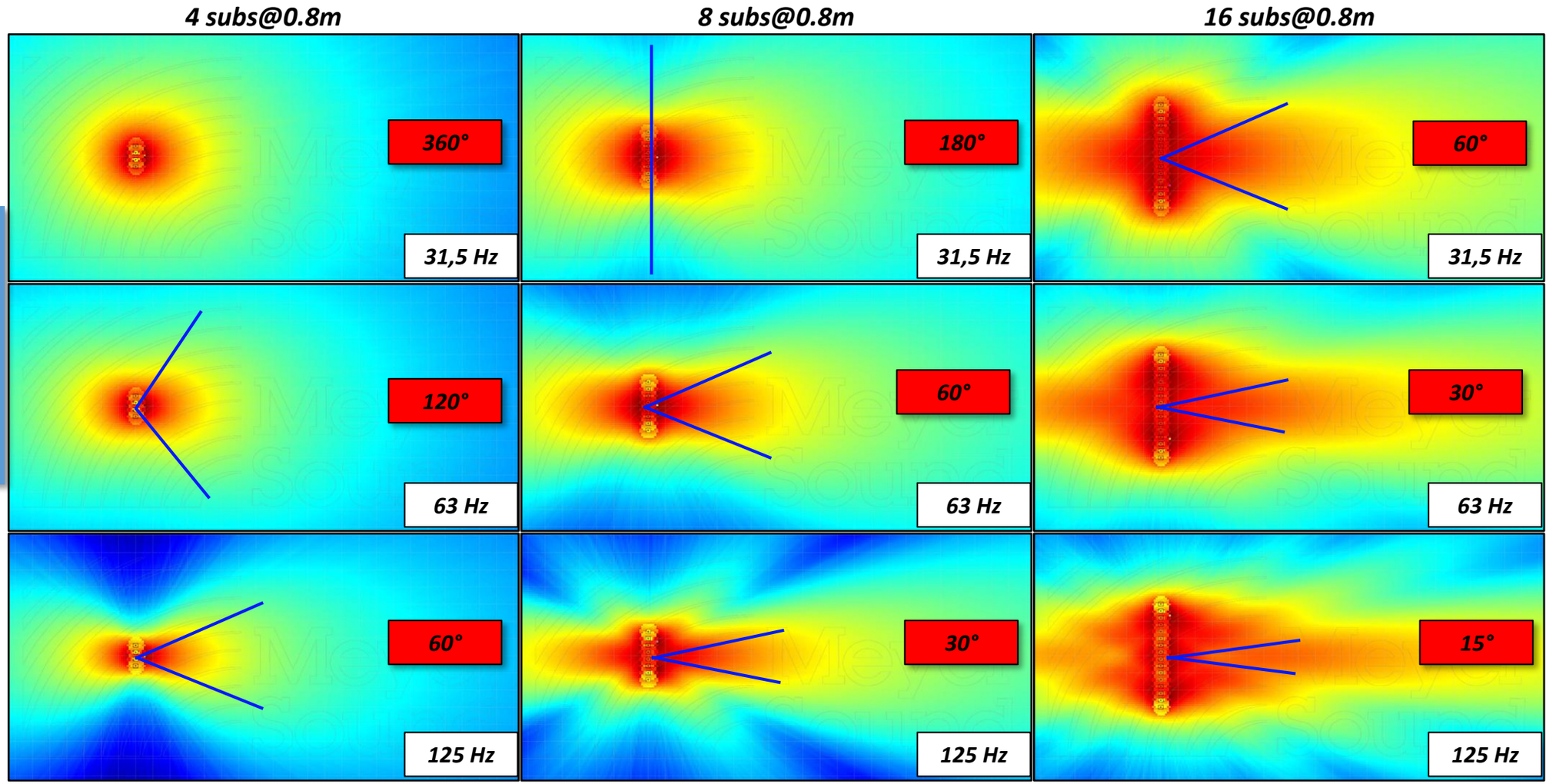


Steering effect
Quantité



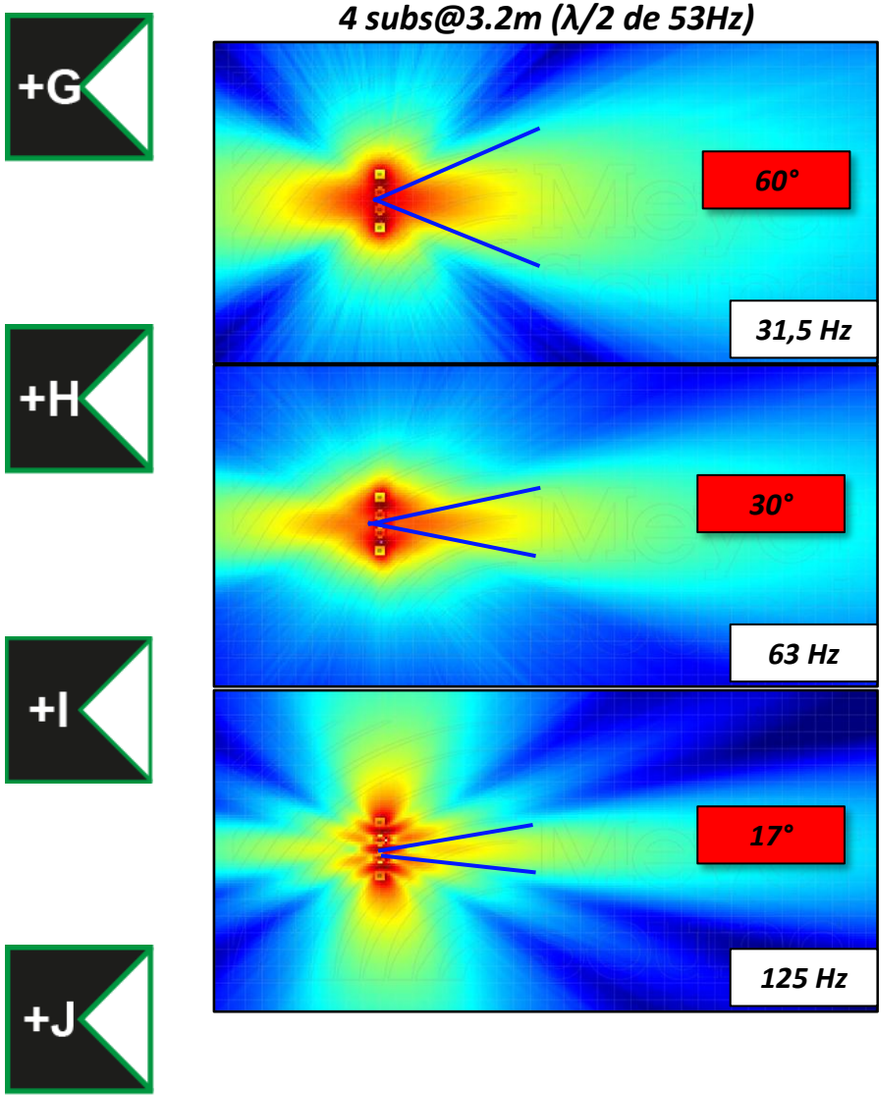
Steering effect
Quantité

Plus la fréquence augmente plus la couverture se resserre.



Plus le nombre de subs augmente plus la couverture se resserre.

Steering effect
Position



Steering effect
Position

+E

+F

+G

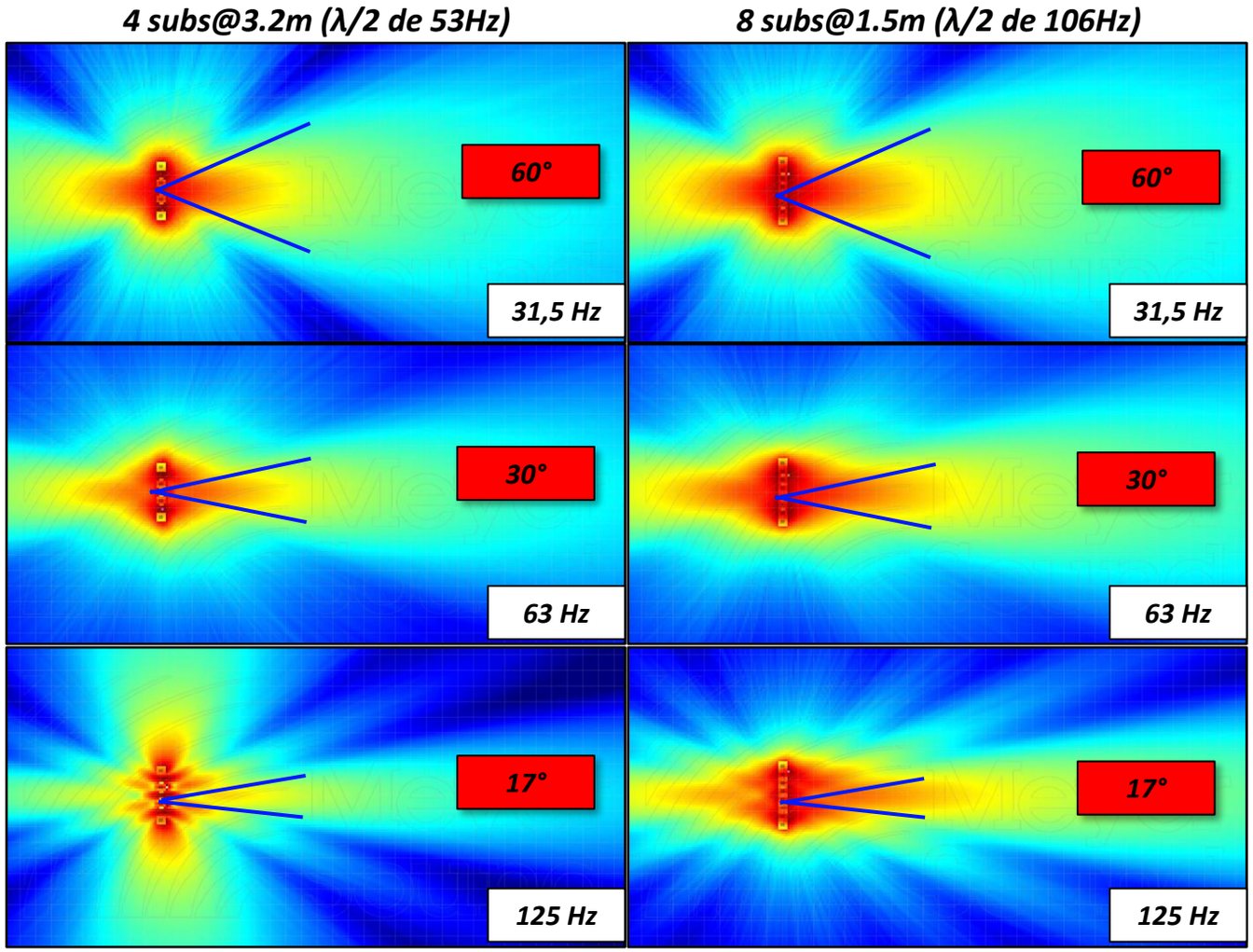
+H

+I

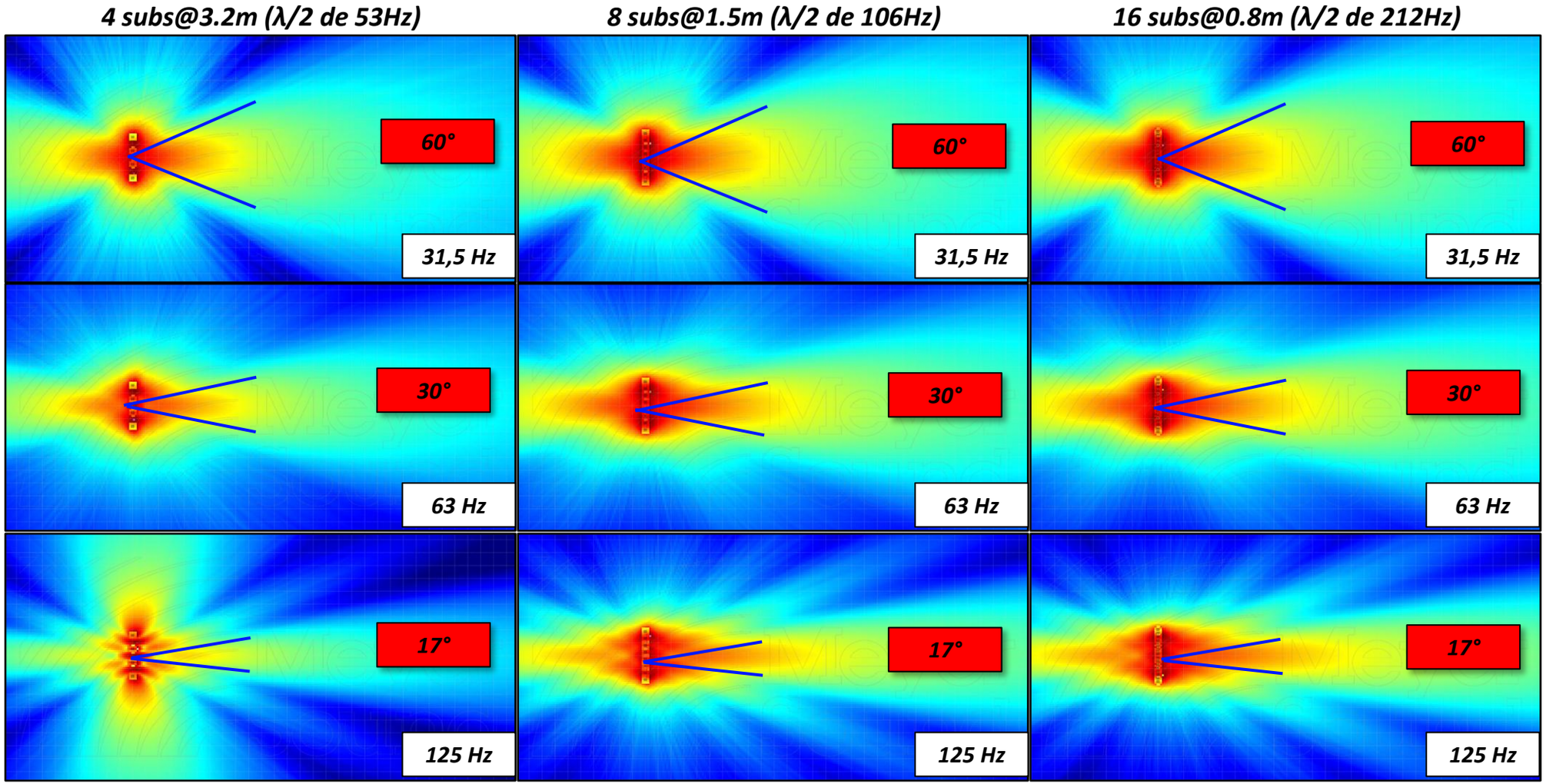
+J

+K

+L

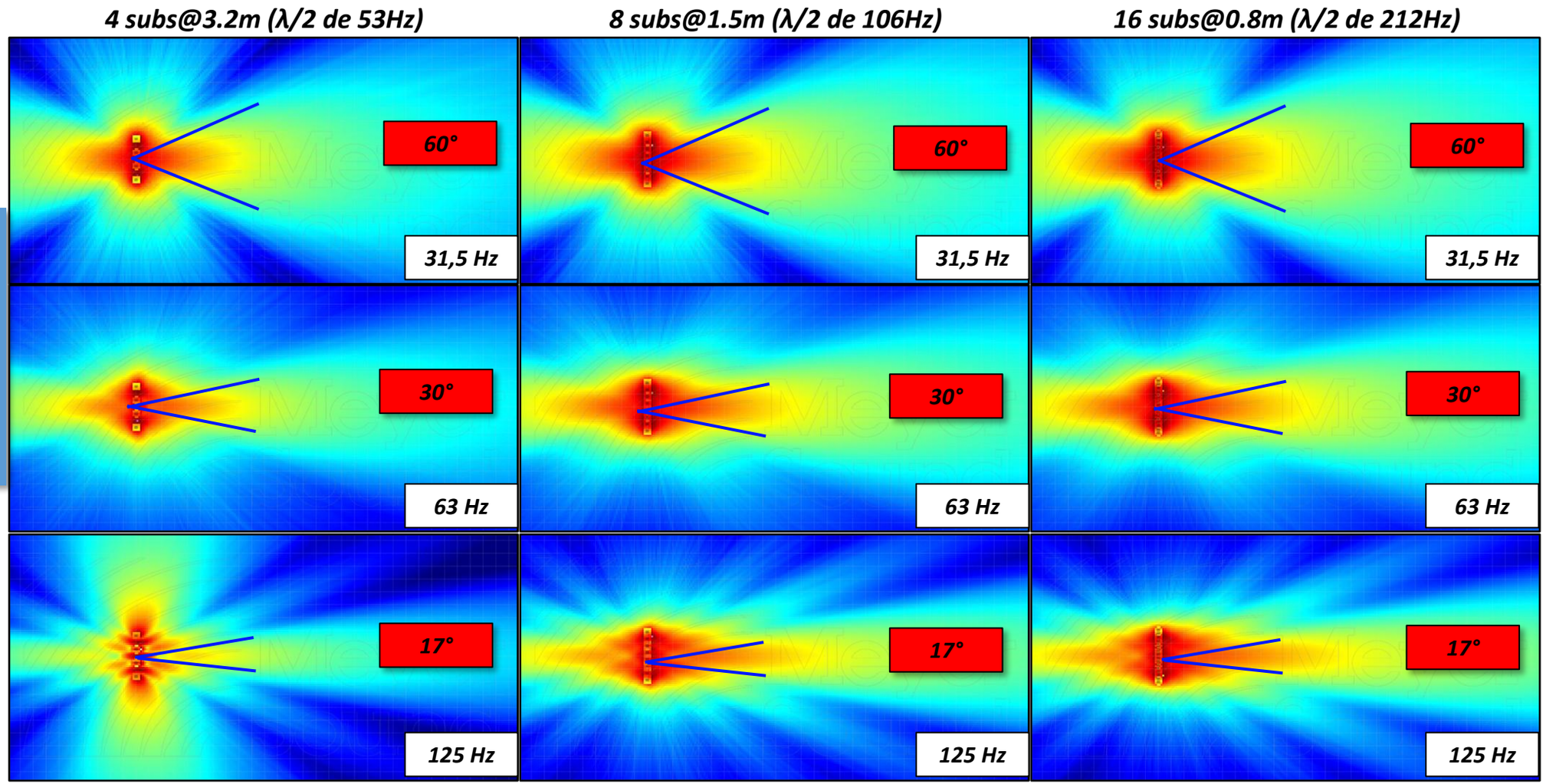


Steering effect
Position



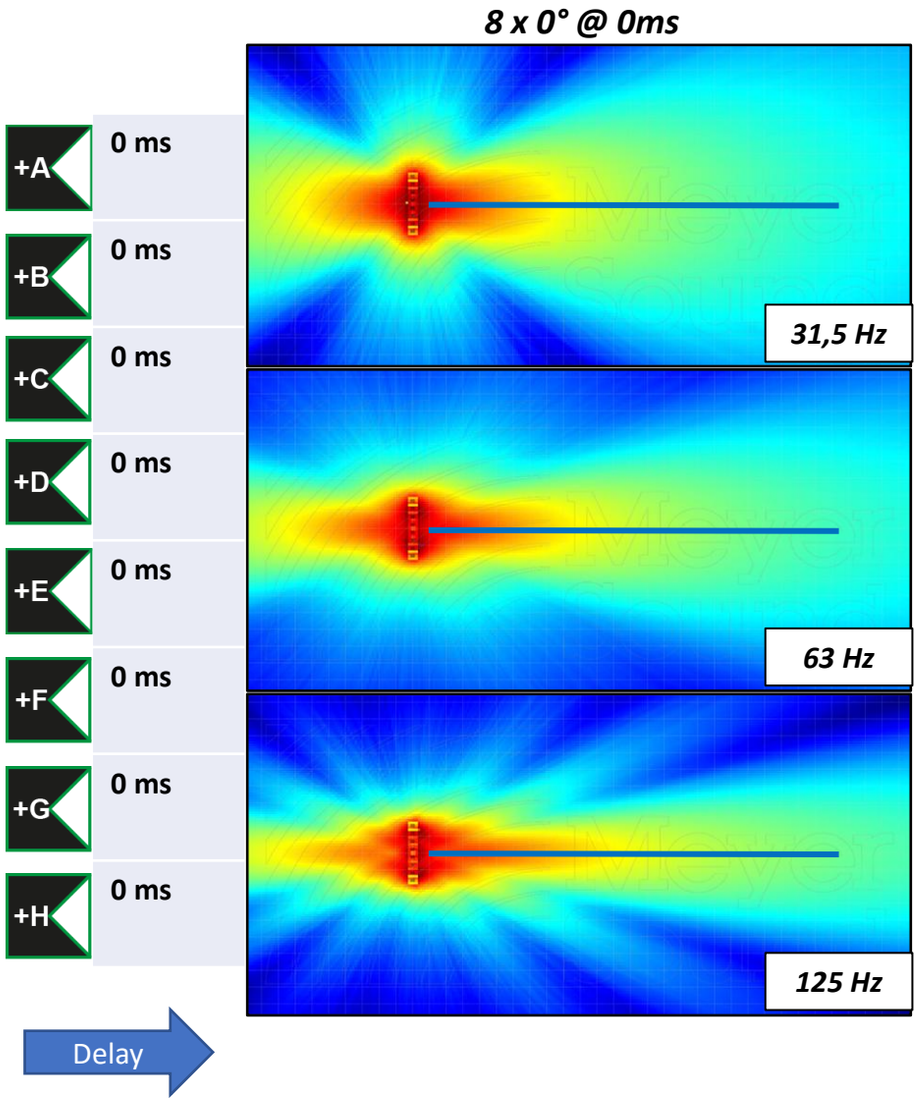
Steering effect
Position

Plus la fréquence augmente plus la couverture se resserre.

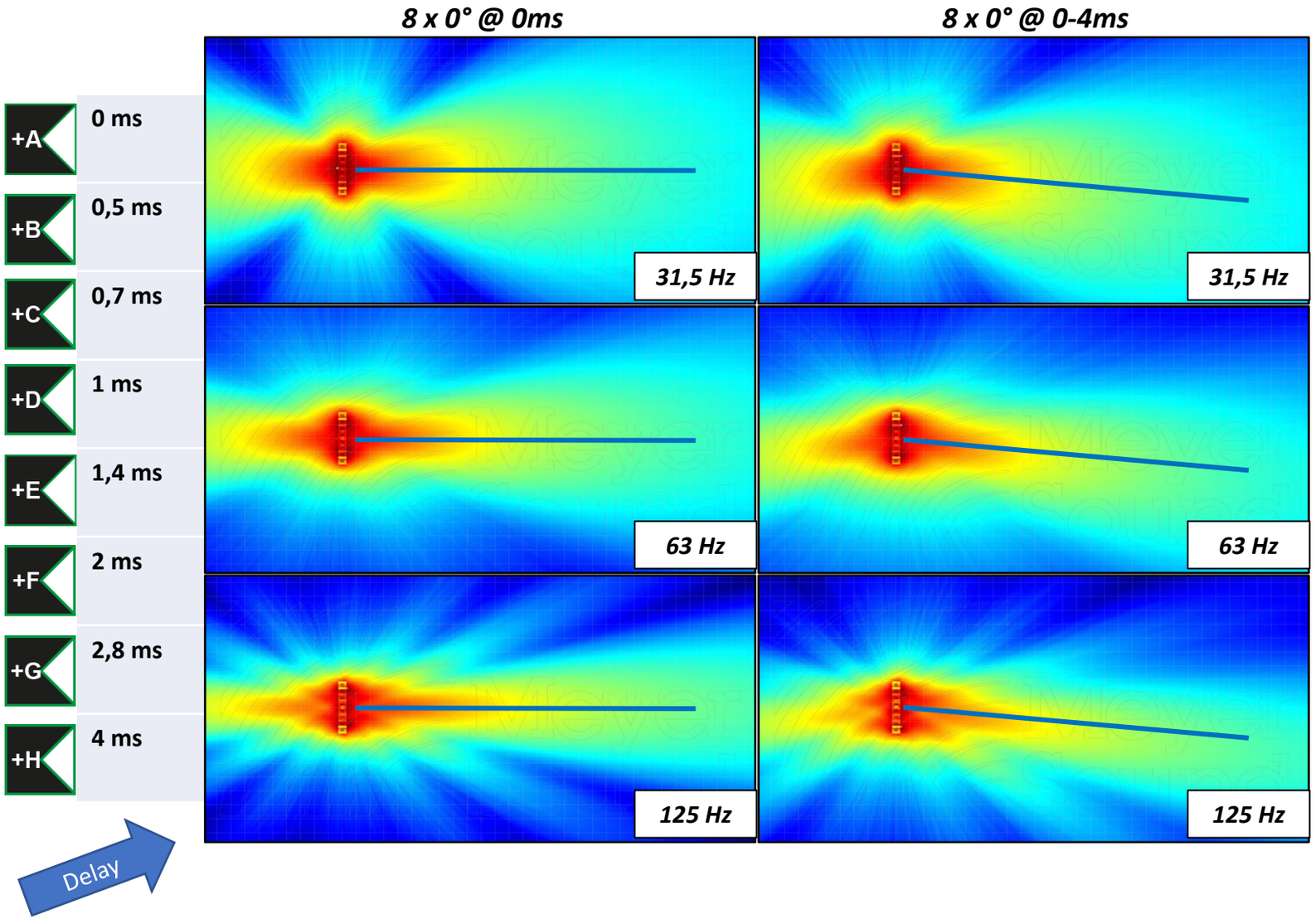


Quand le nombre de subs augmente , la couverture ne change pas.

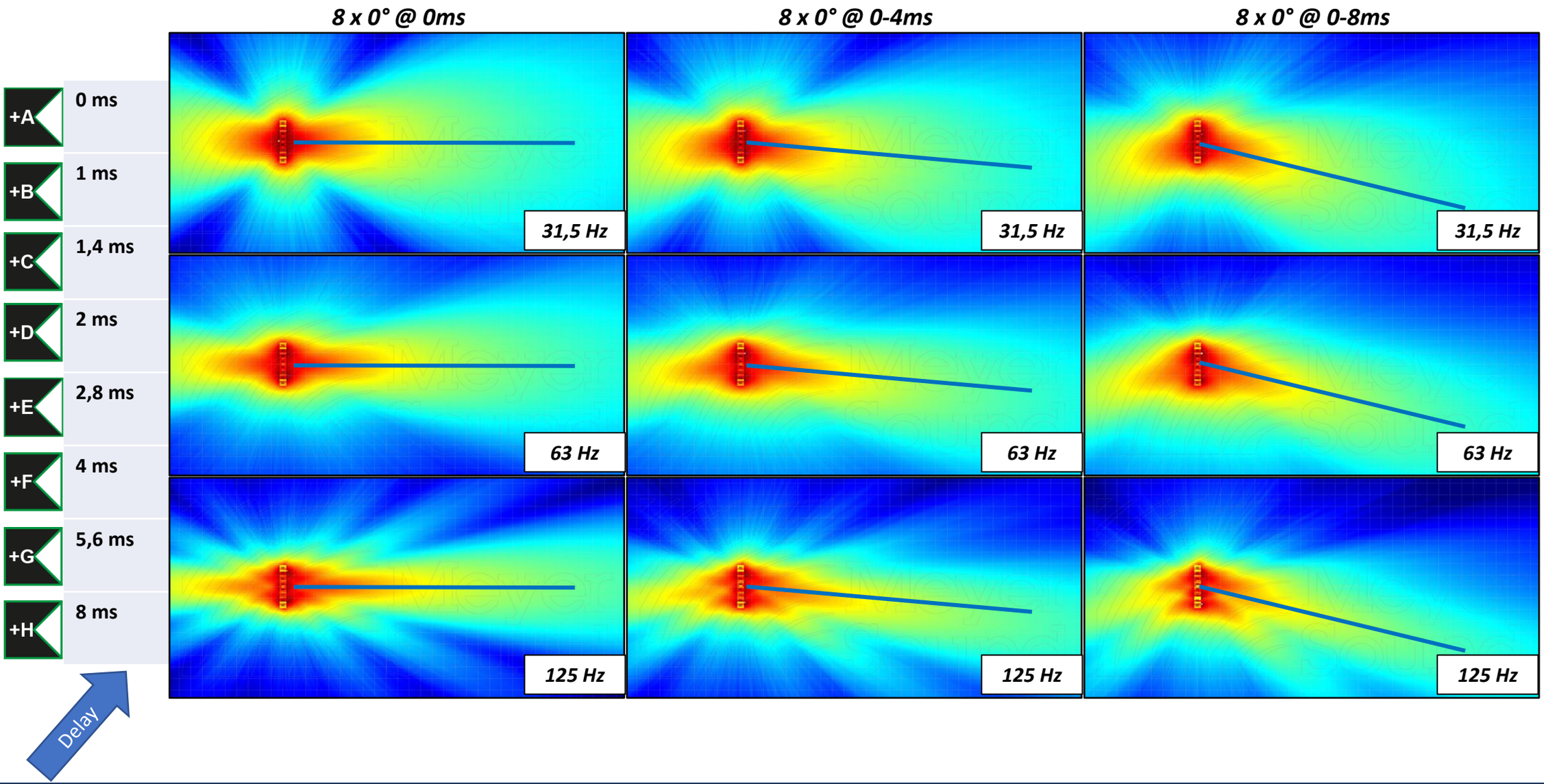
Steering effect
Latéral



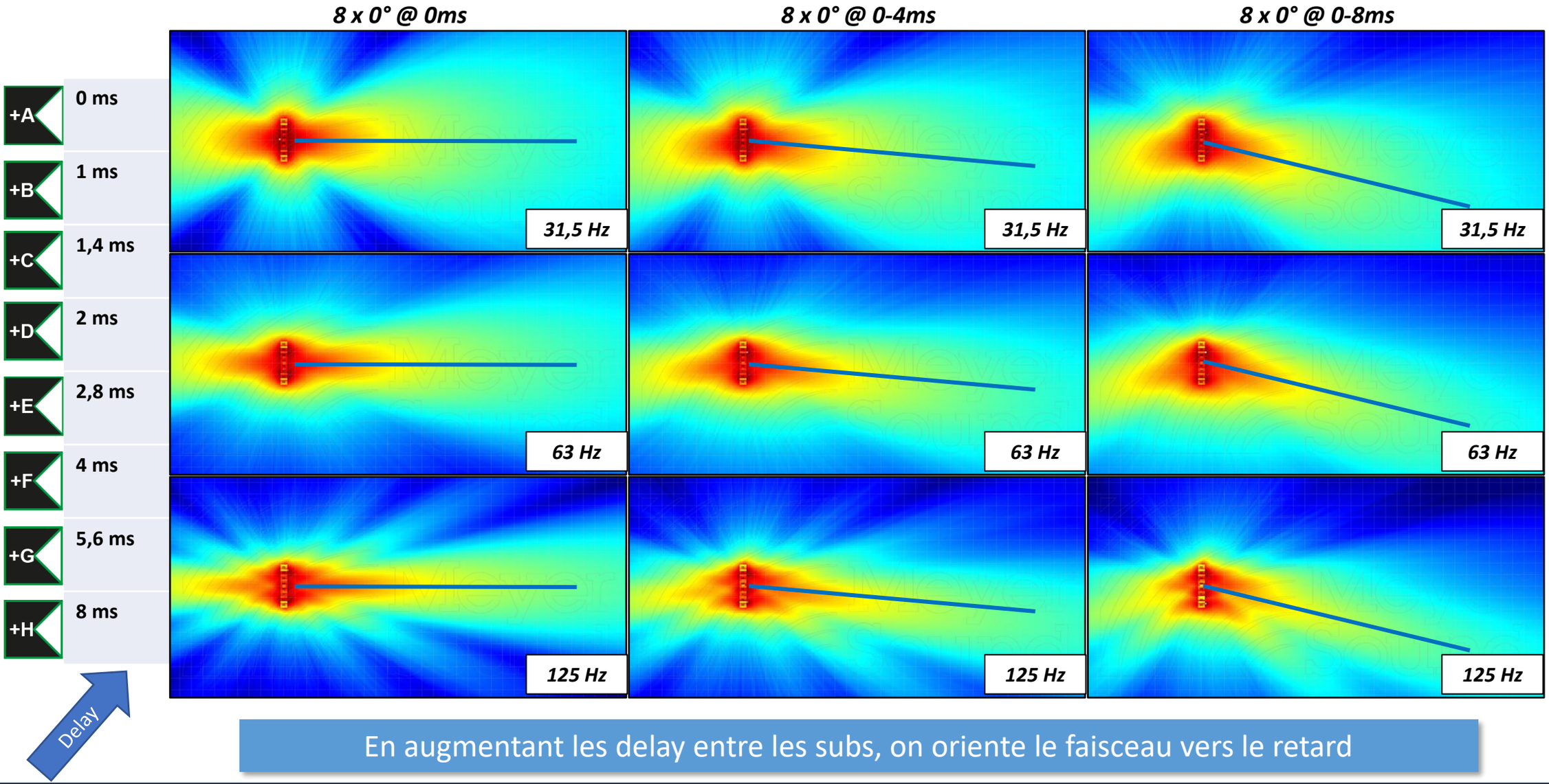
Steering effect
Latéral



Steering effect
Latéral

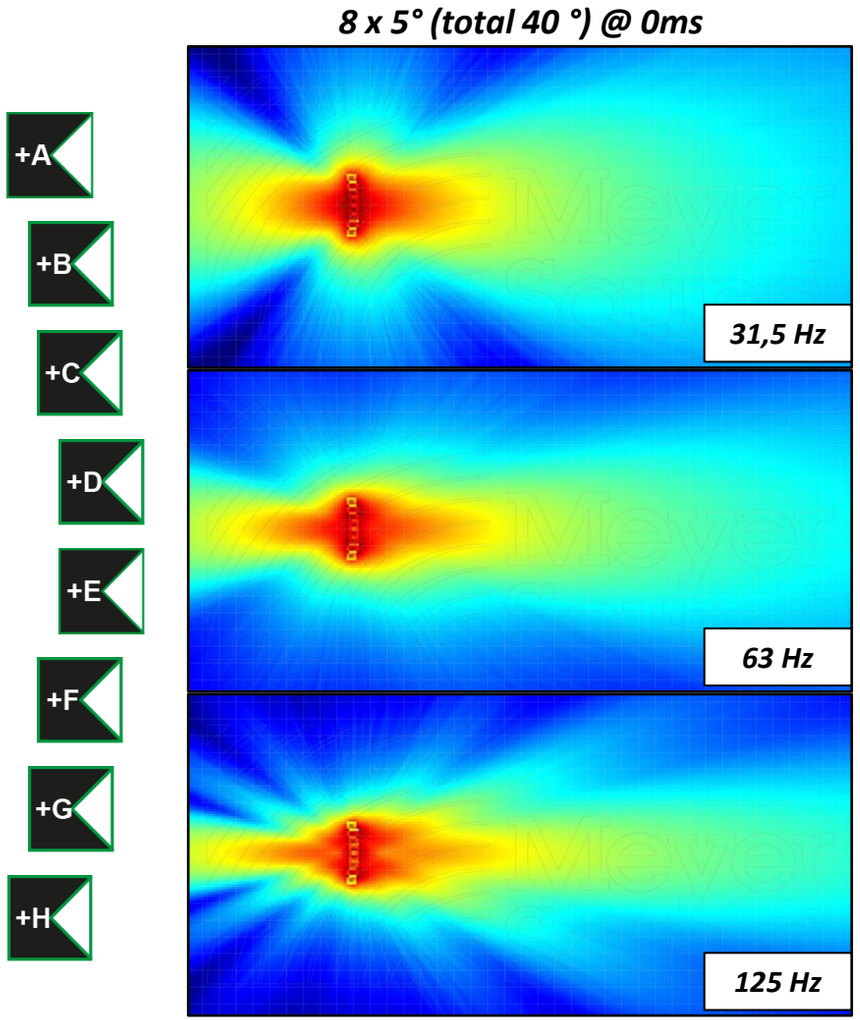


Steering effect
Latéral

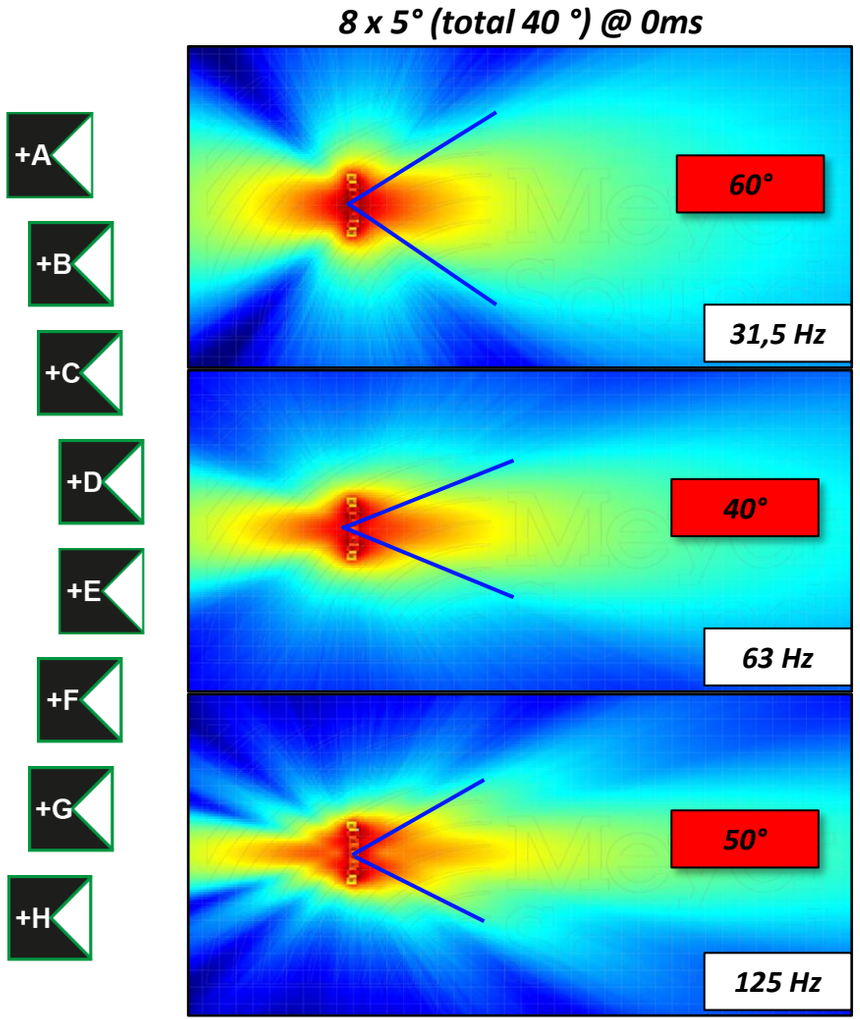


En augmentant les delay entre les subs, on oriente le faisceau vers le retard

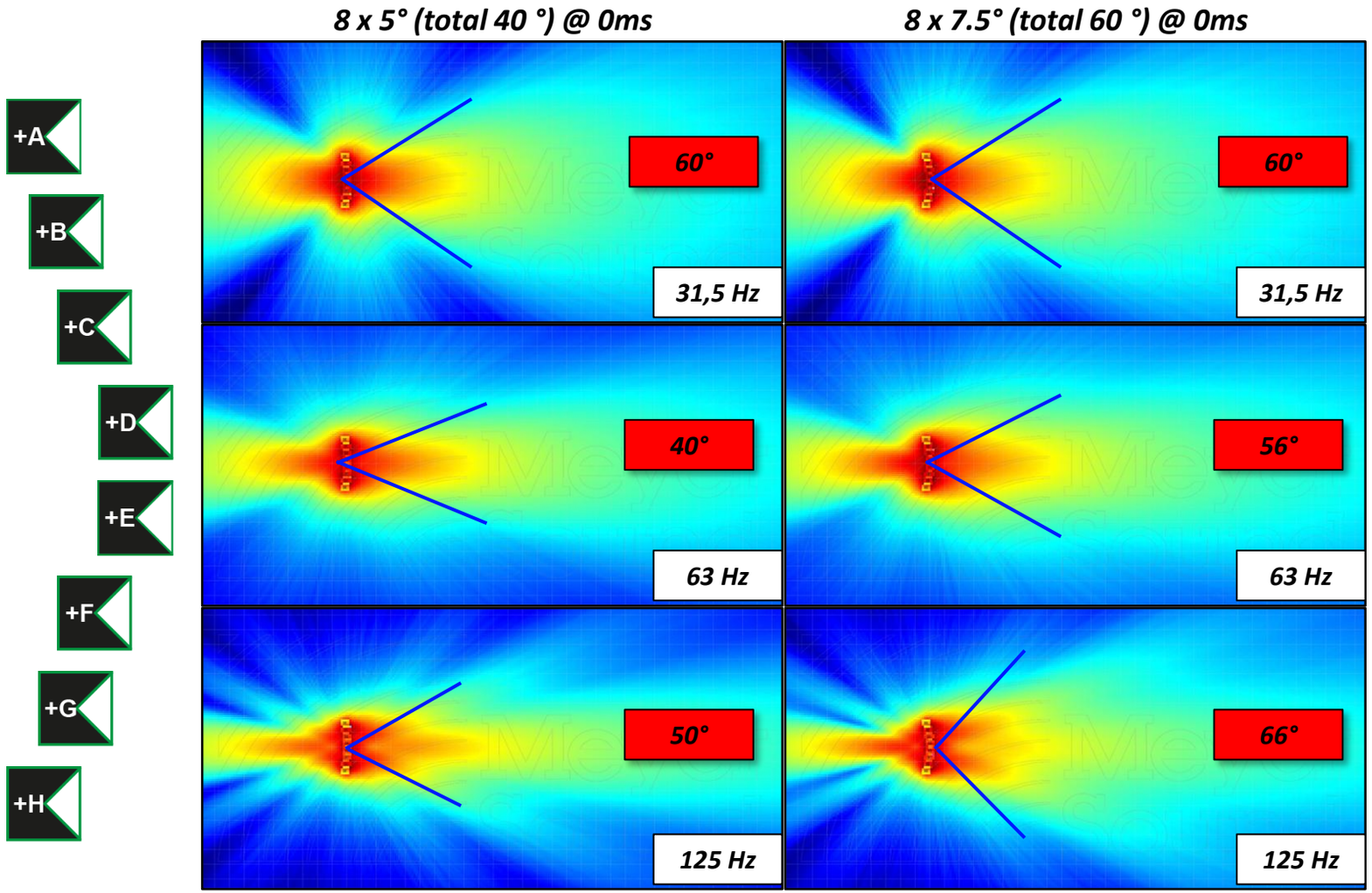
Steering effect
Radial – Arc Sub physique



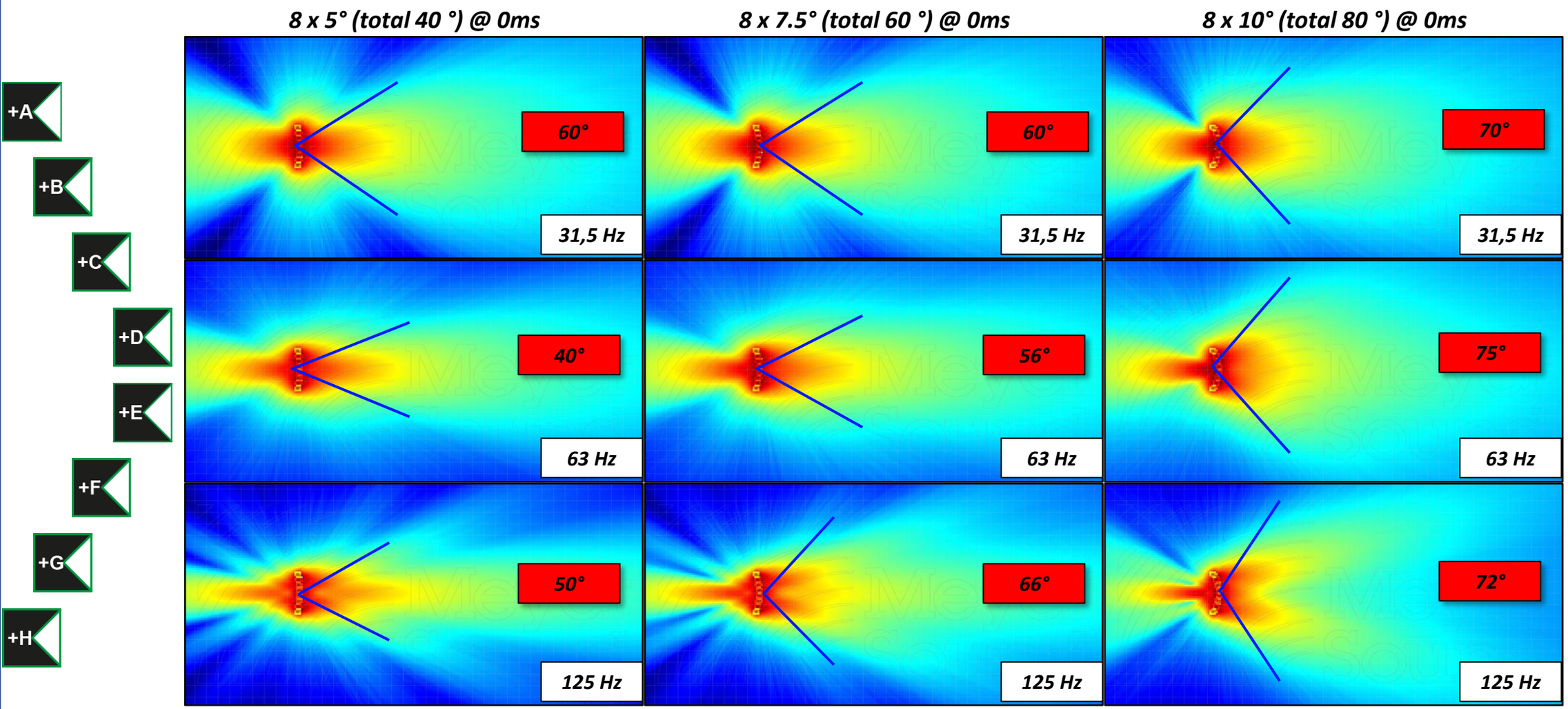
Steering effect
Radial – Arc Sub physique



Steering effect
Radial – Arc Sub physique

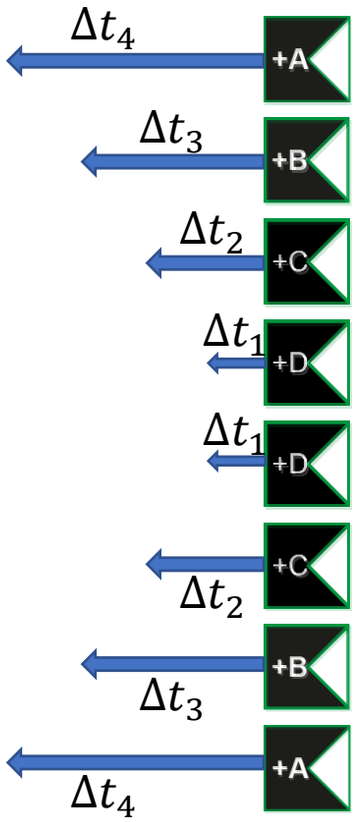


Steering effect
Radial – Arc Sub physique



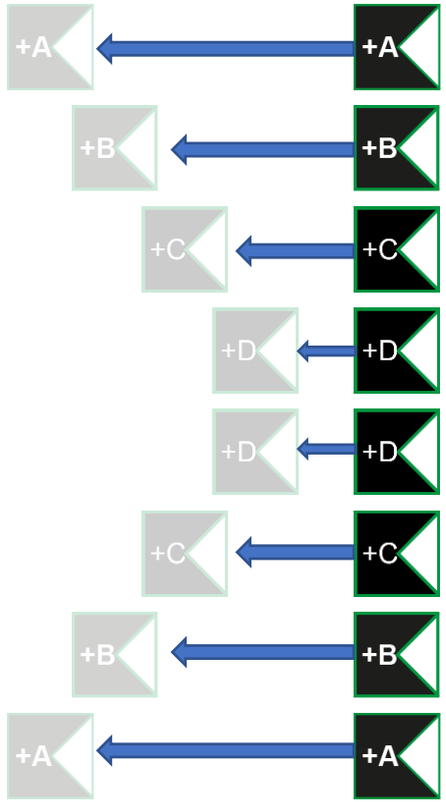
En augmentant la courbure de l'arc, on augmente la couverture.

Steering effect
Radial – Arc Sub virtuel

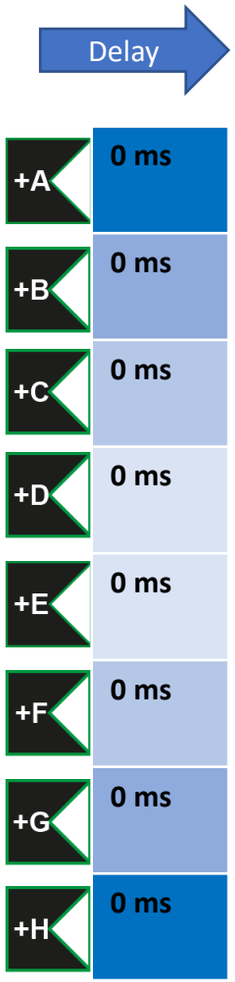


Steering effect

Radial – Arc Sub virtuel



Steering effect
Radial – Arc Sub virtuel

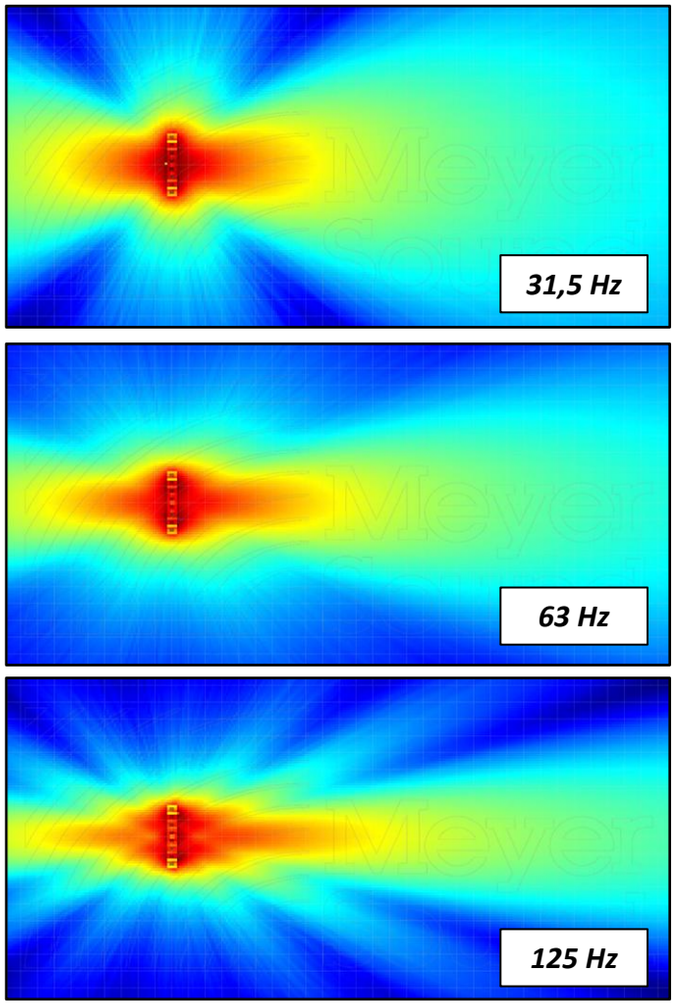


Steering effect
Radial – Arc Sub virtuel

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 °

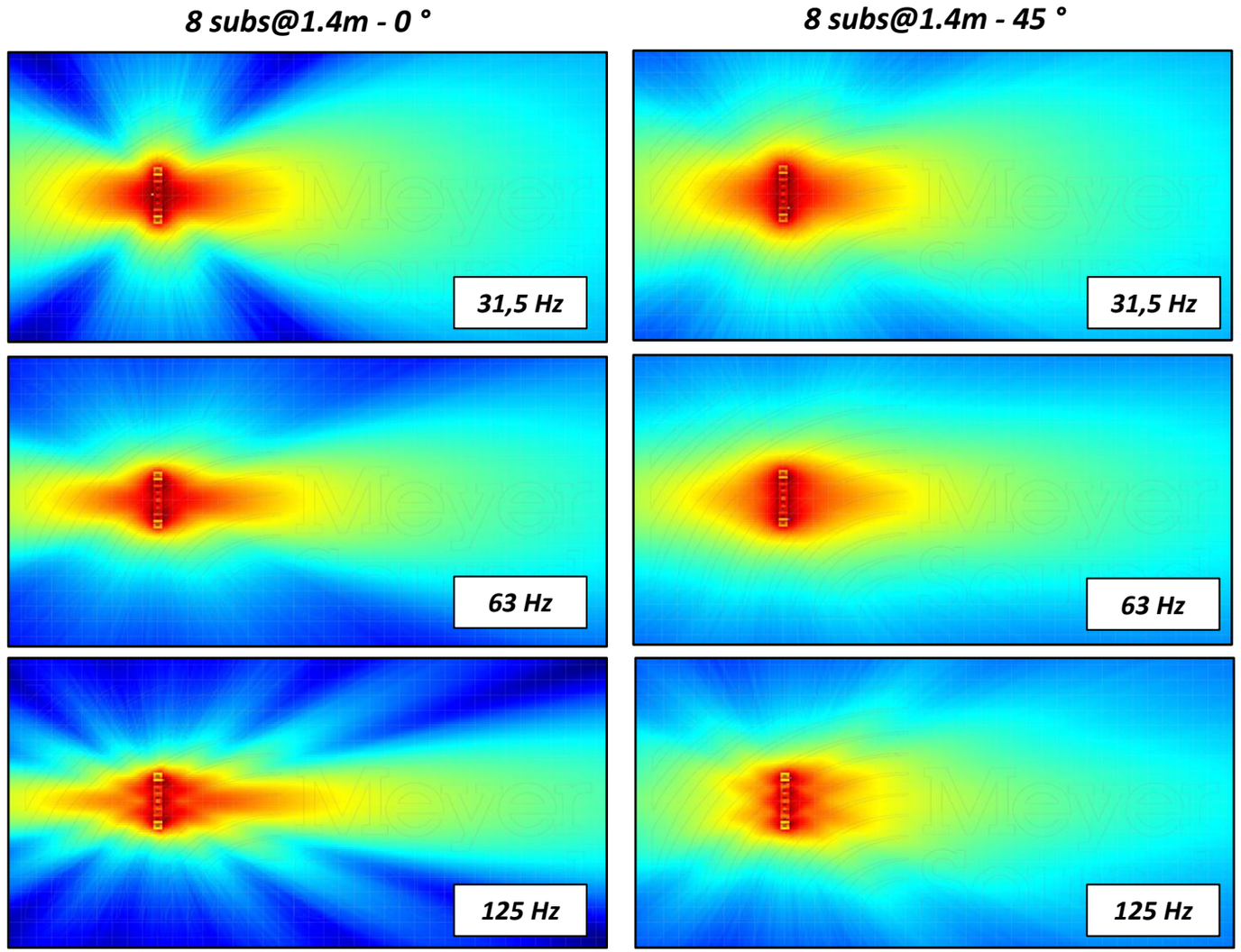


Steering effect

Radial – Arc Sub virtuel

Delay

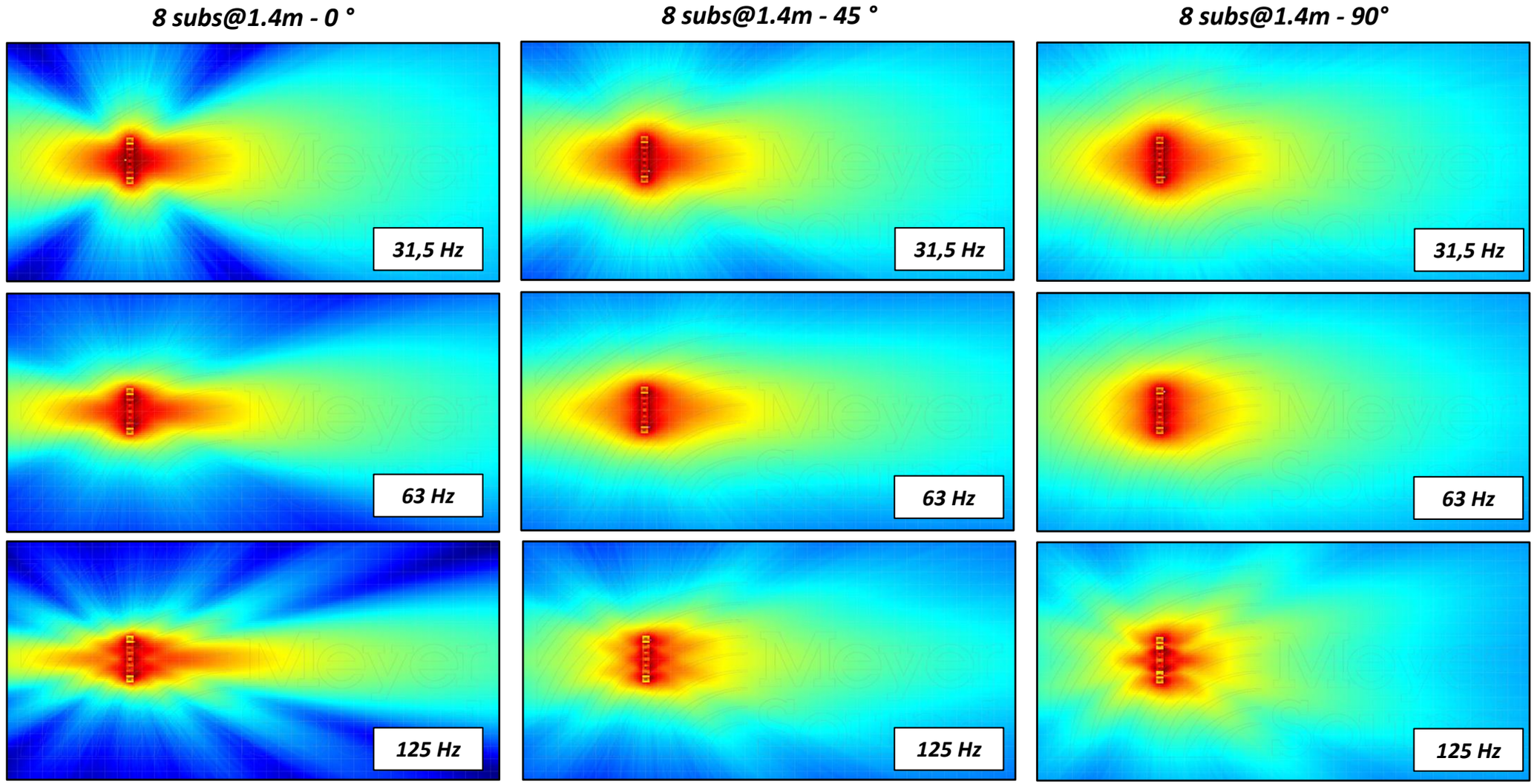
+A	2,6 ms
+B	0,8 ms
+C	0,2 ms
+D	0 ms
+E	0 ms
+F	0,2 ms
+G	0,8 ms
+H	2,6 ms



Steering effect
Radial – Arc Sub virtuel

Delay

+A	4,5 ms
+B	1,3 ms
+C	0,4 ms
+D	0 ms
+E	0 ms
+F	0,4 ms
+G	1,3 ms
+H	4,5 ms



En augmentant les délais de l'arc, on augmente la couverture.

?



3
Forward Steering

Configurations «Cardio»

Directivité

Il existe deux méthodes principales pour rendre des ensembles de subs directifs.

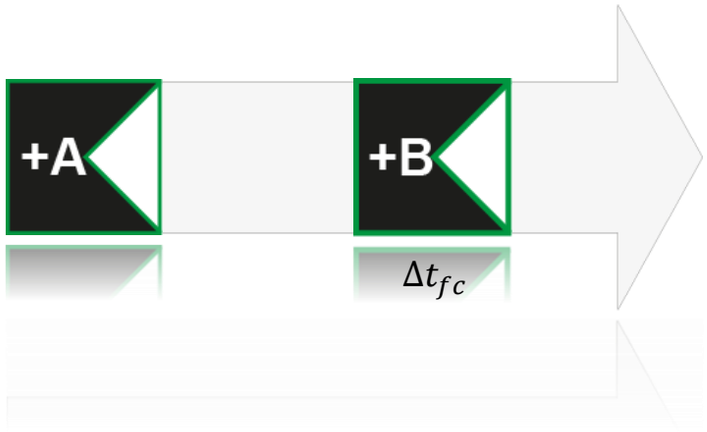
Directivité

Il existe deux méthodes principales pour rendre des ensembles de subs directifs.
Ces ensembles sont souvent nommés par le simple mot «Cardioïde».

Directivité

Il existe deux méthodes principales pour rendre des ensembles de subs directifs.
Ces ensembles sont souvent nommés par le simple mot «Cardioïde».

Configurations «natives»

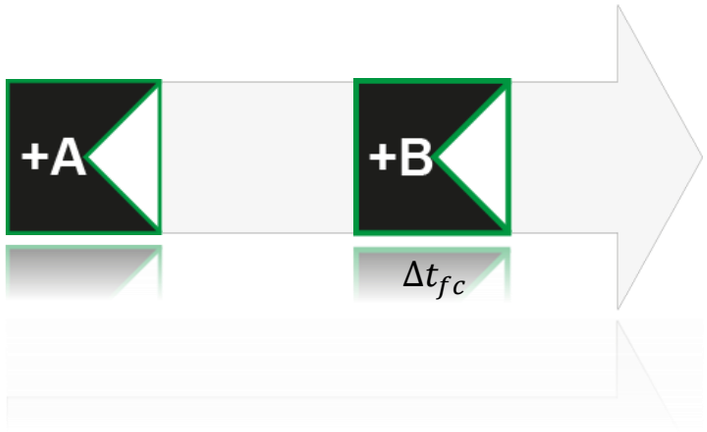


Configurations à «gradient de pression»

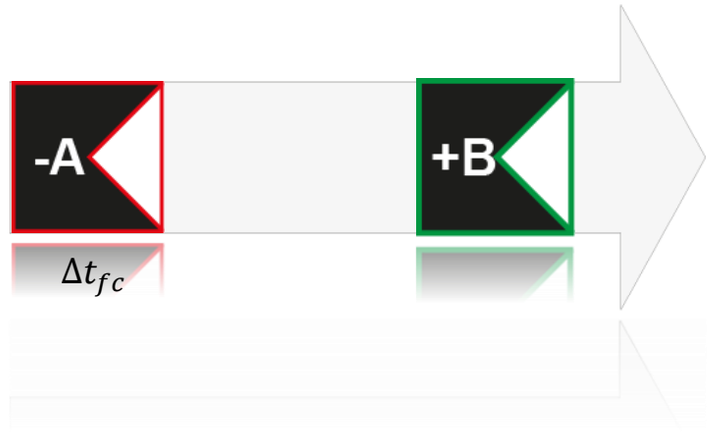
Directivité

Il existe deux méthodes principales pour rendre des ensembles de subs directifs.
Ces ensembles sont souvent nommés par le simple mot «Cardioïde».

Configurations «natives»



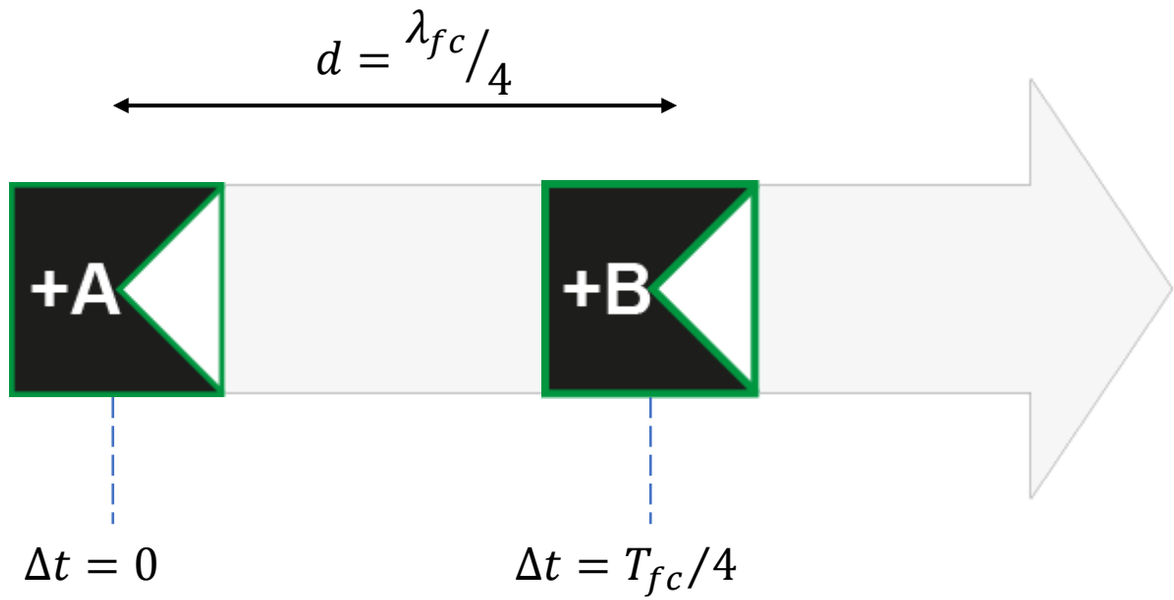
Configurations à «gradient de pression»



Configurations "Natives"

Paramètres	
$fc =$	$\boldsymbol{fc}$
$\lambda =$	$\boldsymbol{\lambda_{fc}}$
$T =$	$\boldsymbol{T_{fc}}$

- $\boldsymbol{fc}$ = *Fréquence centrale*
- $\boldsymbol{\lambda_{fc}}$ = *Longueur d'onde de la fréquence centrale*
- $\boldsymbol{T_{fc}}$ = *Période de la fréquence centrale*



Configurations "Natives"
Visualisation Ondulatoire

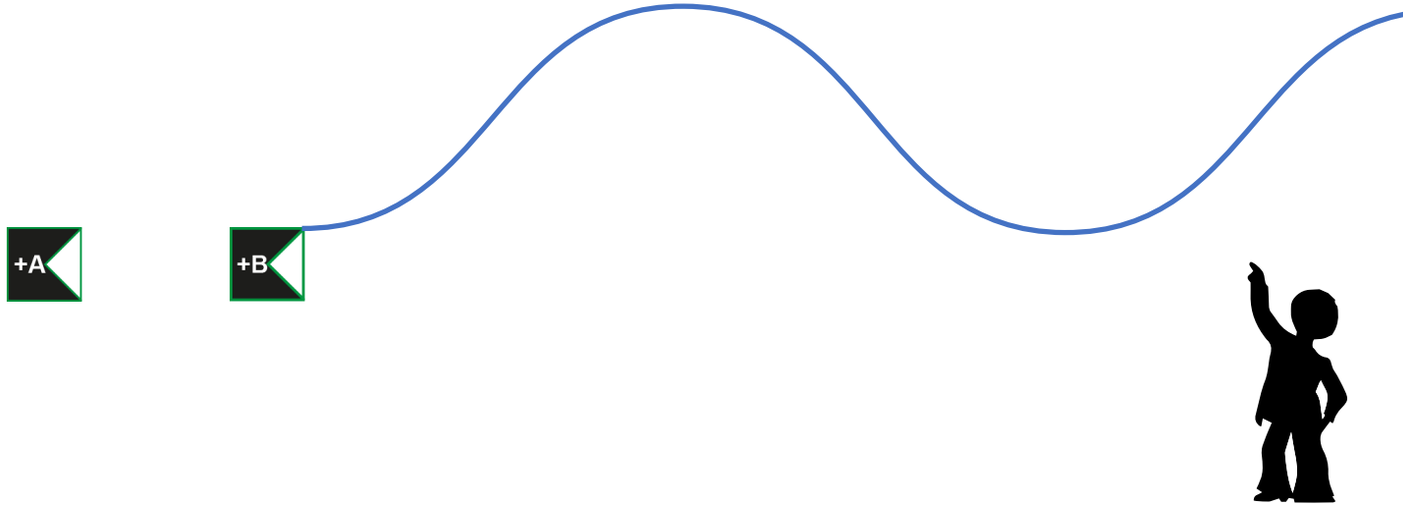




Configurations "Natives"

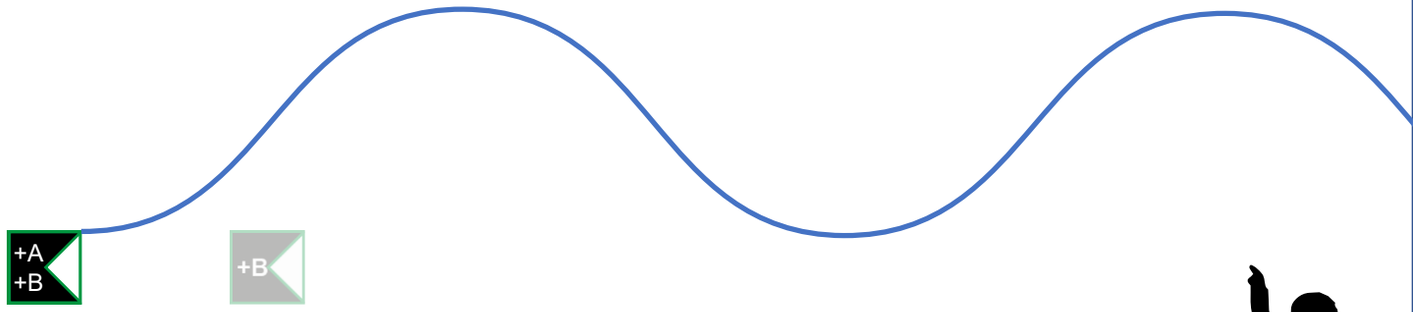
Visualisation Ondulatoire

Vue de l’avant



Configurations "Natives"
Visualisation Ondulatoire

Vue de l'avant

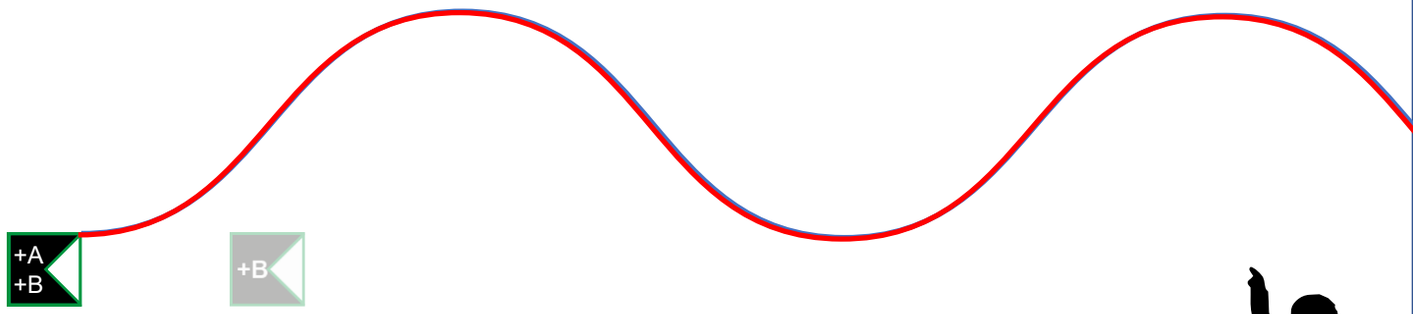


$$\Delta t = T_{fc}/4$$



Configurations "Natives"
Visualisation Ondulatoire

Vue de l'avant

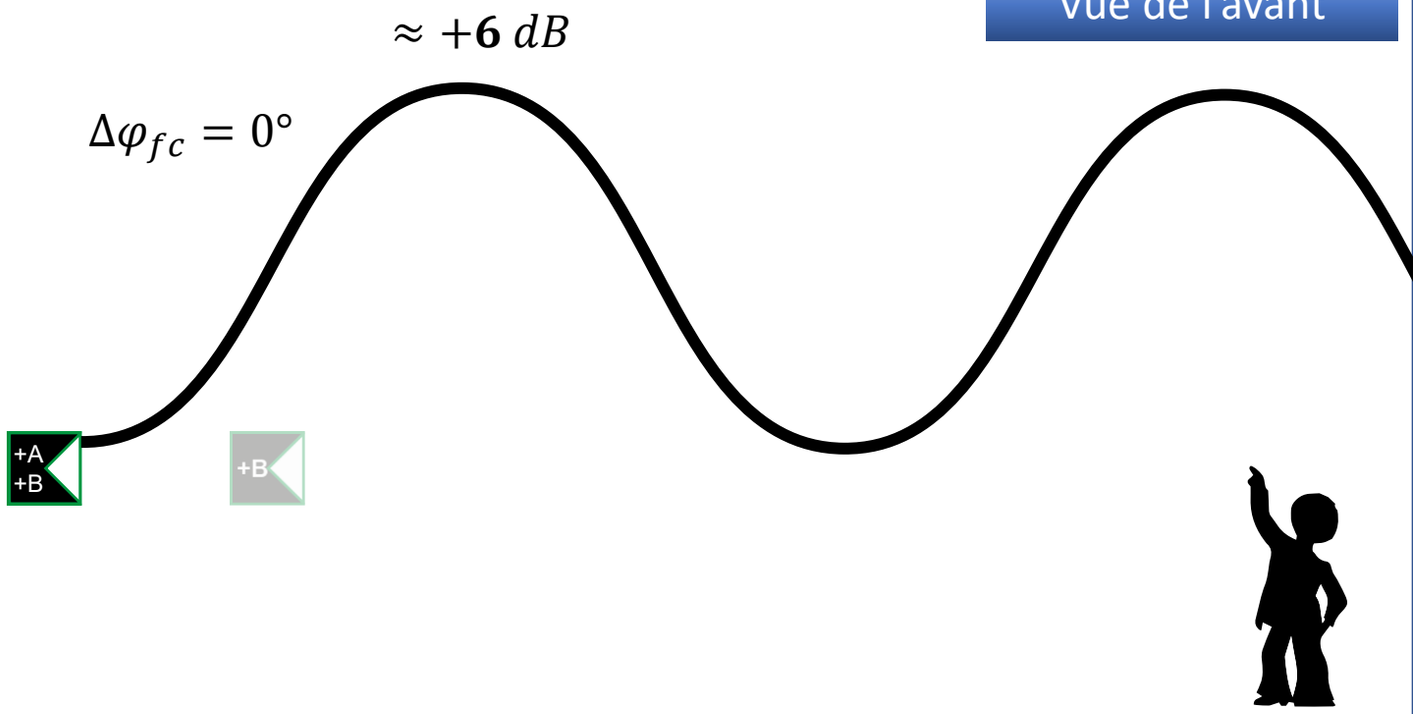


$$\Delta t = T_{fc}/4$$



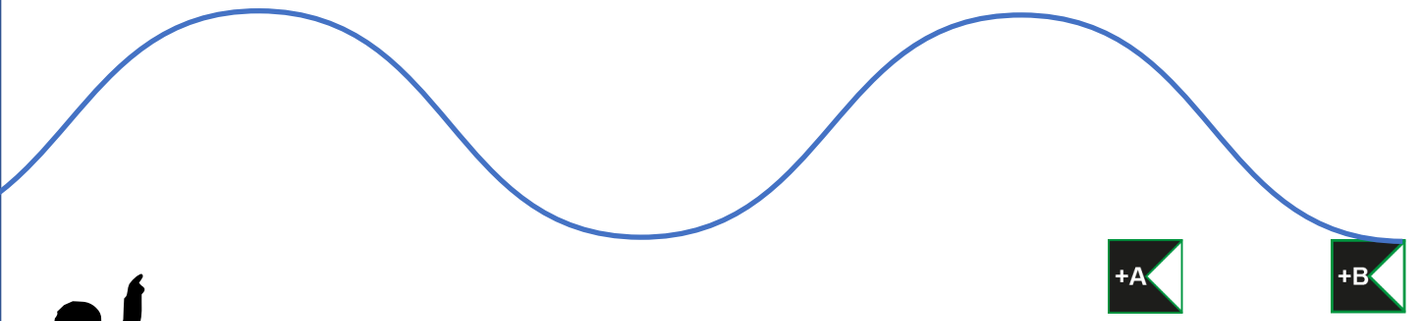
Configurations "Natives"
Visualisation Ondulatoire

Vue de l'avant



Configurations "Natives"
Visualisation Ondulatoire

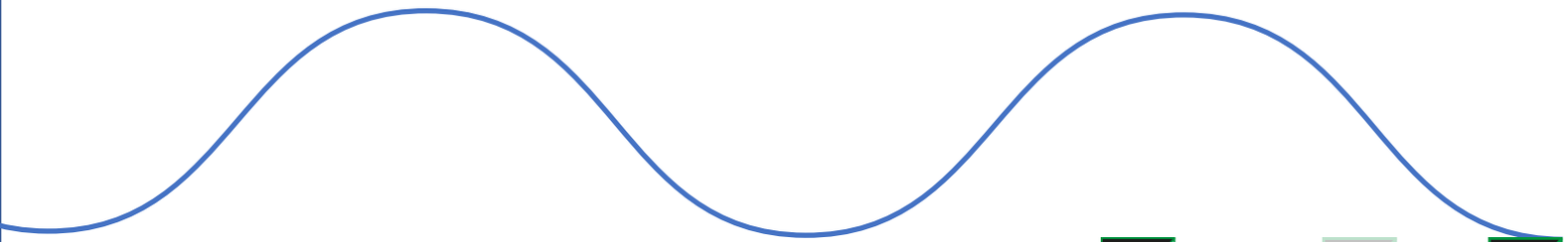
Vue de l’arrière





Configurations "Natives"
Visualisation Ondulatoire

Vue de l'arrière



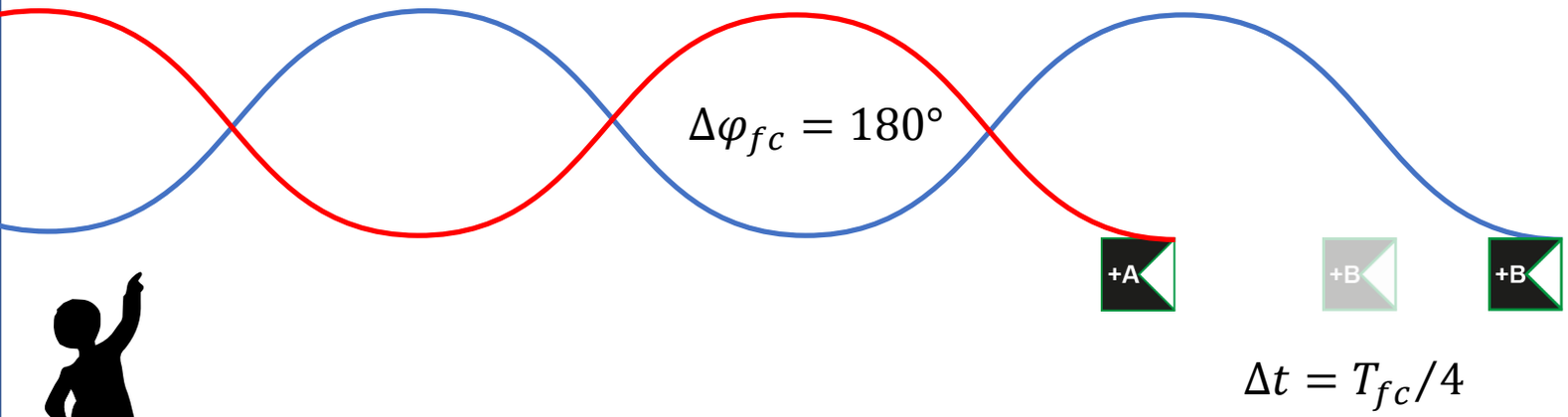




$$\Delta t = T_{fc}/4$$

Configurations "Natives"
Visualisation Ondulatoire

Vue de l'arrière



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

Configurations "Natives"
Visualisation Ondulatoire

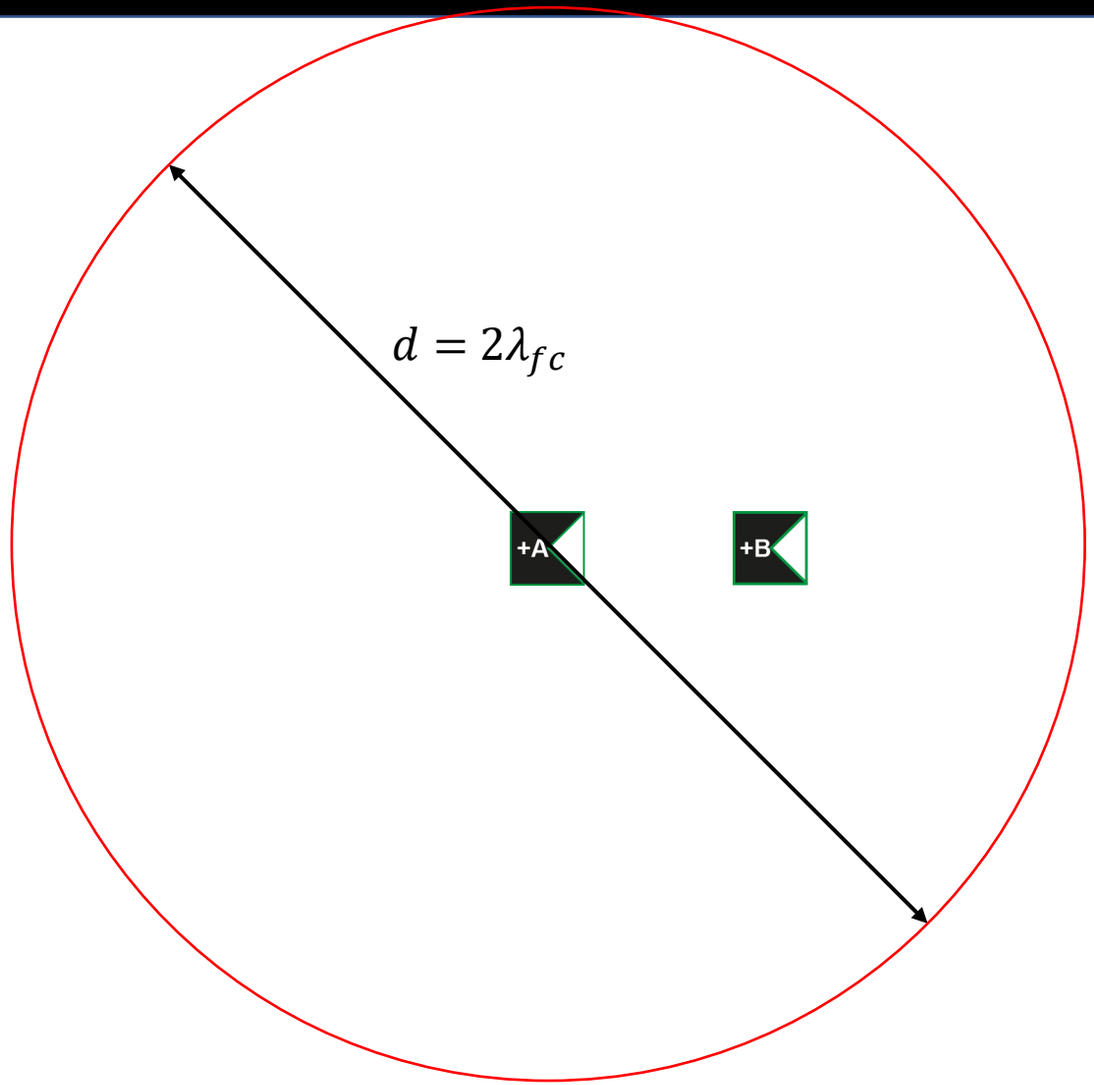
$$\Delta\varphi_{fc} = 180°$$



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

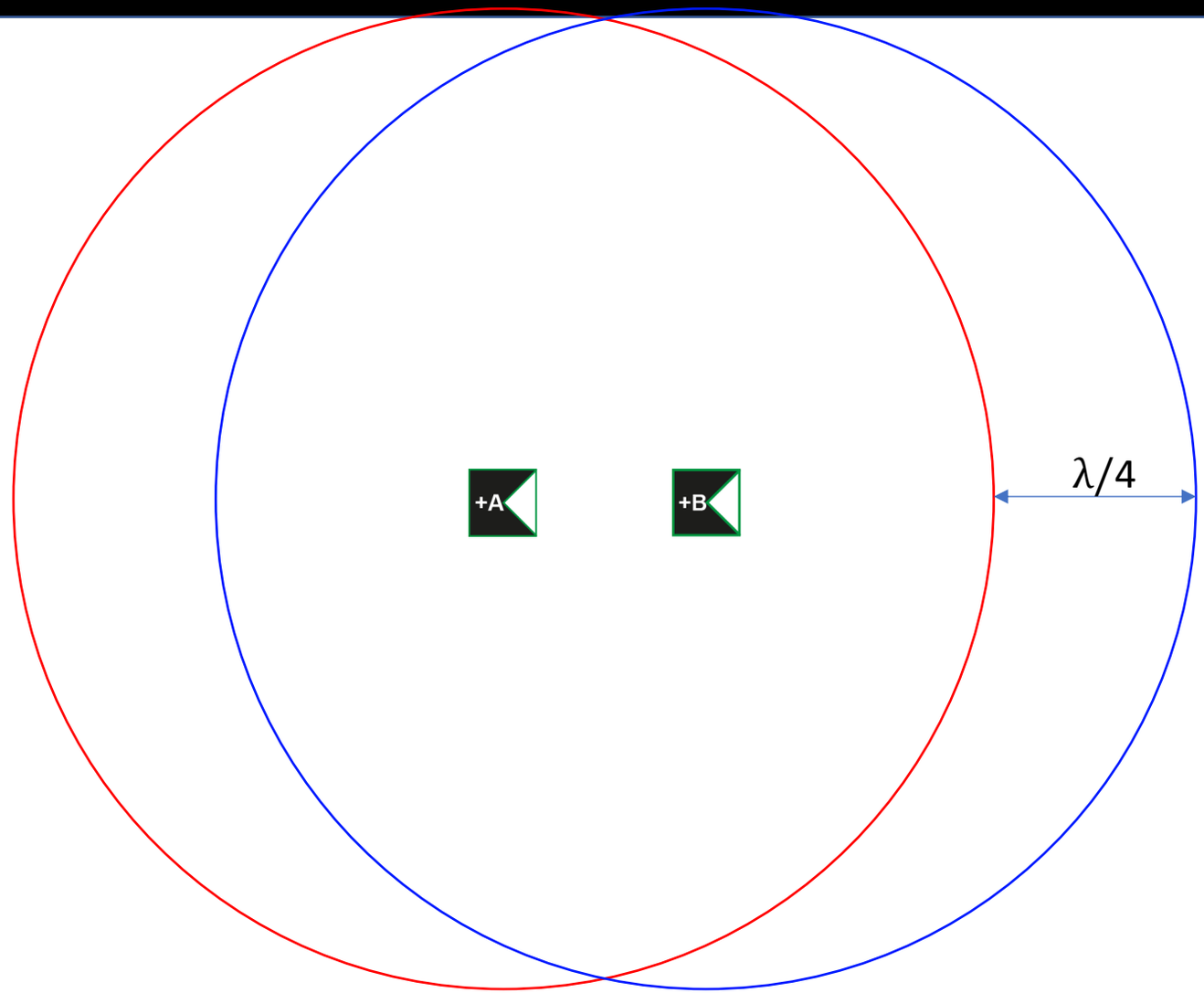
Configurations "Natives"

Visualisation circulaire



Configurations "Natives"

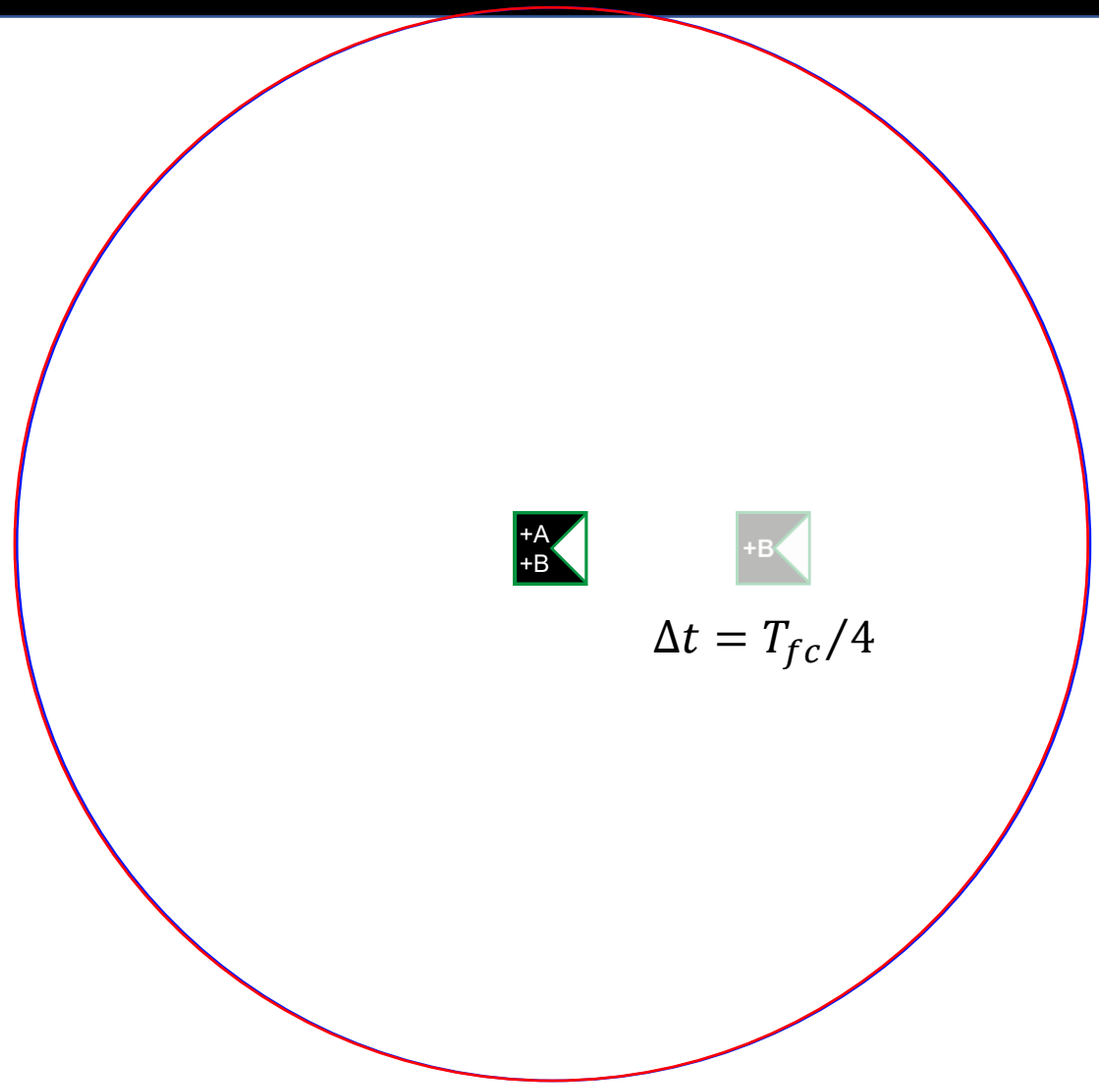
Visualisation circulaire



Configurations "Natives"

Visualisation circulaire

Vue de l'avant

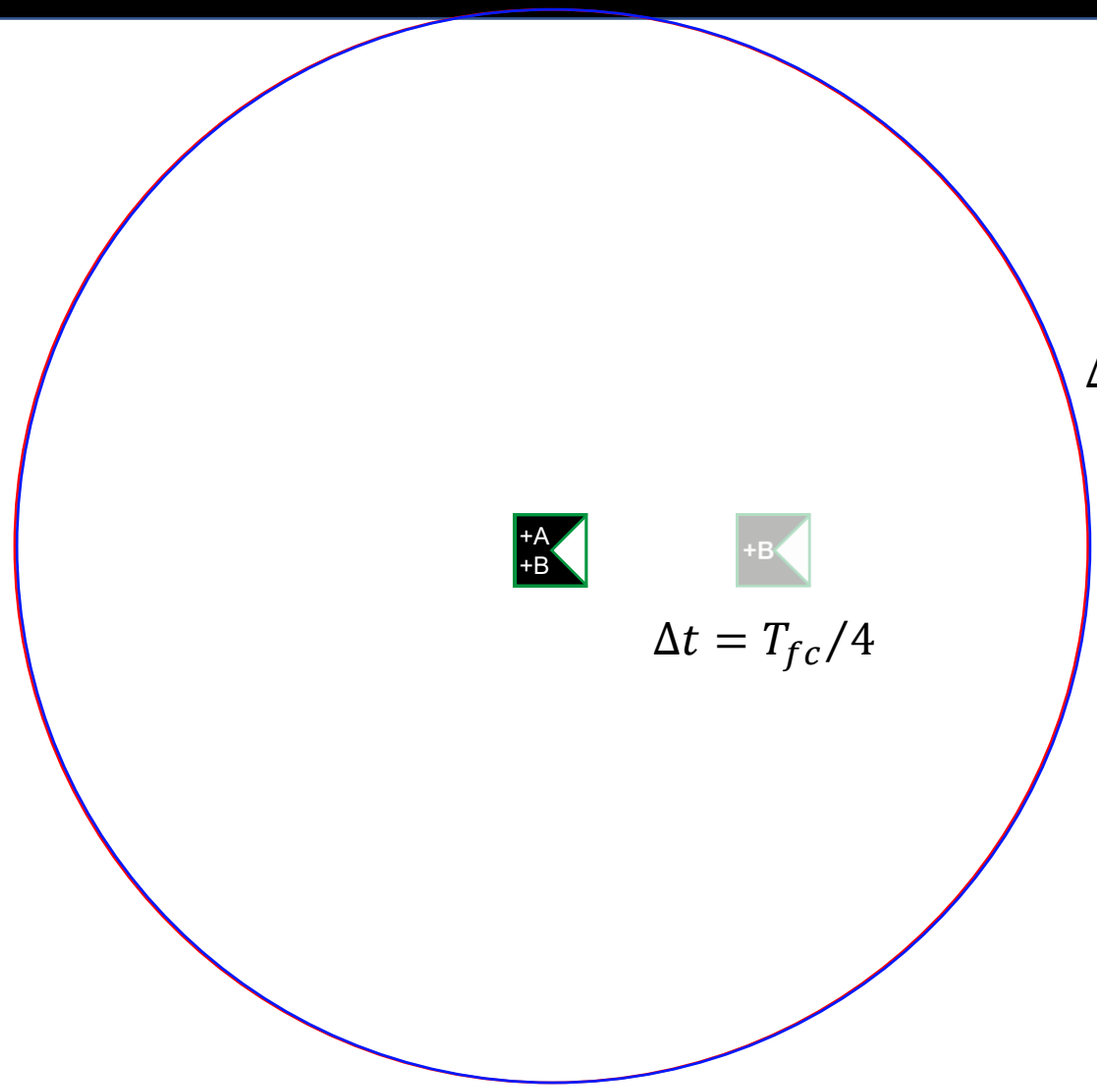




Configurations "Natives"

Visualisation circulaire

Vue de l'avant



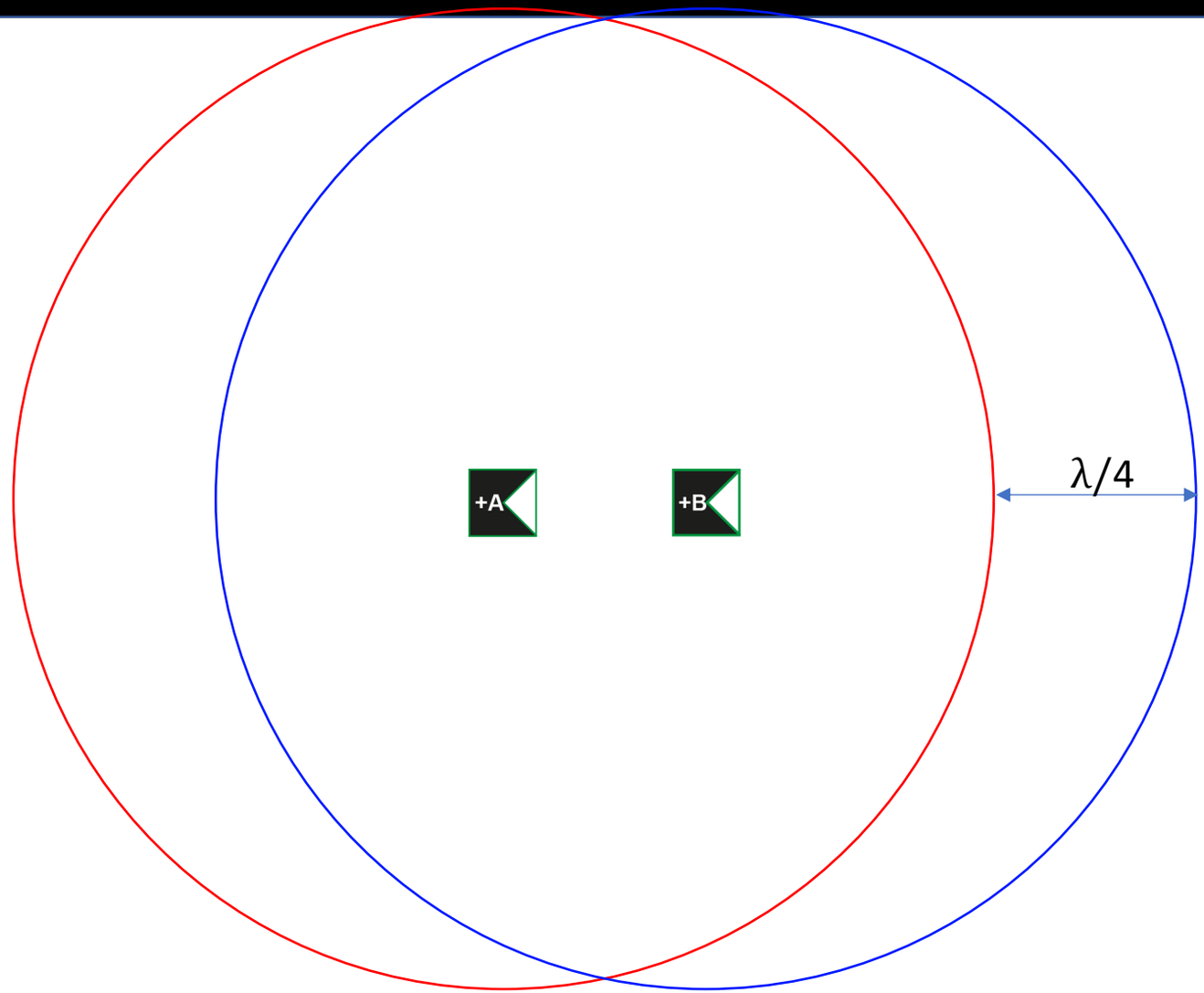
$\Delta\varphi_{fc} = 0°$

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



Configurations "Natives"

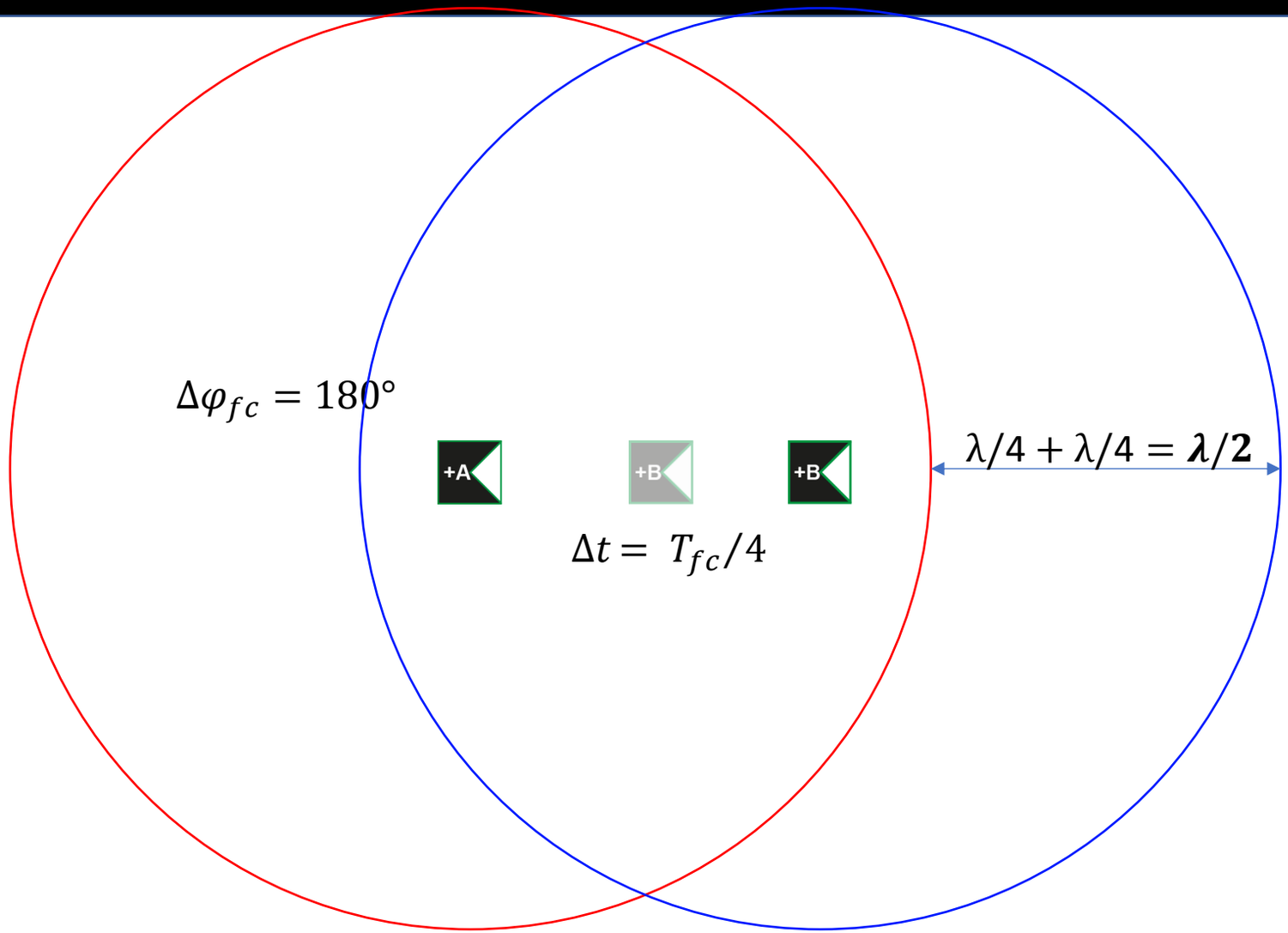
Visualisation circulaire



Configurations "Natives"
Visualisation circulaire

Vue de l'arrière

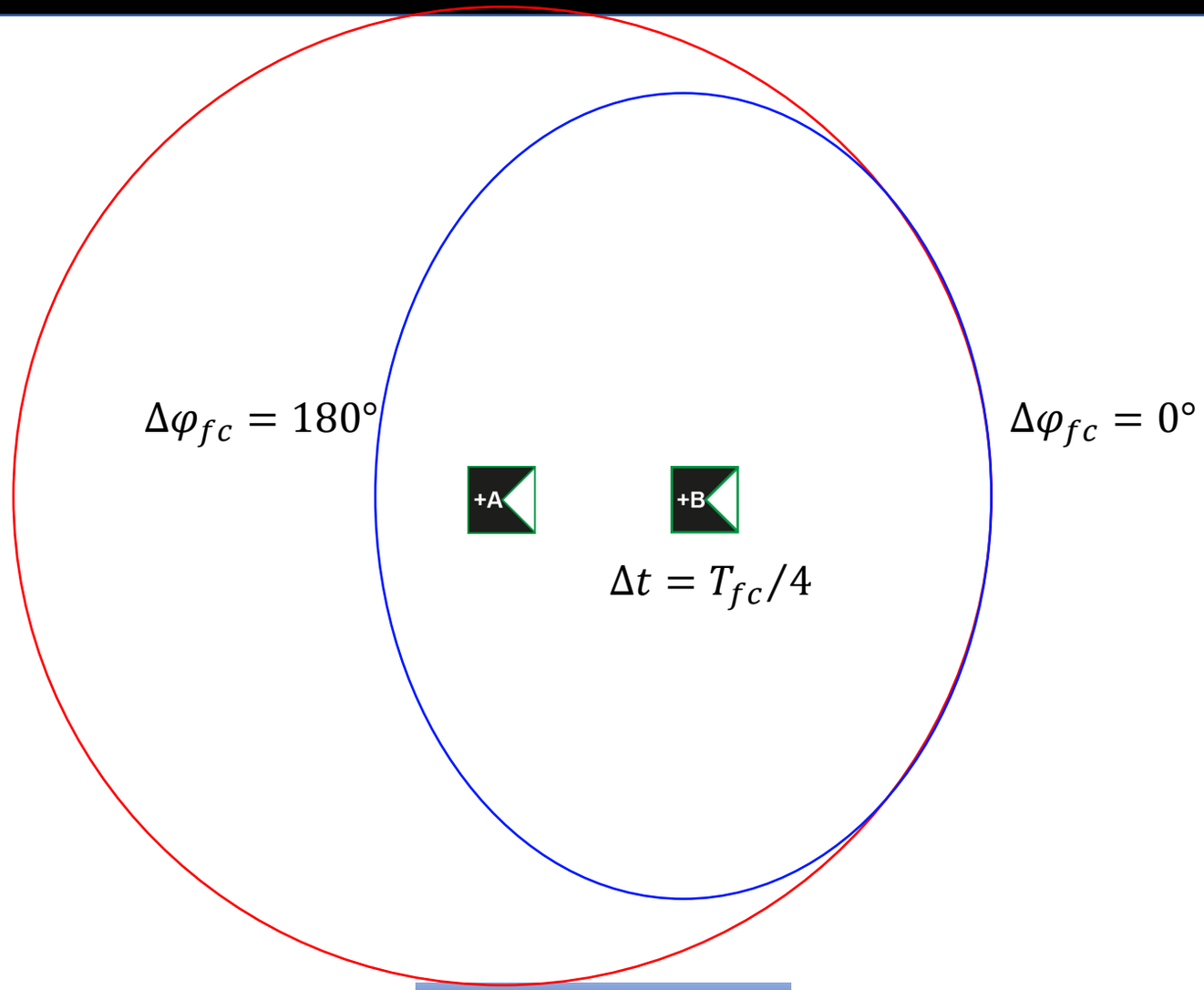




Configurations "Natives"

Visualisation circulaire



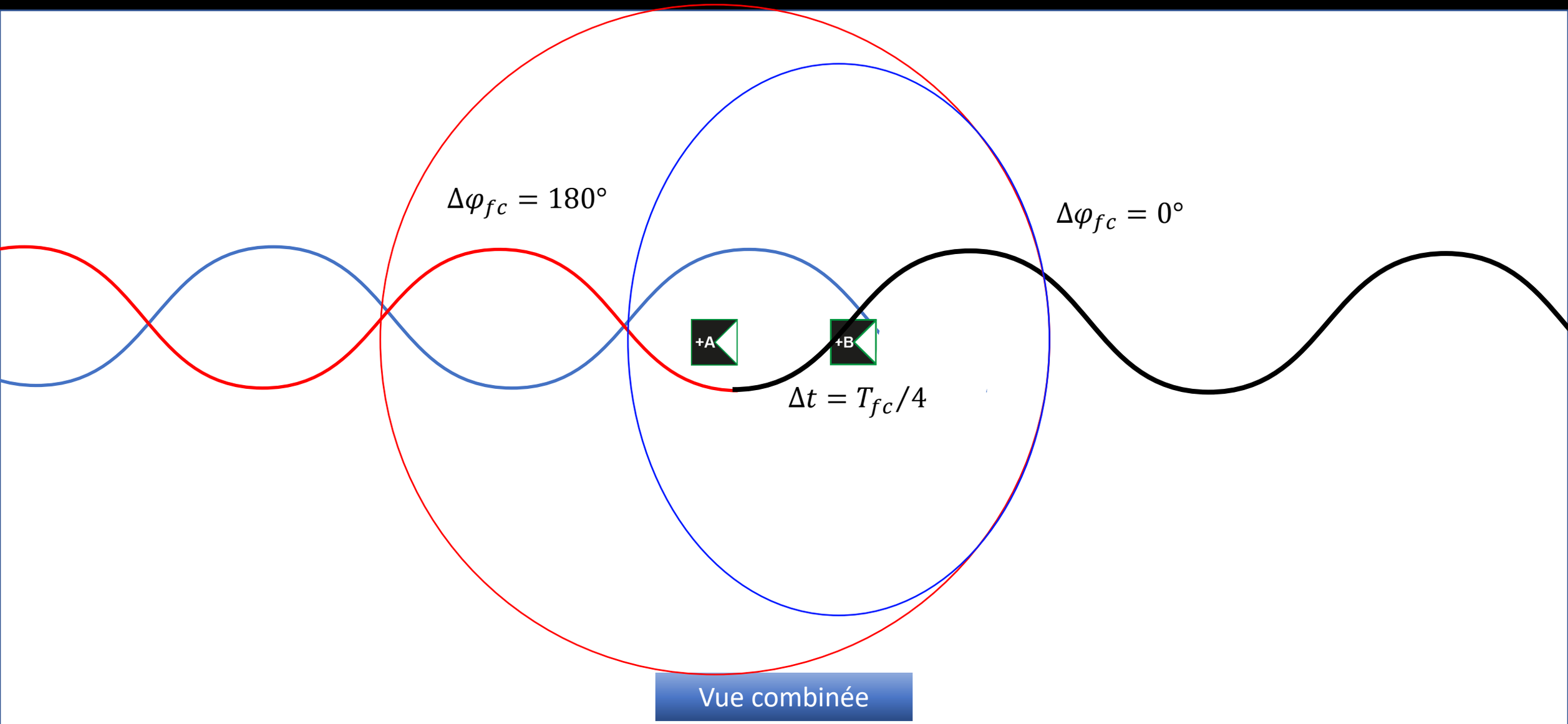




Vue combinée

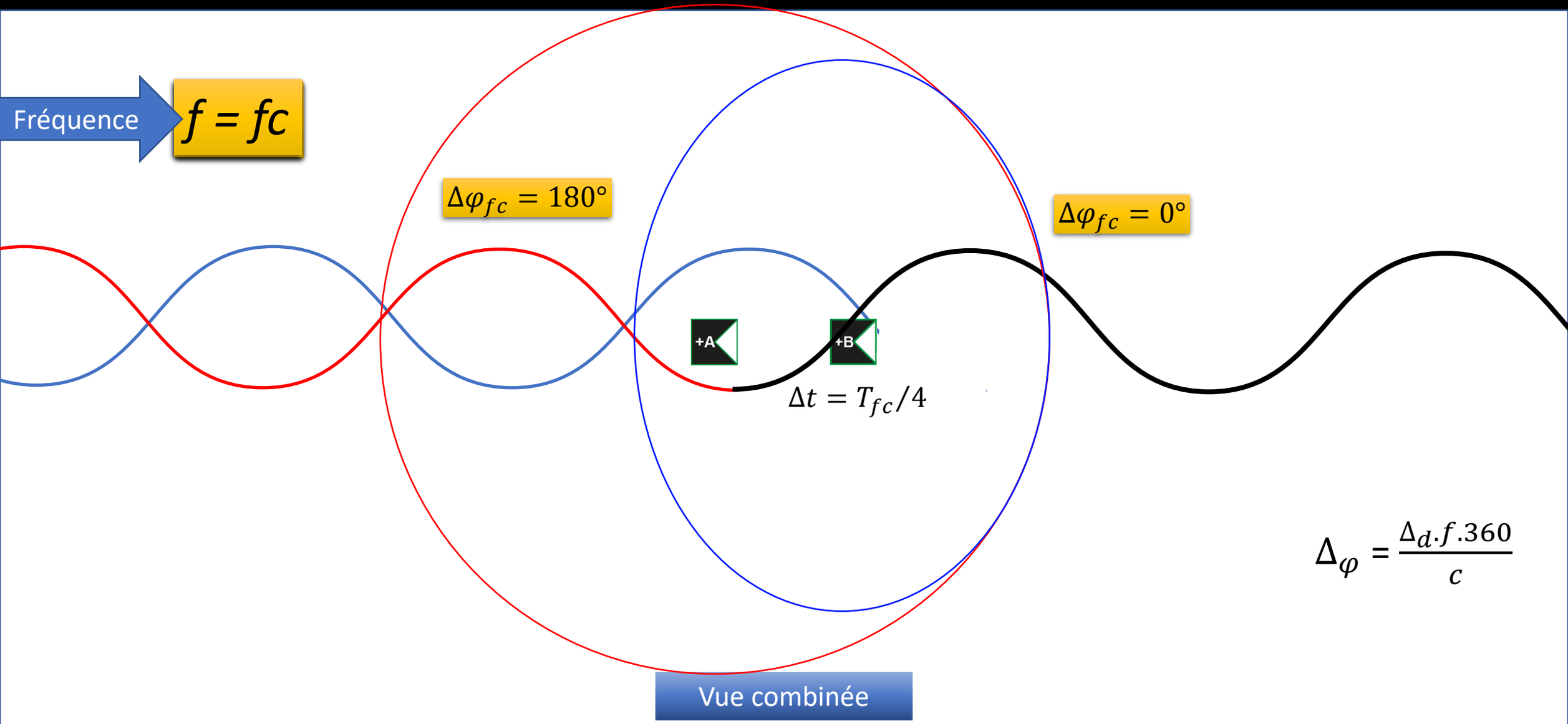
Configurations "Natives"

Visualisation Globale



Configurations "Natives"

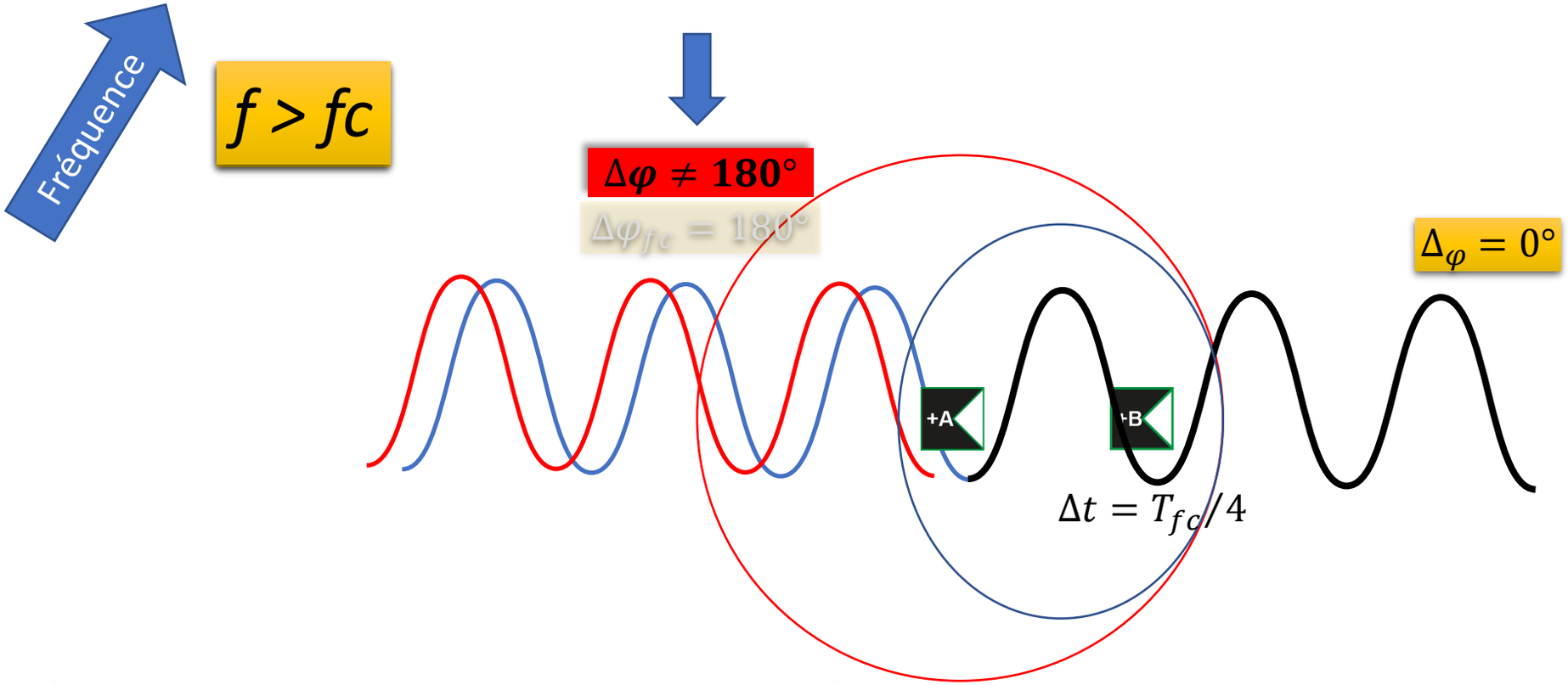
Variations de fréquence = Variation de phase arrière



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

Configurations "Natives"

Variations de fréquence = Variation de phase arrière

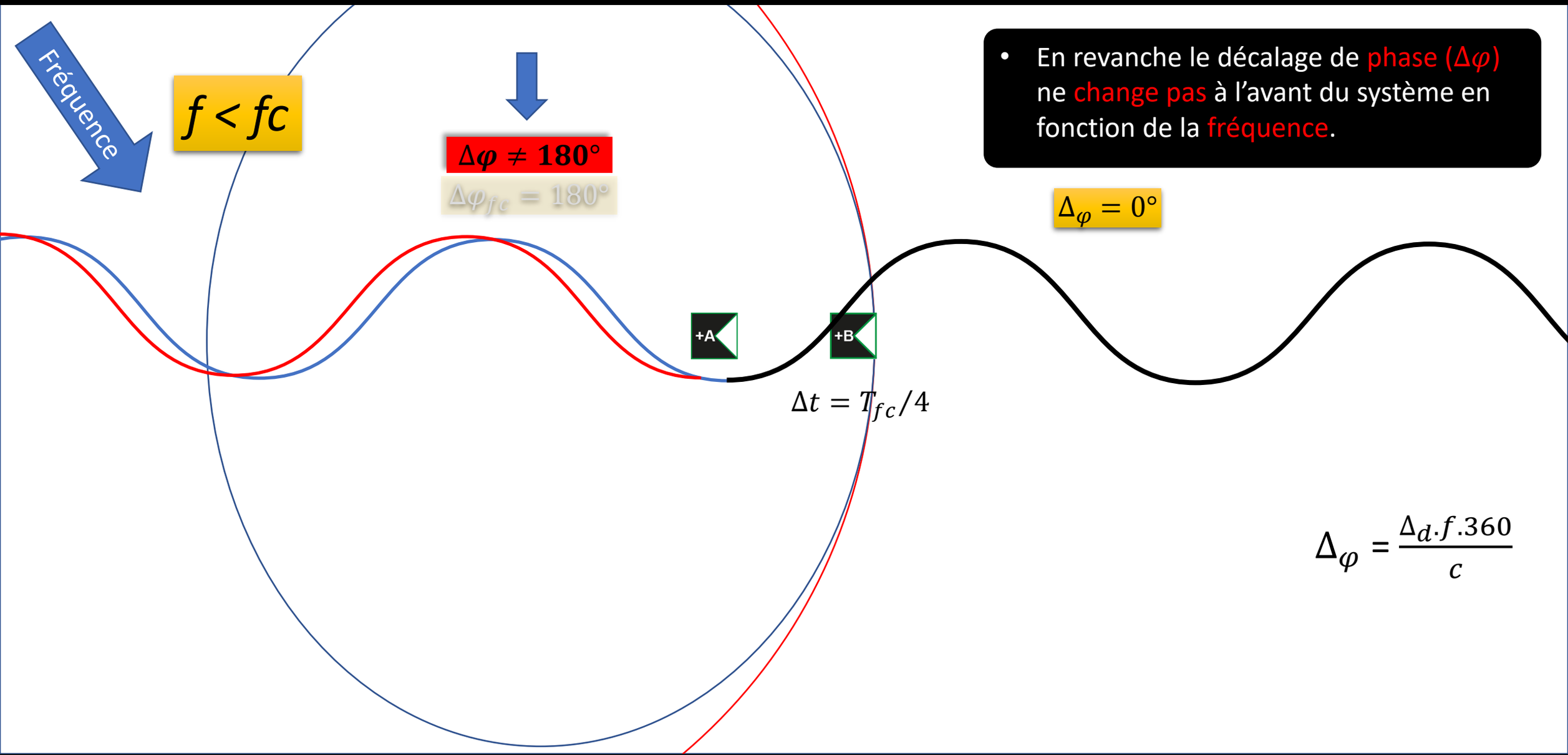


- On constate que le décalage de phase ($\Delta\varphi$) à l'arrière du système varie en fonction de la fréquence.

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

Configurations "Natives"

Variations de fréquence = Variation de phase arrière



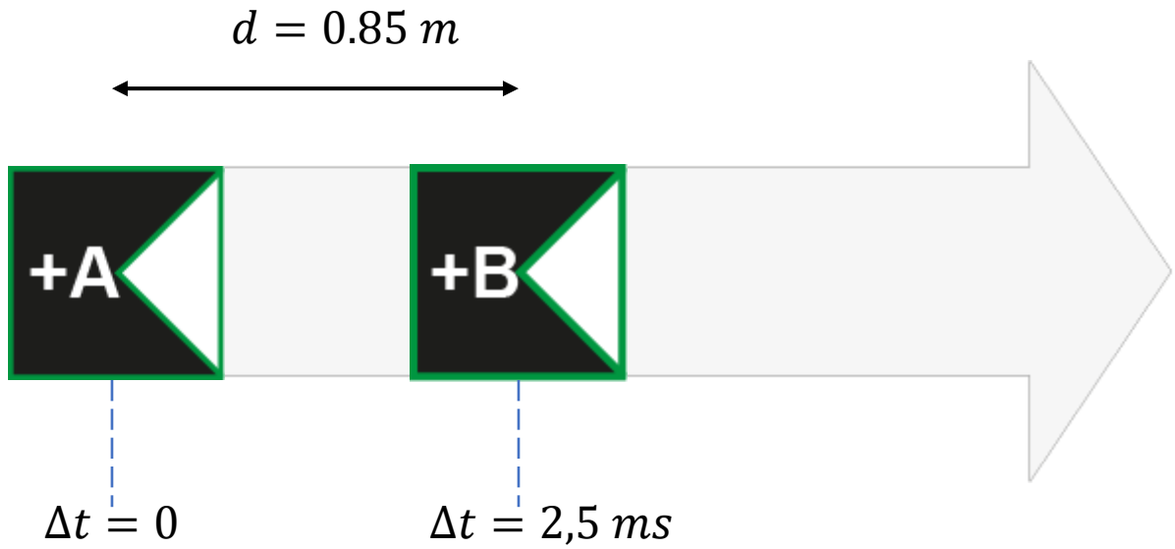
- En revanche le décalage de phase ($\Delta\varphi$) ne change pas à l'avant du système en fonction de la fréquence.

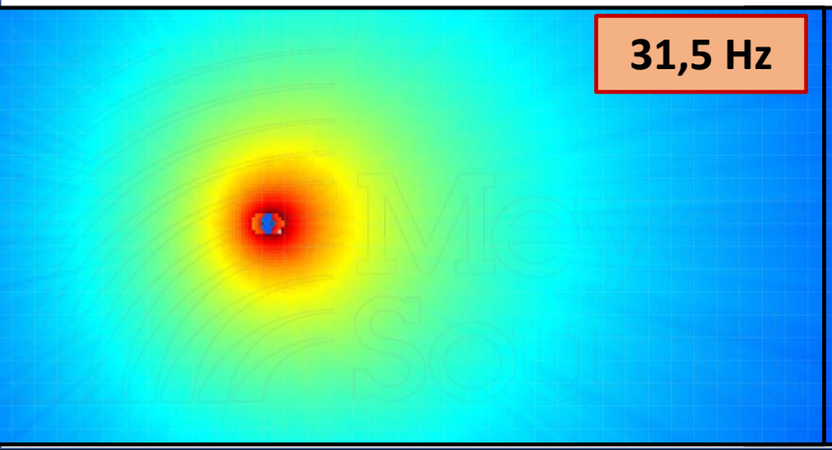
$$\Delta_\varphi = \frac{\Delta_d . f . 360}{c}$$

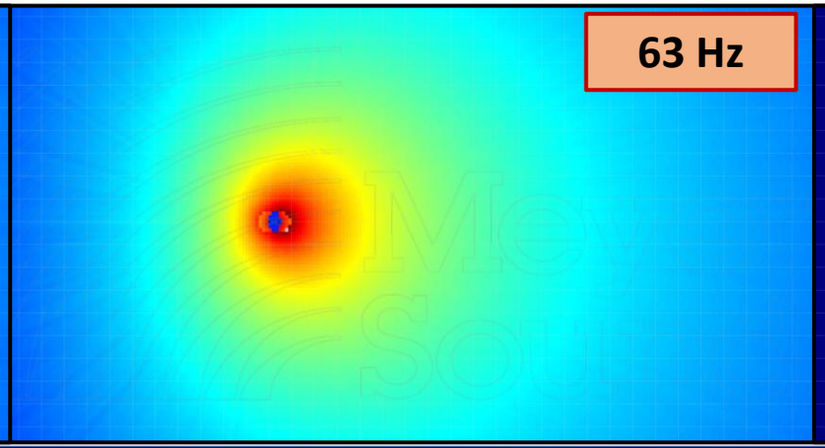
Configurations "Natives"

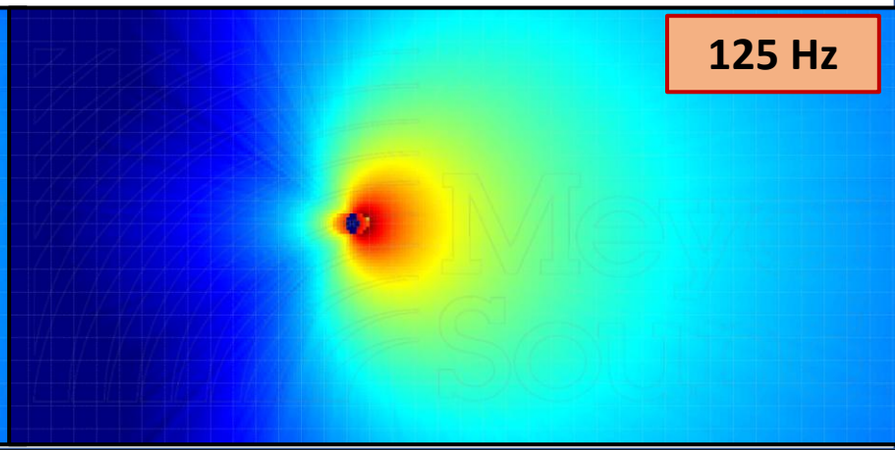
Exemple 0.85 m

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





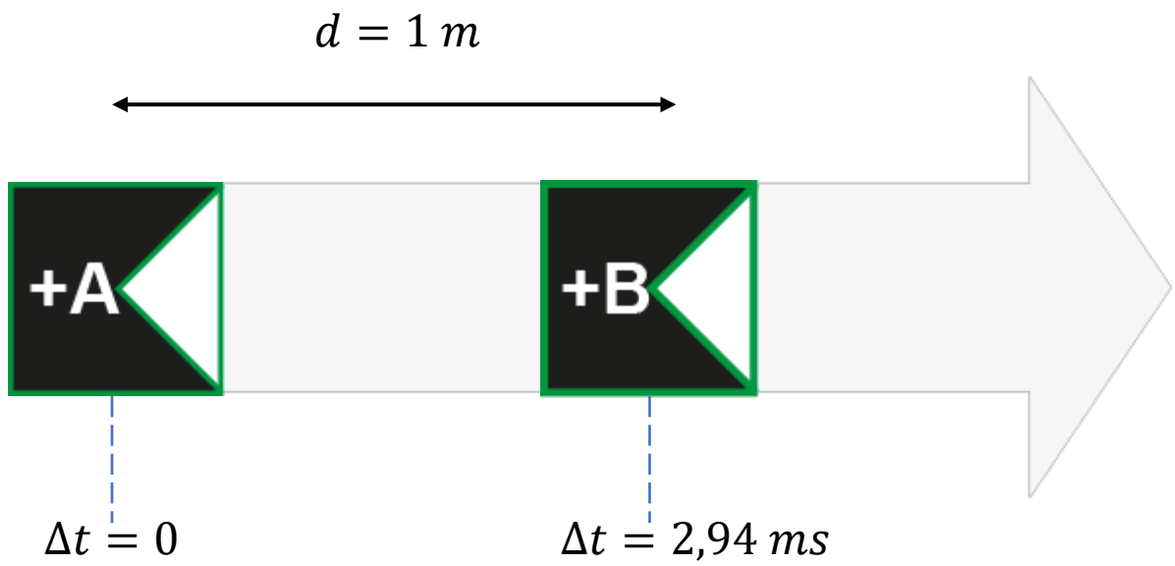


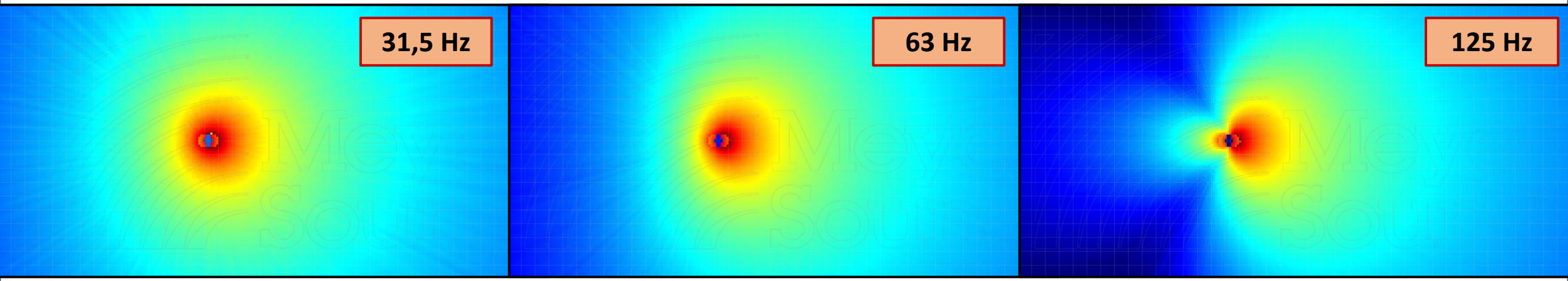


Configurations "Natives"

Exemple 1m

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

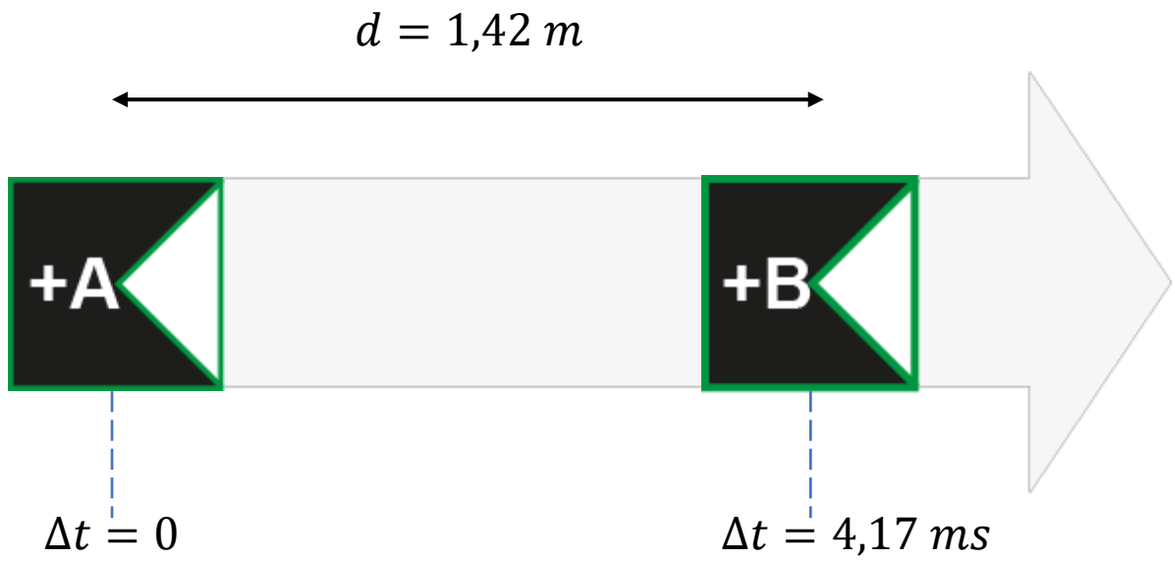


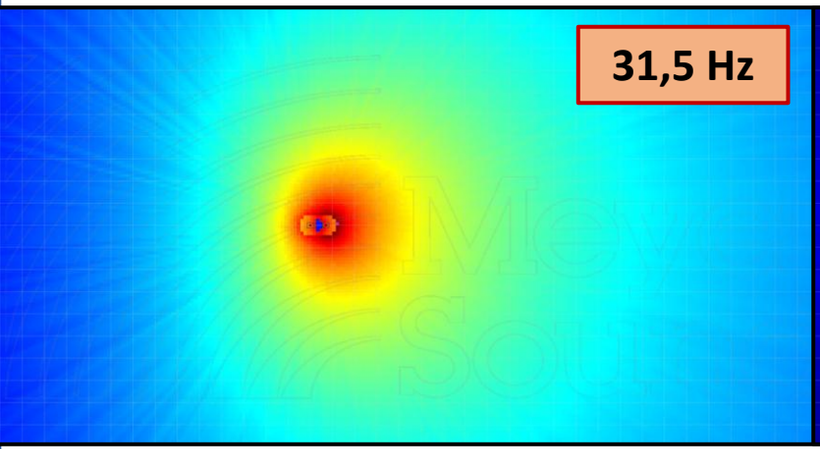


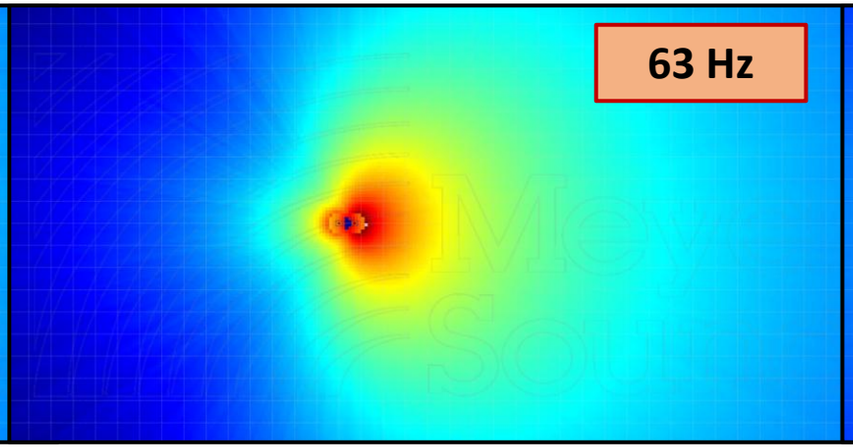
Configurations "Natives"

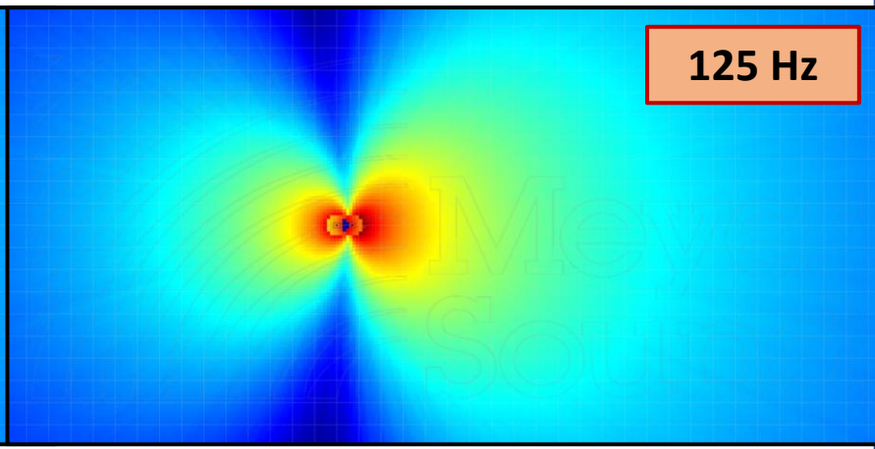
Exemple 1.42 m

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



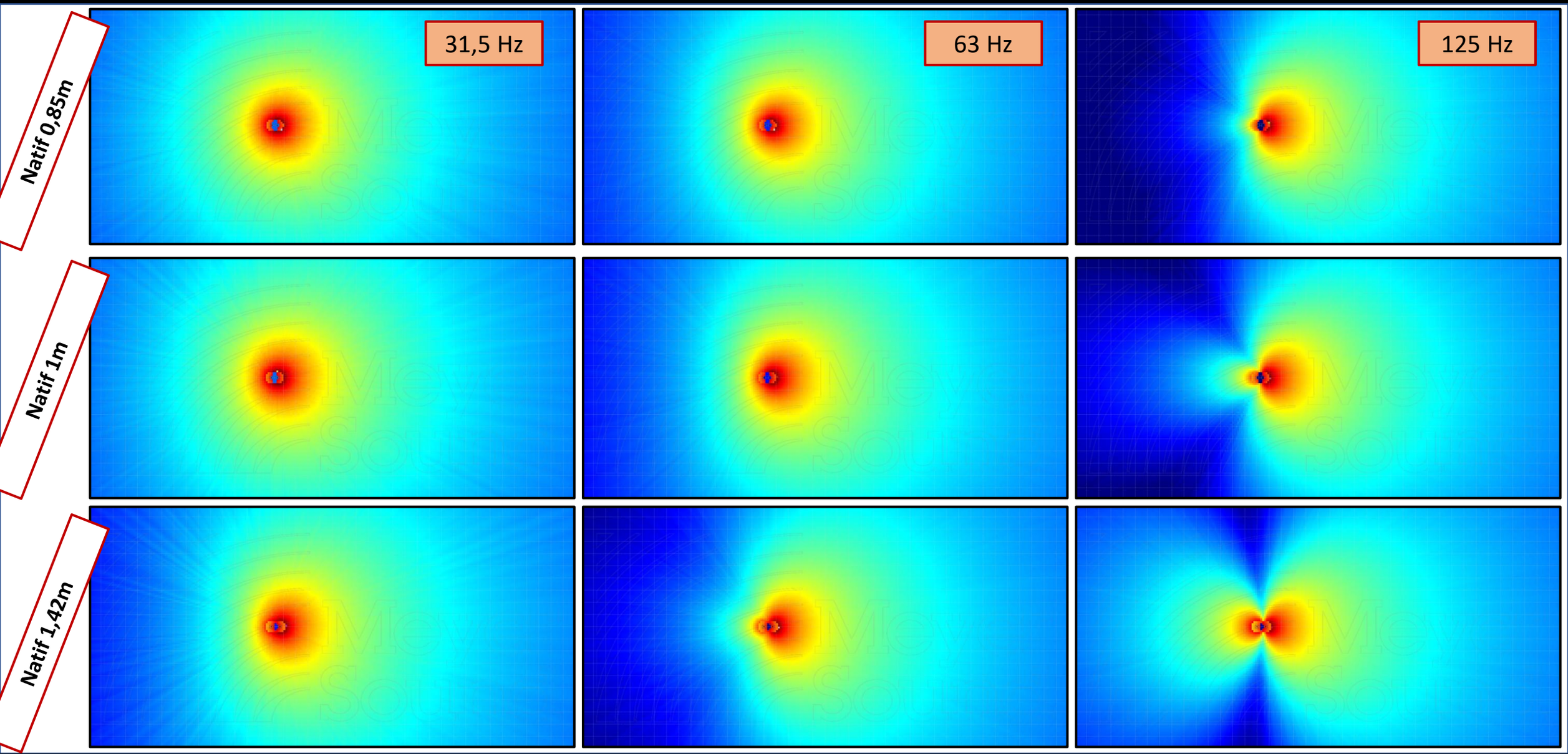




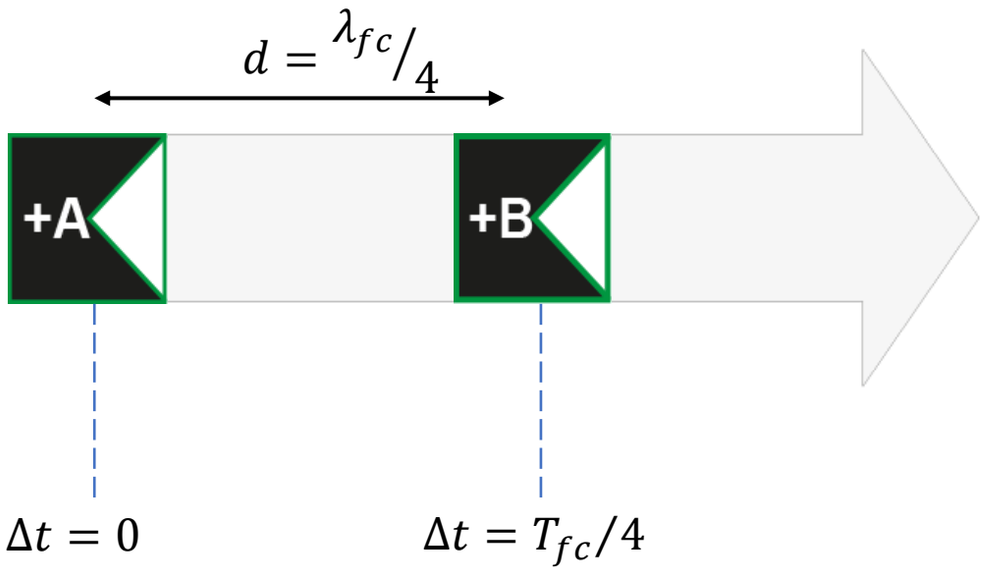


Configurations "Natives"

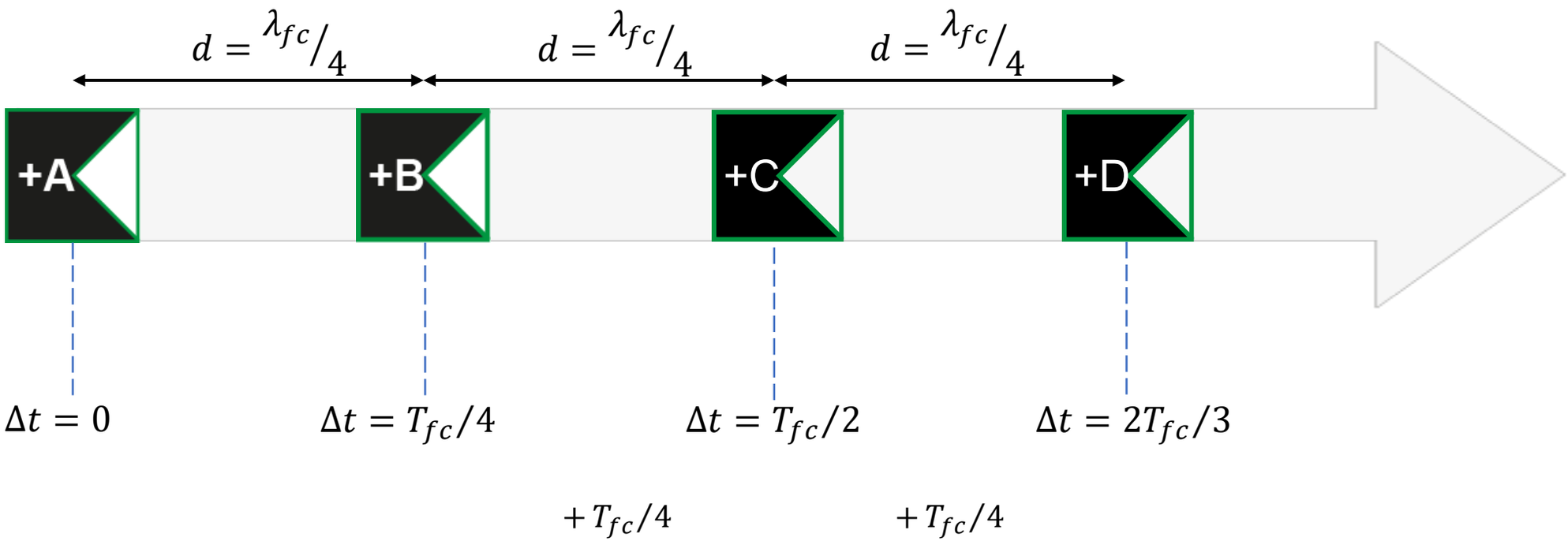
Comparaison



End Fire - Standard



End Fire - Standard



End Fire - Standard



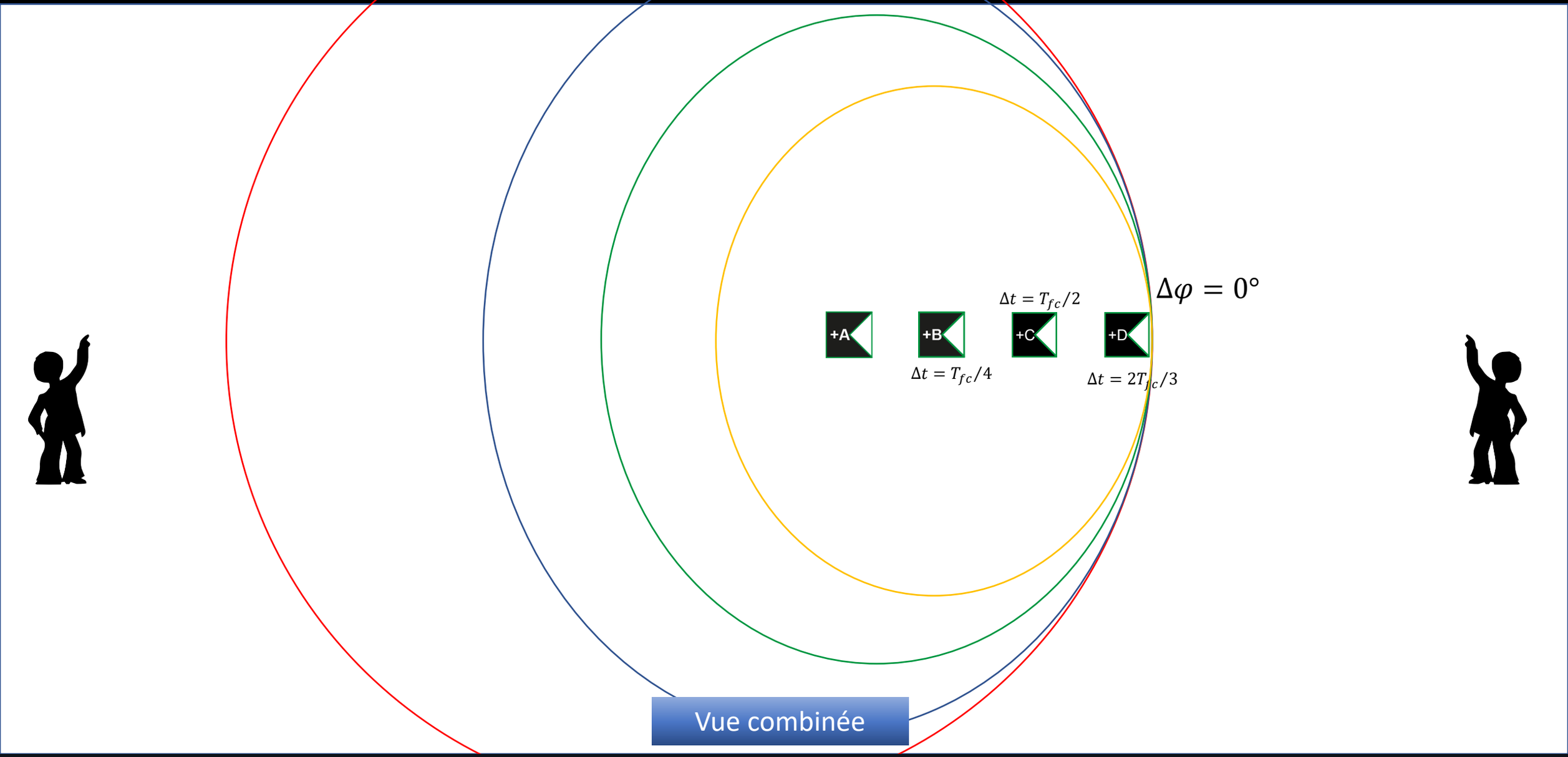




Vue combinée

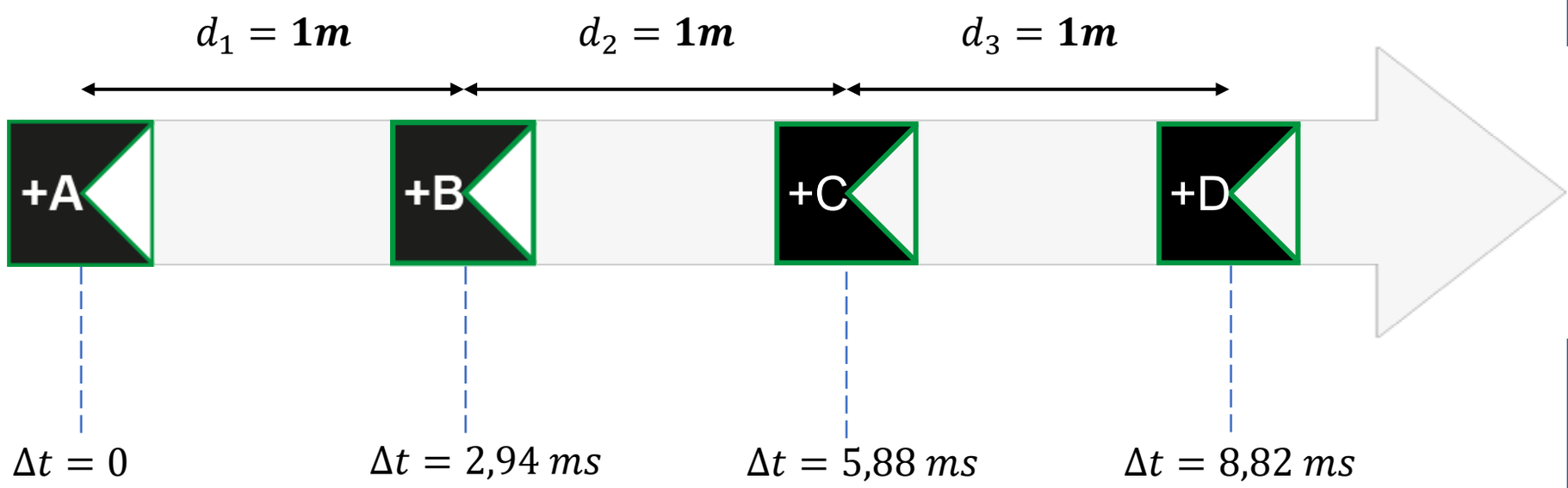
End Fire - Standard

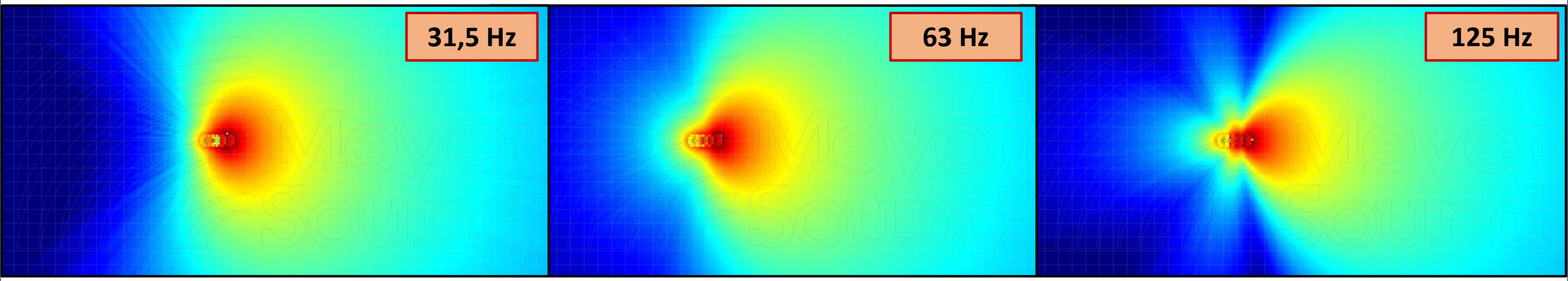
Visualisation circulaire



End Fire - Standard

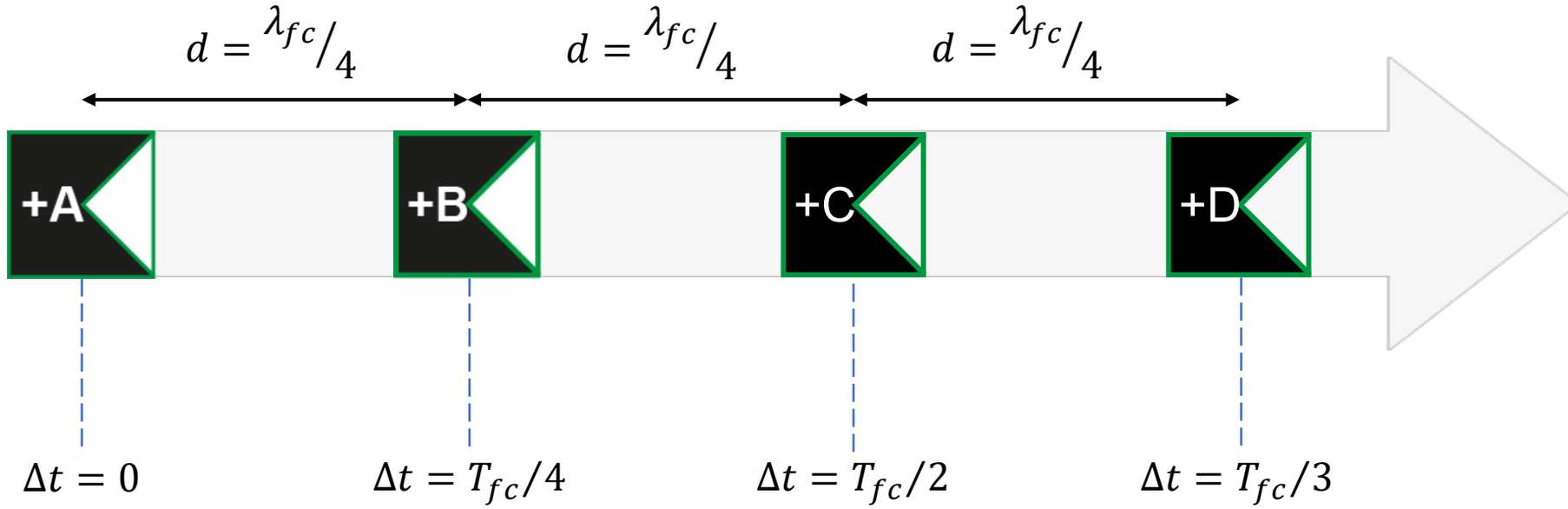
Paramètres	
fc =	85 Hz
λ =	4 m
T =	11.66 ms





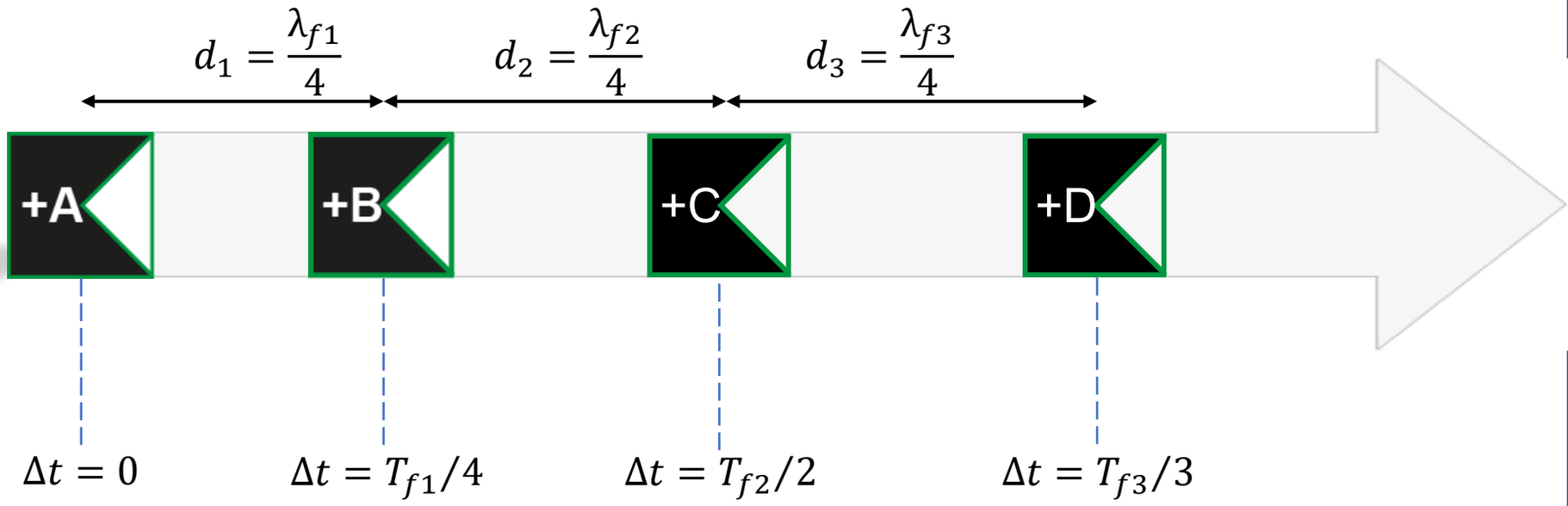
End Fire - Standard

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



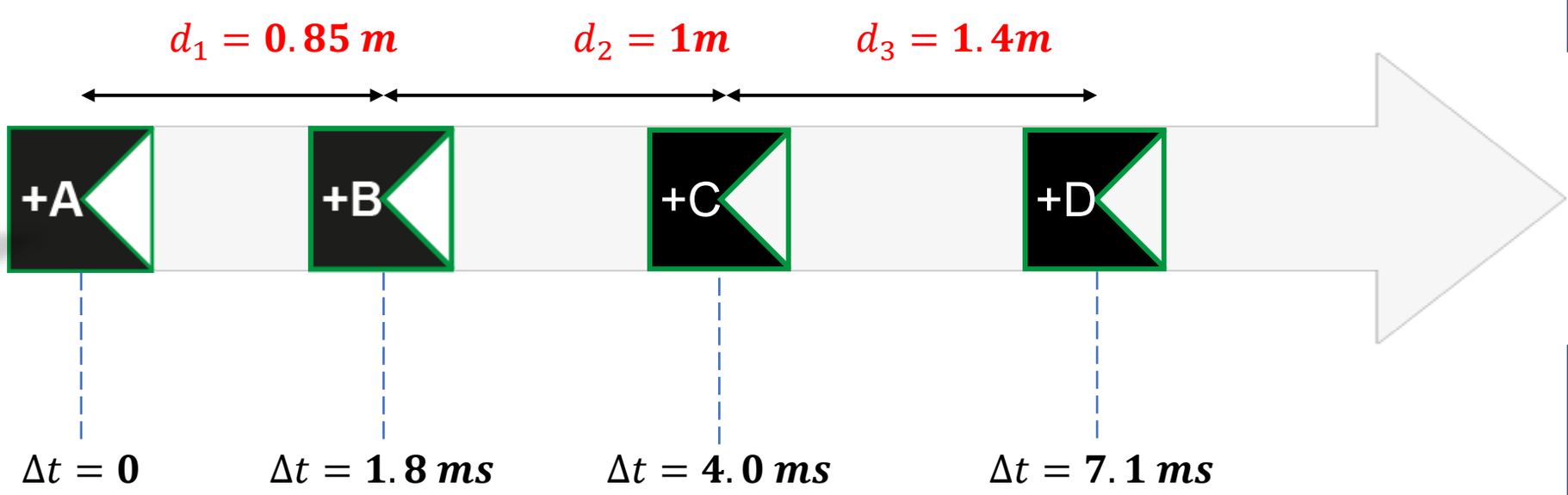
End Fire – Log. 1

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



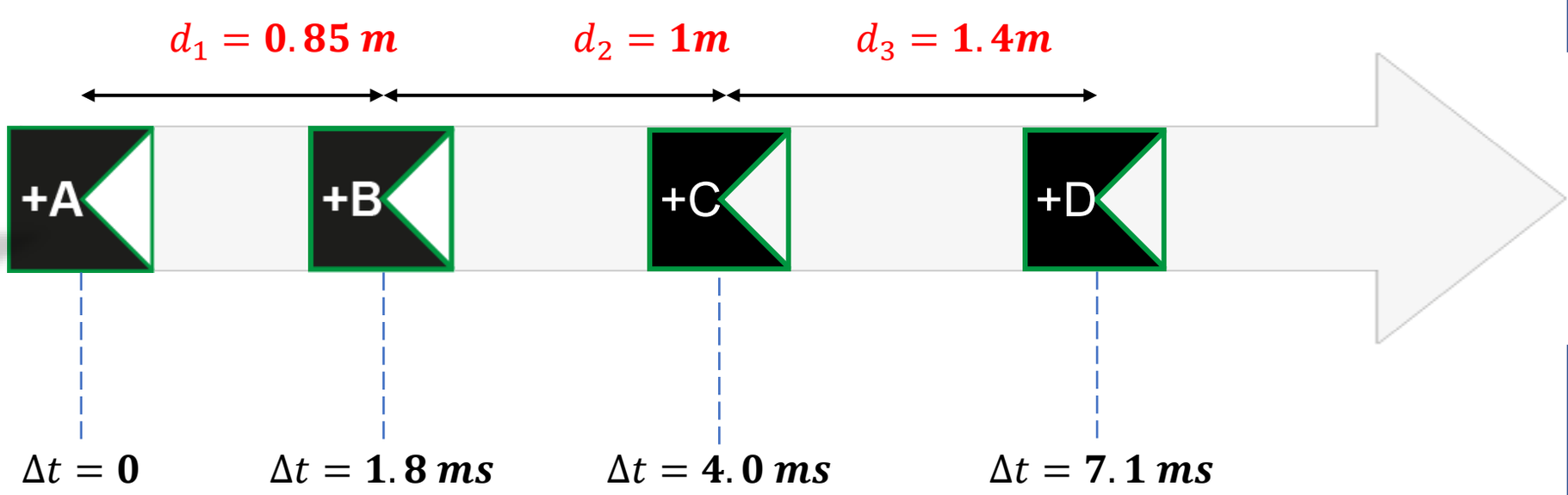
End Fire – Log. 1

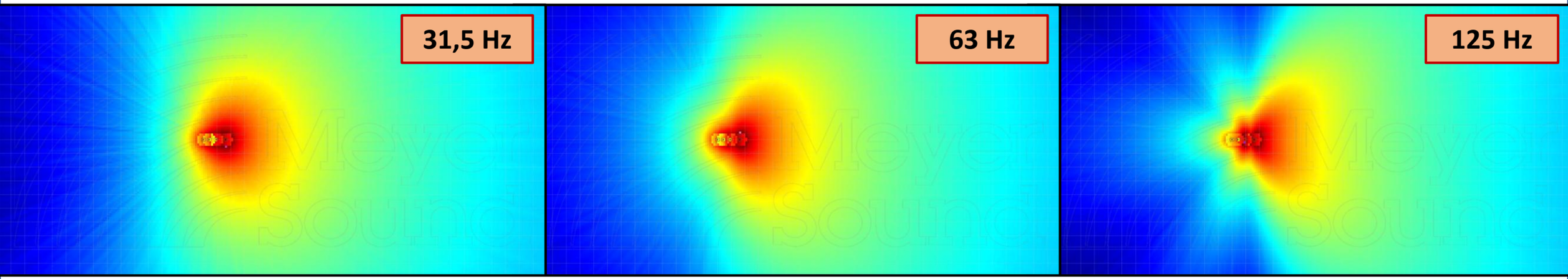
Paramètres	
fc =	100 / 85 / 60 Hz
λ =	3.4 / 4 / 5.67 m
T =	10 / 11.76/ 16.67 ms



End Fire – Log. 1

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

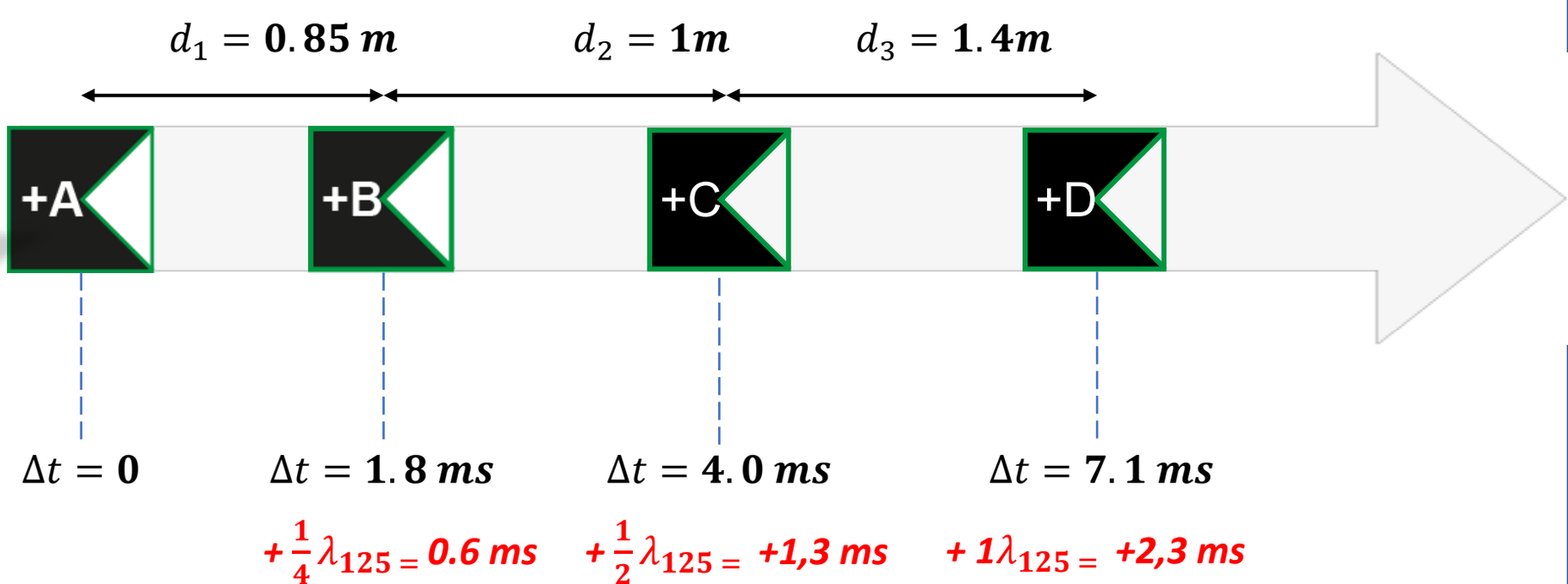




End Fire – Log. 2

(90° de rotation à 125 Hz)

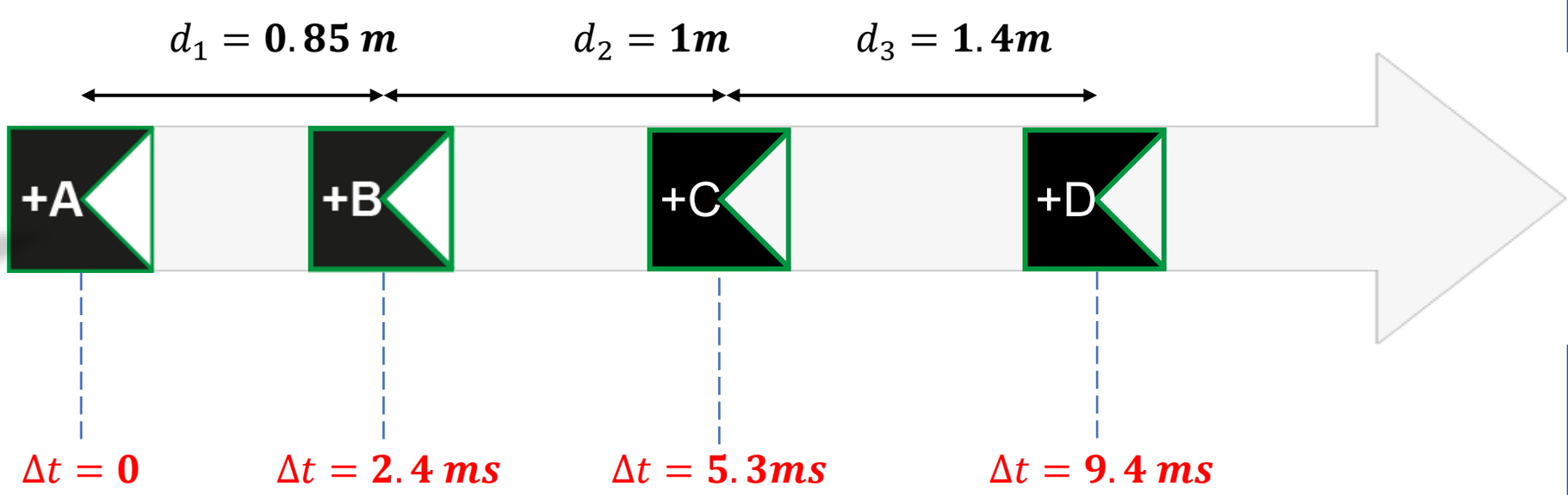
Paramètres	
fc =	100 / 85 / 60 Hz
λ =	3.4 / 4 / 5.67 m
T =	10 / 11.76/ 16.67 ms

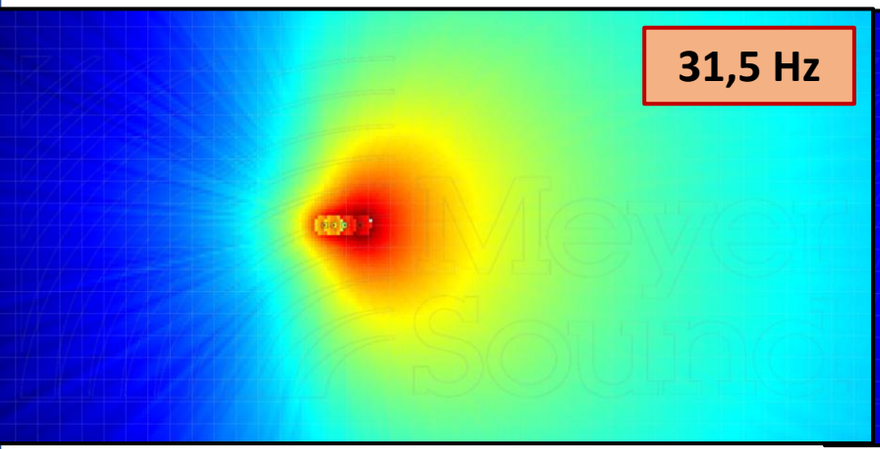


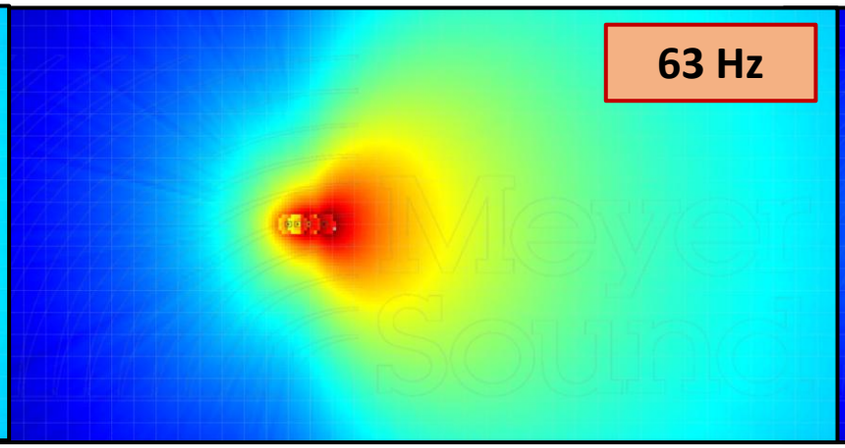
End Fire – Log. 2

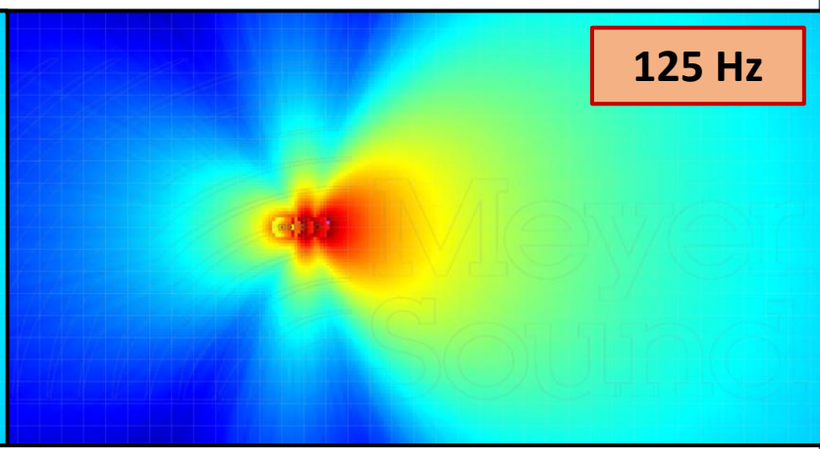
(90° de rotation à 125 Hz)

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









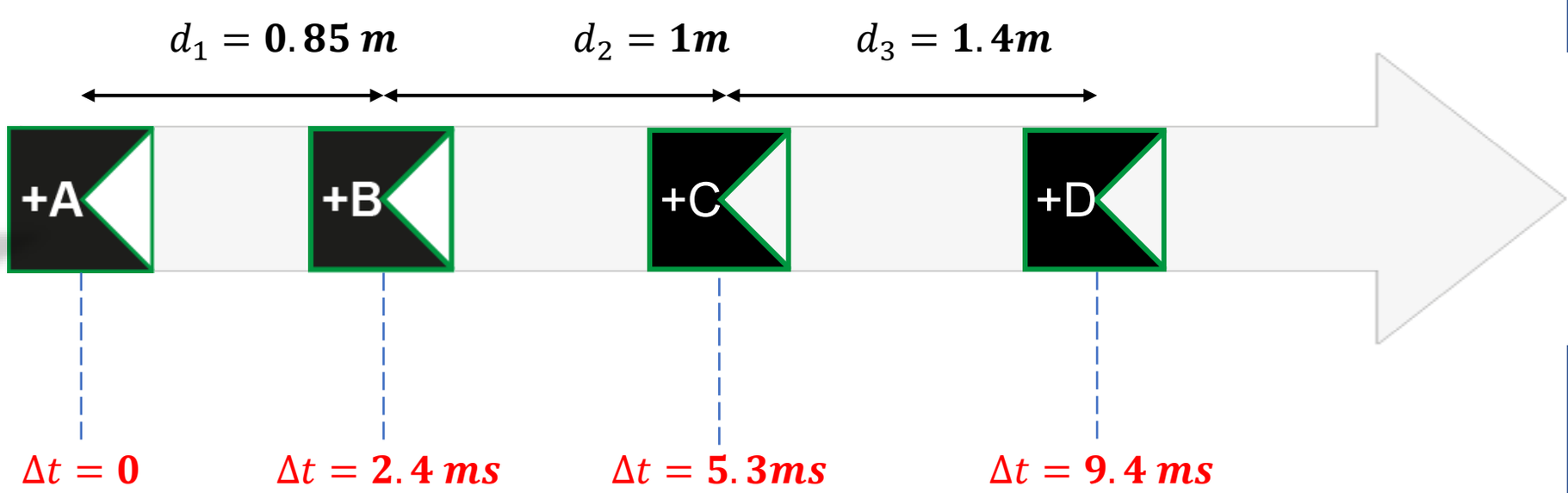
End Fire – Log. 2

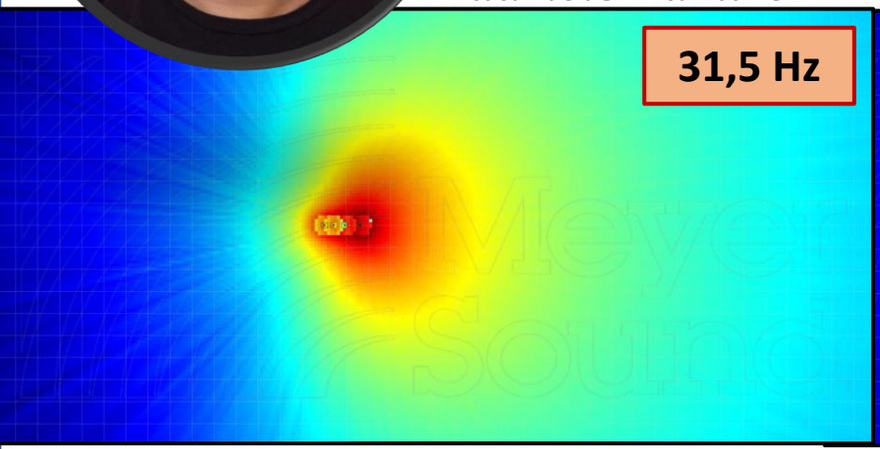
(90° de rotation à 125 Hz)

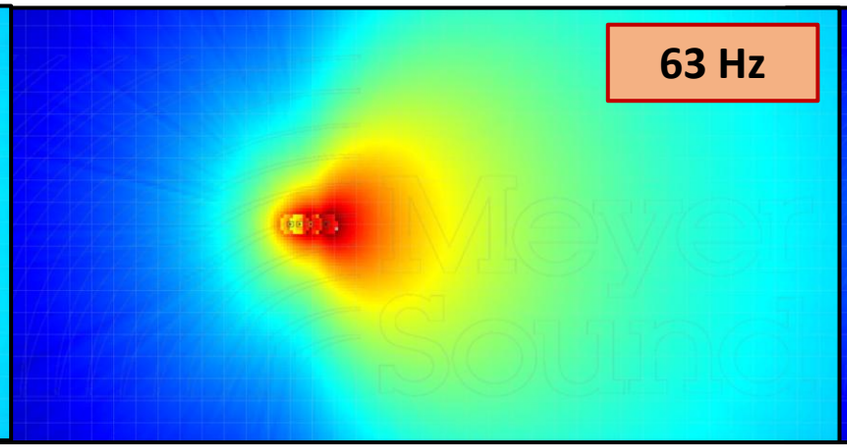
Paramètres	
fc =	100 / 85 / 60 Hz
λ =	3.4 / 4 / 5.67 m
T =	10 / 11.76/ 16.67 ms

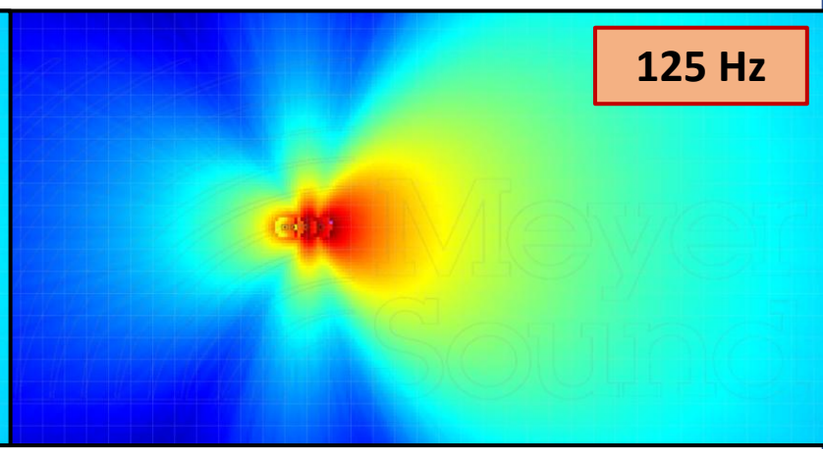


Mauricio Ramirez

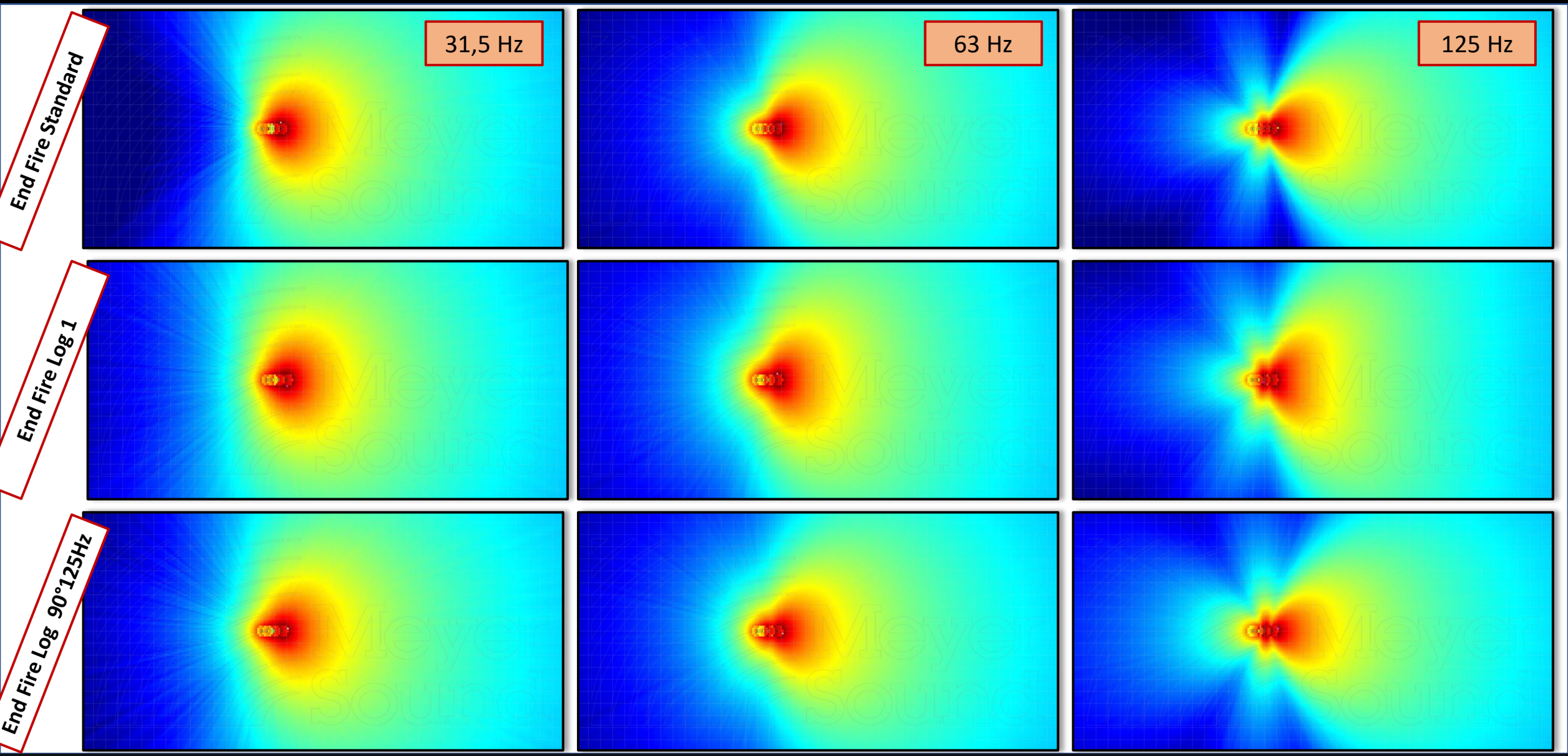








End Fire – Comparaison

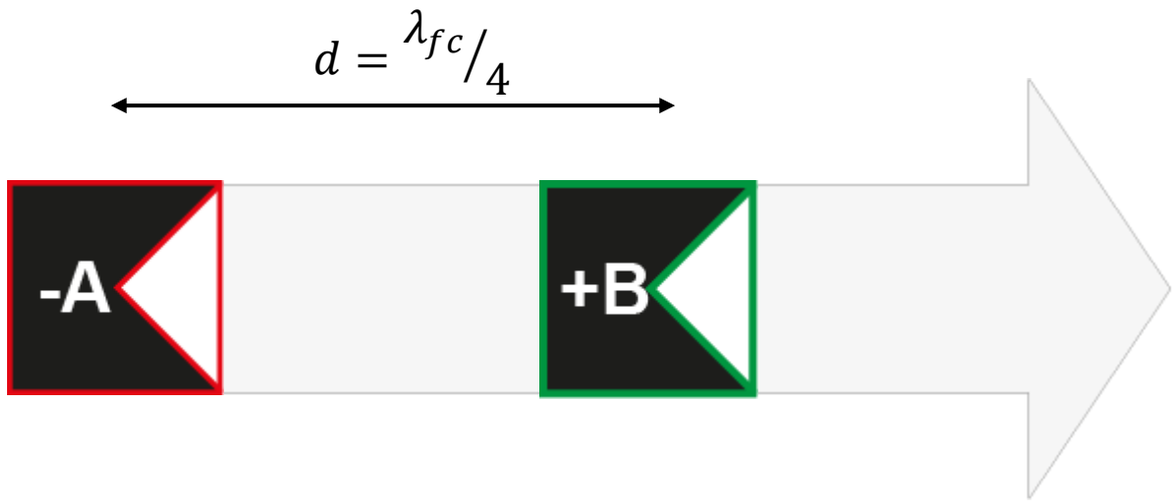


?

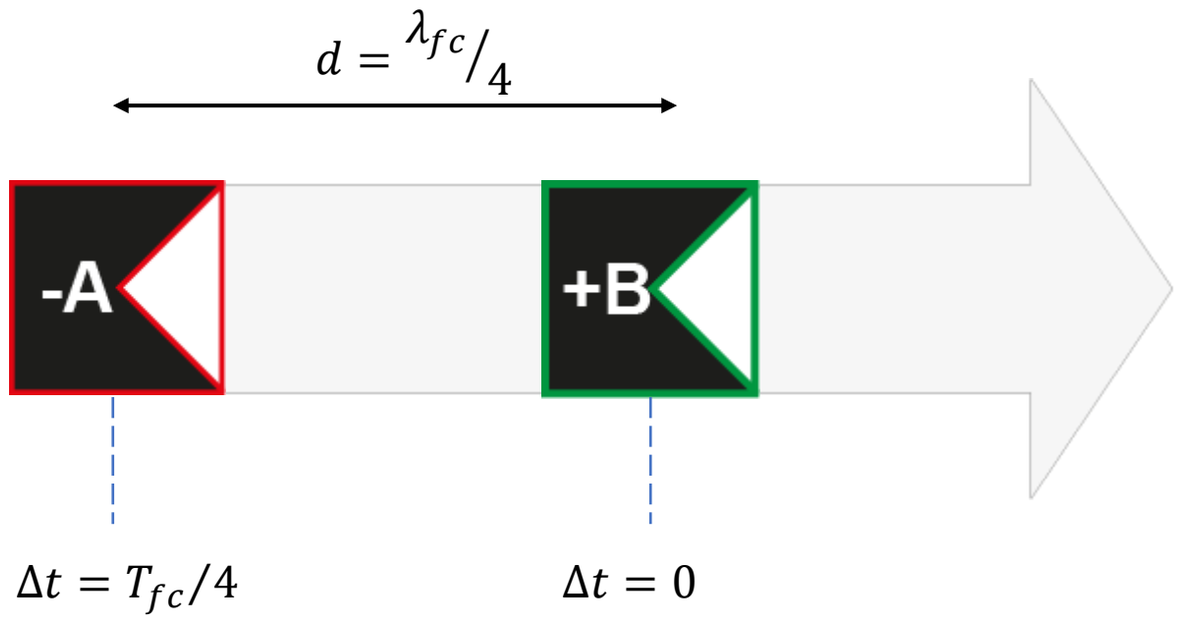
Configuration à "Gradient de pression"



Configuration à "Gradient de pression"



Configuration à "Gradient de pression"



Configuration à "Gradient de pression"

Visualisation Ondulatoire

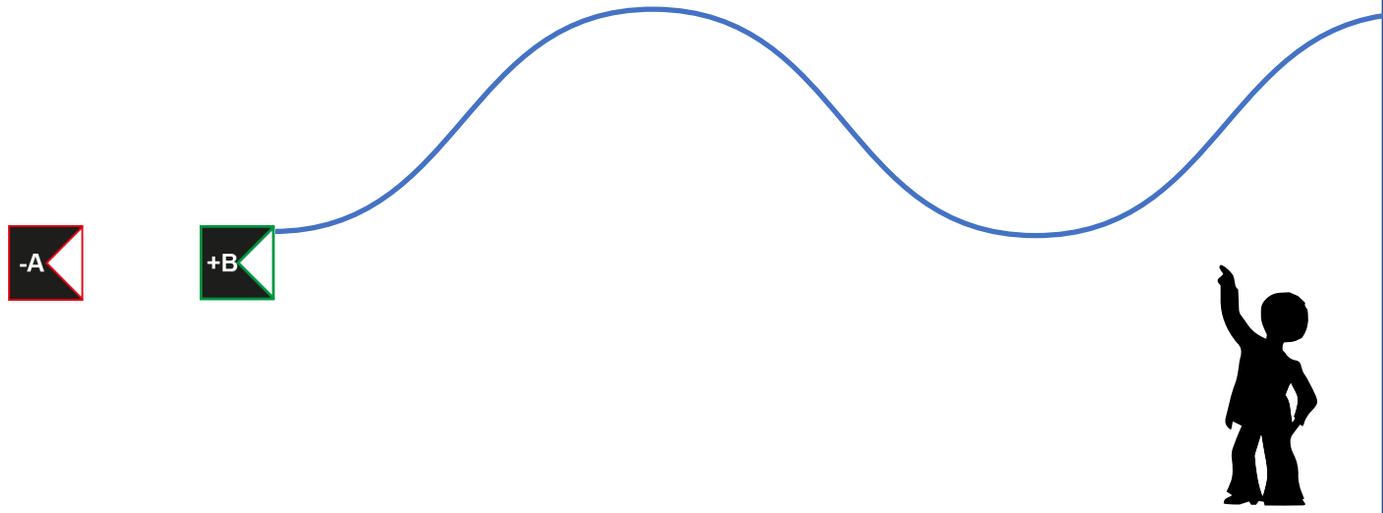




Configuration à "Gradient de pression"

Visualisation Ondulatoire

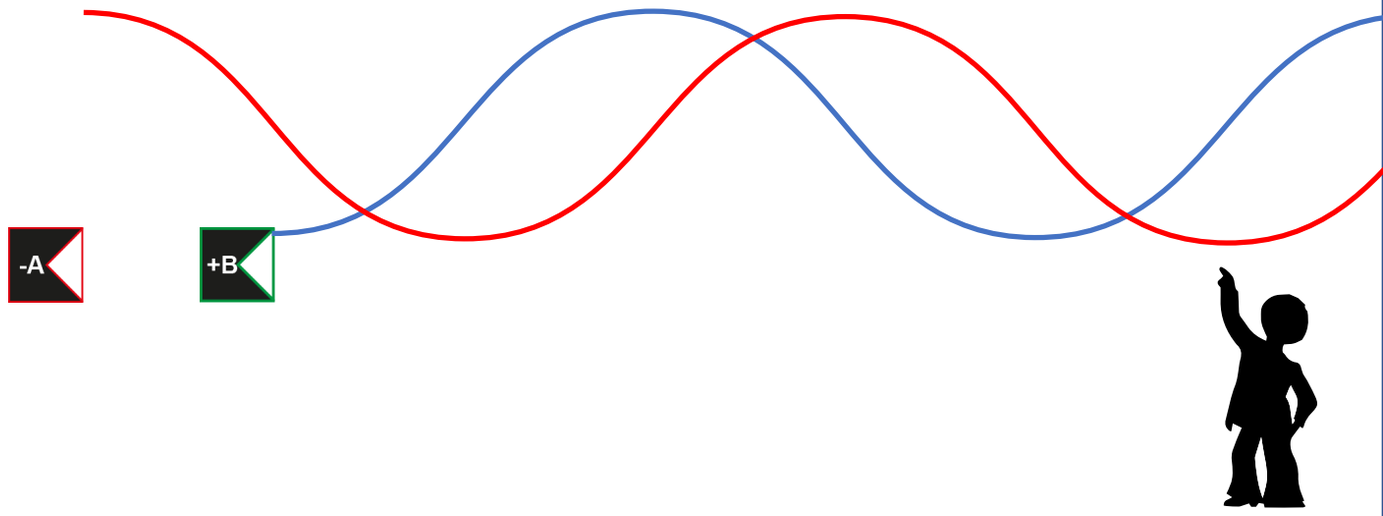
Vue de l'avant



Configuration à "Gradient de pression"

Visualisation Ondulatoire

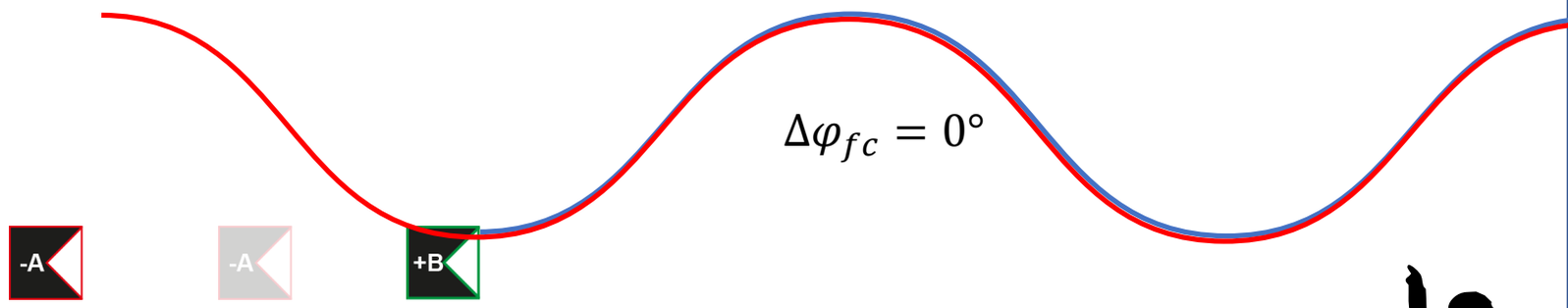
Vue de l'avant



Configuration à "Gradient de pression"

Visualisation Ondulatoire

Vue de l'avant

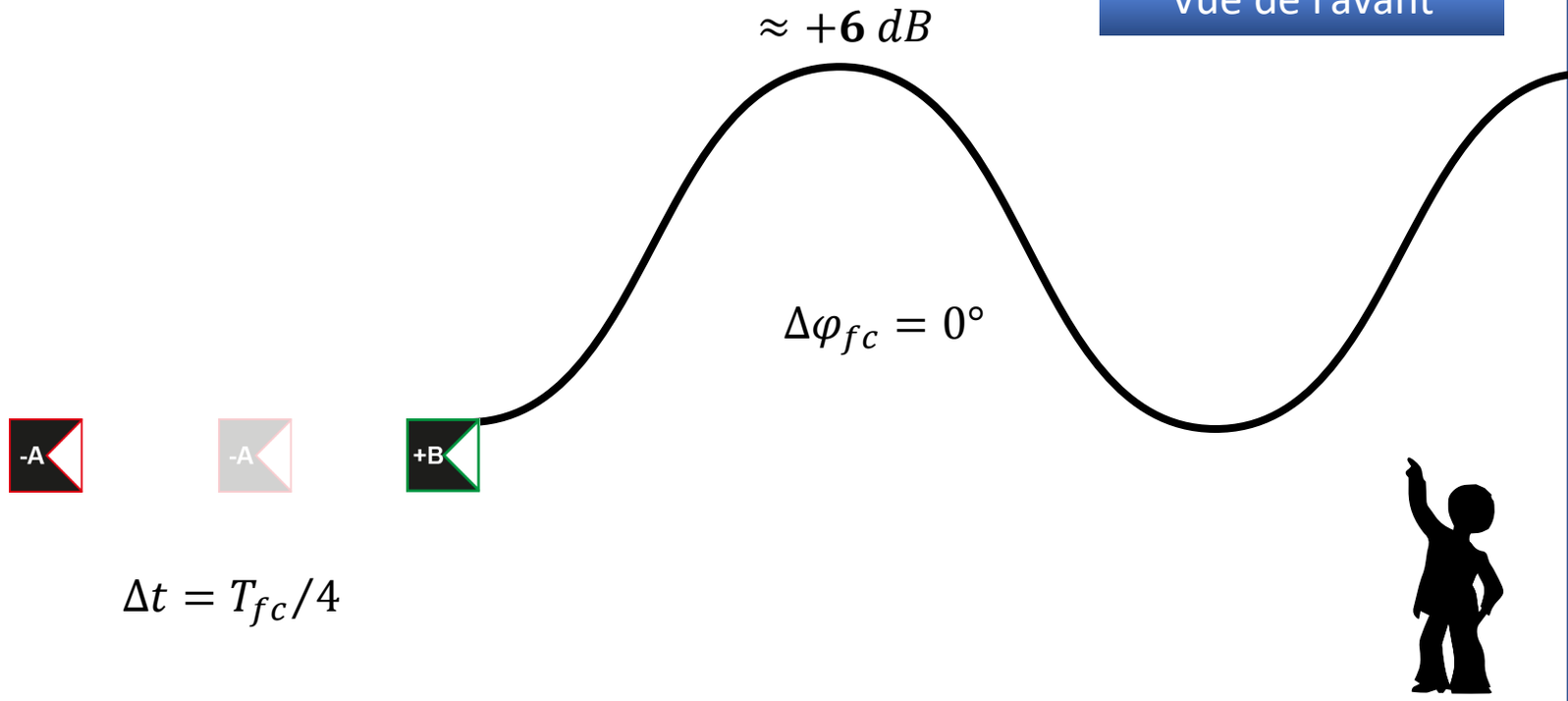


$$\Delta t = T_{fc}/4$$

Configuration à "Gradient de pression"

Visualisation Ondulatoire

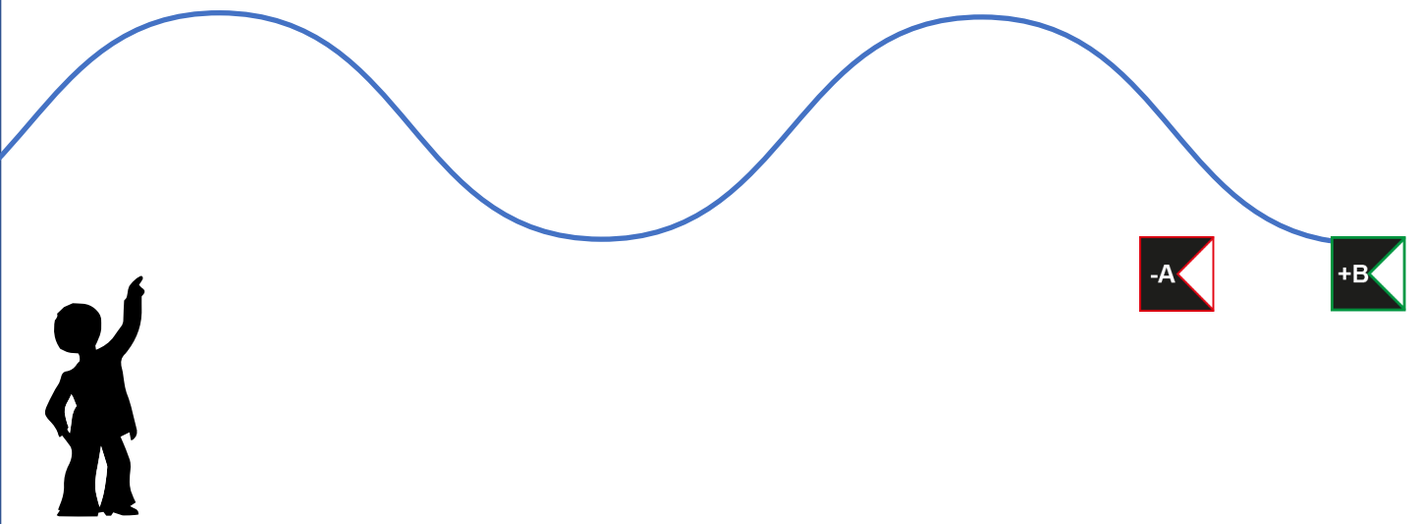
Vue de l'avant



Configuration à "Gradient de pression"

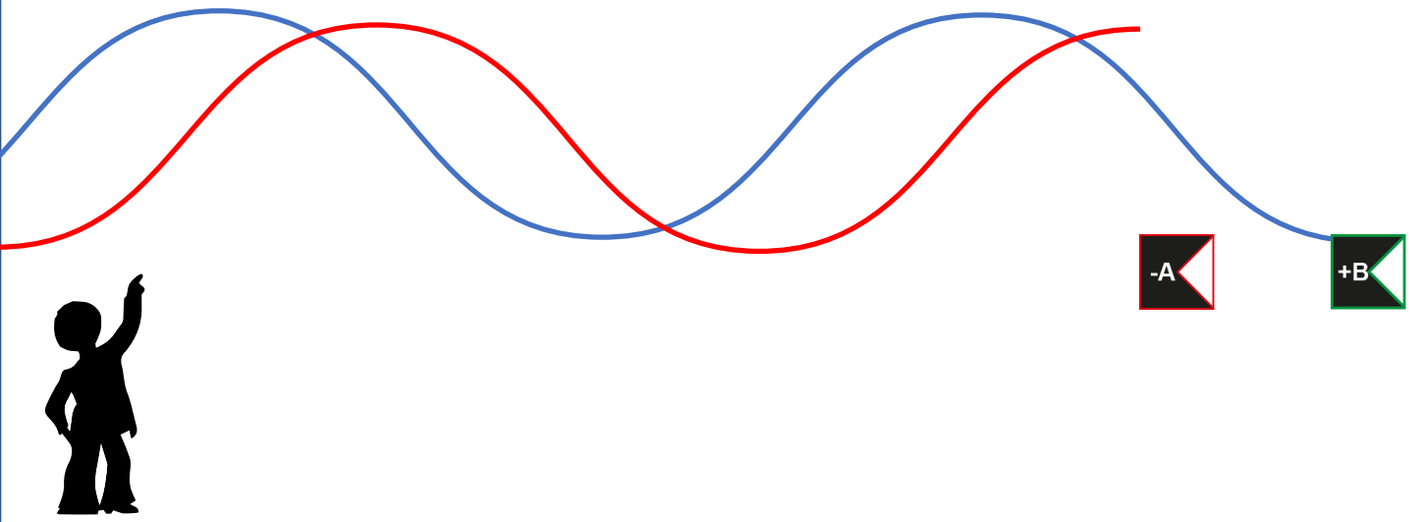
Visualisation Ondulatoire

Vue de l’arrière



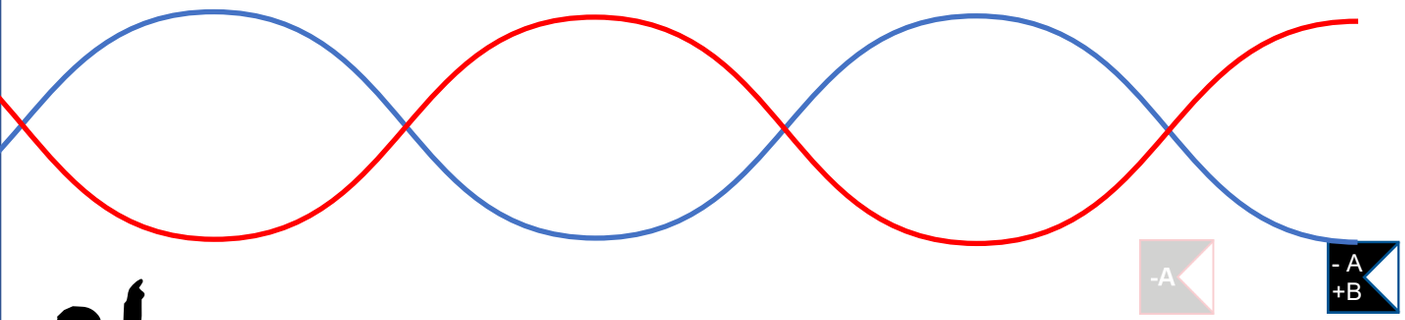
Configuration à "Gradient de pression"
Visualisation Ondulatoire

Vue de l'arrière



Configuration à "Gradient de pression"
Visualisation Ondulatoire

Vue de l'arrière

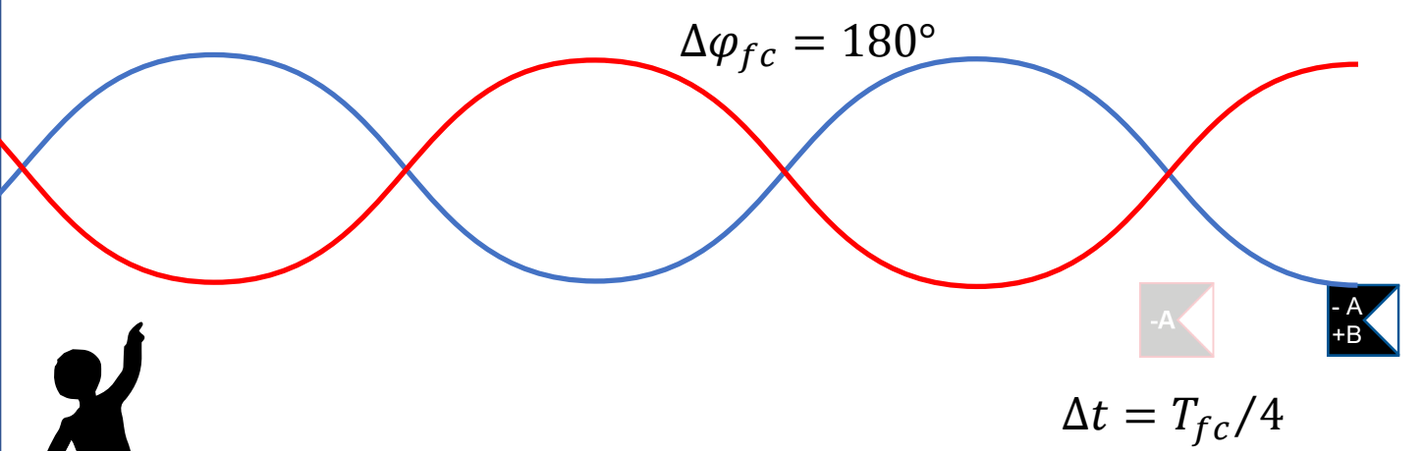




$$\Delta t = T_{fc}/4$$

Configuration à "Gradient de pression"
Visualisation Ondulatoire

Vue de l'arrière



Configuration à "Gradient de pression"
Visualisation Ondulatoire

Vue de l'arrière

$$\Delta\varphi_{fc} = 180°$$

$$-\infty\ dB$$



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

Configuration à "Gradient de pression"

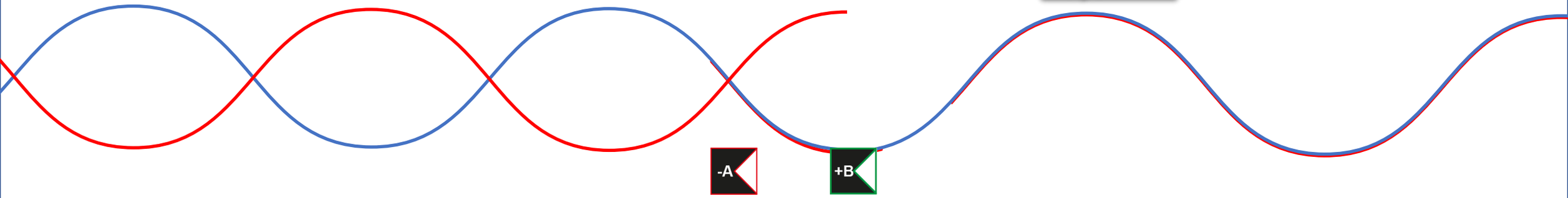
Variations de fréquence = Variation de phase avant

Fréquence

$f = fc$

$\Delta\varphi_{fc} = 180°$

$\Delta\varphi_{fc} = 0°$



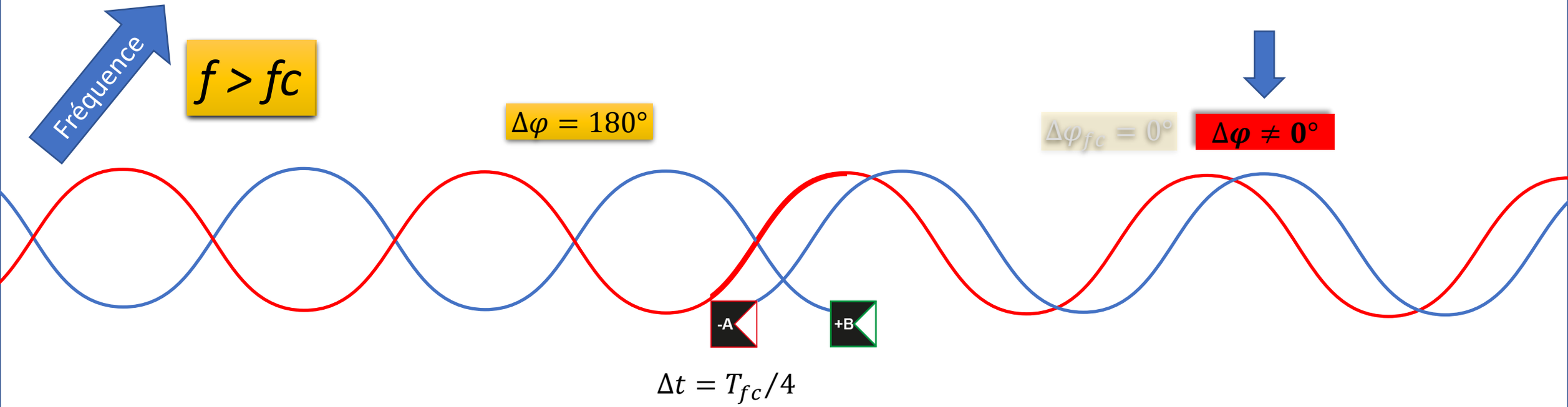
$$\Delta t = T_{fc}/4$$

Vue combinée

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

Configuration à "Gradient de pression"

Variations de fréquence = Variation de phase avant



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

On constate que le décalage de Phase ($\Delta\varphi$) à l'arrière du système ne change pas en fonction de la fréquence.

Vue combinée

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

Configuration à "Gradient de pression"

Variations de fréquence = Variation de phase avant

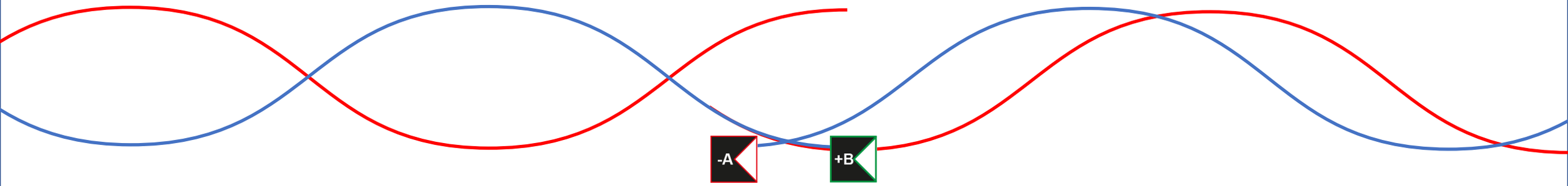
Fréquence

$f < fc$

$\Delta\varphi = 180°$

$\Delta\varphi_{fc} = 0°$

$\Delta\varphi \neq 0°$



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

En revanche le décalage de Phase ($\Delta\varphi$) change à l'avant du système en fonction de la fréquence

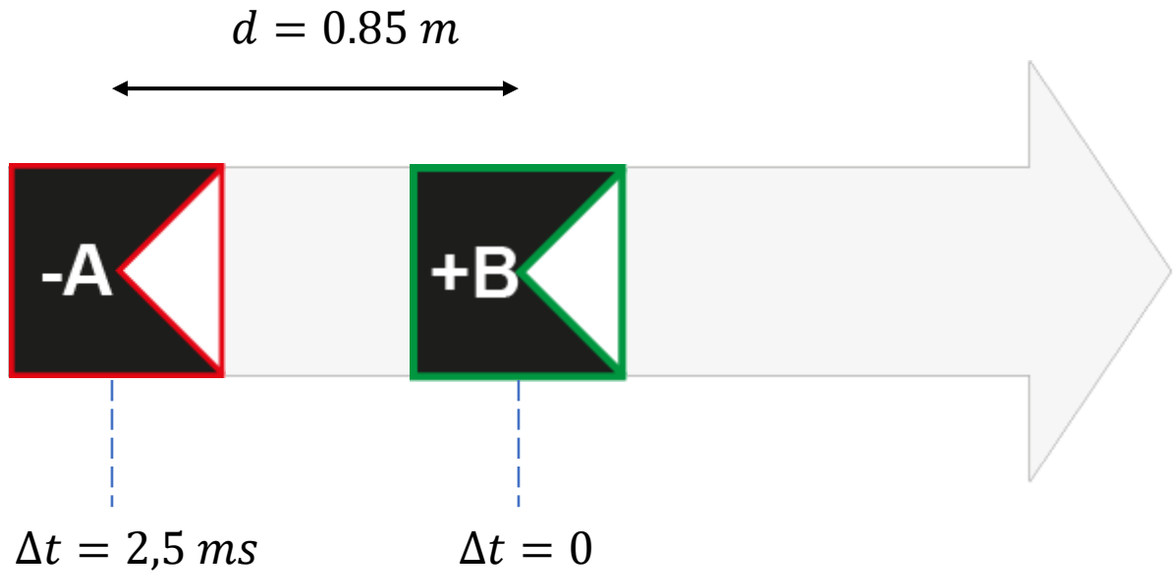
Vue combinée

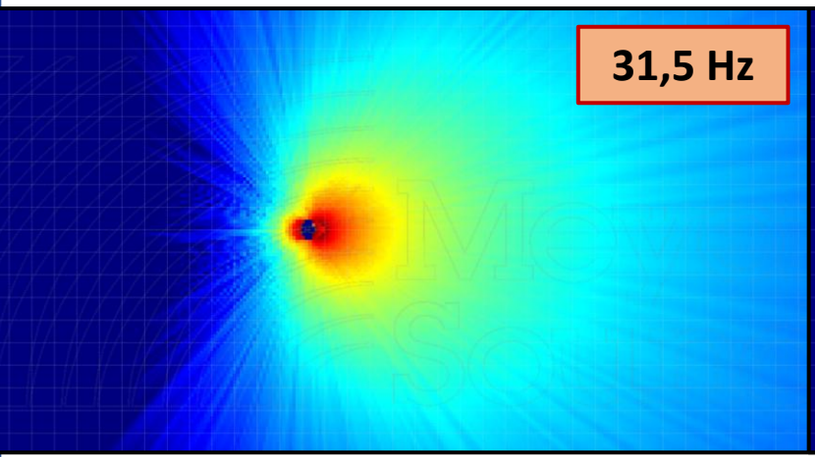
$$\Delta_\varphi = \frac{\Delta_d . f . 360}{c}$$

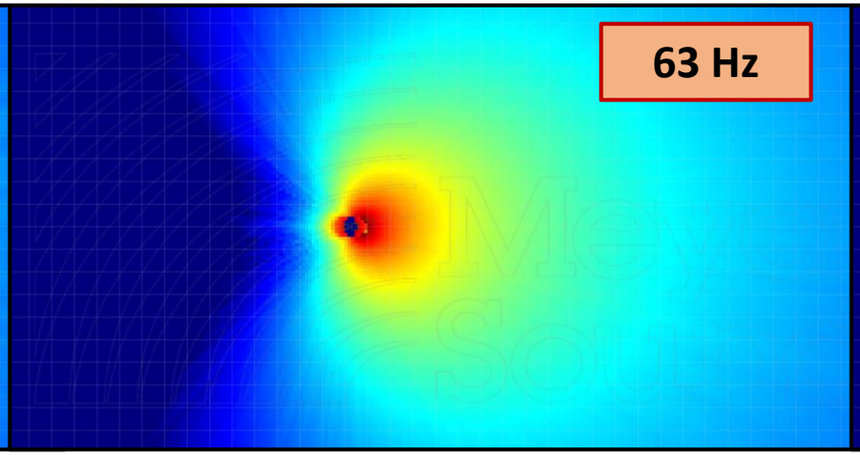
Configuration à "Gradient de pression"

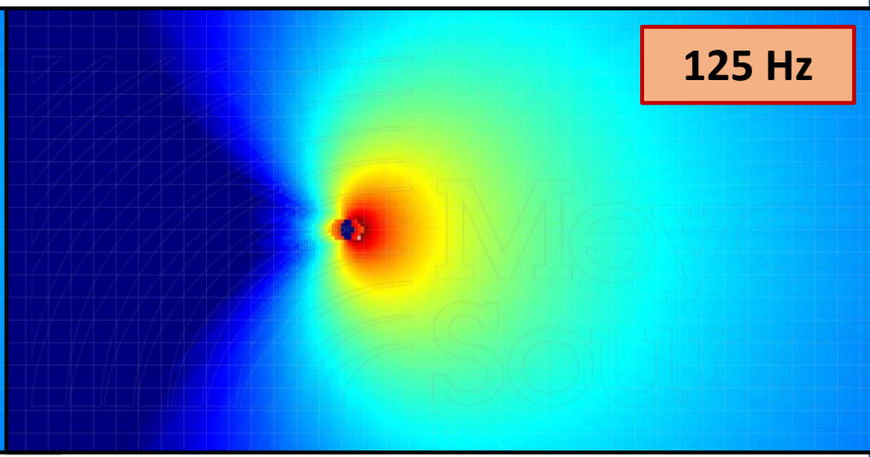
Exemple 0.85 m

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





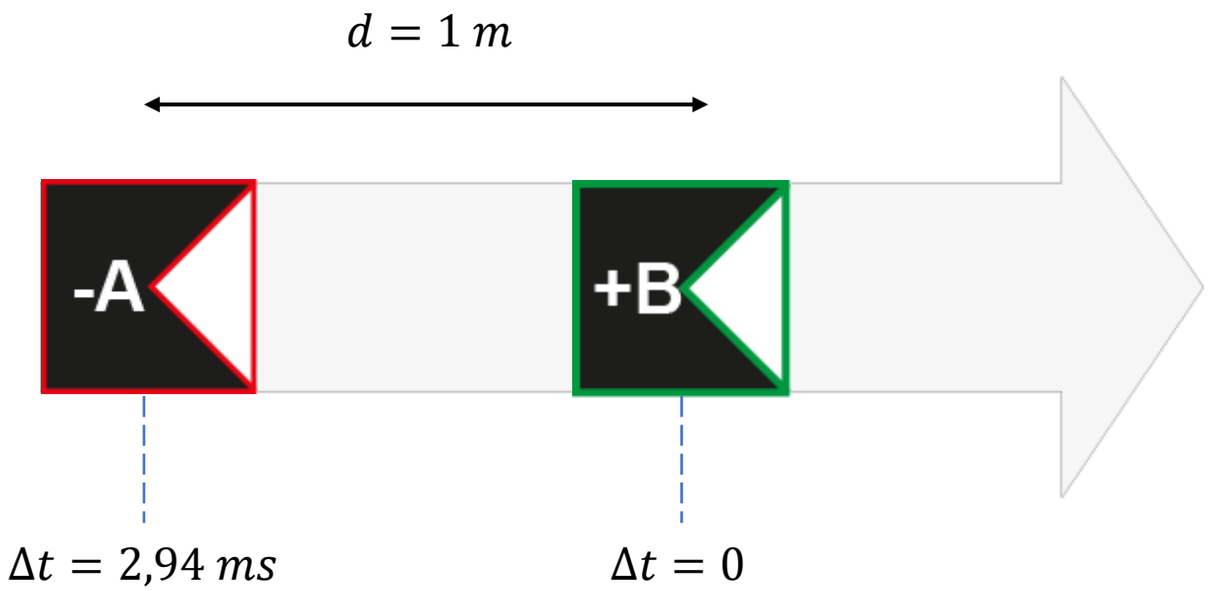


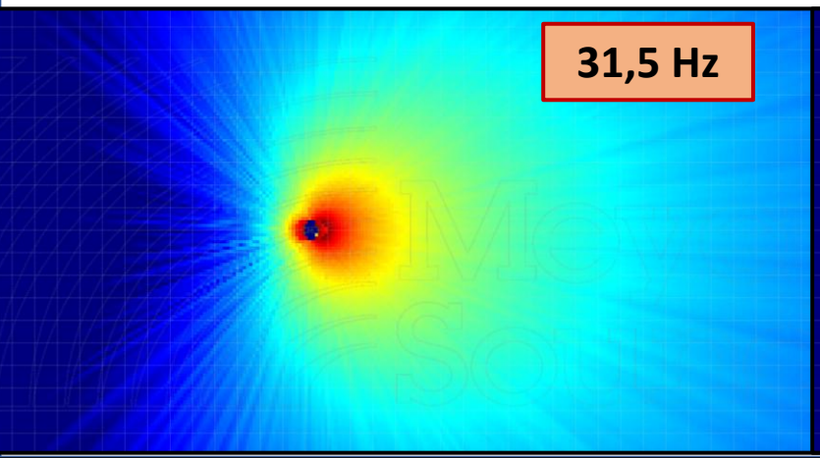


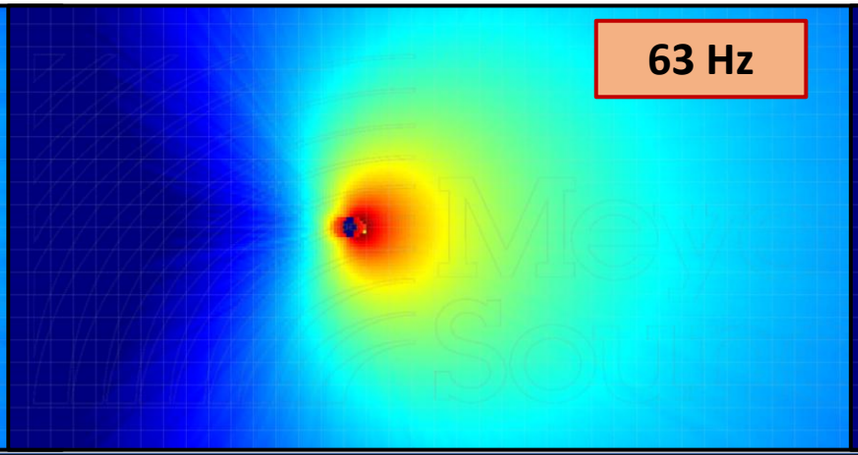
Configuration à "Gradient de pression"

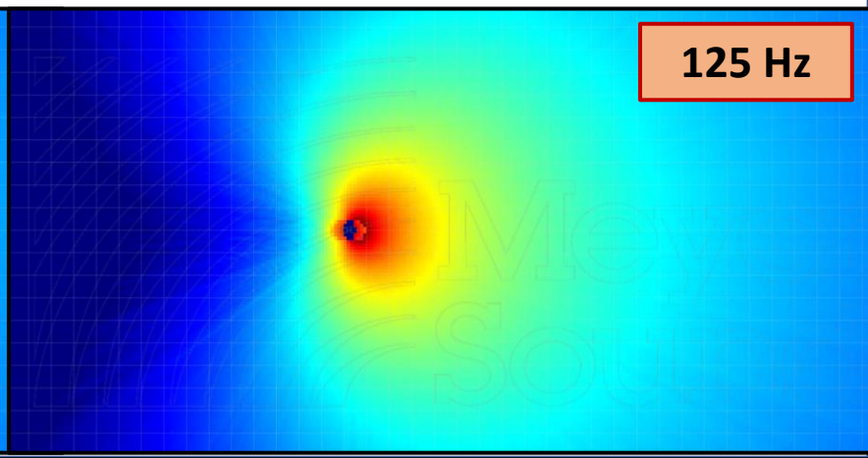
Exemple 1m

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





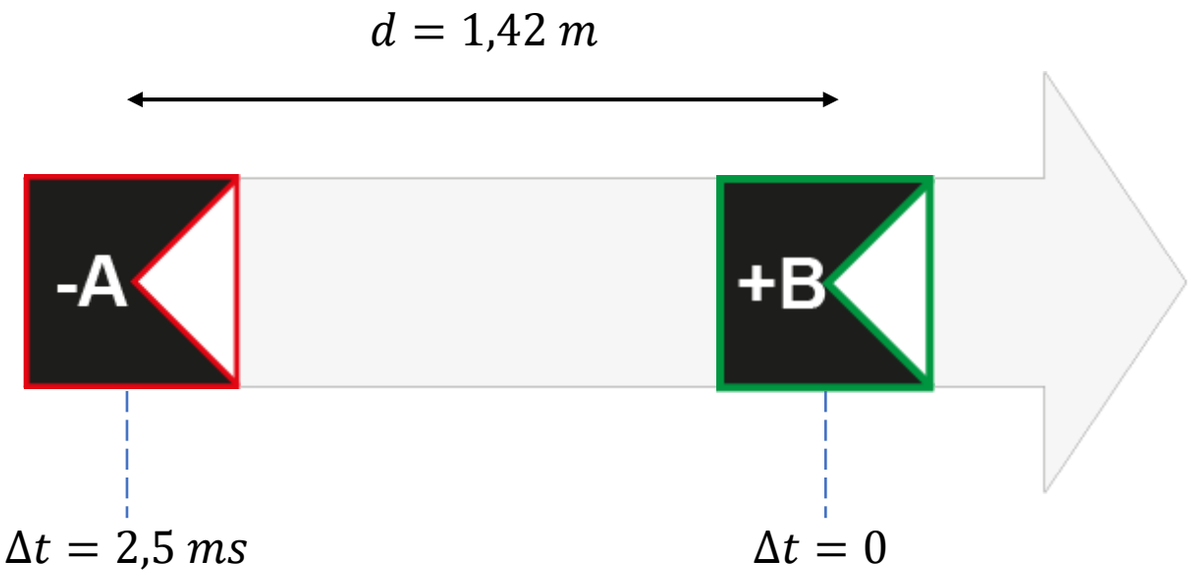


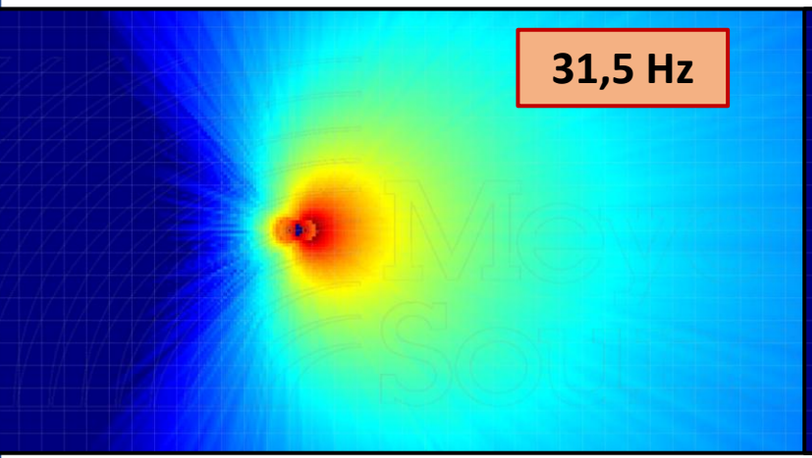


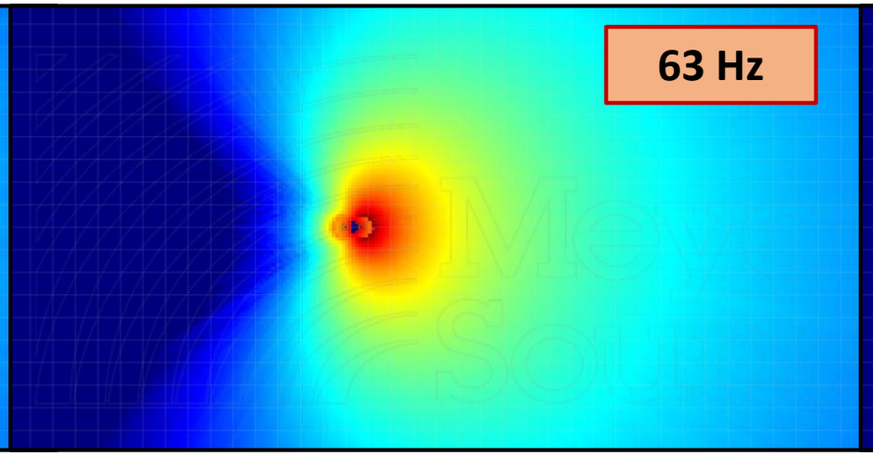
Configuration à "Gradient de pression"

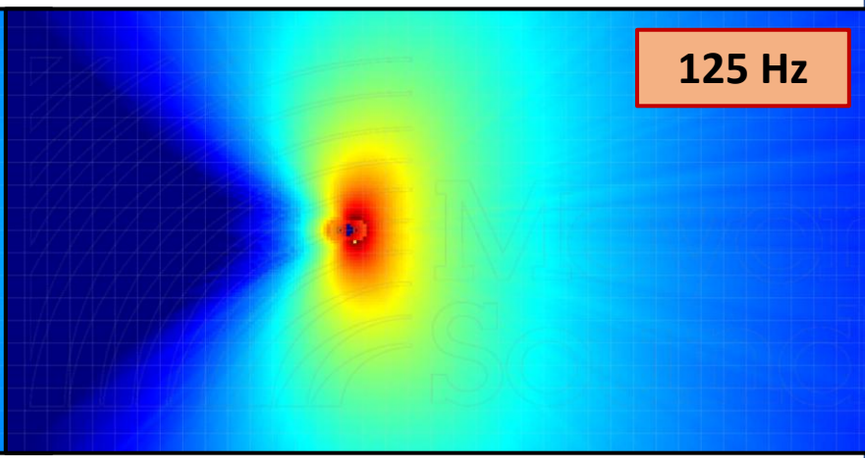
Exemple 1.42 m

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



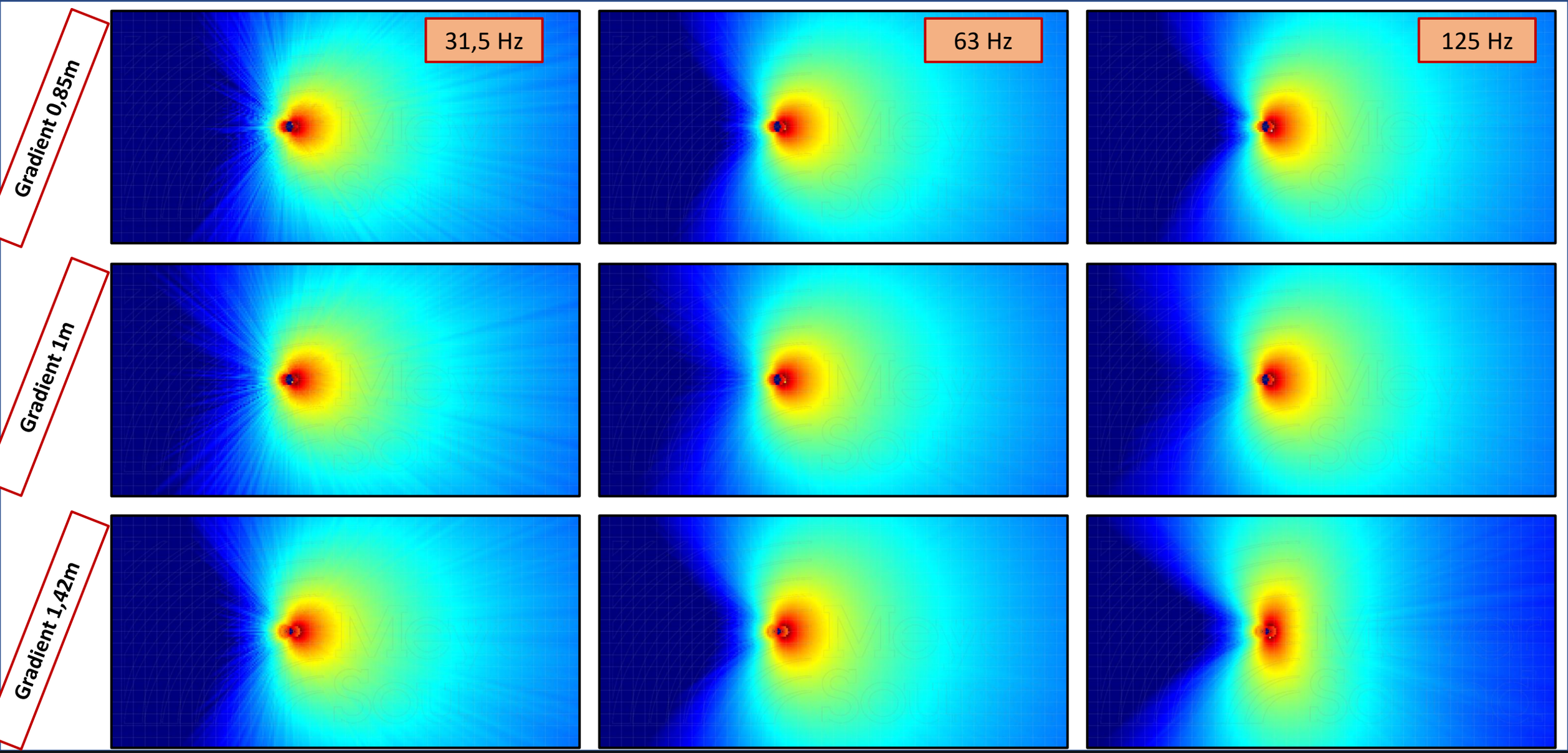






Configuration à "Gradient de pression"

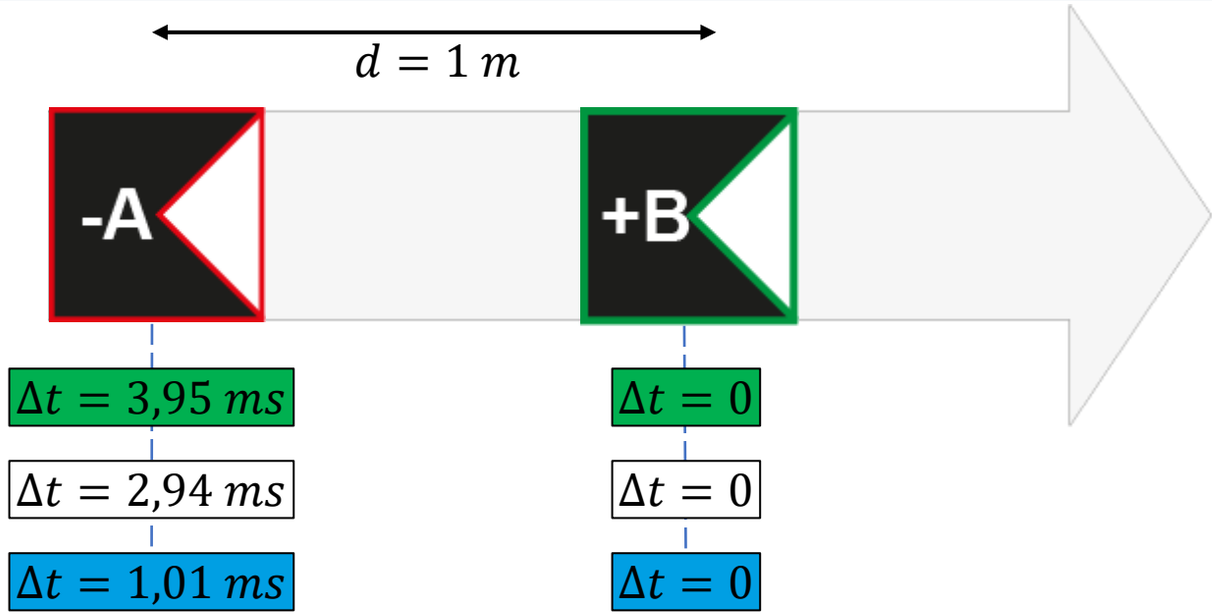
Comparaison

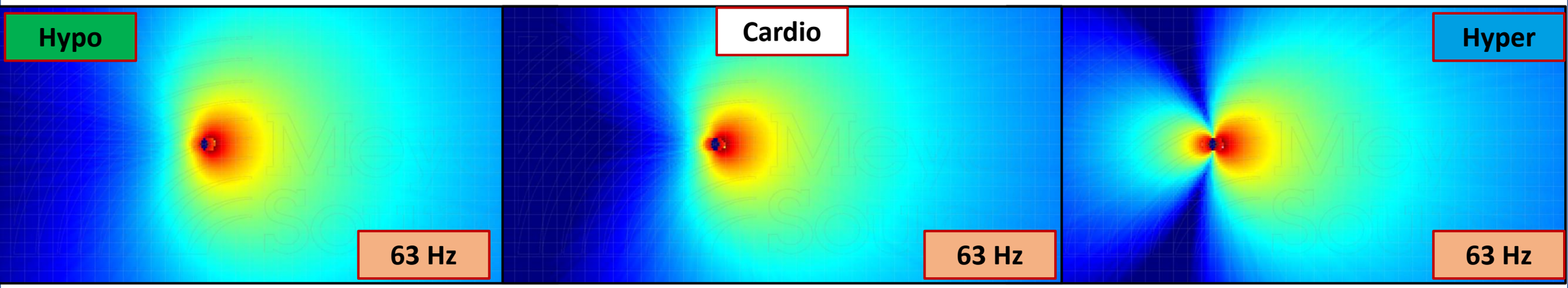


Configuration à "Gradient de pression"

Hypo Cardio – Hyper Cardio

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



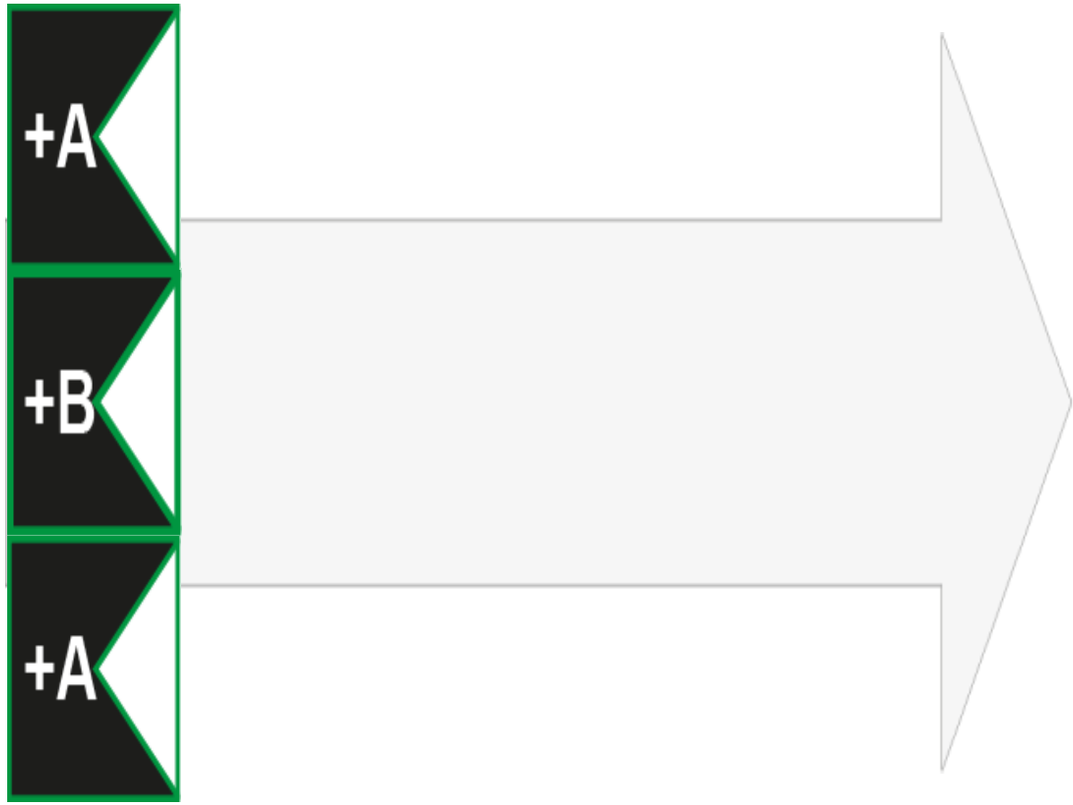


Un beau Gradient

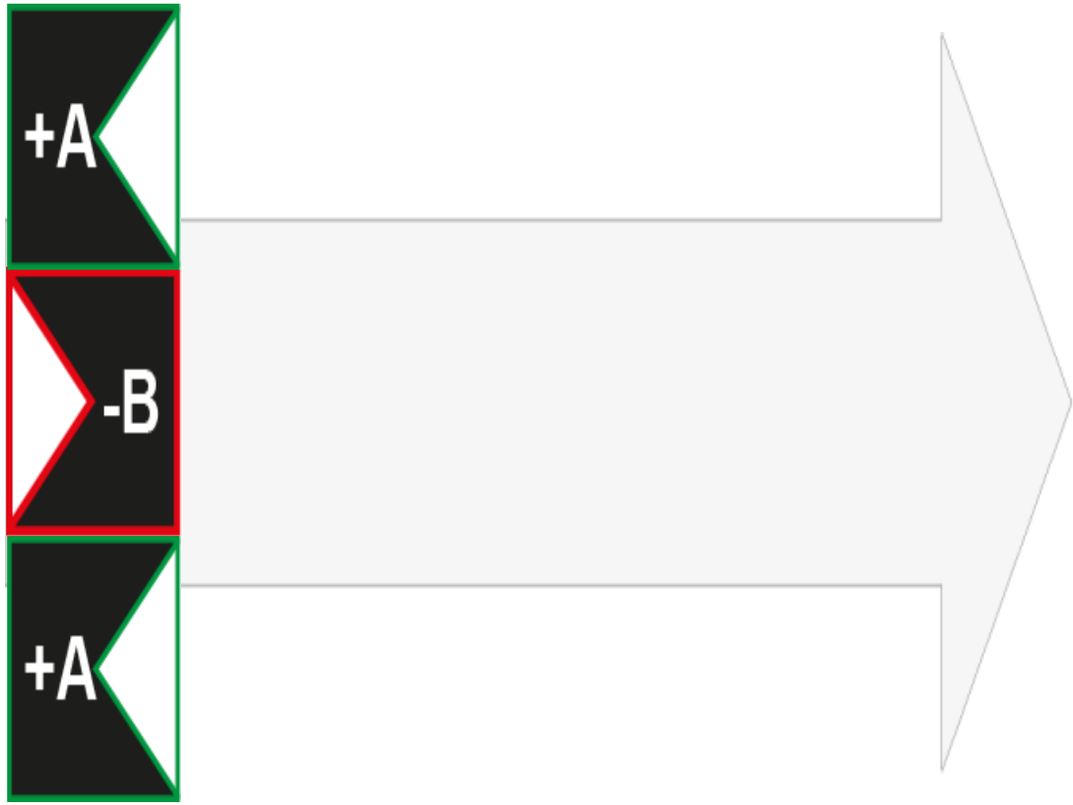


?

Stacks
Gradient Inverted Stack horizontal

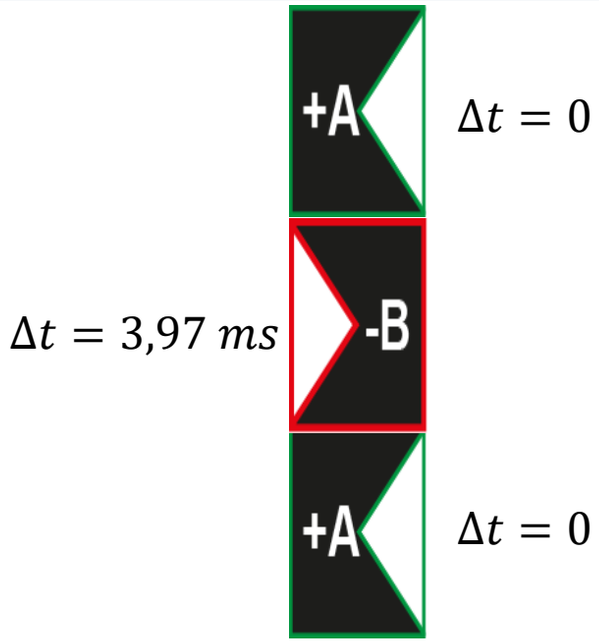


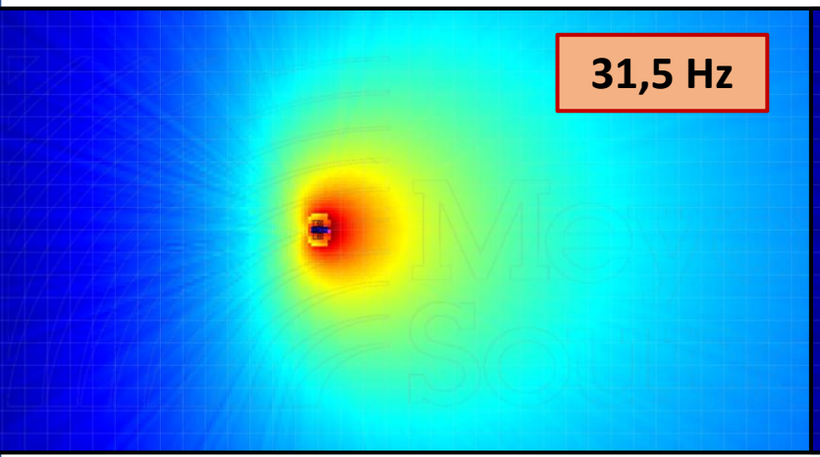
Stacks
Gradient Inverted Stack horizontal

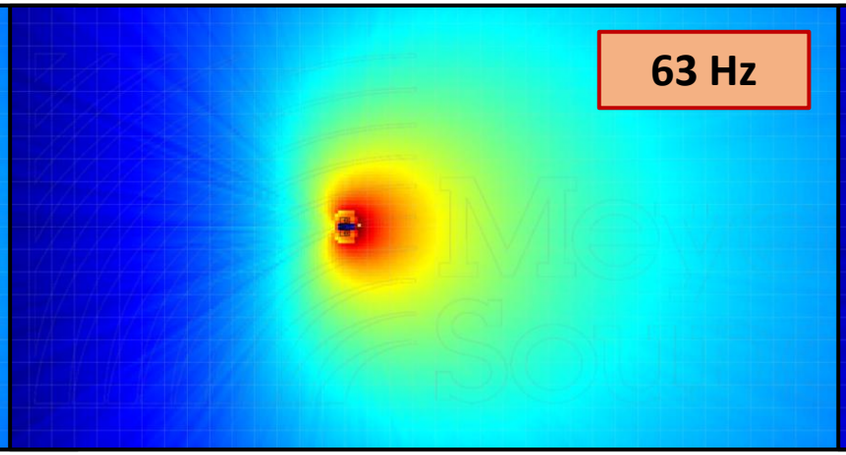


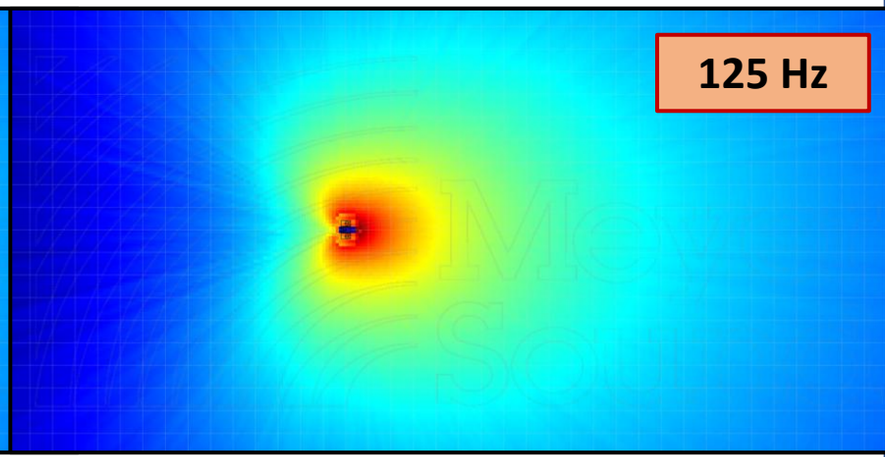
Stacks
Gradient Inverted Stack horizontal

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

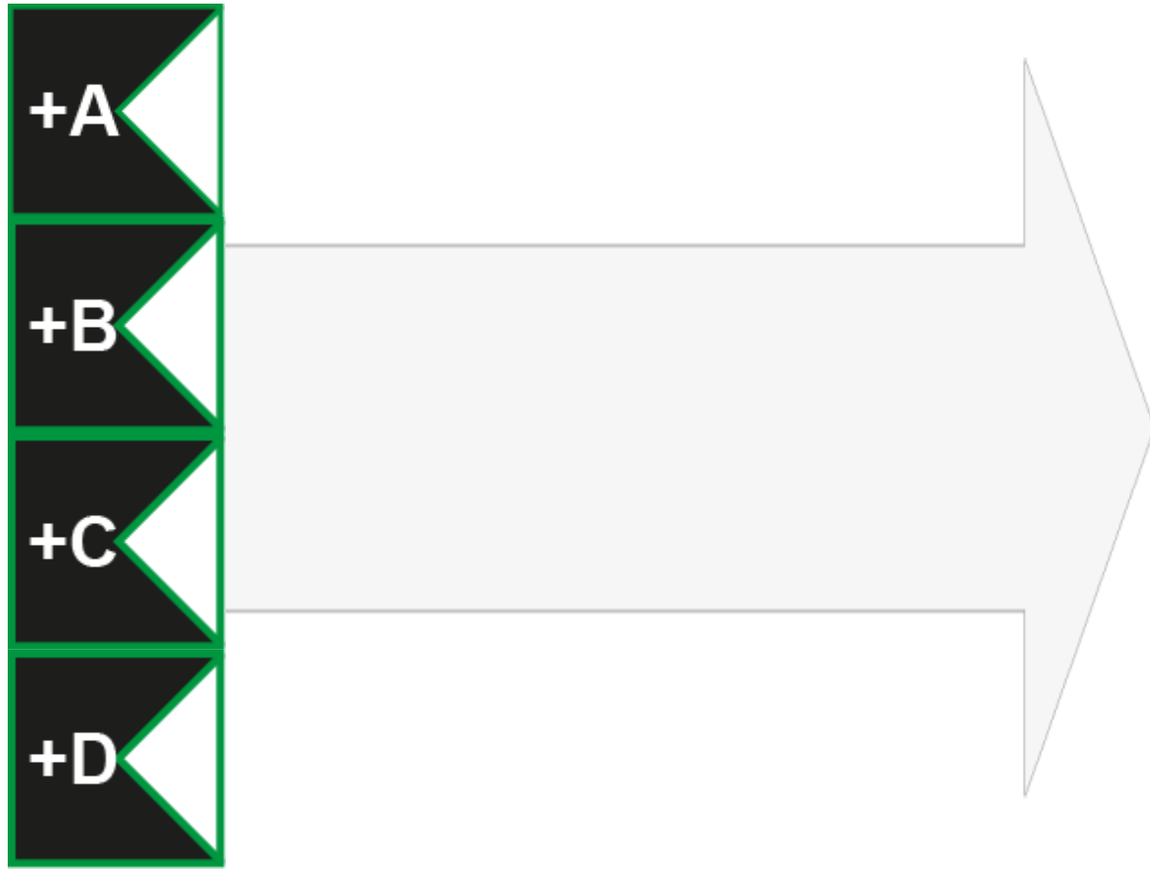




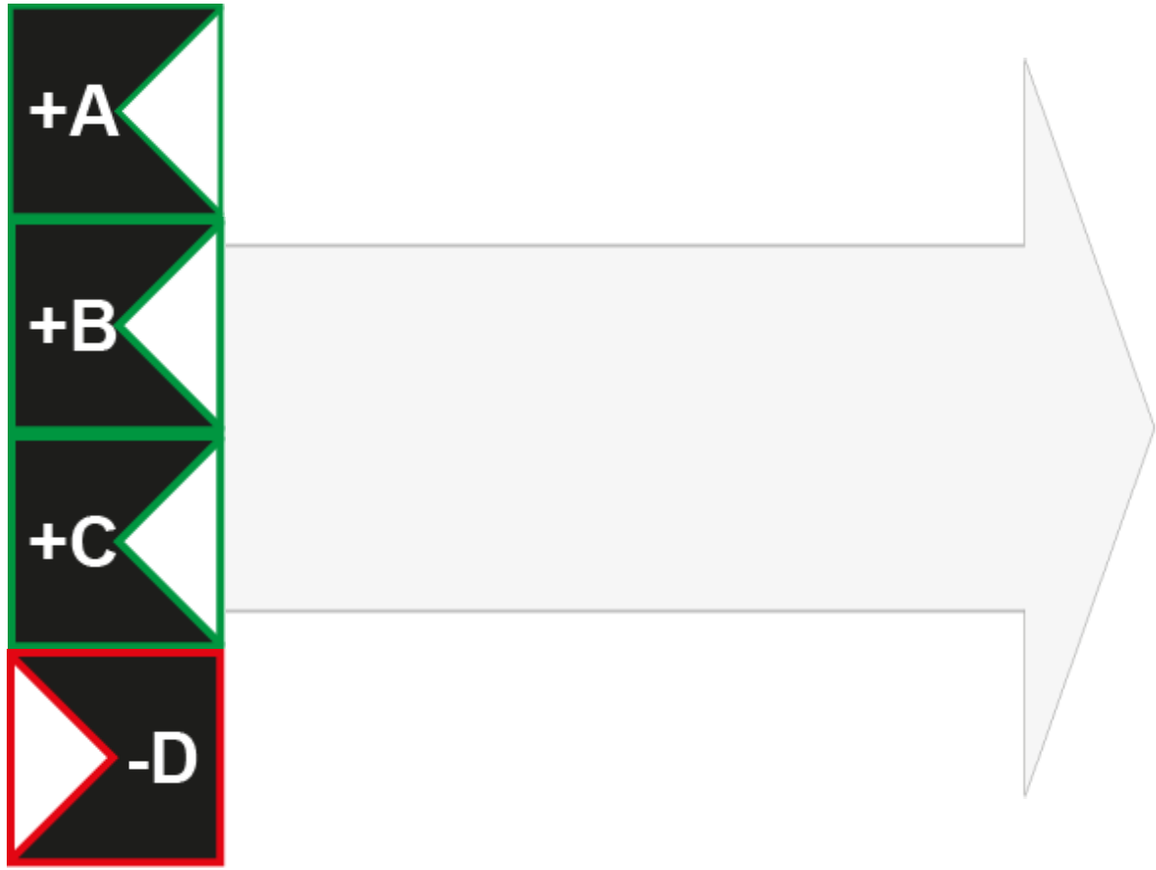




Stacks
Gradient Inverted Stack vertical

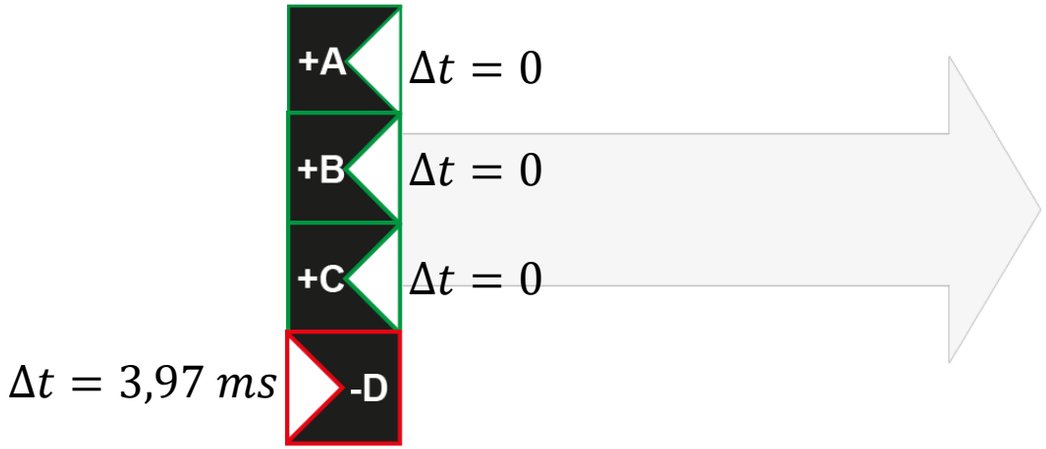


Stacks
Gradient Inverted Stack vertical

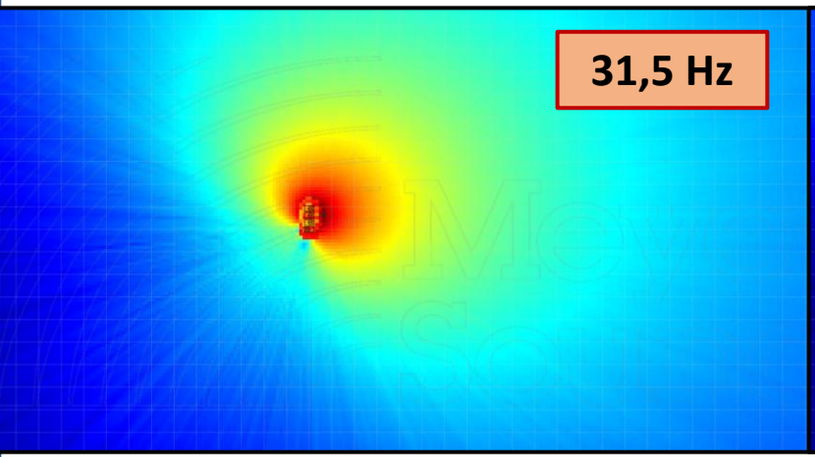


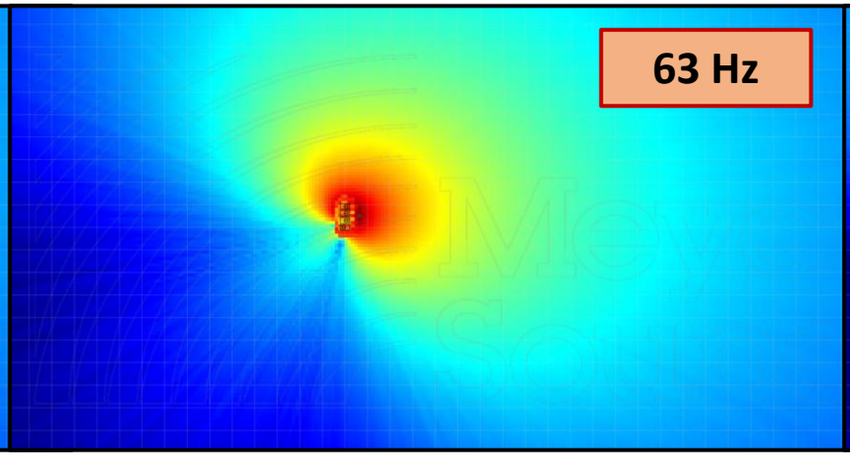
Stacks
Gradient Inverted Stack vertical

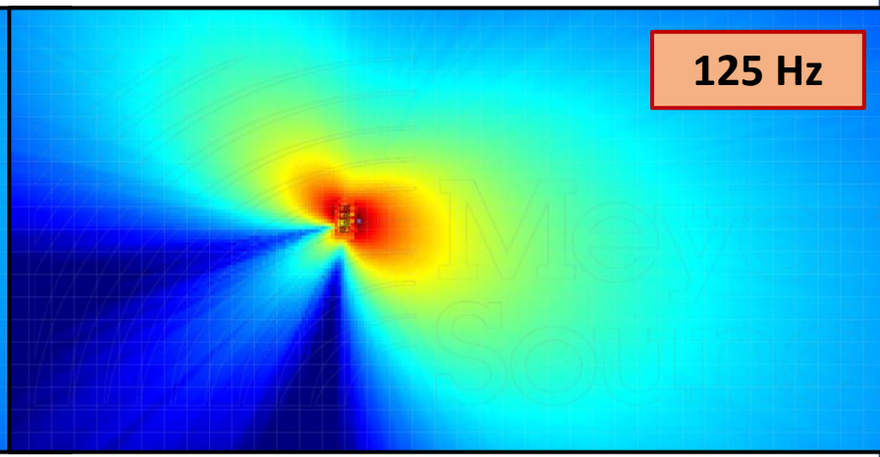
Paramètres	
fc =	≈ 85 Hz
λ =	5.4 m
T =	15.87 ms



- La diffusion s'oriente du côté en avance.



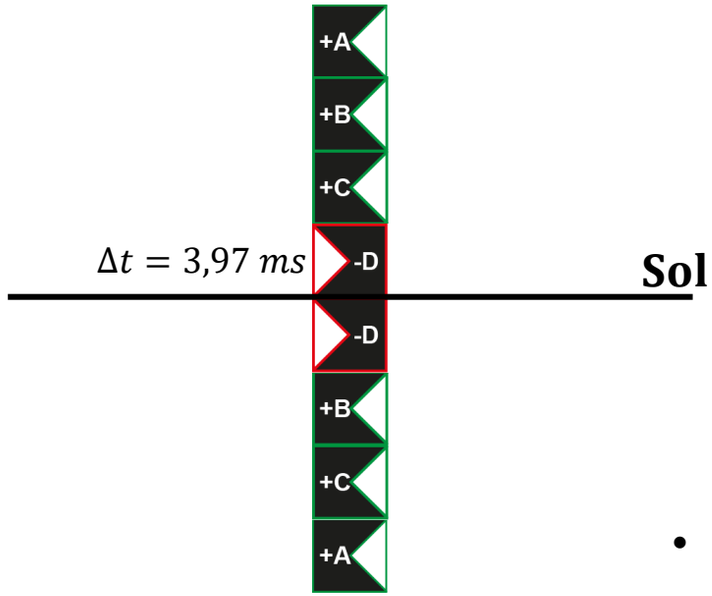




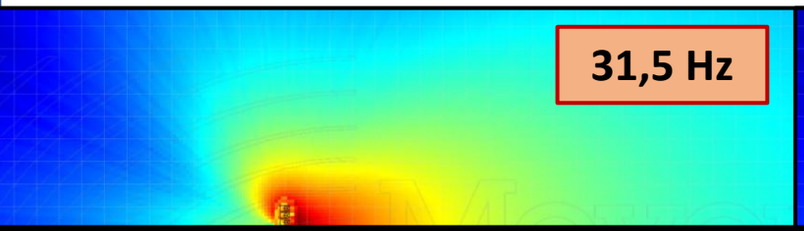
Gradient Inverted Stack vertical

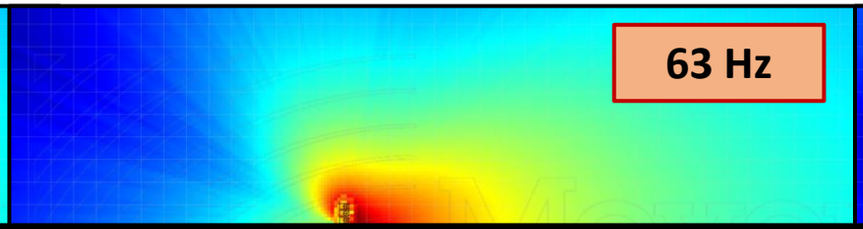
Effet miroir

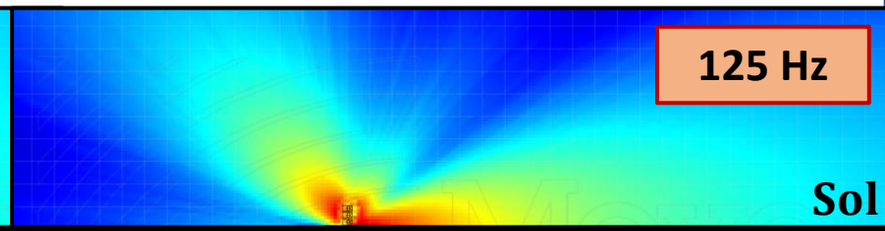
Paramètres	
fc =	≈ 85 Hz
λ =	5.4 m
T =	15.87 ms



- Si on le pose au sol, le couplage avec ce dernier redresse la diffusion.







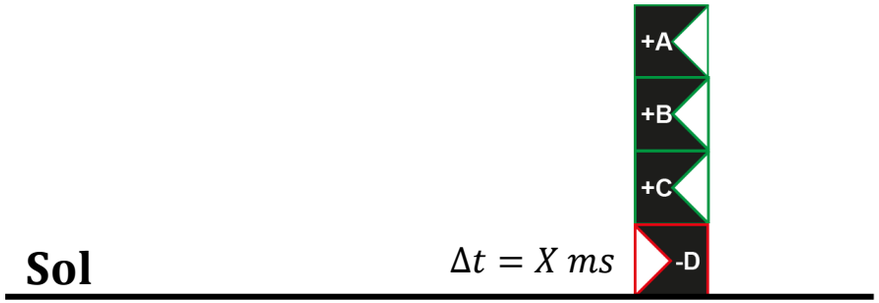
Gradient Inverted Stack vertical

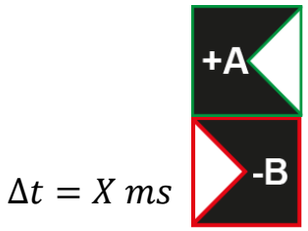
Effet miroir



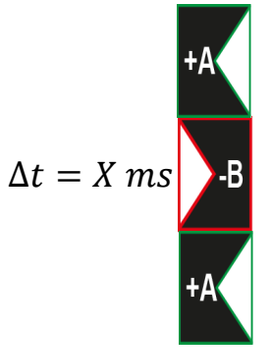


Gradient Inverted Stack
Configurations Constructeur









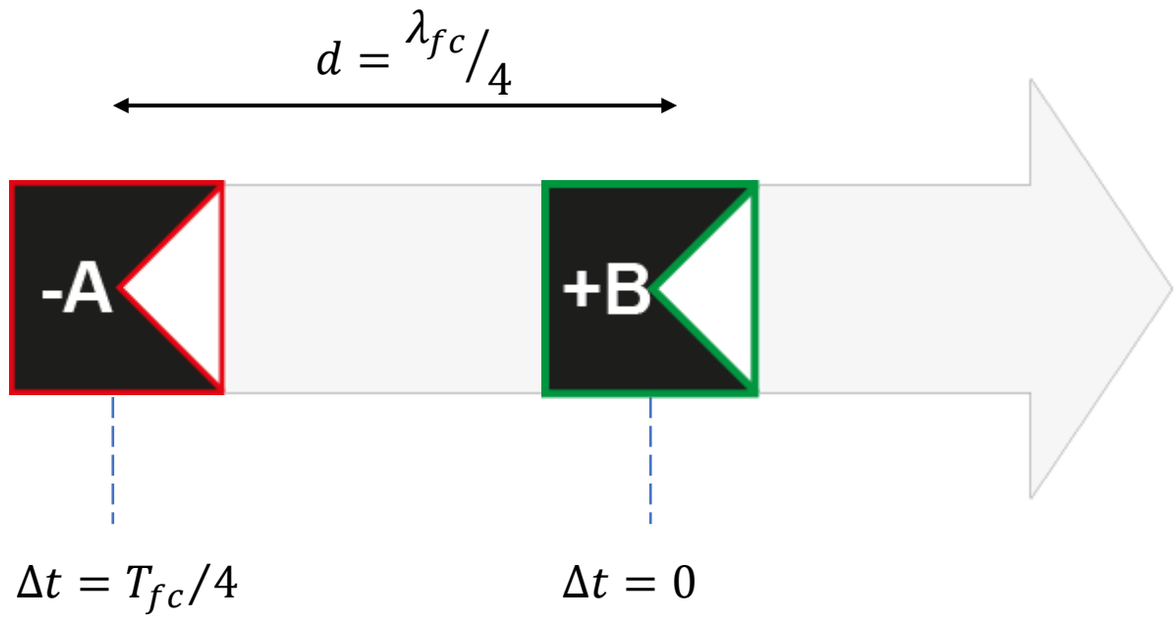
- La plupart des constructeurs proposent des presets de ce genre.
- Chacun applique des paramètres qui leurs sont propres.
- L'utilisation des filtres FIR, permet de contrôler la directivité sur une large bande.
- Il faut toujours lire les notices !

lake

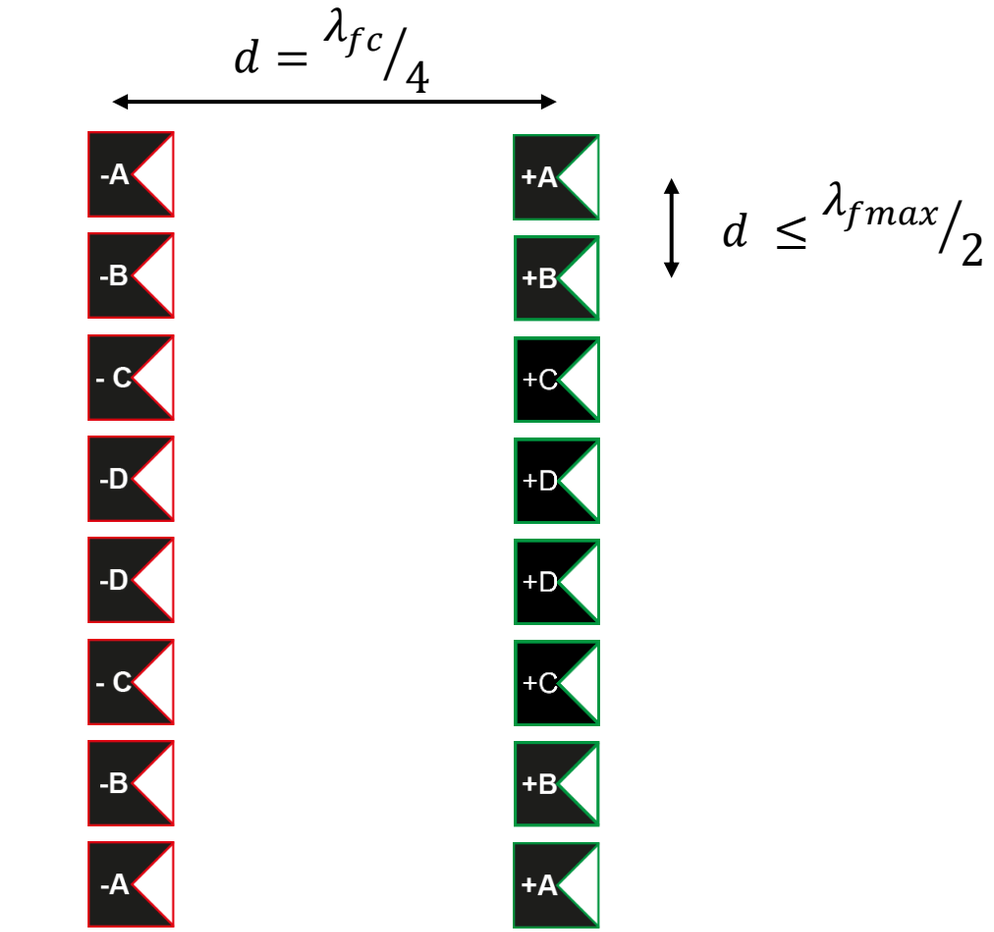
JBL ADAMSON NEXO L-ACOUSTICS Meyer Sound

?

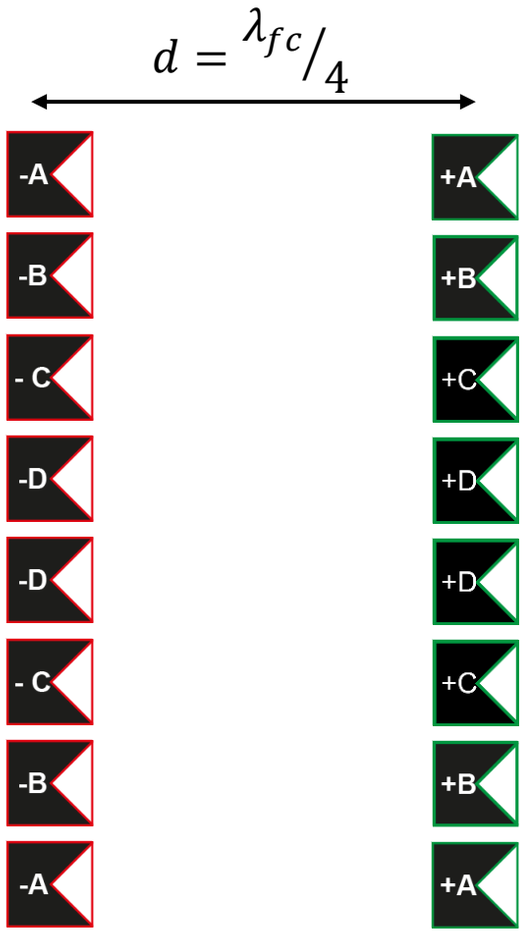
Arc Sub Cardio - Gradient



Arc Sub Cardio - Gradient

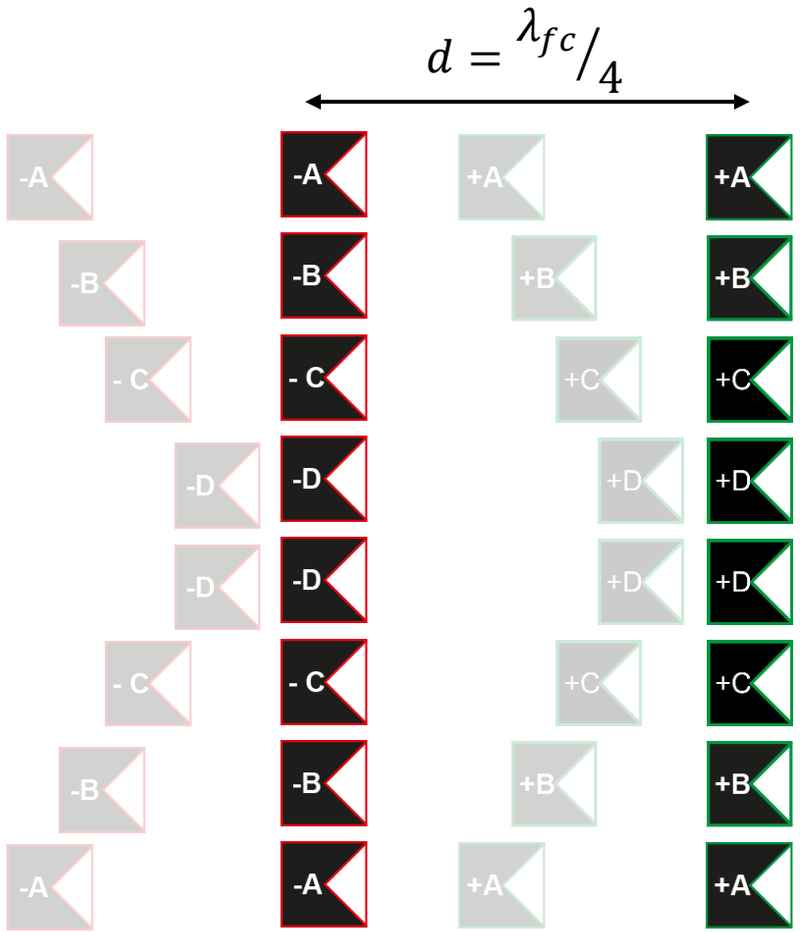


Arc Sub Cardio - Gradient



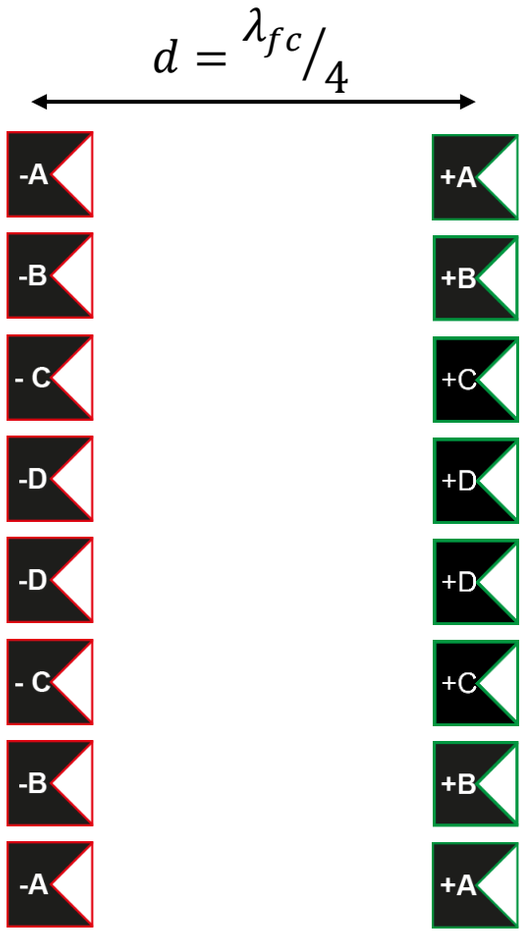
$$\Delta t = \frac{T_{fc}}{4} + \Delta t_{disp} \qquad \Delta t = 0 + \Delta t_{disp}$$

Arc Sub Cardio - Gradient



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

Arc Sub Cardio - Gradient

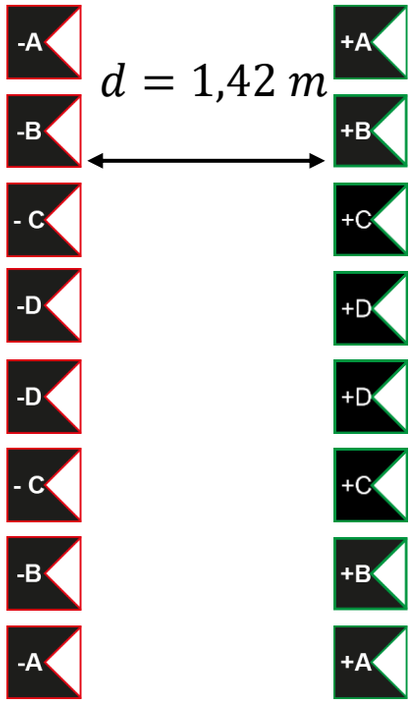


$$\Delta t = \frac{T_{fc}}{4} + \Delta t_{disp} \qquad \Delta t = 0 + \Delta t_{disp}$$

Arc Sub Cardio - Gradient

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

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

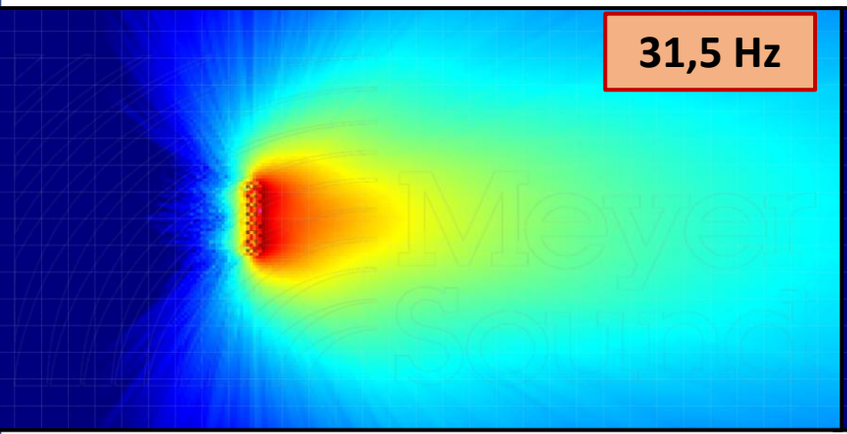


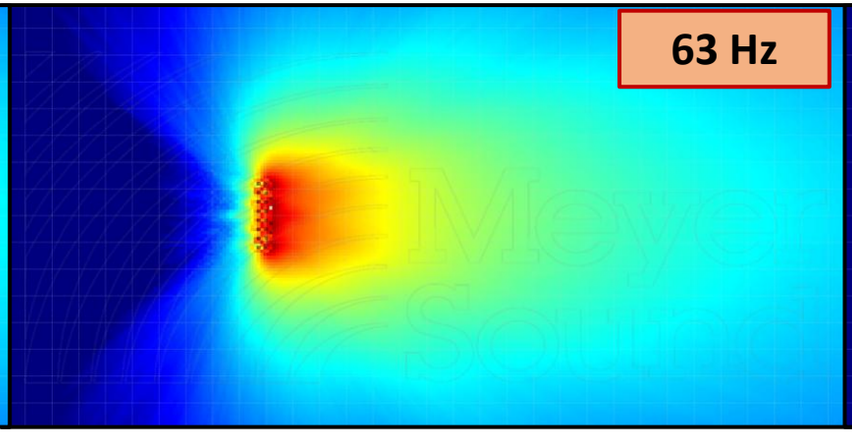
$$d = 1{,}42\ m$$

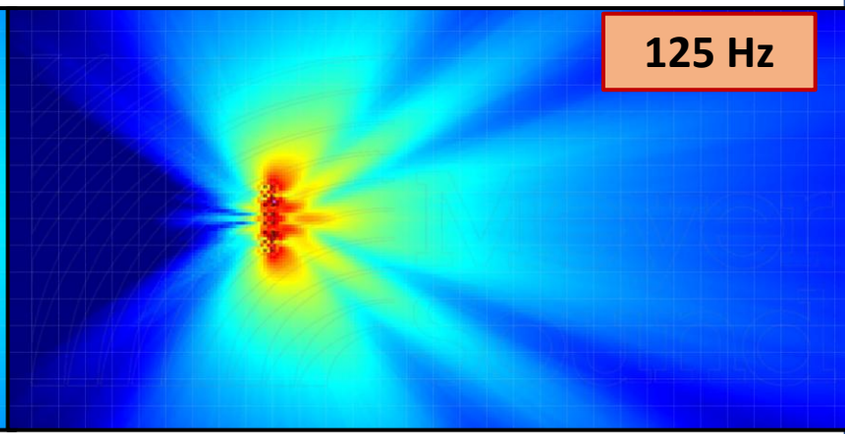
$$d \leq 1{,}42\ m$$

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

C'est une de mes config préférée !

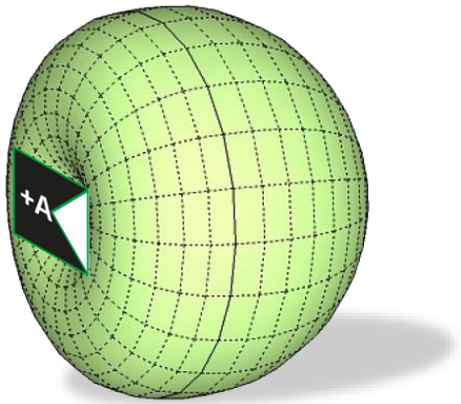






Sub cardio constructeurs

- Nos chers constructeurs ne fabriquent pas seulement des Subs omni.
- Certains fabriquent aussi des subs plus ou moins cardio !

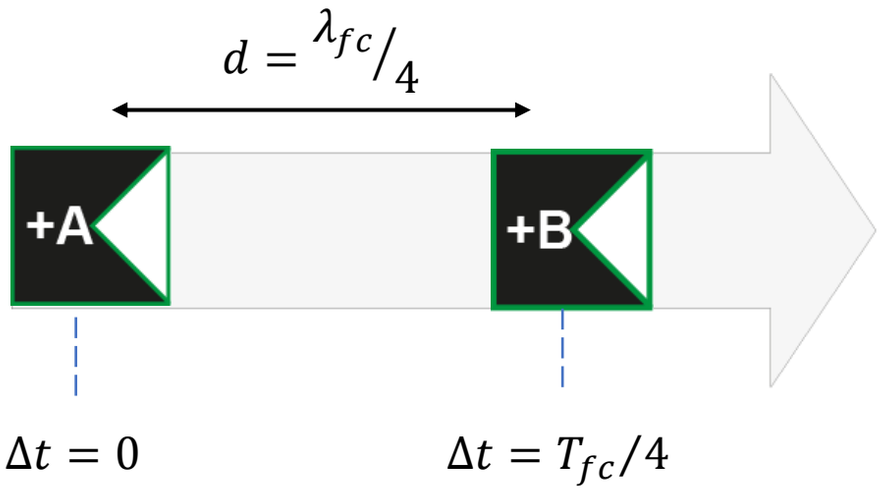




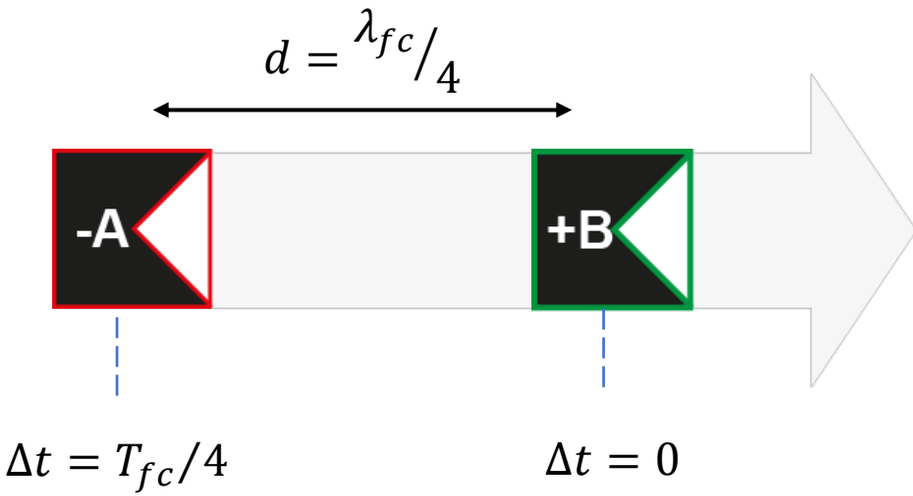


Natif Vs. Gradient

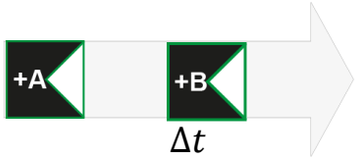
Natif



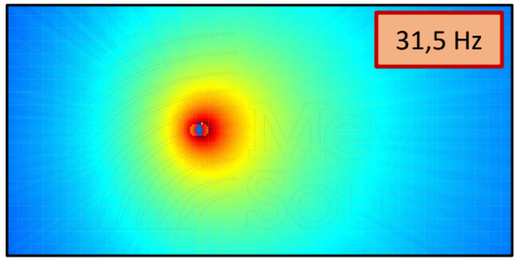
Gradient

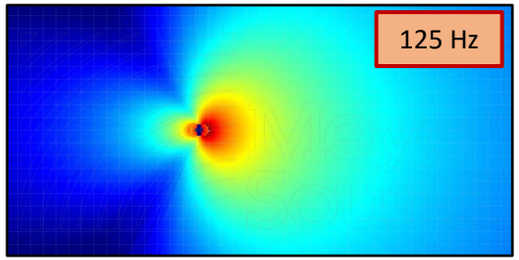


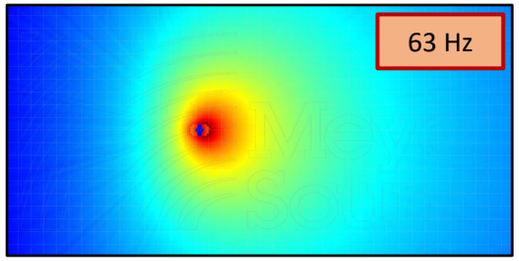
Natif Vs. Gradient



Natif





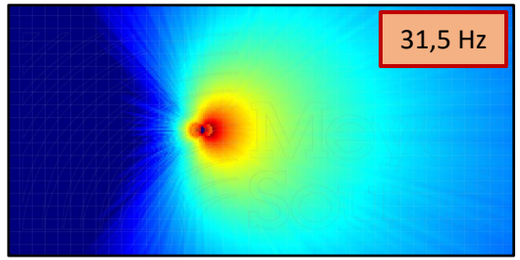


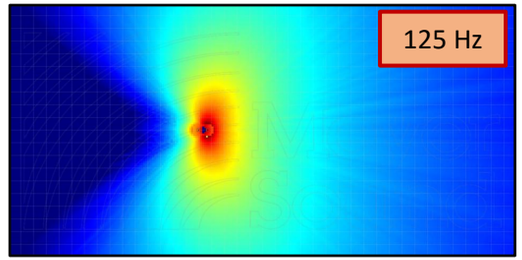
- φ Stable à l'avant du système
- φ Variable à l'arrière

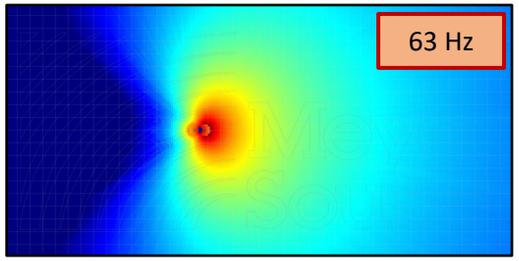
- Isolation moyenne

Gradient









- φ Variable à l'avant du système
- φ Stable à l'arrière

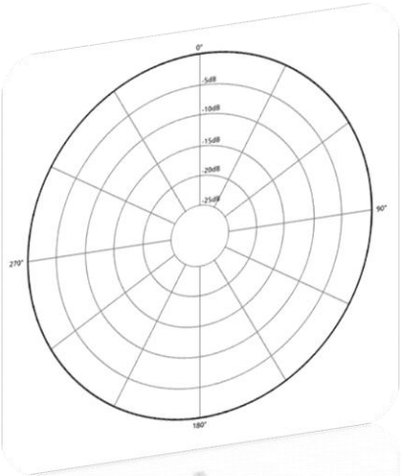
- Isolation forte

Omni Vs Cardio

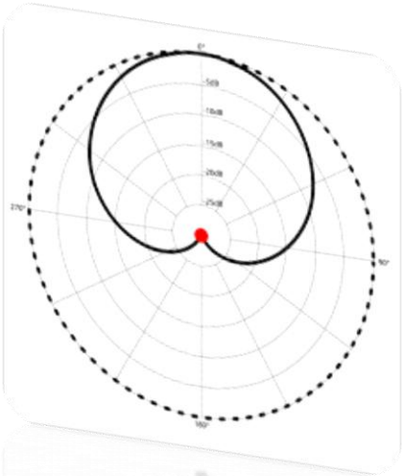
- La plupart des Subs sont fabriqués pour fonctionner d’une manière quasi omnidirectionnelle.

- Jouer sur la directivité en procédant à des couplages modifie la réponse impulsionnelle d’origine.

- Ces modifications impliquent un changement dans la définition.
- Cela se traduit part un «impact» moins prononcé.



- Toutefois, cette légère perte est compensée par la précision de la couverture.



?

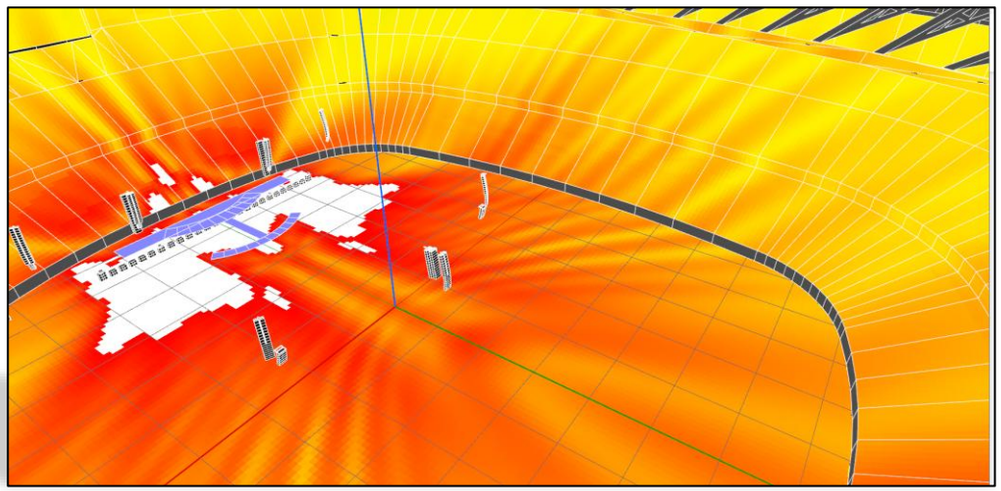
4 Configurations spéciales

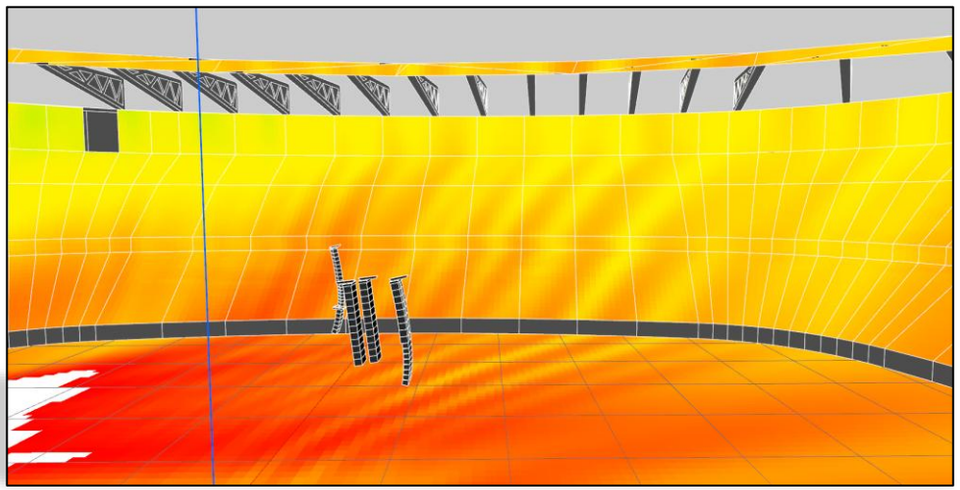


Rappel de subs

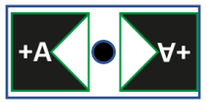
Les fréquences reproduites par les subs ne sont souvent pas prises en compte dans les mesures de niveaux officielles en dBA.

Pour éviter malgré tout de rendre sourds les premiers rangs, il est parfois nécessaire de rajouter des rappels.

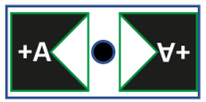




Rappel de subs



Omni x2

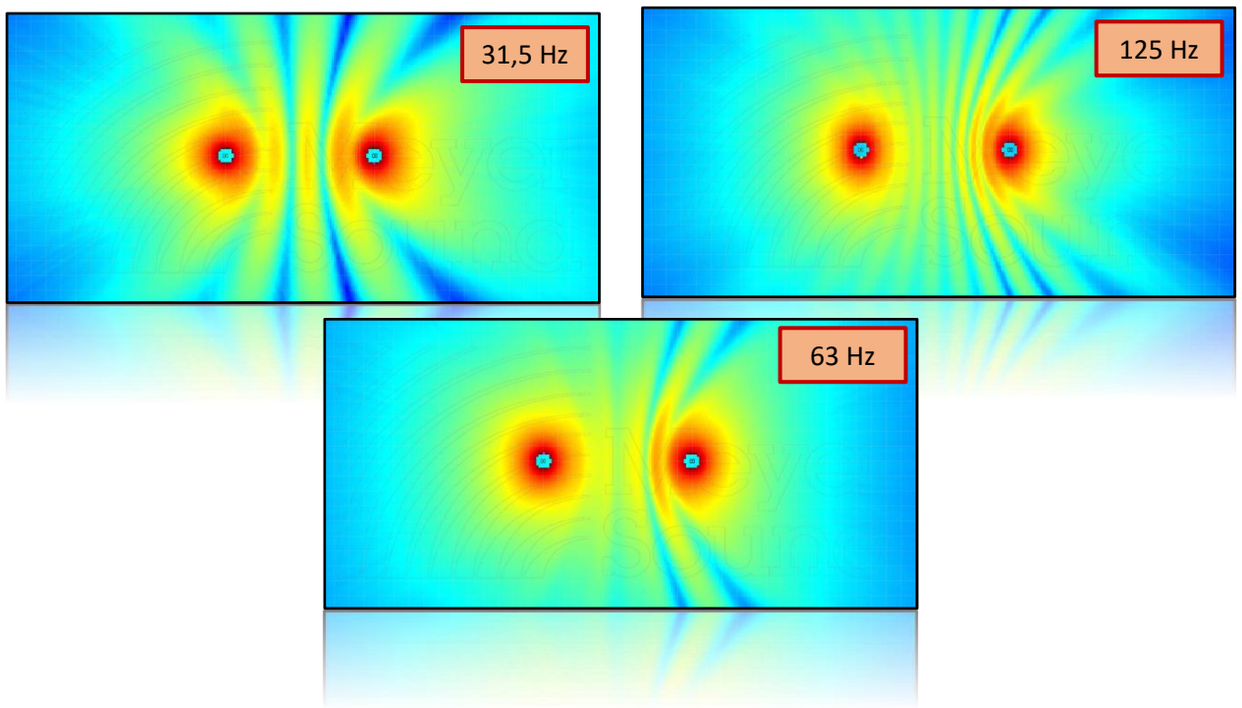


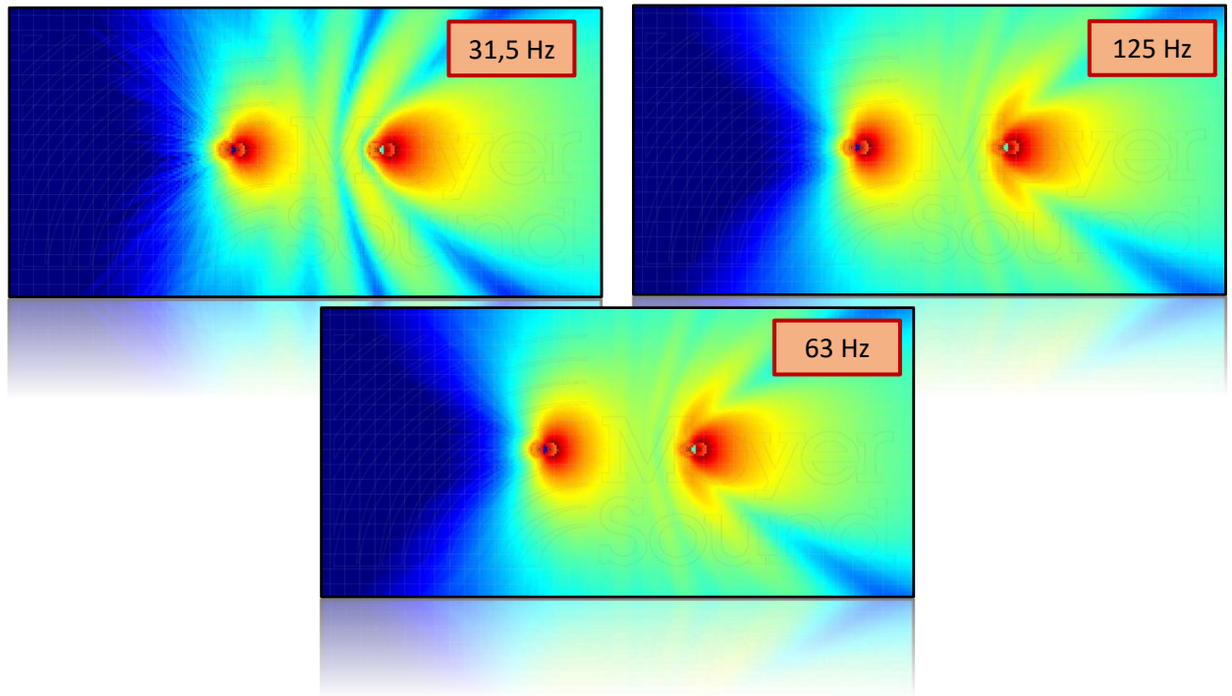


Gradient x2

1m42 – 60Hz

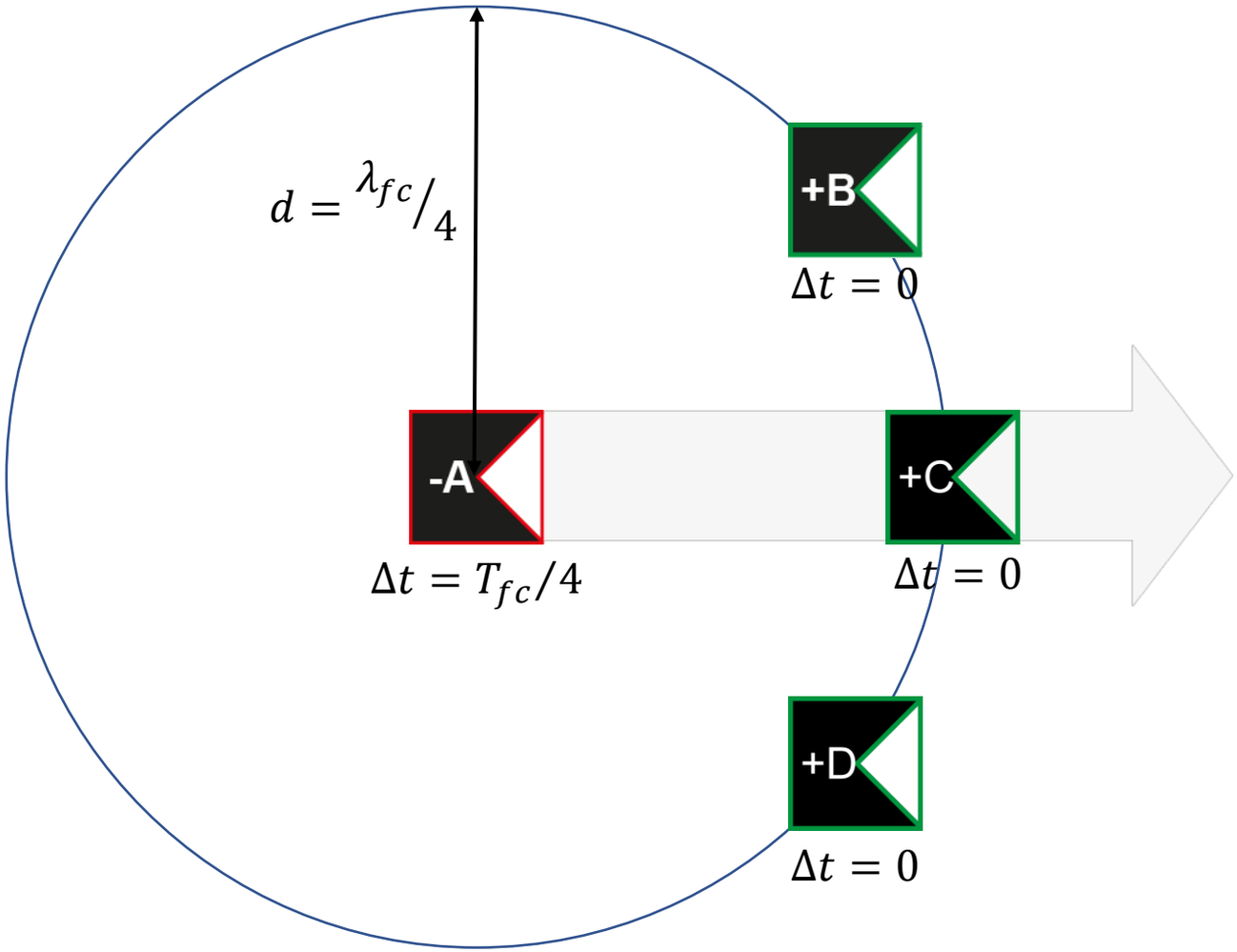




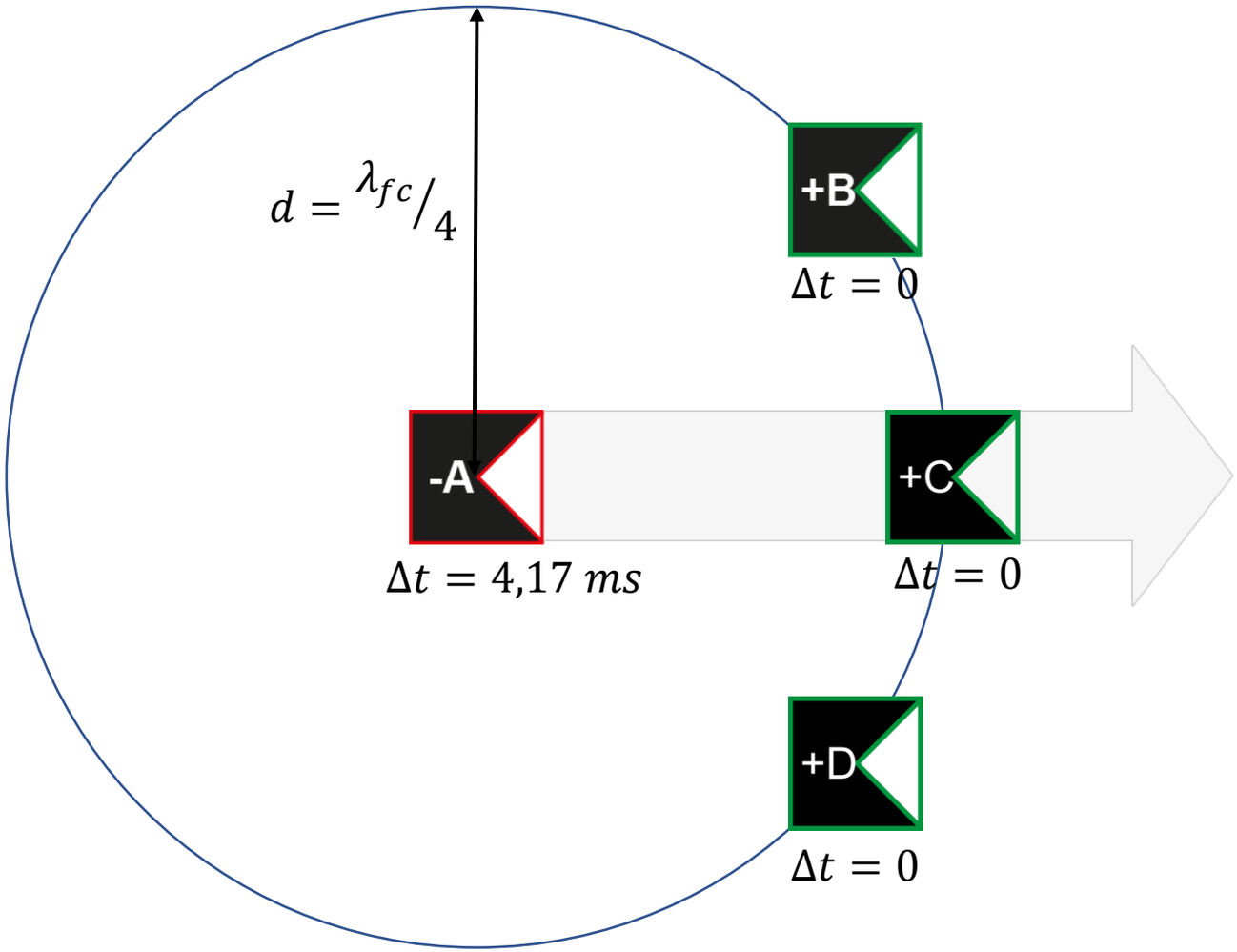


- Il est conseillé d'utiliser des subs cardio en rappel.

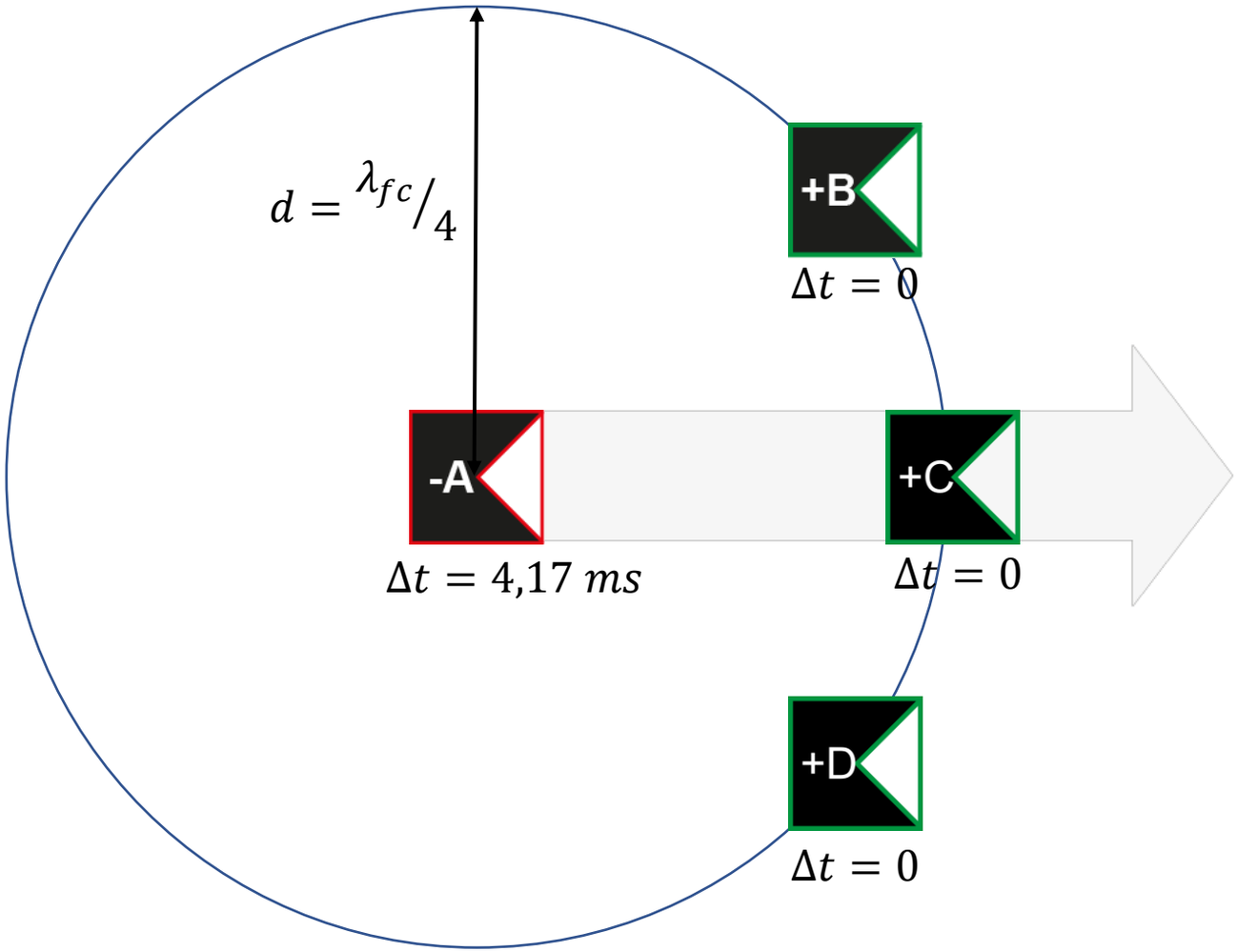
Flower Fire

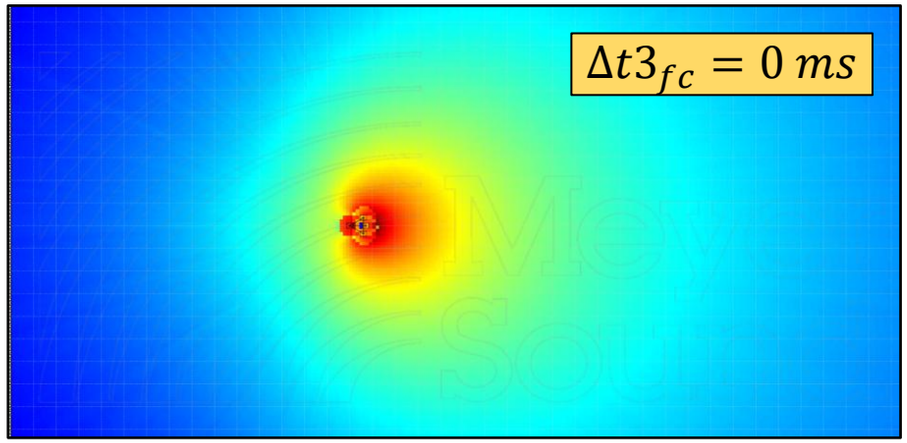


Flower Fire
60 Hz

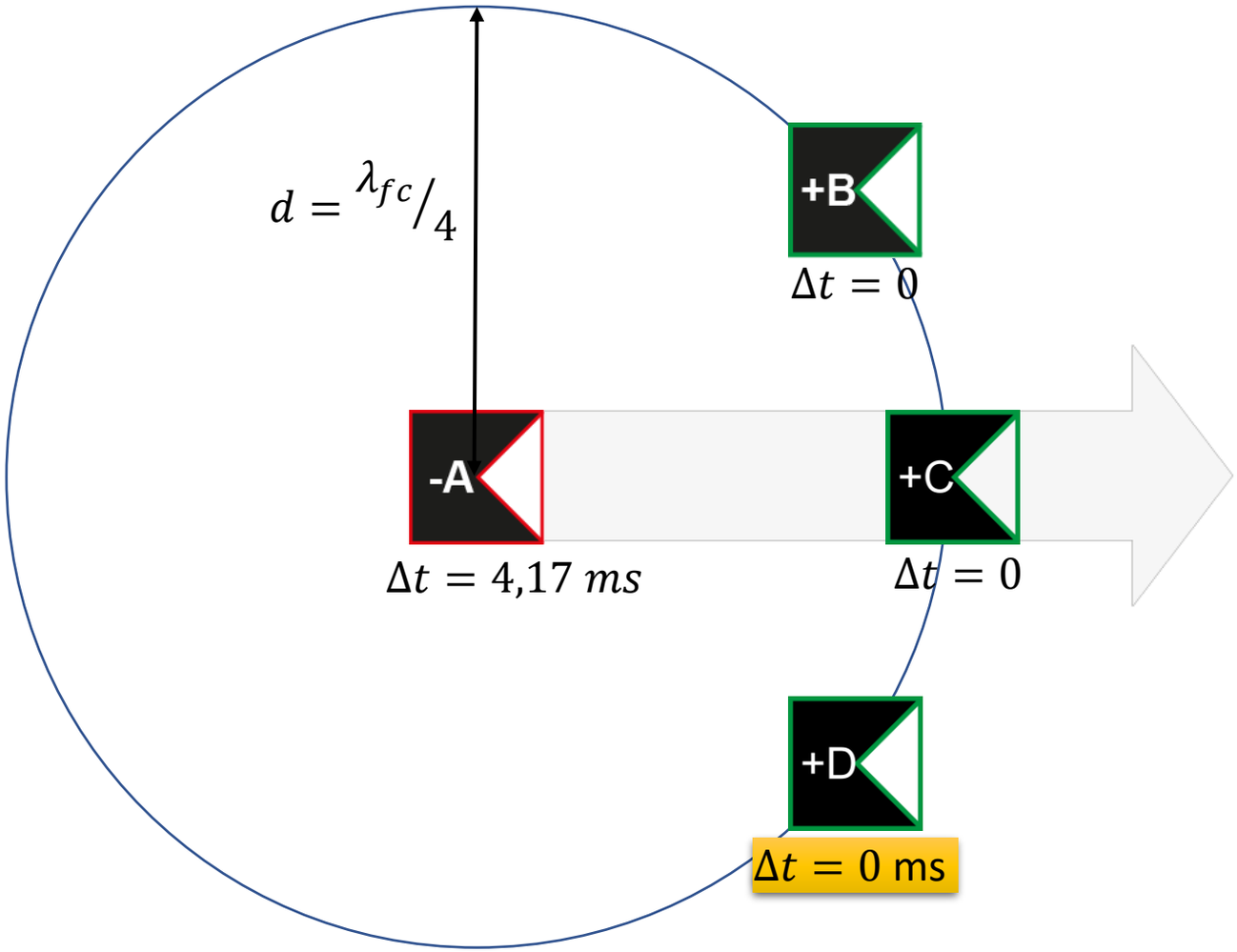


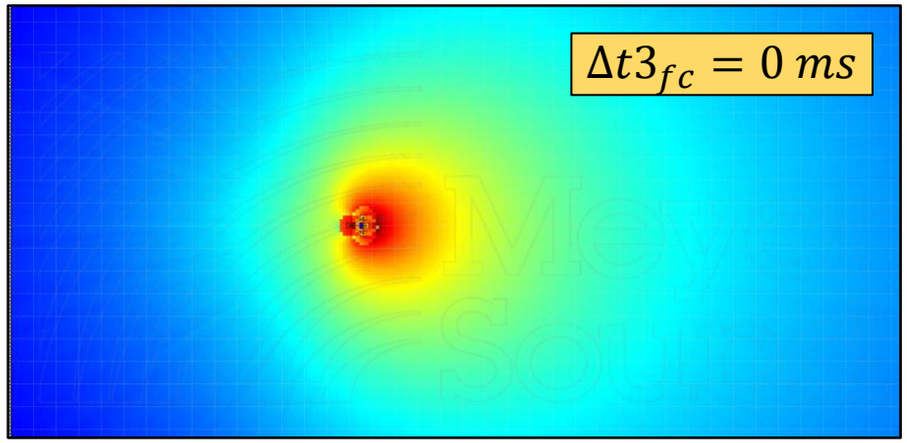
Flower Fire
60 Hz



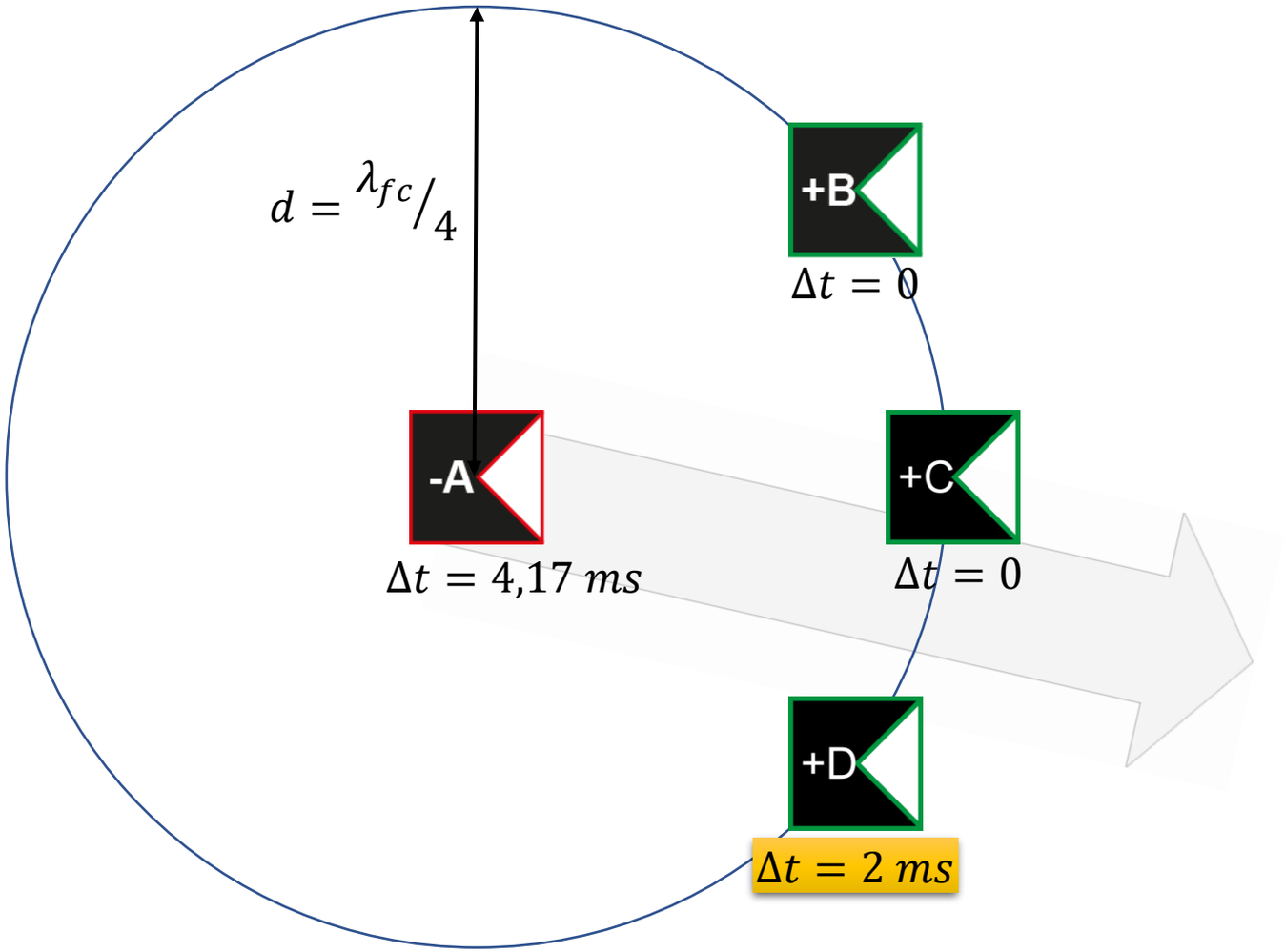


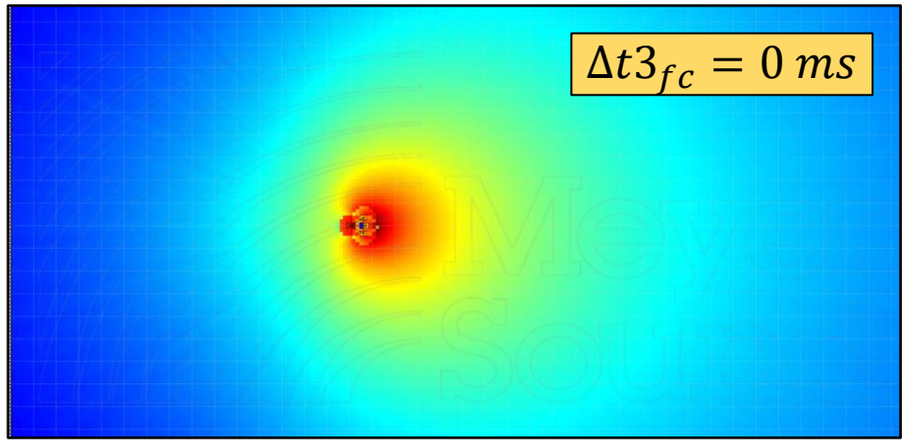
Flower Fire
60 Hz

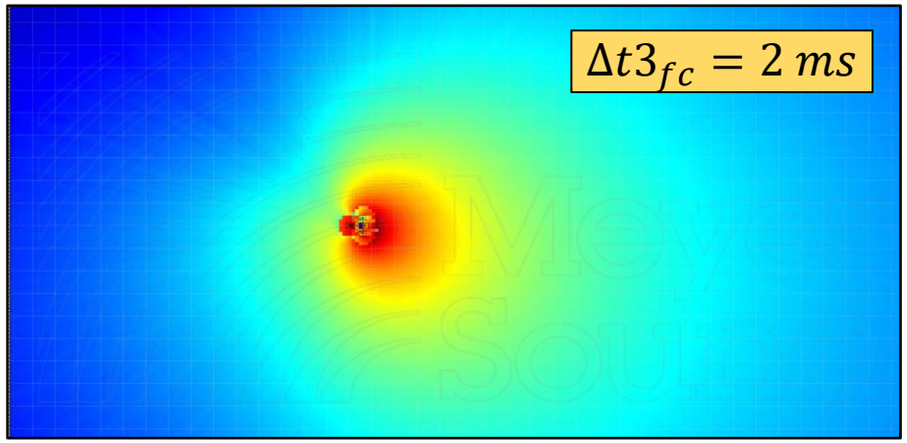




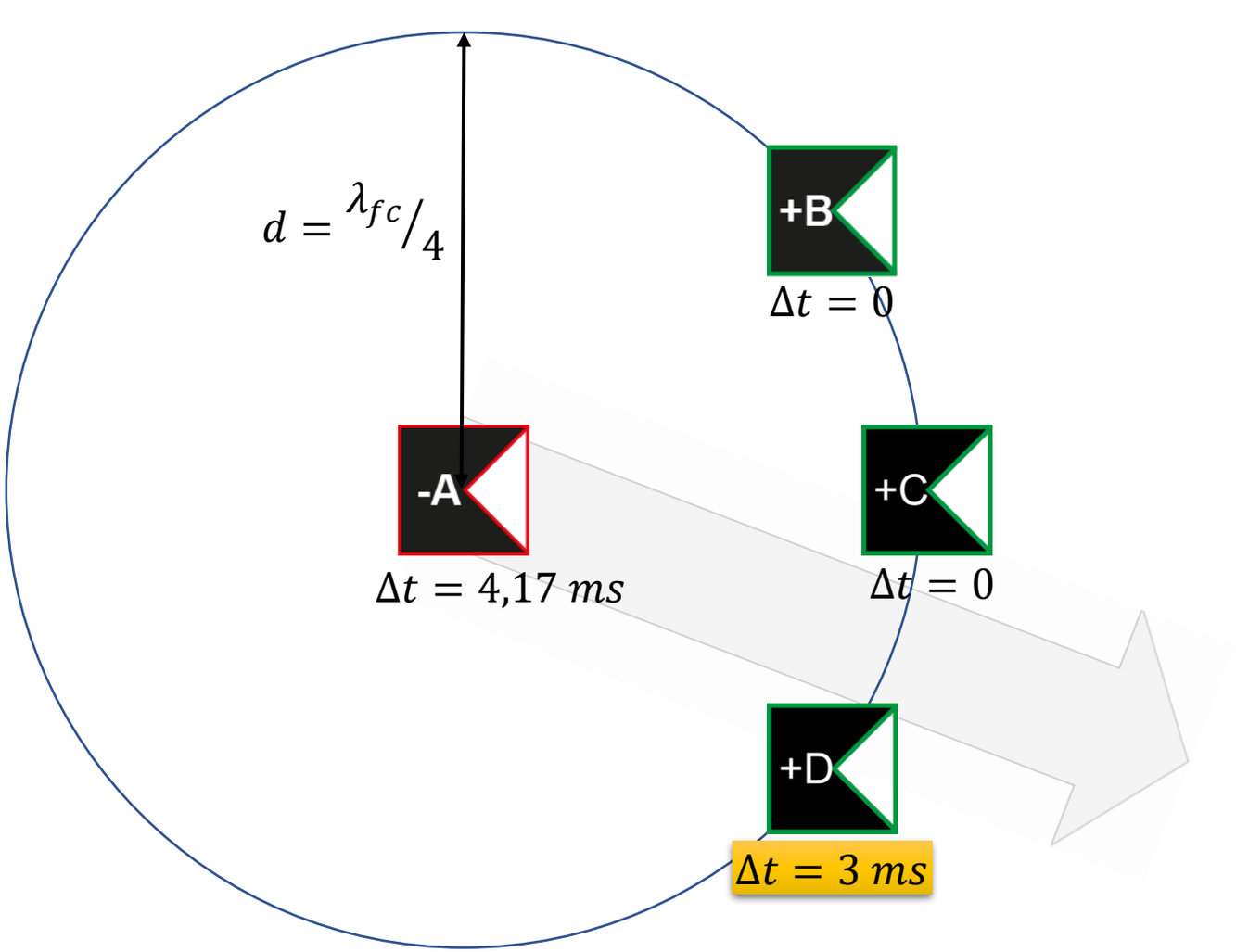
Flower Fire
60 Hz

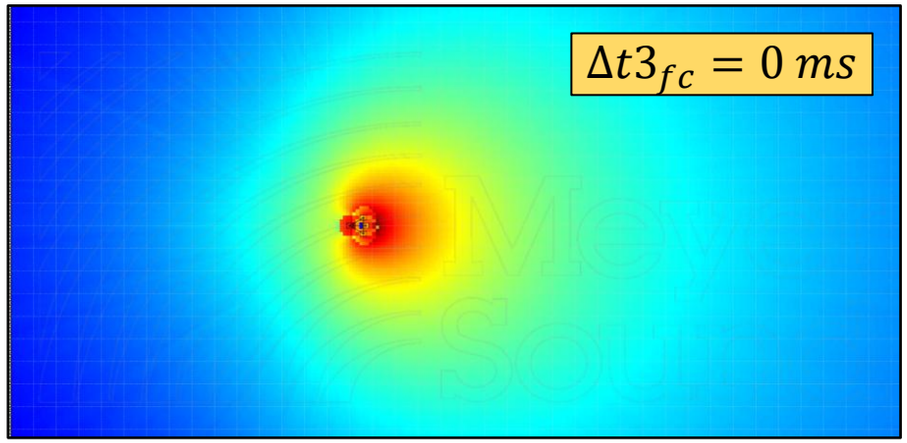


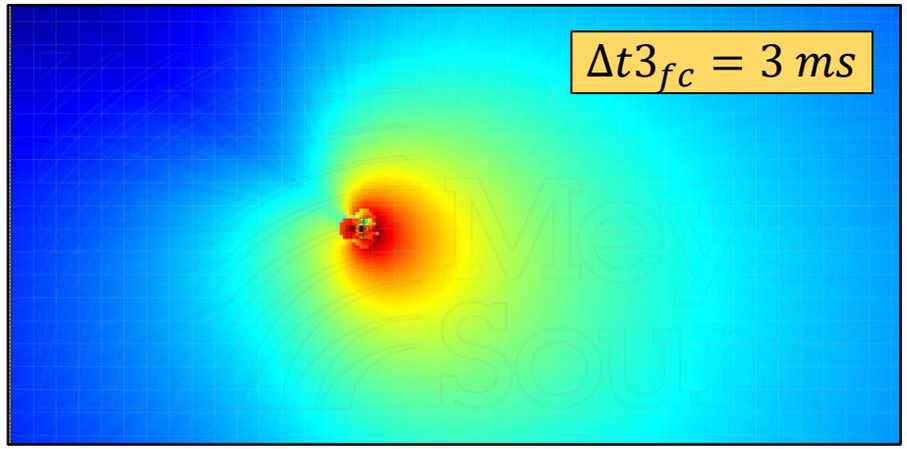




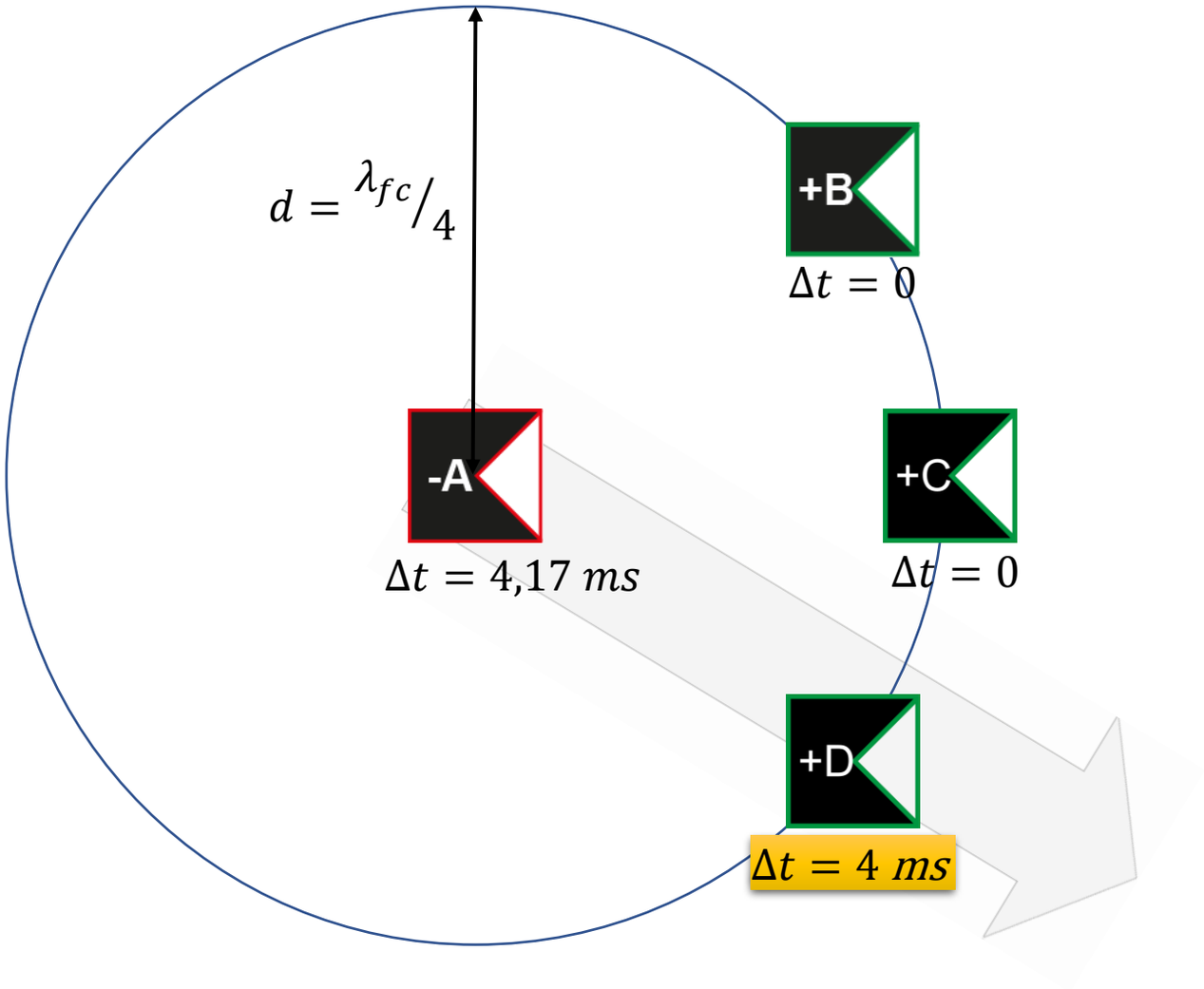
Flower Fire
60 Hz

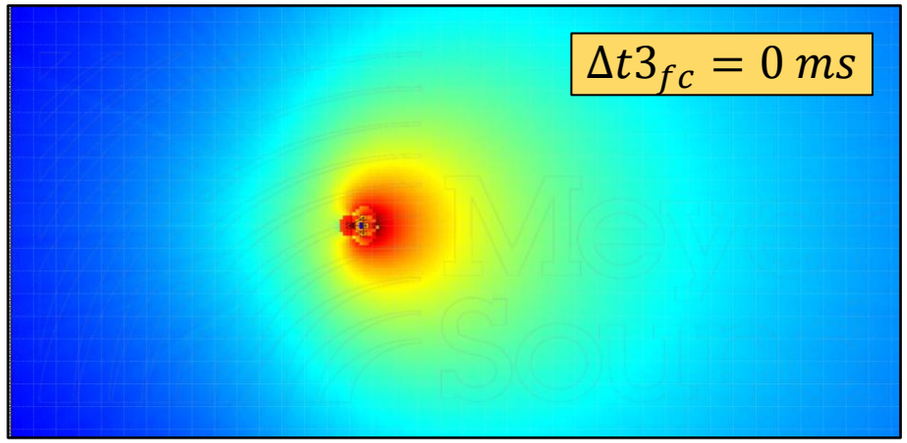


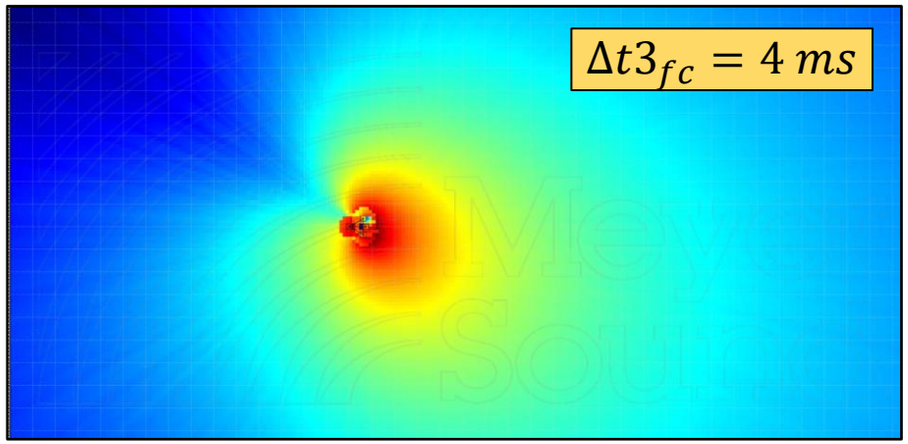




Flower Fire
60 Hz







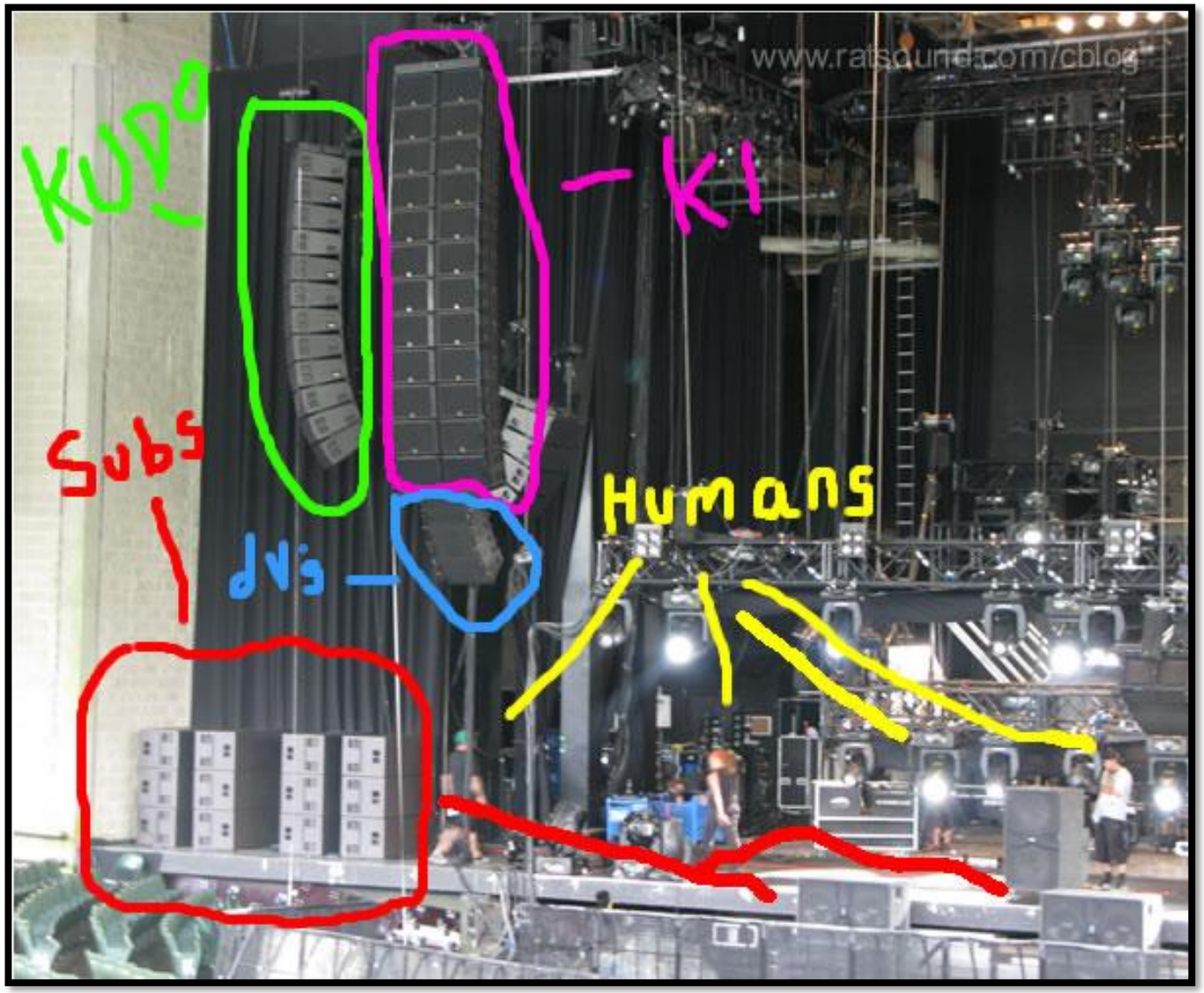
Dave Rat



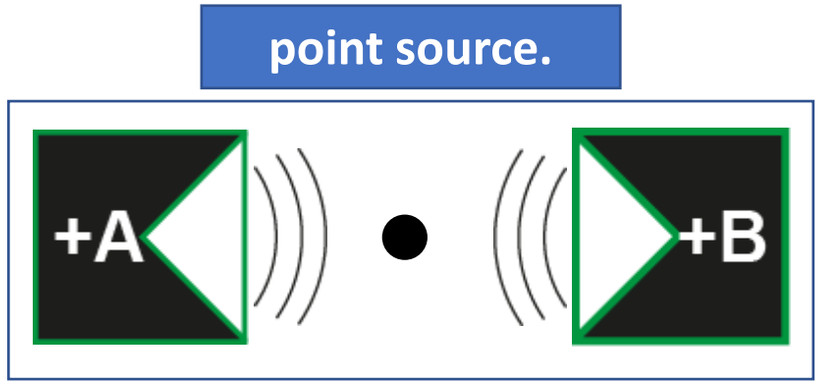


Slot fire

Dave Rat



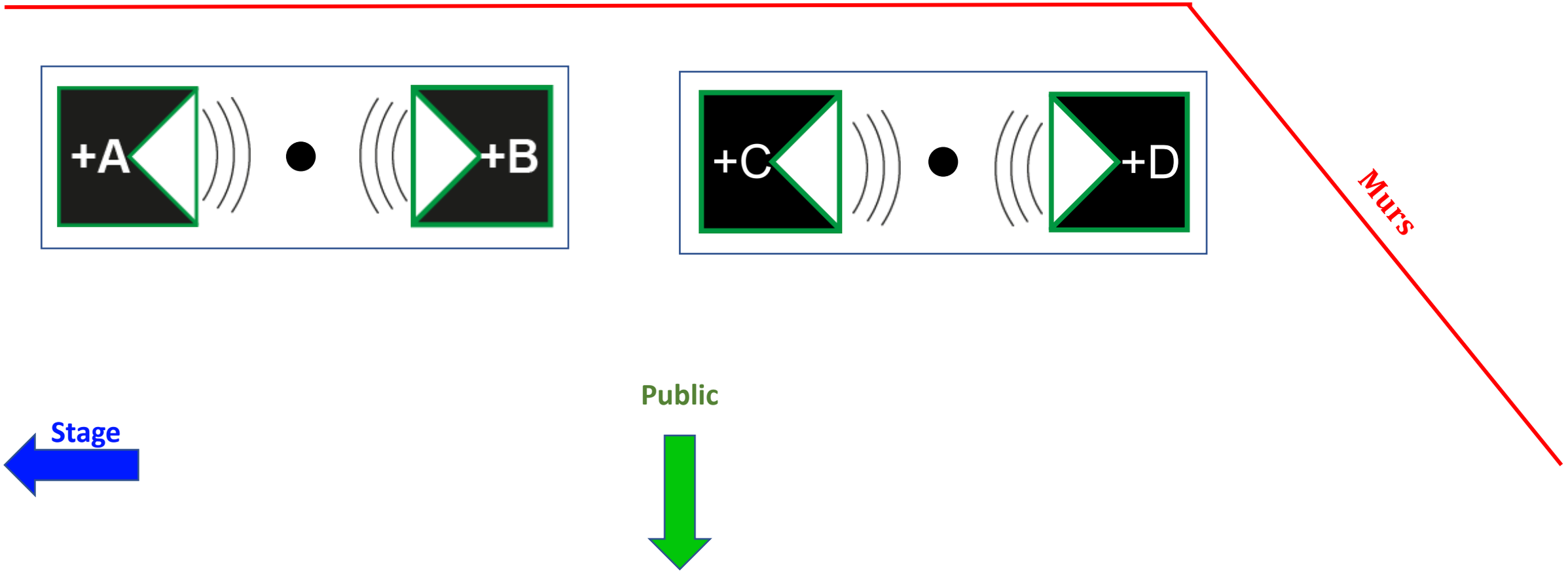




Un sub 100% omni avec un centre acoustique virtuel au centre

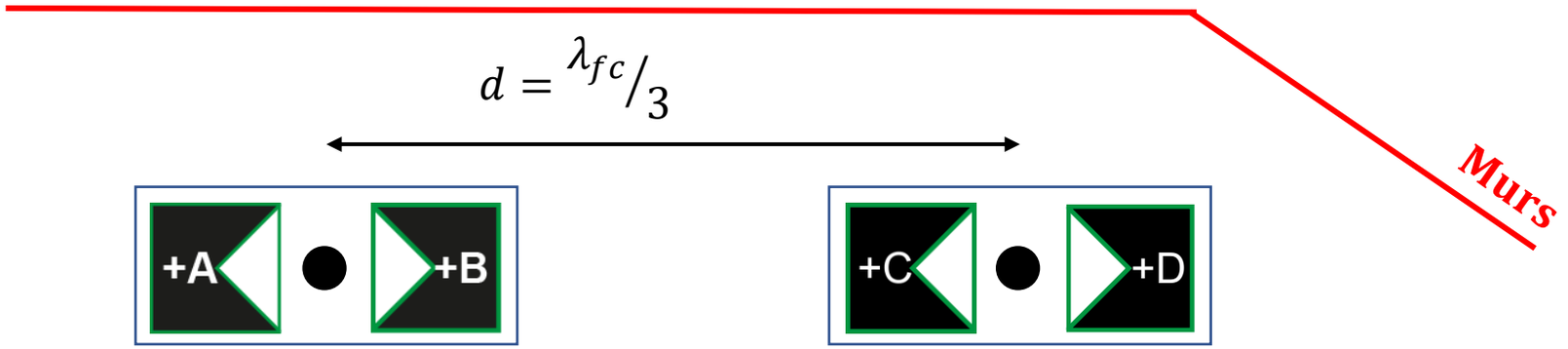
Slot fire

Dave Rat



Slot fire

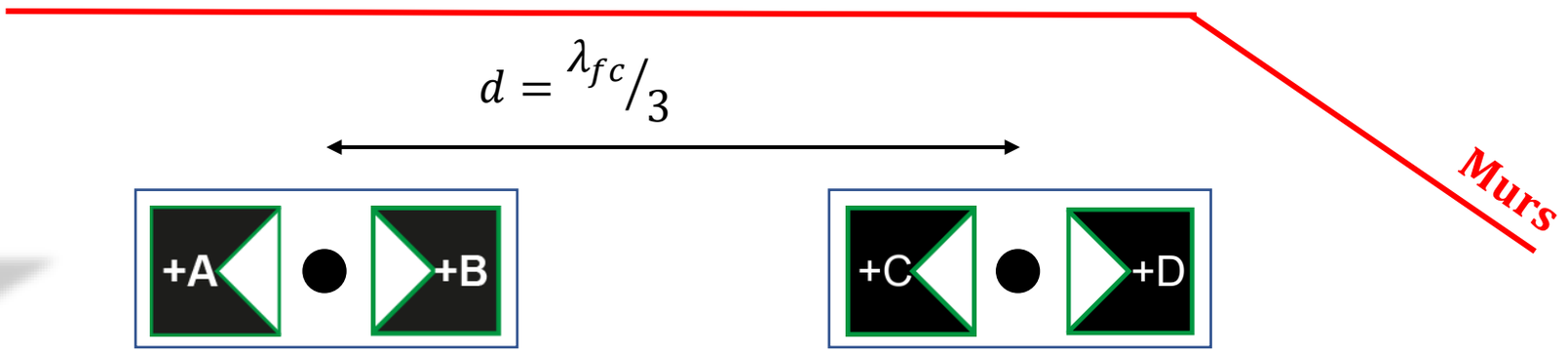
Dave Rat



Slot fire

Exemple 45 Hz

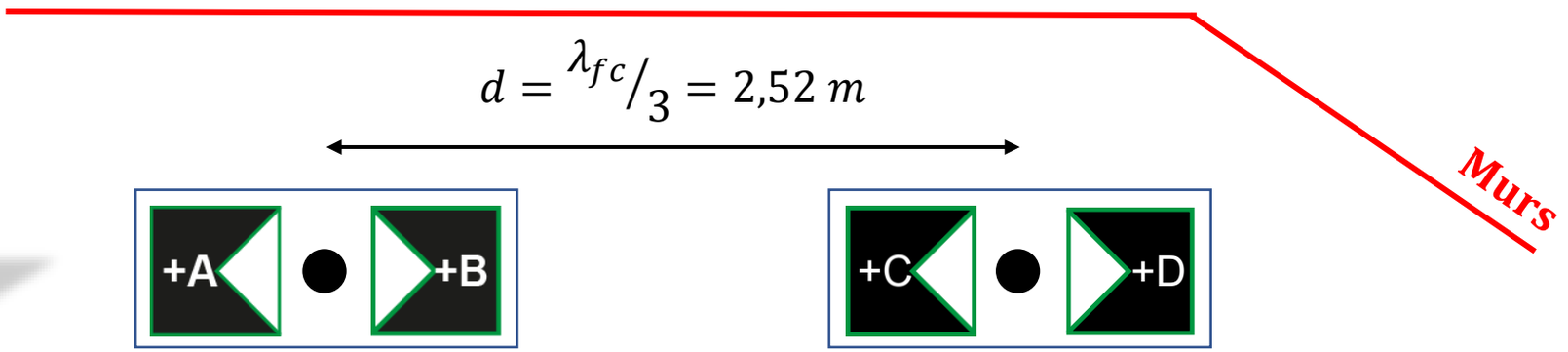
Paramètres	
fc =	**45 Hz**
λ =	**7.56 m**
T =	**22.22 ms**



Slot Fire

Exemple 45 Hz

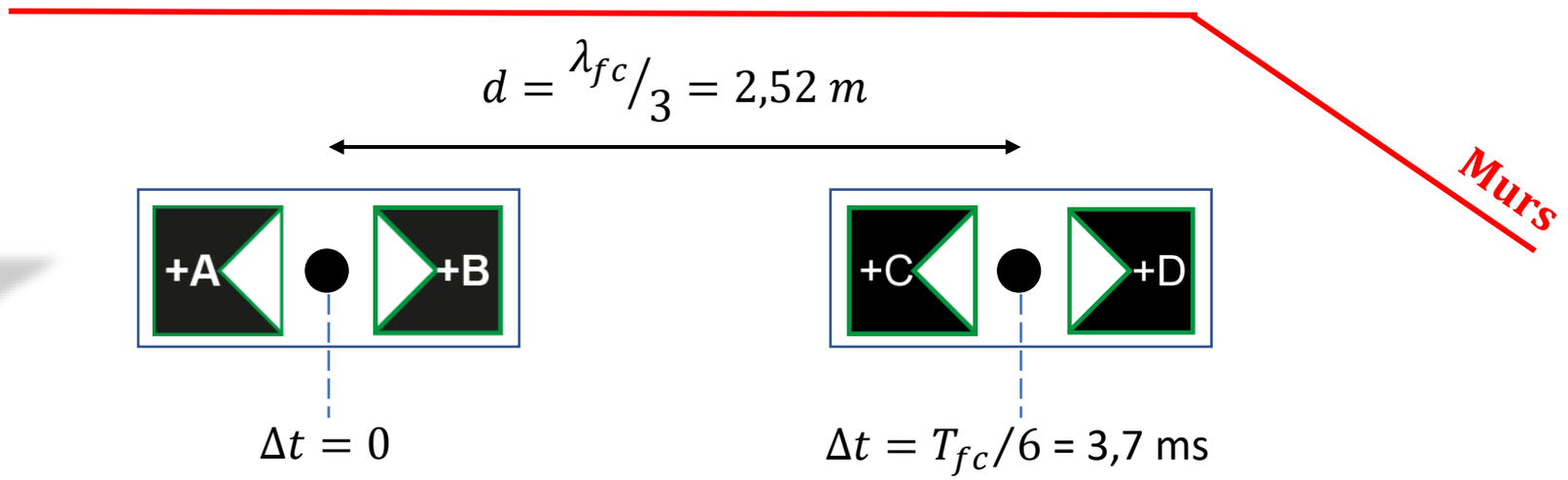
Paramètres	
fc =	**45 Hz**
λ =	**7.56 m**
T =	**22.22 ms**



Slot Fire

Exemple 45 Hz

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

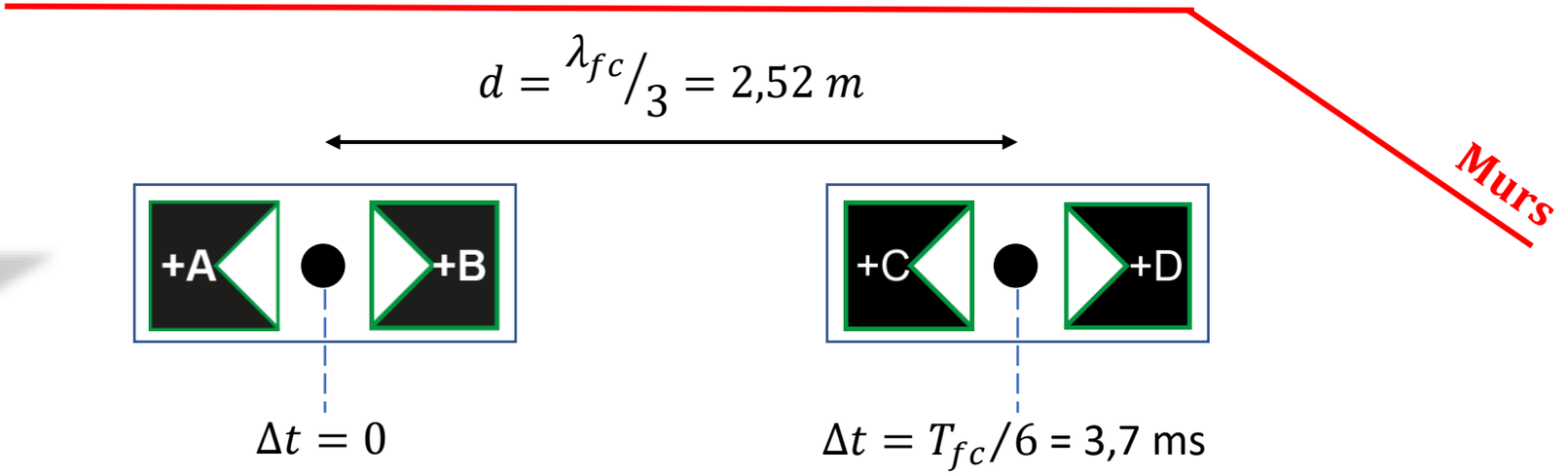


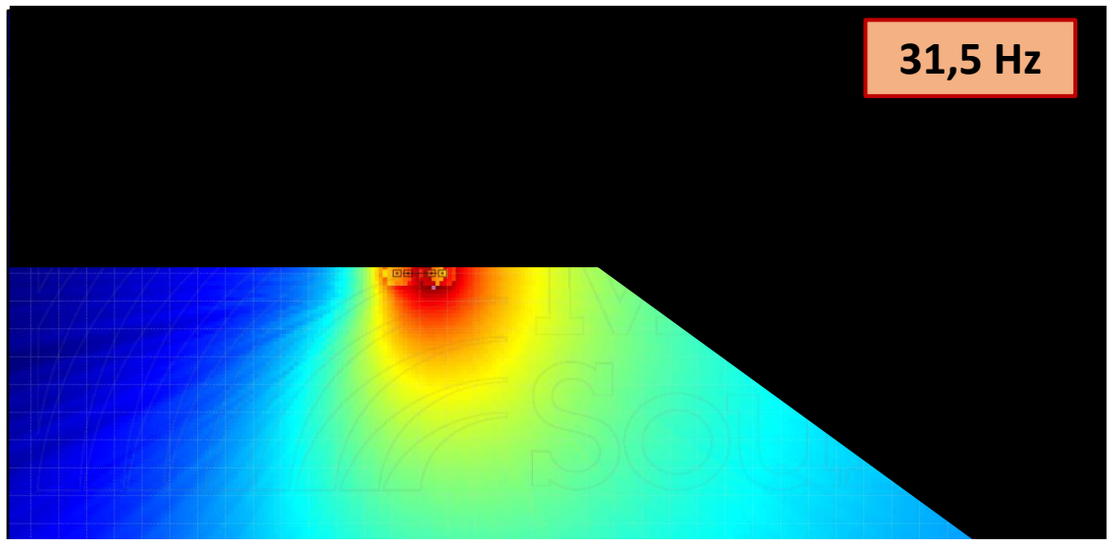
$$\frac{1}{3} + \frac{1}{6} = \frac{1}{2}$$

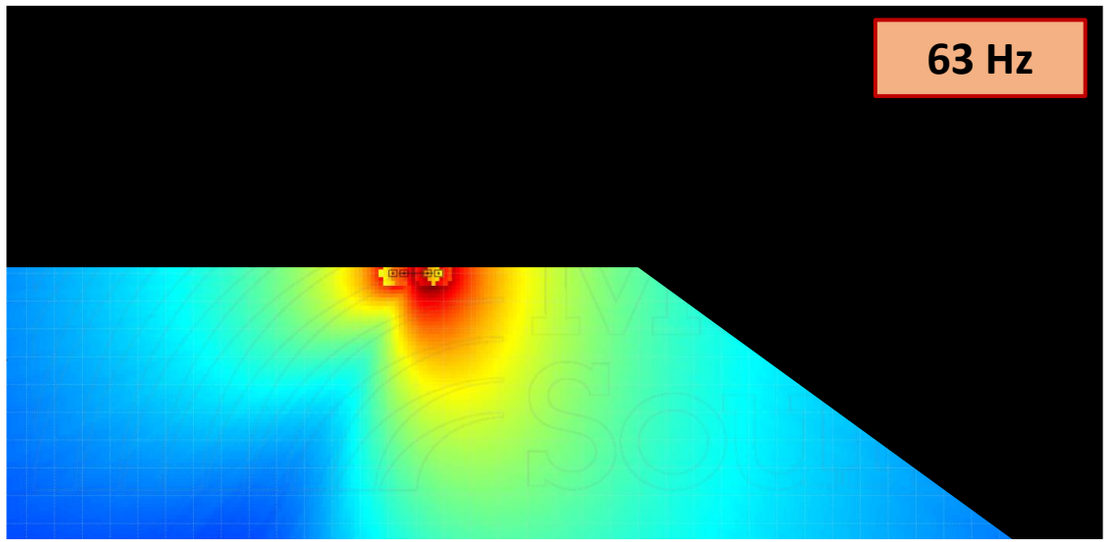
Slot Fire

Exemple 45 Hz

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



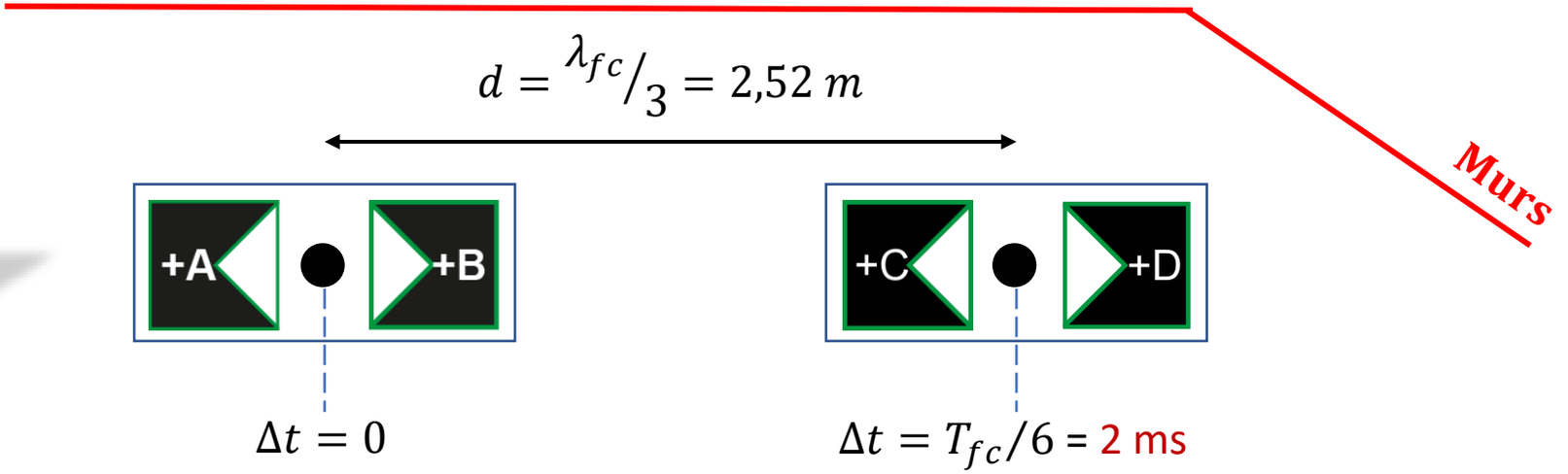


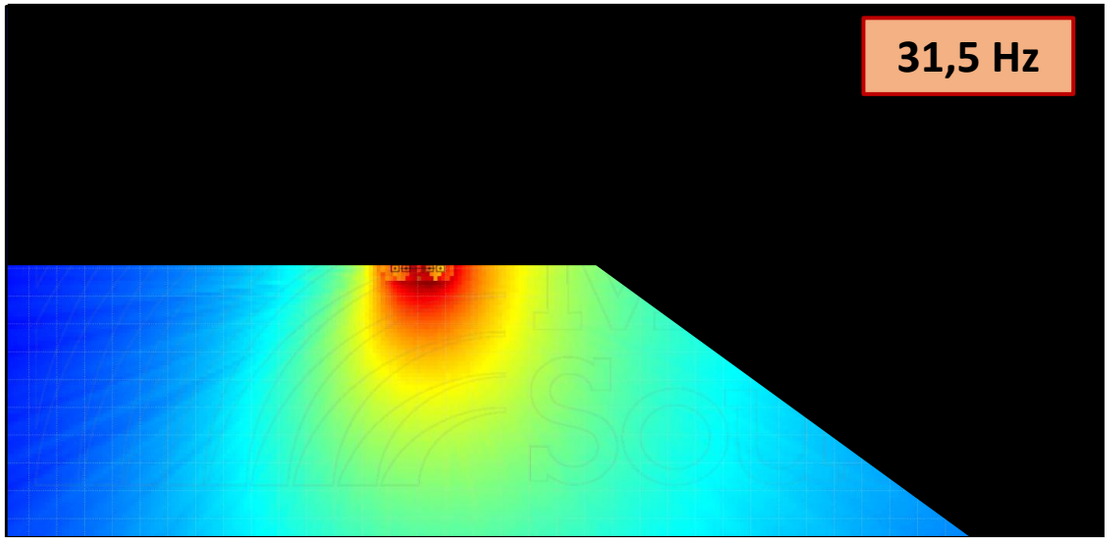


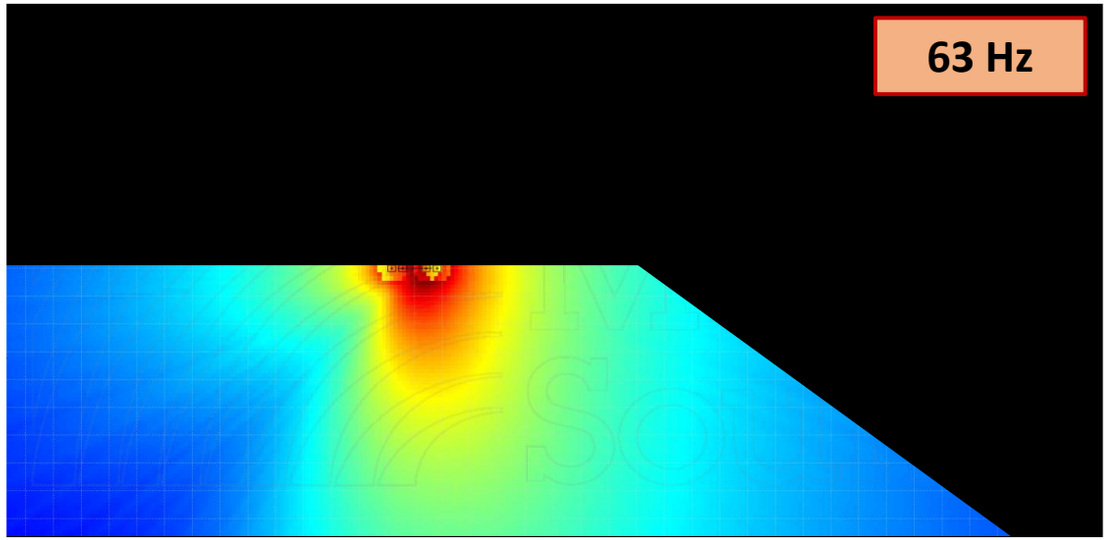
Slot Fire

Exemple 45 Hz

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







Slot Fire

Exemple 45 Hz

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



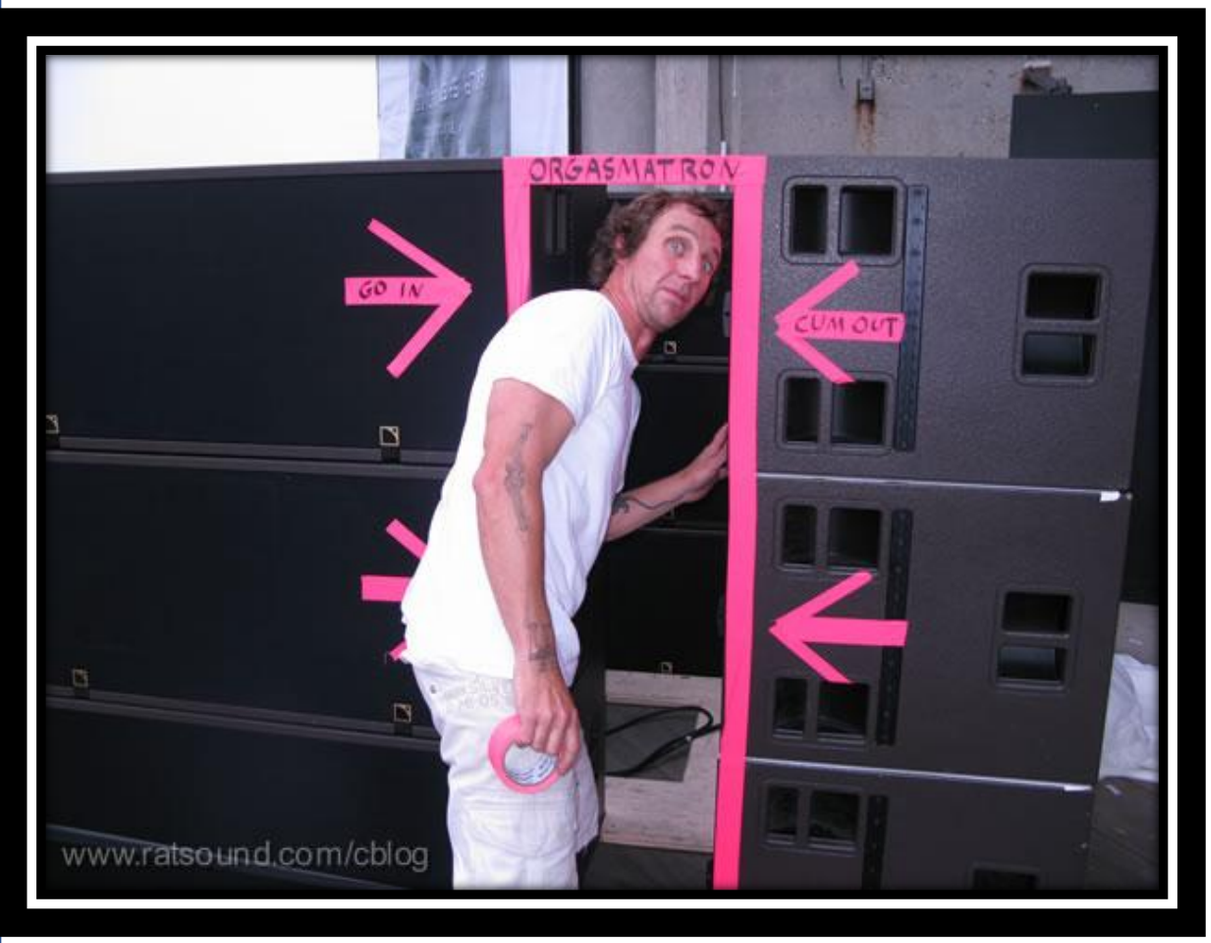
Vortex - Orgasmotron

Dave Rat



Vortex - Orgasmotron

Dave Rat

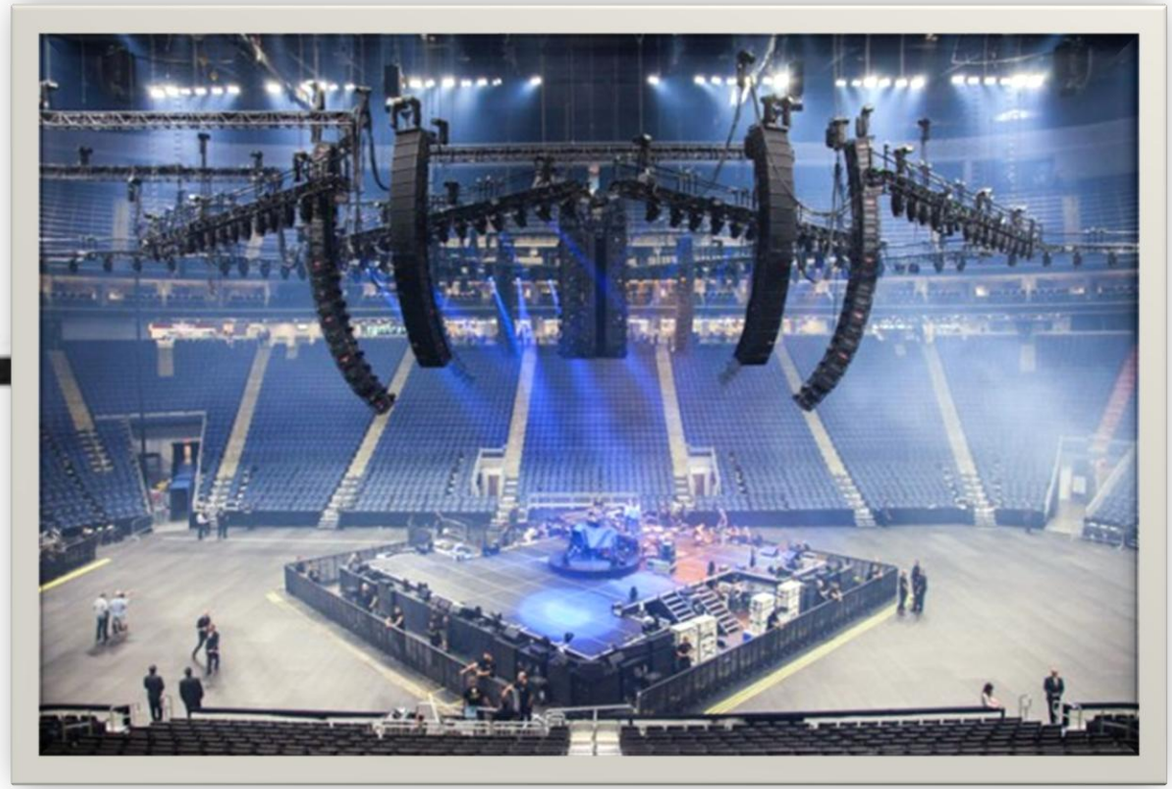




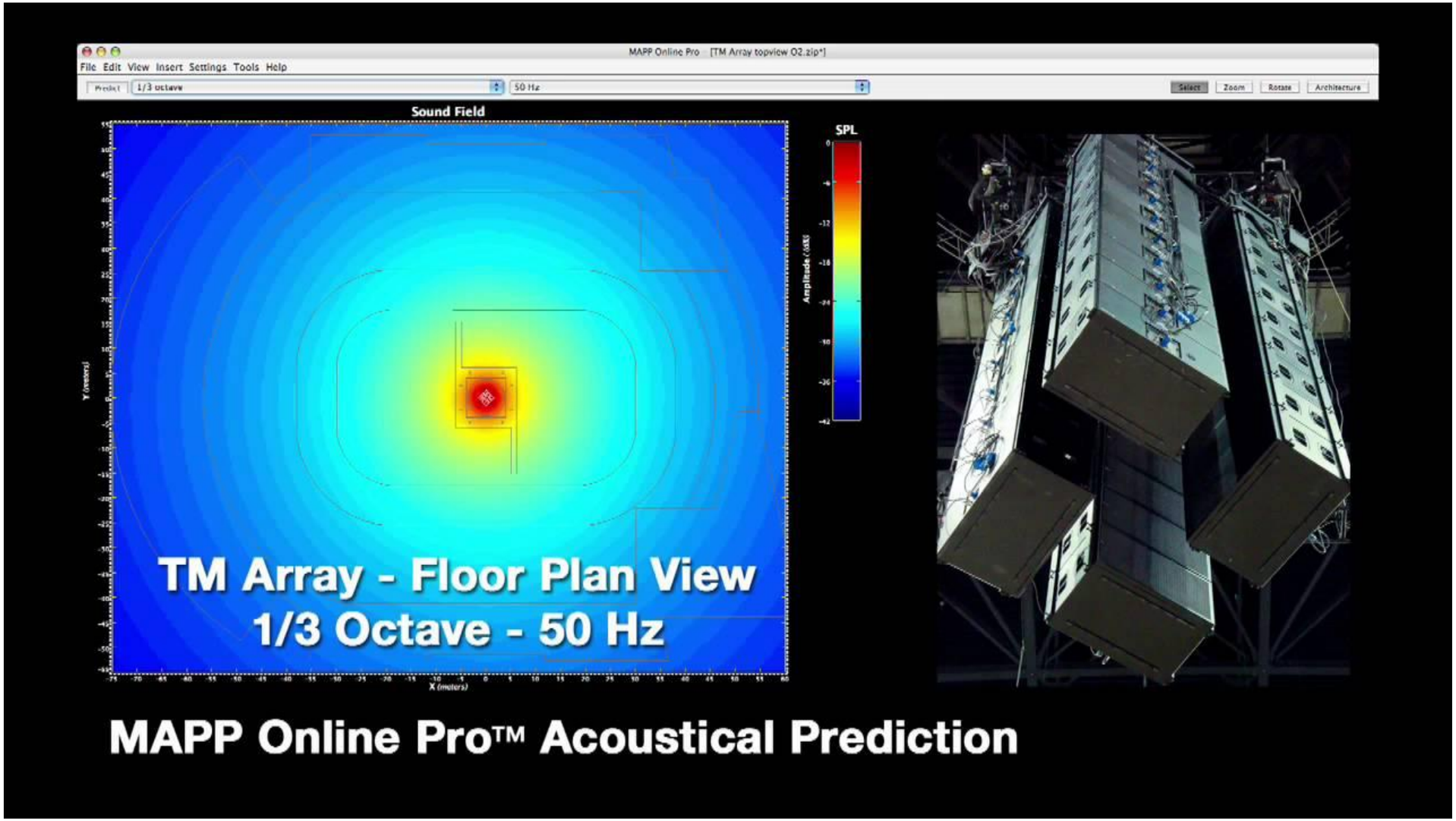
TM Array
Thomas Mundorf



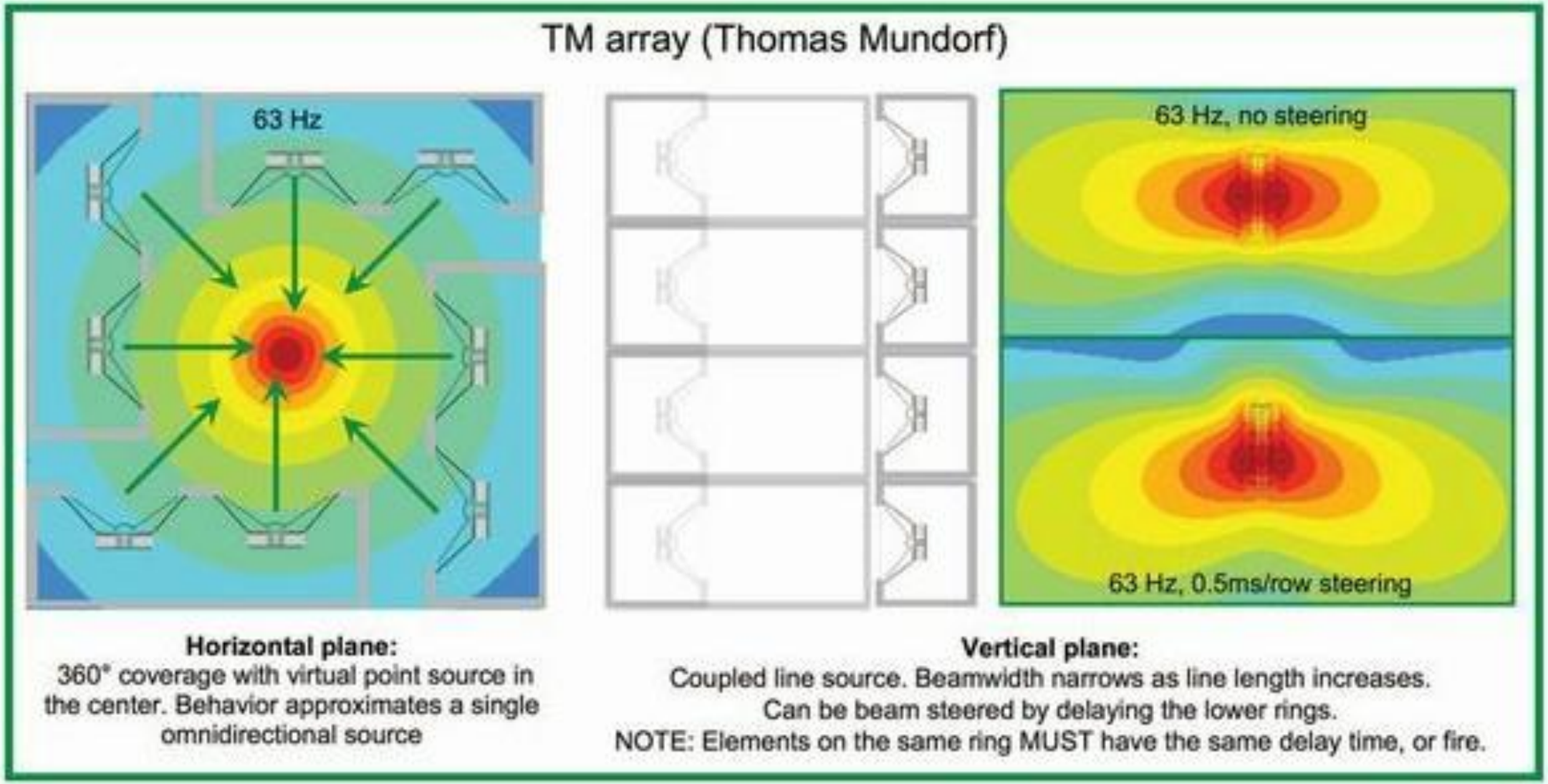
METAL



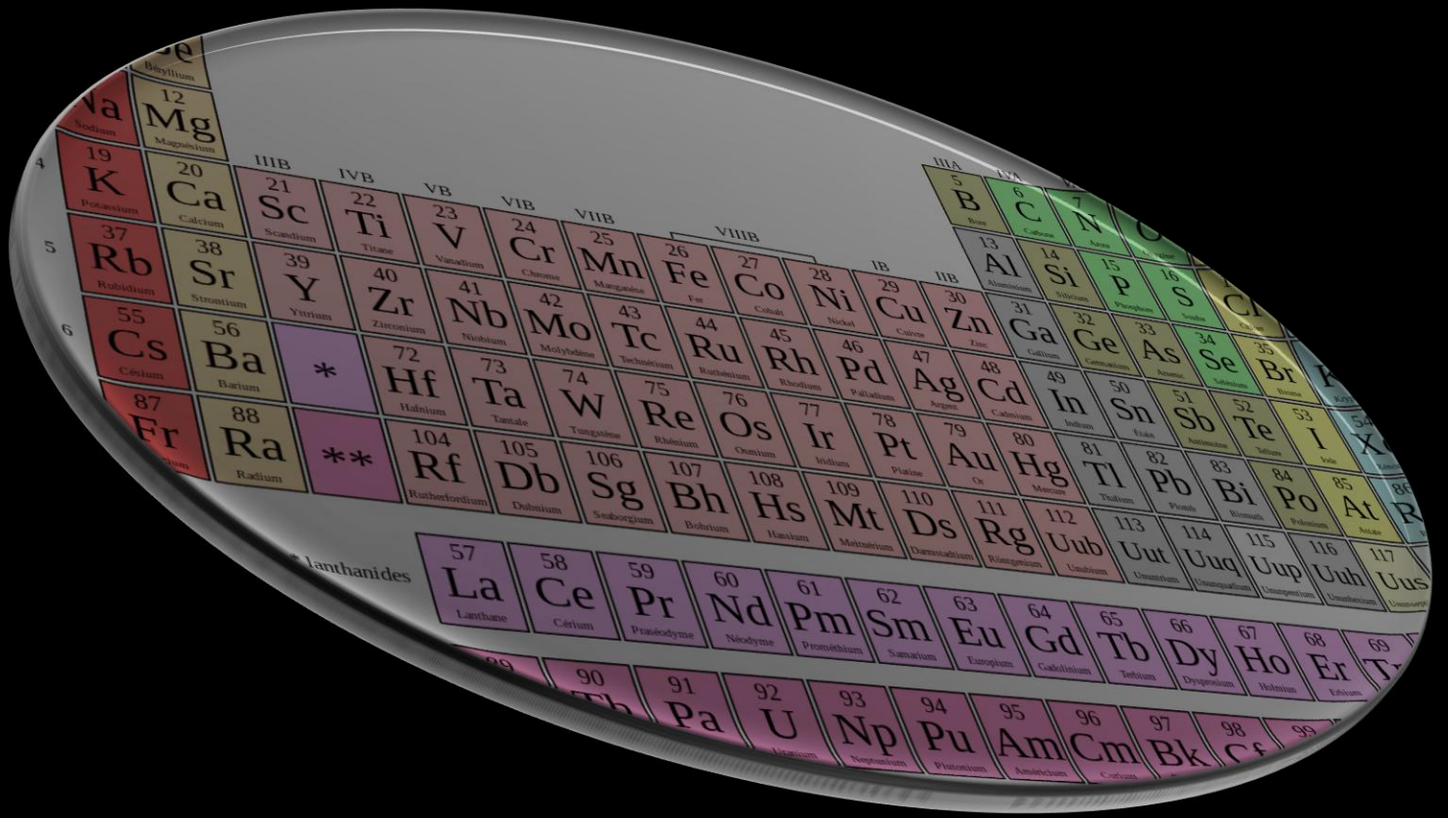
TM Array
Thomas Mundorf



TM Array
Thomas Mundorf



Source : Boc McCarthy – Sound systems: Design and Optimization, third edition



5 Classification

Classification

Types	Natifs				Gradient					
Modèles	**Natif 2**	**End Fire**	**Slot Fire**	**Tm Array**	**Arc Sub Cardio**		**Gradient 2**	**Stacks**	**Flowers**	**Vortex**
Espace Max	1/4λ		1/3λ	≅ 1.20 m	1/4λ		1/4λ	1/4λ + 1/3λ	1/4λ	
Isolation	++	++	++	++	++	++++	++++	+++	+	++
Stabilité de diffusion	+++	+++	++	+++	+++	++	++	++	++	++
Encombrement	+	+++	+++	++++++	++++++	++++++	+	-	++	+++

6 Simulations

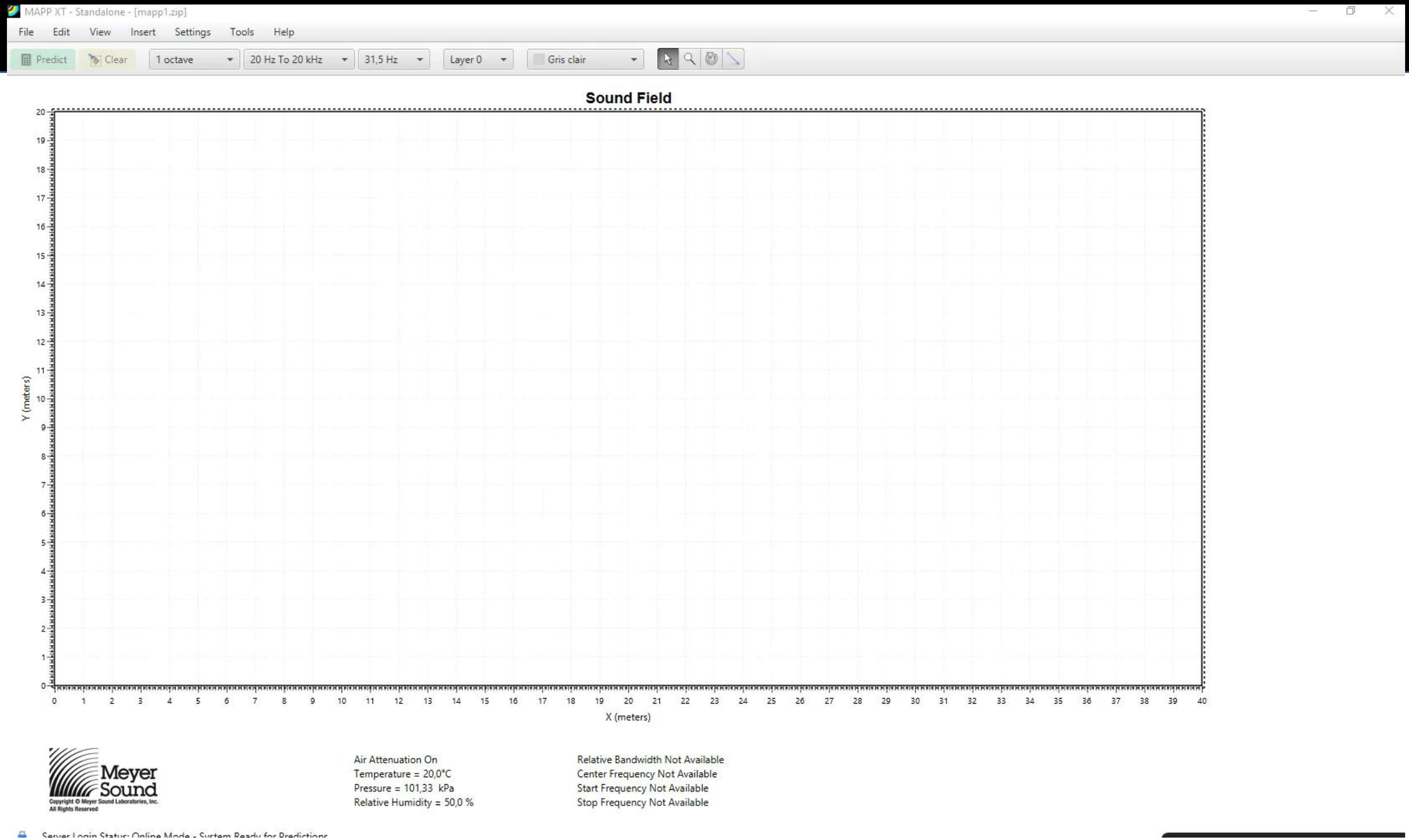


Excel

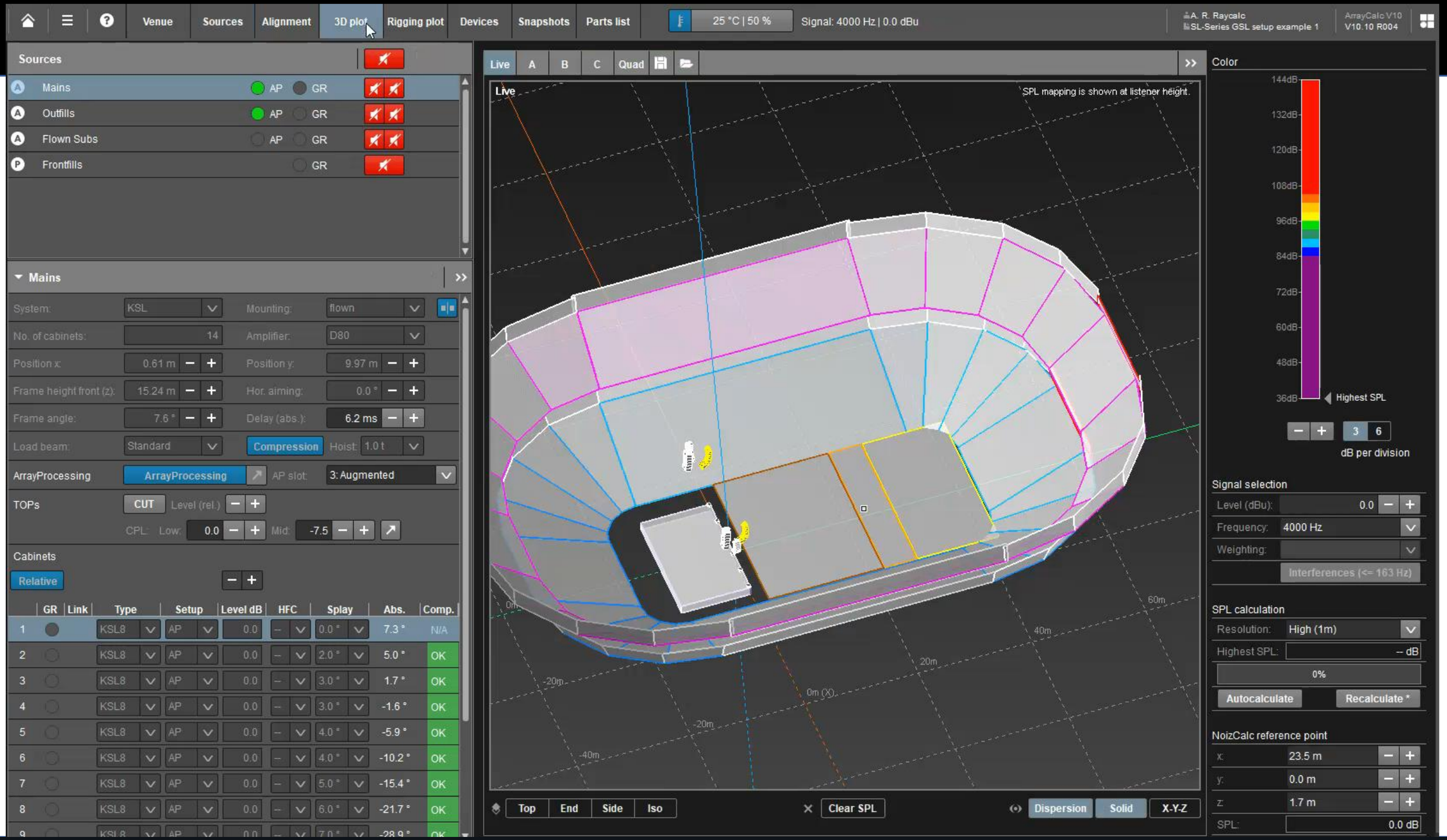
B2 =20.05*RACINE((B1+273.15))

	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															

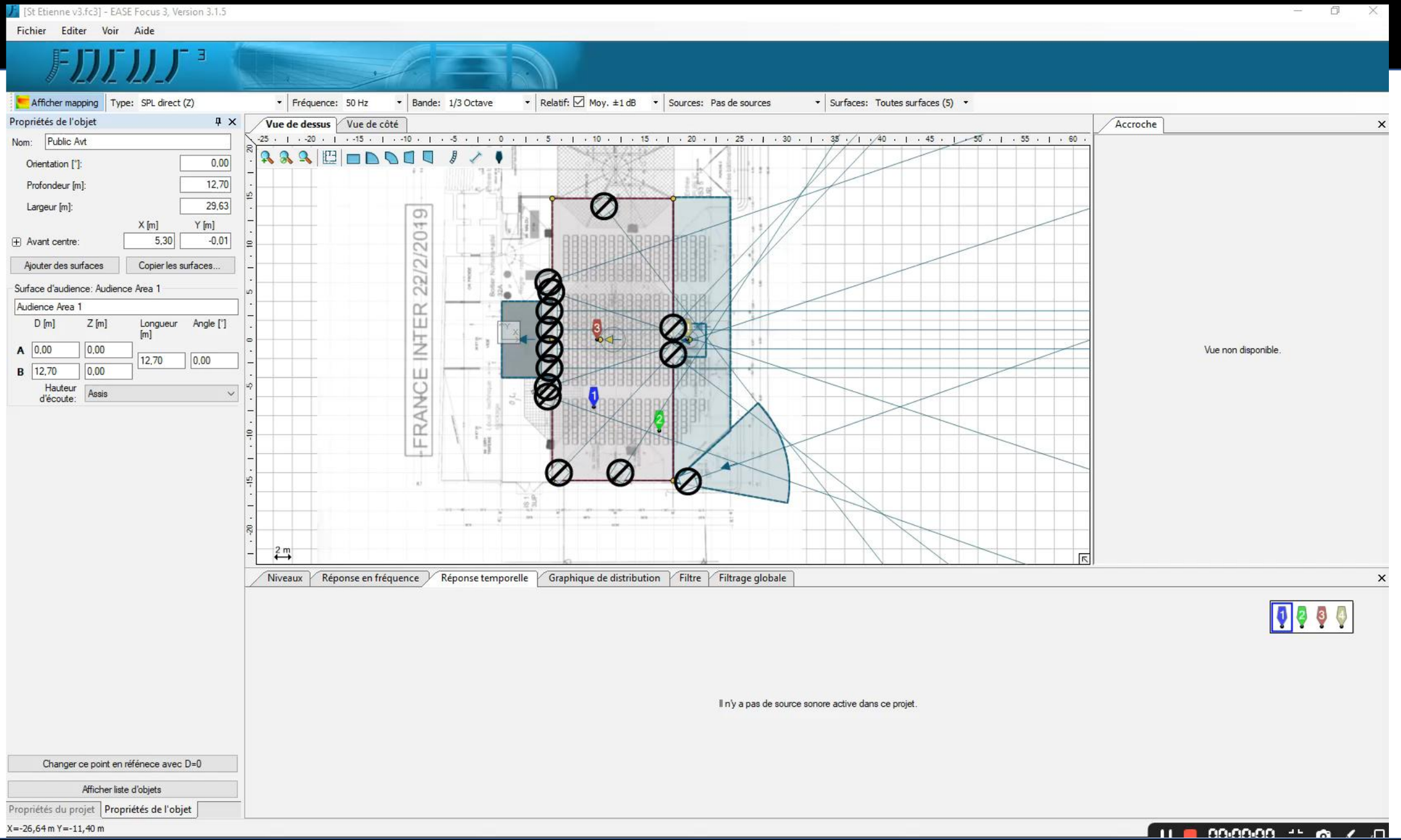
F - Long -- Période | Natif | End fire 2 | End Fire 4 | Gradient 2 | Gradient EF 2 Dfixe | Native 2 Dfixe | Slotfire 2 λ3 | Slotfire 2 λ6 | Slotfire 2 λ12 | Slc ...


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
Server Login Status: Online Mode - System Ready for Predictions

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.
60m
40m
20m
-20m
0m (X)
-20m
-40m
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

Ease Focus 3


[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

Limites des simulations



Les logiciels de simulations ne sont jamais parfaits.
Rares sont ceux qui prennent en compte les caractéristiques acoustiques des lieux.



Selon les configurations, les avantages et les habitudes de chacun, il est utile de passer d'un logiciel à l'autre.



Il est conseillé de toujours vérifier sur le terrain, et de comparer les mesures avec les prédictions.

?

Conclusion

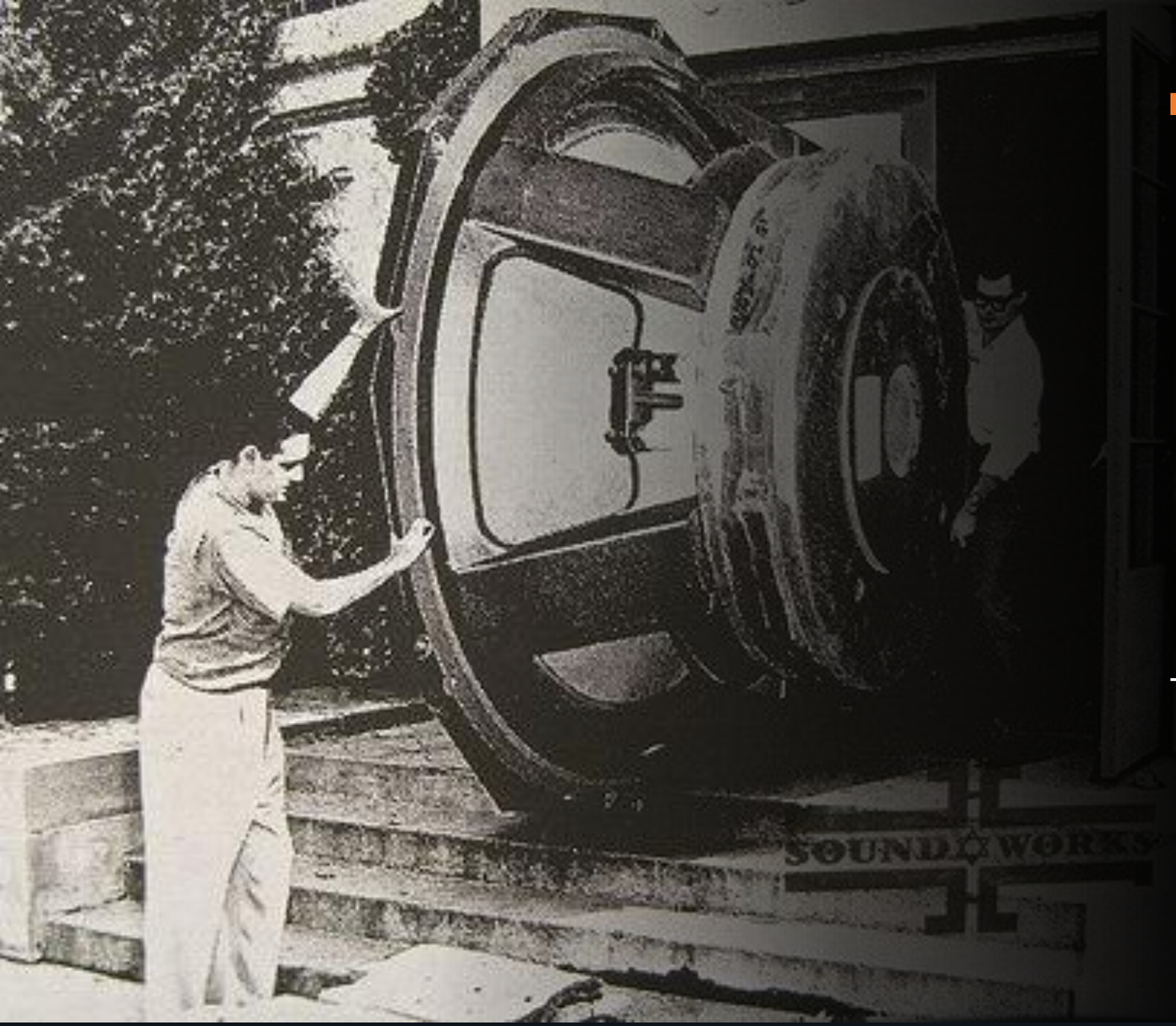


- Comprendre et bien contrôler la directivité des subs est primordial pour assurer une diffusion cohérente et limiter les problèmes acoustiques.
- L'utilisation de logiciels de simulations apporte une aide précieuse.
- Le sujet n'a pas trop été abordé dans ce cours, mais la gestion des niveaux relatifs, ainsi que la gestion électrique sont capitales.
- Et comme toujours, dans le domaine de l'audio, la réponse est souvent :
  « Ca dépend… »



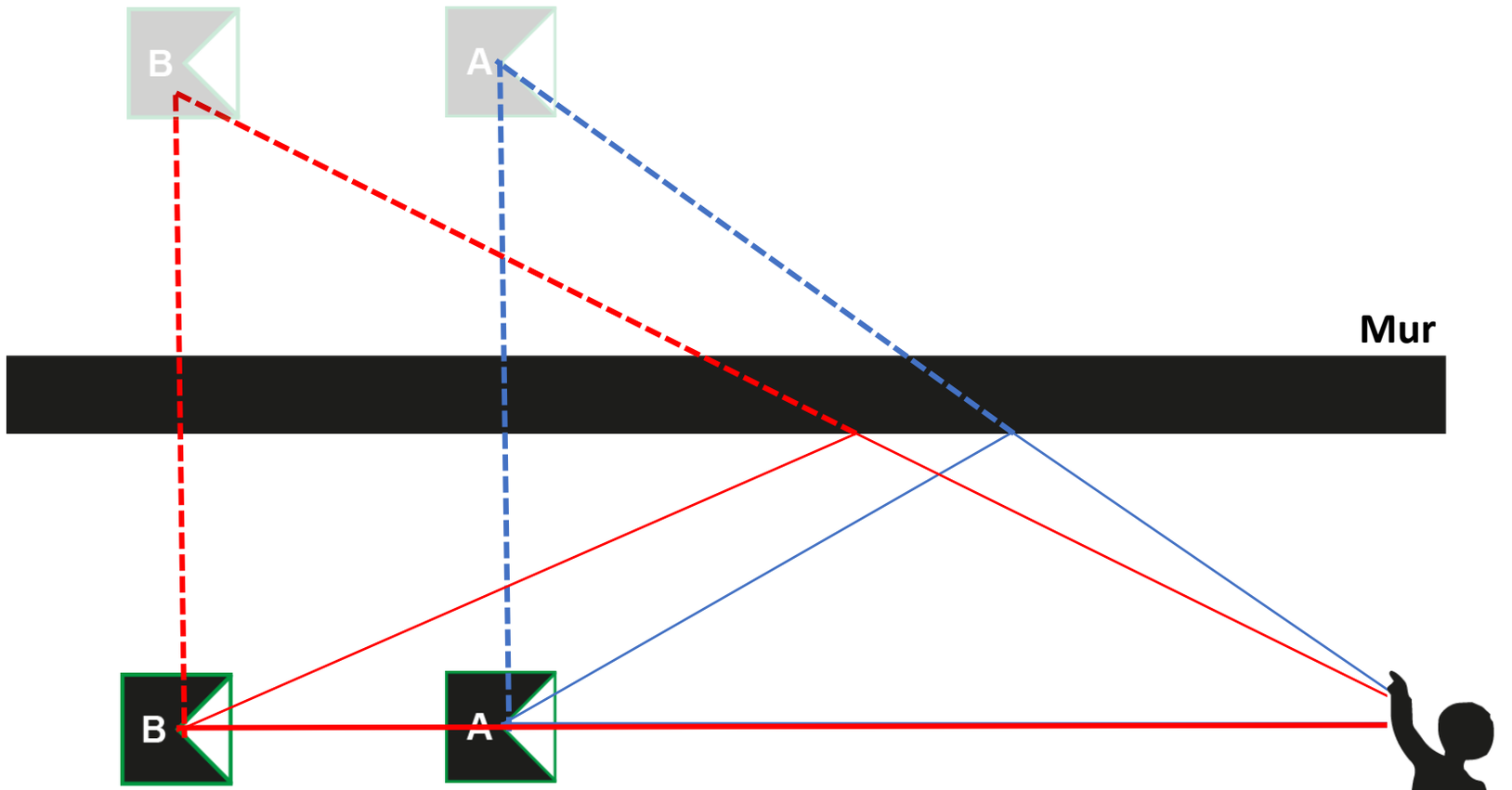


7
Exemples



8
Annexes

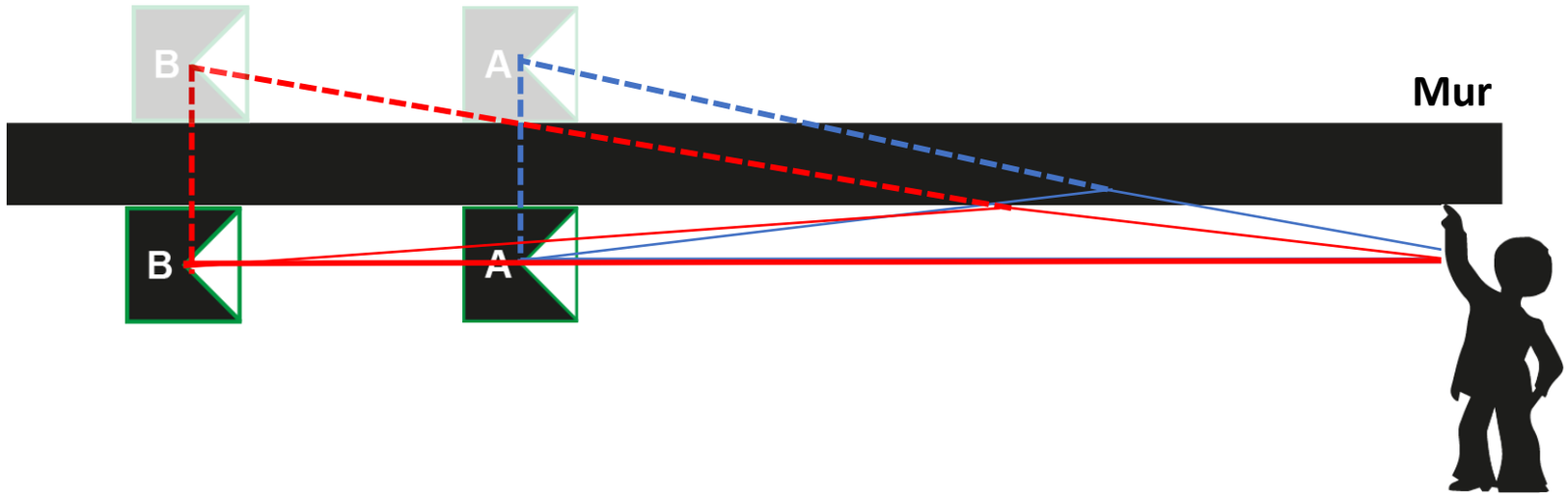
Sources virtuelles



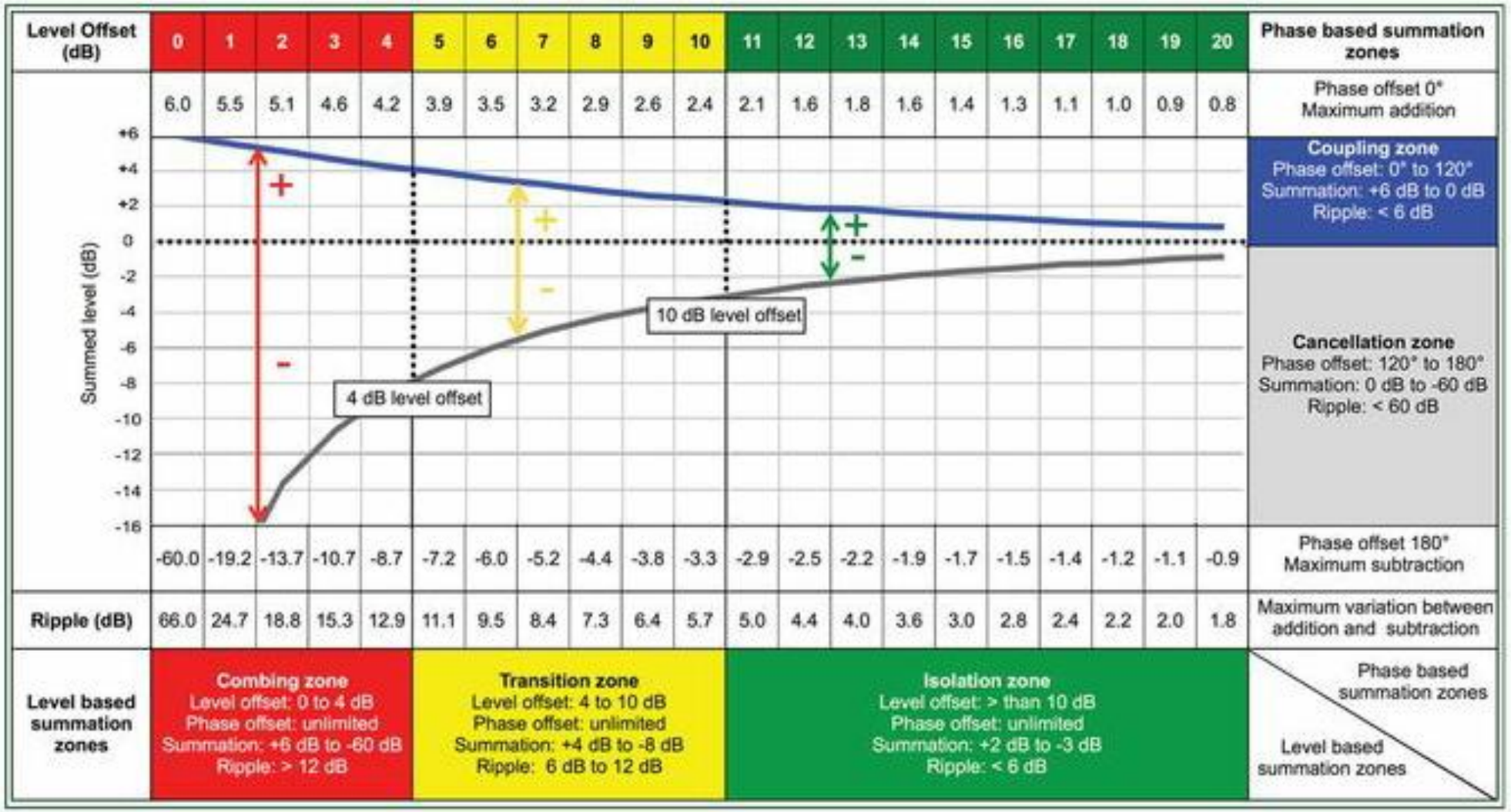
Il est important de prendre en compte les réflexions acoustiques.

La directivité et la réponse impulsionnelle seront modifiées.

Sources virtuelles



Sommations niveaux et phases relatives



Source : Boc McCarthy – Sound systems: Design and Optimization, third edition

Célérité du son

Température

θ en °C	c en m·s^{-1}	ρ en 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 = *température*
- c = *vitesse du son*
- ρ = *masse volumique*
- Ƶ = *Impédance acoustique*

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

Ou

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

- c = *Vitesse du son*
- T_k = *Température en Kelvin*
- θ = *température*

$$T_c = T_k - 273,15$$

Ou

$$T_k = T_c + 273,15$$

Altitude

Altitude en m	θ en °C	P *en 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 = *température*
- P = *pression*
- c = *vitesse du son*
- ρ = *masse volumique*

Calcul différence de phase (Δ_φ)

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

- *avec :*
- *f = fréquence*
- *λ = longueur d'onde*
- *C = Célérité*
- *Δ_d = Différence de distance*

Calcul différence de phase (Δ_φ)

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

- *avec :*
- *f = fréquence*
- *λ = longueur d'onde*
- *C = Célérité*
- *Δ_d = Différence de distance*

Calcul différence de phase (Δ_φ)

Exemple

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

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

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

$$\Delta_\varphi = 110°$$

Pour aller plus loin

- **Bob McCarthy** – Sound sytems: 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/