Beam stripping interactions implemented in cyclotrons with OPAL simulation code

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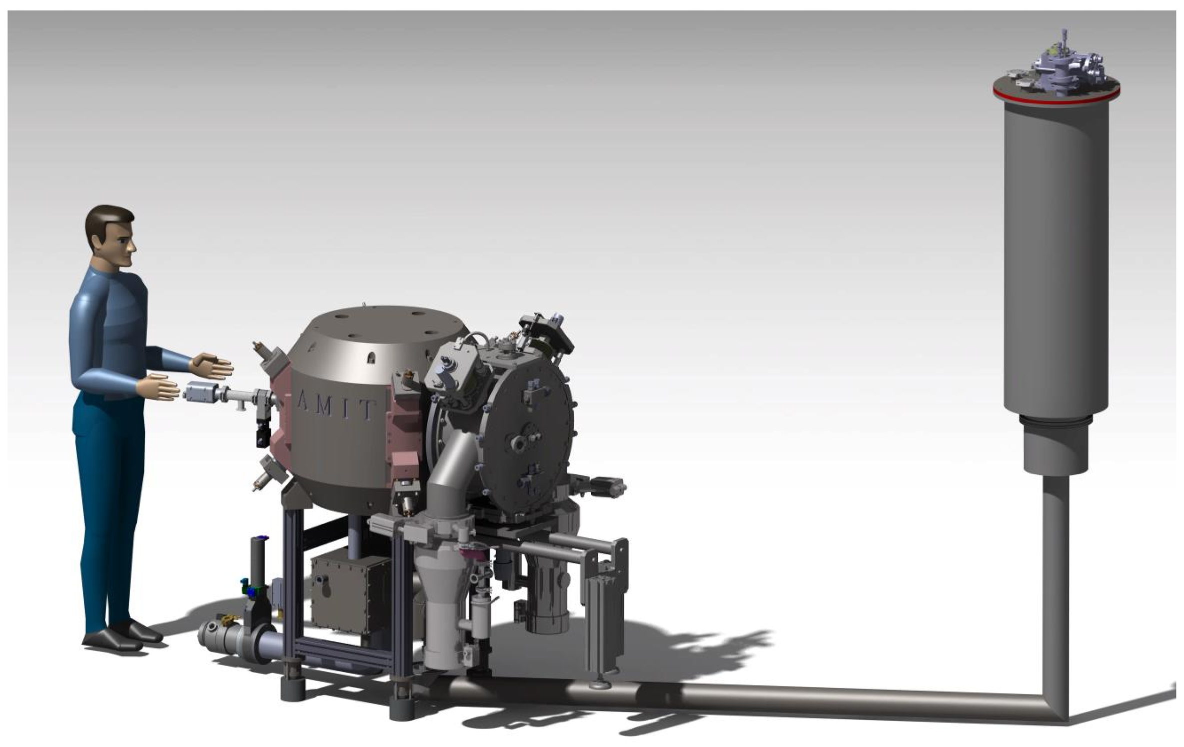
Abstract

Beam transmission optimization and losses characterization, where beam stripping interactions are a key issue, play an important role in the design and operation of compact cyclotrons. A beam stripping model has been implemented in the three-dimensional object-oriented parallel code OPAL-CYCL, a flavour of the OPAL framework. The model includes Monte Carlo methods for interaction with residual gas and dissociation by electromagnetic stripping. The model has been verified with theoretical models and it has been applied to the AMIT cyclotron according to design conditions.

AMIT cyclotron

General	
Cyclotron type	Classical
Energy	> 8.5 MeV
Current	10 μA
RF system	
Configuration	One 180° Dee
Acceleration voltage	60 KV
Ion source	
Type	Internal PIG
Ions	H^-

Magnet	
Type	Low T_c superconductor
Configuration	Warm iron
Superconductor material	NbTi
Central field	4 T
Extraction	
Extraction system	Stripping foil at 110 mm
Position	External
Target	Nitrogen gas $\rightarrow {}^{11}$C ^{18}O enriched water $\rightarrow {}^{18}$F



The high magnetic field required for the compact design of the AMIT cyclotron makes the classical cyclotron choice to be considerably less complicated than the corresponding isochronous solution. A combination of high magnetic field and a high-alternating electric field accelerates the charged particles from the central axis, where they are injected, in an outward spiralling path. The magnetic field decreases along the radius of the orbit providing radial and axial stability of the beam (weak focusing). The oscillation frequency of the gap voltage remains constant while the ion orbital frequency decreases due to the relativistic mass increase with the energy and to the radial decrease of the magnetic field.

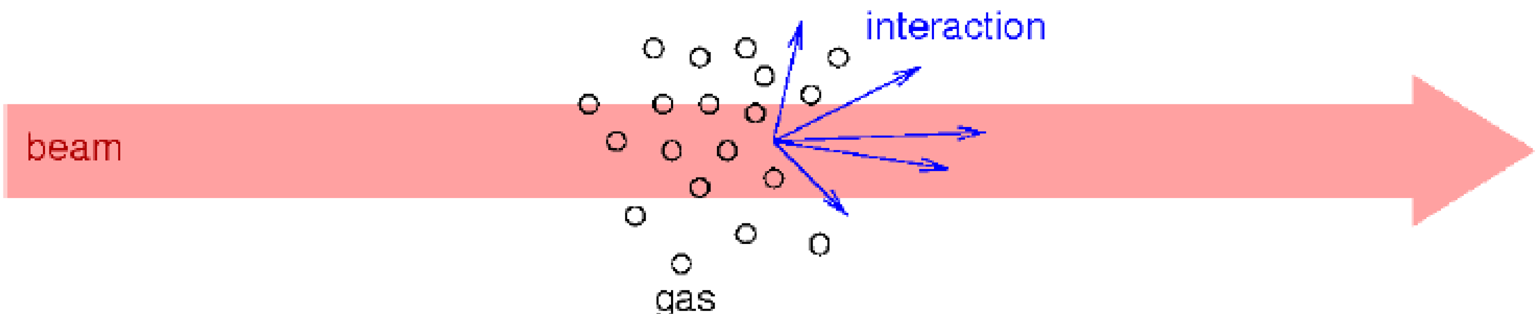
Beam Stripping

Particles incident on a homogeneous medium ⟶ Mean free path, λ ⟶ Statistic cumulative interaction probability

$$P(x) = 1 - e^{-x/\lambda}$$

Electron detachment/Capture interaction processes

Residual gas interaction



$$\frac{1}{\lambda_{total}} = \sum \frac{1}{\lambda_k} = N_{total} \cdot \sigma_{total} = \sum_j N_j \sigma^j_{total} = \sum_j \left(\sum_i N_j \sigma^j_i \right)$$

$$\sigma_{qq'} = \sigma_0 \left[f(E_1) + a_7 \cdot f(E_1/a_8) \right] \qquad qq' \text{ charge state}$$

$$f(E) = \frac{a_1 \cdot \left(\frac{E}{E_R}\right)^{a_2}}{1 + \left(\frac{E}{a_3}\right)^{a_2+a_4} + \left(\frac{E}{a_5}\right)^{a_2+a_6}} \qquad E_R = hcR_\infty \cdot \frac{m_H}{m_e} \qquad E_1 = E_0 - E_{th}$$

Electromagnetic stripping

Electrons and nucleus are bent in opposite directions under a magnetic field

The magnetic field in an accelerator produces an electric field according to Lorentz transformation: $E = \gamma\beta c B$.

$$\lambda = \beta c \gamma \tau$$

$$\tau = \frac{A_1}{E} \cdot \exp\left(\frac{A_2}{E}\right)$$

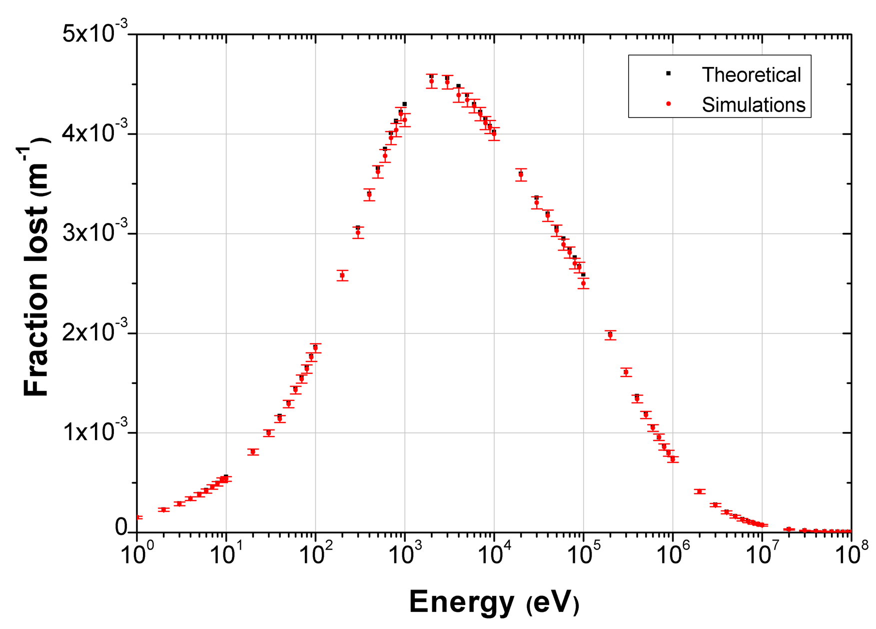
$$A_1 = 3.073\,(10) \cdot 10^{-6} \text{ s V/m} \qquad A_2 = 4.414\,(10) \cdot 10^{9} \text{ V/m}$$

Beam Stripping in OPAL

- Beam stripping implemented for OPAL-CYCL ⟶ New `ParticleMatterInteraction`
- Input parameters: Pressure and temperature (uniform and constant) ⟹ Gas density
- Cross section of the processes in function of energy
- Residual gas considerer as ideal gas
- Residual gas composition ⟶ air
- Beam fraction lost is evaluated individually for each particle in each step through a Monte Carlo method
- Secondary ions produced could be traced

The implementation validated performing simulations of a beam of H^- in a large drift space

- Gas stripping
- Electromagnetic stripping



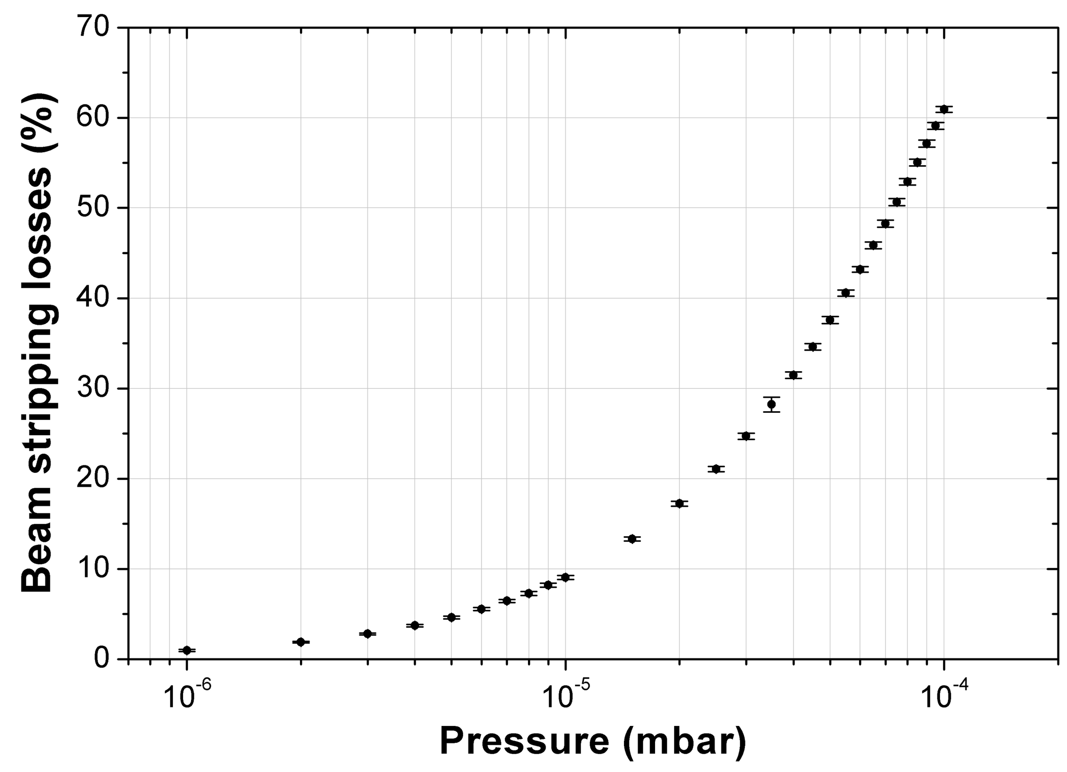
$$B = 2.3 \text{ T} \qquad E = 100 \text{ MeV}$$

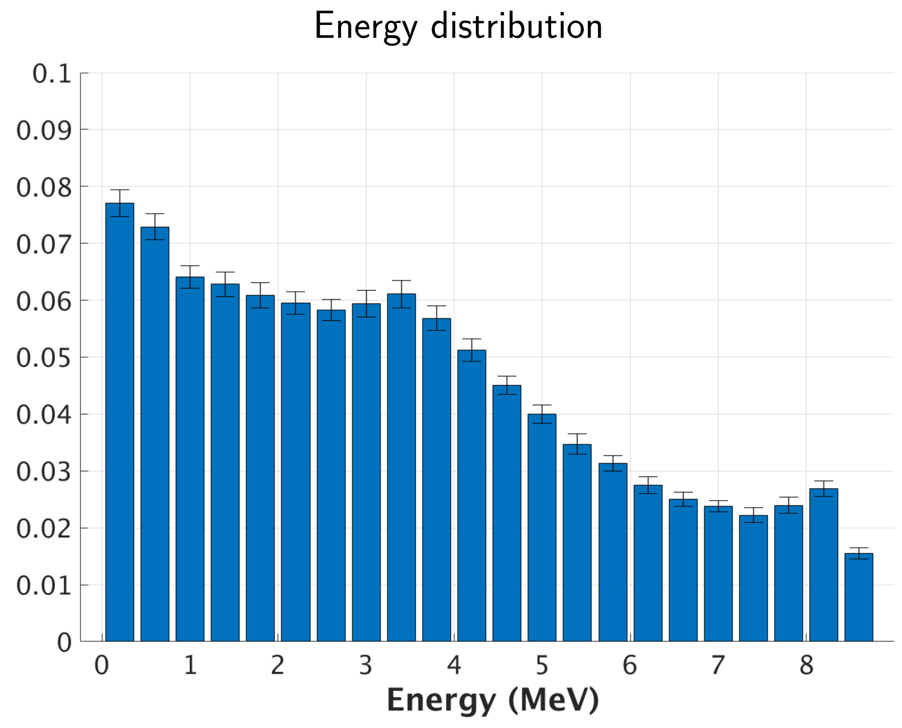
$$\begin{cases} f_L^{Theory} = 0.571 \text{ m}^{-1} \\ f_L^{Sim} = 0.570\,(10) \text{ m}^{-1} \end{cases}$$

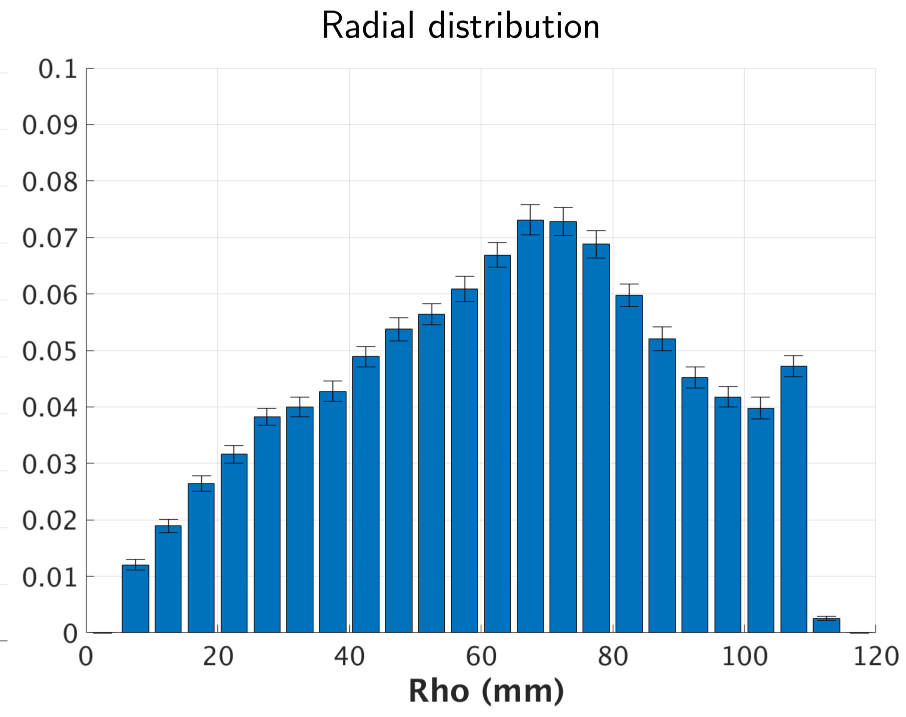
AMIT simulations

The vacuum conditions in compact cyclotrons are of special relevance.

Vacuum level expected in AMIT cyclotron ⟶ $10^{-5} - 10^{-4}$ mbar







Acknowledgements

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