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Review article

Progress in particle-beam-driven inertial fusion research: Activities in Japan

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Abstract

Research activities in Japan relevant to particle beam inertial fusion are briefly reviewed. These activities can be ascended to the 1980s. During the past three decades, significant progress in particle beam fusion, pulsed power systems, accelerator schemes for intense beams, target physics, and high-energy-density physics research has been made by a number of research groups at universities and accelerator facilities in Japan. High-flux ions have been extracted from laser ablation plasmas. Controllability of the ion velocity distribution in the plasma by an axial magnetic and/or electric field has realized a stable high-flux low-emittance beam injector. Beam dynamics have been studied both theoretically and experimentally. The efforts have been concentrated on the beam behavior during the final compression stage of intense beam accelerators. A novel accelerator scheme based on a repetitive induction modulator has been proposed as a cost-effective particle-beam driver scheme. Beam-plasma interaction and pulse-powered plasma experiments have been investigated as relevant studies of particle beam inertial fusion. An irradiation method to mitigate the instability in imploding target has been proposed using oscillating heavy-ion beams. The new irradiation method has reopened the exploration of direct drive scheme of particle beam fusion.

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1. Introduction

The concept of particle beam fusion began with a scheme driven by relativistic electron beams in the 1970s [1]. Although a system design of heavy-ion fusion (HIF) was proposed in 1979 [2], Japanese research activity into particle beam fusion started in earnest in the 1980s using a scheme based on a driver composed of intense light-ion beams (LIBs). There is not a coherent research program in Japan, but a number of research groups at the Tokyo Institute of Technology (TIT), Utsunomiya University (UU), Nagaoka University of Technology (NUT), Osaka University (OU), and the High Energy Accelerator Research Organization (KEK) have advanced studies in fields relevant to particle beam fusion. These research groups have also collaborated with research groups at Lawrence Berkeley National Laboratory (LBNL), Brookhaven National Laboratory (BNL), and Princeton Plasma Physics Laboratory (PPPL) through the US-Japan Collaboration Program.

Basic concepts, technical and physical aspects of intense ion beams, and potential applications to fusion research were reviewed [3]. Fig. 1 schematically depicts the beam parameter regime of energy drivers based on intense particle beams on a plane defined by the beam energy and the beam current.

To drive inertial fusion, the driver beam must be irradiated on the target surface at a 100−1000 TW power level, regardless of beam energy. The power of a particle beam is the product of the particle energy and the beam current. As the particle-beam energy is restricted to the upper limit due to the appropriate range of the energy deposition in the outer region of the target, particle-beam fusion requires a high-current

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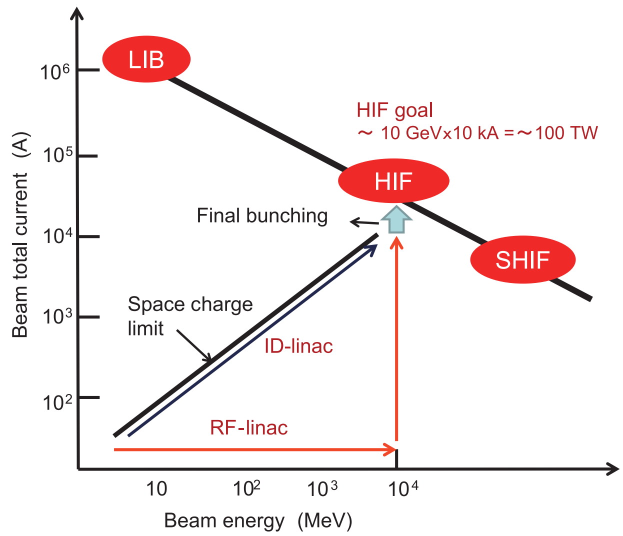

Fig. 1. Parameter regimes of drivers for particle beam inertial fusion. (SHIF: super heavy ion fusion).

beam source. That is, when LIBs such as proton or lithium beams are used as a driver, the upper limit of the beam energy is a 10 MV. Thus, the high-current beam must be extracted, transported, and focused in a controllable manner at a beam current level more than MA [4]. In addition, the high-current beam must be extracted through a diode gap, in which the space-charge effect of ions must be compensated by the electron motion to enhance the ion current density to the required level. Usually, the acceleration gap is directly driven by a low-impedance (Z ~ MV/MA) pulse-powered system. The gap impedance should be regulated to that of the pulse power system as close as possible. However, the complex and nonlinear behaviors of the pulse-powered diode are difficult to control due to the direct connection between the high-current diode gap and the low-impedance power source [4].

Strong efforts have been made in the United States, the Europe Union, and also Japan to improve the controllability [5], focus ability [6], purity [7,8], and transport scheme [9,10] of the extremely high-current beam of light ions. However, the behavior of such a high-current pulse-powered beam was difficult to control for making the driver-quality beam [11,12]. Also, repetitive operation and survival of the diode components were almost impossible.

In the 1990s, the driver of a particle beam fusion shifted from LIBs to schemes using pulse-powered Z-pinch and heavier ion beams (HIBs) with lower currents [13]. In particular, a system based on an intense accelerator was considered to be a possible energy driver for a practical fusion reactor. Then the research efforts have shifted to issues concerning high-power ion accelerators for heavy-ion inertial fusion and related subjects, specifically high-energy-density physics, in the United States [14—17], the European Union [18,19], and Japan [20—23]. The Japanese activities have extended from ion sources to target physics, including a possible accelerator scheme.

For a fusion driver, the total energy of the ions must be at an MJ level. Even HIBs with a 10-GeV particle energy, the total number of ions is estimated to be ~10^{15}. These ions should be transported to the target surface in less than 10 ns. The development of such a heavy-ion source, which can provide high-flux ions at this level, is the first challenge of a particle-beam driver based on HIBs [24]. Laser ablation plasmas (laser ion source (LIS)) have been investigated as a source of high-flux heavy ions at TIT with collaboration of groups in BNL and KEK.

As shown in Fig. 1, there are basically two schemes in the HIF system design: an RF-linac-based accelerator system and an induction (ID) linac. Heavy-ion beams must be transported with a current less than the space-charge limit, as shown by the thick line in Fig. 1. The intense-particle beam is usually dominated by self-fields, clearly demonstrating the beam control under space-charge-dominated conditions has been a critical issue of particle-beam fusion. After acceleration, to increase the beam power, the pulse width must be shortened to one-tenth at the final stage of the system (Fig. 1, arrow). The beam focus ability on the target depends intrinsically on the emittance at the final stage, which degrades by dissipation processes during beam acceleration, modulation, and the final compression.

The second issue is the study of beam dynamics during acceleration, modulation, and transport of high-current beams. After acceleration and modulation, the beam pulse duration must be reduced to almost one-tenth to increase the beam power using a longitudinal drift compression where the beam suffers the strongest effects from the space-charge field. Then the second challenge is the beam dynamics studies during longitudinal compression in the final stage of the intense accelerator, which have been progressed at NUT—TIT.

The conceptual design of heavy-ion beam drivers indicates that they are huge and quite costly [25]. The third issue is to think out a compact and cost-effective scheme of the particle beam driver. A novel recirculator scheme composed of a laser ablation ion source, a repetitive induction modulator, and a multiplex acceleration concept has been proposed at KEK for a compact and cost-effective high-power driver. As the proof-of-principle study on the new scheme is almost complete, research is shifting to the next stage of research & development.

Rational target irradiation scheme is also an important issue. Recent progress in beam-driven target physics may revive the direct implosion scheme in particle-beam fusion. A new scheme of HIB illumination has been proposed at UU for a direct implosion scheme of fusion target. This scheme is robust against nonuniform illumination of the driver. Additionally, using wobbled ion beams can mitigate the Rayleigh—Taylor instability.

Although the property of matter under the warm dense (WD) state is unclear, it determines the hydrodynamic response of a fusion target when intense beams irradiate the target in the dense deposition regime. Because the HIBs can control the energy deposition profile, a study on the WD state of matter is important to improve the implosion efficiency. Intense beams and a pulse power device can provide uniform volumetric heating on a time scale shorter than the hydrodynamic time. Hence the HIB and a pulse power system serve as an excellent tool to produce and study high-energy-density science. Dense plasmas driven by HIB and/or a pulse power device have been evaluated as well-controlled tools for HIF and warm dense matter (WDM) physics. Beam interaction experiments with WDM and related theoretical studies are in progress at TIT and NUT.

2. Extraction and control of high-flux ions from laser ablation plasmas

As shown in the previous section, the first issue of the particle beam driver is the high-flux ion injector. In a stationary plasma source, the maximum available current through an extraction electrode is limited by the Bohm current (J_B), which is given by

$$J_B = n_p e\sqrt{\frac{k_b T_e}{m_i}}, \tag{1}$$

where n_p is the density at the plasma-sheath boundary, e is the elementary charge, k_b is the Boltzmann constant, T_e is the electron temperature, and m_i is the ion mass.

On the other hand, when the drift speed (v_d) dominates the ion motion in the plasma, the available flux from the drifting plasma (J_D) can be given by

$$J_D = Zen_i v_d, \tag{2}$$

where Z is the charge state of the ions and n_i is the ion number density.

For a moving plasma in which ions have an anisotropic velocity distribution, the available flux of ions (J_P) depends on the ion velocity distribution in the plasma, and can be determined as $J_P = \max\{J_B, J_D\}$.

In an ion extraction gap, the electrons in a plasma are repelled while the ions are accelerated. When the gap is dominated by the space charge of ions, the limit of the current density through an extraction gap is given as

$$J_{CL} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m_i}}\frac{V^{\frac{3}{2}}}{d^2}, \tag{3}$$

where the subscript "CL" means the Child—Langmuir criterion, V is the voltage, and d is the width of the extraction gap. The ion extraction (emission) surface of the plasma source is determined by the balance of the fluxes (J_P and J_{CL}). The contour of emission surface is critical for optical quality of ion beams.

Fig. 2 shows a schematic of the extraction of a charged-particle beam from a plasma source through an extraction gap. As shown in the illustration, the ions (a) converge when the source plasma is under-dense: $J_p < J_{CL}$, (b) are parallel for matching condition: $J_p = J_{CL}$, and (c) diverge when the source plasma is over-dense: $J_p > J_{CL}$, owing to the contour of the emission surface.

Plasmas made by laser ablation are capable of delivering charged particles of any elements and are candidates for high-flux high-quality beams [26,27]. Laser ion sources (LISs) are used routinely for various types of accelerators [28]. However, a laser ablation plasma in vacuum expands and drifts perpendicular to the target comprised of the material to be ionized. The pulsed-ion flux expands longitudinally due to the hydrodynamics and the energy spread of ions, resulting in a drift speed and an ion-flux duration longer than the laser-pulse duration. The length of the drift space to the extraction gap determines the duration of the pulsed-ion flux, which is almost proportional to the distance (L). On the other hand, the flux of ions (I) decreases with the increase of L ($I \sim L^{-3}$) due to the plasma expansion [26]. Thus, the ion flux intrinsically has a drifted-Maxwellian-like structure. Then the time-varying structure of the ion flux should be controlled for use of ablation plasmas to realize the high-quality beam optics for ion injectors.

Controllability of the laser ablation plasma by an extraction grid [29,30], a magnetic field [31—35], and external electrodes [36,37], has been studied to evaluate the LIS as a source for a high-flux high-quality ion injector. The charge state of ions in the ablation plasma is primarily determined by the laser intensity (I_L). As the power density level required for singly-ionized Cu ions is estimated to be $I_L = 10^8$—10^9 W/cm^2,

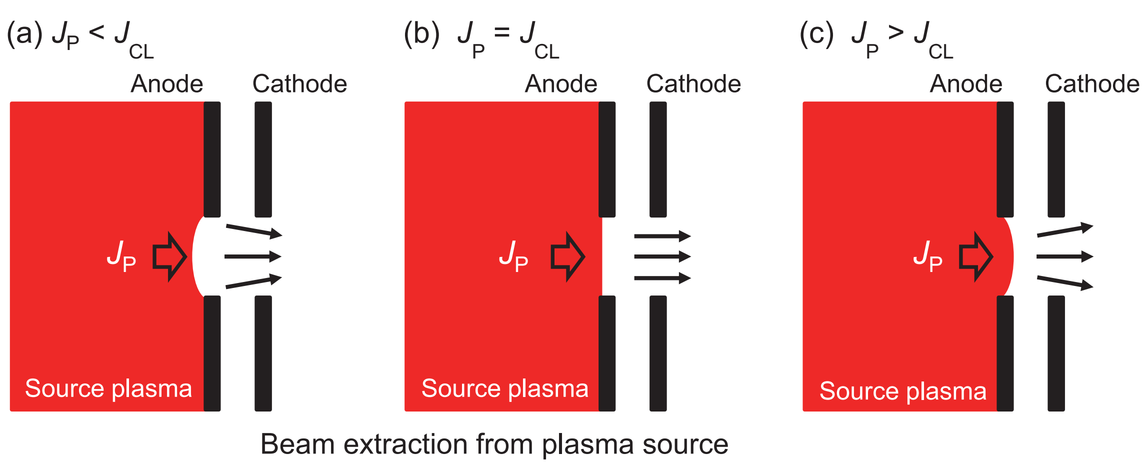

Fig. 2. Behaviors of ion extraction and the emission surface from the plasma source as functions of the flux balance.

almost all of the studies shown below are conducted with a laser irradiation at this intensity level.

2.1. Grid-controlled ion extraction from laser ablation plasmas

When the extraction gap is properly setup in the over-dense regime ($J_p > J_{CL}$), a virtual anode can be formed in front of the extraction electrode, suppressing the flux of the ablation plasma close to the Child–Langmuir current level (J_{CL}). A grid-controlled ion-extraction scheme has been applied to a laser ablation plasma source to suppress the large flux-fluctuation due to the Maxwellian-like structure, and the applicability of the ablation plasma to the source of heavy-ion fusion has been discussed [29].

The experimental setup for a grid-controlled ion extraction from the laser ablation plasma is shown in Fig. 3. A KrF excimer laser irradiates a copper target placed at the end of a 50-cm drift chamber with an intensity at the 10^8 W/cm^2 level. A DC voltage up to 25 kV is applied to the extraction gap with an 18-mm-length, and ions are extracted from the ablation plasma under conditions ranging from the under-dense ($J_p < J_{CL}$) to the over-dense ($J_p > J_{CL}$) regimes. The results show that the grid control works properly by making a virtual anode and that the grid-controlled LIS has potential as a stable and high-current injector for heavy-ion fusion. The shape of the grid determines the ion emission surface. The grid-controlled LIS can also be operated with a spherically focusing diode configuration in which high-current ion beams are extracted from the plasma [30].

2.2. Guiding of laser ablation plasma with axial magnetic fields

To develop a high-flux low-emittance ion source, the ablation plasma should be controlled so as $J_p = J_{CL}$. To control the ablation plasma, a solenoidal magnetic field has been applied [28–32]. The dynamics of the laser ablation plasma through a quasi-static longitudinal magnetic field have been investigated to control the flux waveform. Fig. 4 shows the arrangement for the flux control experiment with a solenoidal field.

Assuming that the Larmor motion of ions can be neglected, the plasma behavior through a magnetic field can be categorized by the magnetic Reynolds number (R_m), which can be derived from the magneto-hydrodynamic (MHD) equations. As shown below, R_m can be represented by the ratio of the convection $(\tau_c = L/u)$ and the diffusion $(\tau_d = L^2\sigma\mu_0)$ times of plasma in the magnetic field. Namely,

$$R_m = \frac{\tau_d}{\tau_c} = \frac{L^2\sigma\mu_0}{L/u} = \sigma\mu_0 uL, \quad (4)$$

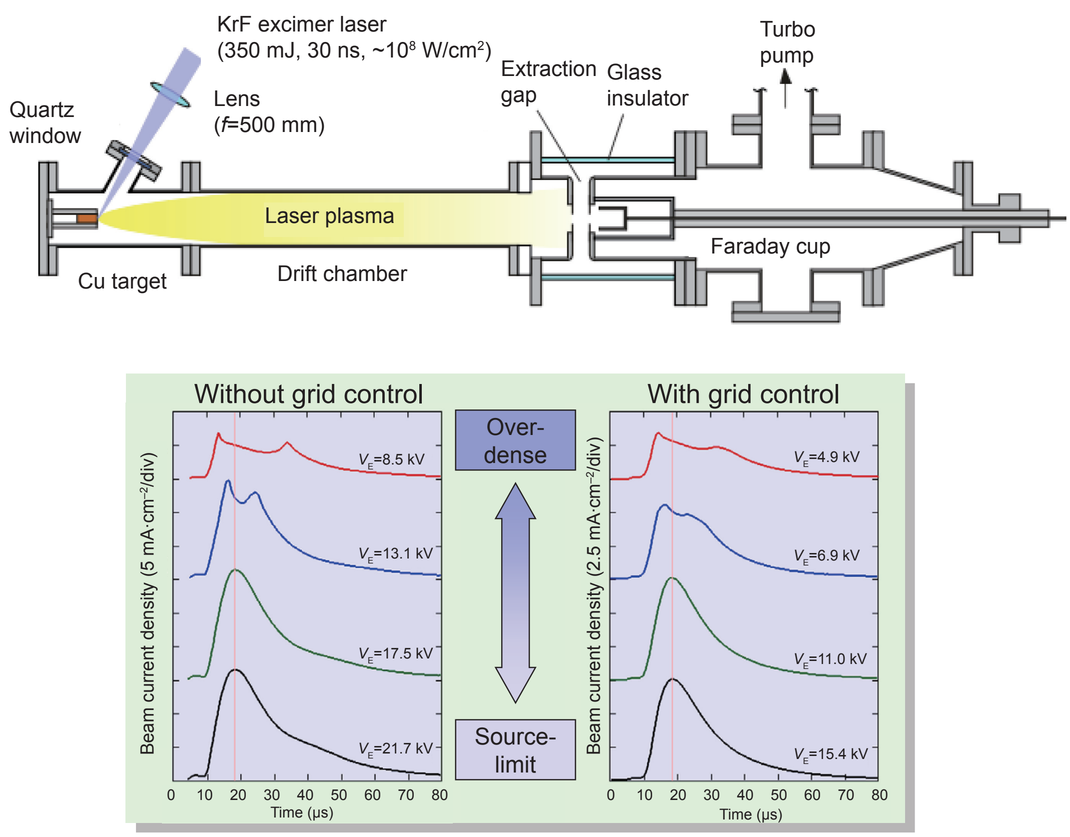

Fig. 3. Experimental setup for grid-controlled ion-extraction experiments.

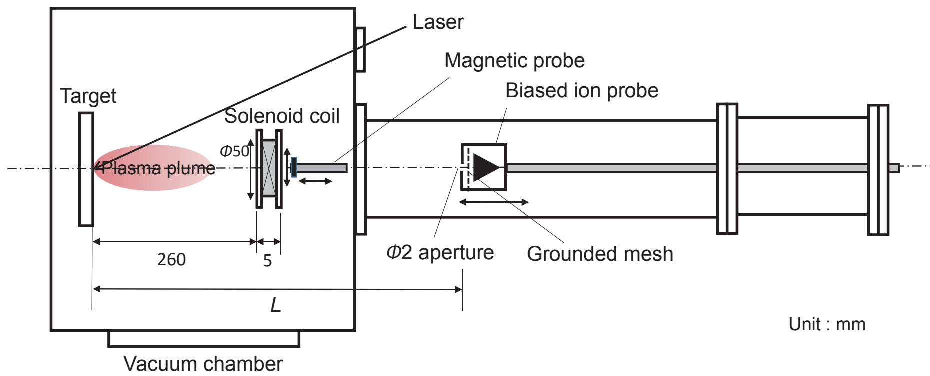

Fig. 4. Arrangement for flux control experiments by axial magnetic fields.

where σ is the conductivity of plasma, μ_0 is the permeability in vacuum, and L is the characteristic length of the phenomena.

Applying a magnetic field to the laser ablation plasma, which is made by a 10^9 W/cm^2 irradiation level, R_m is estimated to be typically around unity at L ~100 mm. The ablation plasma distributes both transversely and longitudinally over a wide range of parameter region. This means that the plasma behaves as a partially magnetized and a partially convective plasma. Therefore, the interaction is not simple, and a structure should be formed in the plasma. In fact, a structure has been observed in the plasma plume in which the ions in the outer region converge due to the magnetic field like a magnetic lens and the ions in the inner region are guided as a magnetic nozzle [31]. The results indicate that although the longitudinal magnetic field can enhance the ion flux by reducing the transverse expansion, a sophisticated parameter setup is needed to realize well-controlled LISs [32]. The temporal structure, controllability, and the potentiality of the laser ablation plasma as an ion injector have also been investigated [33−35]. These papers also discuss the possibility of plasma control by applying a dynamically interacting pulsed-magnetic field.

As discussed above, the interaction process usually proceeds under the condition with R_m ~1. Hence, the behavior cannot be explained by a simple analytical model. The interaction process between the ablation plasma and the magnetic field has been studied using a magnetic probe. The results of the plasma guiding experiments indicate that the diamagnetic current induced by the interaction plays an important role in the guiding mechanism of a longitudinal magnetic field [31].

2.3. Control of plasma potential by external electrodes

The potential of the ablation plasma was controlled positively by external electrodes through a thick electron sheath [34]. Fig. 5 shows a schematic diagram of the experimental setup. Eight ring electrodes made of brass are installed to raise the potential of the laser ablation plasma. In the experiment, a KrF excimer laser irradiates a Cu target with an intensity of

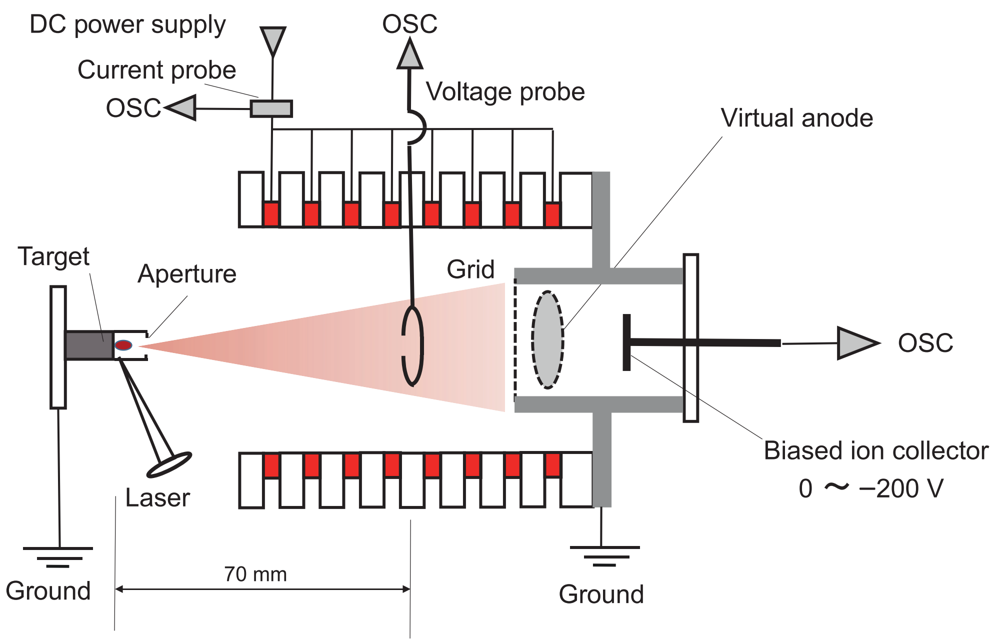

Fig. 5. Schematic of the experiment to control the plasma potential by external electrodes.

10^9 W/cm^2. An aperture placed in front of the target limits the angle of the plume expansion boundary to keep the distance (d), between the plasma boundary and the external electrodes, creating a thick electron sheath that is much thicker than the Debye length: $\lambda_D = (kT/4\pi ne^2)^{1/2}$. Since the bulk of the plasma is distant ($d \gg \lambda_D$) from the external electrodes, the sheath current is limited by the geometrical conditions.

From the positively biased plasma, ions have been extracted through a grounded grid without extraction gap and their behaviors were investigated [35]. Typical waveforms of the plasma ion flux (a) and ion currents through the extraction grid (b) are shown in Fig. 6, where a shows the distance between the grounded grid and the ion collector. As illustrated in Fig. 6(c), space charge field of the ions makes a virtual anode. The first and the second spikes in Fig. 6(b) show a transition to and a return from the virtual anode mode of ion extraction. Comparing Fig. 6(a) and (b) clearly shows that the ions can be extracted directly through the sheath and the currents are suppressed to the J_{CL} levels depending on a due to the formation of a virtual anode between the grid and the collector.

The results confirm that the ion beam is extracted through the high-voltage sheath formed between the plasma and the grounded electrode. Since the plasma is positively biased against the ground wall, ions can be directly extracted without an insulating gap [35]. Utilizing the potential raising method of laser ablation plasma, a new type of ion beam extraction, where a stable ion beam can be formed while keeping the potential of the extraction grid at ground level, is possible.

2.4. Maximum available flux of charged particles from ablation plasmas

In the case of a stationary plasma source, the space potential (V_s) rises and creates an ion sheath between the plasma and a wall boundary so as to balance the plasma-ion flux and the electron flux, and the fluxes can be expressed as

$$J_i = J_e = J_e^{th} \exp\left(-\frac{eV_s}{kT_e}\right), \tag{5}$$

where J_i is the Bohm current, $J_e^{th} = en_e v_e^{th}/4$ is the current provided by the thermal electrons, and T_e is the electron temperature. Fig. 7 illustrates the extraction process of charged particles from a stationary plasma source.

On the other hand, in the case of a source plasma with anisotropic velocity distribution such as an ablation plasma, the ion flux can be written as

$$J_i = J_i^d + J_i^{th} = Zen_i v_d + 0.4Zen_i\left(\frac{2kT_e}{m_i}\right)^{\frac{1}{2}}, \tag{6}$$

where the superscripts "d" and "th" of J denote the drift and the thermal components of the charge fluxes, respectively [38].

The laser ablation plasma has been characterized for high-flux sources of ion and electron beams [38] using the experimental arrangement shown in Fig. 8.

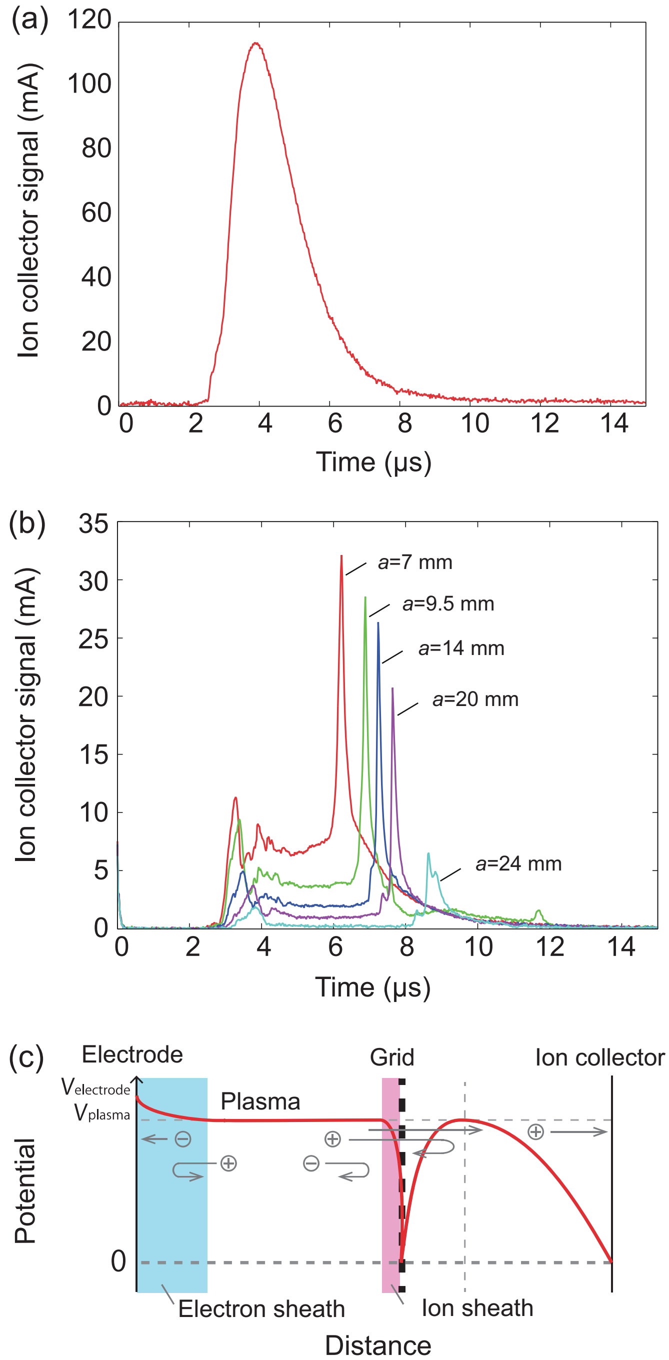

Fig. 6. Typical waveforms of (a) a plasma flux, (b) ion currents extracted through the sheath between the positively biased plasma and grounded extraction grid, and (c) image of potential profile during virtual anode mode.

The ablation plasma is biased with a positive or a negative high voltage, and the fluxes of charged particles through a pair of extraction electrodes are measured as a function of the laser irradiation intensity and the bias voltage. Fig. 9 shows typical waveforms of ion and electron beams from the laser ablation plasma. The fluxes depend on the polarity and the laser intensity. As has been indicated by Eq. (5), the available flux of ions and that of electrons should be the same. However, as Fig. 9 shows, the electron currents are measured to be almost 20 times of ion currents. That is considered also due to a

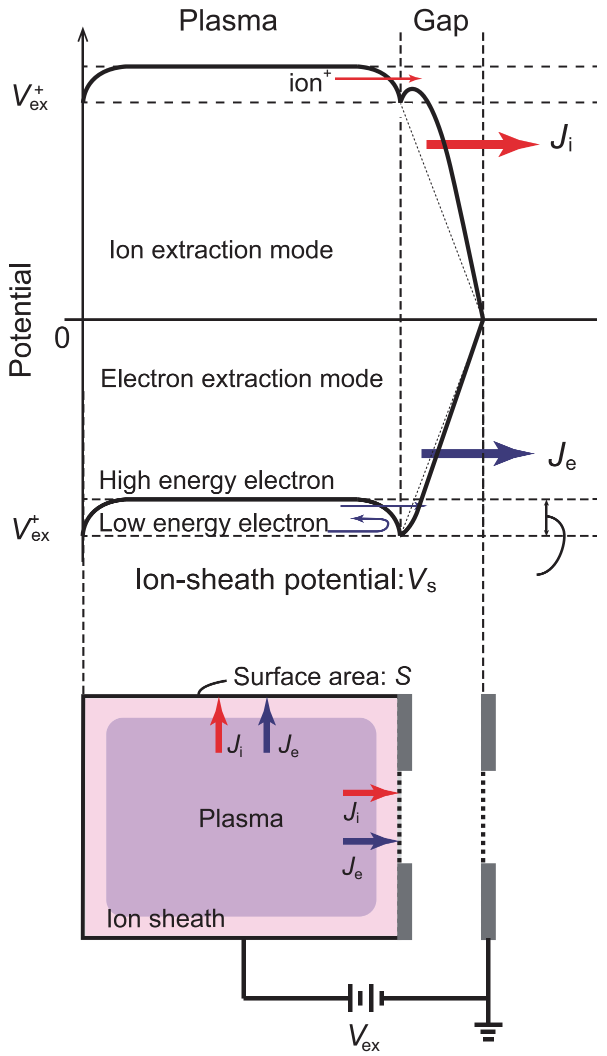

Fig. 7. Schematic illustration of charged particle extraction through a sheath of a stationary plasma source.

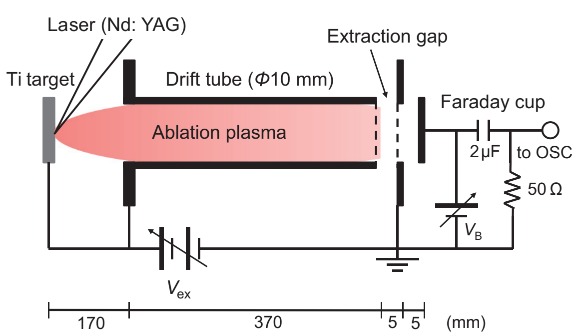

Fig. 8. Experimental arrangement for charged particle extraction from a biased laser ablation plasma.

nonstationary sheath formed by un-isotropic and dynamically evolving ablation plasma. The results confirm that, in the case of a laser ablation plasma source, the ion fluxes are dominated by the drift component of the ion motion. Thus, the available flux of ions is enhanced by supersonically drifting ions in the

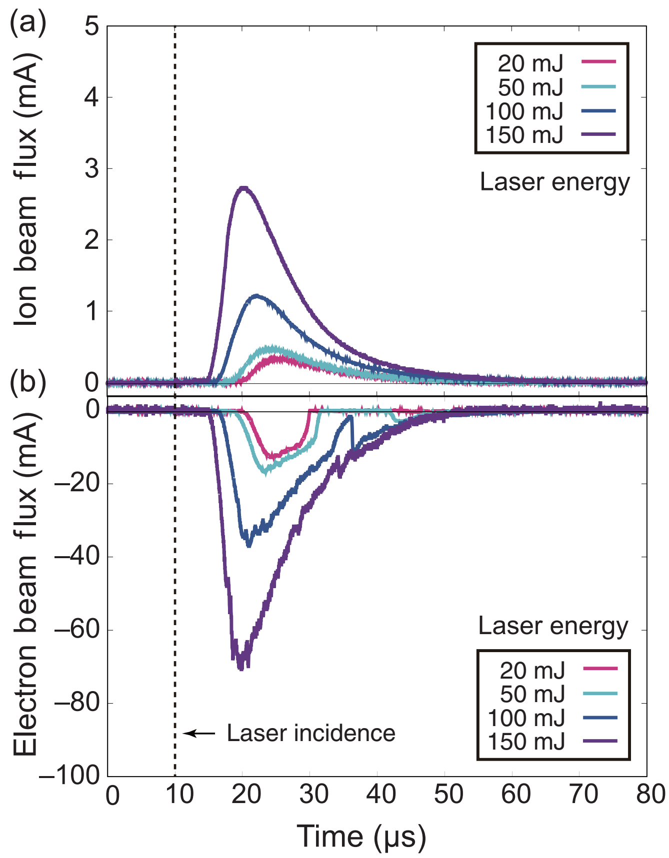

Fig. 9. Typical waveforms of (a) ion and (b) electron beams from laser ablation plasmas.

plasma [39]. The results also show the importance of the plasma sheath at the extraction boundary for charged particle extraction from the plasma source.

Charged particles from plasma sources are extracted through a plasma sheath. Both available flux and quality of the beam are determined by the ion distribution in phase space. However, these processes are incompletely understood [40]. As the extraction processes of charged particles through the sheath formed by a dynamically evolving laser ablation plasma are rich in physics, they are issues to be explored in future.

3. Beam dynamics studies of intense beams

In the final stage of the accelerator, a heavy-ion beam is at a high energy (~10 GeV) and high current (~kA). To enhance the beam power, longitudinal compression of the beam bunch is planned at the final stage where a longitudinal velocity tilt is imposed on the beam bunch to compress it to an appropriate length by the drift compression. The arrow in Fig. 1 shows the current enhancement process by the bunch compression of beam at the final stage of acceleration.

Fig. 10 schematically illustrates the induction buncher for the final compression in which the beam bunch is shortened from 100 ns to 10 ns. The velocity-modulated beam is spatially and temporally focused by the time-of-flight during the drift to the target. For an intense heavy-ion accelerator,

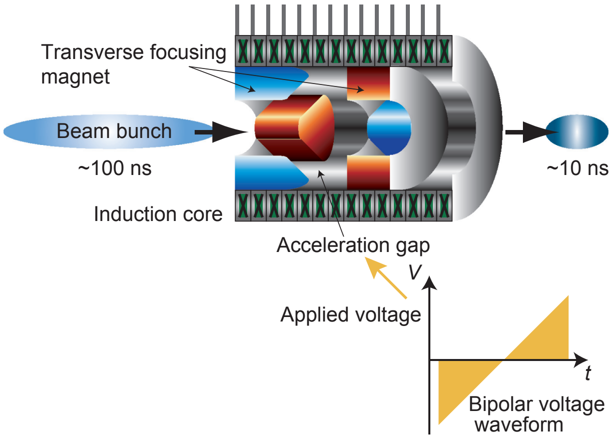

Fig. 10. Schematic diagram of the induction buncher for the final compression of intense ion beams.

either an un-neutralized or neutralized compression is considered as a possible scheme. The beam compression ratios, the pulse durations, and the resulting beam powers at the target are sensitive to the accuracy of the modulation voltage and the beam emittance at the final state. However, because the particle beam is an assembly of many charged particles with the same polarity, its behavior involves collective, unstable, and complex behaviors.

During the bunch compression, the beam is estimated to evolve from an emittance-dominant state to a space-charge-dominant regime over a short period of time. Then the space-charge field should affect the beam behavior in the high-current beam compression process. The nonlinear component of the space-charge field is predicted to redistribute a part of the kinetic and/or the beam potential energy to the transverse motions via the dissipation process induced by the collective motions of the ions. Namely, in the parameter region of final bunching, the beam emittance is no longer conserved and the dissipation process induces an emittance growth that may disturb the final compression process.

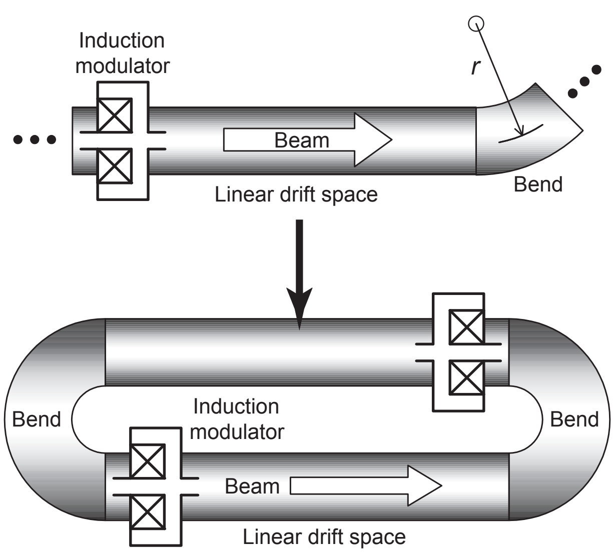

Fig. 11. Recirculator for quasi-equilibrium bunching of intense ion beams.

Generally, an intense beam is in an equilibrium state where the radial confinement force of the accelerator components and the repulsion force of beam are balanced. The repulsion force is composed of gradients of the space-charge and the thermal pressure, which increases according to the dissipation process during beam transport. When the equilibrium particle distribution exhibits a nonlinear field, the space charge field converts the electromagnetic energy of the beam into the thermal energy during the beam transport.

The behavior of beam particles during a longitudinal compression of un-neutralized beam bunch has been investigated to elucidate the compression limit theoretically and experimentally at NUT–TIT. In case of the bunch compression, effects of longitudinal velocity tilt on the dissipation process are considered to be important. Specifically, the dynamics of the intense beam in the final buncher has been investigated numerically, analytically, and experimentally.

3.1. Beam dynamics analysis with numerical methods

Numerical simulations of charged particles are indispensable tools to analyze the complex beam behaviors, specifically in the space-charge-dominated regime. A transport window of the bunching beam to completely avoid the resonance conditions has been estimated and the beam behavior in the final beam buncher has been discussed using a particle-core model [41]. The beam dynamics has also been estimated using transverse two-dimensional particle-in-cell (PIC) simulations [42]. The results indicate that the behavior of the emittance evolution depends on the bunching process; the resonance effect in the transport line is the source of the emittance growth. Additionally, the space-charge oscillations on the Debye scale lead to unfavorable behaviors for high-quality beam transport in the final beam bunching of the HIF accelerator system.

As an alternative to the fast compression scheme, a quasi-equilibrium bunching scheme using a recirculator has been proposed [43]. The configuration of the recirculating beam buncher is schematically shown in Fig. 10. The bunching voltage was applied to compress the beam bunch quasi-statically in the recirculator made by an induction modulator and bending sections. The potentiality of quasi-equilibrium compression has been discussed using an envelope model. The advantages of a recirculating buncher, which include compactness, a low modulation voltage, and a small velocity tilt, may provide a cost-effective bunch compression scheme.

The beam instability induced by the space-charge effect has been investigated by a transverse particle-in-cell simulation with a simple model where the beam current increases during bunch compression [44]. The results indicate that the beam bunching is accompanied by restructuring of the charge density distribution and emittance growth during transport. The main cause of the emittance growth is attributed to the instability excited by a strong space-charge field.

In order to evaluate the field error, a beam bunch was longitudinally compressed during transport with a field error in continuously focusing or alternating field lattices. The beam behaviors in the transport line have been discussed with numerical simulations and emittance growth due to the transverse focusing error evaluated during the final compression [45].

A multi-particle code has been developed to study three-dimensional beam dynamics in the space-charge-dominated regime. The results have been compared with two-dimensional and one-dimensional codes [46]. The beam dynamics with varying beam parameters have been numerically explained using multi-particle tracking. A two-dimensional simulation, including the current increase effects during the bunch compression, has been developed.

Halo generation and its effect on emittance growth during bunch compression have been investigated during a longitudinal compression [47]. The halo particle induces emittance growth, which depends on the drift length of the bunch compression stage. Additionally, it has been clarified that the initial particle distribution affects halo generation.

A multi-particle-in-cell simulation has been developed to analyze the behavior of beam particles in three-dimensional (3D) space, by which the kinetic energy exchanges in the longitudinal and transverse directions of a charged particle beam during the longitudinal compression are discussed. A longitudinal transverse coupling via the space-charge effect is observed by multi-particle simulations [48,49]. The ratio of effective temperatures in the longitudinal and the transverse directions derived from the numerical results was higher than that derived from the quasi-analytical estimation. The results imply that the discrepancy is caused by the nonlinear space-charge effect during the longitudinal compression.

The dynamic emittance growth during longitudinal bunching has been investigated considering the evolving space-charge effects. Fig. 12 shows an example of a numerical simulation on the emittance growth with multi-particle tracking during the longitudinal compression through a magnetic quadrupole lattice for 10 GeV–400 A, P_b^+ beams with Kapchinsky-Vladimirsky (KV), semi-Gaussian (SG), waterbag (WB), and parabolic (PA) initial distributions. The results show that the emittance evolves depending on the ion distribution.

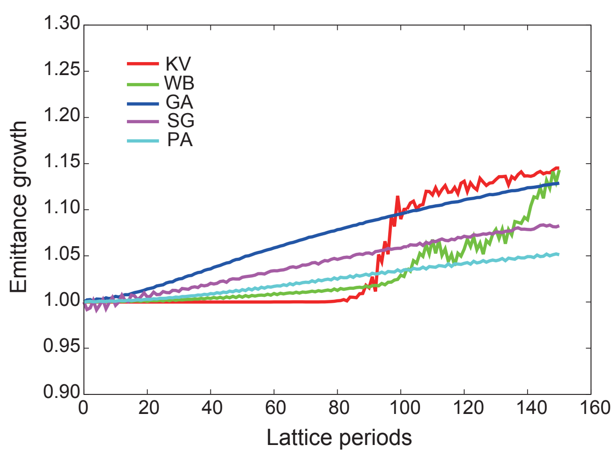

Fig. 12. Numerical simulation results on the emittance growth during a longitudinal bunch compression.

3.2. Quasi-analytical approach for the emittance evolution

In an azimuthally symmetric beam, the nonlinear evolution of the un-normalized emittance (ε) in a transport distance (s) can be described by [50]

$$\frac{\mathrm{d}\varepsilon^2}{\mathrm{d}s} = r_\mathrm{b}^2\left(-\frac{K}{2r_\mathrm{b}}\frac{\mathrm{d}r_\mathrm{b}}{\mathrm{d}s} - \frac{\mathrm{d}E_\mathrm{sf}}{\mathrm{d}s}\right), \tag{7}$$

where r_b is the beam radius, K is the self-field perveance, and E_sf is the normalized self-field energy. An analytical expression for the possible emittance growth due to a nonuniform charge distribution, mismatched beam, and off-centered beam has been derived by M. Reiser using a free-energy parameter [51].

In the case of a nonuniform charge distribution, the possible emittance growth is written as a function of the nonlinear field energy factor (U/w_0) as

$$\frac{\varepsilon_\mathrm{f}}{\varepsilon_\mathrm{i}} = \left[1 + \frac{1}{2}\left(\frac{1}{\sigma^2/\sigma_0^2} - 1\right)\frac{U}{w_0}\right]^{\frac{1}{2}}, \tag{8}$$

where (σ/σ_0) is the tune depression. The tune depression is an index of the space-charge strength where σ and σ_0 are the depressed and undepressed phase advances per lattice period [51]. The field energy difference between a uniform and a nonuniform beams per unit length $(U = w - w_\mathrm{u})$ can be estimated from the field energy for arbitrary distribution as

$$w = \pi\varepsilon_0\int_0^{r_\mathrm{p}} E_\mathrm{r}^2 r\mathrm{d}r, \tag{9}$$

where r_p is the inner radius of the beam pipe, ε_0 is the permittivity of free space, and E_r is the self-field in the radial direction. The nonlinear field energy factor can be derived as

$$\frac{U}{w_0} = a\left(\frac{\sigma}{\sigma_0}\right)^b, \tag{10}$$

then Eq. (8) can be written as

$$\frac{\varepsilon_\mathrm{f}}{\varepsilon_\mathrm{i}} = \left[1 + \frac{a}{2}\left(\frac{\sigma}{\sigma_0}\right)^b\left(\frac{1}{\sigma^2/\sigma_0^2} - 1\right)\right]^{\frac{1}{2}}, \tag{11}$$

where a and b are fitting parameters.

The equilibrium density profile is redistributed according to the change of balance between the space-charge and the thermal potentials. The increase in the beam current during a longitudinal compression is considered by the generalized perveance (K), which is defined as

$$K = \frac{2}{\beta^3\gamma^3}\frac{I_\mathrm{b}}{I_0}, \tag{12}$$

where I_b is the beam current and I_0 is the characteristic current [50].

Based on the numerical and analytical studies, it is shown that the current increase causes a dynamically unbalanced state, which induces the emittance growth.

Beams with a high space-charge intensity require that the initial phase-space distributions are specified. Broad classes of kinetic distributions commonly used in simulations have been reviewed in Ref. [52]. The equilibrium particle distribution is derived by considering the balance between the thermal energy and the electromagnetic energy in the beam. An analytical model for the possible emittance growth has been established [53]. The results show that the electromagnetic energy dissipates to the thermal energy via the space charge field induced by nonuniform profile of the beam.

Using a fitting function, an approximate solution for the possible emittance growth of the thermal equilibrium beam has been derived as a function of tune depression [54]. The maximum possible emittance growth is estimated using the tune depression in the space-charge-dominated regime. The model has been extended for variable radius conditions [55]. In the calculation, the possible emittance growth is studied without the constant radius approximation.

Using the quasi-analytical scheme based on Eq. (11), the possible emittance growth is estimated quasi-analytically considering the tune depression and the nonlinear field energy factor. The results have been compared with the numerical calculations and the experimental results. It is shown that the quasi-analytical calculation can follow the numerical results.

3.3. *Scaled experiments on beam dynamics during longitudinal compression*

The space-charge field of a high current beam affects the beam behavior during beam manipulation processes. As previously mentioned, the final stage of the HIF driver suffers most severely from space-charge effects.

In addition to the numerical and analytical analyses, experimental approaches are also indispensable to understand the complex beam behaviors. However, the current conceptual design of the heavy-ion driver is huge and costly. At TIT, a small electron beam device has been developed for scaled-down experiments on the beam behavior in the dynamically evolving space-charge-parameter region. In the scaled studies, the following envelope equation is used to introduce the scaling parameters for the longitudinally modulated beam behavior [56].

$$\frac{d^2 Z_b}{ds^2} = -\kappa_0 Z_b + \frac{K_L}{Z_b^2} + \frac{\varepsilon_z^2}{Z_b^3}, \tag{13}$$

where $2Z_b$ is the beam bunch length, κ_0 is the longitudinal focusing factor, and K_L is the longitudinal perveance, $\varepsilon_z = \sqrt{5} Z_b (\gamma_0^3 k_b T_L / mc^2)^{1/2}$ is the longitudinal emittance, where γ_0 is the Lorentz factor and T_L is the longitudinal beam temperature.

The longitudinal perveance (K_L) can be expressed as

$$K_L = \frac{3}{2} \frac{gN}{\beta^2 \gamma^5} \frac{q^2}{4\pi\varepsilon_0 mc^2}, \tag{14}$$

where N is the particle number in the bunch, q is the charge, and g is the geometrical factor [56]. Comparing the second and the third terms in the right hand side of Eq. (13) gives the space-charge parameter (S_C) as an index of the beam behavior during the longitudinal beam dynamics as

$$S_C = \frac{K_L Z_b}{\varepsilon_z^2} = \frac{3egI_0\tau_0}{40\pi\varepsilon_0 Z_b \kappa_b T_L}, \tag{15}$$

where I_0 is the beam current, τ_0 is the pulse length, and T_L is the longitudinal beam temperature. S_C provides a guideline of the space-charge effect for the longitudinal beam dynamics. Namely, when $S_C \gg 1$, the beam behavior is predicted to be dominated by the space-charge effect.

In contrast to the electron ring device at the University of Maryland [57], the simulator developed at TIT is specialized for fast bunch compression studies. A schematic of the compact beam simulator is shown in Fig. 13. In the electron beam device, a reproducible and controllable induction voltage adder composed of solid-state switching devices and Finemet cores applies the velocity tilt to the scaled beam compression experiments. A gate controlled MOSFET circuit has been developed for the controllable voltage driver. The MOSFET circuits drive the induction adder at low magnetization levels of the cores, which enable reproducible modulation voltages with jitter less than 0.3 ns. Preliminary beam compression experiments indicate that the induction adder can improve the reproducibility of the modulation voltages and advance the beam physics experiments [58].

The beam behavior during the final bunching in the space-charge-dominated regime has been investigated using the scaled-down electron beam device. By adjusting the $\beta = v/c$ value and the longitudinal perveance (K_L) of the beam and employing a parameter survey using the space-charge parameter (S_C), the behaviors of a 10 GeV–10 kA heavy-ion beam are scaled down to a 3 keV–10 mA electron beam. Preliminary experiments using the beam simulator confirmed a space charge effect when $S_C > 1$. The experimental results also show that the device has a sufficient reproducibility to discuss the bunching beam dynamics in space-charge-dominated regimes [59,60].

4. Accelerator schemes for intense beam drivers

In the 1990s, efforts focused on research and development of accelerator components for intense HIBs [61]. After almost 10 years of struggling to generate a cost-effective high-power particle beam, an accelerator system based on a repetitive induction modulator was proposed as an acceleration component for a new scheme of the intense beam drivers in 2000 [62]. The potentiality of the new scheme of ion acceleration has been evaluated through the first [63–67] and the second [68] stages of R&D by a collaborating group of KEK–TIT–NUT. Based

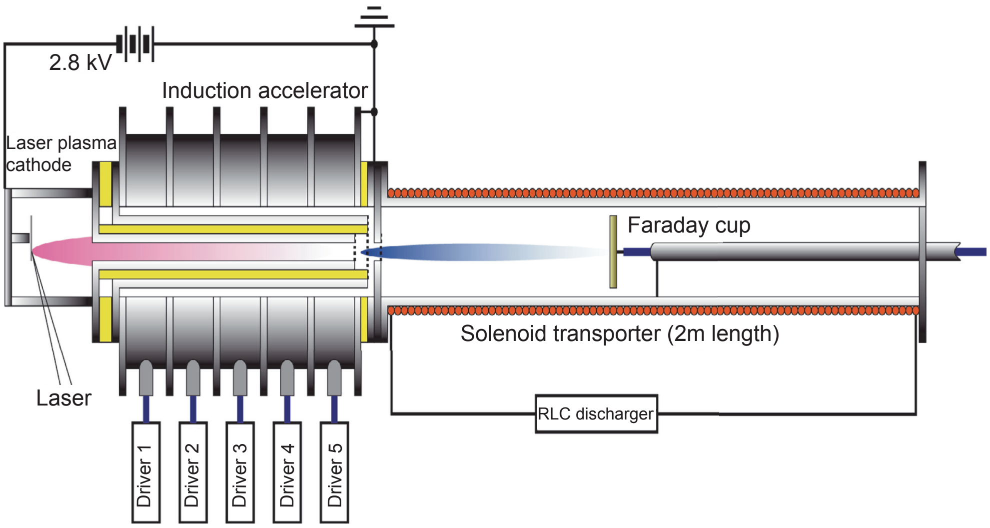

Fig. 13. Schematic diagram of a compact beam-simulator device with an induction adder.

on this system, the KEK group is planning to accelerate all species of ions without an injector [69].

4.1. Research and development on accelerator components

The beam driver based on this induction scheme injects a 10-μs beam bunch, and accelerates and compresses it according to the beam energy. To avoid the space-charge blow-up in the low-energy regime of the accelerator system, as shown in Fig. 1, the beam must start with a low current and a long pulse. Important issues for the long-pulse induction modulator are long-pulse ion injectors, voltage modulation, core material selection, and a realistic scheme for the beam transport [61].

A scheme for the voltage control has been proposed using a stacked induction modulator in which the unit voltages from independently driven power modulators are stacked in the cavity [63]. In this scheme, FET-driven $L-C$ circuits create sinusoidal waveforms, enabling low core-loss operations. Fig. 11 shows a schematic illustration, an example of the core current, the induced voltage, and the stacked voltage of the induction module driven by the FET-based driver. The FET-driven voltage driver can be operated up to the MHz range with a good reproducibility [64–66]. Fig. 14 shows the photograph of FET-voltage driver, its typical output voltage, and a photograph of the modulator installed in the KEK-PS ring.

To accommodate the highly repetitive operations of the induction modulator, magnetic core materials have been characterized, and the magnetization curves of various materials have been derived as a function of magnetization rate ($\mathrm{d}B/\mathrm{d}t$) [65]. When a steep beam bunch comes into the induction unit, the beam current conceivably causes a modulation of voltage due to beam loading. The effects of beam loading on the induction cell have been experimentally investigated [64,65].

The results characterize the voltage (V) of induction modulator as a function of the magnetization rate ($\mathrm{d}B/\mathrm{d}t$), the rise rate of beam current ($\mathrm{d}I/\mathrm{d}t$), the flux swing of the core material (ΔB), the pulse length (τ), and the impedance of the driving circuit (Z_0).

Namely, these elemental studies on the induction voltage modulator reveal that the acceleration voltage can be expressed as

$$V \sim f(\mathrm{d}B/\mathrm{d}t, \mathrm{d}I/\mathrm{d}t, \Delta B, \tau, Z_0). \qquad (16)$$

These data are indispensable not only to regulate the induction voltage but also to evaluate core loss during repetitive operations.

4.2. New quantum beam drivers for HIFs and high energy density science

Several heavy-ion driver systems have already been proposed and upgraded based on existing accelerator technologies [25]. However, they are still too gigantic to investigate beam dynamical issues in the space-charge-dominated regime and to advance research and development of the components for a cost effective accelerator system. Developing a compact, robust, and low-cost heavy-ion-accelerator system remains a critical issue for HIF and high energy density (HED) science [70].

A two-way multiplex induction synchrotron has been proposed based on the development of the highly repetitive induction voltage modulator [71]. A schematic illustration of the concept of the multiplex synchrotron is shown in Fig. 15. The accelerator consists of a two-way and multiplex induction synchrotron and a permanent magnet stacking ring. In the system, induction microtron, which is a racetrack shape induction synchrotron [72], is used as an ion injector.

Existing devices for cluster beams are usually composed of an electrostatic accelerator. Then the achievable energy is limited intrinsically by the electrical breakdown. Meanwhile, induction synchrotron can remove the frequency bandwidth limit, allowing ions to be accelerated through entire energy

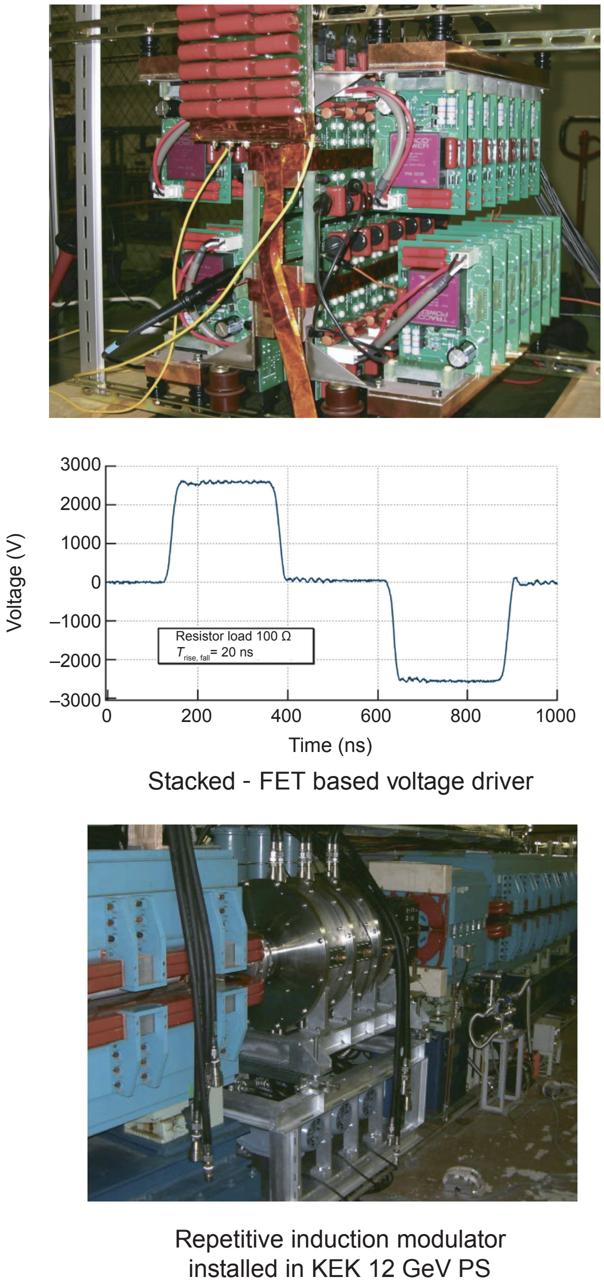

Fig. 14. Typical waveforms of core current, induced voltage, and stacked voltage of an FET-driven stacked induction modulator.

region regardless of the specific charge [68]. A two-way and multiplex induction synchrotron makes maximum use of the guiding magnetic-flux density and the induction-accelerating fields. As shown in Fig. 1, an ion beam with a heavier mass and a higher energy can reduce the current load. The compact system is expected to accelerate a giant cluster beam composed of C-60 toward 120 GeV via a stacking ring composed of permanent magnets, where the giant cluster ions are stacked without a space-charge disturbance to increase the beam intensity.

Recently, a very efficient Si cluster production method has been established, in which Si clusters are considered to be produced in a temporal and spatial confinement state induced by a converging shock wave in a cavity [73]. The super heavy Si cluster (Si-100), which is produced using this method, is a covalent crystal with a good mass spectrum. Then giant clusters such as Si-100 or C-60 of more than 100 GeV can be considered as a possible beam driver for super heavy ion fusion (SHIF).

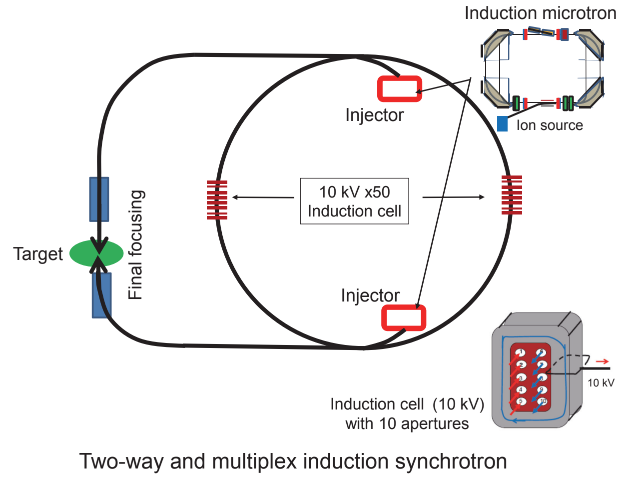

Fig. 15. Conceptual sketch of the quantum beam driver for inertial fusion.

The merits of the accelerator system using the giant clusters for the driver include:

- Reducing the space-charge effect;
- Possibility of a new scheme for the target design using the characteristic power deposition profile and a significant momentum transfer during the stopping process [74];
- Cost-effective acceleration with a compact system.

The proposed system is estimated to create an extremely high-energy-density state equivalent to ten same-sized synchrotrons [71].

5. Beam interaction experiments and target physics

Intense particle beams are attractive not only for inertial fusion but also HED science. Volumetric heating of the particle-beam energy deposition and the pulse-powered target can provide unique opportunities to study dense, strongly coupled plasmas with well-defined, volumetric, and uniform warm dense samples.

Intense particle beams may be advantageous to efficiently drive an implosion because the deposition profiles are predictable and controllable. However, the property of materials at a heated state and the stopping power are unclear. To realize a precise energy deposition profile, beam–plasma interaction experiments and related theoretical studies started in the 1990s using two types of plasma targets at TIT [75–80]. The energy loss and the charge exchange of MeV heavy ions have been measured using Z-pinch discharges and laser plasma targets. The results show an increased striping of the projectile in plasma compared with a cold target [75].

A pulse-powered thin foil target (Thin-Foil-Discharge (TFD)) has also been proposed for beam-WD-plasma interaction experiments [76]. The TFD target expands one-dimensionally in the early stage of the discharge. Then the plasma density and the temperature can be determined from the thickness of the exploding foil and the deposited electrical power with the equation-of-state.

Shockwave heated targets can provide magnetic-free well-defined target conditions. Shock-heated hydrogen has been used in the experiments to create a well-defined magnetic-free plasma target [78−80]. In the beam−plasma interaction experiments, special emphasis has been placed on evaluating the nonlinear effects on the stopping power of beam in a heated and non-ideal state target [78].

Dense plasmas have been produced using pulse-powered exploding wire discharges in water. A streak image of the wire explosion in water is shown in Fig. 16. Thin wires with 50−100-μm diameters and 18−38-mm lengths have been driven in water by a pulse power device composed of cylindrically arranged capacitors (8 × 0.4 μF). The surrounding water is effective for insulating, tamping, and stabilizing the dense, expanding plasma. As shown in Fig. 16, the plasma expands on a μs timescale accompanied by a cylindrical shockwave in water.

From the evolutions of the voltage, the current, and the radius of plasma, the conductivity of the material can be directly estimated in the WD state [81]. The electrical conductivities of copper, aluminum, and tungsten at a WD state have been evaluated using a wire explosion in water [82]. The results show that the conductivities have minimum values of less than 10^4 S/m around $\lg(\rho/\rho_s) = -1.5$ at 5000 K, regardless of the materials. As illustrated in Fig. 16, the hydrodynamics of exploding plasma is determined by the equation of state (EOS) of WDM. By inverse analysis based on a comparative study of experimental and numerical simulation, the EOS can be sophisticated. Using the same technique, the thermal conductivity of tungsten at a WD state has also been evaluated semi-empirically [83].

A new approach for high-energy-density physics experiments using intense ion beams has been proposed. In this approach, a pre-compressed sample cell is heated isochorically

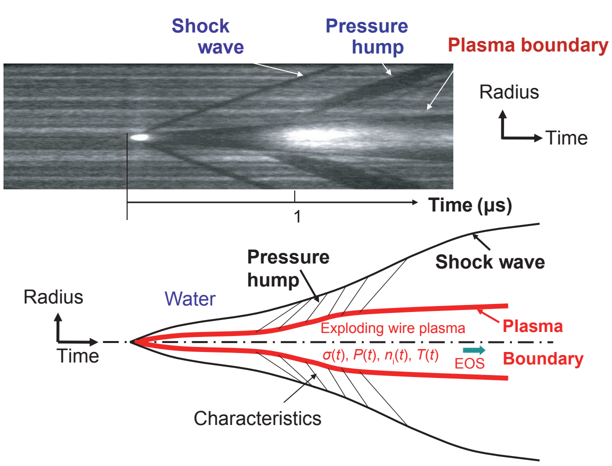

Fig. 16. Streak image and schematic illustration of a pulse-powered wire explosion.

by an intense argon beam. Ion beam heating has also been evaluated as a well-defined sample for the equation-of-state and the radiation hydrodynamics studies [84].

In order to reveal the EOSs of a heavy element under extreme conditions, an experimental setup for a simple, safe, and precise measurement has been proposed [85]. The sample will be homogeneously heated by an intense heavy-ion beam and the subsequent hydrodynamics will be investigated. Since the heated sample evolves coaxially, the hydrodynamic behaviors during and after the beam irradiation have been examined numerically by a one-dimensional radiation hydrodynamic code.

Diagnostics of the WD state is a laborious task. To evaluate the energy deposition process of an intense ion beam to a target plasma, the use of Kα radiation has been proposed as a diagnostic method [86]. An atomic population kinetics code provides the Kα yields. The results show that Kα radiation has the potential to provide information for a plasma temperature profile heated by an intense ion beam.

For an efficient implosion of the target, issues of coupling efficiency, beam illumination symmetry, and mitigation of Rayleigh−Taylor instability have been discussed for spherical heavy-ion-beam-driven targets with and without hohlraums. The illumination uniformity on the target has been evaluated by a mode analysis using rms nonuniformity factor [87]. A direct-indirect hybrid scheme of beam-driven fusion target has been proposed and discussed at UU [88]. The same group has also proposed a mitigation method of the Rayleigh−Taylor instability in the imploding fuel target based on the controllability of HIBs [89,90]. They have proposed a beam wobbling scheme to mitigate the hydrodynamic instability during the target implosion. These efforts have reopened the exploration of the direct drive scheme in HIF [91].

A new ignition scheme has been proposed, in which the compressed DT main fuel is ignited by an impact collision of another fraction of separately imploded DT fuel. The core dynamics of impact ignition have been investigated both numerically and experimentally at OU, where the neutron emission of thermal origin has been observed [92]. Regarding the impact ignition, the ablating plasma flow of an accelerating foil has been investigated theoretically. The obtained scaling laws describe the temporal evolution of the shell and the ablation performances such as the mass ablation rate and the ablation pressure [93].

6. Summary

Almost 40 years have passed since particle-beam inertial fusion was first proposed. Although there is no organized program for particle-beam fusion research in Japan, a number of groups have been conducting coordinated research in relevant fields to contribute ultimately for the particle-beam-driven inertial confinement fusion [94]. The beam source has shifted from pulse powered light ions to accelerator based heavier ions, but research has been continuously dealing with problems relevant to particle-beam-driven inertial confinement fusion. These issues extend from the ion source to the target physics. Experimental and theoretical advances in generation, pulse compression, focusing of particle beams, and sophistication of related pulse-power technologies have been realized to study the physics of high-energy-density and/or warm dense states of materials. This has led to the development of the sophisticated concept of inertial confinement fusion driven by intense heavy-ion accelerators.

High-flux ions can be supplied by controlling a laser ablation plasma with magnetic and/or electric field. The velocity distribution of ions in the plasma should be modified so as to supply a well-controlled flux of ions. Behaviors of the plasma sheath and the space charge field should be considered necessarily to provide a stable and good quality ion-flux to an injector.

The need to reach a HED state in an inertial fusion energy target or a target for the study of high-energy-density physics requires that ion beams are focused not only transversely but also longitudinally; that is, the beam behavior should be controlled with monitoring them in 6-dimensional phase space. Hence pulse compression of intense HIB in the space-charge-dominated regime is a key technology not only for HIF but for WDM and HED sciences also. Herein the current status of the beam dynamics studies, specifically the emittance growth in the final focus, was reviewed.

In addition to the final focus ability of the ion beam, the hydrodynamic efficiency, the fusion gain and the energy density of the target are sensitive functions of the energy deposition profile. The history and the present status of the beam—plasma interaction experiments, the equation-of-state, and HED/WDM studies in Japan were shown. The controllability and the efficient coupling of heavy-ion beams enable targets to be heated and compressed in a controllable manner. Appropriately tailoring the energy deposition and the range of the heavy-ion beam enables the design of an efficient fusion target. Additionally, using the controllability of ion-beam drivers has introduced methods to implode the target while mitigating Rayleigh—Taylor instabilities.

This paper briefly shows the activities in Japan in the quest of particle beam fusion: the high flux beam sources, the beam dynamics, high energy density researches, the accelerator schemes for intense particle beams, the beam dynamics, high energy density research, and the relevant pulse power technology. Although there is still a long way to achieve the goal of the intrinsic potentialities of the fusion energy, the quantity of resources, the safety of the treatment, and the low environmental load, are significantly higher than those for other energy sources. Designing a rational accelerator system from physical, engineering and economical viewpoints is a great contribution to the power generation with HIF because the accelerator system design is a key issue. Currently, the research in Japan is focusing on upgrading the system design based on the new advances in laser ion sources and cluster beam sources, understanding of the beam dynamics, sophistication of target designs, development of the accelerator components, and progress of the system architecture [95].

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Conflict of interest

The authors declare that there is no conflicts of interest.

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