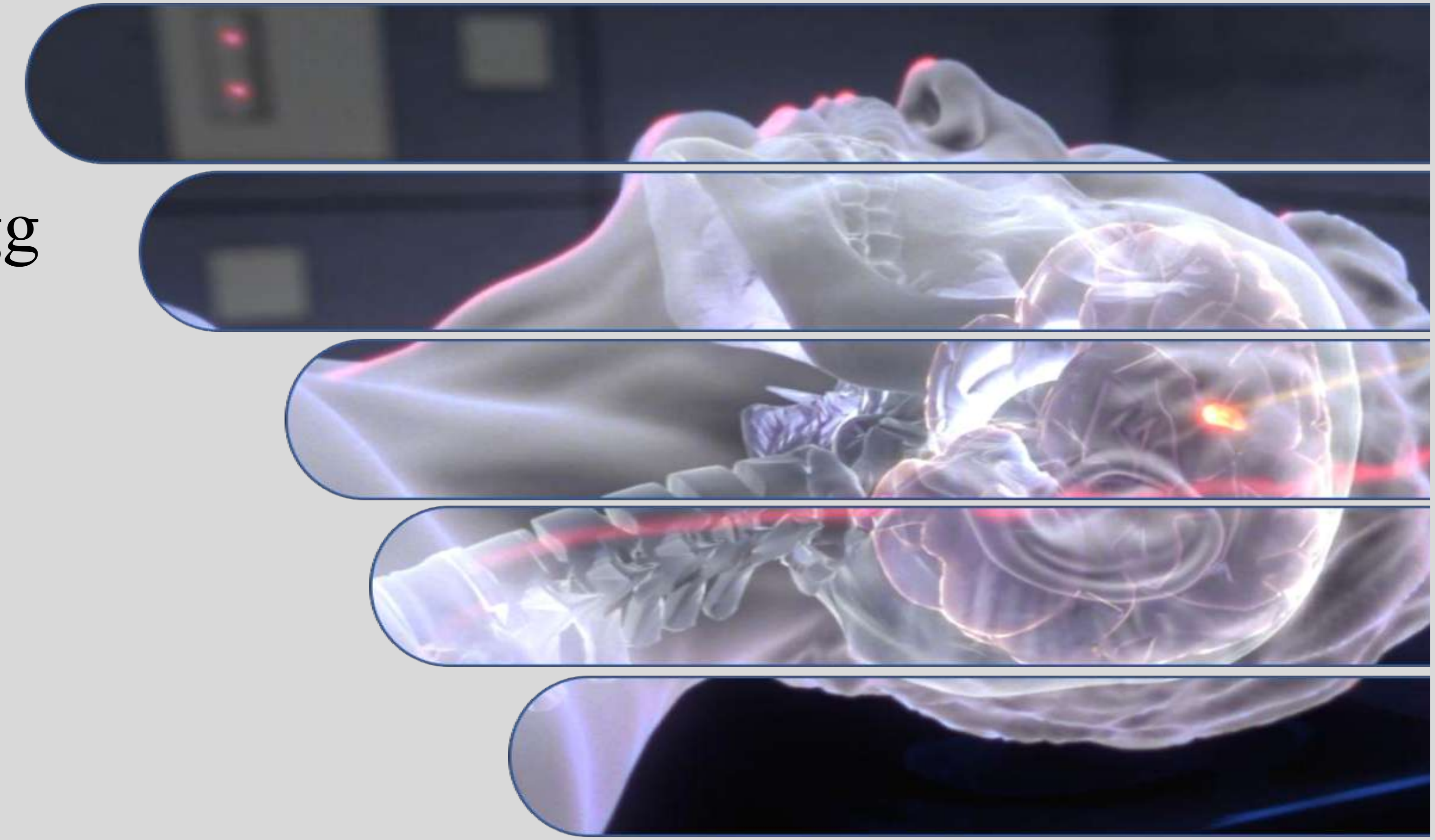
Acoustic location of Bragg peak for hadrontherapy monitoring



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sensors

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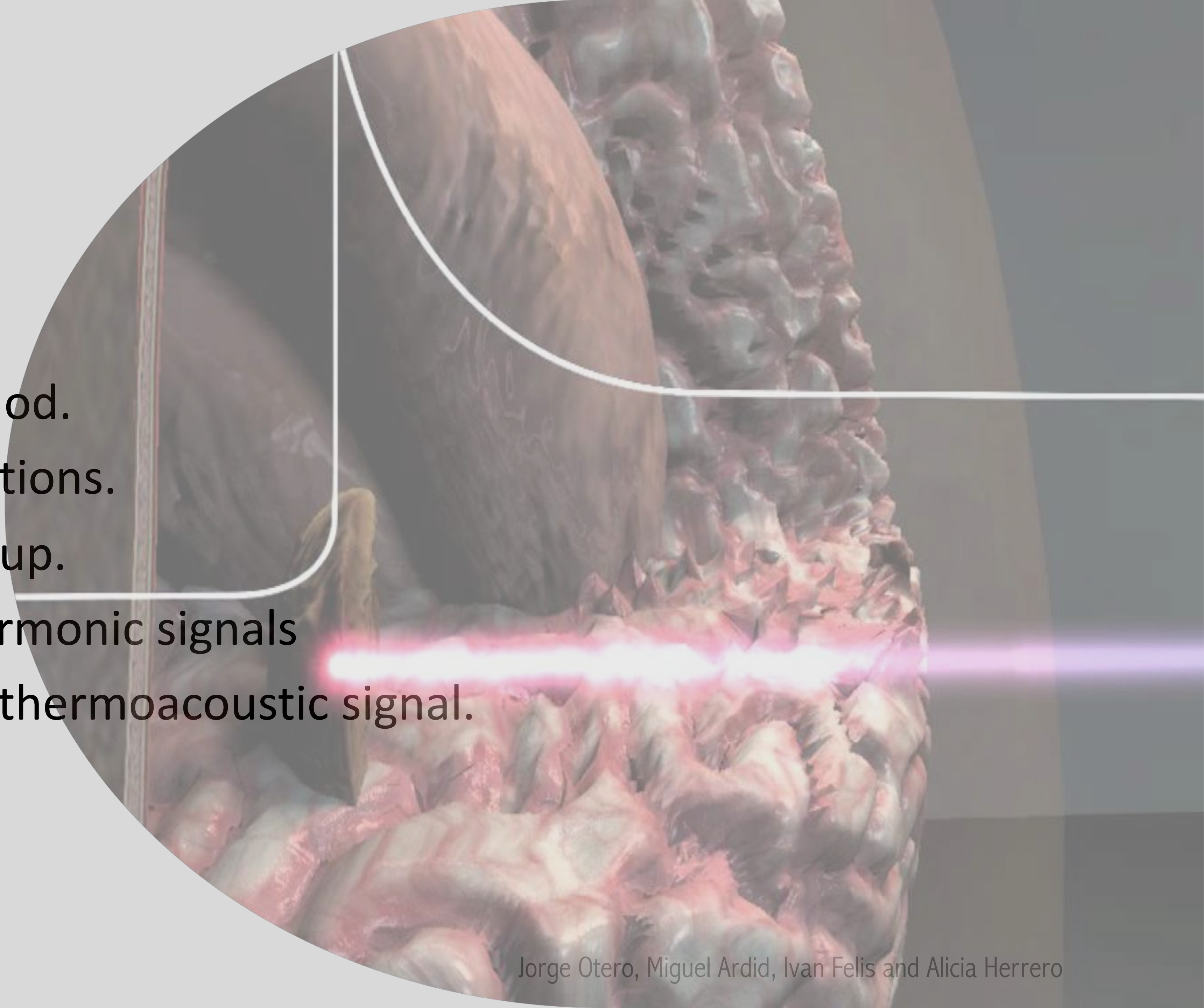
Content



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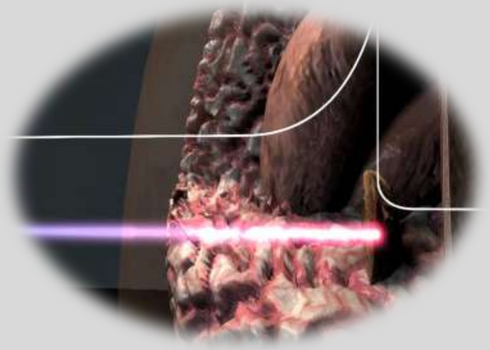
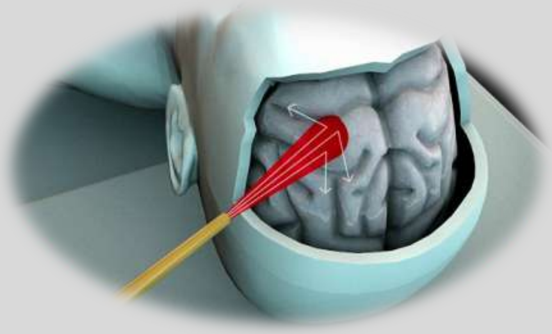
I. Introduction

Hadron therapy makes possible to deliver high doses of energy on cancerous tumours by using the large energy deposition in the Bragg-peak. However, uncertainties in the patient positioning and or in the anatomical parameters can cause distortions in the calculation of the dose distribution. In order to maximize the effectiveness of heavy particle treatments, an accurate monitoring system of the deposited dose depending on the energy, the beam time and the spot size is necessary. The localized deposition of this energy leads to the generation of a thermoacoustic pulse that can be detected using acoustic technologies.

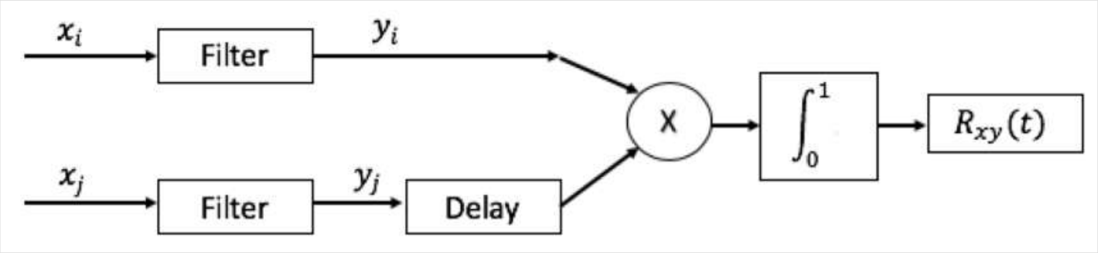
- The use of acoustic sensors to locate sound sources in such practical systems is of great interest to develop quitter and improved performance systems.
- Actually, the method to locate tumour tissue is based in computed tomography scan to find the area that will then be radiated by heavy particles in the Bragg peak region.
- Pressure source localization of the Bragg peak in hadrontherapy will also allow to identify the regions of local heat released due to energy deposition.





II. Localization Method

Techniques based on **cross-correlation** and **generalized correlation** (GCC) have been employed to determinate the time difference of arrival of the signals **(TDOA)** given its computational cost and accuracy of the results. To obtain a better estimate of the TDOA $\hat{\tau}$ is convenient to filter the signal before its integration:



Where $R_{x_i x_j}$ is the **cross-correlation between the signal x_i and x_j filtered by the filters H_i and H_j**, is expressed as a function of the power spectral density $G_{x_i x_j}$

$$R_{x_i x_j}^{GCC}(t') = \int_{-\infty}^{+\infty} H_i(f) H_j^*(f) G_{x_i x_j}(f) e^{i2\pi f t'} df = \int_{-\infty}^{+\infty} \varphi^{GCC}(f) G_{x_i x_j}(f) e^{i2\pi f t'} df$$

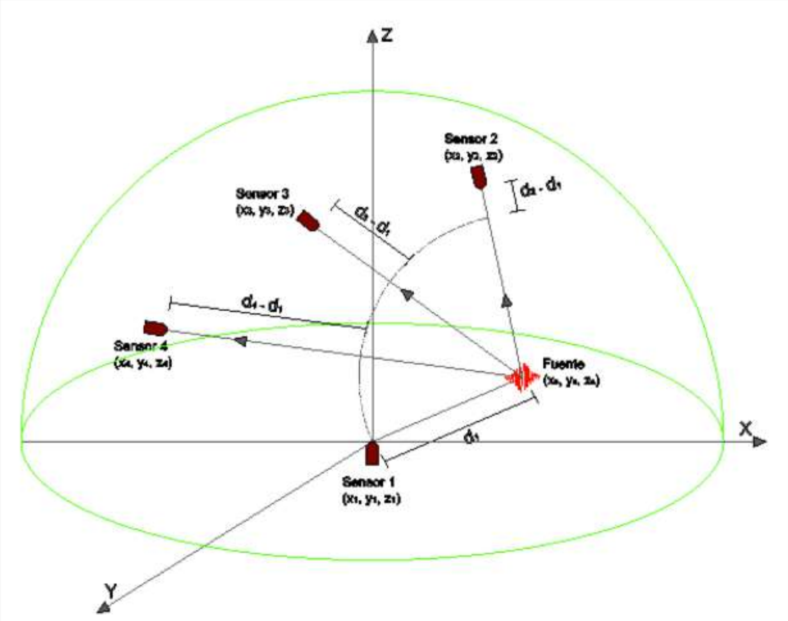
$\varphi^{GCC}(f)$ is a frequency-dependent weight function.

Therefore, to obtain the TDOA the following expression will be used:

$$\hat{R}_{x_i x_j}^{GCC1}(t') = \int_{-\infty}^{+\infty} \varphi^{GCC}(f) \hat{G}_{x_i x_j}(f) e^{i2\pi f t'} df$$

II. Localization Method

For each pair of sensors, **the TDOA is taken as the time delay that maximizes the cross-correlation** between the filtered signals of both sensors, that is: $\hat{\tau}_{ij}^{GCC} = \arg\left(\max_{t'}\left\{\hat{R}_{x_i x_j}^{GCC1}(t')\right\}\right)$.



A general model for three dimensional (3-D) estimation of a source using M receivers is developed. To obtain the location of the source, we start by knowing the spatial position (x_i, y_i, z_i) of a certain number of sensors $N\,(i = 1,2,\ldots,N)$. Let $(x_s, y_s, z_s,)$, the position of the source to be located, **the distance between the source and the i-th sensor** will be:

$$d_i = \sqrt{(x_i - x_s)^2 + (y_i - x_s)^2 + (z_i - x_s)^2}$$

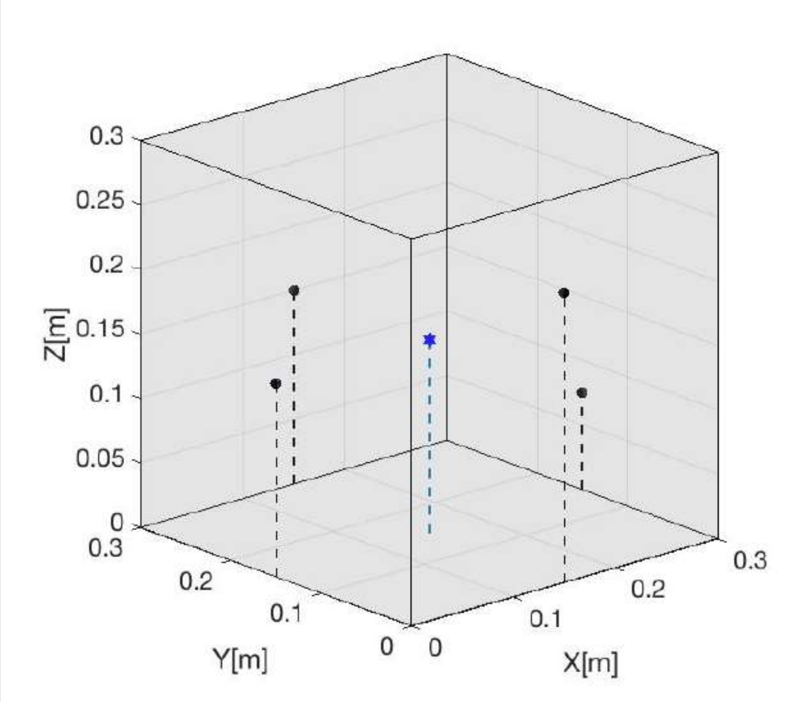
The range difference between receivers with respect to the first receiver is:

$$d_{i1} = c \cdot \tau_{i1} = d_i - d_1 = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2 + (z_i - z_s)^2} - \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2 + (z_1 - z_s)^2}$$

Where c is the sound velocity in the medium, d_{i1} is the range difference distance between the first receiver and the i-th receiver, d_1 is the distance between the first receiver and the source, and τ_{i1} is the estimated TDOA between the first receiver and the i-th receiver. There are different methods to solve this type of systems of equations. In this case, a generalized **Netwon-Raphson method** have been used. Particularly, the location of the source in each simulation and experiment has been computed by defining a **maximum error volume for each coordinate of 0.1 mm**.

III. Numerical Simulations

To evaluate the localization algorithm described, the reconstruction of the location of a Gaussian pulse source of 50 µs is simulated from the reception of 4 sensors located on the lateral surface of different coordinates.



To evaluate the algorithm, the volume of the cube has been modified between $27.0 \cdot 10^{-3}$ to $512.0 \cdot 10^{-3}\ m^3$. The positions of the sensors are shown in the table where H represents the size of the edges, that is, values of edges were $200, 300, 400, 500\ and\ 600\ \ mm$.

Positions of the sensors and the source in the simulated.

	Sensors				Source [mm]		
Axis	**1**	**2**	**3**	**4**	**1**	**2**	**3**
X	H/2	0.0	H/2	H	150	100	80
Y	0.0	H/2	H	H/2	150	180	100
Z	3H/4	H/2	H/2	H/4	150	150	180

III. Numeric Simulations

As a result, the reconstruction of the position can be determinate for different source positions.

Volume $[m^3]$	**Real position** [mm]	**1**	**2**	**3**	**4**	**5**
		$\mathbf{27^{-3}}$	$\mathbf{64^{-3}}$	$\mathbf{125^{-3}}$	$\mathbf{216^{-3}}$	$\mathbf{343^{-3}}$
X	**100**	100.10±0.11	100.10±0.10	100.10±0.10	94.00±0.42	100.0±0.01
Y	**100**	100.10±0.10	98.00±0.14	100.10±0.11	96.00±0.28	100.0±0.01
Z	**100**	100.10±0.10	96.00±0.28	101.20±0.14	94.00±0.42	100.0±0.01
X	**100**	100.00±0.01	100.0±0.01	100.0±0.01	100.0±0.01	102.0±1.4
Y	**180**	100.20±0.56	100.20±0.56	181.2±1.4	150±21	163±12
Z	**150**	100.10±0.32	100.1±00.35	147.4±1.8	146±21	145.8±3.0
X	**80**	80.00±0.01	78.0±1.4	85.0±4.5	71.0±8.0	87.0±4.9
Y	**100**	100.00±0.01	98.0±2.2	106.0±5.2	93.0±6.4	105.0±3.5
Z	**180**	180.10±0.10	178.0±1.4	186.0±5.3	168±12	189.0±6.4

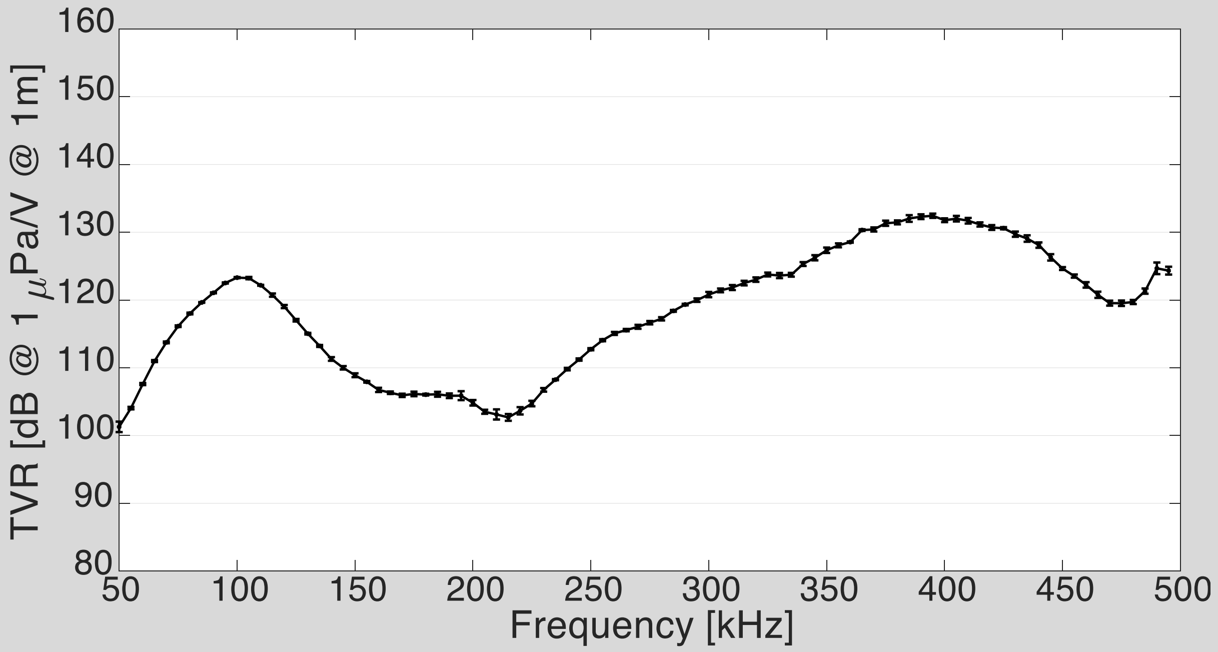
IV. Experimental set up

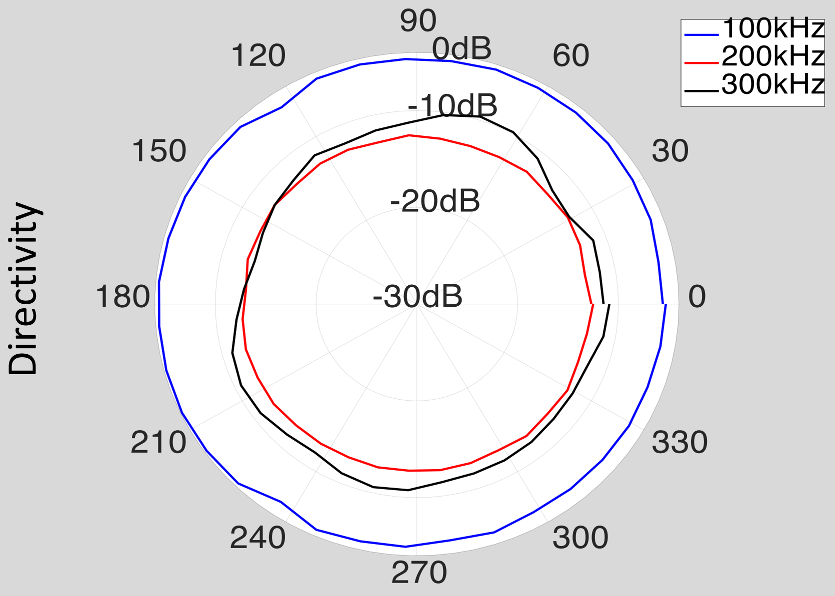
Once the location method has been tested, a piezoelectric transmitter were situated in two different positions inside a tank with four sensors.

Three different signals were emitted: a 100 kHz sine signal, a 150 kHz sine signal, both with five cycles per signal, and a sweep signal from 50 to 400 kHz during 150 μs and the cross-correlation method has been used to detect the start time of arrival on the sensors. The signals were emitted by a ring piezoelectric ceramic.

Piezoelectric device

Transmitting Voltage Response (TVR)





IV. Experimental set up

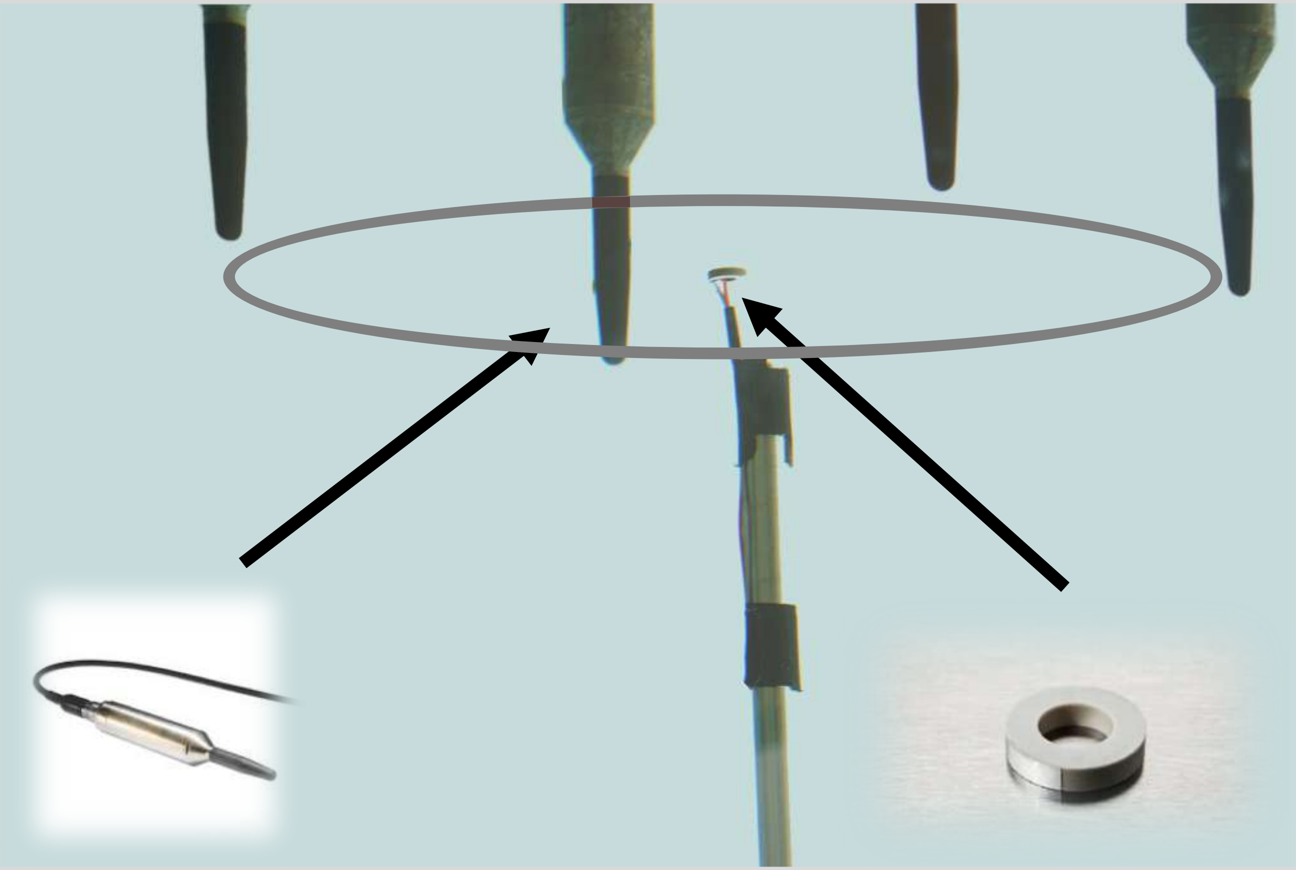
The piezoelectric transmitters were situated in two different positions inside a tank with four sensors.

A temporary window has been used to avoid reflections due to the tank and it has enough time to record the direct signal from the emitter.

The positions referred to the left-corner of the tank

Positions of the sensors and the source inside the tank

	Sensors [mm]				Source [mm]	
Axis	**1**	**2**	**3**	**4**	**1**	**2**
X	600	500	400	500	410	450
Y	550	450	540	650	450	540
Z	380	280	340	340	350	330



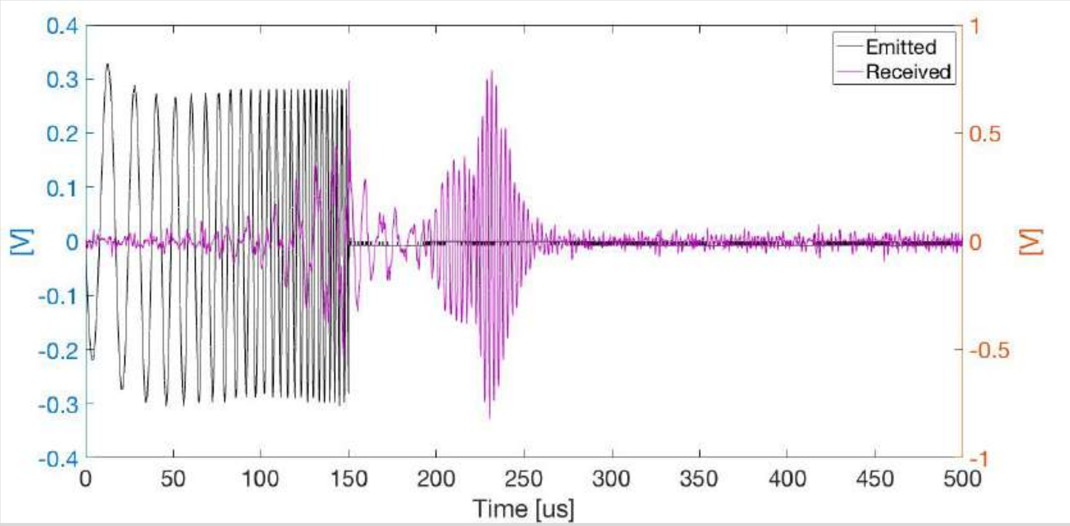
Sensors
Reson TC4014

Transmitter

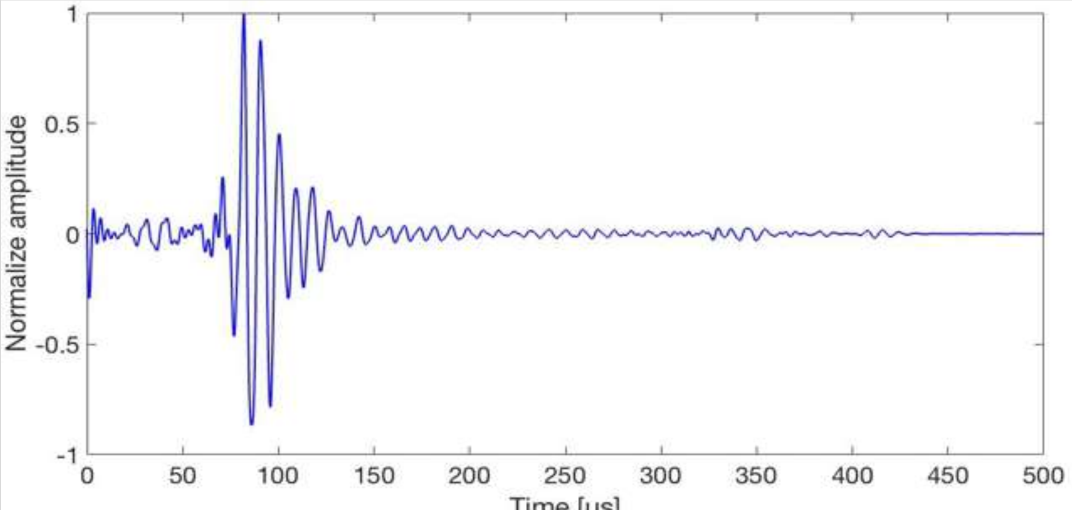
V. Localization in harmonic signals

According to the characteristics of the emitter, the signals were fit to leverage the frequency response of the piezoelectric ceramic.

Sweep Signal emitted and received



Cross-correlation between the signal emitted and received



Estimated positions of two different harmonic sources inside the tank

	Real position [mm]	Sine 100kHz	Sine 150kHz	Sweep signal
X	**450**	459.0±9.0	460.0±9.3	460.0±9.2
Y	**540**	540.00±0.72	540.00±0.55	540.00±0.43
Z	**330**	340.0±9.2	330.00±0.18	330.00±0.32
X	**410**	401.0±8.9	416.0±5.7	418.0±7.0
Y	**450**	448.0±1.3	450.00±0.44	450.00±0.56
Z	**350**	352.0±1.8	350.00±0.36	350.00±0.65

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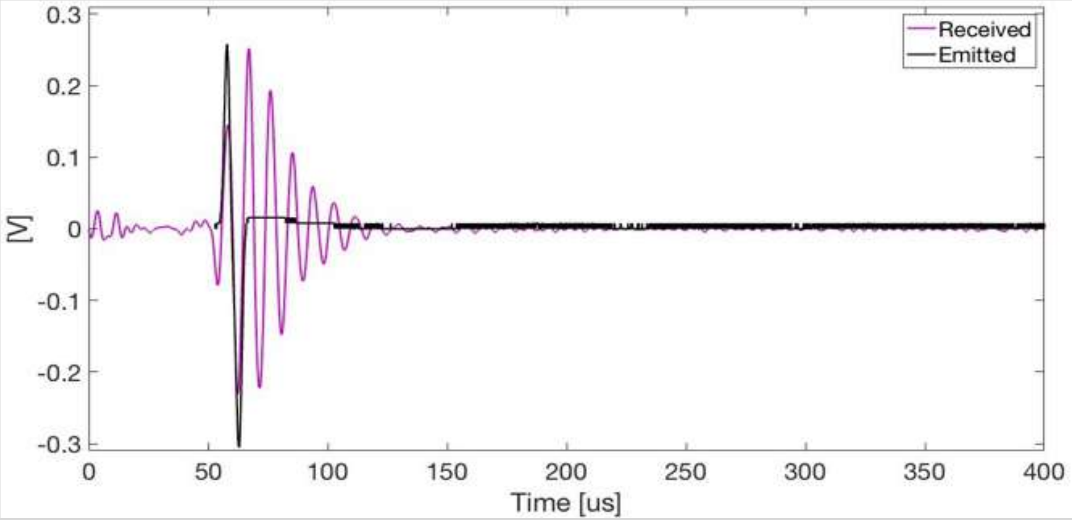
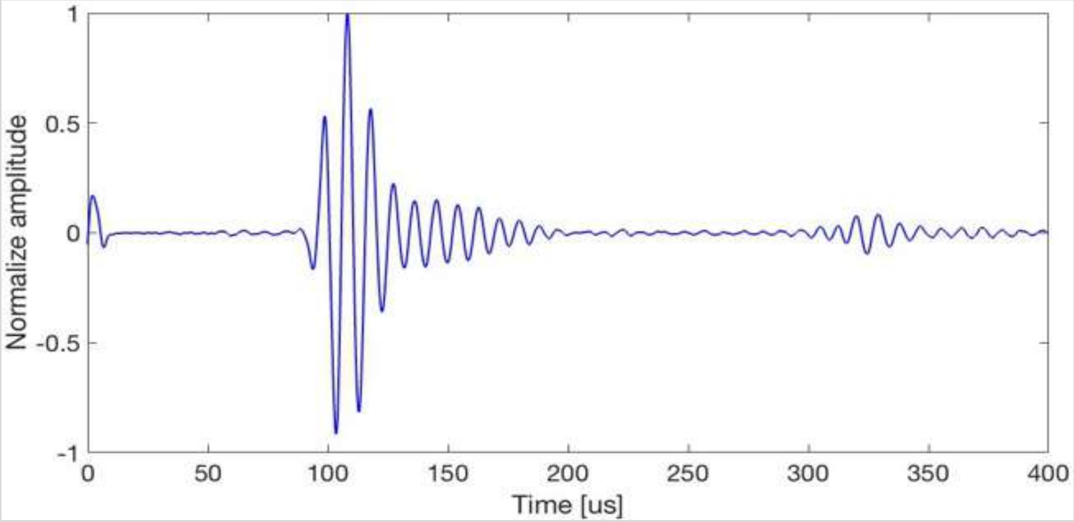
VI. Localization with thermoacoustic signal

To simulate the behaviour of the Bragg peak on a large scale, a bipolar pulse was generated by a thermoacoustic model following characteristics in energy $100\ MeV$, beam time, spot size and number of protons per pulse that are the usual parameters involved in hadrontherapy treatment.

Bipolar pulse generated and received



Cross-correlation between the signal emitted and received



Real and estimated positions of bipolar pulse signal in two different positions

	Real position [mm]	Estimated position [mm]
X	**450**	459.0±8.8
Y	**540**	540.00±0.52
Z	**330**	330.00±0.12
X	**410**	414.0±3.3
Y	**450**	450.00±0.52
Z	**350**	350.00±0.49

VII. Conclusions

- The proposed localization method for the Bragg peak location in hadrontherapy has been tested in different numerical simulations and experiments using different kind of signals. In all of them the results of time of arrival were successful using the cross-correlation method and the uncertainty in the reconstructed position is small and close to the one needed for the application.

- The computational cost of the method is low, as shown for the case of the four sensors studied. So, to have a computational time smaller than 1s should not be an issue even for the case that the number of sensors will be increased. Thus, the technique is valid for the real time application.

- In the hadrontherapy technique, this localization method could be used as an alternative method of computational tomography but with a lower cost than techniques based on image technique. Also, in the last years, the developing of new tools to increase the number of protons will raise the final pressure in the tissue improving the signal to noise ratio and the precision of the difference of time of arrival.

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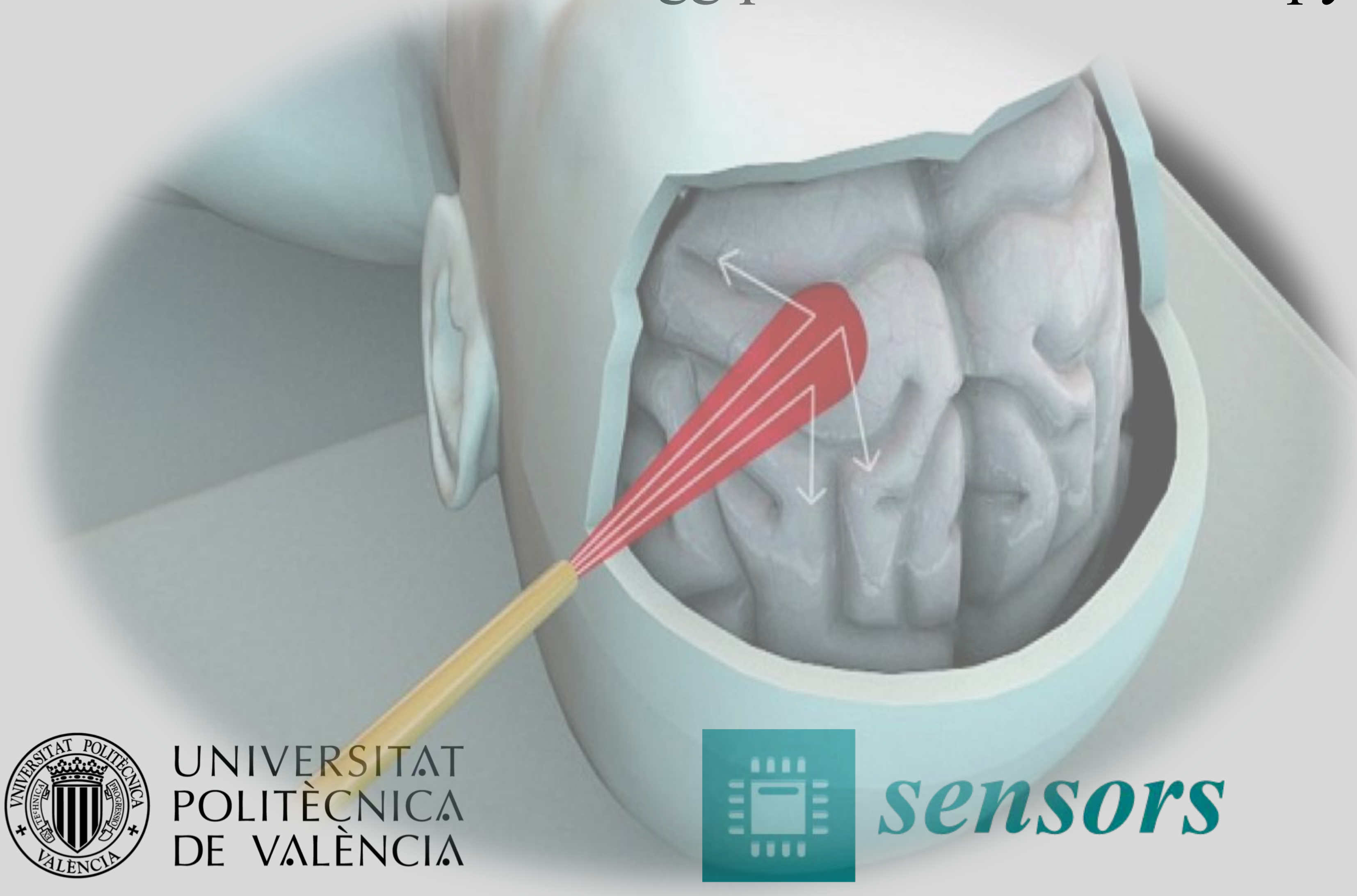

Thank you

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