RECENT TOPICS ON THE DEVELOPMENT OF NEGATIVE ION SOURCES FOR HIGH INTENSITY HADRON ACCELERATORS

Y.Mori
KEK, National Laboratory for High Energy Physics
1-1, Oho-cho, Tsukuba-shi, Ibaraki-ken 305, Japan

Abstract

Negative ion sources become more and more important in the high intensity hadron accelerators. Recent developments in negative ion sources are reviewed.

Introduction

In the recent operational or designed high intensity hadron accelerators, negative ions (H^-/D^- ions) are essential as accelerating particles. This is because charge-exchanged multi-turn injection with negative ion beam is very useful to increase the circulating beam current in a synchrotron.

The H^- ion sources which have been developed for the accelerators can be divided into two groups according to their H^- ion production schemes; one is a surface-plasma production scheme and the other a volume production scheme. In the surface-plasma production scheme, there are various types in generating intense hydrogen plasma, such as PIG[1][2], Magnetron[3][4] and Cusp[5][6]. In all cases, a cesium covered metallic surface immersed in the hydrogen plasma has a dominant role in generating H^- ions. Since this scheme is quite efficient in producing an intense H^- ion beam, most operational hadron accelerators use them.

The recent efforts for H^- ion source development have concentrated on the volume production scheme. The volume production type of H^- ion source is almost liberated from cesium and its beam emittance is relatively small compared with the surface-plasma production scheme. One of the difficulties of the volume production scheme is, since most of this type of ion sources have used an arc discharge for making a plasma, a large arc power is required to obtain an intense H^- ion current. An arc power of more than 30 kW is necessary to extract a total H^- ion beam current of more than 10 mA from a single anode aperture of 5-6mm in diameter.[7] Such an enormous arc power sometimes makes a stable and long period operation of the ion source impossible because of the short lifetime of the hot filament cathode. Another difficulty is a large electron drain current. In beam extraction from negative ion sources, a large numbers of electrons are simultaneously extracted as well as negative ions. In the volume production type H^- ion source, the electron drain current occasionally reaches more than 100 times of the H^- ion current.

Recently, a technical innovation and a new finding which could change these difficult situations dramatically have been submitted:(1) Generation of a dense plasma by high power radio frequency (RF) waves with inductive coupling, and (2) Enhancement of H^- ion production rate and reduction of electron drain current by cesium feeding (cesium catalysis effect).

An RF discharge has been used to produce a relatively thin hydrogen plasma ($n < 10^{11}$ n/cm^3) efficiently, but it has been believed that to make a dense plasma without a strong magnetic field by the RF discharge would be difficult because of the plasma cut off. However, it was found recently that the RF discharge inductivey coupled to the plama could generate a dense plasma ($n > 10^{12}$ n / cm^3) and it has applied successfully for making a dense hydrogen plasma in the volume production type of H^- ion source.[8] As for a mechanism why inductive coupling in the RF discharge was so efficient to make a dense plasma, a recent theory has clarified that a new collisionless electron heating process worked quite efficiently in an inductively coupled plasma. [9]

A cesium catalysis effect in the volume production type of H^- ion source has been observed in many laboratories, although its mechanism is still uncertain. Recently, strong evidence showing that the cesium catalysis effect correlated to the cesium covered surface of the plasma electrode in the ion source was found.[10][11][12]

In addition,

(3) A sheath condition of negative ion plasmas, and
(4) Fast beam chopping in negative ion sources

are also described in this paper.

The configuration of a plasma sheath in the beam extraction region of a negative ion source would be quite different and complicated compared with that of an ordinary positive ion source because the negative ion plasma consists of not only positive ions and electrons but a large number of negative ions. In order to maintain a stable sheath in the negative ion plasma, the sheath potential has to keep a critical condition which is balanced on the population between negative ions and electrons.

Fast beam chopping is very important in beam injection for an intense hadron synchrotron to avoid beam losses due to mismatching in longitudinal phase space. Transverse electrostatic beam deflection in the low energy (several 10 keV) beam transport line has been mostly used so far but it has some problems caused by non-neutralization of the beam space charge. If the fast beam chopping could be made longitudinally in the ion source, it would be ideal.

In this paper, the above 4 topics concerning the recent developments of negative ion sources for intense hadron accelerators are summarized and reviewed.

Production of high density plasma by radio frequency(RF) wave with induction coupling

Most ion sources have used an arc discharge for generating high density plasma. To make an arc discharge, hot filaments made of high temperature materials such as W , Ta or low work function materials such as LaB_6 having large electron emission are normally exploited as the electron emissive cathodes. Recent ion sources used in accelerators, especially for generating intense negative ions or multiple charged heavy ions, normally require high arc power (arc voltage x arc current). Generally speaking, the key issue in obtaining a large beam current from the ion source is how to generate a dense plasma at a relatively low gas pressure(~mTorr). The production rate of ions in the discharge can be expressed by the following equation.

$$R_i \propto N\int n_e v\sigma(v)f(v)dv . \qquad (1)$$

Here, ne is the electron density of the plasma, N the gas molecular density, v the electron velocity, $\sigma(v)$ the ionization cross section and f(v) the electron distribution function, respectively. As can be clearly seen from this equation, making a dense plasma efficiently depends on how the electrons in the plasma get their energies. By raising the arc power brought into the ion source plasma, plasma density and temperature can be increased substantially. In the volume type of H- ion source, for example, the requested arc power to obtain a high beam current density(>10mA/cm^2) reaches sometimes more than 30kW for a relatively small volume (~0.001m^3) plasma chamber. Such a high arc power creates a severe technical difficulty in operation of the ion sources : the life time of the cathodes. To generate a dense plasma without hot filament cathodes, discharges using radio frequency (RF) or microwave fields are very useful. In multiple charged heavy ion sources, for example, a microwave discharge with ECR (electron cyclotron resonance) electron heating has been widely used.

Recently, an inductively coupled RF discharge has become attractive in the ion source fields because it could make a dense and homogeneous plasma without a strong magnetic filed, unlike an ECR discharge. Figure 1 is a schematic layout of the RF driven volume type of H-ion source developed at LBL.[13] One of the features in the recent RF driven ion sources is their RF couplers which are immersed in a plasma as shown in Fig. 1. With this configuration, coupling between the RF wave and the plasma are so strong that not only inductively but also electrically coupling becomes possible.

In a magnetized plasma, the electromagnetic waves can propagate by changing their modes to the plasma wave modes such as an electron cyclotron wave or helicon (Whistler mode) wave.[14][15] On the other hand, in non-magnetized plasma, an RF wave whose frequency is lower than the plasma frequency($\omega<\omega_p$) cannot propagate into the plasma and only penetrates a certain distance from the surface of the plasma by coupling inductively or electrically. Since these inductive and electrical couplings are the "near-field" couplings, it is rather difficult to transfer the large RF power into the plasma without an efficient electron heating process. For the collisionless plasma where the electron collision frequency ν is smaller than the angular RF frequency ω, ohmic heating should be less effective. It has been believed that the "near-field" coupling is inefficient for making a dense plasma. However, recent demonstrations showing that a dense inductively coupled plasma can exist when $\nu/\omega<0.1$ suggest that there is a powerful collisionless heating process in an inductively coupled plasma. [16][17]

Very recently, it has been theoretically clarified by Turne [9] that a collisionless heating mechanism in an inductively coupled plasma was a warm plasma effect, analogous to the anomalous skin effect in metals. In the inductively coupled plasma, the heating of electrons relates to the surface impedance. The time-averaged power absorbed by the plasma can be expressed in terms of the real part of the surface impedance as,

$$P = \frac{1}{2}\zeta_r |J|^2 . \qquad (1)$$

Here, ζ_r is the real part of the surface impedance and J the plasma current density, which relates the electric field induced by the time-varying RF magnetic field as,

$$J = \sigma E, \quad \nabla \times E = -\frac{dB}{dt}, \qquad (2)$$

where σ is the conductivity of the plasma. In a collisional plasma, the real part of the surface impedance ζ_r becomes small when $\nu/\omega<1$, as shown in Fig. 2 In this figure, the vertical axis shows the real part of the surface impedance which associates directly with the absorbed RF power in the plasma.

Turne has found that if the electrons are in thermal motion, the surface impedance can be expressed as,

$$\varsigma_r = \frac{2\mu_0 \omega \delta_a}{3}\left(\frac{1}{\sqrt{3}} + i\right), \qquad (3)$$

where δ_a, the skin depth of the plasma, is

$$\delta_a = \left[\left(\frac{2k_B T_e}{\pi m_e}\right)^{1/2} \frac{c^2}{\omega_p^2 \omega}\right]^{1/3} . \qquad (4)$$

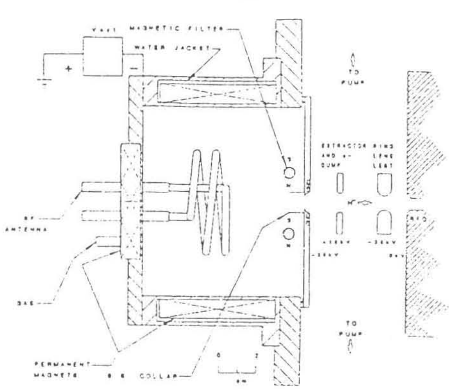

Fig. 1 Schematic layout of the LBL RF driven volume type of H^- ion source.

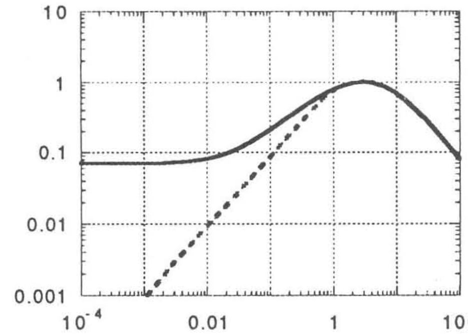

Fig. 2 Surface impedance of the plasma.[ ]

Thus, the real part of the surface impedance is not so small and becomes constant even for the relatively low values of ν/ω when the electrons are in thermal motion as shown in Fig. 2. In a cold collisionless plasma, the electric field E averages to zero everywhere since it has a time-periodic variation, and therefore no net energy gain for electrons occurs. If the electrons are in thermal motion, the electric field does not average to zero along the trajectory. If an electron can traverse the skin depth layer in a time that is short compared to the period of the electric field, it will gain net energy from the field. It has been proven experimentally that this collisionless heating mechanism for the inductively coupled plasma was very useful in making a dense and hot plasma. The RF driven plasma will soon become very important in ion source applications.

Cesium catalysis effect of negative ion formation

Recently, a volume production type of H^- ion source was developed in many laboratories. The H^- ion production mechanism of the volume type of H^- ion source is as follows. The hydrogen plasma in the discharge chamber is separated into two regions by a magnetic filter; one is a high electron temperature region and the other a low electron temperature region, respectively. In the high electron temperature region, a large number of hydrogen molecules excited in the vibrational states(V>5) are generated by collisions between hydrogen molecules and high energy electrons. Passing into the low electron temperature region, the highly excited molecules become H^- ions by dissociative attachment of low energy electrons. This scenario has been widely accepted for interpreting the H^- ion production process in the volume type of ion source .

This type of ion source has some difficulties in real operation compared with the surface-plasma type of H- ion sources. One of the difficulties is that the current density of the extracted beam is limited at a level of about $20mA/cm^2$ by the moderate arc power. Another difficulty is its large drain current of electrons which are simultaneously extracted with H^- ions. The electron drain current reaches sometimes 100 times the H^- ion beam current. However, it has been found recently that most of these difficulties could be overcome by a so-called " cesium catalysis effect". By injecting a very small amount of cesium vapor into the plasma chamber of the ion source, the H^- ion beam current density increases 4-5 times and also the electron drain current drops without any serious beam emittance growth.

The mechanism of the cesium catalysis effect is still not well understood. But it was found that the plasma electrode covered by a thin cesium layer had an important role of causing this effect.[18][19] The enhancement of the extracted H^- ion beam current is strongly related to a decrease of the surface work function of the cesium covered plasma electrode.

One of the explanations for the cesium catalysis effect is that thermal hydrogen atoms which are produced by discharge in the plasma chamber may become negatively ionized at the cesium covered surface of the plasma electrode. The surface H^- ion production probability by scattering thermal hydrogen atoms is considered to be relatively small. Several experiments have been carried out so far to measure the yields of H^- ions by back scattering thermal hydrogen atoms from cesium covered metal or semiconductor targets.[19] Recently, Okuyama et al measured the H^- ion production probability by scattering thermal hydrogen atoms from a cesium covered molybdenum surface.[11] Hydrogen atoms were generated by dissociating hydrogen molecules with a RF dissociator. After passing through a small hole in a skimmer, the atomic hydrogen beam was scattered from a molybdenum surface covered with a partial layer of cesium atoms. The work function of the cesium covered surface was determined by measuring the photo-electric current produced by irradiation of the target surface with a laser beam. The flux density of the incoming atomic hydrogen beam on the molybdenum target was measured by the compression tube method. The H^- ion formation mechanism by scattering hydrogen atoms from the metal surface has been estimated theoretically by many authors and their results show that the H^- ion production probability β^- depends on the velocity of the H^- ion departing from the surface.

$$\beta^- = (2/\pi)\exp[-\pi(\phi - A)/\alpha v_\perp]. \qquad (5)$$

In eq.(5), ϕ is the work function, A is the electron affinity of the scattered atom, and α is the exponential decay constant that gives the electron transition rate between the metal and the negative hydrogen, respectively, and $v_\perp$ is the velocity of the scattered atomic hydrogen beam normal to the surface. When a hydrogen atom comes close to the metal surface, the configuration of the electric field near the metal surface is affected by a mirror image potential caused by the electron and proton of the hydrogen atom. The affinity level of the hydrogen atom is shifted lower towards the Fermi level of the electrons in the metal and its width is also extended. Thus, the probability that an electron of the Fermi level in the metal can penetrate to the surface by tunneling through the potential wall of the work function of the metallic surface, which is lowered by the cesium coverage, is greatly increased and the production possibility of the H^- ion at the surface is also extended. On the other hand, when an H^- ion formed at the surface is leaving the surface with a certain velocity and the process is conceived to be adiabatic, the electron in the affinity level of the H^- ion can move back to the surface and the H- ion returns to the neutral hydrogen atom. The survival rate of the H^- ions depends on their velocity departing from the surface. When the departing velocity becomes large, the survival possibility increases. This is the physical meaning of eq.(5).

In the ordinary volume type of H^- ion source, the temperature of the dissociated hydrogen atoms is ex-

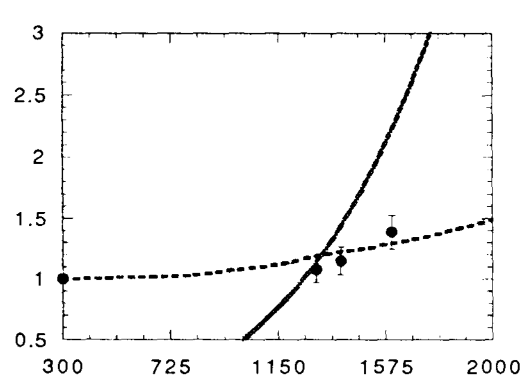

Fig.3 : Measured H^- ion production rate as a function of the atomic hydrogen temperature. The H^- ion yield is normalized against the ion yield measured when the atomic hydrogen temperature is at room temperature(T= 500K).

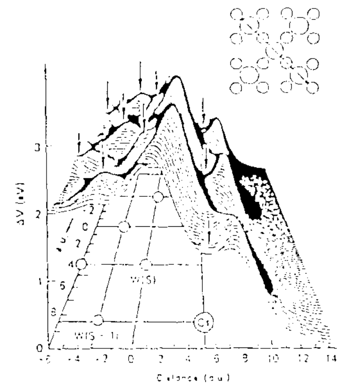

Fig.4 Calculated structure of the cesium induced potential barriers. [24]

pected to be about 0.5 eV.[20] Therefore, the H^- ion production probability for such high energy hydrogen atoms calculated by eq. (5) becomes approximately 0.013. Since the density of the atomic hydrogen in the volume type of H^- ion source is normally more than 10^{14} atoms / cm^3, the expected current density of H^- ions produced at the plasma electrode surface can reach values in excess of $200 mA/cm^2$ assuming no beam loss. This large H^- ion current density seems to be enough to explain the cesium catalysis effect producing enhancement of the H^- ion current from the volume type of H- ion source. As shown in eq. (5), the H^- ion production probability depends on the velocity of H^- ion leaving the surface. Okuyama et al. have measured the dependence of the H^- ion production probability from a cesium covered molybdenum surface. The results of their measurement is shown in Fig. 3 The solid line in the figure presents the calculated H^- ion production rate estimated from eq.(5) when the work function is 2.1eV. Clearly seen from this figure, the theoretical velocity dependence of the H- ion production rate calculated from eq.(5) is further sensitive to the atomic hydrogen velocity compared with the experimental values. At an atomic hydrogen temperature of <1200K, the calculated H^- ion production rate becomes much smaller than the measured values.

This discrepancy is not well understood. The question arises what the velocity range of the atomic hydrogen for which eq. (5) can be applied is. There have been several experiments using negative heavy ions to study the negative ion production probabilities.[21][22][23] From their results, it is well confirmed that eq.(5) is useful for the atomic hydrogen energy of more than 0.1 eV. This means that another mechanism, different from a scattering process, should be invoked for thermal atomic hydrogen to get energy from the cesiated metallic surface. It is very conceivable that the electrostatic configuration of the cesiated metal surface has a very important role in this phenomenon.

The electrostatic potential of the cesiated metal surface is quite different from that of the plain metal surface. Wimmer et al. have made a theoretical study of the nature of the mechanism of the cesiated metal(tungsten) surface(Cs/W) in order to explain the lowering of the work function and to account for the surface electro-static potential behavior.[24] According to their calculations, the Cs valence electrons are polarized towards the W surface leading to an increase of electronic charge in the Cs/W interface region and a depletion of electronic charge on the vacuum side of the overlayer. This gives rise to a dipole barrier which results a raising of the mean electrostatic potential in the interior of the cesiated metal surface. The calculated structure of the Cs-induced potential barriers is shown in Fig. 4. The Coulomb electrostatic potential of the cesiated surface resembles that inside a clean W surface except for the fact that it is shifted 2eV higher. It is remarkable that between the surface atoms, regions of positive Coulomb potential exists. It means that there is a very strong screening effect due to the high electronic density in the surface region. The Coulomb electrostatic potential for the cesiated metal surface is shifted by a value $\Delta\phi$ and becomes slightly positive between the surface atoms. This small positive potential may have a very important role in giving sufficient energy to H^- ion for surviving in vacuum. Once an electron in the Fermi level of the metal is trapped by a thermal atomic hydrogen adsorbed at the cesiated metal surface and an H^- ion is formed at the positive potential region of the surface, the H^- ion can depart immediately from the surface with large velocity because the large repulsive force can be induced by the positive potential. Recently, Shinto has made a calculation of (surviving) H^- ion production probability as a function of the atomic hydrogen temperature using the Coulomb potential shown in Fig. 4.[25] The results is shown in Fig. 3 with a dashed line. In this calculation, the work function of the cesiated metal surface was assumed to be 2 eV. The agreement between the experiment and the calculated values based on the model described above is fairly good.

The velocity of the H^- ion departing from the surface is mainly determined by a repulsive force caused by a positive Coulomb potential at the cesiated surface. Thus, the survival possibility of H^- ions departing from the surface becomes large because their velocity is greater than thermal velocity. The electronic density localization in the cesium-metal interface region shifts the electrostatic potential to higher energy. This leads not only a decrease of the work function of the metal surface but an increase of the positive potential barrier at the surface, which gives enough energy to H^- ions to reach high survival possibilities when departing from the surface.

Sheath condition in negative ion plasma

In a negative ion source plasma, there are three types of charged particles; positive ions, electrons and negative ions. The sheath structure of a plasma including negative ions is predicted to be rather complicated compared with that of ordinary plasma having only positive ions and electrons. Since the quality of the negative ion beam extracted from the ion source depends largely on the sheath configuration in the beam extraction region, it is very important to understand the structure and the condition of sheath formation in a negative ion plasma. In the one-dimensional sheath model for the plasma having positive ions, electrons and negative ions, assuming that the plasma is in thermal equilibrium and collisionless, and the density of each charged particle component shows a Boltzmann distribution, the space-charge potential should obey the following equation.

$$\frac{d^2V}{dx^2}=\left(\frac{en_{ps}}{\varepsilon_0}\right)\left\{\left(1+\frac{V}{V_s}\right)^{-1/2}-\alpha_s\exp\left(-\frac{eV}{kT_n}\right)-(1-\alpha_s)\exp\left(\frac{-eV}{kT_e}\right)\right\}. \quad (6)$$

Here, $\alpha_s=\frac{n_n}{(n_e+n_n)}=\frac{n_n}{n_p}$, and $\alpha=\frac{n_{ns}}{(n_{es}+n_{ns})}=\frac{n_{ns}}{n_{ps}}$.

The subscript "s" in these equations denotes the edge of the sheath. This equation was first analyzed by Itatani [26] and the stable sheath criterion was obtained using Bohm's criterion for a common plasma. According to his analysis, when it hold that $5-\sqrt{(24)} < T_e/T_n < 5+\sqrt{(24)}$, the plasma has one stable sheath structure. For example, when T_e/T_n is 1, $\eta_s(=eV_s/kT_e)$ which satisfies the Bohm's criterion for stable sheath condition becomes constant for any α and αs as shown in Fig. 5-a. It implies that a stable sheath is formed for any values of negative ion to electron ratio in plasma or sheath when the conditions $1/2 < \eta_s < 3/4$, and $T_e/T_n = 1$ are fulfilled. When T_e/T_n is outside above range, the plasma has two different seath structure. When $T_e/T_n = 20$, the stable sheath condition for ηs is shown in Fig. 5-b. As can be clearly seen from this figure, there are two separated regions of ηs which satisfy the stable sheath condition, but both are very limited. This is not a preferred situation for obtaining an intense negative ion beam. A low electron temperature is very important in achieving a stable, negative ion dominanted sheath formation.

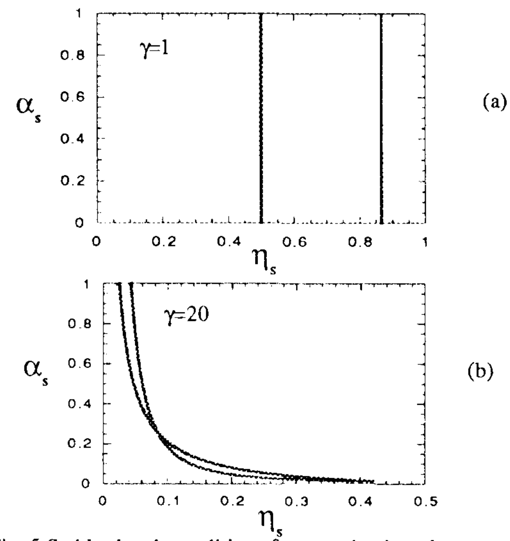

Fig. 5 Stable sheath conditions for negative ion plasma.
(a) γ=1 (b) γ=20

Fast beam chopping in a negative ion source

In beam injection from a linac to a synchrotron, because of the continuous beam configuration, an adiabatic increase of the RF voltage of the synchrotron, "adiabatic capture scheme", has been commonly used. In this scheme, however, a small beam loss is, in principle, unavoidable. For the high intensity synchrotron, the beam loss, even if it were small, would be very harmful because of radiation. A fast beam chopper which can eliminate RF capture losses by accommodating the initial beam distribution in the RF bucket is, therefore, very useful.

The fast beam choppers which have been developed so far are electrostatic deflection devices and are mostly placed at the low energy beam transport(LEBT) line between the ion source and the pre-accelerator such as an RFQ linac. This is simply because the beam energy should be as low as possible to have a large beam deflection angle with low voltage applied to the electrodes. The practical beam energy is limited to less than 50keV. Since the beam velocity is relatively small, the slow-wave type of the beam chopper has been used previously.[27][28] The deflecting electrodes are separated into many strips and the longitudinal length of each strip is adjusted to match the transit time to the required rise time on the beam pulse.

This type of fast beam chopper has been successful. However, several problems have arisen in actual operation. The low energy beam is normally fully space charge neutralized by ionizing the residual gas. The positive ion beam is neutralized by electrons and the negative ion beam by positive ions, respectively. The electrostatic field of the chopper strongly affects the neutralizing electrons or ions in the transport line.[29] The destruction of the space charge neutralization causes a mismatching of the line tune due to the defocusing space charge force and an emittance growth induced by the non-linear space charge force. If the beam is a negative ion beam, these effects becomes serious because the neutralizing ions are positive ions. The mobility of the positive ions is so small that it may take more than several hundred nanoseconds before they are completely swept out from the beam line. The frequency (repetition) of the fast chopper is normally several MHz which is adjusted to the injection RF frequency of the synchrotron. Hence, the tune of the transport line would be largely affected by the chopped pulse length of the beam. This effect sometimes causes a large beam loss and emittance deterioration. If the beam is chopped longitudinally, not transversely, and if the chopped beam is generated in the ion source as well, these non-neutralizing space charge effects can be eliminated and the situation becomes simple and ideal.

At KEK, a preliminary test for the fast beam chopping arranged in their H^- ion source has been carried out recently. The currently used H^- ion source for the 12-GeV proton synchrotron is a surface plasma production type. In this H^- ion source, the concave shape of the molybdenum metal is placed at the center of the plasma chamber and negative voltage of about -500 V is applied to it. A small amount of the cesium vapor is introduced into the plasma chamber and a very thin(~half monolayer) of the cesium atoms is formed at the surface of the molybdenum converter to reduce its work function. By picking up the electrons from the work function lowered molybdenum surface, a large number of H^- ions are generated and accelerated back to the plasma through a very thin plasma ion sheath. If voltage applied to the converter is pulsed, the H^- ion beam might also be modulated according to the applied pulse shape. Of course, the problem in this case is how fast modulation is possible. The voltage applied to the converter has a negative sign, and therefore the plasma is shielded to the converter by the ion sheath. The shielding effect by the ion sheath would be broken if the frequency of the applied voltage became greater than the ion plasma frequency. The ion plasma frequency is given by,

$$\omega_{pi} = \left(\frac{Z^2 e^2 n_i}{\varepsilon_0 m_i} \right)^{1/2} , \qquad (7)$$

where ni is the ion density, mi the mass of ion and Z the charge number of ion.
Assuming that $n_i = 1\times10^{12}$ n/cm^2, T_i=2eV and the plasma ions are H^+ ions only, then,

$$f_{pi} = \frac{\omega_{pi}}{2\pi} = 210 \text{ MHz} . \qquad (8)$$

The frequency range of the RF at the beam injection in the synchrotron is around a few MHz (For the KEK 500-MeV booster synchrotron, the RF frequency at the beam injection is about 2 MHz). The estimated ion plasma frequency is almost two orders of magnitude larger than the RF frequency. Thus, fast beam chopping in the H^- ion source by applying a fast pulsed voltage to its converter seems to be possible.

In order to examine this type of fast beam chopping, a preliminary test has been carried out. The voltage applied to the converter is modulated by an RF voltage from the amplifier at the maximum frequency of 10 MHz. The measurements were done at the test stand for ion source development at KEK and the extracted H^- ion beam energy was about 30 keV. Figure 6 shows the modulated H^- ion beam configuration measured by a Faraday cup. As can be clearly seen from this figure, the H^- ion frequency response is good even at 10 MHz.

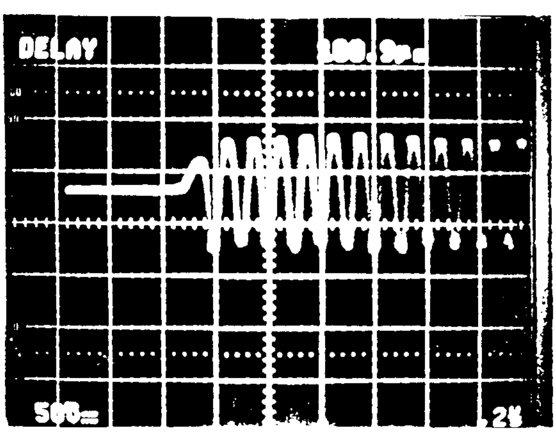

Fig. 6 H- ion beam configuration modulated by10MHz RF.

We believe that this type of fast beam chopping could be very useful. A further test using a rectangular fast pulser is in progress.

As for the volume type of H^- ion source, the possibility of fast beam modulation has been shown by a LANL group. York et al have tested fast beam modulation on the volume H- ion source by biasing the plasma electrode. [30] They have reported that 90% of the extracted beam current could be suppressed if the plasma electrode was biased at -150 or +40 volts. The time response of the beam intensity was measured to exactly correspond to the applied voltage whose turn-on time was approximately 100 ns. This is a very impressive result. In both cases for a surface plasma or a volume type of H^- ion source, a fast beam chopping which can be accomplished in the ion source itself seems to be very attractive and promising.

Summary

This paper described the following four topics concerning recent developments of negative ion sources for intense hadron accelerators.
(1) Generation of a dense plasma by high power RF with inductive coupling,
(2) Enhancement of H^- ion production rate and reduction of electron drain current by cesium feeding (cesium catalysis effect),
(3) The sheath condition of negative ion plasma, and
(4) Fast beam chopping in negative ion source.

The author would like to express his sincere appreciation to all of the program advisory committee members of LINAC'94 for giving him an opportunity to present this paper. He is also indebted to his colleagues in the injector group of the 12-GeV PS at KEK for valuable discussions and encouragement.

References

[1]H.V. Smith et al., Rev. Sci. Instrum.,64, 393(1993).
[2]Yu.Belchnko et al., Rev. Phys. Appl. 23,1847(1988).
[3]J. Alessi, AIP Conf. Proc., No. 158, 419(1986).
[4]C. Schmitt. et al., ibid, 475(1986).
[5]R.L.York, AIP Conf. Proc., No.111,410(1984).
[6]Y.Mori et al., AIP Conf. Proc., No.158,378(1986).
[7]J.Kwan et al., Rev. Sci. Instrum., 61,369(1989).
[8]K.N.Leung et al., Rev. Sci. Instrum., 62,100(1991).
[9]M.M.Turne, Phys. Rev. Lett., 71, 1844(1993).
[10]T. Inoue et al., Rev. Sci. Instrum., 61,496(1990).
[11]T.Okuyama et al., Rev. Sic. Instrum., 63, 2711(1992).
[12]A.Ando et al., Rev. Sci. Instrum., 63, 2683(1992).
[13]K.Saadatmand et al., Rev. Sci. Instrum.,65,1173(1994).
[14]H.Watanabe et al., Jpn. J. Apply. Phys., 6,6341(1967).
[15]R.W.Boswell, Phys. Lett., 33A,457(1970).
[16]J.B. Keller,"Abst. 42 Gaseous Electronics Conf. Palo Alto, 1989,p.197.
[17]T.Shirakawa et al., Jpn. J. Apply. Phys.,29,L1015(1990).
[18]Y. Mori et al., Nucl. Instr. Meth., A301,1(1991).
[19]S.T.Melnychuk et al., J.Vac.Sci.Technol.,A7,2127(1989).
[20]H.V.Smith et al., Rev.Sci. Instrum.,61,424(1990).
[21]M.L.Yu, Phys. Rev. Lett.,47,1235(1981).
[22]Y.Mori, Rev. Sci. Instrum., 63,2357(1992).
[23]H.Tsuji et al., Proc. 14th Symp. on Ion Sources and Ion-Assisted Technology ISIAT91,Tokyo,1991,p99.
[24]E. Wimmer et al., Phys. Rev., B28,3074(1983).
[25]K.Shinto, Private Communications.
[26]R.Itatani, Proc. 11th Symp. on Ion Sources and Ion-Assisted Technology ISIAT87, Tokyo, 1987,p189.
[27]J.S. Lunford et al., IEEE Trans. Nucl. Sci., NS-30,2830(1983).
[28]J.M.Brennar et al., IEEE PAC Conf. Proc.,1989,p1154.
[29]J.M.Brennar et al., IEEE PAC Conf. Proc.,1992,p1003.
[30]R.L.Yori et al., IEEE PAC Conf Proc.,1993,p3175.