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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 flavor 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.

INTRODUCTION

Compact cyclotrons are one of the most versatile accelerators involved in radioisotope production employed in PET scans as diagnostic tools in hospitals. Due to short lifetimes of some radioisotopes, it is recommended that the accelerator facility is located inside the hospital, thus the compactness is a relevant factor. Hence, superconducting magnets can be used to increase the magnetic field, minimizing the acceleration region and consequently reducing the overall cyclotron size. An internal ion source must be considered as well. However, technical complications arise in the design and manufacturing processes. Given the worsening of the vacuum due to the internal source, combined with the limited space of acceleration region and the amount of components in the accelerator, the vacuum conditions could be a considerable source of losses, even more in the case of H^- beams. As a consequence, beam current will be reduced, as well as the efficiency and radioisotope production. Additionally it could increase the activation of the machine. Thus, optimization of beam transmission as well as minimization of activation associated with lost particles, is of great importance in compact cyclotrons. Specifically, it is essential to study the effect of some residual physics phenomena, as the interaction of the beam with residual gas and electromagnetic stripping. In this paper a general beam stripping model is presented being integrated into the particle accelerator framework OPAL [1]. It allows a more realistic description of the beam dynamics and a characterization of the losses.

AMIT CYCLOTRON

A compact cyclotron is being developed as part of the AMIT project, aimed at the production of single doses of ^{18}F and ^{11}C radioisotopes. The AMIT cyclotron has been designed to improve the size and cost efficiency limitations through a careful study of the electromagnetic design [2] and the beam dynamics [3]. The machine aims to produce a 10 μA beam of 8.5 MeV protons. It is a Lawrence type cyclotron with weak focusing. It employs two superconducting coils in a Helmholtz arrangement and magnetic iron yoke to provide the 4 T magnetic field and a 180° Dee attached to the RF cavity, with a 60 kV accelerating peak voltage imposed by the non RF-particle isochronism, to accelerate H^- ions produced by a cold cathode Penning Ion Source, and with stripping mechanism for beam extraction. The superconducting magnet [4] of NbTi has a warm iron configuration, where only the coils are kept cold inside a common cryostat. It is cooled down with two-phase helium, circulating in a closed circuit and recondensed externally.

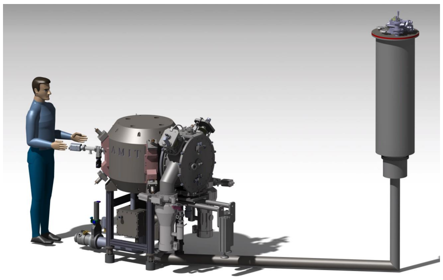

Figure 1: General arrangement of the AMIT cyclotron.

BEAM STRIPPING

H^- ions have become increasingly popular in cyclotrons due to high efficiency extraction process. However, the second electron of this type of hydrogen has a low bounding energy (0.75419 (2) eV [5]). Therefore, the electron has a high probability of being stripped by interaction with residual gas or with electromagnetic field, increasing beam losses. Other types of ions, or even neutral particles, are also affected, although with less probability. The processes are classified according to the charge state of the particle, $\sigma_{qq'}$, where q represents the charge state before and q' after the process. The processes to be considered in case of H^- are single- or double-electron-detachment (σ_{-10} or σ_{-11}). Regarding protons, the process available is electron capture.

Assuming that particles are normally incident on a homogeneous medium and that they are subjected to a process with a mean free path λ between interactions, the probability density function for the interaction of a particle after travelling a distance x is [6]:

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

where $F(x)dx$ is the probability of having an interaction between x and $x+dx$. Hence, the probability of an interaction

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before reaching a path length x can be deduced:

$$P(x) = \int_0^x F(x)dx = 1 - e^{-x/\lambda} \qquad (2)$$

where $P(x)$ is the statistic cumulative probability of the interaction process. In case of interaction between a beam with particles of a material, the process is generally described under some considerations in terms of the cross section, σ, and the number of interaction particles per unit volume, N: $\lambda = 1/N\sigma$.

Residual Gas Interaction

The fraction loss of the beam travelling a unit length is, according to Eq. (2):

$$f_g = 1 - e^{-x/\lambda_{total}} \qquad (3)$$

where λ_{total} is the summation over all gas components and over all physical processes for each component, supposing a beam flux incident in an ideal gas.

The cross section data have been measured experimentally for the most important gases [7–11]. However, analytic expressions fitted to cross section data have been semiempirically developed for collisions of hydrogen atoms and ions with some gaseous atoms and molecules [12]:

$$\sigma_{qq'} = \sigma_0 \left[f(E_1) + a_7 \cdot f(E_1/a_8) \right] \qquad (4)$$

where σ_0 is a convenient cross section unit ($\sigma_0 = 1 \cdot 10^{-16}$ cm^2); and $f(E)$ and E_1 are given by:

$$f(E) = \frac{a_1 \cdot \left(\frac{E}{E_R}\right)^{a_2}}{1 + \left(\frac{E}{a_3}\right)^{a_2+a_4} + \left(\frac{E}{a_5}\right)^{a_2+a_6}} \qquad (5)$$

$$E_R = hcR_\infty \cdot \frac{m_H}{m_e} = \frac{m_H e^4}{8\varepsilon_0^2 h^2} \qquad (6)$$

$$E_1 = E_0 - E_{th} \qquad (7)$$

where E_0 is the incident projectile energy in keV, E_{th} is the threshold energy of reaction in keV, and a_i $(i = 1, \ldots, 8)$ denote adjustable parameters. Experimental data and analytical function results for σ_{-10} on H_2 are shown in Fig. 2.

Electromagnetic Stripping

When a particle is in a magnetic field, electrons and nucleus are bent in opposite directions according to their electric charge. If magnetic field is strong enough, the slightly bounded electron can be stripped. Electromagnetic stripping for ions in an accelerator are able to be analysed as the decay of an atomic system in a weak and static electric field, as the magnetic field produces an electric field according to Lorentz transformation, $E = \gamma\beta cB$.

The fraction of particles dissociated by electromagnetic fields after a travelled distance x during a time t is a function of energy and magnetic field B, according to Eq. (2):

$$f_{em} = 1 - e^{-x/\beta c\gamma\tau} = 1 - e^{-t/\gamma\tau} \qquad (8)$$

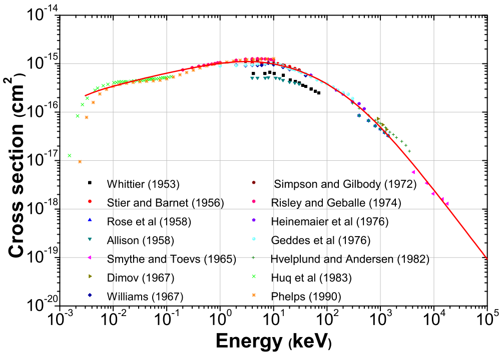

Figure 2: Single electron detachment cross sections experimental data for H^- on H_2 with analytic fit.

where τ is the particle lifetime in the rest frame.

Theoretic studies [13] have determined the lifetime τ of an H^- ion in an electric field E. Nevertheless, it is more common to parametrize the decay time taking into account approximations according to experimental approach [14]:

$$\tau = \frac{A_1}{E} \cdot \exp\left(\frac{A_2}{E}\right) \qquad (9)$$

where A_1 and A_2 are functions of binding energy experimentally determined [15]: $A_1 = 3.073\,(10) \cdot 10^{-6}$ s V/m and $A_2 = 4.414\,(10) \cdot 10^{9}$ V/m.

RESULTS AND DISCUSSION

One of the unique features of OPAL is to perform not only the particle tracking through an accelerator or beam line, but also a Monte Carlo simulation of the beam interaction with matter. Hence, beam stripping has recently been incorporated in OPAL-CYCL to improve physical interaction models. The variables that determine vacuum conditions have been included through assignment of pressure and temperature, considered constant in the first approximation. The magnetic field map, already incorporate in OPAL-CYCL, is taken into account. Thus, beam fraction lost is evaluated individually for each particle in each step of the tracking through a Monte Carlo method according to the description presented in previous section. The implementation for beam stripping is focused on atomic hydrogen ion interaction although the model can be easily extended to other ions as H_2^+. The cross section values are derived from Eq. (4) and evaluated as function of particle energy. Furthermore the code development for beam stripping allows to trace optionally secondary particles produced during the interaction.

The implementation of the residual gas interaction has been validated evaluating beam losses in simulations of H^- particles in air at different energies in a drift space at $P = 1.0 \cdot 10^{-6}$ mbar, compared in Fig. 3 with theoretical fraction lost. In a similar way, the electromagnetic stripping has also been tested for a beam at 100 MeV in a 2.3 T magnetic field, getting a fraction lost of 0.570 (10) m^{-1}, which is in a good agreement with the theoretical results (0.571 m^{-1}).

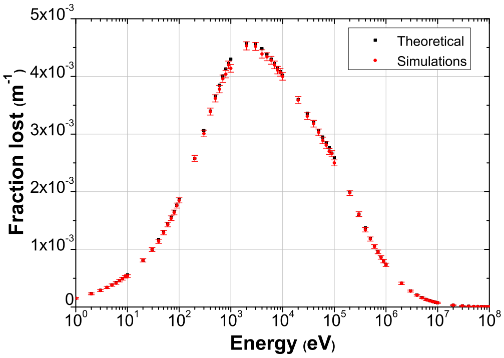

Figure 3: Fraction lost by residual gas interaction of a H^{-} beam as function of energy.

Once the code validation was achieved, simulations applied to the AMIT cyclotron have been carried out to evaluate losses due to beam stripping. The vacuum conditions are of special relevance, since being a compact cyclotron, ultra high vacuum cannot be achieved. An internal study concludes that a vacuum level between 10^{-5} and 10^{-4} mbar could be achieved. However, the level depends on the nominal flow in the ion source. Thus, firstly, some characterization measurements of the AMIT internal ion source have been performed in a versatile test bench designed for the optimization of ion sources [16]. The flow rate has been optimized considering the discharge characteristics of the source and reached beam current. Beam stripping analysis allows us to obtain the relationship between vacuum level and beam losses (Fig. 4), as well as characterize the energy profile of the losses (Fig. 5), which would increase the activation of the facility, and could cause hot spots in some components.

CONCLUSION

A new feature of physics interaction model in the beam dynamics code OPAL for beam stripping reactions was presented. The model uses analytic expressions to evaluate individually the cross section of different reactions as function of energy of the particles and theoretical studies about lifetime of hydrogen ions in electromagnetic fields. The model implementation shows excellent agreement with the analytical model. Moreover, this new implementation is an essential tool that allows us to optimize the design of the AMIT cyclotron to characterize beam transmission and minimize losses.

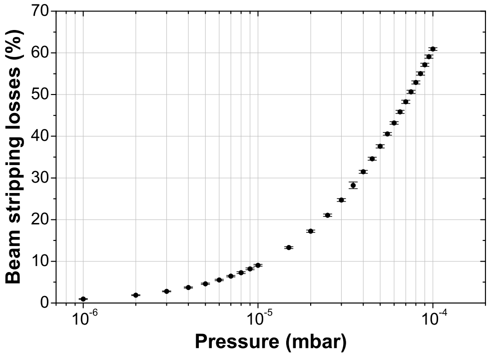

Figure 4: Beam stripping losses as a function pressure for optimum AMIT operational conditions.

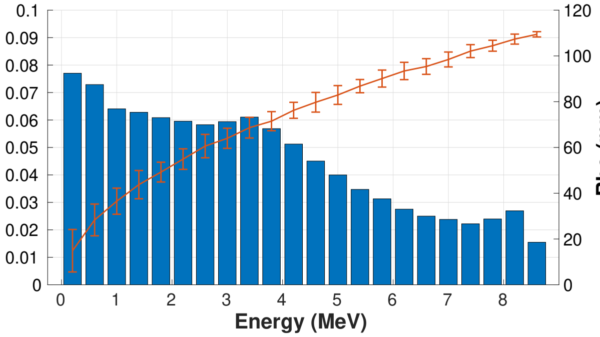

Figure 5: Beam stripping losses characterization at $P = 1.0 \cdot 10^{-5}$ mbar. Energy distribution normalised (left side) and confidence interval of radial position (right side) of corresponding particles to each bar of the histogram.

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