



Proposta de uma técnica unidimensional para o experimento $T_2 \times T_2$ Exchange

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Sumário

▪ Introdução

- O que é Experimento *$T_2 \times T_2$ Exchange 2D*
- Modelo de troca teórico para dois sítios
- Simulações para o modelo 2D
- O que é Experimento *$T_2 \times T_2$ Exchange 1D*

Proposto por: $\left\{ \begin{array}{l} \text{Tito José Bonagamba} \\ \text{Marcel Nogueira D'Eurydice (Ex-aluno de doutorado do grupo)} \end{array} \right.$

▪ *Minha reais contribuições:*

- Modelo Teórico para o experimento 1D
- Simulações para o modelo 1D
- Manufatura de um **meio poroso artificial** para comparar os modelos 1D e 2D

Colaboração com Carlos Alberto Fortulan (Escola de Engenharia de São Carlos - USP)

▪ Resultados Experimentais

- **Comparar resultados 1D e 2D**

▪ Conclusões e perspectivas

Experimento $T_2 \times T_2$ Exchange

Sequência de pulsos do Experimento $T_2 \times T_2$ Exchange:
(Proposto em 1993 por J. H. Lee ¹)

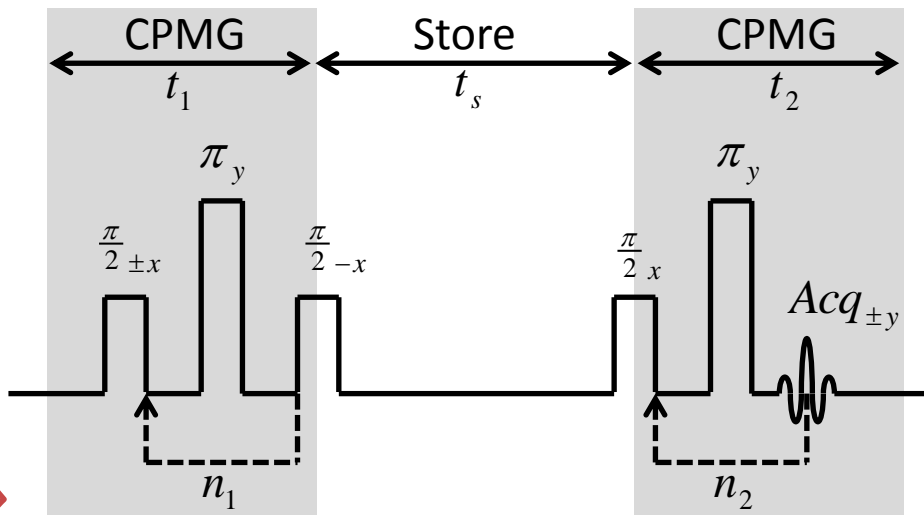
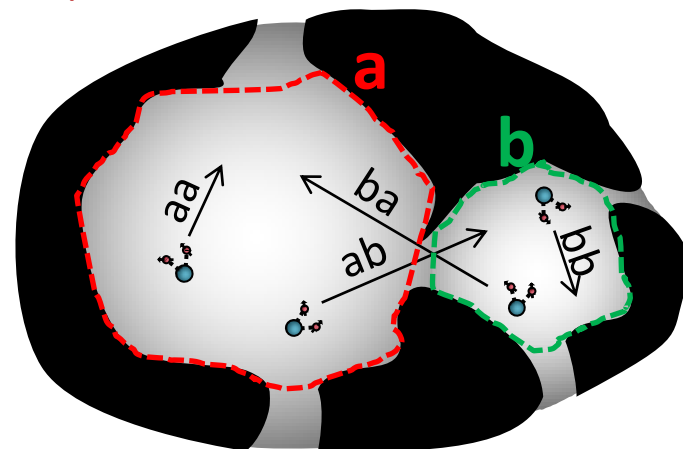
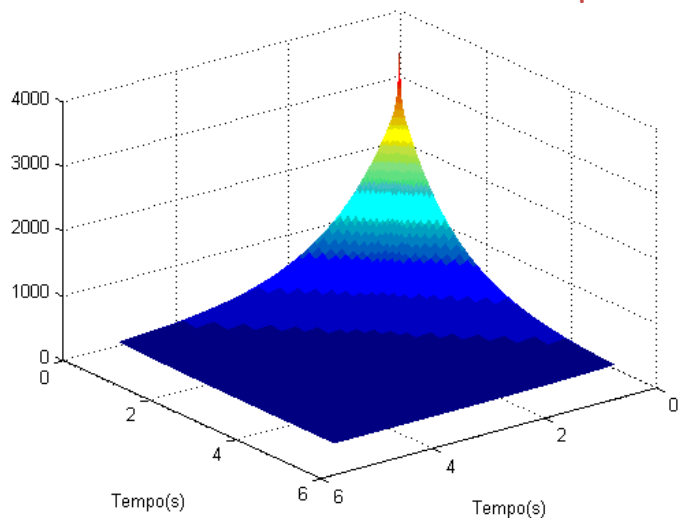


Ilustração da migração de moléculas de água entre poros vizinhos:



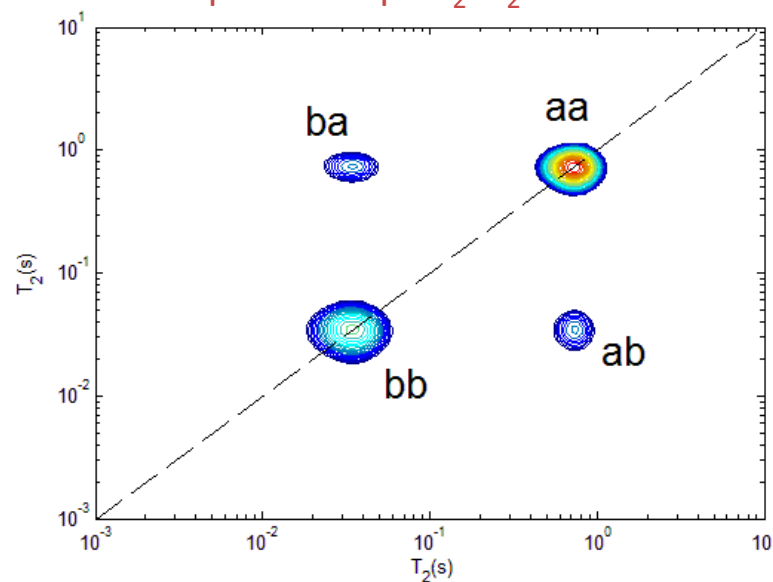
Decaimento bidimensional obtido pelo experimento



Transformada Inversa de Laplace 2D ²



Exemplo de mapa $T_2 \times T_2$ obtido:

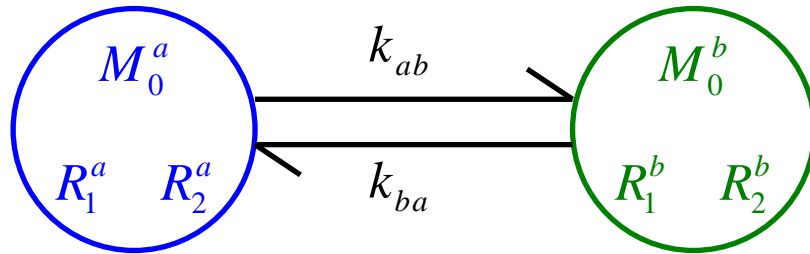


¹ Lee J. H.; Labadie C.; Springer Jr. C. S.; Harbison G. S.; *J. Am. Chem. Soc.*, 1993, 115 (17), 7761-7764.

² Venkataramanan L.; Song Y. Q.; Hürlimann M. D.; *IEEE T. Signal Proces.*, 2002, 50(5), 1017-1026.

Modelo de *Exchange* para dois sítios

Modelo de dois sítios conectados ^{1,2}:



Condição de equilíbrio de massas:

$$k_{ab}M_0^a = k_{ba}M_0^b$$

Magnetizações de equilíbrio: M_0^a e M_0^b .

Taxas de relaxações: $R_{1,2}^a = 1/T_{1,2}^a$ e $R_{1,2}^b = 1/T_{1,2}^b$. Taxas de trocas: $k_{ab} = 1/\tau_{ab}$ e $k_{ba} = 1/\tau_{ba}$.

Tempos de relaxação

Tempos característicos de troca

As relaxações das magnetizações transversais (M_{\perp}^a e M_{\perp}^b) e longitudinais (M_z^a e M_z^b) dos reservatórios são dadas pelas equações de Bloch-McConnell:

$$\begin{cases} \text{Transversal} & \left\{ \begin{array}{l} \frac{d}{dt} M_{\perp}^a(t) = -k_{ab}M_{\perp}^a(t) + k_{ba}M_{\perp}^b(t) - R_2^a M_{\perp}^a(t) \\ \frac{d}{dt} M_{\perp}^b(t) = -k_{ba}M_{\perp}^b(t) + k_{ab}M_{\perp}^a(t) - R_2^b M_{\perp}^b(t) \end{array} \right. \\ \text{Longitudinal} & \left\{ \begin{array}{l} \frac{d}{dt} M_z^a(t) = -k_{ab}M_z^a(t) + k_{ba}M_z^b(t) - R_1^a (M_0^a - M_z^a(t)) \\ \frac{d}{dt} M_z^b(t) = -k_{ba}M_z^b(t) + k_{ab}M_z^a(t) - R_1^b (M_0^b - M_z^b(t)) \end{array} \right. \end{cases}$$

¹ Monteilhet L.; Korb J.-P.; Mitchell J.; McDonald P. J.; *Phys. Rev. E*, 2006, 74(6), 061404.

² Dortch D. R.; Horch E. A.; Does M. D.; *J. Chem. Phys.*, 2009, 131(16), 164502.

Modelo de *Exchange* para dois sítios

A equações anteriores podem ser escritas na forma matricial:

$$\left\{ \begin{array}{l} \frac{d\vec{M}_z(t)}{dt} = [\bar{K} + \bar{R}_1] \vec{M}_z(t) - \vec{M}_0 \\ \frac{d\vec{M}_\perp(t)}{dt} = [\bar{K} + \bar{R}_2] \vec{M}_\perp(t) \end{array} \right.$$

Em que:

$$\vec{M}_0 = \begin{bmatrix} M_0^a \\ M_0^b \end{bmatrix} \quad \vec{M}_\perp = \begin{bmatrix} M_\perp^a \\ M_\perp^b \end{bmatrix} \quad \vec{M}_z = \begin{bmatrix} M_z^a \\ M_z^b \end{bmatrix} \quad \bar{R}_{1,2} = \begin{bmatrix} -R_{1,2}^a & 0 \\ 0 & -R_{1,2}^b \end{bmatrix} \quad \bar{K} = \begin{bmatrix} -k_{ab} & k_{ba} \\ k_{ab} & -k_{ba} \end{bmatrix}$$

Definindo $\bar{L}_1 \equiv [\bar{K} + \bar{R}_1]$ e $\bar{L}_2 \equiv [\bar{K} + \bar{R}_2]$:

$$\left\{ \begin{array}{l} \frac{d\vec{M}_z(t)}{dt} = \bar{L}_1 [\vec{M}_z(t) - \vec{M}_0] \\ \frac{d\vec{M}_\perp(t)}{dt} = \bar{L}_2 \vec{M}_\perp(t) \end{array} \right.$$

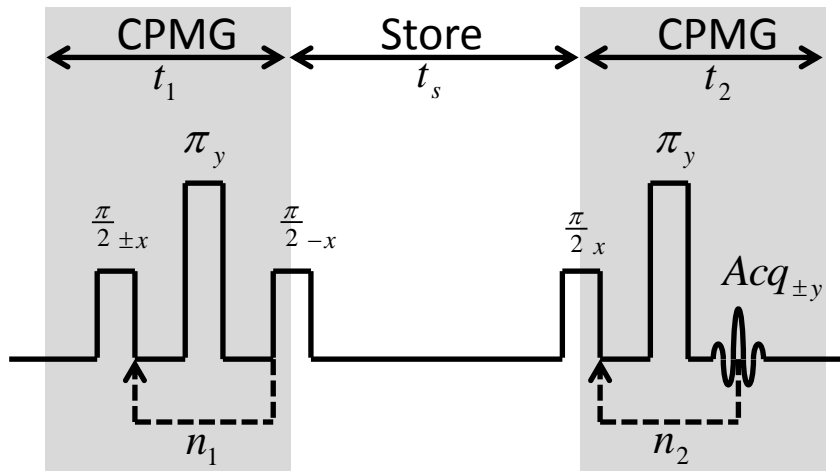
As soluções gerais das equações matriciais são:

$$\left\{ \begin{array}{l} \vec{M}_z(t) = \vec{M}_0 - \exp(\bar{L}_1 t) [\vec{M}_0 - \vec{M}_z(0)] \\ \vec{M}_\perp(t) = \exp(\bar{L}_2 t) \vec{M}_\perp(0) \end{array} \right.$$

As equações anteriores podem ser facilmente implementadas para modelos de N sítios.

Modelo de *Exchange* para dois sítios

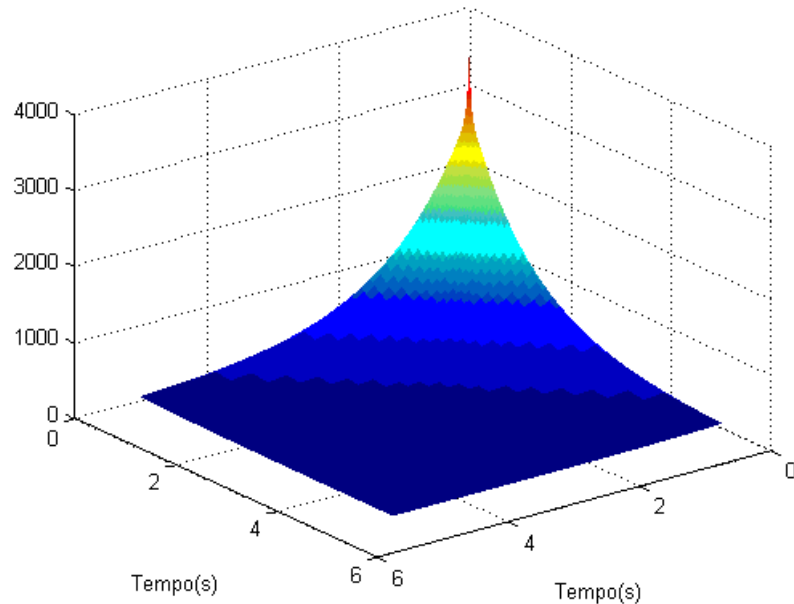
Experimento $T_2 \times T_2$ Exchange:



Assumindo os dois ciclos de fase do experimento $T_2 \times T_2$ Exchange, o sinal observado será:

$$\vec{S}(t_1, t_s, t_2) = 2 \exp(\bar{L}_2 t_2) \exp(\bar{L}_1 t_s) \exp(\bar{L}_2 t_1) \vec{M}_0$$

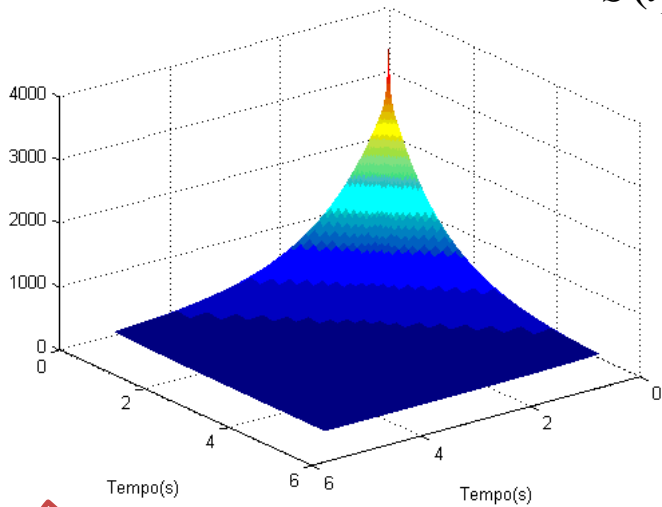
$$S_{obs}(t) = \sum_{i=a,b} S_i(t)$$



Simulações Numéricas

$$\vec{S}(t_1, t_s, t_2) = 2 \exp(\bar{L}_2 t_2) \exp(\bar{L}_1 t_s) \exp(\bar{L}_2 t_1) \vec{M}_0$$

$$S_{obs}(t) = \sum_{i=a,b} S_i(t)$$



Parâmetros das simulações:

$$T_1^a = 2,6s$$

$$T_1^b = 0,7s$$

$$T_2^a = 1,3s$$

$$T_2^b = 0,03s$$

$$k_{ab} = \frac{1}{\tau_{ab}}$$

$$M_0^a = 0,82.M_0^b$$

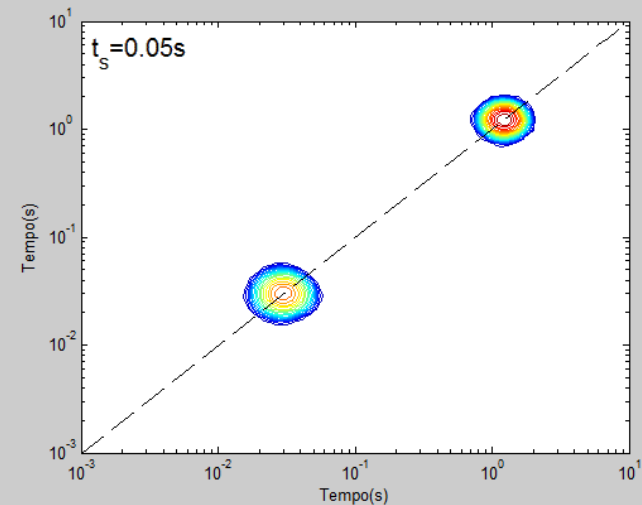
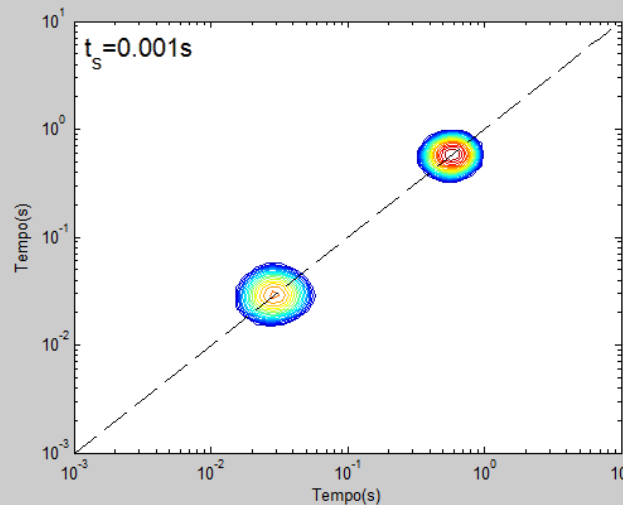
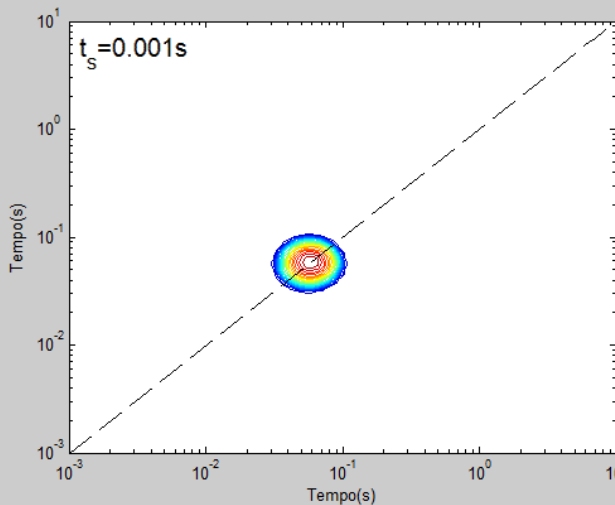
$$k_{ab}M_0^a = k_{ba}M_0^b$$

Transformada Inversa de Laplace 2D

$$\tau_{ab} = 0,01s$$

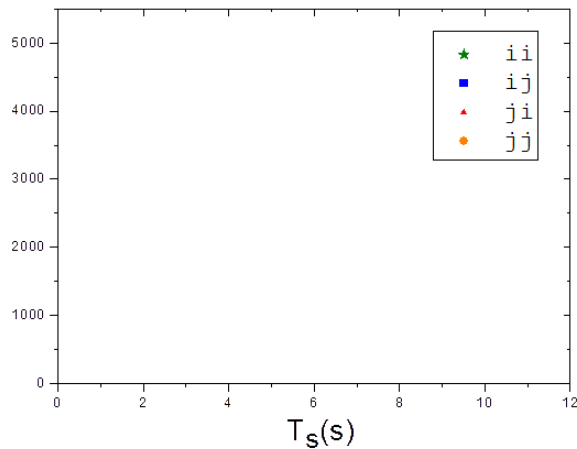
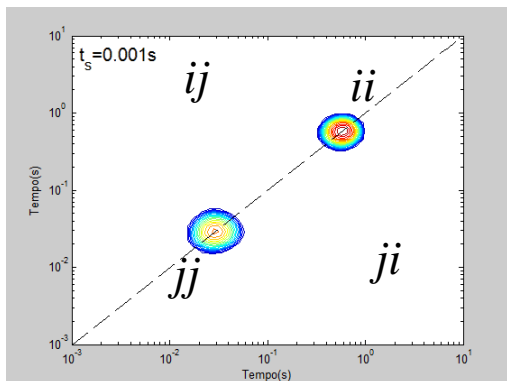
$$\tau_{ab} = 1s$$

$$\tau_{ab} = 20s$$

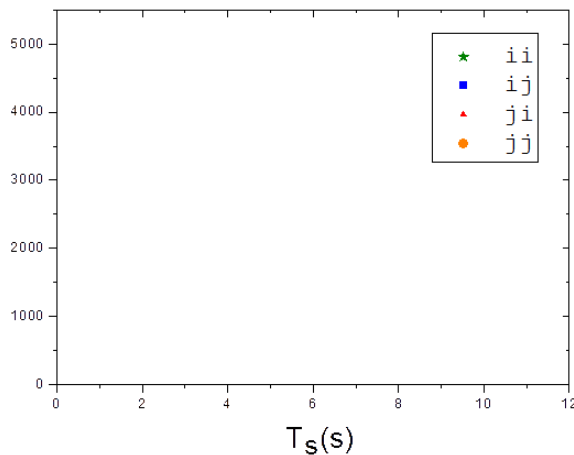
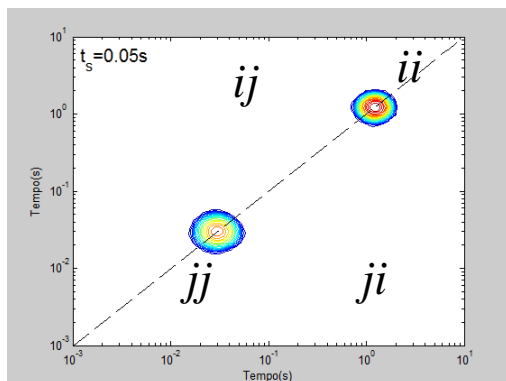


Simulações Numéricas

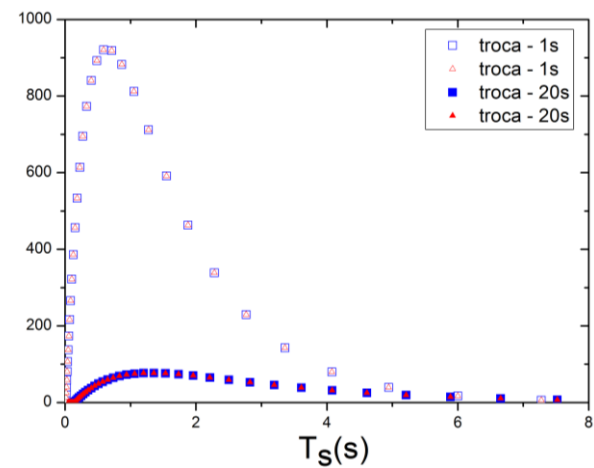
$$\tau_{ab} = 1s$$



$$\tau_{ab} = 20s$$



Picos de troca:



Como são os comportamentos dos picos?

Comportamento dos Picos

A solução geral, mesmo para dois sítios, é de difícil interpretação devido à quantidade de termos que aparecem na expressão. Para facilitar, será desconsiderada a troca durante as CPMGs (caso em que $\tau_{ab} \gg T_2^a, T_2^b$):

$$\vec{S}(t_1, t_s, t_2) = 2 \exp(\bar{R}_2 t_2) \exp(\bar{L}_1 t_s) \exp(\bar{R}_2 t_1) \vec{M}_0$$

A exponencial $\exp(\bar{L}_1 t_s)$ pode ser expandida em termo dos autovalores e autovetores:

$$\exp(\bar{L}_1 t_s) = \bar{U}_{L1} \begin{pmatrix} \exp(-\lambda_{L1}^+ t_s) & 0 \\ 0 & \exp(-\lambda_{L1}^- t_s) \end{pmatrix} \bar{U}_{L1}^{-1} \quad \begin{array}{l} \lambda_{L1}^+, \lambda_{L1}^- : \text{Autovalores} \\ \bar{U}_{L1} : \text{Matriz de autovetores} \end{array}$$

Em que:
$$\left\{ \begin{array}{l} \lambda_{L1}^\pm = \frac{1}{2} (R_1^a + k_{ab} + R_1^b + k_{ba}) \mp \frac{1}{2} \Delta \\ \Delta \equiv \sqrt{(R_1^a + k_{ab} + R_1^b + k_{ba})^2 - 4[(R_1^a + k_{ab})(R_1^b + k_{ba}) - k_{ab}k_{ba}]} \end{array} \right.$$

Assim, com simples manipulações algébricas:

$$S_{obs}(t_1, t_s, t_2) = ii + ij + ji + jj$$

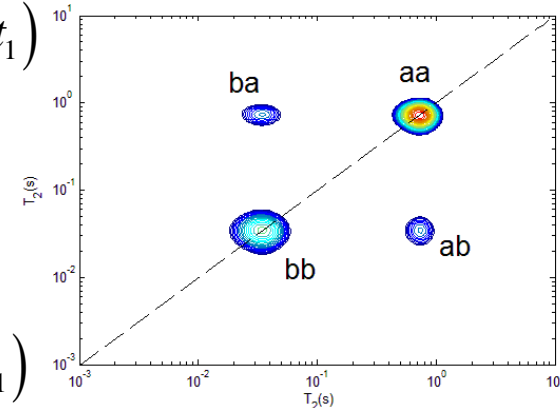
$$ii = M_0^a \left[(1 + \delta) \exp(-\lambda_{L1}^+ t_s) + (1 - \delta) \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^a t_2) \exp(-R_2^a t_1)$$

$$ij = \frac{k_{ab} M_0^a}{\Delta} \left[\exp(-\lambda_{L1}^+ t_s) - \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^b t_2) \exp(-R_2^a t_1)$$

$$ji = \frac{k_{ba} M_0^b}{\Delta} \left[\exp(-\lambda_{L1}^+ t_s) - \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^a t_2) \exp(-R_2^b t_1)$$

$$jj = M_0^b \left[(1 - \delta) \exp(-\lambda_{L1}^+ t_s) + (1 + \delta) \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^b t_2) \exp(-R_2^b t_1)$$

Em que: $\delta = (R_1^b + k_{ba} - R_1^a - k_{ab}) / \Delta$



Comportamento dos Picos

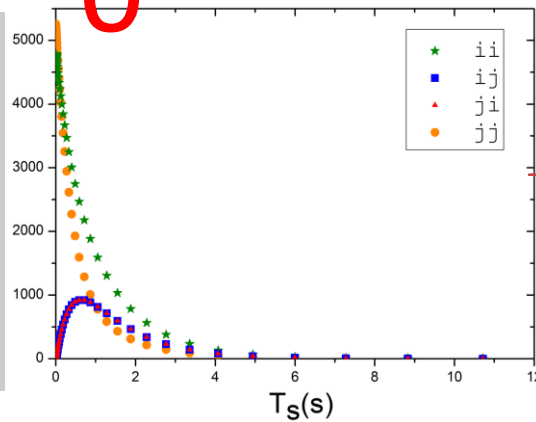
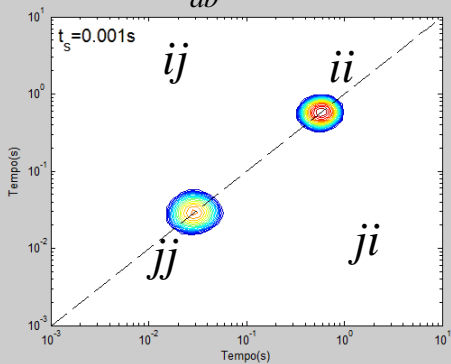
$$ii = M_0^a \left[(1 + \delta) \exp(-\lambda_{L1}^+ t_s) + (1 - \delta) \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^a t_2) \exp(-R_2^a t_1)$$

$$ij = \frac{k_{ab} M_0^a}{\Delta} \left[\exp(-\lambda_{L1}^+ t_s) - \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^b t_2) \exp(-R_2^a t_1)$$

$$ji = \frac{k_{ba} M_0^b}{\Delta} \left[\exp(-\lambda_{L1}^+ t_s) - \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^a t_2) \exp(-R_2^b t_1)$$

$$jj = M_0^b \left[(1 - \delta) \exp(-\lambda_{L1}^+ t_s) + (1 + \delta) \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^b t_2) \exp(-R_2^b t_1)$$

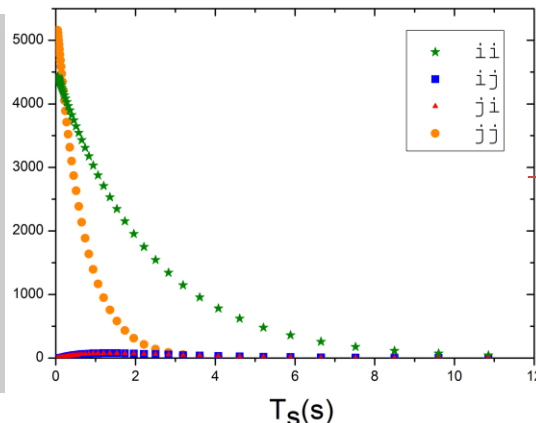
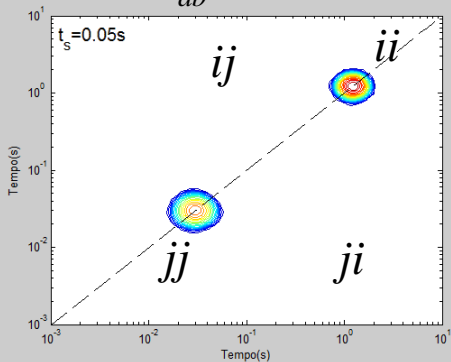
$\tau_{ab} = 1s$



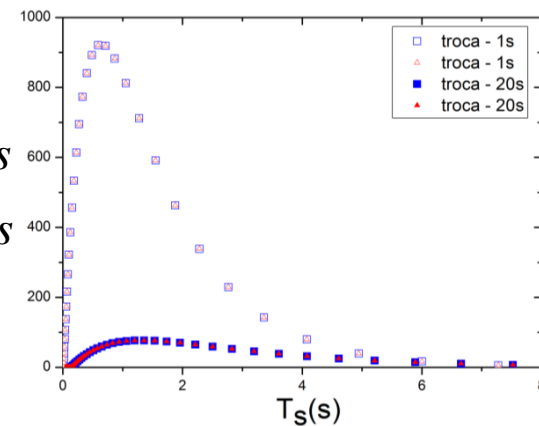
$$\left. \begin{aligned} (\lambda_{L1}^+)^{-1} &= 1,23s \\ (\lambda_{L1}^-)^{-1} &= 0,35s \\ \delta &= 0,43 \end{aligned} \right\}$$

$$\left. \begin{aligned} T_1^a &= 2,6s \\ T_1^b &= 0,7s \\ T_2^a &= 1,3s \\ T_2^b &= 0,03s \end{aligned} \right\}$$

$\tau_{ab} = 20s$



$$\left. \begin{aligned} (\lambda_{L1}^+)^{-1} &= 2,31s \\ (\lambda_{L1}^-)^{-1} &= 0,68s \\ \delta &= 0,996 \end{aligned} \right\}$$



Comportamento dos Picos

Considerando $\tau_{ab} \gg T_1^a, T_1^b$ e $M_0^a \approx M_0^b \equiv M_0 \rightarrow k_{ab} \approx k_{ba} \equiv k$ obtém-se:
$$\left\{ \begin{array}{l} \lambda_{L1}^+ = R_1^a \\ \lambda_{L1}^- = R_1^b \\ \delta \approx 1 \end{array} \right.$$

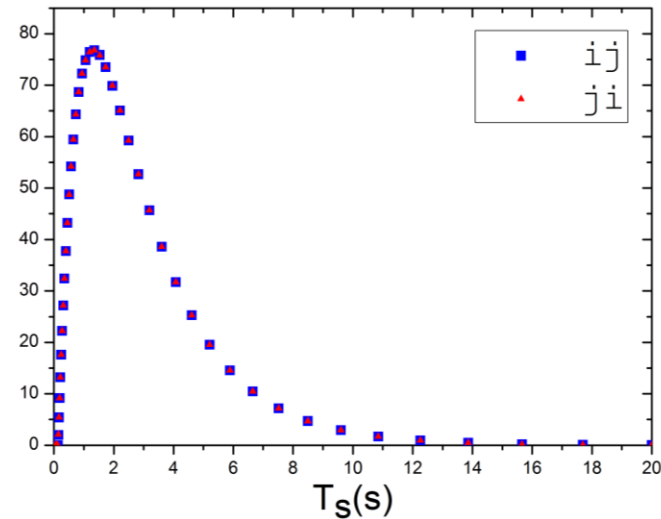
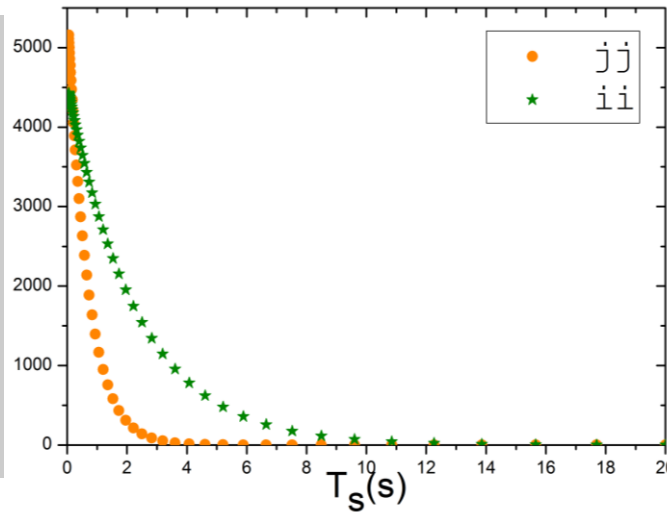
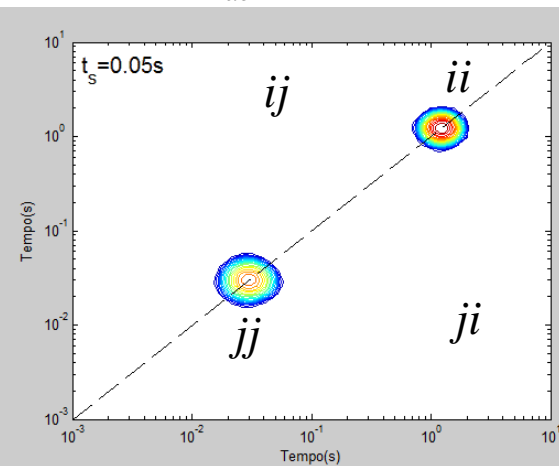
$$ii = 2M_0 \exp(-R_1^a t_s) \exp(-R_2^a t_2) \exp(-R_2^a t_1)$$

$$ij = \frac{kM_0}{\Delta} \left[\exp(-R_1^a t_s) - \exp(-R_1^b t_s) \right] \exp(-R_2^b t_2) \exp(-R_2^a t_1)$$

$$ji = \frac{kM_0}{\Delta} \left[\exp(-R_1^a t_s) - \exp(-R_1^b t_s) \right] \exp(-R_2^b t_1) \exp(-R_2^a t_2)$$

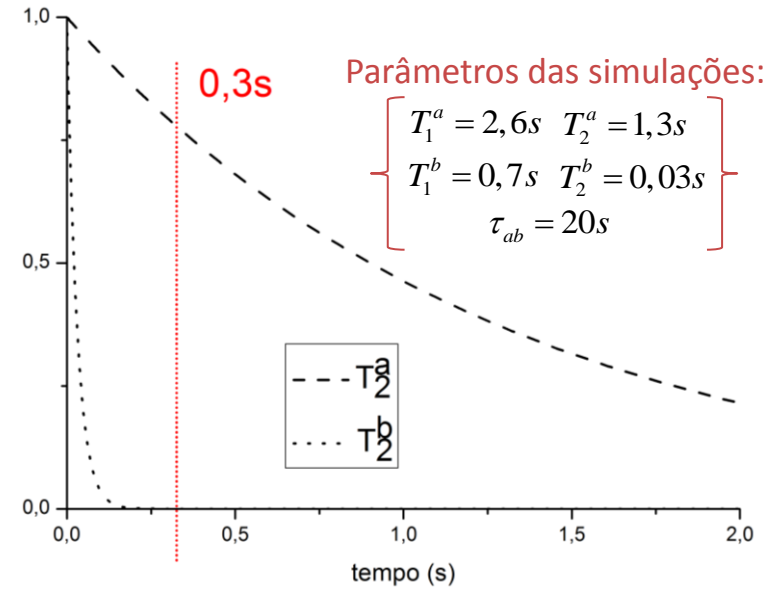
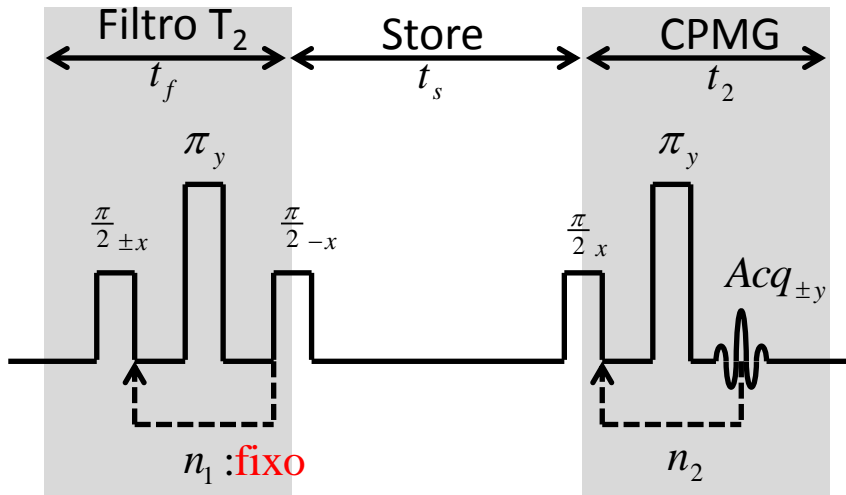
$$jj = 2M_0 \exp(-R_1^b t_s) \exp(-R_2^b t_1) \exp(-R_2^b t_2)$$

$$\tau_{ab} = 20s$$



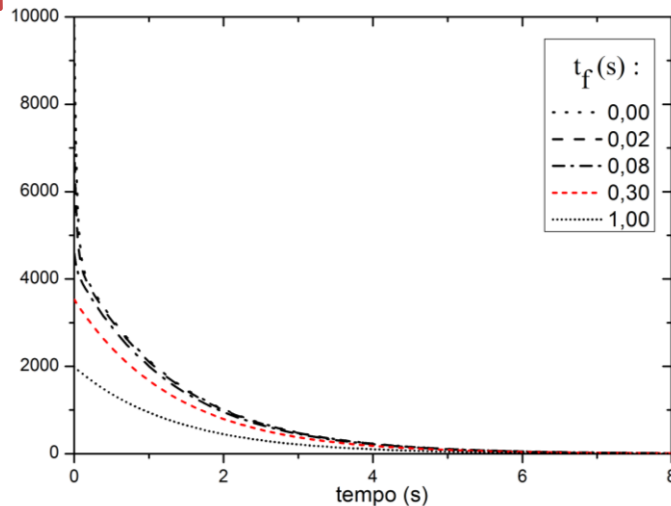
Proposta de filtro T_2 para um $T_2 \times T_2$ Exchange unidimensional

Agora a ideia é fazer um filtro de T_2 para a magnetização do pico de menor tempo T_2 :

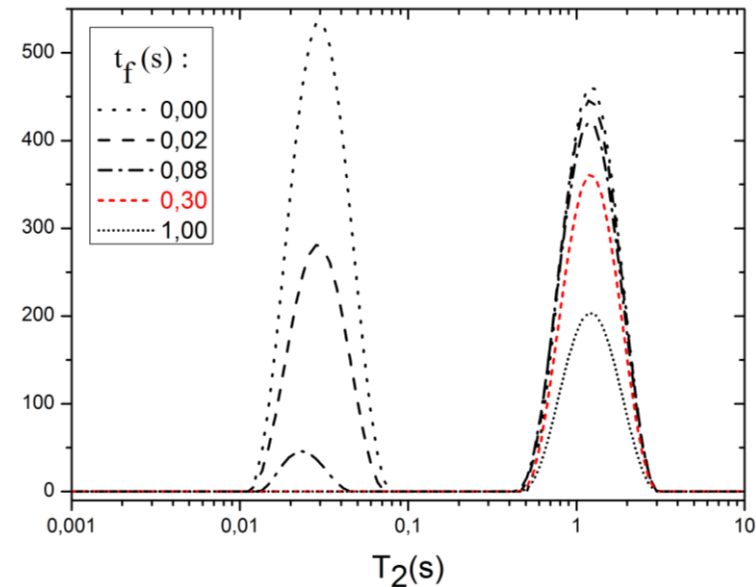


$$\vec{S}(t_1, t_s, t_2) = 2 \exp(\bar{L}_2 t_2) \exp(\bar{L}_1 t_s) \exp(\bar{L}_2 t_f) \vec{M}_0$$

Simulação para valores de filtros ($t_s = 0$):

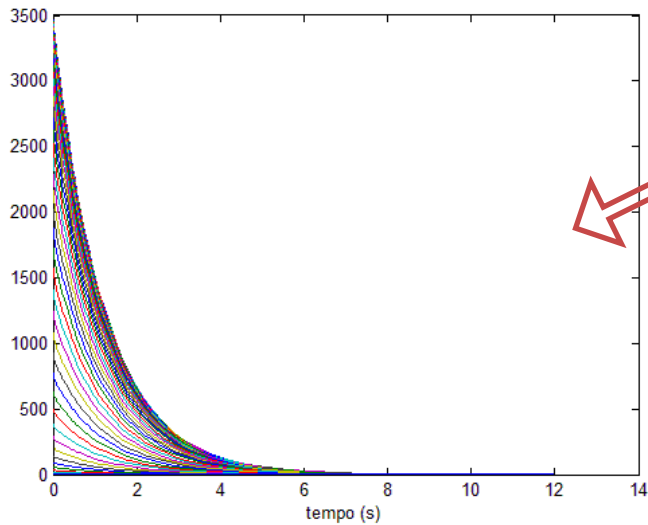


Transformada Inversa de Laplace 1D



Comportamento dos Picos

Agora variando t_s para um certo filtro T_2 é possível observar que o pico suprimido volta a aparecer devido a migração de spins do poro que contém magnetização:



$$\vec{S}(t_1, t_s, t_2) = 2 \exp(\bar{L}_2 t_2) \exp(\bar{L}_1 t_s) \exp(\bar{L}_2 t_f) \vec{M}_0$$

$$S_{obs}(t) = \sum_{i=a,b} S_i(t)$$

Parâmetros das simulações:

$$T_1^a = 2,6s$$

$$T_1^b = 0,7s$$

$$T_2^a = 1,3s$$

$$T_2^b = 0,03s$$

$$k_{ab} = \frac{1}{\tau_{ab}}$$

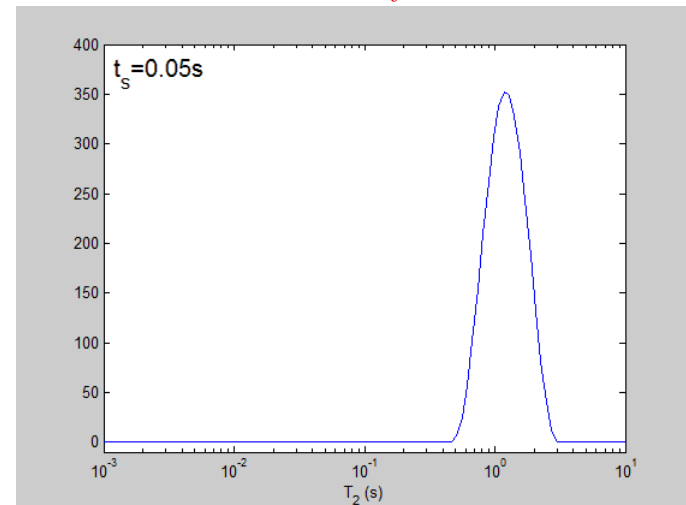
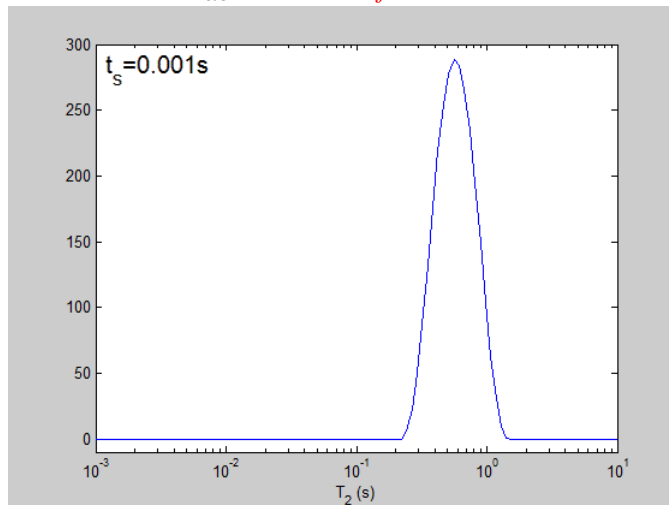
$$M_0^a = 0,82.M_0^b$$

$$k_{ab} M_0^a = k_{ba} M_0^b$$

Transformada Inversa de Laplace 1D

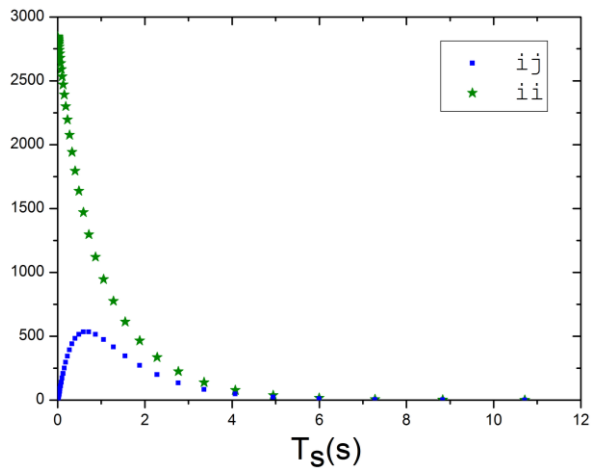
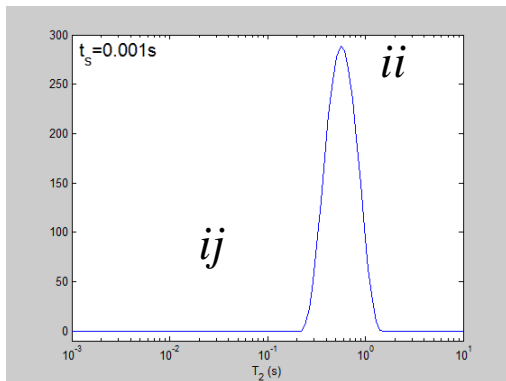
$$\tau_{ab} = 1s \quad t_f = 0,3s$$

$$\tau_{ab} = 20s \quad t_f = 0,3s$$

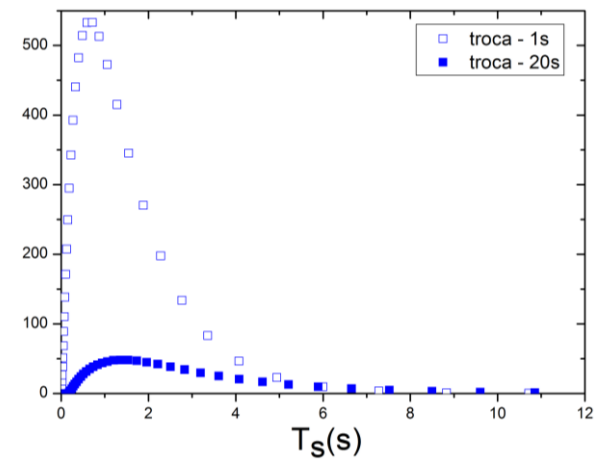


Simulações Numéricas

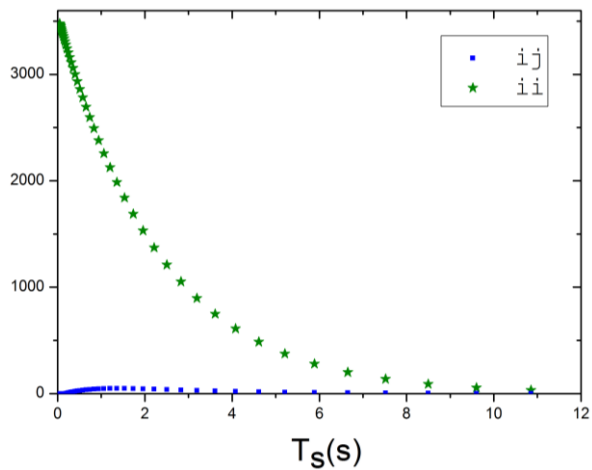
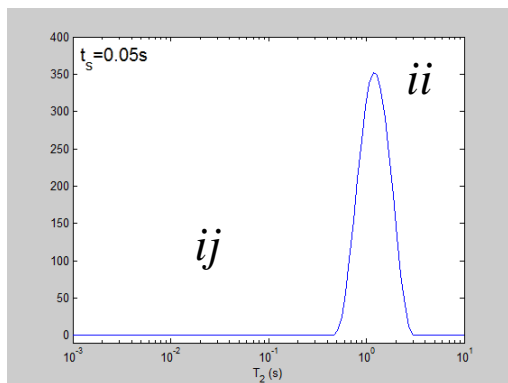
$$\tau_{ab} = 1s \quad t_f = 0,3s$$



Picos de troca:



$$\tau_{ab} = 20s \quad t_f = 0,3s$$



Como são os comportamentos dos picos?

Comportamento dos Picos

$$ii = 2M_0 \exp(-R_1^a t_s) \exp(-R_2^a t_2) \exp(-R_2^a t_f)$$

$$ij = \frac{M_0 k}{\Delta} \left[\exp(-R_1^a t_s) - \exp(-R_1^b t_s) \right] \exp(-R_2^b t_2) \exp(-R_2^a t_f)$$

$$ji = \frac{M_0 k}{\Delta} \left[\exp(-R_1^a t_s) - \exp(-R_1^b t_s) \right] \exp(-R_2^a t_2) \exp(-R_2^b t_f)$$

$$jj = 2M_0 \exp(-R_1^b t_s) \exp(-R_2^b t_2) \exp(-R_2^b t_f)$$

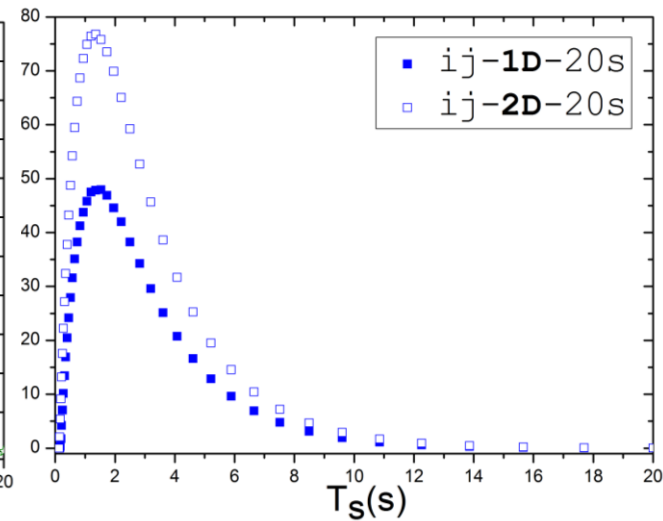
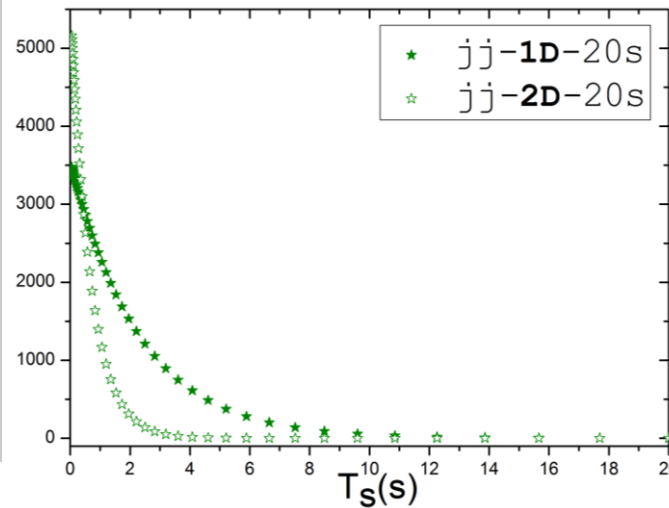
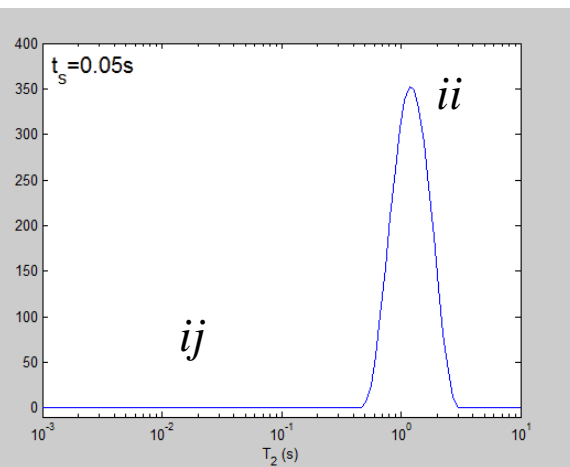
Filtro: $\exp(-R_1^b t_f) \approx 0$

$$ii = 2M_0 \exp(-R_2^a t_f) \exp(-R_1^a t_s) \exp(-R_2^a t_2)$$

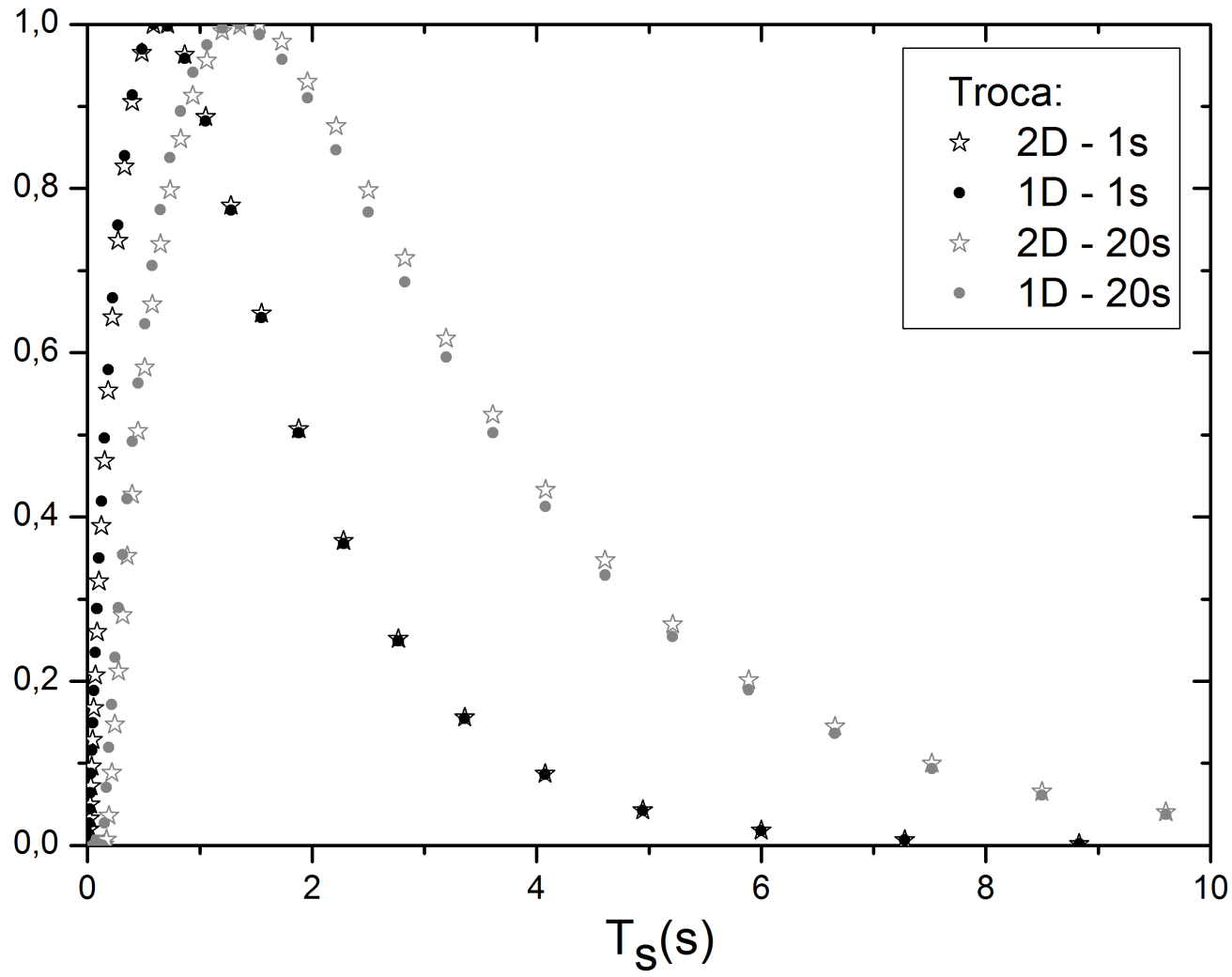
$$ji \approx 0$$

$$ij = \frac{M_0 k}{\Delta} \exp(-R_2^a t_f) \left[\exp(-R_1^a t_s) - \exp(-R_1^b t_s) \right] \exp(-R_2^b t_2)$$

$$jj \approx 0$$



Normalizando as trocas

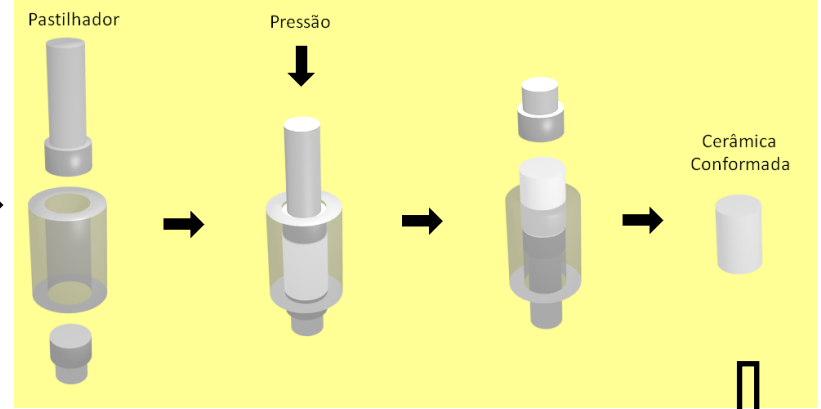


Manufatura de um meio poroso artificial

A ideia para construção um meio poroso com duas distribuições de tamanhos de poros diferentes foi a manufatura da cerâmica pelo método de prensagem a seco e sinterização (gerando porosos chamados de intrínseco), junto com o método de agente porogênico (gerando porosos maiores chamados de induzido).



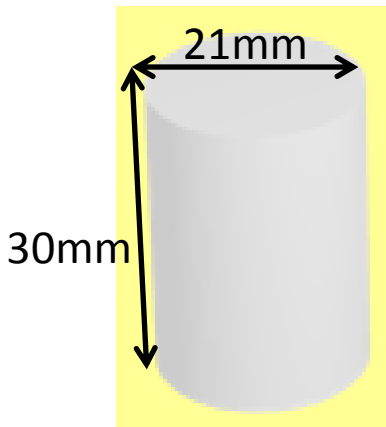
Grânulos de alumina



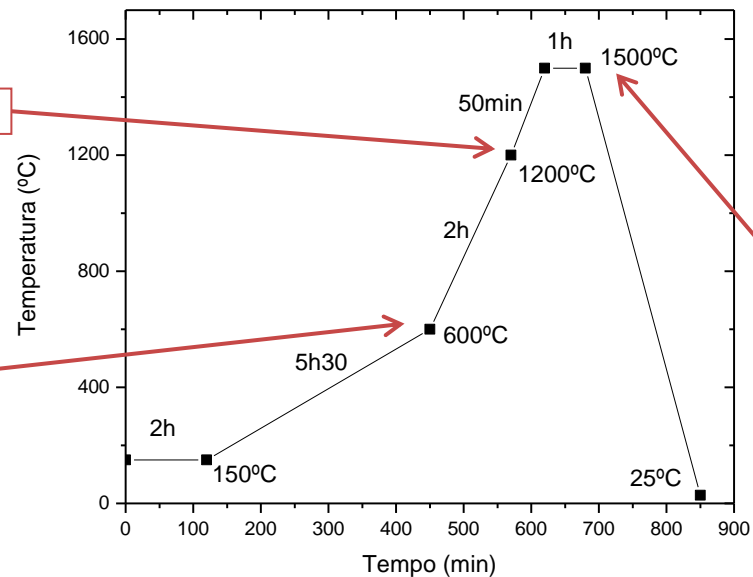
Forno

Cristais de sacarose (agente porogênico)

Peneira inferior	Peneira superior
300 μ m	600 μ m



Cerâmica pronta



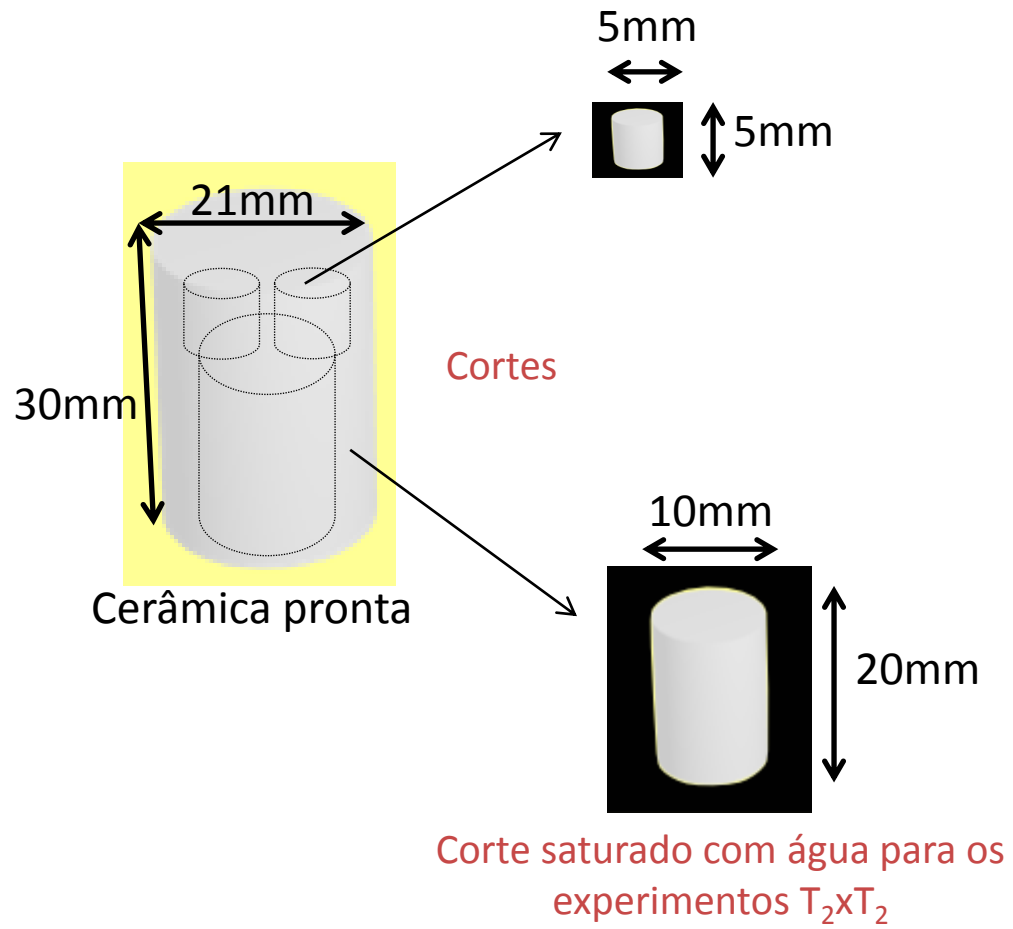
≈ 0% de Sacarose

≈ 5,7% de Sacarose

Sinterização

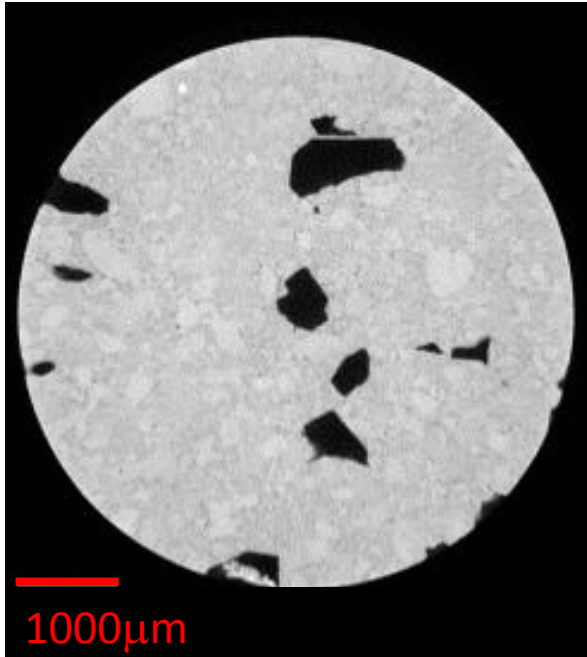
Caracterização da cerâmica

Um corte para microtomografia por raios-x (μ CT) e outro para porosimetria por intrusão de mercúrio (PIM)

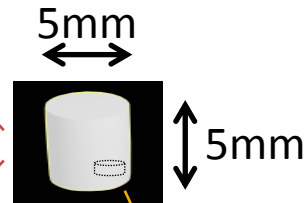


Caracterização da cerâmica

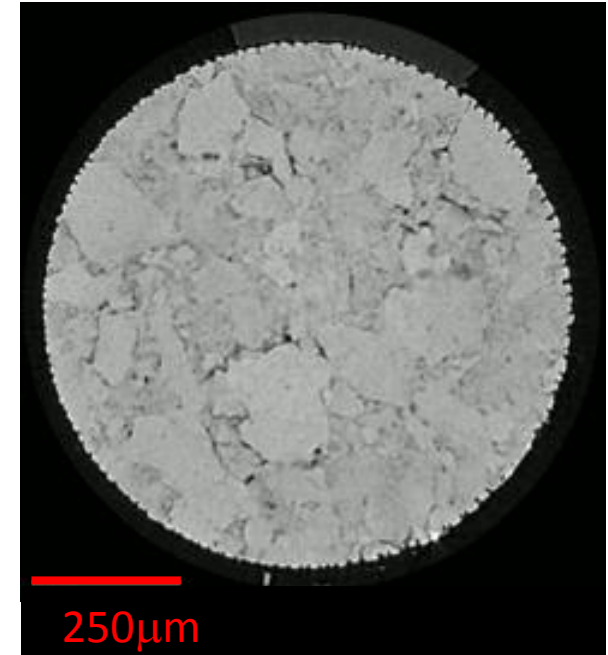
μ CT com resolução de $5,9\mu\text{m}$



As manchas pretas são os poros induzidos



μ CT com resolução de $1\mu\text{m}$



As manchas pretas são os poros intrínsecos

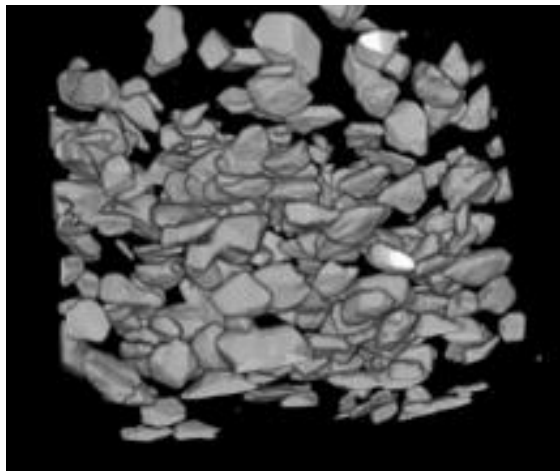
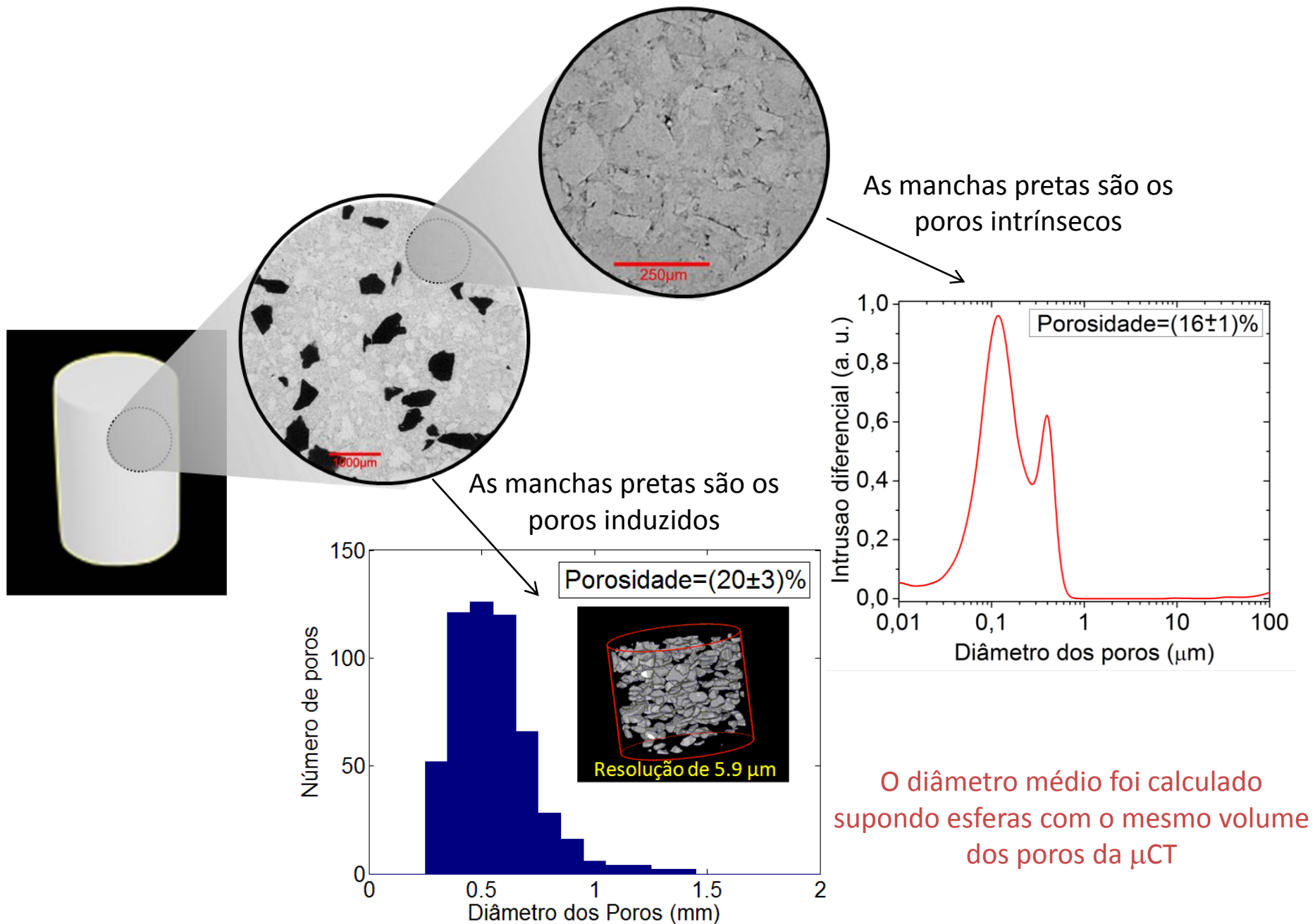


Imagem negativa, os poros estão em cinza e somente é possível ver os poros induzidos devido a resolução

1mm x 1mm

Caracterização da cerâmica

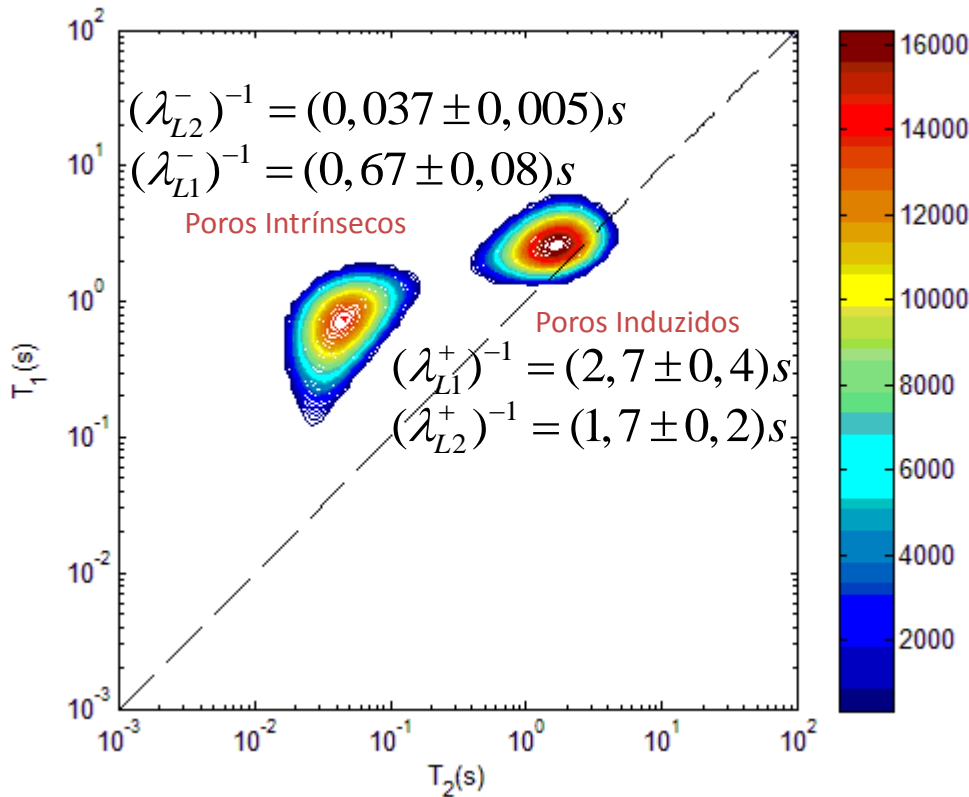


O diâmetro médio foi calculado supondo esferas com o mesmo volume dos poros da μCT

Resultados Experimentais

Para os experimentos as amostras foram saturadas com H_2O aplicando uma pressão de 200 MPa. Todos foram realizados a temperatura ambiente com tempo entre ecos de 150 μs usando um console TECMAG RedStone operando um magneto supercondutor Oxford 2 T (85 MHz para núcleos 1H).

Mapas $T_1 \times T_2$:



$$k_{ab}, k_{ba} = 0 \left\{ \begin{array}{ll} (\lambda_{L1}^+)^{-1} = T_1^a & (\lambda_{L1}^-)^{-1} = T_1^b \\ (\lambda_{L2}^+)^{-1} = T_2^a & (\lambda_{L2}^-)^{-1} = T_2^b \end{array} \right.$$

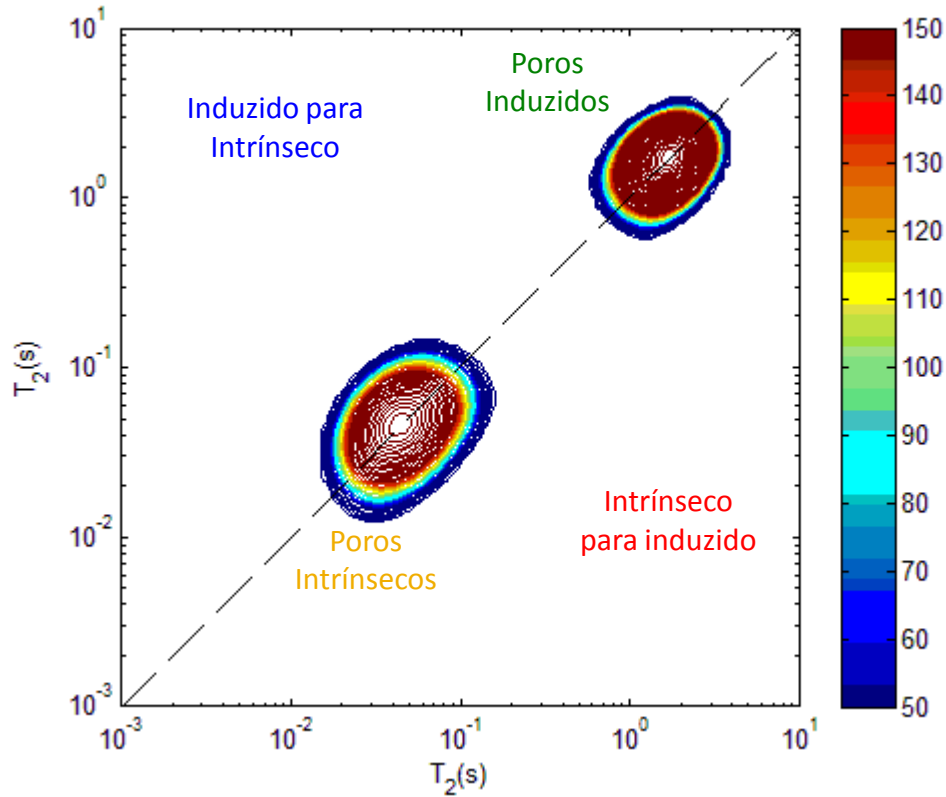
$$\begin{array}{l} k_{ab}, k_{ba} \approx R_2^a, R_2^b \\ k_{ab}, k_{ba} \approx R_1^a, R_1^b \end{array} \left\{ \begin{array}{ll} (\lambda_{L1}^+)^{-1} \neq T_1^a & (\lambda_{L1}^-)^{-1} \neq T_1^b \\ (\lambda_{L2}^+)^{-1} \neq T_2^a & (\lambda_{L2}^-)^{-1} \neq T_2^b \end{array} \right.$$

$$\begin{array}{l} k_{ab}, k_{ba} \ll R_2^a, R_2^b \\ k_{ab}, k_{ba} \approx R_1^a, R_1^b \end{array} \left\{ \begin{array}{ll} (\lambda_{L1}^+)^{-1} \neq T_1^a & (\lambda_{L1}^-)^{-1} \neq T_1^b \\ (\lambda_{L2}^+)^{-1} \approx T_2^a & (\lambda_{L2}^-)^{-1} \approx T_2^b \end{array} \right.$$

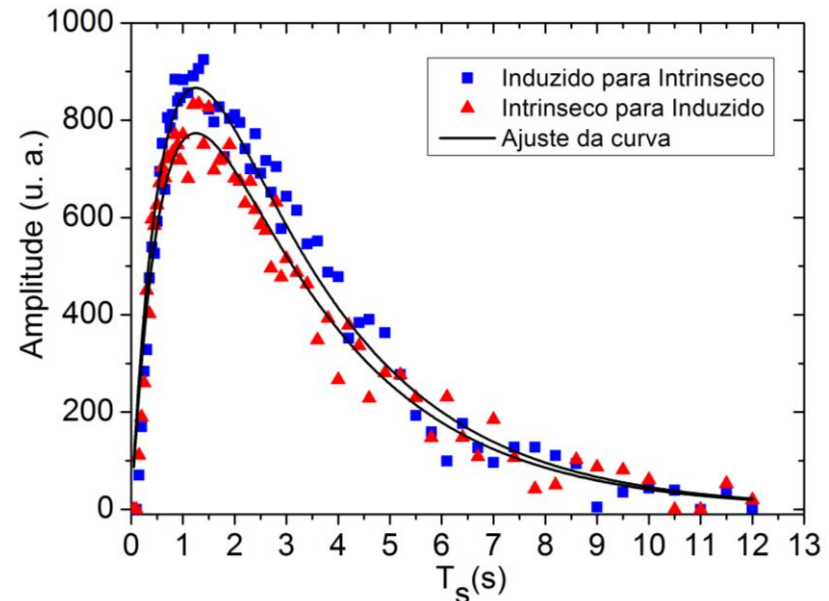
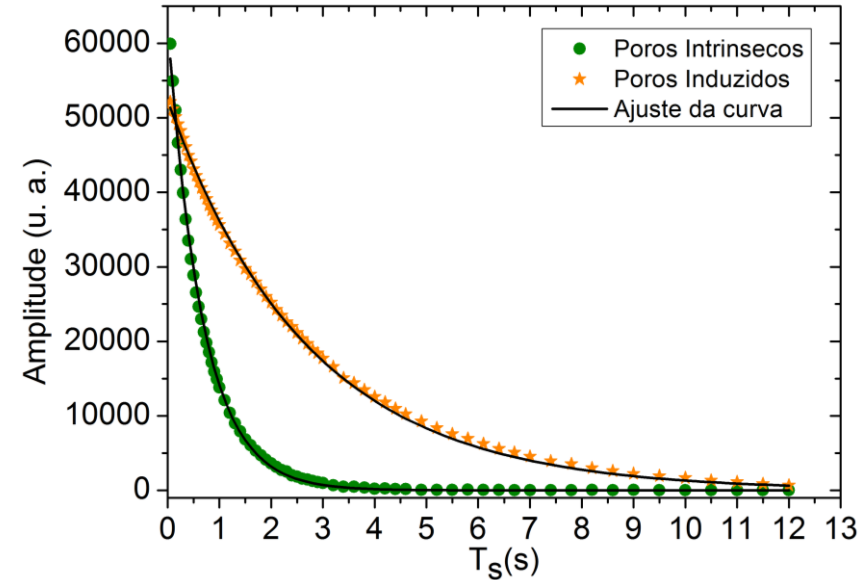
$$k_{ab}, k_{ba} \ll R_2^a, R_2^b \left\{ \begin{array}{ll} (\lambda_{L1}^+)^{-1} \approx T_1^a & (\lambda_{L1}^-)^{-1} \approx T_1^b \\ (\lambda_{L2}^+)^{-1} \approx T_2^a & (\lambda_{L2}^-)^{-1} \approx T_2^b \end{array} \right.$$

Resultado 2D $T_2 \times T_2$ Exchange

Mapas $T_2 \times T_2$:



Curvas de troca:



Os experimentos 2D $T_2 \times T_2$ Exchange foram realizados gerando decaimentos bidimensionais compostos por 44 x 44 pontos espaçados logaritmicamente. Cada mapa levou aproximadamente 40 min (apenas 2 médias). Para os 67 pontos de t_s totalizou **44 h**.

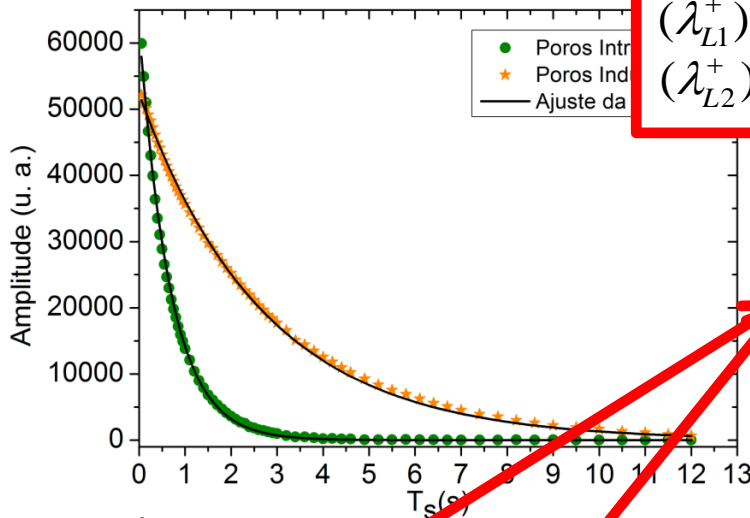
Resultado 2D $T_2 \times T_2$ Exchange

$$ii = M_0^a \left[(1 + \delta) \exp(-\lambda_{L1}^+ t_s) + (1 - \delta) \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^a t_2) \exp(-R_2^a t_1)$$

$$ij = \frac{k_{ab} M_0^a}{\Delta} \left[\exp(-\lambda_{L1}^+ t_s) - \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^b t_2) \exp(-R_2^a t_1)$$

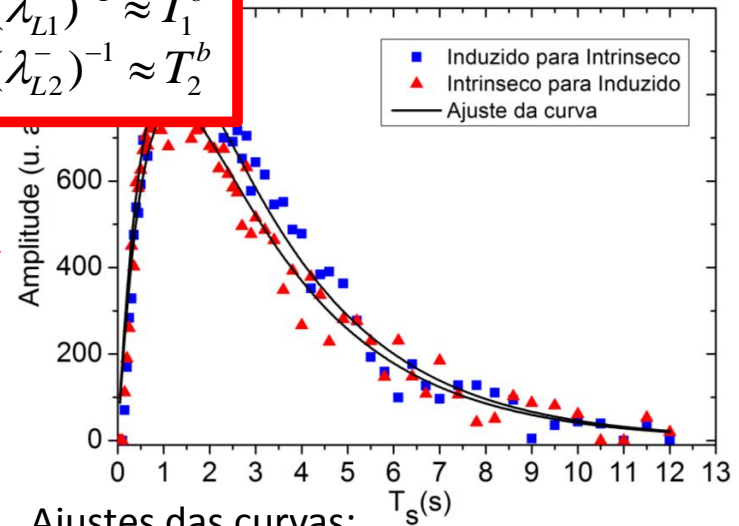
$$ji = \frac{k_{ba} M_0^b}{\Delta} \left[\exp(-\lambda_{L1}^+ t_s) - \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^a t_2) \exp(-R_2^b t_1)$$

$$jj = M_0^b \left[(1 - \delta) \exp(-\lambda_{L1}^+ t_s) + (1 + \delta) \exp(-\lambda_{L1}^- t_s) \right] \exp(-R_2^b t_2) \exp(-R_2^b t_1)$$



$$\begin{aligned} (\lambda_{L1}^+)^{-1} &\approx T_1^a & (\lambda_{L1}^-)^{-1} &\approx T_1^b \\ (\lambda_{L2}^+)^{-1} &\approx T_2^a & (\lambda_{L2}^-)^{-1} &\approx T_2^b \end{aligned}$$

$$\delta \approx 1$$



Ajustes das curvas:

$$ii = (52100 \pm 200) \exp\left[\frac{-t_s}{2,7}\right] + (400 \pm 400) \exp\left[\frac{-t_s}{0,67}\right]$$

$$jj = (0 \pm 200) \exp\left[\frac{-t_s}{2,7}\right] + (62800 \pm 400) \exp\left[\frac{-t_s}{0,67}\right]$$

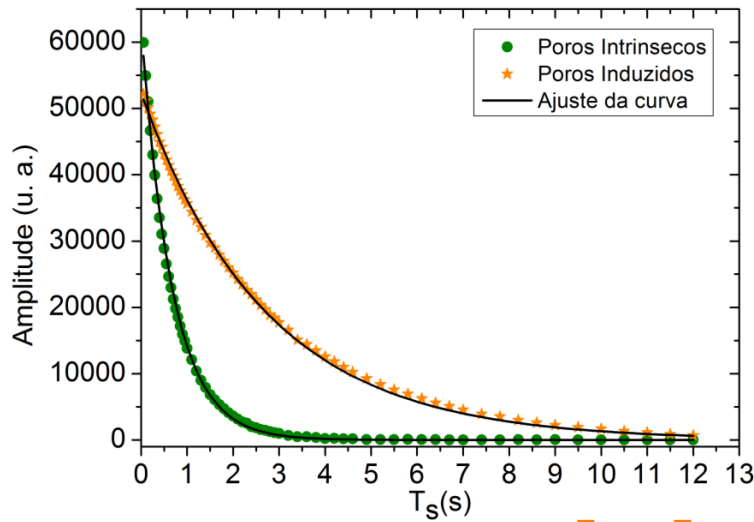
Ajustes das curvas:

$$ij = (1820 \pm 30) \left\{ \exp\left[\frac{-t_s}{2,7}\right] - \exp\left[\frac{-t_s}{0,67}\right] \right\}$$

$$ji = (1630 \pm 20) \left\{ \exp\left[\frac{-t_s}{2,7}\right] - \exp\left[\frac{-t_s}{0,67}\right] \right\}$$

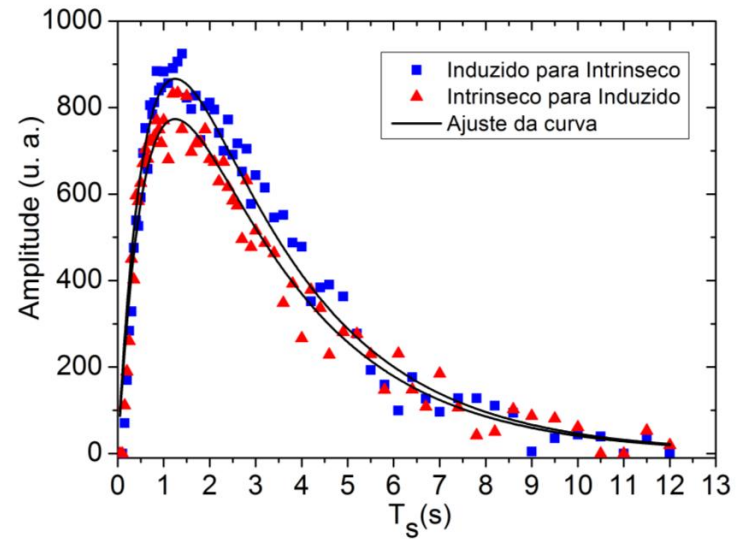
Resultado 2D $T_2 \times T_2$ Exchange

$$\left. \begin{aligned}
 ii &= 2M_0 \exp(-R_1^a t_s) \exp(-R_2^a t_2) \exp(-R_2^a t_1) \\
 ij &= \frac{kM_0}{\Delta} \left[\exp(-R_1^a t_s) - \exp(-R_1^b t_s) \right] \exp(-R_2^b t_2) \exp(-R_2^a t_1) \\
 ji &= \frac{kM_0}{\Delta} \left[\exp(-R_1^a t_s) - \exp(-R_1^b t_s) \right] \exp(-R_2^b t_1) \exp(-R_2^a t_2) \\
 jj &= 2M_0 \exp(-R_1^b t_s) \exp(-R_2^b t_1) \exp(-R_2^b t_2)
 \end{aligned} \right\} \begin{aligned}
 (ij + ji) / 2 &= \frac{2kM_0 / \Delta}{2M_0} = \frac{k}{\Delta}
 \end{aligned}$$



$$ii = (52300 \pm 100) \exp\left[\frac{-t_s}{2,7}\right]$$

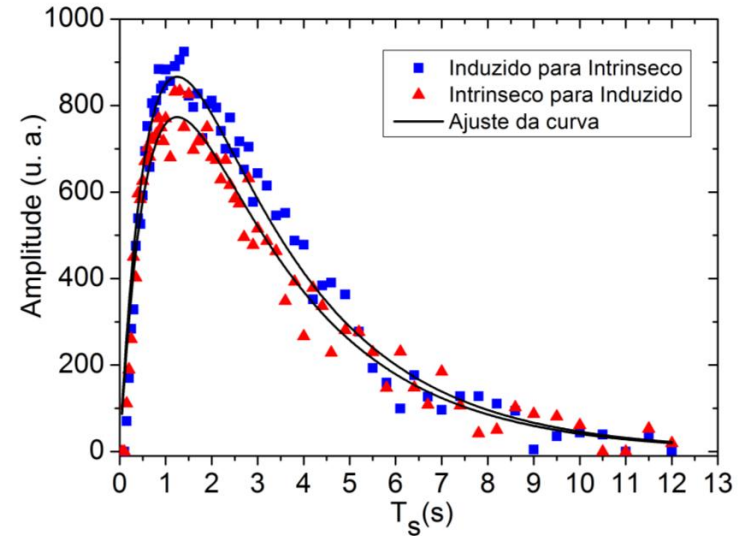
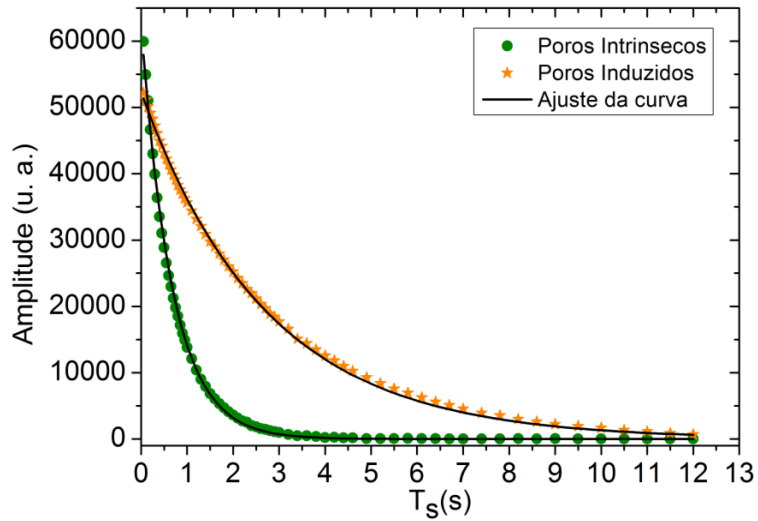
$$jj = (62400 \pm 200) \exp\left[\frac{-t_s}{0,67}\right]$$



$$ij = (1820 \pm 30) \left\{ \exp\left[\frac{-t_s}{2,7}\right] - \exp\left[\frac{-t_s}{0,67}\right] \right\}$$

$$ji = (1630 \pm 20) \left\{ \exp\left[\frac{-t_s}{2,7}\right] - \exp\left[\frac{-t_s}{0,67}\right] \right\}$$

Resultado 2D $T_2 \times T_2$ Exchange



$$ii = (52300 \pm 100) \exp\left[\frac{-t_s}{2,7}\right]$$

$$jj = (62400 \pm 200) \exp\left[\frac{-t_s}{0,67}\right]$$

$$ij = (1820 \pm 30) \left\{ \exp\left[\frac{-t_s}{2,7}\right] - \exp\left[\frac{-t_s}{0,67}\right] \right\}$$

$$ji = (1630 \pm 20) \left\{ \exp\left[\frac{-t_s}{2,7}\right] - \exp\left[\frac{-t_s}{0,67}\right] \right\}$$

$$\frac{(ij + ji) / 2}{(ii + jj) / 2} = \frac{2kM_0 / \Delta}{2M_0} = \frac{k}{\Delta} = \frac{(1725 \pm 25)}{(57350 \pm 150)}$$

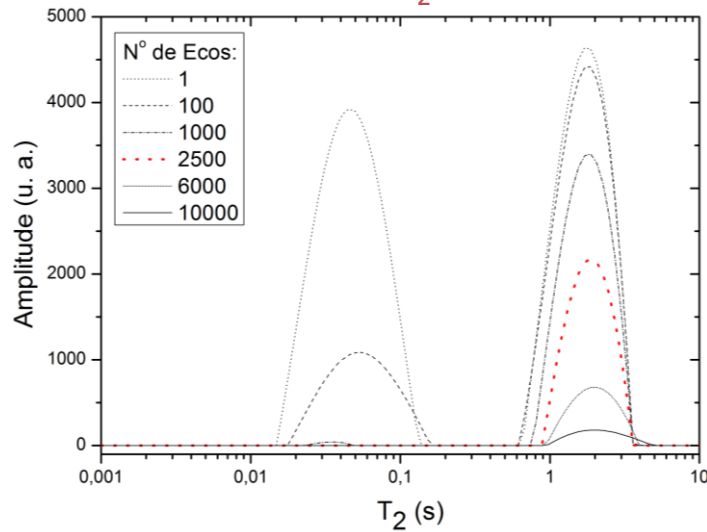
$$\Delta = R_1^b - R_1^a = (0,67 \pm 0,08)^{-1} - (2,7 \pm 0,4)^{-1} = (1,1 \pm 0,2) \text{ s}^{-1}$$

$$k = (0,033 \pm 0,007) \text{ s}^{-1}$$

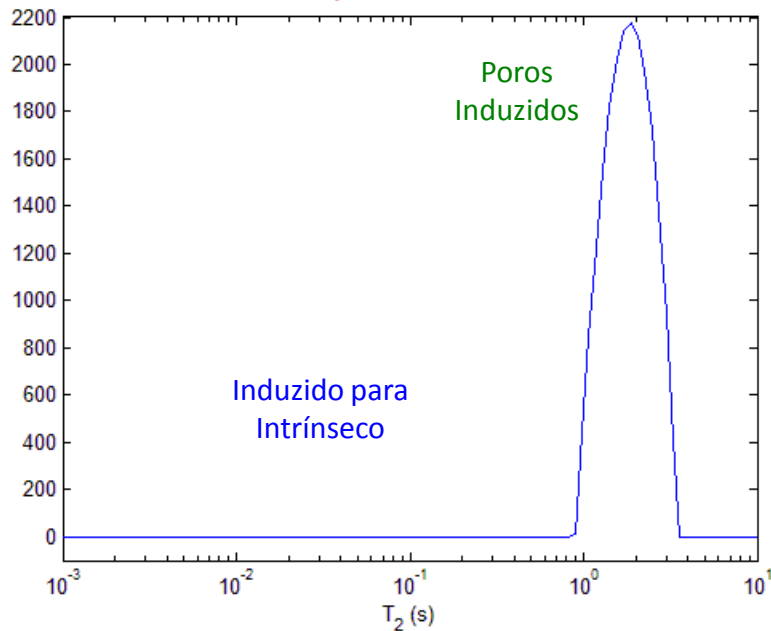
$$\tau_{2D} = (30 \pm 6) \text{ s}$$

Resultado 1D $T_2 \times T_2$ Exchange - Filtro T_2

Filtros de T_2 :

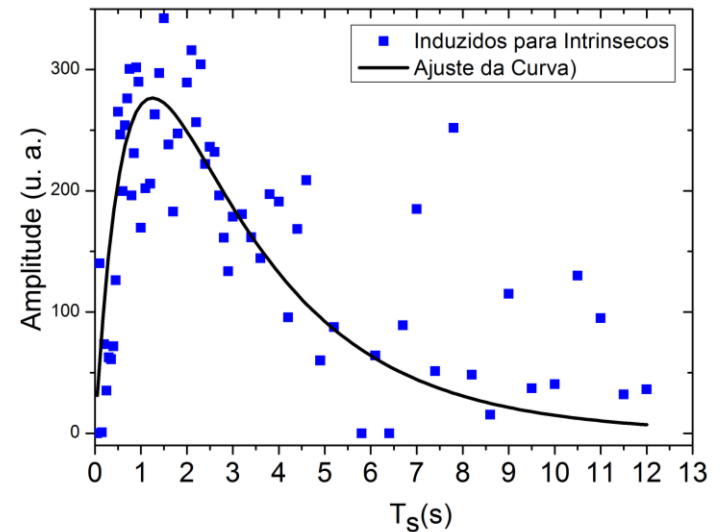
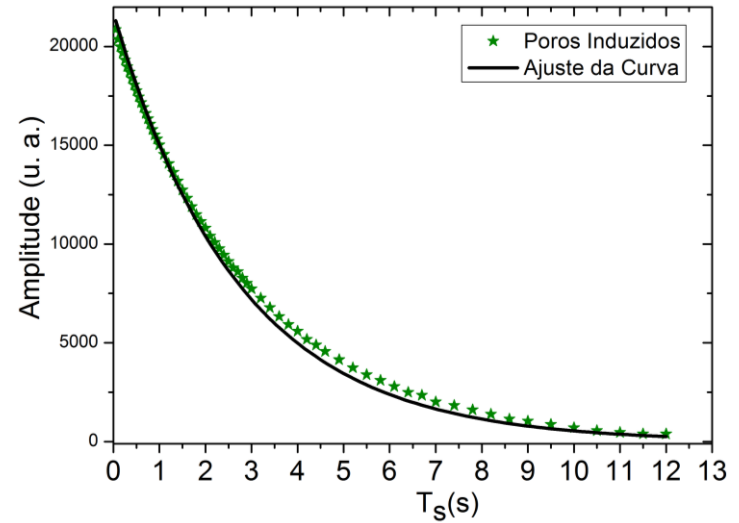


Variando T_s (filto=2500ecos):



Cada decaimento 1D leva aproximadamente 1 min (apenas 2 médias). Para os 67 pontos de t_s foram gastos **1 h**.

Curvas de troca:

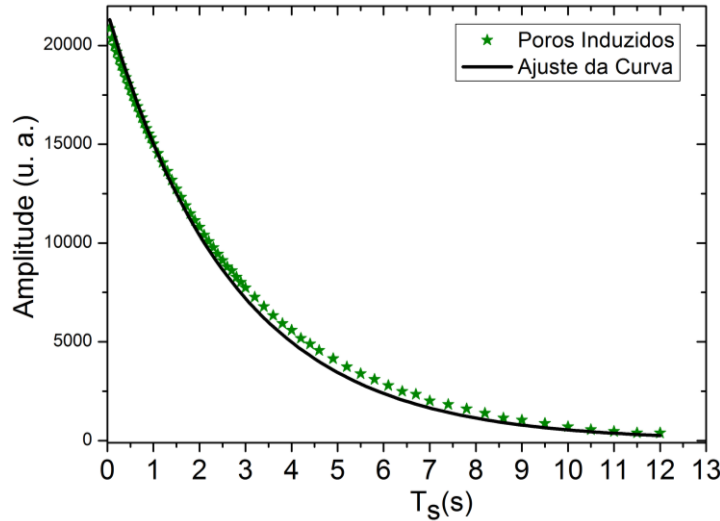


Resultado 2D $T_2 \times T_2$ Exchange

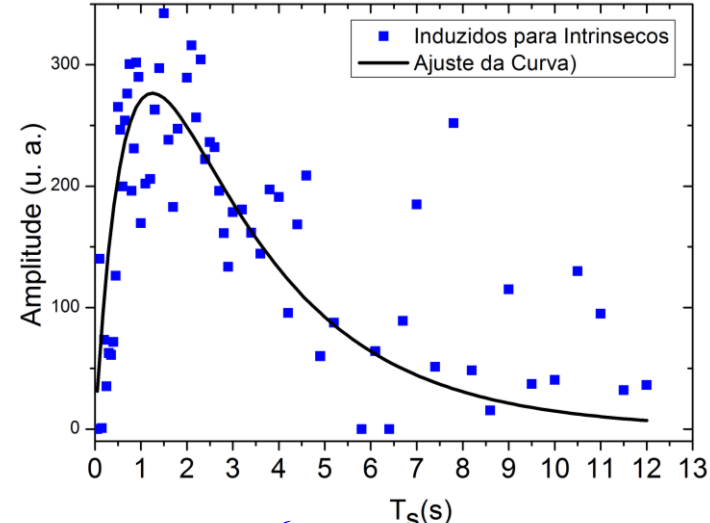
$$ii = 2M_0 \exp(-R_2^a t_f) \exp(-R_1^a t_s) \exp(-R_2^a t_2)$$

$$ij = \frac{M_0 k}{\Delta} \exp(-R_2^a t_f) \left[\exp(-R_1^a t_s) - \exp(-R_1^b t_s) \right] \exp(-R_2^b t_2)$$

$$\frac{ij}{ii} = \frac{2kM_0 \exp(-R_2^a t_f) / \Delta}{2M_0 \exp(-R_2^a t_f)} = \frac{k}{\Delta}$$



$$ii = (21700 \pm 90) \exp\left[\frac{-t_s}{2,7}\right]$$



$$ij = (580 \pm 30) \left\{ \exp\left[\frac{-t_s}{2,7}\right] - \exp\left[\frac{-t_s}{0,67}\right] \right\}$$

$$\frac{ij}{ii} = \frac{2kM_0 \exp(-R_2^a t_f) / \Delta}{2M_0 \exp(-R_2^a t_f)} = \frac{k}{\Delta} = (0,0267 \pm 0,0015)$$

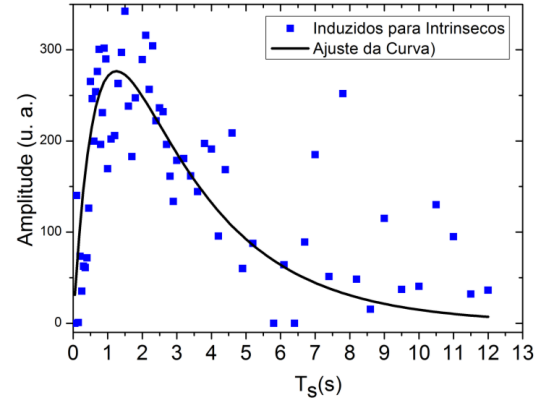
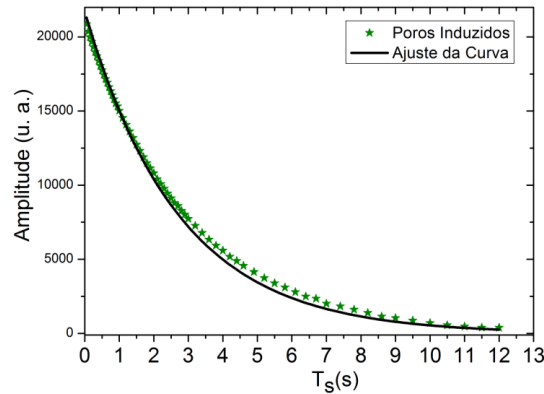
$$\Delta = R_1^b - R_1^a = (0,67 \pm 0,08)^{-1} - (2,7 \pm 0,4)^{-1} = (1,1 \pm 0,2) \text{ s}^{-1}$$

$$k = (0,029 \pm 0,008) \text{ s}^{-1}$$

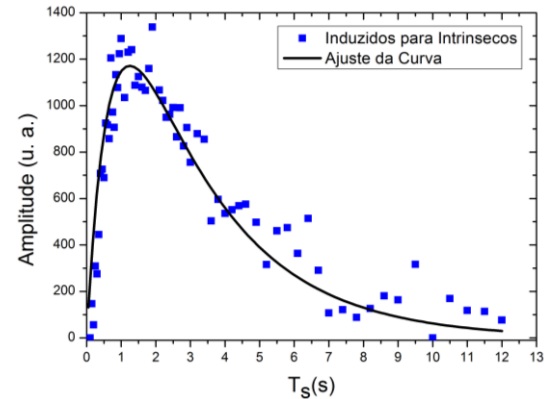
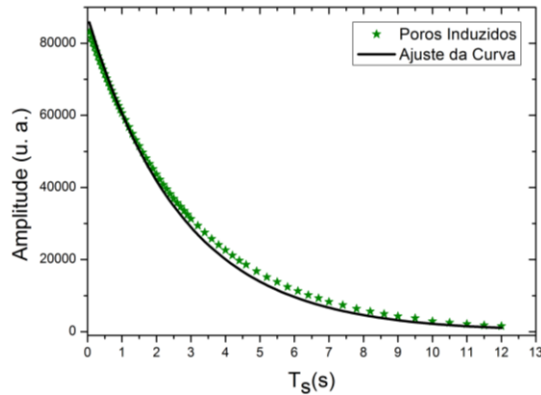
$$\tau_{1D-2medias} = (34 \pm 9) \text{ s}$$

Resultado 1D $T_2 \times T_2$ Exchange - Filtro T_2

2 médias -> 1h :



8 médias -> 4h :



$$ii = (87400 \pm 400) \exp\left[\frac{-t_s}{2,7}\right]$$

$$ij = (2470 \pm 60) \left\{ \exp\left[\frac{-t_s}{2,7}\right] - \exp\left[\frac{-t_s}{0,67}\right] \right\}$$

$$k = (0,031 \pm 0,006) \text{ s}^{-1}$$

$$\tau_{1D-8medias} = (32 \pm 6) \text{ s}$$

Conclusões

- Concordância entre os resultados 1D e 2D
- Redução do tempo de experimento

$$\tau_{2D} = (30 \pm 6) \text{ s} \quad 44 \text{ h}$$

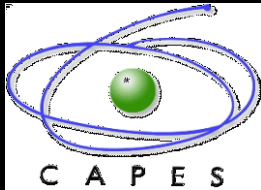
$$\tau_{1D-2medias} = (34 \pm 9) \text{ s} \quad 1 \text{ h}$$

$$\tau_{1D-8medias} = (32 \pm 6) \text{ s} \quad 4 \text{ h}$$

Perspectivas

- Manufatura de cerâmica com três distribuições de tamanho de poros distintas.
- Contaminar a cerâmica com impureza para magnética mudando os tempos relaxação dos poros induzidos e intrínsecos e verificar se mantém a consistências das curvas de troca com a teoria.
- Realizar os experimentos num campo magnético mais baixo como 2 MHz (frequência de 20 MHz já mostrou resultados).
- Implementar a sequência 1D com filtro em T_1 proposta por Dortch et al. (troca no sentido inverso do filtro em T_2) comparando também com o 2D.

Agradecimentos



Obrigado pela atenção!