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STUDY ON THE THETA PINCH PLASMAS FOR APPLIED AS ION STRIPPER

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Abstract

Regarding the development of new accelerator facilities for high-intensity ion beams, the transfer of ions to higher charged states is a prerequisite achieve the desired energies. At present, mainly gas and film stripper are used for increasing the particle charge state. However, the stripping technologies such as film and gas stripper either requires great effort or are not suitable. One promising alternative to the before mentioned methods is the use of a plasma as stripper. The advantages of a plasma stripper are a higher effectiveness as a gas stripper and a higher lifetime as a film stripper. For this reason, stripper is proposed for the FAIR project (Facility for Antiproton and Ion Research), a new international accelerator laboratory at the GSI in Darmstadt, Germany.

In experiments with a Z-pinch plasma, the effect of a plasma as a stripper method for increasing the equilibrium charge states has already been demonstrated [1]. A disadvantage of Z-pinch, however, is the electrode erosion, whereby the lifetime of the system is limited.

In the case of an inductive ignition of a plasma no electrode erosion occurs, and the magnetic field extends predominantly in the centre of the coil parallel to the beam has no influence on the beam optics.

Due to a high interest in the stripping method based on the ion beam-plasma interaction, the plasma physics group of the Institute of Applied Physics at the University of Frankfurt is researching on an alternative for the Z-pinch plasma cell. During our research, various prototypes and solutions have been investigated. As a result, the optimal ignition criterion for the inductively coupled plasma ignition was determined, the optimal geometry of the discharge vessel, the required particle density and temperature of the plasma were calculated [2] [3]. Different coil configurations have been developed, built and tested [4] [5] [6]. With some of them (spherical theta pinch and spherical screw pinch), beam time experiments were performed [7].

This contribution presents the current state of plasma strippers with fully ionized hydrogen with simultaneously high particle densities in the range of some 10^{17} cm^{-3} for FAIR.

INTRODUCTION

Several processes are responsible for the interaction between ion beam and stripping medium. The projectile ions are deprived of electrons on their way through the target by Coulomb collisions, but at the same time the electrons are trapped by various recombination processes. Since these processes are simultaneous, the final state of ions is determined by dynamic equilibrium. When ionization cross sections for plasma and cold gas targets are virtually identical, the recombination cross sections are determined by several state dependent processes. Recombination is the sum of capture-bound electrons, radiative recombination, and Auger recombination (dielectric recombination).

In cold gas, the capture of bound electrons is the recombination with the largest cross section. An example of iodine projectiles with 1.5 MeV / u in hydrogen gas may be up to 10^{-8} cm^3 / s (Figure 1).

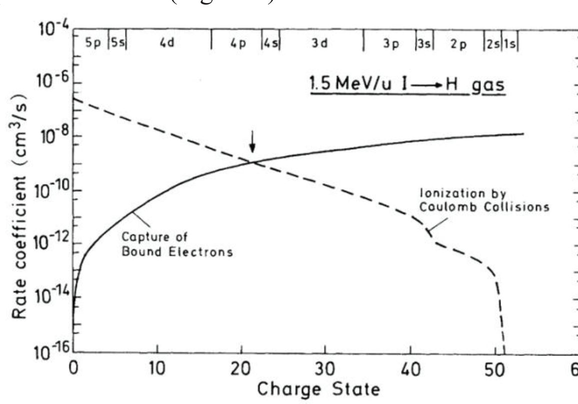

Figure 1: Rates for 1.5 MeV/u iodine in cold hydrogen gas with n_e = 10^{17} cm^{-3}. Here the equilibrium charge state is about 21 (arrow), thus considerably less than in the plasma case [8].

However, this type of recombination is not relevant to the fully ionized plasma target because of the absence of such electrons (Figure 2).

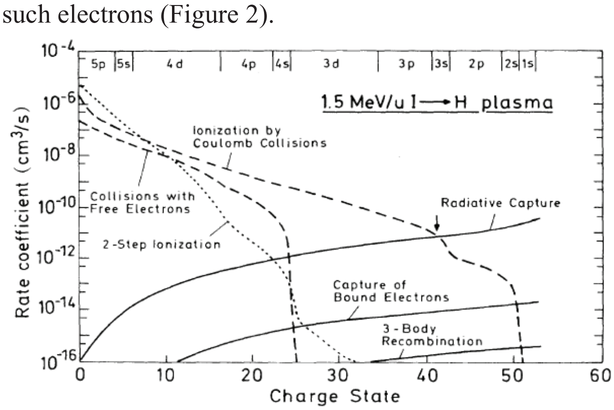

Figure 2: Equilibrium charge state Zeq for I → H. The target is either 10 eV hydrogen plasma with n_e= 10^{17} cm^{-3} or cold gas of the same density. Dielectronic recombination is not considered [8].

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The equilibrium charge states for the uranium ions (Table 1) and gold ions (Figure 3) have been calculated by V. Shevelko in the framework of expertise requested by the working group.

Table 1: Theoretical calculation of the equilibrium charge state of uranium beam with an initial charge state of Q = 4+ with cold gas and plasma.

Energy MeV/u	Cold gas < Q >	Plasma < Q >	λ cm n_e= 10^{17}cm^{-3}	λ cm n_e= 10^{18}cm^{-3}
1	13	49	230	23
3	37	64	800	80
10	75	86	2200	220

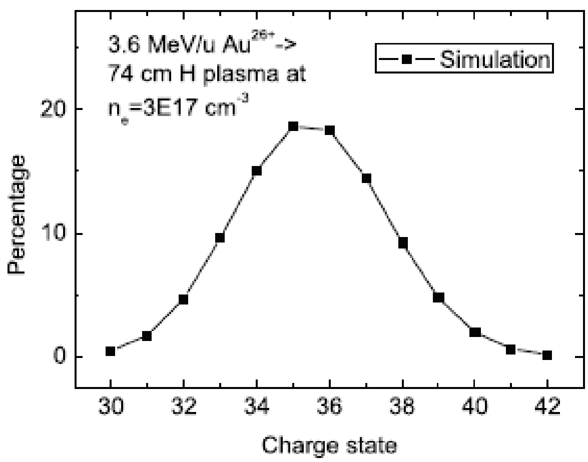

Figure 3: Simulated charge state distribution for gold ions with initial charge state of 26+.

EXPERIMENTAL SETUP

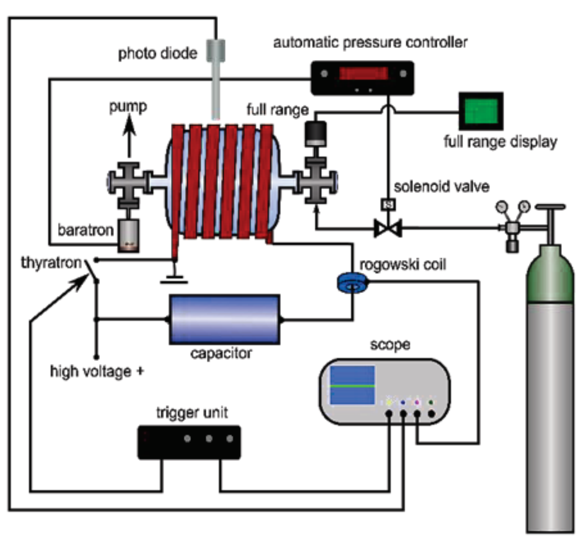

Figure 4: Experimental set-up of the Theta Pinch plasma.

The plasma stripper experiment is one of the most important research activities of our research group. A major feature of the pinch plasma is the use of a large cylindrical discharge vessel surrounded by a spiral induction coil, which is connected to a capacitor bank via coaxial transmission line. In resonant circuit the discharge is working with an own frequency below 10 kHz.

The measurements were done with a stored energy of around 15kJ and can be increased up to 50kJ. The induction currents reach high values and moderate current rise times. The stored energy is switched by a thyratron switch. One of the principal advantages of this concept is the high energy transfer efficiency of up to 40% and the potential of high pulse repetition rates. For the integration into the beam line, differential pumping systems are at each side of the discharge vessel. Figure 4 shows the experimental set up of the plasma stripper device. In addition, a differential pump system is symmetrically connected for attaching the experiment to the beam line.

EXPERIMENTAL RESULTS

Results from beam times with spherical theta pinch and screw pinch were previously presented at IPAC [9]. So, what is hereby presented are the newly obtained results from the beam time at GSI end of March 2019.

For synchronisation of the plasma of the theta pinch to the ion beam the investigation of the ignition behaviour are of importance. The ignition and luminous effect of the Plasma was measured with a fast photodiode. The following Figure 5 shows the current and ignition behaviour of the Spherical Theta Pinch. The capacity of the experimental set up was 60 µF. The measurement was performed at a voltage of 20 kV at a pressure of 30 Pa (H2). From the oscillating photodiode signal can be seen that the ignition of the plasma will start during the second negative half wave of the oscillating current and the brightest luminescence effect is within the second positive half wave.

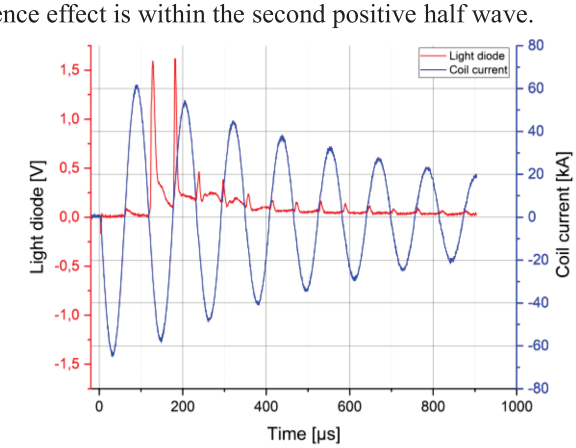

Figure 5: Current and ignition behaviour of the Theta Pinch plasma.

Another important factor for the efficiency of ion stripping is the electron density. For this, time-resolved measurements of the electron density were performed. The electrical parameter like capacity (60µF), voltage (20kV) and the pressure (30Pa) were almost identically to those of the beam time. It was decided, during the beam time to increase the voltage to 22kV. In this way, pressure could raise to 40 Pa as well. To determine the electron density the Hβ

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broadening was measured. Like the luminescence behaviour, the first peak of the electron density was measured at the second negative current half wave and the maximum electron density of around $4.5{*}10^{16}$ cm^{-3} was achieved at the second positive current half wave (Figure 6).

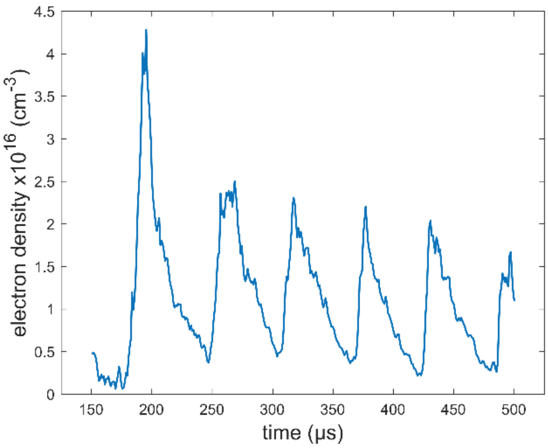

Figure 6: Time resolved electron density.

During the beam time the charge state distribution was measured for cold gas and plasma. The beam was Au+26 with an energy of 3.6MeV/u. Figure 7 shows the charge state distribution after crossing the stripping cell with cold gas and plasma. On the top of the Fig. 7 are the different achieved charge states. The electron density was in the range of $1{*}10^{16}cm^{-3}$.

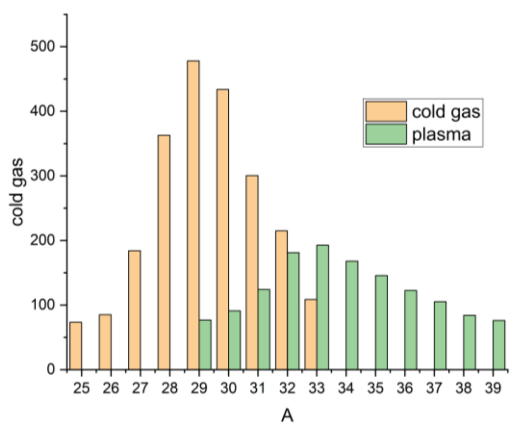

Figure 7: Charge state distribution of a 3.6MeV/u Au26+ Ion beam after crossing a hydrogen plasma in comparison to a cold gas.

During the gas discharge, the transmission of the ion beam through the stripper cell was very low, which was very likely due to parasitic magnetic field components outside the coil. Consequently, the ion beam must be delayed for several hundred microseconds. In this case the magnetic field was not so strong, but it led, on the other side to lower plasma density. The charge state distribution with plasm is shifted to a higher ionisation degree of the Au-beam. The maximum charge state with plasma is between +32 to + 34, whereas with cold gas the main charge distribution is between +28 to +30.

Not all data has been evaluated by the just finished beam time. Because the beam-plasma interaction took place much later, the plasma temperature must be determined at the time.

CONCLUSION

The beam transfer through the experiment needs to be improved. For this purpose, work is currently being carried out on the shielding of the ion beam before and after the coil. Also, the enlargement of orifices in differential pumping system must lead to better transmission.

In general, the experiment was designed for much larger voltages, which could not be completely exhausted due to strong magnetic fields. After the problem with the influence of the magnetic field on beam penetration is solved, discharge energy can be increased up to 50 kJ. With the higher discharge energies, the energy input into plasma also increases. This leads to much higher densities and temperatures of plasma, which in turn results in better stripping properties of the device. To separate the pressure from the stripper to the vacuum of the accelerator a plasma window was designed and is now under investigation.

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