REVIEW OF REST GAS INTERACTION AT VERY LOW ENERGIES APPLIED TO THE EXTRA LOW ENERGY ANTIPROTON RING ELENA

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Abstract

The Extremely Low ENergy Antiproton ring (ELENA) is a small synchrotron equipped with an electron cooler, which shall be constructed at CERN to decelerate antiprotons to energies as low as 100 keV. Scattering of beam particles on rest gas molecules may have a detrimental effect at such low energies and leads to stringent vacuum requirements. Within this contribution scattering of the stored beam on rest gas molecules is discussed for very low beam energies. It is important to carefully distinguish between antiprotons scattered out of the acceptance and lost, and those remaining inside the aperture to avoid overestimation of emittance blow-up. Furthermore, many antiprotons do not interact at all during the time they are stored in ELENA and hence this is not a multiple scattering process.

INTRODUCTION

ELENA is a small synchrotron constructed at present at CERN [1-6] with a particularly low energy range aiming at decelerating antiprotons down to 100 keV. H^- ions and protons will be injected as well at 100 keV from an external source for efficient commissioning. Rest gas effects are very significant at such low energies and motivate the nominal pressure as low as $3\,10^{-12}$ Torr, which can be reached only by a fully bakeable vacuum system and NEG coated chambers wherever possible. This design pressure at room temperature corresponds to a molecule density of $n = 9.6 \cdot 10^{10}\,\mathrm{m}^{-3}$.

This report reviews rest gas effects such as nuclear interactions and scattering on rest gas molecules leading to beam loss and emittance blow-up similar to a study [7] done for the Antiproton Decelerator, but with particular attention to the low energy and pressure found at ELENA. Accumulation of ions in the potential of the antiproton beam leading as well to scattering and other adverse effects will be briefly mentioned. Throughout this paper, the pessimistic assumption that the rest gas consists only of N_2 molecules is made. In reality, a significant fraction of the rest gas molecules will be H_2 affecting the circulating beam less with some contribution from heavier molecules leading to larger loss and blow-up rates. Effects will be estimated for the two plateaus, where electron cooling is applied: first at a momentum of 35 MeV/c corresponding to a relativistic $\beta = 0.037$ and then at the final energy 100 keV or $\beta = 0.0146$

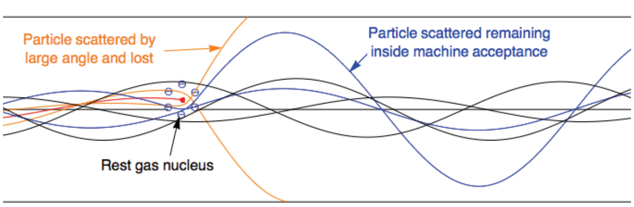

Figure. 1: Trajectories of particles interacting with a rest gas molecule. Particles may come very close to the nucleus and undergo nuclear interactions (red), be scattered out of the acceptance of the accelerator (orange) or be deflected and stay within the acceptance (blue).

INTERACTION WITH REST GAS MOLECULES

Nuclear Interaction

Some beam particles, described by red trajectories in Fig. 1 will undergo nuclear interactions leading to beam loss. However, the relevant cross sections are sufficiently small to neglect the loss rates caused. This can be concluded without detailed computations of cross sections and loss rates as many experiments decelerate the beam from the AD using degrader foils. The number of encounters with nuclei during this deceleration process over a bit more than the ELENA energy range is orders of magnitudes larger than during a typical machine cycle and still leads to few nuclear interactions.

Total Cross Section

A particle not entering the electron shell of a neutral molecule is not scattered and, thus, does not interact at all. With the approximate formula Scatter for the atom radius, the total cross section for a Nitrogen atom becomes $\sigma_{tot} = r_a^2 \pi = 0.79 \cdot 10^{-21} Z^{2/3} \mathrm{m}^2 = 2.9 \cdot 10^{-20} \mathrm{m}^2$, where $Z = 7$ is the atomic number. The interaction rates at the two plateaus with cooling become $2 n \beta c \sigma_{tot}$ with c the velocity of light; the factor two is added to take into account the fact that the molecule consists out of two atoms. This yields interaction rates of $0.062\,\mathrm{s}^{-1}$ and $0.024\,\mathrm{s}^{-1}$ for the two plateaus with cooling expected to last about 10 s. This means that typically a circulating particle experiences about one interaction with a rest gas molecule on the intermediate plateau and significantly less than one interaction along the low energy plateau. Furthermore, scattering on rest gas molecules is not a multiple scattering phenomenon, but rather a single scattering one for the case considered.

Scattering of a Beam Particle

When a beam particle enters the electron shell of a rest gas atom, it is deflected by the electric field inside. For close encounters between a beam particle and a nucleus of a rest gas molecule, the large deflection angle is given by

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the Rutherford scattering angle. However, in a sufficiently good approximation, this scattering angle is given by:

$$\phi = \frac{zZe^2}{4\pi\varepsilon_0}\frac{2}{mv_i^2 b} \,. \qquad (1)$$

where $z = \pm 1$ the charge state of the beam particle, m and v_i its mass and velocity, b the impact parameter as indicated in Fig. 2 and ε_0 the electric permittivity of free space.

Scattering by large angles, such that the beam particle ends up outside the machine acceptance, leads to beam loss. Assuming a small initial betatron oscillation amplitude, i.e. that the beam has an emittance small compared to the acceptance of the machine, this leads to the condition that a particle is lost for a deflection of more than $\phi_{loss} = \sqrt{A/\beta_T}$, with β_T the Twiss betatron function and A the acceptance of the machine defined as the square of the maximum betatron amplitude divided by β_T. Using equ. 1, this leads to a maximum impact parameter b leading to beam loss of:

$$b_{loss} = \frac{zZe^2}{4\pi\varepsilon_0}\frac{2}{mv_i^2}\sqrt{\frac{\beta_T}{A}}$$

and a cross section of:

$$\sigma_{loss} = b_{loss}^2\pi = 4\pi\left(\frac{zZe^2}{4\pi\varepsilon_0}\frac{1}{mv_i^2}\right)^2\frac{\beta_T}{A} \,.$$

Note that this cross section for beam loss due to scattering is large in our case due to the low energy. However, life-times (for values see further below) long compared to the machine cycle expected to last about 30 s are obtained due to the low pressure and velocity, and, thus, are not a serious performance limitation.

Smaller scattering angles corresponding to impact parameters in the range $b_{loss} < b < r_a$ lead to blow-up of the rms emittance ε_{rms} defined as the square of the rms betatron beam size divided by the Twiss betatron function (i.e. without factor π). The change of the rms emittance due to rms scattering is:

$$\Delta\varepsilon_{rms} = \frac{\beta_T}{2}\left\langle(\Delta z')^2\right\rangle = \frac{\beta_T}{4}\left\langle\phi^2\right\rangle$$

where $\left\langle(\Delta z')^2\right\rangle$ denotes the expectations for the square of the change of the slope of the trajectory (and z is either the horizontal x or vertical y position). The factor four comes from two contributions: first the total scattering angle ϕ contributes to a changes of the slope of the trajectory in both transverse planes giving a factor two; a second factor two comes from the derivation (see e.g. appendix D in [8] and [9]) of blow-up caused by scattering. The probability that a beam particle

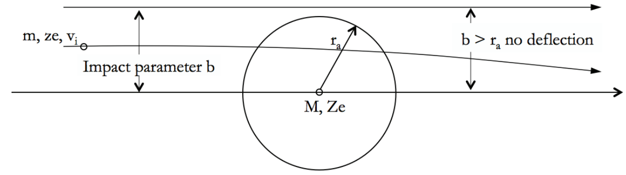

Figure2: Scattering of a beam particle on a rest gas nucleus

encounters a rest gas molecule with an impact parameter between b and $b+\Delta b$ within a time interval Δt is $n\,2\pi\,b\,\Delta b\,\beta c\Delta t$. This gives a contribution of $n\,2\pi\,b\,\Delta b\,\beta c\Delta t\,(\phi^2(b)\,\beta_T/4)$ to the rms emittance blow-up. Integration over all relevant impact parameter b results in:

$$\frac{\Delta\varepsilon_{rms}}{\Delta t} = \frac{2n\beta c\beta_T}{4}\int_{b_{loss}}^{r_a} db\,2\pi\,b\left(\frac{zZe^2}{4\pi\varepsilon_0}\frac{2}{mv_i b}\right)^2$$

with the first factor two again to take into account that an N_2 is consists of two atoms. After evaluation of the integral, this leads to a growth rate for the physical rms emittance of:

$$\frac{d\varepsilon_{rms}}{dt} = 2n\beta c\sigma_{bu} \text{ with } \sigma_{bu} = 2\pi\beta_T\left(\frac{zZe^2}{4\pi\varepsilon_0}\frac{1}{mv_i}\right)^2\ln\left(\frac{r_a}{b_{loss}}\right)$$

The logarithmic term in the last equation, often named Coulomb logarithm, deserves particular attention. For the very low energies in ELENA, the minimum impact parameter relevant for emittance blow-up b_{loss} is large compared to typical cases at higher energy leading to a small value of this Coulomb logarithm. Thus, standard formulas as found e.g. in [8, 9], that are valid in higher energy machines, overestimate blow-up due to scattering on rest gas molecules at very low energies.

The physical reason to obtain smaller transverse emittance blow-up rates with equations derived here is that particles lost due to scattering by a large angle are not included in the computation of the blow-up rate. Due to this reason, the blow-up rates depend on the acceptance of the ring. Furthermore, for ELENA, the process is not multiple scattering, but a single scattering effect. Thus, many small scattering events do not add up to an overall effect close to a Gaussian. Only few particles experience deflections, which may lead to creation of significant tails.

Assuming the nominal ELENA acceptance A = 75 μm and an average betatron function of β_T = 3m one obtains:

- At the 35 MeV/c momentum intermediate plateau:
  - A beam loss cross section of $\sigma_{loss} = 3\ 10^{-23}$ m^2 resulting in a loss rate of $2n\ \beta c\ \sigma_{loss}$ = 1/15530 s (factor two as one N_2 molecule consists of two atoms)
  - A blow-up coefficient of $\sigma_{bu} = 2.6\ 10^{-21}$ m^{2}μm resulting in a blow-up rate of $2n\ \beta c\ \sigma_{bu}$ = 0.006 μm/s. The standard formulas would have resulted in a blow-up rate of about 0.014 μm/s.
- At the 100 keV final kinetic energy:

- A beam loss cross section of $\sigma_{loss} = 1.3\ 10^{-21}\ m^2$ resulting in a loss rate of $2n\ \beta c\ \sigma_{loss} = 1/930$ s
- A blow-up coefficient $\sigma_{bu} = 5\ 10^{-20}\ m^2 \mu m$ resulting in a blow-up rate of $2n\ \beta c\ \sigma_{bu} = 0.04\ \mu m/s$. The standard formulas would have resulted in a blow-up rate of about 0.24 μm/s.

These results on beam-life-time are very similar to the ones found in numerical study [10]. The time constants for beam losses at nominal pressure are long compared to the cycle duration and, thus, losses due to scattering acceptable. Transverse emittance blow-up rates found are smaller than the ones due to intra beam scattering and, thus, not the main performance limitation.

Charge Changing Processes of H⁻ Ions and Protons

H^- ions and protons will be used mainly at the lowest kinetic energy 100 keV and injected from a dedicated external source. Losses and transverse blow-up due to scattering are described by the same formulas derived here for antiprotons. However, H^- ions and protons can undergo charge exchange processes leading to loss. Cross sections for these processes have been compiled in [11].

Stripping of H^- ions: The cross sections for stripping, i.e. removing one electron from an H^- ions due to interactions with a N_2 molecule at the intermediate and the 100 keV electron cooling plateaus in ELENA are $0.4\ 10^{-19}\ m^2$ and $1\ 10^{19}\ m^2$. Double ionization cross sections for the detachment of both electrons are almost an order of magnitude lower and neglected. Resulting beam loss rates are 1/23 s and 1/24 s. Again, these values should be considered pessimistic estimates, as the relevant cross sections are significantly lower for H_2 molecules and only slightly larger for heavier molecules typically present in accelerators. These life-times are sufficient to study optics properties of the ring at different energies (requires acceleration) and to commission the transfer lines to the experiments with H^- ions.

Recombination of a proton with an electron from a rest gas molecule: The cross section for capture of an electron from a rest gas molecule by a proton due to interaction with an N_2 molecule is about $0.2\ 10^{-19}\ m^2$ at 100 keV and $2\ 10^{-23}\ m^2$ at the intermediate 35 MeV/c plateau. Resulting loss rates are 1/119 s at 100 keV and 1/13 h at the intermediate plateau. Thus, proton losses due to capture of an electron are larger than the ones resulting from large angle scattering on a rest gas molecule. Still, these pessimistic estimates yield life-times largely sufficient for all investigations foreseen and, in particular, to commission the electron cooler with protons.

CONCLUSIONS AND OUTLOOK

Rest gas effects for very low beam energies and, in particular, scattering effects that may cause beam loss and emittance blow-up have been reviewed. The main conclusions are that scattering on rest gas molecules at low energy in ELENA is not a multiple scattering, but rather a single scattering phenomenon. Care has to be taken for computations of the emittance blow-up; estimates reported here have been made assuming typical average betatron functions. To refine beam loss and blow-up rates, we plan to extend the formalism to a more realistic case taking the variations of betatron functions around a realistic lattice into account.

First investigations on the generation and accumulation of rest gas ions in the potential of the circulating antiproton beam and blow-up due to these trapped ions have been made. The preliminary conclusion is that accumulation rates are too low for full neutralization of the potential of the antiproton beam and beam losses and transverse emittance blow-up due to interactions with trapped ions are small compared to the ones due to interactions with the rest gas. Again, the low beam energy and intensity have to be taken into account with care: due to the low energy, most ions that are created have a too high energy to be trapped in the potential of the beam and it is currently unclear whether trapped ions can survive when the beam is bunched.

In general, rest gas effects were found having a tolerable impact on ELENA performance with the nominal $3\ 10^{-12}$ Torr pressure.

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