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Review article

Laser ion source for heavy ion inertial fusion

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Abstract

The proposed heavy ion inertial fusion (HIF) scenarios require ampere class low charge state ion beams of heavy species. The laser ion source (LIS) is recognized as one of the promising candidates of ion beam providers, since it can deliver high brightness heavy ion beams to accelerators. The design of LIS for the HIF depends on the accelerator structure and accelerator complex following the source. In this article, we discuss the specifications and design of an appropriate LIS assuming two major types of the accelerators: radio frequency (RF) high quality factor cavity type and non-resonant induction core type. We believe that a properly designed LIS would satisfy the requirements of both types, while some issues need to be verified experimentally.

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Keywords: Inertial fusion; Accelerator; Ion source; Laser ablation; Heavy ion source

1. Introduction

In the past, various scenarios of accelerator complexes for a heavy-ion inertial fusion (HIF) were proposed. The specification for every proposed beam to ignite a fusion condition is more demanding than what we have achieved using the existing accelerator technologies. If we assume 1 MJ beam energy with 1 GeV/u at the final irradiation point, 1 mC beam charge is required. Assuming a 10 µs beam pulse width, 100 A total beam current is required. The desirable current is much larger than the maximum available value provided by a single ion source; therefore, an accelerator configuration using multiple front-ends is envisioned. In other words, an ion source is required to provide a beam current as high as possible to simplify the accelerator complex. In addition, a small transverse beam size is crucial to reduce the size of accelerator components, and consequently, the beam emittance is the most important key to the realization of a HIF power plant. The ion source for HIF must provide a high brightness beam with a large beam current in a pulsed operation mode. To fulfill the requirements, we believe a laser ion source (LIS) provides the most suitable and promising solution.

For the ion species of the driver beam, we propose to use mono-isotopic elements, such as ^{89}Y, ^{93}Nb, ^{103}Rh, ^{127}I, ^{133}Cs, ^{197}Au and ^{209}Bi. For example, if we use lead, which is a typical heavy mass element, it has four isotopes, where ^{208}Pb occupies only 58% of its natural abundance, and the other three isotopes have lighter masses and may cause beam losses somewhere in the accelerator chain. One also needs to consider the chemical stability of the species which is used as a laser target. For example, Ti and Zr capture a large amount of surrounding gases and those impurities may create unwanted ions. Thus, we advocate adopting Au^{+} ions for the HIF driver beams. If a higher charge-to-mass ratio ion is preferred in order to shorten the accelerator, we propose using Nb^{+} rather than requiring beams of Au^{2+}. This is because the laser irradiation conditions to produce charge state 2+ will typically

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produce ions of neighboring charge states. In this article, Au^+ ion beams with currents in the ampere range and good emittance are assumed.

2. Principle of a laser ion source

The first descriptions of laser ion sources can be found in the articles from the 1960's [1,2]. The laser was invented in 1960, and the first laser ion source was proposed within a decade. Therefore, the laser ion source was one of the earliest applications of laser. The principle is very simple. An intense pulse of laser light is focused on a solid target, which is placed within a vacuum vessel. The laser energy is used to ionize the target material and an ablation plasma is induced. Since the laser irradiation period is very short, typically less than a few tens of nanoseconds, the heated plasma does not have time to expand much during the pulse and its density remains high. No extra confinement forces, such as magnetic field, are needed. After laser irradiation, the plasma expands slowly and simultaneously moves away from the target surface, so that the gravity center of the expanding plasma has a velocity perpendicular to the target surface. Fig. 1 shows the expanding plasma emanating from the target to the extraction electrodes. When the head of the plasma plume reaches the extraction voltage gap, ion beam formation starts. This process continues until the end of the plasma plume reaches the extraction electrode. Although the laser irradiation is very short (~10 ns), the pulse width of the extracted ion beams can be extended to the microsecond scale.

3. Driver laser

Historically, CO_2 lasers was used as the driver for laser ion sources [3–5]. They can emit large laser energy with high duty factors and are widely used for industrial machining applications. To obtain high charge state heavy ions, a high temperature plasma is required. This requirement matches the CO_2 laser's capability. The typical wavelength is about 10 μm, which is in the infrared spectral region. Therefore, a vacuum window made from zinc selenide or salt crystal is used, which is transparent for the CO_2 laser wavelength. A CO_2 laser has a gas mixture medium and requires a discharge to obtain a population inversion. Due to the discharge process, special attention is required to obtain good stability. The pulse length is typically more than a few tens of nanoseconds with a long tail. Fig. 2 shows a typical laser pulse of a CO_2 laser (Ushio TEA 10.6 μs 6.4 J). Within the long laser pulse period, the plasma expansion starts. The laser is continuously transferring the energy to the plasma deep within the expanding plasma, so that the plasma is not heated evenly. Therefore, the momentum distribution of the ions in the plasma does not represent a shifted Maxwell–Boltzmann distribution. A CO_2 laser is one of the candidates of driver lasers.

Fig. 1. Principle of laser ion source.

We have been using Q-switched Nd:YAG lasers for ion source application for more than 10 years [6]. Many reliable models in a reasonable cost range are available in market. The fundamental wavelength and typical pulse duration are 1064 nm and 6–10 ns respectively. The laser energy can be controlled easily by changing the interval between the flash lamp trigger and Q-switch timing or the flash lamp's excitation. To minimize undesired target damage, a contrast of the Q-switch is important since a laser leakage before opening the Q-switch may heat the target before starting the main laser pulse. For the HIF purpose, we only need a moderate laser energy because relatively low plasma temperature is required for low charge state ions. The pulse length of Nd:YAG lasers is adequate to achieve thermal equilibrium and the obtained ion pulse shape is quite reproducible. Here, an Nd:YAG laser would be a good driver for HIF.

We have tested shorter pulse length lasers including a sub nanosecond laser system which is equipped with a stimulated Brillouin scattering (SBS) cell [7]. This may result in reduced target consumption; however, we did not yet find significant advantages compared to a typical Nd:YAG laser. The selection of the driver laser is important for the reliable application for HIF and we need to keep an eye on the developments in the laser technology field.

4. Laser target

As mentioned above, we assume solid gold or niobium foils as the target material. The required charge state is only 1+ and the laser power density needs to be controllable between 2×10^8 and 10^9 W/cm^2 for efficient ion production. The laser spot size on the target surface would be several mm in diameter, when we use several hundred mJ of laser energy. In that case, the damage on the target surface caused by a single

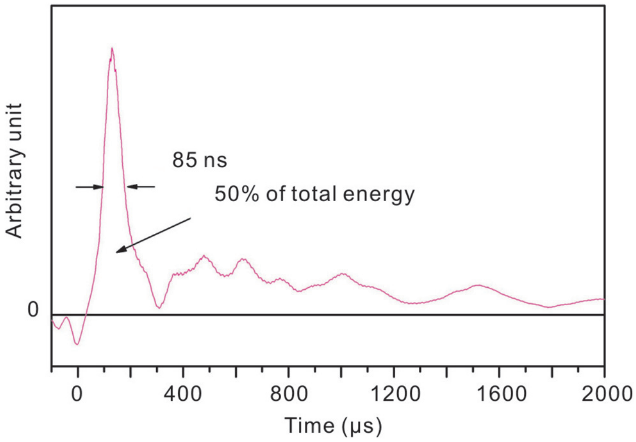

Fig. 2. Typical waveform of CO_2 laser.

laser irradiation is minor. In order to provide highly charged ions, the laser beam should be focused on the target using a short-focal-length lens, which creates craters with a depth more than 100 μm. Once the surface is deformed heavily, it is difficult to obtain reproducible plasmas from the same target surface. However, for the lower power densities required to induce singly charged ions, we can apply multiple shots on the same spot up to a few hundred times. After many irradiations, the surface becomes damaged by ablation. A very thin surface layer on the target, less than 1 μm, is turned into plasma and an adjacent deeper layer is just evaporated as neutral particles. The remaining melted surface after the laser irradiation is rapidly resolidified. During the very short time that the target material is liquefied, surface tension causes blisters formation. Sequential multiple irradiations increase the size of the blisters and a visible pattern shows up. This solid geometry induces nonuniformity of the laser irradiation condition within a laser spot. For example, a bulge makes a shadow of the laser light or lower laser power density area, and those areas do not provide plasmas. This surface deformation gradually reduces the ion beam current and has to be compensated by increasing the laser energy or a plasma guiding solenoidal magnetic field which will be explained later. A used gold target is shown in Figs. 3 and 4. For long-term maintenance-free operation, target scanning methods and deformation of the target surface need to be studied.

5. Solenoid confinement of laser ablation plasma during expansion and beam extraction

When we design a LIS for a HIF application [8,9], the first parameter we need to determine is the required ion pulse length. The laser power density is restricted to provide mostly singly charged ions and it also characterizes the plasma expansion velocity and moving velocity against the target surface of the entire plasma. Once the pulse length of the ion beam is chosen, the distance between the target and extraction point, and the plasma drift distance, can be determined. In the plasma expansion stage, each ion moves straight with constant velocity, and the expansion occurs in a three-dimensional space. The difference in arrival times of the fastest and slowest ions at the extraction point defines the ion beam pulse width. Therefore, the pulse width is proportional to the plasma drift distance which usually defines the total length of the LIS.

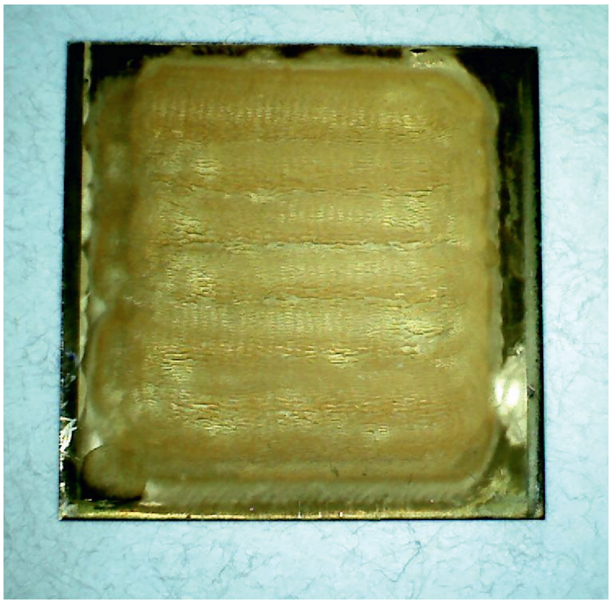

Fig. 3. Gold target sample after irradiation. The target was irradiated by 1.5 million laser shots with 4 mm spot diameter and ~400 mJ energy from a Q-switched YAG laser. The target plate is 25 mm × 25 mm and was scanned for uniform target surface consumption. A single laser shot ablated about 1 μg.

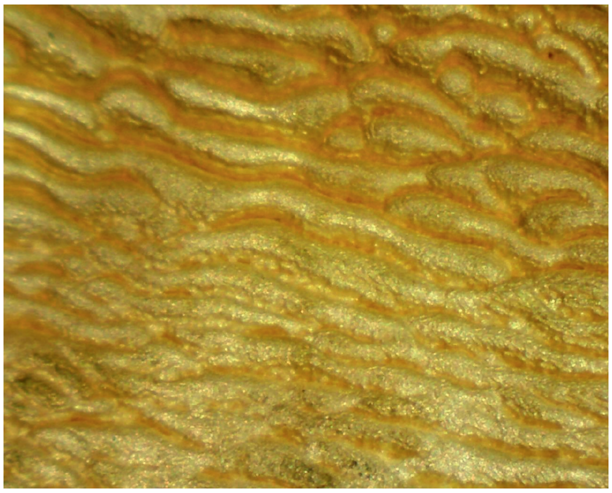

Fig. 4. Closed-up view of the used target surface.

Since the plasma expands in space, a long drift length gives a longer ion pulse width and simultaneously dilutes the ion density at the extraction point. The plasma density at the beam extraction point is inversely proportional to the cube of the drift distance because the plasma expands in three dimensions. For example, if we extend the ion beam pulse length twice, the drift distance needs to be doubled and the obtained beam current goes down to one eighth. To compensate for this steep beam current reduction, a longitudinal solenoid field is quite effective. As shown in Fig. 5, a solenoid field suppresses the transverse expansion of the plasma and enhances the beam current dramatically. Typically, by applying a static solenoidal field of a few tens of Gauss, the ion beam peak current can be increased easily by several times compared to the case with no magnetic field. The enhancement factor is adjusted by

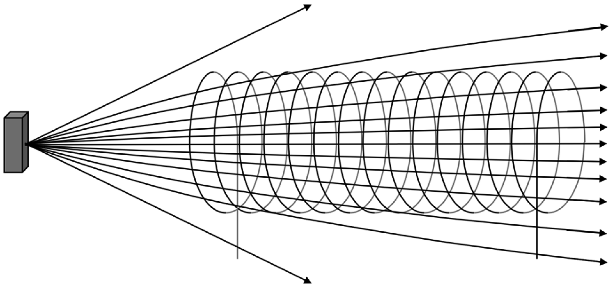

Fig. 5. Effect of solenoid magnetic field on expanding ablation laser plasma.

changing the position, length, aperture size and field strength of the solenoid magnet. An example is shown in Fig. 6. Our recent study has revealed that a certain low field strength region may ignite the instability of the expanding plasma. The solenoid needs to be designed to avoid this unstable field range.

Of course, an ion beam current can also be adjusted by a laser energy without changing the laser power density. This means, the laser spot area must be adjusted according to the laser energy. Typically, a small table-top 1 J-class Nd:YAG laser can provide a few hundreds of mA of gold ion beam easily without a solenoid enhancement.

6. Ion beam current profile manipulation

A typical ion current profile has a shifted Boltzmann—Maxwell distribution as shown by the red curve in Fig. 6. At the beam extraction point, ion density changes as a function of time and this causes a time dependent variation in beam divergence. This variation in beam divergence increases the total beam emittance compared to a constant-current ion beam pulse. Also, this current variation within the ion beam pulse is not suitable for a HIF accelerator, as the design value of the space charge limit of the whole accelerator chain needs to be designed using the peak current of the ion pulse at the ion source. Therefore, modification of the ion pulse to produce a flat top beam current profile is extremely preferable. To obtain a flat top profile, we are investigating a fast ramping scheme using a solenoid at the plasma expansion region near the target. By varying the solenoid magnetic field strength during a beam pulse, the beam current profile can be tailored. A single rapid excitation of a short solenoid was demonstrated and has been implemented in the LIS at Brookhaven National Laboratory (BNL). An example is shown in Fig. 7. More sophisticated manipulation schemes are being studied. This technique is very important for the realization of a LIS for the HIF application.

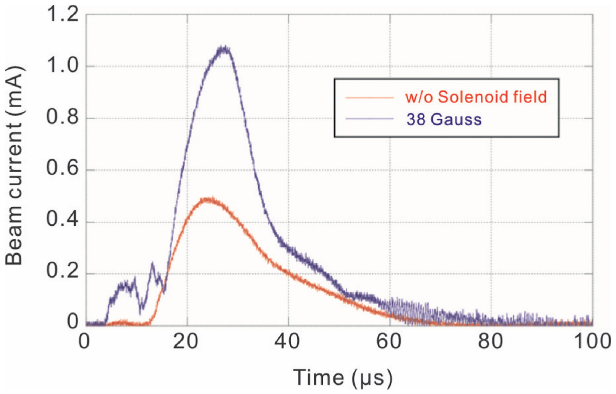

Fig. 6. Ion beam current enhancement by a solenoid magnet. The red curve shows the beam current from an iron target irradiated by 6 ns, 630 mJ, 1064 nm laser. The ion current collector was placed at 560 mm away with a 2 mm sensing aperture. The blue curve shows the enhanced ion current by a solenoid with 480 mm length, 74 mm aperture and 88 Gauss axial magnetic field. The entrance of the solenoid was 320 mm away from the target. The ion collector's position is at the center of the solenoid. Some peaks before the main ion current were caused by the impurities of the iron target such as hydrogen and oxygen. Since those impurities have lighter mass than iron, the current enhancement was more effective than that of the main iron pulse. Those impurities will not be accepted by the subsequent accelerator chain and do not seem to be harmful for a HIF application.

7. Ion beam extraction

The design of the ion beam extraction system depends on the type of the first stage accelerator. Currently two types of accelerating structures are planned. The first is an induction accelerator. A series of induction modules are placed with solenoid focusing lenses. An induction accelerator can handle ampere class ion beams and this high current capability matches well to the HIF application. The most serious drawback is its low acceleration field gradient. The second choice is radio frequency (RF) accelerating structure which is in use at many accelerator complexes. For the first acceleration stage, the radio frequency quadrupole (RFQ) seems to be the best solution, since it can provide a strong focusing force necessary for the transport of low velocity, high current ion beams.

The designed beam current limit should be accommodated by the accelerator complex. To explore the beam current limit, the Child—Langmuir law, commonly called “the three halves law”, is applied. A space charge force compensates the ion extraction electric field and defines the theoretical beam current limit. However, in the case of a LIS, the plasma has an initial velocity towards the beam extraction electric field region, which results in an enhanced beam current compared to the maximum predicted by the simple application of the Child—Langmuir law. This effect gives us a large enhancement factor for fast-moving plasmas [10—12]. Unfortunately, for the case of singly-charged ion production, the typical plasma velocity is only ~1 eV/u and significant current enhancement cannot be expected.

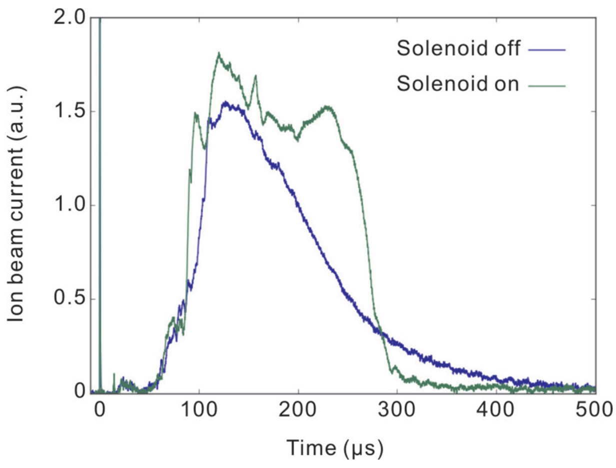

Fig. 7. Effect of the rapidly ramping solenoid in the LIS at BNL. An iron target was irradiated by a 300 mJ Nd:YAG laser. The beam currents were detected to be 3360 mm from the target. The green curve shows the effect of the rapid solenoid, which was placed at 190 mm from the target and had 56 mm length with 80 mm of the inner diameter. The excited magnetic field rose up to 60 Gauss during a 2.5 μs ramping period.

For rapid cycling beam extraction, the evacuation system needs to be carefully designed to achieve and maintain good vacuum condition. In addition to the main plasma pulse, a neutral vapor reaches the extraction area which may cause electron recombination of ions and may also trigger discharges.

7.1. Beam extraction for induction accelerator

To match the large current limit of an induction accelerator, a large extraction voltage with relatively large extraction area can be applied. A typical induction module can accommodate a large aperture ion source very close to the first acceleration gap, so that various types of the extraction system can be used. In this section, two examples will be shown, although they were not originally designed for an induction accelerator. Fig. 8 illustrates a single-hole extraction system similar to the one that is currently used at the LIS in BNL. The light blue cone is the beam extraction electrode with a 15 mm aperture. The purple disk is an intermediate electrode which defines the voltage applied across the extraction gap and can be adjusted to obtain a flat meniscus for minimizing the beam emittance. Fig. 9 shows a multi-hole extraction grid system which had been used in the electron cyclotron resonance proton source installed at an optically-pumped polarized ion source [13]. The extraction system is comprised of three multi-hole apertures, including a backstreaming electron suppression electrode. Both types of extraction systems can be designed to be used by an induction linear accelerator for the HIF application.

7.2. Beam extraction for RF accelerator

The RFQ was established during the early 1980's at Los Alamos National Laboratory. The transverse focusing force is induced using a principle of Paul's trap and this mechanism is commonly adopted in mass spectrometers. To have a focusing force on low velocity charged particles, electric field focusing is effective and by adding modulation on the quadrupole trap electrodes, an acceleration force can be applied simultaneously to the trapped charged particles. An RFQ accelerator creates a bunch structure, accelerates particles and maintains the beam size in a single RF resonant cavity. Therefore, an RFQ accelerator is widely used as the first stage accelerator in many laboratories in the world. The transverse motion can be described by

$$0=\frac{\mathrm{d}^2x}{\mathrm{d}t^2}+\left(\frac{qI}{2\pi\varepsilon_0 c\beta\gamma^2a^2}+\frac{qV}{mr_0^2}\cos\omega t\right)x, \tag{1}$$

here, x, q, a, m, I, r_0, ε_0, β, γ and ω are the transverse position, charge, beam radius, particle mass, total current of the beam, electrode position, permittivity of the vacuum, velocity ratio, relativistic factor and angular velocity of RF respectively. This differential equation is known as the Mathieu's equation. The condition of beam equilibrium in the channel is the balance between the space charge term and the RF focusing term. To accommodate high current high mass beam, a low RF frequency is desired. For Au^+ beams greater than 100 mA, 10 MHz or less is adequate; however, the RF resonator may become large in size.

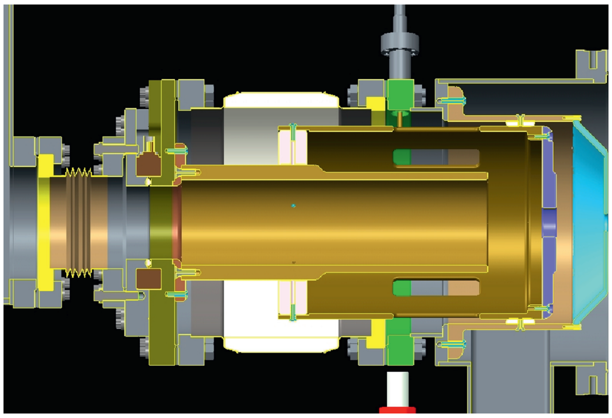

Fig. 8. Single-hole extraction system. The plasma moves from the right side of the system. The blue cone has a 15 mm aperture which is biased at around 20 kV with respect to the grounded transport line. The plasma which cannot go through the extraction hole is evacuated by the pipe toward the bottom of the picture. The white parts are insulators. The intermediate electrode is adjusted to obtain 2–5 kV across the first voltage gap for the beam extraction. The central pipe connected to the left side flange is the grounded electrode. The brown ring shows a current transformer for measuring the beam current. Typical beam currents range from 100 μA to 1 mA.

Fig. 9. Multi-hole extraction system. This system has been used to extract hydrogen ions using only 2.8 kV voltage. This grid system provides beam currents more than 100 mA.

Once the high current beam is injected into an RFQ, the ions are captured by a longitudinal and transverse RF buckets and are delivered to the following accelerator structure. The most vulnerable section to the ion beam loss is the low energy beam transport (LEBT) line between the ion source and the RFQ. Since the maximum platform voltage of the ion source in air is limited to a few hundred kV, single charge ions with heavy mass are seriously affected by the space charge repulsion force. To overcome the beam loss and emittance growth at the LEBT, we propose to use direct plasma injection scheme (DPIS), which effectively eliminates the LEBT. Fig. 10 shows a beam extraction electrode in a DPIS setup. The induced ablation plasma by a LIS moves from the target. DPIS uses this velocity to transport plasma from the LIS to the RFQ without extracting charged ions from the plasma. The plasma

Fig. 10. DPIS injection region. The vertical rods are RFQ's vanes. At the center of the end flange, a stainless steel conical extraction electrode is shown. The electrode is filled by the delivered plasma. The RFQ operates at 100 MHz with 120 kV intervane voltage. The extraction voltage is 60 kV for a 100 mA C^{4+} beam. This RFQ setup is operational at BNL.

is transported through a beam pipe with solenoid guiding. The beam extraction is done inside the RFQ cavity. In this manner, it has been demonstrated that a high density neutral plasma can be delivered to an RFQ without beam loss [14].

8. Summary

The design strategy of a LIS for the HIF application is briefly explained. Using state of the art techniques, 100 mA class Au^+ or 200 mA class Nb^{2+} beams can be provided to induction or RF linear accelerators. To maximize the efficiency of the entire accelerator system, the beam current profile needs to be tailored and more sophisticated beam shaping system is under investigation. In addition, the beam stability analysis of the plasma transportation with solenoidal field is made. Feasibility tests using high current beams is foreseen.

Conflict of interest

The authors declare that there is no conflicts of interest.

Acknowledgments

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References

[1] N.J. Peacock, R.S. Pease, Sources of highly stripped ions, Br. J. Appl. Phys. 2 (1969) 1705.
[2] Y. A. Byckovsky, V. F. Eliseev, Y. P. Kozyrev, S. M. Silnov, Sov. Patent 324 938, Oct. 1969.
[3] B. Sharkov, R. Scrivens, Laser ion sources, IEEE Trans. Plasma Sci. 33 (2005) 1778.
[4] P. Fournier, H. Haseroth, H. Kugler, N. Lisi, R. Scrivens, et al., Novel laser ion sources, Rev. Sci. Instrum. 71 (2000) 1405.
[5] M. Okamura, T. Katayama, R.A. Jameson, T. Takeuchi, T. Hattori, et al., Carbon beam acceleration using a simple injection method into an RFQ, Nucl. Instrum. Meth. Phys. Res. B 188 (2002) 216−220.
[6] H. Kashiwagi, M. Fukuda, M. Okamura, R.A. Jameson, T. Hattori, et al., Acceleration of high current fully stripped carbon ion beam by direct injection scheme, Rev. Sci. Instrum. 75 (2004) 1569−1571.
[7] M. Kumaki, D. Steski, S. Ikeda, T. Kanesue, M. Okamura, et al., Contribution of material's surface layer on charge state distribution in laser ablation plasma, Rev. Sci. Instrum. 87 (2016) 02A921.
[8] M. Okamura, M. Sekine, K. Takahashi, K. Kondo, T. Kanesue, Laser ablation ion source for heavy ion inertial fusion, Nucl. Instrum. Meth. Phys. Res. 733 (2014) 97−102.
[9] M. Yoshida, J. Hasegawa, S. Fukata, Y. Oguri, M. Ogawa, et al., Development of a high-current laser ion source for induction accelerators, Rev. Sci. Instrum. 71 (2000) 1216.
[10] G. Jaffe, On the currents carried by electrons of uniform initial velocity, Phys. Rev. 65 (1944) 91.
[11] M.S. Benilov, The Child-Langmuir law and analytical theory of collisionless to collision-dominated sheaths, Plasma Sources Sci. Technol. 18 (2009) 014005.
[12] S. Liu, R.A. Dougal, Initial velocity effect on space-charge-limited currents, J. Appl. Phys. 78 (1995) 5919.
[13] A. Zelenski, G. Atoian, D. Raparia, J. Ritter, D. Steski, The RHIC polarized H-ion source, Rev. Sci. Instrum. 73 (2002) 888.
[14] T. Kanesue, Y. Fuwa, K. Kondo, M. Okamura, Laser ion source with solenoid field, Appl. Phys. Lett. 105 (2014) 193506.