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Research Article

New developments of HIF injector

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Abstract

The ultra-high intensity heavy-ion beam is highly pursued for heavy-ion researches and applications. However, it is limited by heavy-ion production of ion source and space-charge-effect in the low energy region. The Heavy-ion Inertial Fusion (HIF) facilities were proposed in 1970s. The HIF injectors have large cavity number and long total length, e.g., there are 27 injectors in HIDIF and HIBLIC is 30 km in length, and the corresponding HIF facilities are too large and too expensive to be constructed. Recently, ion acceleration technologies have been developing rapidly, especially in the low energy region, where the acceleration of high intensity heavy-ions is realized. Meanwhile, superconducting (SC) acceleration matures and increases the acceleration gradient in medium and high energy regions. The length of HIF injectors can be shortened to a buildable length of 2.5 km. This paper will present a review of a renewed HIF injector, which adopts multi-beam linac-based cavities.

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Keywords: Heavy-ion inertial fusion (HIF); Radio frequency quadrupole (RFQ); IH cavity; Heavy-ion; Multi-beam accelerator

1. Introduction

In the 1970s, a serious energy crisis triggered by oil crisis damaged the global economy. Accelerator scientists proposed several HIF projects to solve the energy problem, such as HIBALL [1], HIDIF [2,3] and HIBLIC [4] in USA, Germany and Japan respectively. The heavy-ion beams were used to irradiate the deuterium-tritium (D-T) target and to increase the plasma temperature and density to reach the Lawson criterion, and to initiate the D-T fusion reaction. In this case, the D-T fusion would be caused by the initially confined D-T plasma. All proposed HIF plans were large scale facilities. For example, there are 16 injectors in the design of HIBLIC [4], and the total length of the driver linac is more than 30 km. Compared with magnetic-field confined Tokomak facilities and the National Ignition Facility [5], the proposed linac-driven HIF injectors are too large to be built. Nevertheless, for linac-driven HIF facilities, the energy gain is about 3 times that of Tokomak facilities, and the linac-driven HIF is safer [6].

Over recent decades, there were three breakthroughs of high intensity heavy-ion acceleration [6]. The first is the invention of radio frequency quadrupole (RFQ) type accelerator, which could accelerate more than dozens of milli-ampere ion beams and is a good solution to space-charge-effect of heavy-ion acceleration at low energy [7] [8]. The second is the direct plasma injection scheme (DPIS), which provides a way to produce a very high intensity heavy-ion beam [9–11], and the

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third is multi-beam Interdigital H-mode (IH) RFQ type accelerating structure, which successfully accelerated 108 mA carbon ions in 2010 by using DPIS [12]. Shown in Fig. 1, the IH structure is a power-efficiency structure than Alvalez structure in the low and medium energy region because of its high shunt-impedance [13–15]. These breakthroughs, especially, the invention of multi-beam RFQ which is suitable for accelerating heavy-ions in the very low energy region, make the production and acceleration of very high intensity heavy-ion beam possible.

We proposed a 4-beam type IH-RFQ in the HIF2014 conference held in Lanzhou. The goal of the Proof of Principle (PoP) multi-beam IH-RFQ is to design an IH-RFQ which can accelerate four 125 mA Pb^{12+} or Au^{12+} beams up to 100 keV/u from 3 keV/u in 3 m with over 97.6% transmission. A conceptual multi-beam type drift tube linac (DTL) was proposed in LINAC2016 conference at MSU in 2016 [16]. In this paper, a layout of a renewed HIF driver and a multi-beam linac-based demo HIF facility will be reported, including the designs of a PoP 4-beam RFQ and the designs of a PoP dual beam type DTL (DB-DTL).

2. Breakthroughs in high intensity heavy-ion acceleration

For 1 GW HIF plant, the driver linacs must accelerate 400 mA heavy-ion (such as Pb^{+} ions or Bi^{+} ions) beams up to 50 MeV/u [4] [6]. However, it is very difficult to produce and accelerate 400 mA Pb^{+} ions because of the limitations of existing ion sources, strong space-charge-effect and acceleration technologies. The DPIS was invented by Prof. Hattori and Dr. Okamura in the Tokyo Institute of Technology in 2001. The DPIS can produce high intensity heavy ions and inject them to the RFQ by using a laser ion source (LIS). Using multi-beam type RFQ, the driver linacs can simultaneously accelerate multiple beams in a single cavity.

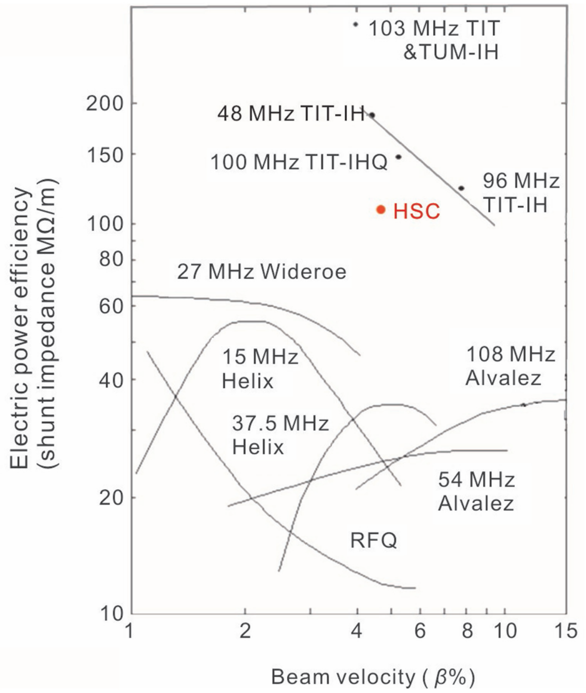

Fig. 1. Effective shunt impedance of the IH structure and other accelerating structures.

The schematic of the DPIS is shown in Fig. 2. The mechanism of DPIS is irradiating a high purity solid target by a pulsed laser to produce plasma, which can be efficiently injected to RFQ with the thermal expansion velocity of the plasma suppressing Coulomb repulsion [17,18]. Compared to the traditional gas-ionized ion source, DPIS can produce high-intensity highly-charged ions from the high purity solid target. Due to directly injecting the ion plasma to the RFQ without low energy transport line, the RFQ can accelerate very high intensity ion beams. The principle test of the DPIS successfully accelerated 9.22 mA C^{4+} carbon ions up to 214 keV/u by using an old 4-vane type RFQ at Tokyo Institute of Technology in 2001 [9]. Moreover, using a new RFQ, the same team measured 60 mA C^{4+} ions and 18 mA C^{6+} ions accelerated to 100 keV/u from 20 keV/u at RIKEN in 2004 [10,11].

The multi-beam accelerating structure was also developed by the Hattori Laboratory in 2005. The invention of multi-beam RFQ, which is suitable for accelerating heavy ions in the very low energy region with a weak space-charge-effect, makes HIF possible. In the prototype of multi-beam cavity, two sets of four RFQ-rods were assembled into a power-efficient IH cavity, and successfully accelerated 54 mA/beam-channel ions up to 60 keV/u from 5 keV/u with DPIS in 2010 [12]. The total accelerated C^{2+} beam reached 108 mA. The structure of two-beam IH-RFQ is shown in Fig. 3. These developments prove that multiple beams can be accelerated in a single cavity and it is possible to accelerate 400 mA beams using four sets of four RFQ-rods.

3. New design of an HIF injector

Since the invention of RFQ, RFQ-based 1 GW HIF plans have been proposed in Japan, Europe and the Soviet Union,

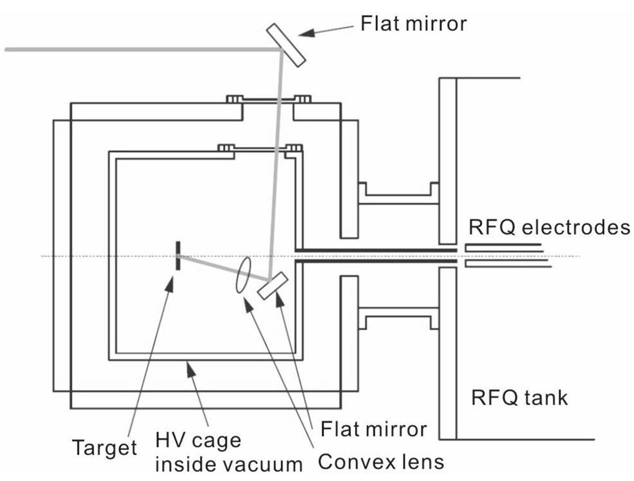

Fig. 2. Image of the DPIS with a LIS. The ablation plasma will be produced by using a laser in a vacuum chamber and will be injected into the RFQ by using high voltage extraction structure through a plasma pipe.

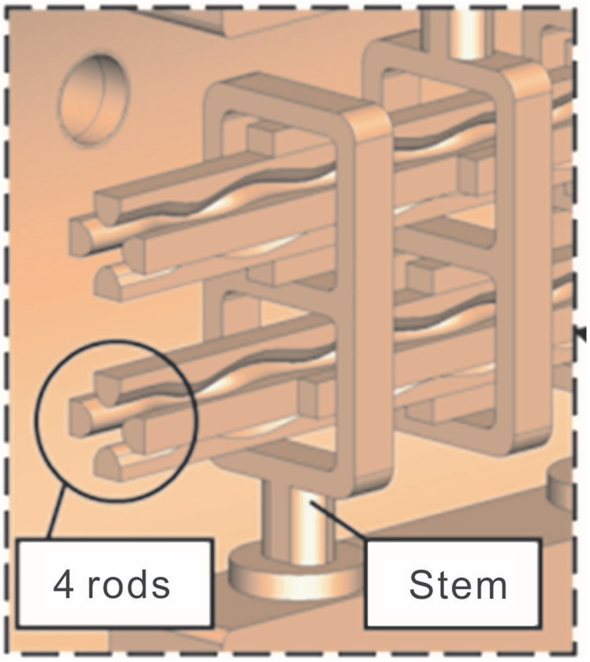

Fig. 3. Image of two-beam IH-RFQ. Two sets of four RFQ-rods are arranged with vertical symmetry and the stems are arranged as IH structure.

such as HIBALL, HIDIF and HIBLIC. In these plans, driver linacs were numerous, huge and complicated. Considering the space-charge-effect of the intense heavy ions (400 mA Pb^+ or Bi^+ ions) in low energy regions, 16 RFQs were used to accelerate heavy ions in the HIBLIC design, however, each RFQ was over 500 m in length [6].

We are trying to design a new HIF driver using the DPIS technology and multi-beam acceleration. A simple layout of HIF driver system is shown in Fig. 4. In this system, a powerful laser will split into four and produce four high intensity Pb^+ ion beams (115 mA/channel), which will be directly injected into a four-beam type IH-RFQ, where the four 125 mA beams will be accelerated to 300 keV/u from 3 keV/u. Two beam funnelling systems will be adopted to funnel the accelerated ion beams from the RFQ. The beam intensity will be enhanced to 220 mA/channel before injecting into an IH DB-DTL system. The IH DB-DTLs will accelerate the 220 mA/channel ions up to 1.2 MeV/u with an operation frequency of 81.25 MHz. When the beams came out from the DB-DTLs, another beam funnelling system will work. The driver system could also offer one-beam type DTLs, which will accelerate 410 mA/channel ions up to 4.7 MeV/u with an operation frequency of 162.5 MHz. Finally, SC linacs (HWRs and spokes [19,20]) will offer high accelerating fields to accelerate 400 mA ions up to 50 MeV/u with operation frequencies of 162.5 MHz and 325 MHz. Compared with the initially proposed HIF driver, the total length of the renewed HIF injector is only about 2.5 km, which is buildable. The parameters of the renewed HIF driver are listed in Table 1.

3.1. Design of a 4-beam type IH-RFQ

The structure of a 4-beam type RFQ is shown in Fig. 5, which consists of 4 sets of 4-rod type quadrupole electrodes. TE_{111} mode is chosen because of the arrangement of the IH stems shown in Fig. 5. The 4-beam type IH-RFQ has a larger capacitance compared with the normal 4-rod RFQ. The 4-beam IH-RFQ allows a very low resonance frequency to be achieved within a small diameter cavity and suits well for heavy-ion acceleration in the low energy region. Our proposed RFQ has the advantages of cost saving and weak space-charge-effect.

The frequency of the PoP 4-beam IH-RFQ was chosen to be 40.625 MHz. Considering the beam dynamics simulations and the extraction voltage of LIS, the input energy was set at 3

Table 1
Main parameters of a lead linac driven 1 GW HIF plant.

	4-beam IH-RFQ	2-beam IH-DTL	1-beam IH-DTL	HWR	spoke
Input energy (MeV/u)	0.005	0.3	1.2	4.7	10.0
Output energy (MeV/u)	0.3	1.2	4.7	10.0	50.0
Beam current (mA)	115	220	410	400	400
Beam width (ms)	0.5	0.5	0.5	0.5	0.5
Beam number	4	2	1	1	1
Pulse length (ms)	0.5−0.7	0.5−0.7	0.5−0.7	0.5−0.7	0.5−0.7
Repetition rate (Hz)	10	10	10	10	10
Phase (deg.)	$-90 \rightarrow -30$	−45	−45	−45	−45
E_{eff} (MV/m)	0.23	2.0	2.5	7.0	9
H (kG/cm)	–	12	22	60	65
Voltage (MV)	0.087 (vane)	187	728	6510	8320
Average voltage (kV)	–	285	428	814	1575
Cell number	1385	656	1702	8000	5283
Total length (m)	231	94	291	930	925

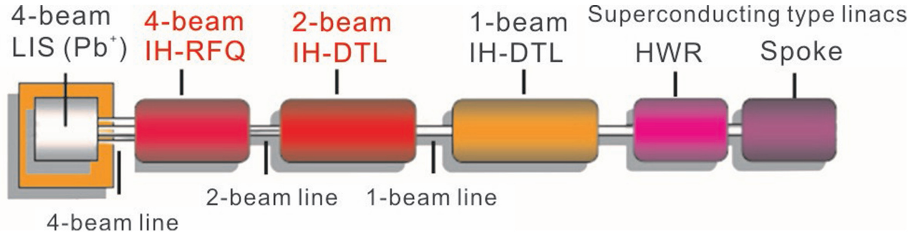

Fig. 4. A simple layout of a driver system for 1 GW HIF plant. A 4-beam type laser ion source would provide four high intensity heavy-ion beams which could be directly injected into a 4-beam type IH-RFQ. After being accelerated by 4-beam IH-RFQ cavities, the four beams will be funnelled into two beams. These two beams will be injected into 2-beam type IH-DTL cavities. After another funnelling system, the two beams will be funnelled into one beam which will be accelerated by single-beam type IH-DTLs. Using multi-beam type cavities, the HIF driver could cut down the cost and complexity of construction.

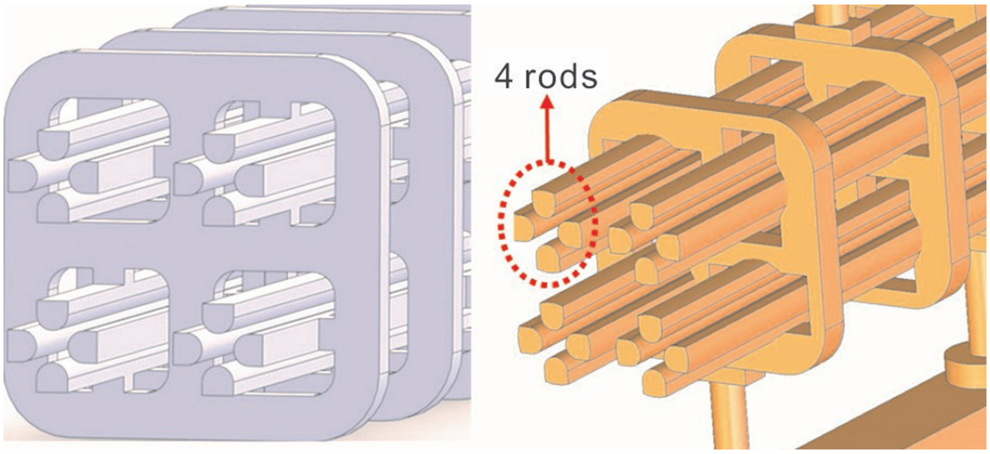

Fig. 5. CAD images of the 4-beam IH-RFQ.

keV/u and the input ions are Pb^{12+} or Au^{12+} ions. According to the calculations, the proposed RFQ cavity could accelerate the four 115 mA beams up to 100 keV/u in 3 m with 97.6% transmission efficiency, operating in 1 ms duration and 10 Hz repetition. As shown in Table 2, the designed cavity is 450 mm in diameter and 3 m in length. The Kilpatrick factor of the cavity was chosen to be 1.8 [13]. The design was done by RFQGen and Microwave Studio (MWS) [21]. The RFQGen was used for the RFQ design and beam dynamics simulation. The MWS was used to simulate the 3D electromagnetic distribution, the Q factor and the power loss of the resonator. The optimized parameters of the cavity are listed in Table 3. The calculated power loss is over 380 kW @100 kV of the inter-rod voltage. Fig. 6 shows the Pb^{12+} beam profile at the end cell. Fig. 7 shows the surface current of the cavity simulated by MWS. From Fig. 7, it can be seen that the stems are the most heated parts. As shown in Fig. 8, the two cooling water routes were designed to cool the stems.

Table 2
Main parameters of the PoP 4-beam type IH-RFQ.

Frequency (MHz)	40.625
Mass to charge ratio, A/q	17.25 (Pb), 16.45 (Au)
Rod-tip type	$0.75r_0$
Modulation type	Standard
Synchronous phase (deg.)	$-90 \rightarrow -30$
Input energy (keV/u)	3
Output energy (keV/u)	100
Input beam current (mA)	$115 \times 4 = 460$
Output beam current (mA)	$110 \times 4 = 440$
Rod length (m)	2.9
Total number of cells	155
Focusing strength, B	8.378
Bore diameter (mm)	13.2
Cavity length (m)	3.0
Cavity diameter (cm)	35
Max. rod voltage (kV)	100
Maximum surface field (Kp.)	2.0
Pulse width (ms)	1
Repetition (Hz)	10

Table 3
Optimized structure of the 4-beam IH-RFQ cavity.

Cavity diameter (cm)	40
Cavity length (m)	3.0
R_0	6.67
Number of stems	30
Stem height (mm)	43.75
Ridge length (mm)	2800
Ridge thickness	80
Q factor	4569
Inter-rod voltage (kV)	100
Power loss (kW) @100 kV with 85% Q_0	362

3.2. Design of a dual beam type IH-DTL

Our goal is to design a prototype DB-DTL which can accelerate ions from 560 keV/u up to 2.5 MeV/u in 1 m. We adopted the method of alternative phase focusing (APF) [13]. Using APF method, a CW IH DTL successfully accelerated P^{2+} ions up to 1.5 MeV in 2009 [13], and another DTL successfully accelerated 10 mA protons up to 7.4 MeV from 1.5 MeV in 2010 [22]. The DB-DTL can double the existing beam current and can be used as a post-accelerator to accelerate two high intensity heavy-ion beams. Our proposed DB-DTL is an IH-DT structure, which operates in TE_{111} mode and uses drift tubes to accelerate beams. The two beam channels are off-set from the center of the DT and are both located in the vertical direction of cavity axis. An image of the proposed DB-DTL is shown in Fig. 9.

The beam orbit was simulated by Pi Mode Linac Orbit Calculation (PiMLOC) [23]. The MWS was utilized to perform electromagnetic simulations of the cavity. In this research, the structure, especially the DT structure and location of the beam channels, was firstly studied by using MWS. In Fig. 10(a) and (b), one DT has two beam channels on either side of the cavity axis, and both channels are either in horizontal direction or in vertical direction. The structure shown in Fig. 10(c) is a 4-beam type DTL, where one DT has four beam channels.

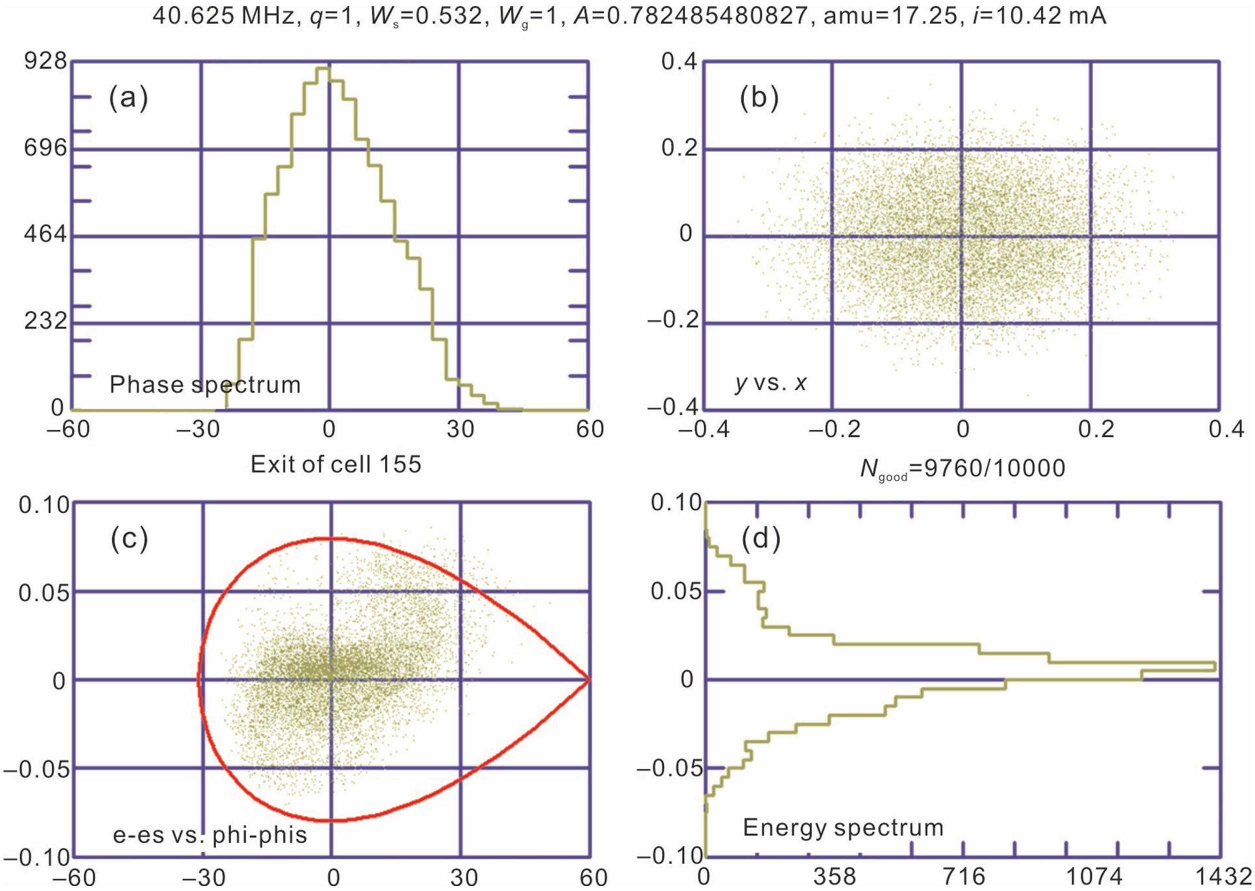

Fig. 6. Pb^{12+} beam profile at the end cell of the RFQ simulated by RFQGen. (a) Phase spectrum; (b) Particle distribution on the real plane; (c) Energy and phase space from synchronous particles; (d) Energy spectrum.

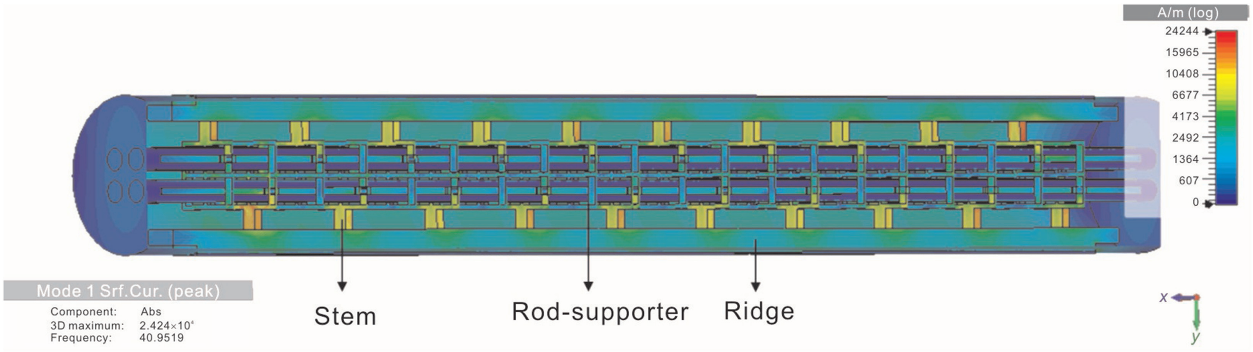

Fig. 7. Image of simulated surface current of PoP 4-beam IH-RFQ. It is clearly indicated that the stems will be much hotter than other parts without cooling.

The electric field distributions shown in Fig. 11 indicate that the structures of Fig. 10(a) and (b) have the same resonated property, and both the field distributions of the beam channels agree well. As shown in Fig. 12, all the field distributions of the beam axis shown in Fig. 10(c) are almost identical. The simulated field distributions in Figs. 11 and 12 imply that the structures shown in Fig. 10 are suitable for multi-beam acceleration, and the properties of the resonated mode are the same to that of the normal DT linac, which also means that the APF method can be used in the multi-beam type DTL structure. Finally, we adopted the structure of Fig. 10(b), because that structure can adopt an ellipse DT (with the semi major axis in the vertical direction), which is more flexible to design a better distance between two beam channels. Furthermore, the core parts of the DB-DTL, including ridges, stems and elliptical DTs, can be shaped out from a block copper by using numerically-controlled (NC) machines. The NC shaping method from a block copper has a high accuracy with fewer assemblies and a better cooling effect [2,23].

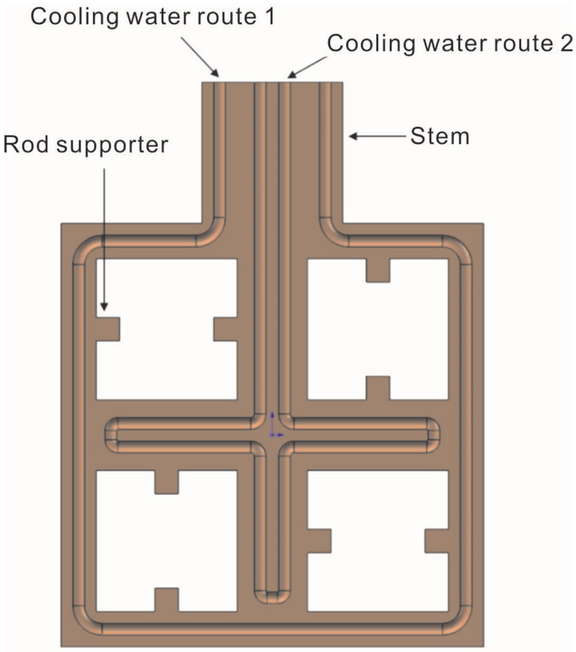

Fig. 8. Image of the front view of the frame and the view of the two sets of water routes. One route is along the frame edge. The other route is to cool the cross part.

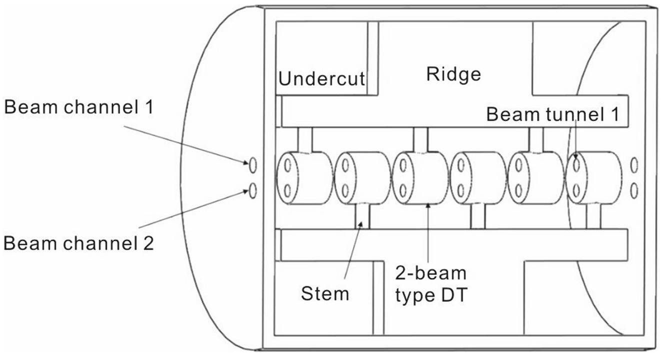

Fig. 9. Image of the proposed IH DB-DTL. The structure of the DB-DTL is the same with normal one beam type DTL. Connection parts between DTs and ridges are stems. The beams can be accelerated in the gaps. The electric field distribution can be tuned by the undercuts.

The PiMLOC is a good simulation code for DTL designs. A CW operated DTL was designed using PiMLOC and successfully commissioned in 2009 [6]. The designed parameters of the DB-DTL are listed in Table 4. The inner length of the cavity is designed to be less than 1 m and the cavity will operate in CW mode with a resonated frequency of 81.25 MHz. The input and the output energies of the 2-beam type were redesigned as 560 keV/u and 2.5 MeV/u because a 4-vane RFQ with an output energy of 560 keV/u will be adopted as a pre-accelerator. According to the latest calculation shown in Fig. 13, the transmission of the DB-DTL is over 87.3%. From Fig. 14, the inter-influence between two beams has not been observed.

The DB-DTL is under design and the 560 keV-RFQ is already prepared. When the designs and simulations are finished, the DB-DTL will be fabricated as soon as possible. The test bench of the DB-DTL is shown in Fig. 15. In this bench, a Penning ion gauge (PIG) type ion source will provide proton beams, an accelerating tube will accelerate proton ions up to 30 keV for RFQ injection, 4 F cups (FCs) will measure the beam current, an Einzel lens (EL) and a triplet electric Q (TEQ) will focus the ions, and a magnet will bend the ions. It is planned that the upper beam channel will accelerate the proton beam first, and then after lifting the DB-DTL to make the lower beam channel match the RFQ-beam line, the lower beam channel of the DB-DTL will be tested.

3.3. Proposal of the post-accelerators

When the beam comes out from the DB-DTLs with the output energy of 1.2 MeV/u, there are single-beam type normal conducting IH-DTLs and single-beam type SC linacs for continuously accelerating the heavy-ion up to a higher energy. The single-beam type DTLs will operate with a frequency of 162.5 MHz. The single-beam type SC linacs have two kinds of cavities: one is the taper type half wave resonant (HWR) cavities, which could offer a more stable operation with few RF power and will operate with a frequency of 162.5 MHz; the other is the spoke type cavities, which will operate with a frequency of 325 MHz. Both the HWR cavities and the spoke cavities are fully functional and ready for mass production [24] [25]. The proposed effective accelerating fields of the HWR cavities and the spoke cavities are 7 MV/m and 9 MV/m respectively, which are easy to achieve. These cavities are suitable for post-driver of HIF facility.

3.4. Production of high intensity heavy-ion beam

There are some data shown in Fig. 16 indicating that 2 mA/cm^2 Pb$^{11+,\ 12+,\ 13+}$ ions (the sum of ions with the three charge states of 11$^+$, 12$^+$ and 13$^+$, all the ions with charge states of 11$^+$, 12$^+$ and 13$^+$ could be simultaneously accelerated in RFQ) and 3 mA/cm^2 Au$^{11+,\ 12+,\ 13+}$ ions can be detected after 1 m drift [7]. The injected beam current is listed in Table 5 using the formula: $I \propto L^{-3}$, here, I is the detected current and L is the distance from target to extraction point [9]. From Table 5, the calculated distance from the target to the RFQ is 25 cm or 29 cm with an 11 mm diameter hole of plasma pipe, where the LIS could inject 125 mA Pb^{12+} or Au^{12+} beams to the RFQ.

4. Demo facility for future plan

The breakthroughs mentioned above make it highly possible to construct HIF facilities. We redesigned and upgraded our designs of a HIF driver system. Adopting many multi-beam linac-based cavities, as shown in Fig. 4 and Table 1, we have reduced the total length of the redesigned driver linac to about 2.5 km.

However, beam bunching, final focusing and target heating have not been studied or tested. Thus, as shown in Fig. 17, we propose a demo facility for these researches [6]. In the demo

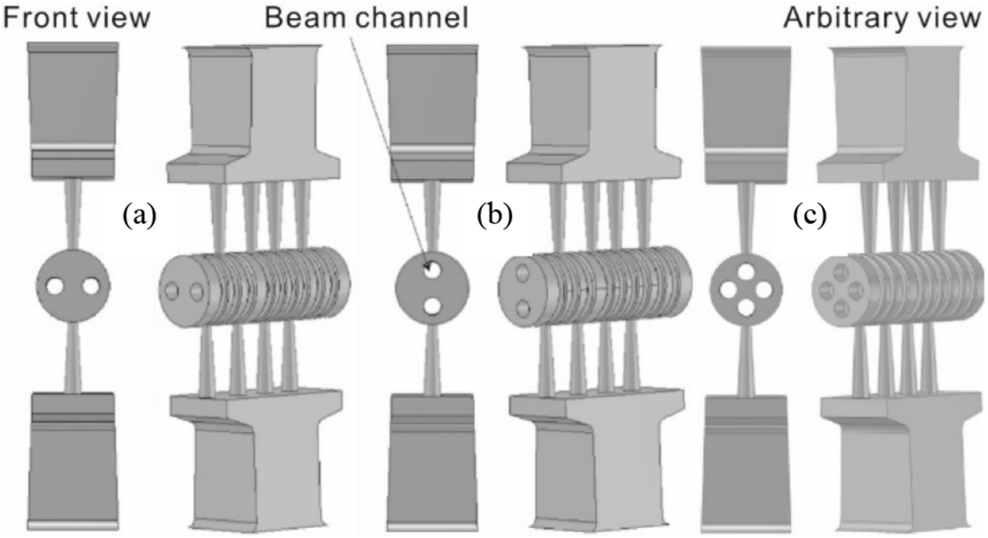

Fig. 10. Structures used to verify the electric field distribution on the gaps, which are helpful to decide the beam channel position.

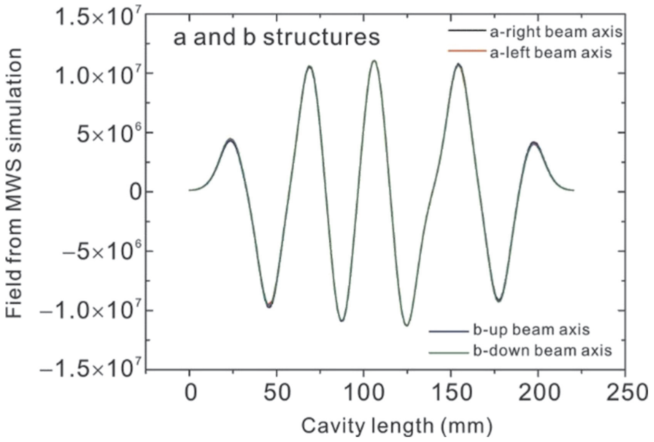

Fig. 11. Field distributions of the beam axes shown in Fig. 10(a) and (b). It is clearly indicated that both field distributions on the two beam centers shown in Fig. 10(a) agree well with each other. The two field distributions on the two beam centers shown in Fig. 10(b) also meet well, and these four distributions are almost the same.

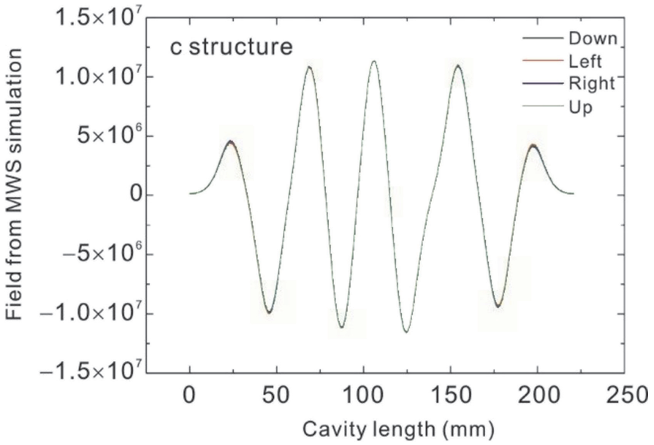

Fig. 12. Four field distributions along the beam axes in the structure shown in Fig. 10(c). It is obvious that the four distributions are almost the same.

Table 4
Main parameters of the two-beam type DTL.

ions	H^+
Frequency (MHz)	81.25
Inner cavity length (m)	<1
Number of beam channels	2
Distance between two beam channels	30
Diameter of beam channel	20
APF phase (deg.)	−48, −48, 25, 31, 31, 31, 10, −60, −70
Input energy (keV/u)	560
Output energy (MeV/u)	2.5
Kp.	1.5
Operation mode	pulse

facility, a 240 mA heavy-ion beam will be accelerated up to 10 MeV/u and 50 MeV/u by a 600-m-long linac driver and a heavy-ion synchrotron system. There is a four-time storage ring where RF storage, electron cooling and stochastic cooling technologies can be developed. After bunch compressors, the bunched heavy-ions will be injected into four induction

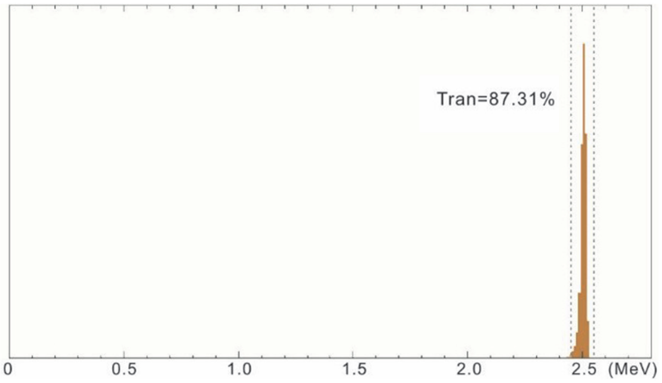

Fig. 13. Accelerated proton energy distribution of the DB-DTL. The energy resolution of the accelerated beam is good and the transmission achieves 87.3%.

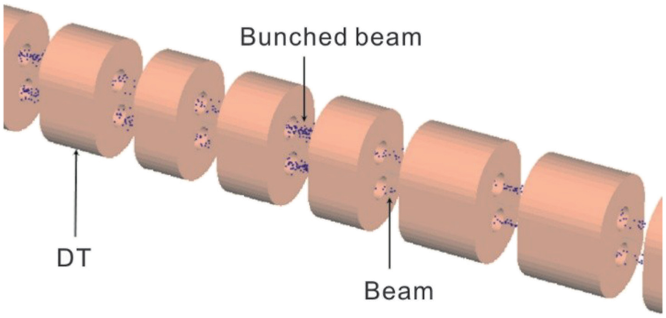

Fig. 14. Accelerating image of two beams of the DB-DTL. According to the simulations, the bunched beams can be observed by setting APF method and inter-influence between the two beams has not been observed, which imply APF method works well and both beams can be accelerated independently.

bunches for recompressing and strengthening. Finally, the recompressed beams will be delivered to the experimental fusion facilities. The width of the final bunch is 10−20 ns, which requires superconducting focusing technology for target heating.

The design of 4-beam type IH-RFQ was done in 2014 and the structure was proposed at the 20th International Symposium on Heavy Ion Inertial Fusion (HIF2014). The thermal analysis and deformation research of the 4-beam type IH-RFQ are not finished yet, and the electromagnetic structure will be optimized based on the thermal analyses. Fortunately, the DB-DTL is being funded by National Natural Science Foundation of China with contract No. 11535016. In the future, a PoP DB-DTL will be fabricated and operate with high power proton acceleration, as mentioned in Fig. 15. An LIS was also developed [26]. With this LIS, the 4-beam injection for a 4-beam RFQ can be studied.

5. Summary

As an alternative energy source, the HIF facilities are much safer than Tokomak facilities. Moreover, the energy gain of HIF facilities is three times that of Tokomak facilities. Therefore, HIF facilities, especially the PoP HIF facility, are critical. However, the previously proposed HIF drivers are unrealistic for their large scale. Based on existing technologies, we proposed a multi-beam linac-based 1 GW HIF driver which could cut down the cost and has a total length of about 2.5 km. Additionally, we proposed and calculated a 4-beam type IH-RFQ and a DB-DTL. The PoP 4-beam IH-RFQ was designed for Pb^{12+} or Au^{12+} ion acceleration. The high-power proton acceleration of the DB-DTL will operate in the next few years. For future study, we propose a demo facility where multi-beam linacs are adopted as drivers. The final beam bunching and target heating can be studied by using this demo

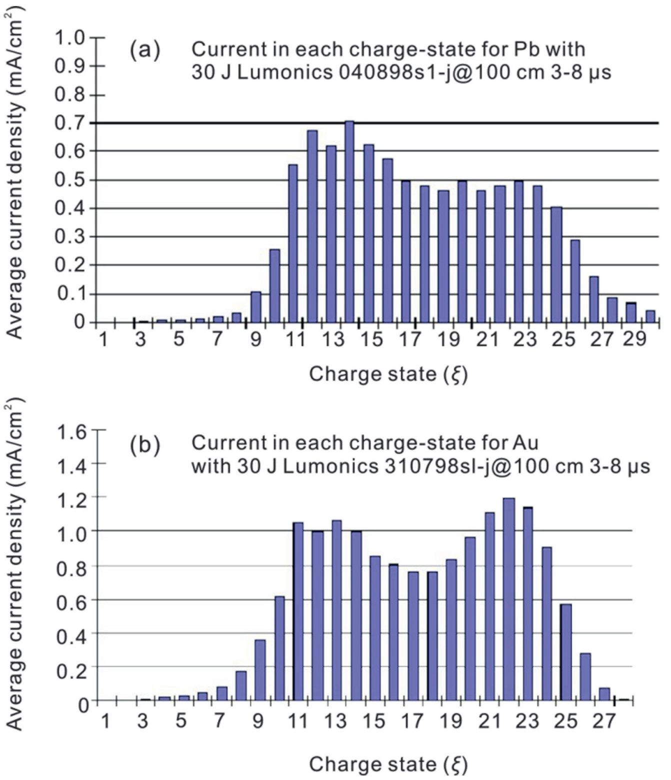

Fig. 16. Detected current of Pb ions and Au ions with a 30 J laser. The detection distance from the target was 1 m. (a) Shows the currents of Pb ions in each charge-state and (b) shows the currents of Au ions in each charge-state.

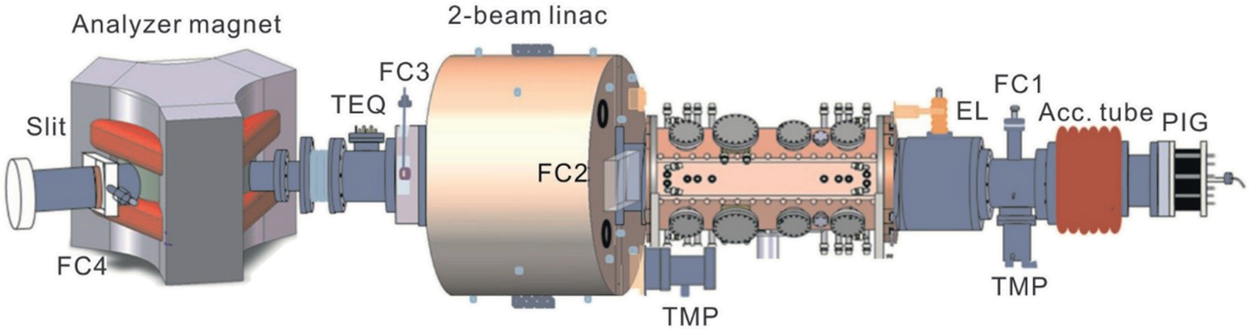

Fig. 15. Test bench of the DB-DTL. A PIG source is planned to provide proton beam, and an accelerating tube is adopted to accelerate ions up to the desired energy. The FCs will be used to measure the beam current and calculate the beam transmission. An EL and a triplet electric Q will be used to focus the beam at the entrance of the RFQ and the exit of the DTL. A magnet is used to analyze the accelerated beam energy.

Table 5
Calculation of the distance from the target to the RFQ for 125 mA injection.

Distance from target to RFQ (m)	^{206,207,208}Pb current density (mA/cm^2)	^{197}Au current density (mA/cm^2)
1.00 (original data)	2 (0.65 × 3) (original data)	3 (1 × 3) (original data)
0.50	16	24
0.40	31	47
0.30	74	111
0.29	82	123
0.25	128	192
0.20	250	375

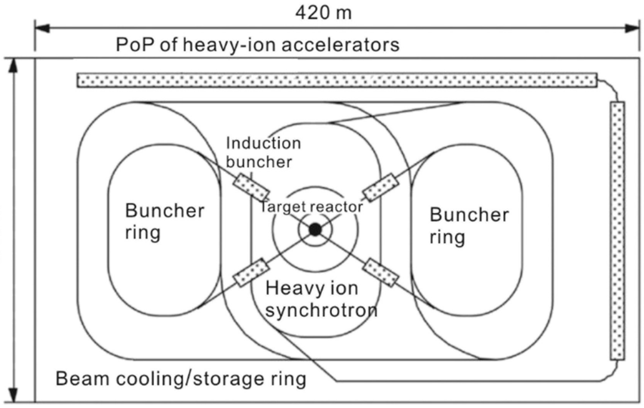

Fig. 17. Demo facility of multi-beam linac-based HIF system. The effective length of the driver is 350 m and the heavy-ion synchrotron will operate in 10 Hz with a scale of 190 m × 80 m. The scales of the storage ring and buncher ring are 400 m × 200 m and 95 m × 70 m, respectively.

facility. And the operating system will be further developed in this demo facility for beam matching and emittance control of the high intensity heavy-ion. The biggest problem of the HIF beam matching is the magnetic field strength because of the big pipe size of the matching section. Fortunately, HIF drivers will operate at a pulse mode, thus, the beam matching and beam control are challenging. Especially, the technologies of superconducting magnet are developed at Michigan State University and Institute of Modern Physics for FRIB and HIAF projects [27,28], which will help the beam matching and emittance control.

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Conflict of interest

The authors declare that there is no conflicts of interest.

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