

**K. Cistakov^{1*}, P. Christ¹, L. Manganelli¹, R. Gavrillin^{1,2},
A. Khurchiev^{1,2}, S. Savin^{1,2}, M. Iberler¹, J. Jacoby¹**

¹Institute for Applied Physics, Germany, Frankfurt am Main

²Institute for Theoretical and Experimental Physics, Russia, Moscow

*e-mail: Cistakov@iap.uni-franfurt.de

STUDY ON A DENSE THETA PINCH PLASMA FOR ION BEAM STRIPPING APPLICATION FOR FAIR

The transfer of ions to a higher charge state is of central importance for the development of new accelerator facilities. That is why the comparative analysis of the current stripping alternatives is a relevant topic. Currently, mainly gas and foil strippers are used for increasing the particle charge state. Even when their efficiency or lifetime has proved to be less than optimal, as these alternatives either require great effort or are not suitable. Compared to the gas and foil stripper the alternative of using a plasma stripper has a much higher effectiveness and a higher lifetime [1-13] That is why the plasma stripper has been proposed for the FAIR project (Facility for Antiproton and Ion Research) in Darmstadt, Germany.

To further develop this subject, 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 [4-6], [8], [11], [14-16]. 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. Different coil configurations have been developed, built and tested. With some of them (spherical theta pinch and spherical screw pinch), beam time experiments were performed.

This contribution presents the current state of plasma strippers with fully ionized hydrogen with simultaneously high particle densities in the range of some 10^{16} cm^{-3} for FAIR. Charge distributions after the ion beam plasma and ion beam cold gas interactions were measured and compared. As expected, the effective state of charge after interaction with plasma was higher than after interaction with gas ($q_p = 32.84$ versus $q_{\text{gas}} = 29.41$).

Key words: pinch plasma, FAIR, plasma physics, ion beam stripping.

К. Чистяков^{1*}, Ф. Христ¹, Л. Манганелли¹, Р. Гаврилин^{1,2},
А. Хурчиев^{1,2}, С. Савин^{1,2}, М. Иберлер¹, И. Якоби¹

²Қолданбалы физика институты, Германия, Франкфурт-на-Майне қ.

¹Теориялық және эксперименттік физика институты, Ресей, Мәскеу қ.

*e-mail: Cistakov@iap.uni-franfurt.de

FAIR жобасы үшін тета пинч плазмасы негізінде иондық стрипперді зерттеу

Үдеткіш қондырғылардың жаңа түрін жасауда иондарды сыдыру әдісімен жоғары зарядты күйге ауыстыру соңғы кездері басты назар аудартып отыр және осы себепті салыстырмалы анализді қажет ететін өзекті тақырыптардың біріне айналды. Қазіргі уақытта бөлшектердің зарядын жоғарылату үшін сыдыру ортасы ретінде негізінен газ және фольга қолданылады. Алайда олардың тиімділігі және жұмыс жасау мерзімі төмен. Бұлармен салыстырғанда, баламалы сыдыру ортасы ретінде плазманы пайдалану газға қарағанда әлдеқайда жоғары тиімділікке ие және фольгаға қарағанда ұзақ мерзімде жұмыс жасайды [1-13]. Сондықтан Германияның Дармштадт қаласындағы FAIR (Facility for Antiproton and Ion Research) жобасына плазмалық стриппер ұсынылды.

Осы тақырыпты одан әрі дамыту үшін Франкфурт университетінің қолданбалы физика институтының плазма физикасы тобы Z-пинчті плазманы баламалы сыдыру ортасы ретінде зерттеп келеді. Осы зерттеулердің негізінде әртүрлі прототиптер мен шешімдер алынды [4-6], [8], [11], [14-16]. Сонымен қатар осы зерттеулердің нәтижесінде индуктивті байланысқан плазманы генерациялау үшін оңтайлы параметрлер анықталды, разряд түтігінің оңтайлы геометриясы, бөлшектердің концентрациясы және плазма температурасы септелді, әр түрлі катушалар конфигурациясы жасалды және экспериментте сыналды. Сондай-ақ олардың

кейбіреулерімен (сфералық тета пинч және сфералық бұрандалы пинч) өмір сүру уақыттары бойынша салыстырулар жүргізілді.

Бұл зерттеулер FAIR үшін шамамен 10^{16} см⁻³ диапазонында бөлшектердің концентрациясы жоғары толық иондалған сутегі плазмалық стрипперлерінің қазіргі жағдайын көрсетеді. Иондар ағыны мен плазманың өзара әсерлесуінен кейінгі және иондар ағыны мен салқын газ арасындағы өзара әрекеттесуден кейінгі зарядтың таралуы өлшеніп, алынған нәтижелер бір-бірімен салыстырылды. Күткендей, плазмамен әсерлескеннен кейінгі зарядтың тиімді күйі газбен әсерлескеннен гөрі жоғары болатындығы анықталды ($q_p = 32,84$ versus $q_{gas} = 29,41$).

Түйін сөздер: пинч плазмасы, FAIR, плазма физикасы, иондық стриппер.

К. Чистяков^{1*}, Ф. Христ¹, Л. Манганелли¹, Р. Гаврилин^{1,2},
А. Хурчиев^{1,2}, С. Савин^{1,2}, М. Иберлер¹, И. Якоби¹

¹Институт прикладной физики, Германия, г. Франкфурт-на-Майне

²Институт теоретической и экспериментальной физики, Россия, г. Москва

*e-mail: Cistakov@iap.uni-franfurt.de

Исследование плотности плазмы тета-пинча для применения в качестве ионного стриппера для проекта FAIR

Перевод ионов в более высокое зарядовое состояние имеет центральное значение для разработки новых ускорительных установок. Поэтому сравнительный анализ существующих альтернатив зачистки является актуальной темой. В настоящее время для увеличения зарядового состояния частиц используются в основном газовые и фольговые стрипперы. К сожалению, из-за своей низкой эффективности, как газовой мишенью или недолговечны как углеродные пленки. В отличие от этих методов, плазменная альтернатива имеет гораздо более высокую эффективность по сравнению с газовым стриппером и более длительный срок службы по сравнению со стриппером фольги [1-13]. Плазменная мишень была предложена для проекта FAIR (Установка для исследования антипротонов и ионов) в Дармштадте, Германия.

Для дальнейшего развития этой темы группа физики плазмы Института прикладной физики Франкфуртского университета исследует альтернативу плазменной ячейке с Z-пинчем. В процессе этой работы были исследованы различные прототипы и решения [4-6], [8], [11], [14-16]. В результате был определен оптимальный критерий зажигания для индуктивной плазмы, рассчитаны оптимальная геометрия разрядного сосуда, требуемая плотность частиц и температура плазмы. Были разработаны, изготовлены и испытаны различные конфигурации катушек. С некоторыми из них (сферический тета-пинч и сферический винтовой пинч) были проведены эксперименты на ионном ускорителе в Дармштадте.

Эта статья представляет текущее состояние плазменных стрипперов с полностью ионизованным водородом с одновременно высокими плотностями частиц в диапазоне примерно в несколько 10^{16} см⁻³ для FAIR. Распределения заряда после взаимодействия ионного пучка с плазмой были измерены и сравнены с распределением после взаимодействия ионного пучка с холодным газом. Как и ожидалось, эффективное состояние заряда после взаимодействия с плазмой было выше, чем после взаимодействия с газом ($q_p = 32,84$ против $q_{gas} = 29,41$)

Ключевые слова: плазмы тета-пинча, FAIR, физика плазмы, ионный стриппер.

Introduction

The higher effectiveness of the plasma stripper has already been demonstrated in several experiments with Z-Pinch plasma [10].

As effective as a plasma stripper might be, this method needs improvement, since the lifetime of the system is limited, due to the electrode erosion. A solution to this disadvantage is an electrodeless inductive ignition of the plasma. Additionally, with an inductive ignition the magnetic field extends predominantly in the center of the coil parallel to the beam, having no influence on the beam optics.

The interaction between the ion beam and the stripping medium is determined by several simul-

taneous processes and the final state of the ions is a result of their dynamic equilibrium. Beam ions loose electrons due to the coulomb collisions and at the same time capture electrons by various recombination processes. While the ionization cross sections for plasma and cold gas targets are practically identical, the recombination cross sections are determined by several state dependent processes. Recombination is the sum of the capture of bound electrons, radiative recombination and 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} cm³/s (Figure 1). How-

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

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

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 a coaxial transmission line. The components form a resonant circuit at a frequency of 8.65 kHz.

The measurements were done with a stored energy of around 15kJ, which can be increased up to 50kJ. The alternating current reaches peak values of 71.5 kA and current rise times (20%-80%) of 4.65 kA/ μ s. The stored energy is switched by a thyatron 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. Fig. 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.

A dipole magnet was used as charge state separator to perform the charge state distribution diagnostics. In this context, a scintillator was utilized as the detector.

Energy loss diagnostics were made with Time of Flight (TOF) method. For this reason, a diamond detector was used, because it possesses a high response time (less than 0.1 ns) and high sensitivity. The diamond detector was installed at 6324 mm from the centre of theta pinch coil. Pulsed microbunches of the heavy ion beam registered by the diamond detector with time intervals of 27.67 ns have a certain phase (shift) to the reference signal from the accelerator RF. In the case of a vacuum target, this displacement is a fixed value that is used as a reference for determining the energy loss.

Due to the stopping power of the cold gas target or the plasma target, the fast heavy ion beam suffers energy loss and its velocity decreases, which causes a longer flight time along the TOF flight path. Therefore, the registered microbunch of ion beam show an increased phase shift which is proportional to the energy loss.

Results from beam times with spherical theta pinch and screw pinch were previously presented at IPAC [8]. The results presented here are newly obtained from the beam time at GSI end of March 2019.

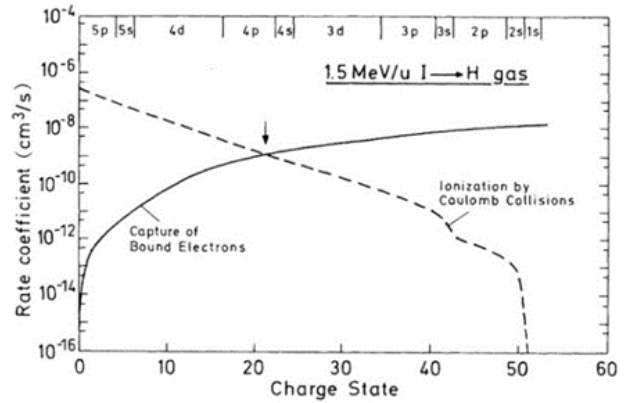


Figure 1 – Rates for 1.5 MeV/u iodine in cold hydrogen gas with $n_e 10^{17} \text{ cm}^{-3}$. Here the equilibrium charge is about 21 (arrow), thus considerably less than in the plasma case [12]

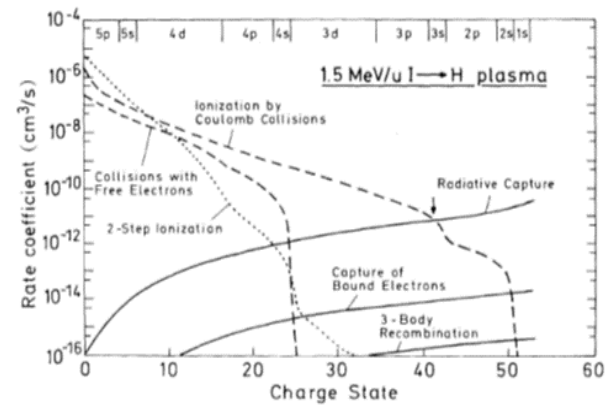


Figure 2 – Rates of electron capture and loss for a 1.5 MeV/u iodine beam in a 10 eV hydrogen plasma with $n_e 10^{17} \text{ cm}^{-3}$. The intersection between capture and loss is close to the equilibrium charge $Z_{eq}(V_p)$ at constant velocity (arrow) [12]

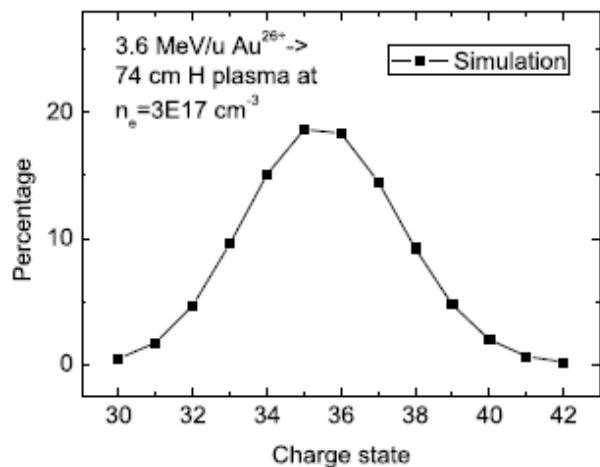


Figure 3 – Simulated charge state distribution for gold ions with initial charge state of 26+. Experimental setup and results

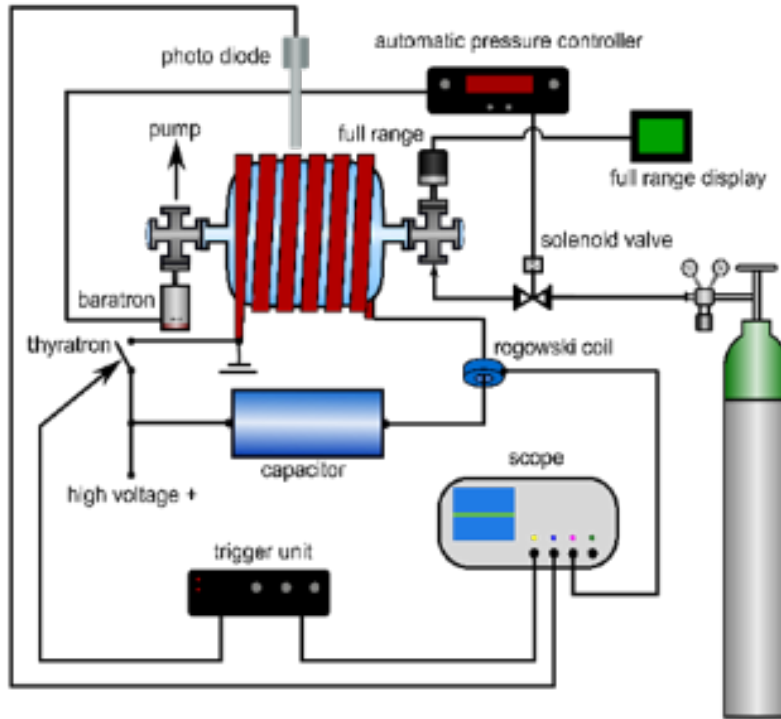


Figure 4 – Experimental set-up of the Theta Pinch Plasma Stripper.

For synchronisation of the plasma of the theta pinch to the ion beam the investigation of the ignition behaviour is of importance. The ignition and light emission of the Plasma was measured with a fast photodiode. The following Figure 5 shows the current and ignition behaviour of the cylindrical Theta Pinch. The capacity of the experimental set up was $60 \mu\text{F}$. The measurement was performed at a voltage of 20 kV at a pressure of 30 Pa (H_2). The photodiode signal shows that the ignition of the plasma starts during the second negative half wave of the oscillating current and the brightest luminescence effect is within the second positive half wave. In the beam time was decided to increase the voltage to 22 kV . In this way, pressure could be raised to 40 Pa accordingly. Plasma ignition time has remained the same.

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 the plasma density and temperature have already decreased significantly.

The electron density, as well as the electron temperature, are an important factor for the efficiency of ion stripping. Consequently, time-resolved meas-

urements of the electron density were performed (Figure 7). The electrical parameter like capacity ($60 \mu\text{F}$), voltage (22 kV) and the pressure (40 Pa) were identical to those of the beam time. The electron density (n_e) was calculated from a semi-empirical formula Fleurier by measuring the Stark-broadening ($\Delta\lambda_s$) of the H beta line [17].

$$n_e = 1.03 \cdot 10^{16} (\Delta\lambda_s [\text{nm}])^{1.488} \text{ cm}^{-3}.$$

It is based on Griem's formula [18], but unlike it, it does not depend on density and temperature coefficients.

Like the luminescence behaviour, the maximum of the electron density of around $4.5 \times 10^{16} \text{ cm}^{-3}$ was measured at the third and fourth current half. At the time of the charge distribution measurement, the electron density decreased significantly and oscillated in the range from $0.2 \times 10^{16} \text{ cm}^{-3}$ to $1 \times 10^{16} \text{ cm}^{-3}$. The time resolution of density measurements is $0.4 \mu\text{s}$. The error of the electron density measurements is approximated to 10%. The electron temperature was measured time-resolved with a resolution of $2 \pm 1 \mu\text{s}$. Fig. 6 shows the electron temperature during measurement of charge distribution. The error of the electron temperature measurements is between 4% and 25% depending on the absolute value.

During the beam time the charge state distribution was measured for cold gas and plasma. The initial ion beam charge state was Au+26 with an energy of 3.6MeV/u. Fig. 8 shows the charge state distribution after crossing the stripping cell with cold gas and plasma. The charge state distribution with plasma is shifted to a higher ionisation degree of the Au-beam. As expected, the effective state of charge after interaction with plasma was $q_p = 32.84$ versus after interaction with gas $q_{gas} = 29.41$.

Another important result is an energy loss of heavy ions in plasma. An attempt was made to get a time-resolved evaluation of complete macrobunch. Unfortunately, due to technical problems, the macro bunch was not continuous, but had gaps in the micro bunch structure making a time-resolved evaluation quite difficult.

The Fig. 9 shows that along with the expected deceleration in the plasma, there is an unexpected short-time acceleration of ions after each change in the direction of the current. Maximum measured phase shift of 2.45 ns when decelerating and 2.48 ns when accelerating ions corresponds to an energy loss or gain of 14.45 and 14.63 MeV respectively. The reasons for an acceleration of ions are still being investigated.

The Fig 10 show the phase shift of the ion beam temporal behaviour starting from 800 μ s after experiment trigger. The beam transmission has become significantly better. Before each ion stopping phase through the plasma there is a short acceleration phase, which was likely caused by space charges in the plasma.

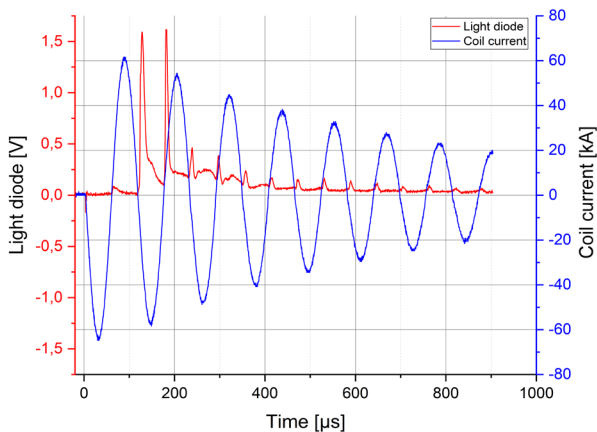


Figure 5 – Current and ignition behaviour of the Theta Pinch plasma

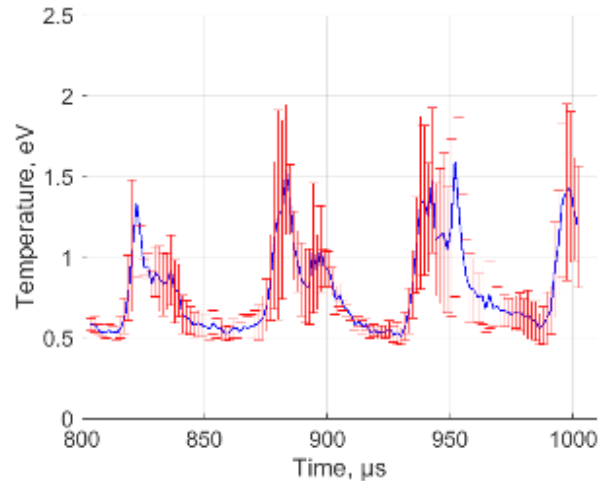


Figure 6 – Time-resolved electron temperature.

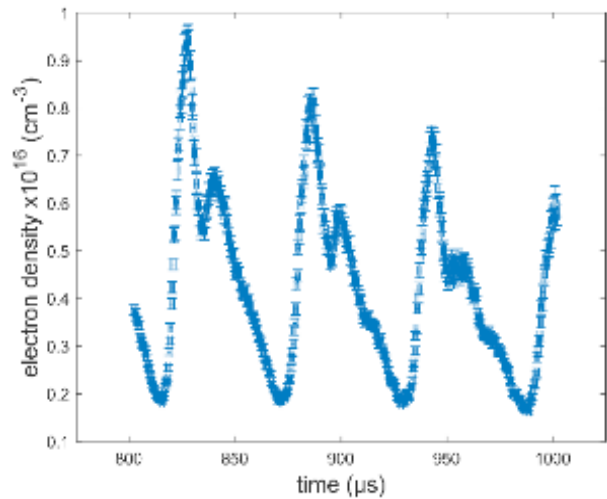


Figure 7 – Time-resolved electron density.

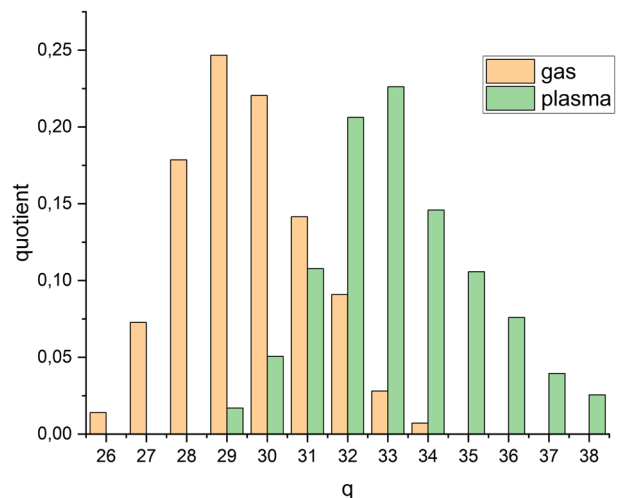


Figure 8 – Charge distribution of ion beam after passing cold gas and plasma

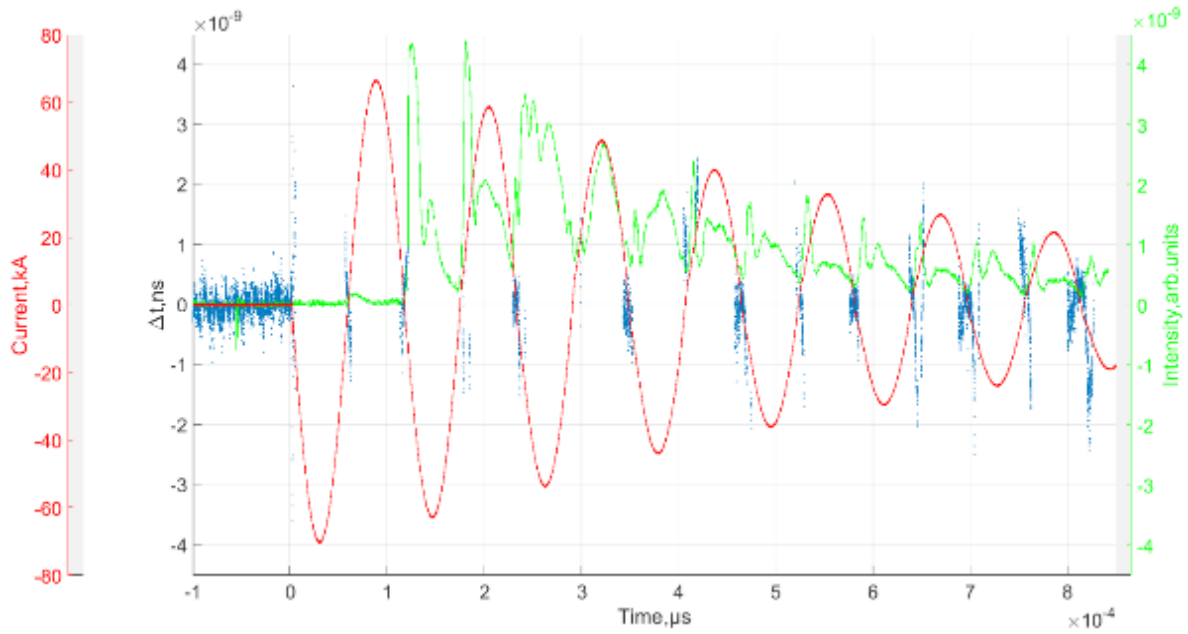


Figure 9 – Blue is time of flight difference (Δt) between the ion beam signal after plasma and the reference signal after cold gas. Red is discharge current signal from Rogowski coil and green is photo diod signal.

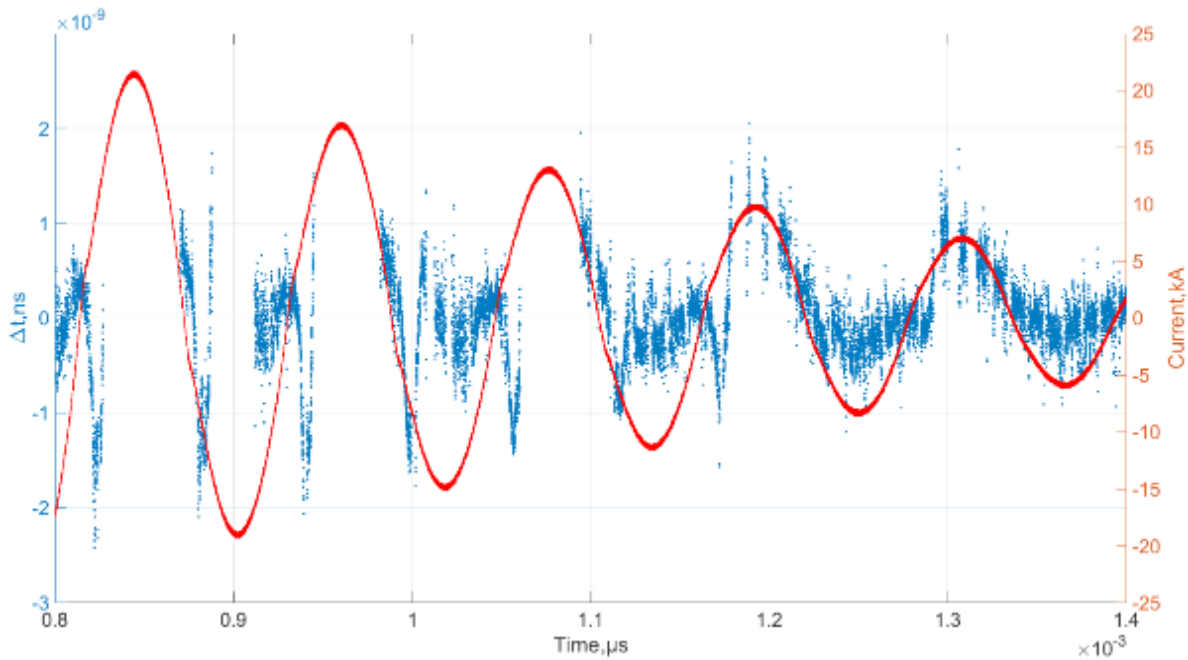


Figure 10 – Blue is time of flight difference (Δt) between the ion beam signal on the diamond detector after plasma and the reference signal after cold gas during measurement of charge distribution. Red is discharge current signal from Rogowski coil.

Conclusion

The beam transfer through the experiment needs to be improved. For this reason, a new enlarged diaphragm system is currently being worked on. It

is also planned for the next beam time that the ion beam will not be focused on the center of the experiment but will go parallel to the Z axis of the magnetic field. The Penning source is not very suitable for TOF measurements because it has its own «sput-

ter» frequency of approx. 100 kHz. This property, together with the low particle current, made data analysis even more difficult.

Unfortunately, measurements were taken very late after the trigger experiment. However, experiment has shown the advantages of a plasma over cold gas even at low electron density and temperature. The short acceleration phase immediately after each plasma ignition needs to be investigated extensively. The working hypothesis is the creation of a large space charge in the plasma compression phase. Since the pinch phase of interest to us begins much later, this acceleration does not lead to a disadvantage for plasma strippers.

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 [19].

Acknowledgment

Many Thanks Sero Zächter, Kristina Zerbe, Christofer Wagner, Alex Müller-Münster, Thilo Ackermann and the whole plasmaphysics group and the Goethe-University Frankfurt for supporting. Also, many thanks to BMBF (Bundesministerium für Bildung und Forschung) and HIC for FAIR (Helmholtz International Center for FAIR) for the financial support.

References

- 1 Barth W. et al. High current uranium beam measurements at GSI-UNILAC for FAIR //Proceedings, IPAC'18, 2018. – 4 p.
- 2 Barth W. et al. Carbon stripper foils for high current heavy ion operation //J Radioanal Nucl Chem. – 2013. – Vol. August – P.1047-1053.
- 3 Cayzac W. et al. Ion energy loss at maximum stopping power in a laser-generated plasma. – Darmstadt: Technische Universität Darmstadt, 2013. – 331 p.
- 4 Christ P. et al. Study on a dense and high ionized plasma for ion beam stripping /GSI-FAIR scientific report. – 2017. – P.256.
- 5 Loisch G., Xu G., Cistakov K., Fedjuschenko A., Iberler M., Liu Y., Rienecker T., Schönlein A., Senzel F., Wiechula J. et al. Review of the State-of-the-Art Development of the Spherical Theta Pinch Plasma Source //IEEE Transactions on Plasma Science. – 2014. – Vol. 42. – P.1163.
- 6 Xu G. et al. Beam transmission for a plasma stripper device //High Energy Density generated by Heavy ION and Laser Beams. – 2014. – P.17.
- 7 Hoffmann D. Beam-plasma interaction experiments with heavy ion beams //Journal de Physique Colloques. – 1988. – Vol. 49, No. C7. – P C7-159-C7-168.
- 8 Iberler M. et al. Development and Investigation of Pulsed Pinch Plasmas for The Application as FAIR Plasma Stripper /Part of Procs 7th Intern. Particle Accelerator Conference (IPAC 2016). – 2016. – 3 p.
- 9 Jacoby J. et al. Interaction of heavy ions with plasma //Nuclear Instruments and Methods in Physics Research B. – 1996. – Vol.115. – P.7-13.
- 10 Jacoby J. et al. Stopping of Heavy Ions in a Hydrogen Plasma //Physical Review Letters. – 1995. – Vol.74. – P.1550
- 11 Loisch G., Xu G., Blazevic A., Cihodariu-Ionita B. et al. Hydrogen Plasma Dynamics in the Spherical Theta Pinch Plasma Target for Heavy Ion Stripping //Physics of Plasmas. – 2015. – Vol.22. – Art.No 053502.
- 12 Peter T. and Meyer-ter-Vehn J. Energy loss of heavy ions in dense plasma. II. Nonequilibrium charge state and stopping powers //Phys. Rev. – 1990. – Vol. 43. – P.2015.
- 13 Shevelko V.P., Winkler N., Yu I. et al. Gas-pressure dependence of charge-state fractions and mean charges of 1.4 MeV/u-uranium ions stripped in molecular hydrogen //Nuclear Instruments and Methods in Physics Research B. – 2016. – Vol.377. – P.77.
- 14 Teske C., Jacoby J., Senzel F. and Schweizer W. Energy transfer efficiency of a spherical theta pinch //Physics of Plasmas. – 2010. – Vol. 17. – Art.No. 043501.
- 15 Teske C., Liu Y., Blaes S. and Jacoby J. Electron density and plasma dynamics of a spherical theta pinch //Physics of Plasmas. – 2012. – Vol.19. – Art.No.033505.
- 16 Teske C.J. and Jacoby J. Pulsed Low Frequency Inductively Coupled Plasma Generator and Applications //IEEE transactions on plasma science. – 2008. – Vol.36, No.4. – P.1930.
- 17 Fleurier C., Sanba A., Hong D., Mathias J. and Pellicier J.C. Plasma Diagnostics in The Heavy Ion Beam-Dense Plasma Interaction Experiment at Orsay //Journal De Physique Colloques. – 1988. – Vol.49, No.C7. – P.141-149.
- 18 Griem, H.R. Plasma Spectroscopy. – McGraw-Hill, New York; Univ. Microfilms International, 1964.
- 19 Bohlender B., Michel A., Jacoby J., Iberler M. and Kester O. Characterization of a plasma window as a membrane free transition between vacuum and high pressure //Physical Review Accelerators and Beams. – 2020. – Vol.23 – Art.No 13501.

References

- 1 W. Barth, High current uranium beam measurements at GSI-UNILAC for FAIR, Proceedings, IPAC'18, 4, (2018).
- 2 W. Barth, J Radioanal Nucl Chem, 29 August, 1047-1053 (2013).
- 3 W. Cayzac, Ion energy loss at maximum stopping power in a laser-generated plasma, (Darmstadt: Technische Universität Darmstadt, 2013).
- 4 P. Christ et al, Study on a dense and high ionized plasma for ion beam stripping, (GSI-FAIR scientific report, 2017), 256 p.
- 5 G. Loisch, G. Xu, K. Cistakov, A. Fedjuschenko, M. Iberler, Y. Liu, T. Rienecker, A. Schönlein, F. Senzel, J. Wiechula et J. Jacoby, IEEE Transactions on Plasma Science, 42, 1163 (2014).
- 6 G. Xu et al., High Energy Density generated by Heavy Ion and Laser Beams, 17, (2014).
- 7 D. Hoffmann, Journal de Physique Colloques, 49, C7-159-C7-168 (1988).
- 8 M. Iberle et al., Development and Investigation of Pulsed Pinch Plasmas for The Application as FAIR Plasma Stripper, Part of Procs 7th Intern. Particle Accelerator Conference (IPAC 2016), 3 (2016).
- 9 J. Jacoby, Nuclear Instruments and Methods in Phys. Research B, 115, 7-13 (1996).
- 10 J. Jacoby, Physical Review Letters, 74, 1550 (1995).
- 11 G. Loisch, G. Xu, A. Blazevic, B. Cihodariu-Ionita et J. Jacoby, Physics of Plasmas 22, 053502 (2015).
- 12 T. Peter and J. Meyer-ter-Vehn, Physical Review, 43 (4), 2015 (1990).
- 13 V.P. Shevelko, N. Winkler, I. Yu et I.Y. Tolstikhina, Nuclear Instruments and Methods in Physics Research B, 377, 77 (2016).
- 14 C. Teske, J. Jacoby, F. Senzel and W. Schweizer, Phys. of Plasmas, 17, 043501 (2010).
- 15 C. Teske, Y. Liu, S. Blaes, and J. Jacoby, Physics of Plasmas, 19, 033505 (2012).
- 16 C. Teske and J. Jacoby, IEEE transactions on plasma science, 36 (4), 1930 (2008).
- 17 C. Fleurier, A. Sanba, D. Hong, J. Mathias and J. C. Pellcier, Journal De Physique Colloques, 49, C7, 141-149 (1988).
- 18 H. R. Griem, Plasma spectroscopy, McGraw-Hill, 1964.
- 19 B. Bohlender, A. Michel, J. Jacoby, M. Iberler and O. Kester, Physical Review Accelerators and Beams, 23, 13501 (2020).