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A PLASMA BASED, CHARGE STATE STRIPPER FOR HEAVY ION ACCELERATORS

G. Rodrigues*,[1], Surender Kumar Sharma[2], Rishi Verma[2], Rahul Singh[4], Ramesh Narayanan[3], Marcus Iberler[5], R. Mehta[1], J. Jacoby[5], Wolfgang Quint[4], Archana Sharma[6]
[1]Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi, India
[2]Bhabha Atomic Research Centre, Visakhapatnam, Andhra Pradesh, India
[3]Indian Institute of Technology, New Delhi, India
[4]GSI Helmholtzzentrum fur Schwerionenforschung GmbH, Darmstadt, Germany
[5]Institute for Applied Physics, Frankfurt, Germany
[6]International Institute of Information Technology, Naya Raipur – Chhattisgarh, India

Abstract

The ionization of ions to a higher charge state is of central importance for the development of new accelerator facilities like FAIR (Facility for Antiproton and Ion Research) at GSI, Darmstadt,and the resulting cost savings. That is why the comparative analysis of the charge state stripping alternatives is a relevant topic. Currently, mainly gas and foil strippers are used for increasing the charge state even after using a high performance ECR ion source in a typical Accelerator chain. Even when the foil or/and gas efficiency or lifetime has proved to be less than optimal, as these alternatives either require great effort or are practically not suitable for smooth operation in the long term.

INTRODUCTION

Free electrons in highly ionized plasmas can be effectively used for improving the charge state of heavy ions as the rates of radiative recombination of free electrons are much smaller than those of electron capture on bound electrons, which leads to a substantial increase of the effective charge in a plasma compared to a cold-gas target of the same element. Therefore, the use of highly ionized plasmas for charge state enhancement are more effective than in the case of using gas and foil stripper mediums and are advantageous when compared to the limited lifetime of foils and lower mean charge state distributions in gaseous media. In order to realize such a plasma device, various types of pinch plasmas have been explored to look into the possibility of heavy ion stripping with an enhanced mean charge state distribution. Theta and Z pinch plasmas are possible options which have been explored and experimentally studied at IAP, Frankfurt, Germany [1]. Typical electron line densities required to be achieved are in the range of 10^{16} to 10^{19} cm^{-3} and electron temperatures of the order of few tens of eV are found to be favourable as per modelling with the FLYCHK code [2], but also challenging. Such a plasma device, the challenges to be overcome, together with their design details will be presented.

A collaboration [3] between BARC, Vishakhapatnam and IUAC, New Delhi has been initiated to further modify plasma pinch devices and optimise them for the accelerator conditions, in particular for the High Current Injector [4] programme at IUAC, New Delhi, and to plan for the beam tests as "proof of principle".

With regard to the development of new accelerator technologies for high-intensity ion beams and efficient acceleration, the transfer of beam ions into higher-charged states is a necessary prerequisite for numerous experiments. The acceleration of heavy ions is being pursued with increasing efforts and especially during the last, few ten years, acceleration techniques have been studied in detail. In reaching the goal to produce intense beams of ions as heavy as uranium and energetic enough to overcome the Coulomb barrier even for the heaviest targets, many new problems must be solved which were not important for the design of conventional light particle accelerators. One of these problems concerns the ionic charge of heavy ions which is an influential new parameter. In this paper, the variation of ionic charge due to collisions with matter ("stripping") will be discussed, as well as some associated phenomena of practical interest.

The effects of charge stripping on heavy ion acceleration are twofold, On the one hand, the passage of heavy ions through specially designed strippers can be exploited to produce a substantial increase of the ion charge which reduces the effective potential required for further acceleration, In order to find the most suitable stripper and to utilize the highest possible charge states, it is necessary to investigate the effects of strippers on heavy ion beams in great detail. On the other hand, random stripping in the residual gas of an accelerator may lead to beam losses. In order to calculate the vacuum which guarantees a satisfactory particle transmission, it is necessary to know charge changing cross sections. These cross sections are very complex quantities and they can hardly be estimated without extensive knowledge about fundamentals of charge changing processes.

BACKGROUND INFORMATION

Plasma has been discussed as a possible medium for ion strippers since the 1960s. In his paper from 1991, T. Peter calculated the achievable equilibrium charge states in cold gas and plasma for iodine ions [5,6]. The equilibrium charge states for uranium ions were calculated by V. Shevlko in 2012

* gerosro@gmail.com

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for the parameters and requirements of the plasma stripper of the AG Plasmaphysik. They confirm an advantage of a plasma stripper over a gas stripper. In the 1990s, experiments with a Z-pinch were carried out by D. H. H. Hoffman, J. Jacoby et al. [7] at GSI, Germany. Despite the results, the Z-pinch is not suitable for use in beam operation due to its instabilities. For this reason, the plasma physics group of the IAP at Goethe University has been working for several years on an inductively coupled theta pinch as a more stable, homogeneous solution for use as a plasma stripper. The plasma stripper built and investigated in recent years was already developed with a view to the beam intensities required at FAIR. With discharge energies of 50 kJ, electron densities of over 10^{17} cm^{-3} are achieved.

In heavy-ion accelerator facilities, solid or gaseous media are often used to strip electrons from the projectile ions between acceleration stages because higher energies for a given acceleration voltage result from higher charge states. The stripping properties of these media have been studied for many years. The charge state distribution of ions traversing a stripping medium reaches equilibrium after passage through a certain thickness of the target. Equilibrium charge states in a solid material are generally higher than those in gaseous media due to the density effect. However, owing to radiation damage, sputtering, as well as thermal and mechanical stresses due to the irradiation, lifetimes of solid media are limited. Also, the quality of ion beams from solid strippers are degraded more than that from gas strippers. The above disadvantages of conventional gaseous or solid strippers can be overcome by using a hot plasma as a new stripping medium. Not only in a plasma but also in cold matter, the charge states of projectile ions are determined by ionization and recombination processes in the target. The free electrons are captured by projectile ions less often than the bound electrons. This difference is based on the fact that in the case of free electron capture, the excess binding energy and momentum have to be removed by one of the less probable processes, such as radiative recombination.

If the projectile-ion velocity v is larger than the electron thermal velocity v_{th} in plasma, the stopping power of plasma free electrons for non-relativistic ions is determined by the Bohr formula

$$-\left[\frac{dE}{dx}\right]_{plasma} = \left(\frac{Z_{eff}\ e\ \omega_p}{v}\right)^2 ln\frac{mv^3}{Z_{eff}\ e\ \omega_p}\ , \qquad (1)$$

$$v >> v_{th} = \sqrt{\frac{k_B T}{m}}\ , \qquad (2)$$

where T is the plasma temperature, k_B is the Boltzmann constant, Z_{eff} is the effective charge of incident ions, and ω_p is the plasma frequency, defined as follows, where is the density of free electrons.

$$\omega_p = \left(\frac{4\pi N_e e^2}{m}\right)^{\frac{1}{2}}\ , \qquad (3)$$

where N_e now refers to the density of bound electrons in gas.

In the case of the stopping power for non-relativistic ions propagating in a (gas) target, the following Eq. (4) can be re-written in a form similar to Eqs. (1) and (3):

$$-\left[\frac{dE}{dx}\right]_{gas} = \left(\frac{Z_{eff}\ e\ \omega_p}{v}\right)^2 \ln\frac{2mv^2}{I}\ . \qquad (4)$$

Equations (1) and (4) differ from each other by the expression under the logarithm sign. This means that even if the effective charges in plasma and gas targets are the same, the stopping power of free electrons in a plasma is always greater than that in a gas due to the logarithmic term. For a partially ionized plasma, the ion energy loss is defined by the sum of expressions (Eq. (4)) for the bound electrons of atoms and ions in a plasma and Eq. (1) for free electrons, where each term has to be multiplied by the corresponding particle density in a plasma.

A comparison of ionization losses in a gas and in a fully ionized plasma is schematically shown in Fig. 1. The stopping power for a fully ionized gas is larger than for a cold gas, for example, in a plasma, free electrons are much easier to excite (plasma waves) than bound electrons in atoms and ions. This is further confirmed by experimental data shown in Ref. [7–10].

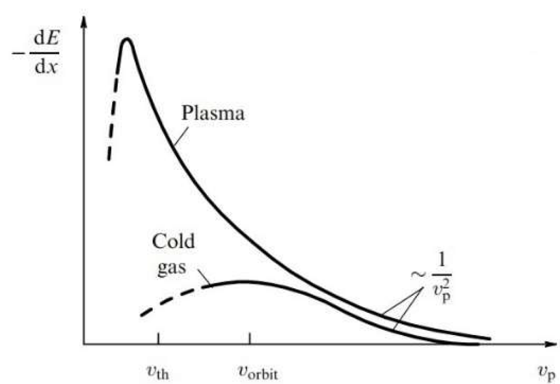

Figure 1: Stopping power in a plasma compared with a cold gas as a function of ion velocity, assuming that the effective charge is the same for both cases. Adapted from Ref. [5].

In general, while the slowing down of heavy ions in solid and gaseous targets have been studied sufficiently well and many theoretical models adequately reproduce the experimental results, the interaction of charged particles with a plasma have been investigated in less detail, and the number of available experimental data is also limited. The experiments carried out so far have been mainly using plasma pinch devices (theta pinch, Z pinch, screw pinch etc.) for studying the stopping power of heavy ions and the ultimate charge states which are achievable. However, few experimental groups have also utilised laser induced plasma devices with ‘in-situ’ interaction with heavy ions which is presently not discussed in this contribution.

PLASMA PINCH DEVICES

The current stripper technology is only suitable to a limited extent for heavy ion beams with the desired intensity. In the proposed project, a plasma stripper with fully ionised hydrogen and simultaneously high particle densities in the range of a few 10^{17} to 10^{18} cm^{-3} is to be developed and investigated. In Ref. [10] the ionization percentages for several pressures as a function of plasma temperature are depicted using the Saha equation, and above 2 eV, ionization is larger than 80 %. In order to study the energy loss measurements, the ion stopping should not perturb the plasma thermodynamics. Considering typical plasma parameters, i.e, n_e = 5×10^{17} cm^{-3} and T_e ~20.000 K, the stored energy per unit volume is ~0.4 J·cm^{-3}. The actual projectile energy loss of the beam would be much smaller, typically few orders of magnitude, smaller than the stored energy. The plasma stripper is being designed to be positioned in the high energy part of the High Current Injector facility (where the final energy is 1.8 MeV/u) located at the object plane of the first achromatic bend. Due to the pulsed nature of the beam, the beam bunches are separated in time 82.47 ns apart, corresponding to the bunching frequency of 12.125 MHz of the multi-harmonic buncher which is placed upstream of the 48.5 MHz, RFQ and the 97 MHz drift tube LINAC accelerators. The plasma device needs to be ON for a sufficient time of at least 1 ns or even more, in order to utilise most of the bunched beam. Similar to the gas stripper, the beam ions lose the outer electrons through collisions and thus reach higher charge states. The plasma stripper is characterised by a lower recombination rate, so that higher charge states can be achieved. These higher charge states facilitate the further acceleration of the ions. The electron density to be achieved and the degree of ionisation to be achieved are of importance for the effectiveness of the plasma stripper. The frequency of the Coulomb impacts responsible for ionisation increases with density. The degree of ionisation achieved is important for the recombination process: The recombination cross-section of ions with bound electrons is a factor of 1000 larger than with free electrons. This means that even a proportion of 0.1 % of not fully ionised ions/atoms negates the advantages of the plasma stripper compared to other stripper systems. The plasma devices which have been designed, fabricated and routinely used for various applications at BARC, Vishakhapatnam [11, 12] are presently being modified to be compatible for the upcoming beam tests in the High Current Injector facility for validation as a 'proof of principle" device.

HIGH PRECISION DIAGNOSTICS

In order to be able to advance the targeted further development, high-precision diagnostic equipment is required that enables access to the parameters of the plasma [13]. For this purpose, a combination of a vibration-compensated, heterodyne laser interferometer and a polarimeter for the time- and spatially-resolved determination of the electron density including magnetic field distribution of the new stripping cell would be required to be adapted to the experimental conditions. The methods used so far by some working groups to diagnose electron density are essentially limited to spectroscopy with the observation of the broad H β-line, i.e. diagnostics with passive electromagnetic radiation. Although this type of spectroscopy is to be regarded as a standard procedure, it nevertheless has certain shortcomings, which are partly intrinsic, but are also partly caused by special experimental conditions: On one hand, the intensity of the recombination radiation is not necessarily temporally correlated with the electron density, so that at the time of highest density, little light intensity can be available for spectroscopy. This non-mandatory temporal correlation means that when using different optical recording systems, such as ICCD or streak camera, the measured temporal course of the electron density does not match. On the other hand, with regard to the necessary time resolution, a compromise must be found between the maximum resolvable time interval and the brightness of the radiation at the detector, since the light intensity available to the optical system decreases with a better time resolution. It is problematic to perform a diagnosis with only one physical method. Verification and confirmation, as well as the avoidance of systematic errors, can only be achieved by using different physical measurement methods. In order to avoid the problems mentioned above, plasma diagnostic capabilities may be considered by establishing laser interferometric diagnostics alongside spectroscopy would be required. Although laser interferometric diagnostics can be classified as complex, it nevertheless has reliability and precision when used correctly, which means that a wide density range of the plasma can be investigated with good time resolution down to the sub-nanosecond range. An interferometer can be used to directly measure and that is crucial for the interaction with an ion beam, the integrated axial electron density. The interferometer/polarimeter combination is to be so powerful that the plasma parameters that are decisive for the interaction with an ion beam, including the magnetic field distribution of the stripper cell, can be determined radially spatially resolved with a precision that has never been achieved before and at the same time with high time resolution.

CONCLUSION

Plasma based heavy ion strippers are promising candidates for use in heavy ion accelerators as they are rugged, efficient and have a long lifetime when compared to gas and foil strippers. For the upcoming FAIR project and other projects worldwide, the use of plasma strippers will benefit the projects by further lowering the operating voltages of the LINAC cavities and reducing the running costs.

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