Beam stripping losses in AMIT cyclotron

Pedro Calvo Portela

Particle Accelerators Unit - Department of Technology - CIEMAT

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1 Introduction

2 Gas stripping

3 Lorentz stripping

4 Beam stripping in OPAL
Motivation

- Study the physics processes of loss particle in accelerators
- Develop a model of losses for OPAL code
- Estimate the losses in accelerators with great sensibility to the beam stripping losses → AMIT project
AMIT cyclotron

Development of a compact cyclotron able to produce short half-life isotopes for sintering PET radiotracers, including:

- Capability of producing radiopharmaceuticals on demand
- Extending the production of radioisotopes to hospitals and institutes which are not prepared for hosting conventional facilities
- Disposing a back-up system for producing selected radiotracers at prices that can compete in specific cases with those of standard production centers

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Target</th>
<th>Reaction</th>
<th>$T_{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{F}$</td>
<td>Water enriched in $^{18}\text{O}$</td>
<td>$^{18}\text{O} + ^{1}\text{H} \rightarrow n + ^{18}\text{F}$</td>
<td>109 min</td>
</tr>
<tr>
<td>$^{11}\text{C}$</td>
<td>Nitrogen gas</td>
<td>$^{14}\text{N} + ^{1}\text{H} \rightarrow ^{4}\text{He} + ^{11}\text{C}$</td>
<td>20 min</td>
</tr>
</tbody>
</table>

Cyclotron requirements:
- $^{11}\text{C}$ and $^{18}\text{F}$ on-site production
- Single dose production
- Minimum size and weight
- Minimum radiation levels
- Affordable price

Beam requirements: $E > 8.5\text{MeV}$, $I > 10\mu\text{A}$
Beams losses

Evaluate the beam losses in a particle accelerator has great importance to achieve the final beam requirements

Causes

- Intercepting devices
- Component misalignment
- Beam instabilities
- Beam - residual gas interactions
- Electromagnetic field stripping

Consequences

- Heating
- Thermal shock
- Deterioration
- Oxidation, radiolysis, ozone production
- Equipment activation
- Radiation in public spaces and shielding requirements
Interaction probability

Assume that particles are normally incident on a homogeneous medium and that they are subject to a process with a mean free path $\lambda$ between interactions

$$F(x) = \frac{1}{\lambda} \cdot e^{-x/\lambda}$$

Probability density function for the interaction of a particle after a travelling distance $x$

$$P(x) = \int_{0}^{x} F(t) \, dt = 1 - e^{-x/\lambda}$$

Probability of suffering an interaction in a distance $x$

$\lambda >> x \implies \{ F(x) \approx \frac{1}{\lambda} \quad P(x) \approx \frac{x}{\lambda} \}$
In the case of collision interactions between a beam with particles of a material, the interaction is generally described in terms of the cross section $\sigma$

\[
dF(x) = N \sigma \, dx \quad \longrightarrow \quad F(x) = N \sigma \cdot e^{-xN\sigma}
\]

\[
P(x) = \int_0^x F(\xi) d\xi = 1 - e^{-xN\sigma}
\]

\[
\lambda = \int_0^\infty x F(x) \, dx = \frac{\int x P(x) \, dx}{\int P(x) \, dx} = \frac{1}{N \sigma}
\]

$N \sigma \equiv \mu \quad \longrightarrow \quad$ Attenuation coefficient

$N \sigma \equiv \Sigma \quad \longrightarrow \quad$ Macroscopic cross section
Gas stripping

Mean free path → \( \frac{1}{\lambda} = \sum_k \frac{1}{\lambda_k} = N_{\text{Total}} \sigma_{\text{Total}} = \sum_j N_j \sigma^j_{\text{total}} = \sum_j \left( N_j \sum_i \sigma^j_i \right) \)

Fraction lost → \( f_g = 1 - e^{-x/\lambda} \)

Ideal gas law → Gas density → \( N \)

\[ P = N k_B T \rightarrow N = \frac{P}{k_B T} \]
H\(^-\) beam

First electron tightly bound \(\rightarrow E_b = 13.6\) eV

Second electron slightly bound \(\rightarrow E_b = 0.754\) eV

\[
H^- + X \rightarrow H^0 + e^- + X \quad \sigma_{-10}
\]

\[
H^- + X \rightarrow H^+ + 2e^- + X \quad \sigma_{-11}
\]

\[\Delta H^- + H_2\]

\[\sigma_{-10}\]

\[\sigma_{-11}\]
\[ H^- + N_2 \]

\[ \sigma = 10 \]

\[ H^- + O_2 \]

\[ \sigma = 10 \]

\[ \sigma = 11 \]
H$_2^+$ beam

Molecular structure

Dissociation cross section

- Proton production $\rightarrow \sigma(H_1^+)$

- Neutral hydrogen atoms production $\rightarrow \sigma(H_1^0)$

- Negative hydrogen ions production $\rightarrow \sigma(H_1^-)$
$\Delta \quad H_2^+ + H_2 \rightarrow H_1^+$

$\Delta \quad H_2^+ + N_2 \rightarrow H_1^+$
Analytic cross section function

\[
\sigma_{qq'} = \sigma_0 \left[ f(E_1) + a_7 \cdot f\left(\frac{E_1}{a_8}\right) \right]
\]

\[
f(E) = \frac{a_1 \cdot \left( \frac{E}{E_R} \right)^{a_2}}{1 + \left( \frac{E}{a_3} \right)^{a_2+a_4} + \left( \frac{E}{a_5} \right)^{a_2+a_6}}
\]

\[\sigma(H^-)\]

\[
\sigma_0 = 1 \cdot 10^{-16} \text{ cm}^2
\]

\[E_1 = E_0 - E_{th}\]

\[E_R = \hbar c R_\infty \cdot \frac{m_H}{m_e} = \frac{m_H e^4}{8 \varepsilon_0^2 h^2} \approx 25.00 \text{ keV}\]

\[\sigma(H^+)\]
\[
\ln [\sigma(E)] = \frac{1}{2}a_0 + \sum_{i=1}^{k} a_i \cdot T_i(X)
\]

\[
X = \frac{(\ln E - \ln E_{min}) - (\ln E_{max} - \ln E)}{\ln E_{max} - \ln E_{min}}
\]

\(T_i(x) \equiv \text{Chebyshev polynomials of the first kind}\)

\[
T_0(x) = 1
\]

\[
T_1(x) = x
\]

\[
T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)
\]
Lorentz stripping

Ions + Magnetic field $\rightarrow$ Electrons and nucleus are bent in opposite direction

A laboratory magnetic field produce a rest-frame field $\rightarrow$ $E = \beta c \gamma B$

Mean free path $\rightarrow$ $\frac{1}{\lambda} = \frac{1}{\beta c \gamma \tau}$

Fraction lost $\rightarrow$ $f_L = 1 - e^{-L/\lambda}$

Lifetime $\rightarrow$ $\tau = \frac{4mz_T}{S_0 N^2 \hbar (1 + p)^2 \left(1 - \frac{1}{2k_0 z_t}\right)} \cdot \exp\left(\frac{4k_0 z_T}{3}\right)$

$k_0 = 2m\varepsilon/\hbar^2$

Binding energy $\rightarrow$ $\varepsilon = 0.754$ eV

Spectroscopic coefficient $\rightarrow$ $S_0 = 0.783$

Polarization of ionic wave function factor $\rightarrow$ $p = 0.0126$

Classical outer turning radius $\rightarrow$ $z_T = \varepsilon/eE$

Ionic potential $\rightarrow$ $V(r) = -V_0 \left[e^{-\alpha r}/(1 - e^{-\alpha r})\right]$ $\alpha = 3.81 \cdot 10^{10} \text{ m}^{-1}$

Normalization constant $\rightarrow$ $N = [2k_0 (k_0 + \alpha)(2k_0 + \alpha)]^{1/2}/\alpha$
Parametrization

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

\[ A_1(\varepsilon) = C_1 \frac{\varepsilon}{S_0 N^2} = 3.073 (10) \cdot 10^{-6} \text{ s V/m} \]

\[ A_2(\varepsilon) = C_2 \varepsilon^{3/2} = 4.414 (10) \cdot 10^9 \text{ V/m} \]
Beam stripping in OPAL

- Beam stripping implemented for cyclotrons
- Input parameters: Pressure and temperature ➞ Gas density
- Pressure field map is available
- Cross section of the processes in function of energy
- Input particles ➔ $H^-$, $H^+$, $H_2^+$, $H$
- Residual gas composition ➔ air / $H_2$
- Residual gas considerer as ideal gas
- Beam fraction lost is evaluated individually for each particle in each step through a random number generator
- Secondary ions produced could be traced
Validation of the simulations $\rightarrow$ Gas stripping in a large drift for $H^-$ beam

Lorentz stripping with $B = 2.3$ T at $E = 10$ MeV $\rightarrow$ \[ f_L^{\text{Theory}} = 0.5714 \text{ m}^{-1}, \quad f_L^{\text{Sim}} = 0.5703 (74) \text{ m}^{-1} \]
Residual stripping interactions in AMIT
Future work...

♦ Include AMIT pressure field map
Acknowledgments

- Andreas Adelmann
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- Christian Baumgarten

Thank you very much for your attention!
Extra slides
AMIT cyclotron: Specifications

Cyclotron properties
- Classical cyclotron
- Energy > 8.5 MeV
- Current > 10 µA

RF System
- Configuration: One 180°
- Acceleration voltage > 60 KV

Source
- Type: Internal PIG
- Ions: H⁻

Extraction
- Stripping foil
- Targets

Magnet
- Low Tc superconductor
- Superconductor material: NbTi
- Warm Iron
- Central field = 4 T
- Decreasing field → Focusing

Cryogenics
- Closed-loop LHe circuit
- Single commercial cryocooler
Simulations for AMIT cyclotron have been realized to check the beam stripping

- Distribution $\rightarrow$ Uniform random distribution of 10000 particles

- Pressure $\rightarrow$ $P = 1 \cdot 10^{-6}$ mbar

- $\sim 1.5\%$ of particles stripped by residual gas

- None particle stripped by magnetic field for this magnet at required energy