# Development of the analytical model RAMBI of irradiation beamline

E. Testa[1], M. Pedrosa Rivera[2], M. Alcocer-Ávila[1], A. Bertrand[1], R. Delorme[2] and M. Beuve[1]

[1]Univ. Lyon, Univ. Claude Bernard Lyon 1, CNRS/IN2P3, IP2I Lyon, UMR5822, F-69622, Villeurbanne, France
[2]Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, LPSC-UMR 5821, Grenoble, France

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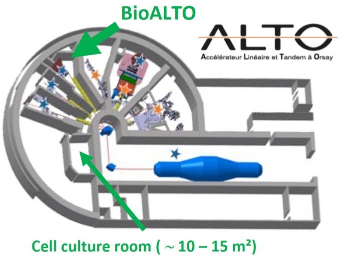
NUCLÉAIRE & PARTICULES

# “BioALTO” Projet: “Hadron biology” Platform @ ALTO

## Objective

- Development of a platform dedicated to radiobiological research for therapies involving ions (hadrontherapy, Targeted Alpha Therapy, Boron Neutron Capture Therapy)
- BioALTO beamline based on Radiograaff device (previously at the IP2I 4 MV accelerator in Lyon)




## Characteristics of ALTO

- 14.5 MV Tandem “Van de Graaff” accelerator
- Wide range of intense (up to µA) ions beams ($^{1}$H $\rightarrow$ $^{79}$Au)
- Continuous beam
- Additional pulsed beam possible (100 ns to 100 µs)

| Part. | Energies [MeV] (MeV/u) | Ion range in water [µm]* |
|---|---|---|
| $^{1}$H | 4 – 25 (4 – 25) | 160 – 6190 |
| $^{4}$He | 15 – 43 (3.8 – 10.8) | 130 – 1290 |
| $^{7}$Li | 50 (7.1) | 480 |
| $^{12}$C | 87.5 (7.29) | 170 |
| $^{16}$O | 128 (8) | 140 |

*(at 5 cm air)

Project funded by the Ile de France Region

# "BioALTO" Projet: Main tasks

## Instrumentation

- Upgrade the Radiograaff device to exploit the wide range of ions
- Development of new beam diagnostics and dosimetry tools
  - In line: Diamond & scintillating fibre counters
  - Exit: Microdosimeters and beam monitoring profiler based on air fluorescence

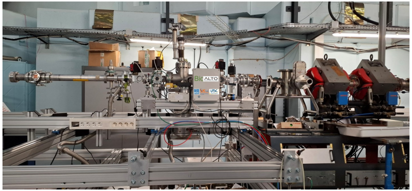


Fig. 1: BioALTO beamline under installation

## Biology

- Equipment of a cell culture room nearby

⇒ Access to external users → platform in 2-3 years

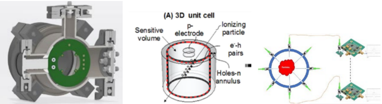



Fig. 2: From left to right: Diamond counter, Si micro-dosimeter, beam profiler based on air fluorescence

## Modeling

- Digital twin (Monte Carlo simulations): reference calculations
- Analytical model: optimization and operation of the beamline

## Specifications

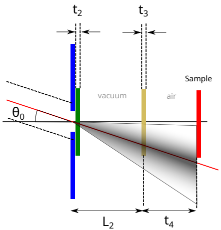
- Diameter of the irradiation field (sample): 15 mm
- Dose homogeneity: $\epsilon_{\Phi_4} = 2\%$
- Dose rate: $\sim$ Gy/min ($\Rightarrow$ Beam intensity of $\sim$0.1 - 1 pA)

## Accelerators for nuclear physics

- Examples: 4 MV @ IP2I, BioALTO
- Uncertainties on beam direction (1° $\rightarrow$ 17 mm at 1 m)
- Nominal beam intensities > 1 nA

## Solution: 2 “collimated diffusors” (CD)

- Single CD: sensitivity to incident beam direction
- 2 CD:
  - Outcoming particles aligned with the beam line
  - Typical factor of beam intensity reduction: $100 - 1000$ for $\theta_0 = 0$



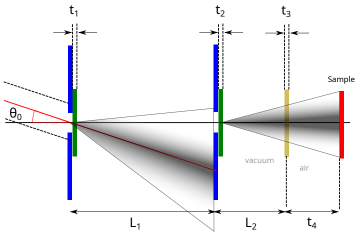
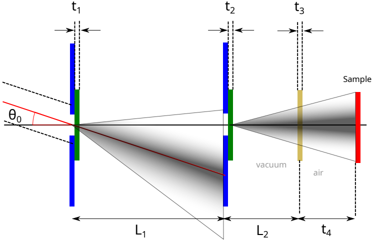




Fig. 3: Top: Single CD design sensitive to incident beam direction uncertainties: bottom: 2 CD design.

# Objectives of the analytical model




## 2 modes

- "Inverse mode": Optimization of the diffusors thicknesses and determination of the required incident beam intensity
- "Direct mode": Prediction of the flux distribution and intensity at beamline exit

| **General input data** |
|---|
| Beam radius $R_0$ |
| Angle $\theta_0$ |
| $L_1, L_2, t_3, t_4$ |
| Collimator radius $R_1, R_2$ |
| Collimator material (gold) |
| Sample radius $R_4$ |

| **Specific data** | **Inverse** | **Direct** |
|---|---|---|
| **Input** | Energy $E_4$<br>Intensity $I_4$ (dose rate)<br>Homogeneity $\epsilon_\Phi = 2\%$ | Energy $E_0$<br>Intensity $I_0$<br>Thicknesses $t_1, t_2$ |
| **Output** | Thicknesses $t_1, t_2$<br>Energy $E_0$<br>Intensity $I_0$ | Energy $E_4$<br>Flux $\Phi_4(r_4)$ $(I_4, \sigma_{r,4})$ |

## Parametrization of $A_\Omega$ and $\sigma_\Omega$

$$\frac{dP}{d\Omega}(E,Z,t) = A_\Omega(E,Z,t)\exp\left(-\frac{1}{2}\frac{r^2}{\sigma_\Omega(E,Z,t)^2}\right)$$

- where, at first order:

$$\sigma_\Omega(E,Z,t) \propto \frac{\sqrt{t}}{E} \quad \text{and} \quad A_\Omega(E,Z,t) \propto \frac{E}{t}$$

## Relationship between angular and spatial distrib.

$$\sigma_r = \sigma_\Omega L \quad \text{and} \quad A_r = \frac{A_\Omega}{L^2}$$

## Simulated geometry (GATE v9.3)

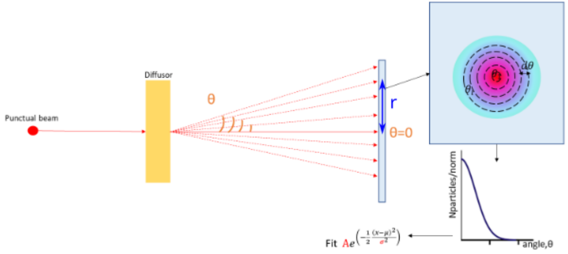



Fig. 4: Simulated geometry for obtaining the parameters of the Gaussian distribution

## Advantage of MC sim. wrt Moliere's theory[1]

- Consistency of the results with the MC simulation used to validate the model

[1] (H. A. Bethe [Mar. 1953]. "Molière's Theory of Multiple Scattering". In: *Physical Review* 89 [6], p. 1256. DOI: 10.1103/PhysRev.89.1256)

# Beam diffusion model: Results and limit of validity

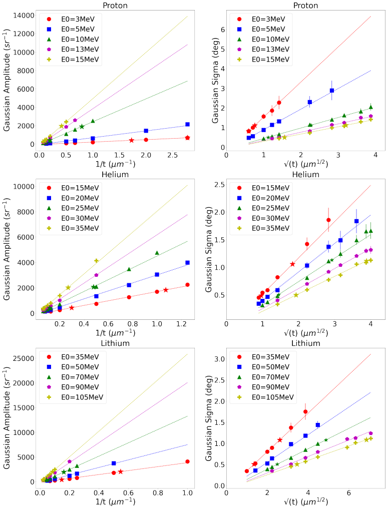



Fig. 5: $A_\Omega$ and $\sigma_\Omega$ values obtained with MC simulations.

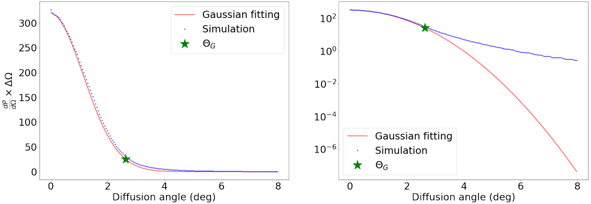



Fig. 6: Illustration of the limit of validity of the Gaussian model (10 MeV) $\alpha$ particles on 2 μm gold foil.

## Conclusions

- $A_\Omega$ and $\sigma_\Omega$ vary according the expected scaling laws (slight deviations taken into account in additional terms in the parametrization)
- Limit of validity: $\theta_G$ where the deviation between simulated and Gaussian distrib. equal to 10%

## Critical angles $\theta_C$

$$\theta_{C,C2} = \theta_0 + \frac{R_2}{L_1} < \theta_G$$

$$\text{et} \quad \theta_{C,C4} = \frac{R_4}{L_2 + t_3 + t_4} < \theta_G$$

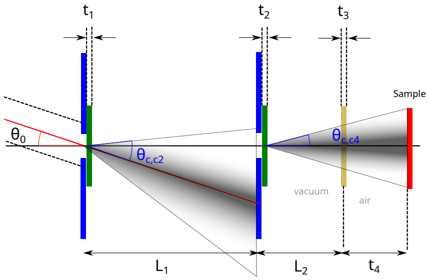



Fig. 7: Definition of the critical angles $\theta_{C,C2}$ and $\theta_{C,C4}$ to properly model the beam transport.

## Constraint on the minimal foil thicknesses ($t_{min}$)

One can show that:

$$\theta_G = C_G \frac{Z}{E}\sqrt{t}$$

$$\Rightarrow t_{min} = \frac{{\theta_C}^2 E^2}{C_G Z^2}$$

where $C_G$ is a proportionality coefficient

# Criteria of validity of the beamline model: Other criteria

## Hole-size criterion

- Extension of collimator's hole (radius $R$) taken into account by means of convolution of the calculated distributions with Gaussians of $\sigma = \sqrt{2R}$

$$\sigma^2_{\Omega,1,conv} = \sigma^2_{\Omega,1} + \left(\frac{R_1}{\sqrt{2}L_1}\right)^2$$

$$\sigma^2_{\Omega,2,conv} = \sigma^2_{\Omega,2} + \left(\frac{R_2}{\sqrt{2}(L_2 + t_3 + t_4)}\right)^2$$

$\Rightarrow \frac{R_1}{\sigma_{r,2}} \ll 1$ and $\frac{R_2}{\sigma_{r,4}} \ll 1$

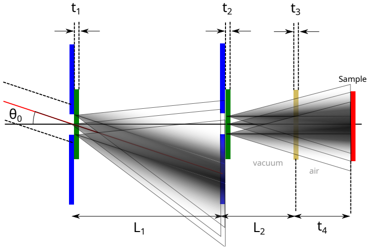



Fig. 8: Illustration of the convolution of the calculated distributions to take intro account the extension of collimator's hole.

## Energy-loss criterion

- Parametrization of diffusion model depends on ions' energy

$\Rightarrow$ Ion's energy loss in the diffusors must be negligible $\Rightarrow$ Limit on the diffusor thickness $t_{max}$

### (Gaussian) flux distribution at sample position

$$\Phi_4(r_4) \propto A_{r,4} \exp\left(-\frac{1}{2}\left(\frac{r_4}{\sigma_{r,4,conv}}\right)^2\right)$$

### Homogeneity criterion ($\epsilon_{\Phi_4}$)

One can show that:

$$\epsilon_{\Phi_4} = \frac{\sigma_{\phi_4}}{\overline{\phi_4}(R_4)} \sim \frac{1}{\sqrt{48}}\left(\frac{R_4}{\sigma_{r,4,conv}}\right)^2$$

- Optimization for a given ion type and energies $E_4$ (sample) and $E_3$ (beam exit):

$$\epsilon_{\Phi_4} = 2\% \rightarrow \sigma_{r,4,conv} \xrightarrow{\text{Gaussian model}} t_2 \rightarrow E_1 \quad \text{(before 2}^{nd}\text{ diffusor)}$$

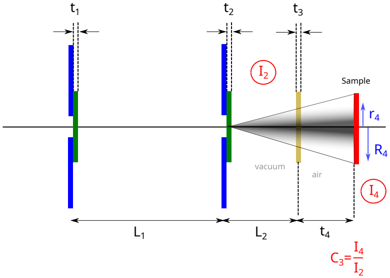



Fig. 9: Illustration of the transmission coefficient $C_3$.

### Transmission coeff. ($C_3$)

$$C_3 = a\left(\frac{R_4}{\sigma_{r,4,conv}}\right) A_{r,4}\pi R_4^2$$

# Modeling and optimization of the $1^{st}$ diffusor

## Transmission coefficients of the collimators

- $C_1 = \frac{S_1(\theta_0)}{S_0} \sim \frac{S_1}{S_0}$
- $C_2 \sim \frac{dP_1}{d\Omega}(\theta_0)\Delta\Omega = A_{\Omega,1,conv} \exp\left(-\frac{1}{2}\left(\frac{\theta_0}{\sigma_{\Omega,1,conv}}\right)^2\right)\frac{S_2}{L_1^2}$

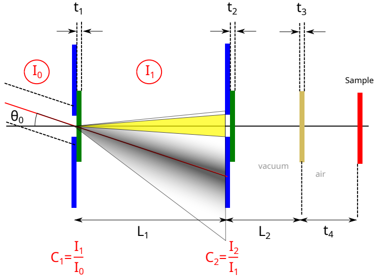



Fig. 10: Illustration of the transmission coeff. $C_1$ and $C_2$.

## Optimization

- Use of the scaling laws of $\sigma_\Omega$ and $A_\Omega$ neglecting the impact of hole's extension

$$\frac{I_2}{I_0} = C_1 C_2 \propto \frac{1}{t_1} \exp\left(-\frac{1}{2}\left(\frac{\theta_0^2}{t_1 \times (g(Z,E))^2}\right)\right)$$

$\Rightarrow$ $I_2$ max for $t_1 = \frac{\theta_0^2}{2(g(Z,E))^2}$

where $g(Z,E)$ is obtained through the Gaussian model of diffusion

# Validation of the model against MC simulations: Transmission coeff. $C_2$ and $C_3$

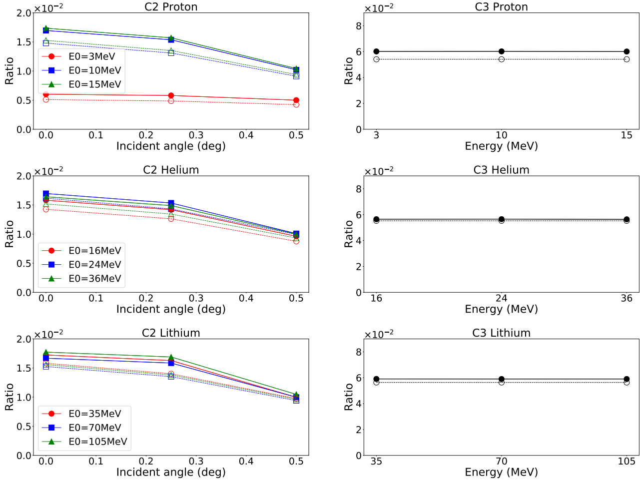



Fig. 11: Transmission coefficients obtained by MC simulations (full symbols) and analytical model (open symbols).

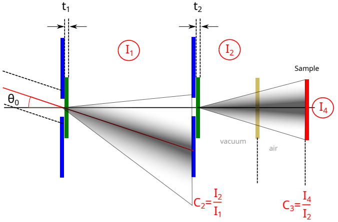



Fig. 12: Transmission coefficients $C_2$ and $C_3$.

- Calculations with optimized ticknesses
- Agreement within $\sim$ 10% between Monte Carlo simulations and the analytical model

# Application of the model: Thicknesses of the diffusors

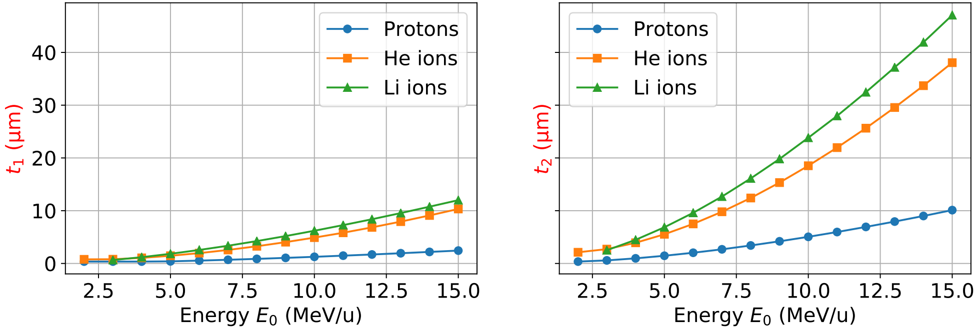



Fig. 13: Diffusor thicknesses $t_1$ and $t_2$ as a function of the incident beam energy $E_0$ with $\theta_0 = 0.5°$.

## Orders of magnitude

- 1st diffusor: a few µm
- 2nd diffusor: a few tens of µm

## Trend as a function of beam energy

- Quadratic behavior consistent with $\sigma_\Omega(E,Z,t) \propto \frac{\sqrt{t}}{E}$

# Application of the model: Beam current at the beamline entrance/exit

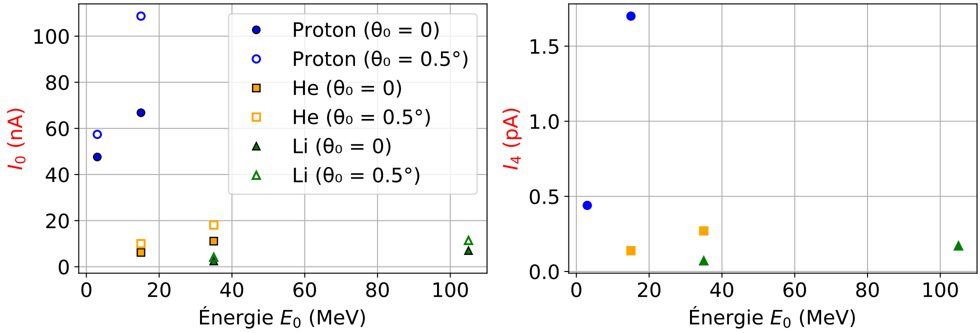



Fig. 14: Initial and final beam intensities required to achieve a dose rate of 2 Gy/min.

## Orders of magnitude for a dose rate of 2 Gy/min

- Exit: a few tenth of pA
- Entrance: from a few nA (He, Li) to tens of nA (protons)

## Impact of the incident beam angle $\theta_0$

- $\sim$ 50% between 0° and 0.5°

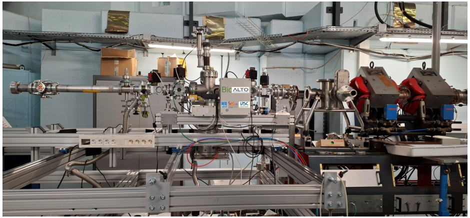
# Conclusion

## Development of the analytical model "RAMBI"

- Modeling of the 2 "collimated-diffusor" BioALTO beamline distribution and intensity at beamline exit
- "Inverse mode": Optimization of the diffusors thicknesses and determination of the required incident beam intensity

## Perspectives

- Application to the BioALTO platform
  - Wide range of ions and energies
  - Radioprotection issues (beam limitations ⇒ re-optimization)
- Potential application to new irradiation beamlines
  - Advantage of the 2 "collimated-diffusor" design: Robust wrt uncertainties in incident beam direction



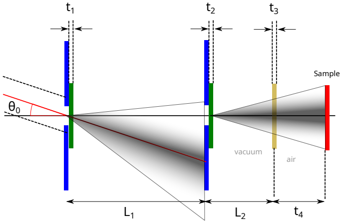



Fig. 15: BioALTO beamline under installation (top) and scheme (bottom).

# Acknowledgments


## Current collaborators of the “BioALTO” project

- IJCLab: Philippe Lanièce, Amélia Maia Leite, Quentin Mouchard, Louis Hardouin
- IP2I: M. Alcocer-Avila, M. Beuve, G. Garde, E. Testa, Y. Zoccarato
- LPSC: R. Delorme

## Fundings


Thank you for your attention

# Criteria of validity of the beamline model: Validity of the beam transport

## Critical angles $\theta_C$

$$\theta_{C,C2} = \theta_0 + \frac{R_2}{L_1} < \theta_G$$

$$\text{et} \quad \theta_{C,C4} = \frac{R_4}{L_2 + t_3 + t_4} < \theta_G$$

## Constraint on the minimal foil thicknesses ($t_{min}$)

$$\theta_G \propto \sqrt{N} = \sqrt{\frac{t}{\lambda}} \propto \sqrt{\sigma t} = C_G \frac{Z}{E}\sqrt{t}$$

$$\Rightarrow t_{min} = \frac{{\theta_C}^2 E^2}{C_G Z^2}$$

where $C_G$ is a proportionality coefficient

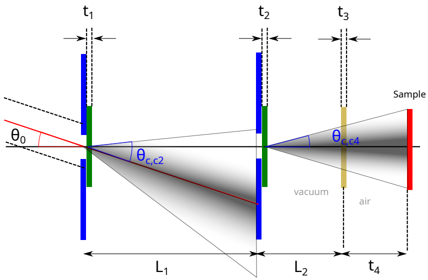



Fig. 16: Definition of the critical angles $\theta_{C,C2}$ and $\theta_{C,C4}$ to properly model the beam transport.

# Modeling and optimization of the 2$^{nd}$ diffusor

## Flux distribution at sample position

$$\Phi_4(r_4) = \left(\frac{I_0\ C_1\ C_2}{Ze}\right) A_{r,4} \exp\left(-\frac{1}{2}\left(\frac{r_4}{\sigma_{r,4,conv}}\right)^2\right)$$

## Homogeneity criterion ($\epsilon_{\Phi_4}$)

One can show that:

$$\epsilon_{\Phi_4} = \frac{\sigma_{\phi_4}}{\overline{\phi_4}(R_4)} = \left(\frac{a\left(\frac{\sqrt{2}R_4}{\sigma_{r,4,conv}}\right)}{\left[a\left(\frac{R_4}{\sigma_{r,4,conv}}\right)\right]^2} - 1\right)^{\frac{1}{2}} \sim \frac{1}{\sqrt{48}}\left(\frac{R_4}{\sigma_{r,4,conv}}\right)^2$$

where $a(X) = \int_0^X x \exp\left(-\frac{1}{2}x^2\right) \mathrm{d}x = \frac{2}{X^2}\left(1 - \exp\left(-\frac{1}{2}X^2\right)\right)$

- Optimization for a given ion type and energies $E_4$ (sample) and $E_3$ (beam exit):

$$\epsilon_{\Phi_4} = 2\% \rightarrow \sigma_{r,4,conv} \xrightarrow{\text{Gaussian model}} t_2 \rightarrow E_1 \quad (\text{before } 2^{nd} \text{ diffusor})$$

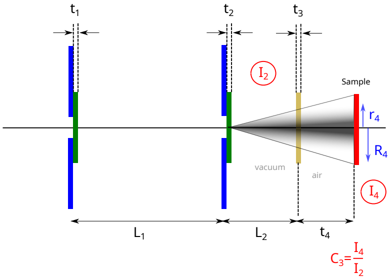



Fig. 17: Illustration of the transmission coefficient $C_3$.

## Transmission coeff. ($C_3$)

$$C_3 = a\left(\frac{R_4}{\sigma_{r,4,conv}}\right) A_{r,4}\pi R_4^2$$