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Comprehensive research facility for negative ion source neutral beam injection at CRAFT: design and first operations

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Abstract

Neutral beam injection (NBI) has been proven as a reliable heating and current drive method for fusion plasma. For the high-energy NBI system (particle energy > 150 keV) of large-scale fusion devices, the negative ion source neutral beam injection (NNBI) system is inevitable, which can obtain an acceptable neutralization efficiency (> 55%). But the NNBI system is very complex and challengeable. To explore and master the key NNBI technology for future fusion reactor in China, an NNBI test facility is under development in the framework of the Comprehensive Research Facility for Fusion Technology (CRAFT). The initial goal of CRAFT NNBI facility is to achieve a 2 MW hydrogen neutral beam at the energy of 200–400 keV for lasting 100 s. In the first operations of the CRAFT NNBI facility, a negative ion source with dual RF drivers was developed and tested. By using the 50 keV accelerator, the long-pulse and high-current extractions of negative hydrogen ions have been achieved and the typical values were 55.4 keV, 7.3 A (~ 123 A/m^2), 105 s and 55.0 keV, 14.7 A (~ 248 A/m^2), 30 s, respectively. By using the 200 keV accelerator, the megawatt-class negative hydrogen beam has also been achieved (135.9 keV, 8.9 A, 8 s). The whole process of the gas neutralization of negative ion beam, electric removal of residual ions, and beam transport have been demonstrated experimentally.

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Keywords: beam acceleration, magnetic confinement fusion, negative ion source, neutral beam injection

(Some figures may appear in colour only in the online journal)

1. Introduction

Comprehensive Research Facility for Fusion Technology (CRAFT) is one of national large science and technology infrastructures of China, which aims to explore and master the key technologies, standards and methods for the construction and operation of future fusion reactors (especially for the China Fusion Engineering Test Reactor, CFETR). CRAFT program is divided into two research systems (for the superconducting magnet and the divertor, respectively) and includes 20 test facilities or prototypes totally. Neutral beam injection (NBI) is an effective auxiliary heating method for magnetically confined plasma, which can inject energic deuterium (or its isotopes) atomic beam into the fusion device and deliver the kinetic energy and momentum to the plasma. NBI has made great contributions in the milestones of fusion development [1–8] and is still promising in future fusion reactors for not only plasma heating but also current drive, plasma rotation, burning control, and so on [9–14]. Hence, the research on NBI technology is included in the CRAFT program.

As the size of the fusion device enlarges, the required injecting beam energy also increases to attain the core plasma heating and current drive (e.g., 125 keV for JET [15], 500 keV for JT-60SA [16], 1,000 keV for ITER [17]). For the beam energy is larger than 150 keV, the negative ion source based NBI (NNBI) system is more practical than the positive ion source based NBI (PNBI) system, because the neutralization efficiency of negative ion beam can stay above 55% but that is below 30% for positive ion beam [18]. However, according to the research and operation experiences of the only two routine NNBI systems for JT-60U tokamak [19] and LHD heliotron [20] respectively, the NNBI system is more complex and challenging than the PNBI system in views of the negative ion production, negative ion extraction and acceleration, multiply higher acceleration voltage, multiply larger beam size, negative ion neutralization, residual ion removal, and so on. Moreover, the demanded operating parameters of future NNBI system are much higher than the achievements worldwide.

CRAFT NNBI facility, also called CRANE (Comprehensive Research Facility for NNBI Experiment), is formally started construction in 2019 and planned to be completed in 2025. The aim of the CRAFT NNBI facility is to explore and master the key technologies for future CFETR NBI system [21, 22]. An acceptance mark for the construction completion of CRAFT NNBI

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facility is to attain a hydrogen neutral beam with the particle energy of 200–400 keV, beam power of > 2 MW, and pulse duration of > 100 s.

The CRAFT NNBI facility mainly contains two testbeds: HONOR (Hefei Open-facility for Negative-ion Source Research) focuses on the negative ion source research for fusion, CAN·BE (CFETR Advance Neutral Beam Equipment) is the full-function prototype for the CFETR neutral beam injector. There are other supporting systems, for example, the acceleration voltage power supply, cooling plant, cryogenic plant. The HONOR and CANBE started the first operations in April 2023 and December 2023, respectively.

This paper mainly reports the design and developments that have been carried out to realize the CRAFT NNBI facility, and highlights the experimental results made in their first operations.

2. Overall design of CRAFT NNBI facility

The layout of the whole CRAFT NNBI facility is shown in figure 1. HONOR and CANBE are designed to be operated individually. So there are independent control systems, high voltage (HV) platform or tank, assembly areas for the two testbeds. The electrical power system, cooling water plant and cryogenic plant can also support the simultaneous operation of the two testbeds. Considered the construction cost, the acceleration voltage power supply is shared by HONOR and CANBE. There are several research and development units for NNBI relevant technologies, for example, caesium (Cs) dynamics, laser neutralizer, HV insulation in vacuum.

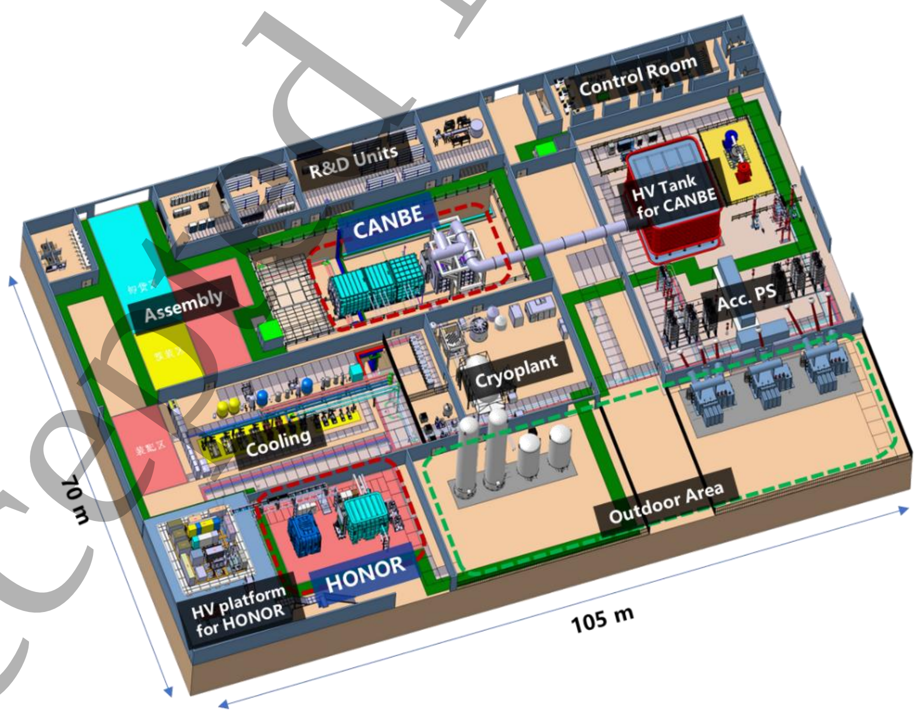

Figure 1. Layout of CRAFT NNBI facility (i.e., CRANE site).

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2.1. HONOR

The negative ion source is the most critical and challenging component in an NNBI system. The technology for the negative ions production, extraction, acceleration and steering is still immature especially in the long-pulse and high-power operation. Intuitively, the required parameters of ITER negative ion source (1,000 keV, 40 A and 1 h D^- beam) have never been reached simultaneously until now. HONOR devotes to tackle the key physics and engineering issues of the large-scale negative ion source for fusion application.

An overall view of HONOR and the HV platform are shown in figure 2. Due to the potential advantages of low maintenance, simple structure and high stability and repeatability in the long-term operation, radio frequency (RF) driven plasma source is more promising for future NBI system and it has been chosen for the ITER and CFETR NNBI systems [23–26]. Two RF generators on the HV platform are used to produce the plasma with the power of 200 kW and the frequency of 1–1.5 MHz for each [27]. Another large power supply on the HV platform is the extraction voltage power supply of 16 kV/80 A for negative ions extraction, which is based on the pulse step modulation (PSM) technology [28–30]. There are some small power supplies assembled in a unit on the HV platform: two bias power supplies of 100 V/600 A for changing the plasma potential and suppressing the co-extracted electrons [31, 32]; one magnetic filter power supply of 15 V/6000 A to produce the filter field across the source for lowering the electron temperature and reducing the loss of negative ions [33, 34]; one starter filament power supply including two voltage regulators for the filament current and filament bias respectively. The high-temperature water supply is also placed on the HV platform, which can provide the high-pressure hot water up to 200 ℃ for optimizing the Cs surface condition and enhancing the negative ion production. Note that, HONOR can only operate at the acceleration voltage up to 200 kV, so the insulating supports and the isolation transformer are designed to insulate against the 200 kV voltage.

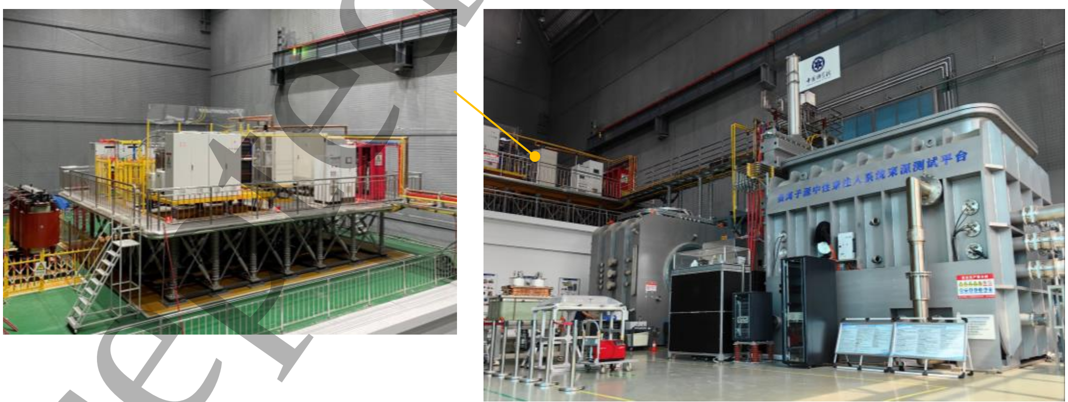

Figure 2. View of the HONOR testbed at the CRANE site.

A view of the HONOR in-vessel components is shown in figure 3. The rectangular beamline vacuum vessel is 5 m in length, 4 m in width and 4 m in height [35]. The top plate of the vacuum vessel can be removed for the installation of inner components.

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The front port of the vacuum vessel is connected to a gate valve with the opening of 2 m in diameter. The major inner components are the beam dump and the cryopumps for the ion beam operation only. The beam dump adopts an ITER heating neutral beam (HNB) like design that consists of two multi-pipe arrays [36–38]. There are two cryopumps of cryo-absorption type installed on the two lateral walls. The cryopump is of modular structure, and each unit is designed to have a pumping speed of 500,000 L/s with the pumping opening of 2.3 m (height) × 1.0 m (width) [39–44]. One cryopump contains 4 units (displayed in figure 3) and another one contains 2 units to make room for beam diagnostics. 4 turbo molecular pumps (with pumping speed of 2,200 L/s for each) and 2 units of rotary vane pump and Roots pump are used as the backing pumps.

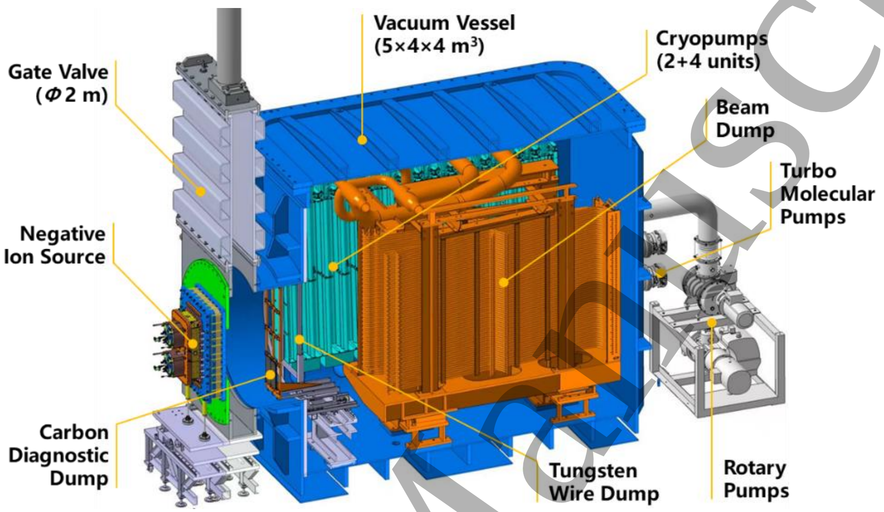

Figure 3. 3D model of the HONOR main structure with in-vessel components.

The most important feature of HONOR is the application of various plasma and beam diagnostic systems. Table 1 lists the diagnostic systems which have been equipped already. By installing a special diagnostic flange in front of the plasma grid (PG) in the negative ion source, the key parameters of the plasma (for example, electron density, electron temperature, Cs density, negative ion density) in the extraction region can be measured and analyzed via different diagnostic techniques. By using the carbon fibre composite (CFC) dump downstream the negative ion source, the multi-beamlet footprints can be measured via the infrared (IR) camera, and then, the multi-beamlet divergences and orbits can be evaluated. The other beam diagnostic techniques (e.g., W-wire dump, visible light camera, secondary electron emission) can give the profile, uniformity, divergence of the whole beam. Hence, the plasma and the beam parameters can be comparably investigated in different designs or operation conditions.

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Table 1. Diagnostics equipped on the HONOR.

Plasma diagnostics	**Objects**	**Beam diagnostics**	**Objects**
Langmuir probe [45]	Electron density, electron temperature, plasma potential	Carbon dump with infra-red camera [47]	Beamlet divergence, beamlet alignment
Optical emission spectroscopy	H_α, H_β, H_γ, Cs^+, impurities' line density	Tungsten wire dump with camera [48]	Beam uniformity, beam divergence
Cavity ring-down spectroscopy [46]	H^- line density	Doppler shift spectroscopy [49]	Beam energy, beam divergence, stripping loss
Laser absorption spectroscopy	Cs^0 line density	Visible light camera	Beam uniformity, beam divergence
Microwave interferometer	Electron line density	Secondary electron emission [50]	Beam uniformity, beam divergence
		Water flow calorimetry [51]	Power load on grid

2.2. CANBE

As the CFETR NBI prototype, CANBE can carry out the whole working process of an NNBI injector including the negative ion beam launch, negative ion beam neutralization, residual ions removal, neutral beam transport to the beam dump, except the beam transport in the drift and injection tubes. Significantly, CANBE adopts an electric deflection technique for removal of the powerful residual ions that is the same with the ITER NBI design. CANBE is the first NBI equipment that can test the electric deflection technique ahead of the ITER NBI system and its test facility [52–54].

An overall view of CANBE and the HV tank is shown in figure 4. The components and their design parameters inside the CANBE HV tank are similar to that of HONOR HV platform, including RF generator, extraction voltage power supply, magnetic filter power supply, bias power supply, high-temperature water supply. The difference is that the CANBE HV tank is design to insulate against 400 kV voltage.

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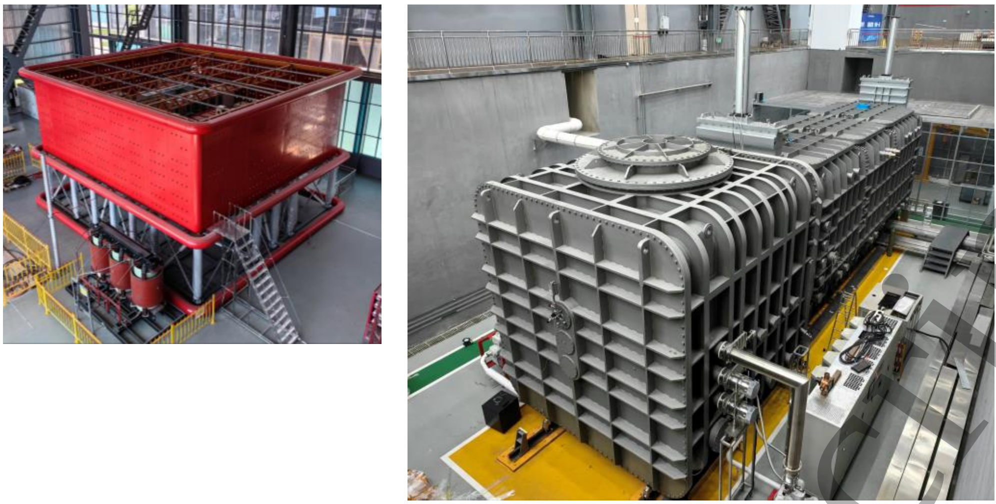

Figure 4. View of the CANBE testbed at the CRANE site.

A view of the CANBE in-vessel components is shown in figure 5. There are two vacuum vessels connecting via the gate valve. One vacuum vessel is for negative ion source ($5\times5\times5$ m^3) and the other one is for beamline ($12\times4\times4$ m^3). It means that a vacuum insulated negative ion source can be operated inside the vacuum vessel for better insulation and lower stripping loss, like ITER negative ion source [55]. The acceptance beam energy of CRAFT NNBI facility is 200–400 keV, which is no necessary to use a vacuum insulated negative ion source. However, according to the operation experience of the ITER neutral beam test facility SPIDER [56–58], several problems arose and powerful negative ion beam was hardly produced during the source operation immersed in the vacuum. So the vacuum vessels for negative ion source are prepared on both HONOR and CANBE for future research on the vacuum insulated negative ion source.

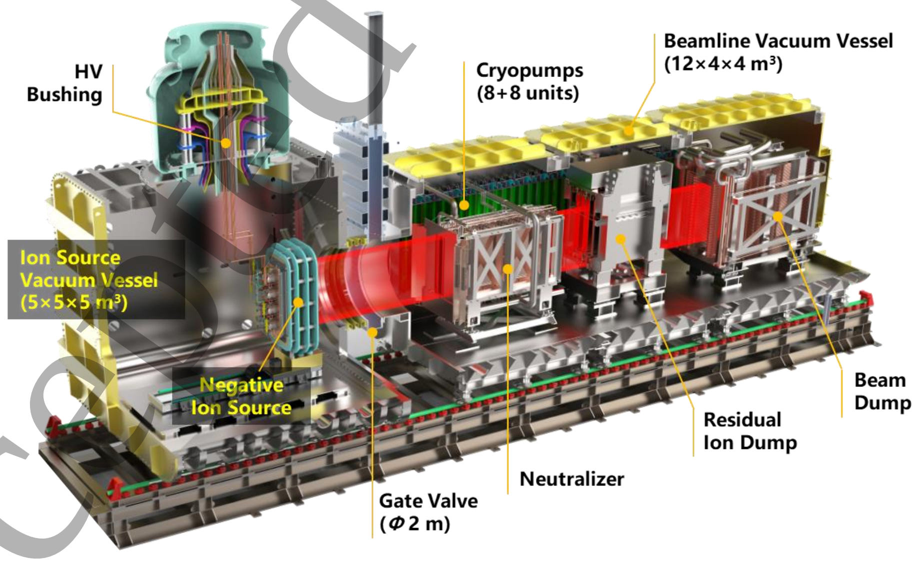

Figure 5. 3D model of the CANBE main structure with in-vessel components.

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A gas neutralizer with the length of 3 m is used for the neutralization of the negative ion beam [59–61]. The neutralizer is divided into two narrow beam channels to reduce the gas inlet for forming optimal gas target. The maximal cross section of each channel is 1.7 m (height) × 0.3 m (width) which can be changed according to different negative ion source.

An electrical residual ion dump (ERID) is applied to CANBE following the ITER NBI design [62]. Although the previous NBI systems all use the magnetic field to deflect the residual ions onto the dumps, a bending magnet for removing the energic and widespread ions in ITER or CFETR NBI (i.e., 1 MeV D^+ or D^- with a cross section of 0.6 m in width and 1.5–2 m in height) is enormous and uneconomical. Hence, the ERID concept is more realisable. The ERID of CANBE also has two beam channels (0.31 m in width for each) forming by three ion dumps. The middle dump is connected to the positive HV which absorbs the negative ions; the two lateral dumps are grounded which collect the positive ions. Actually, two identical ERIDs have been manufactured, each of which is 1.5 m in length. One can assembly the two modules together to form the 3 m long channels, or just use one module according to the experiments. Thus, ERID can provide with more convenient experimental plan, as the first facilities to test the electric deflection technique.

The beam dump of CANBE is the same with that of HONOR. The cryopumps are also installed on the two lateral walls in the beamline vacuum vessel of CANBE. Each cryopump comprises 8 units with a total length of 8 m. The positions of each component in the beamline vacuum vessel are shown in figure 6.

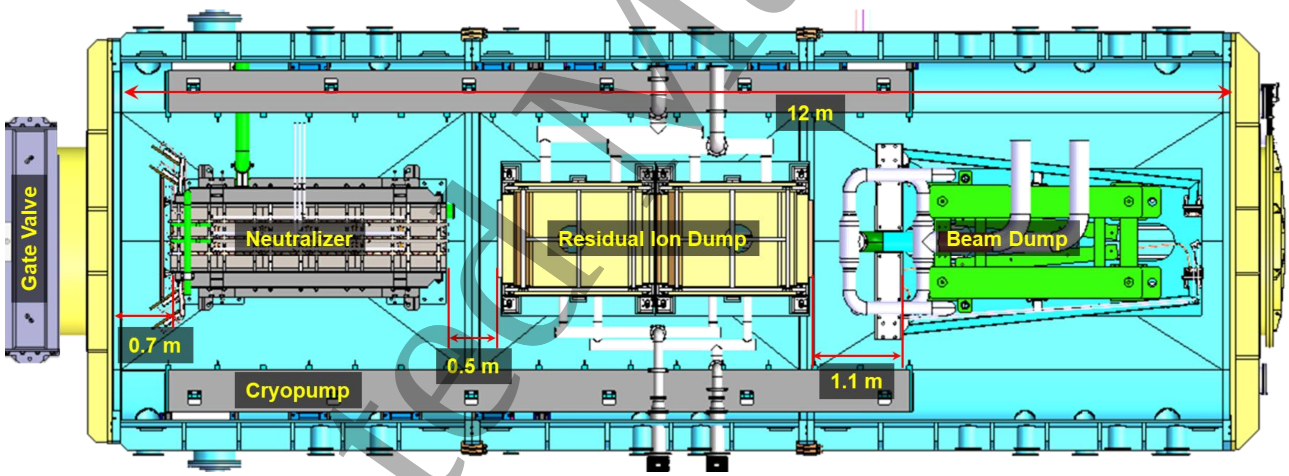

Figure 6. Positions of the in-vessel components in the CANBE beamline.

2.3. Roadmap of negative ion source research

The science and technology of negative ion source is developed step by step in the CRAFT project. Four negative ion sources are being or will be tested, as shown in figure 7: the number of RF driver (and also source size) is increased from one, two, to four with 2×2 arrangement or 1×4 arrangement; the accelerator is upgraded from single-stage acceleration of 50 kV, single-

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stage acceleration of 200 kV, to two-stage acceleration of 400 kV working in air or vacuum. Therefore, the major key issues for future CFETR negative ion source about the multi-driver, large-area, high-current, multi-acceleration and vacuum immersed operation are included in the development progress of those four CRAFT negative ion sources.

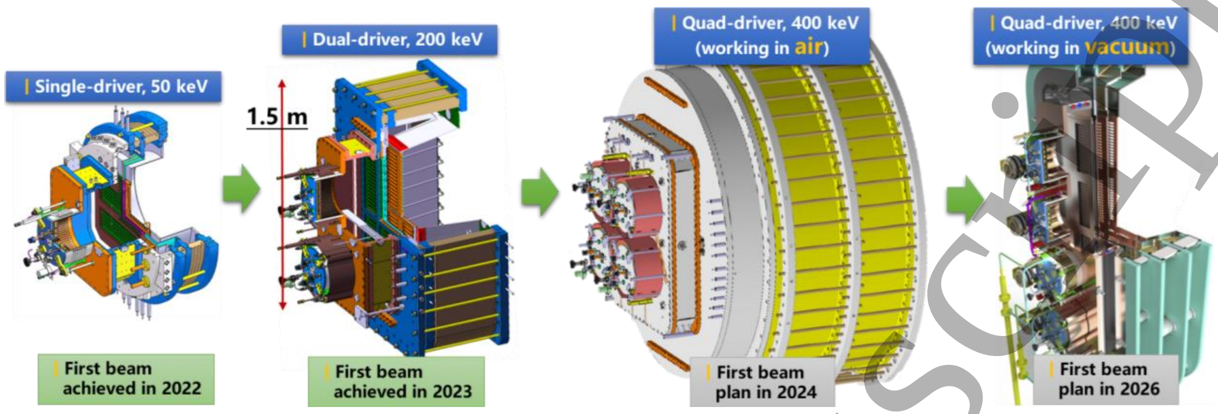

Figure 7. R&D progress of negative ion source in the framework of CRAFT project.

The single-driver negative ion source has been put into operation since 2022 on a previous testbed HUNTER and successfully achieved the repeatable long-pulse (> 100 s) extractions of negative ions (H^-) with an available current density (> 150 A/m^2) [63–66]. The single-driver negative ion source is used to understand and optimize the physical issues on RF plasma discharge and power transfer, plasma transport in magnetic field, Cs dynamics and conditioning, plasma characteristics near the PG [67–74]. The dual-driver negative ion source is the first source operating on the CRAFT NNBI facility and its experimental results are discussed in section 3. Both of the quad-driver negative ion sources are being manufactured, as shown in figure 8 [75–77]. The 2×2 driver source will work in air and can take the ITER half-size source ELISE as reference [78–80], thus it deems to be easier to reach. Besides studying the operation in vacuum, the 1×4 driver source with large aspect ratio is more favourable to the beam neutralization, although its non-uniformity of plasma or beam is probably more difficult to deal with.

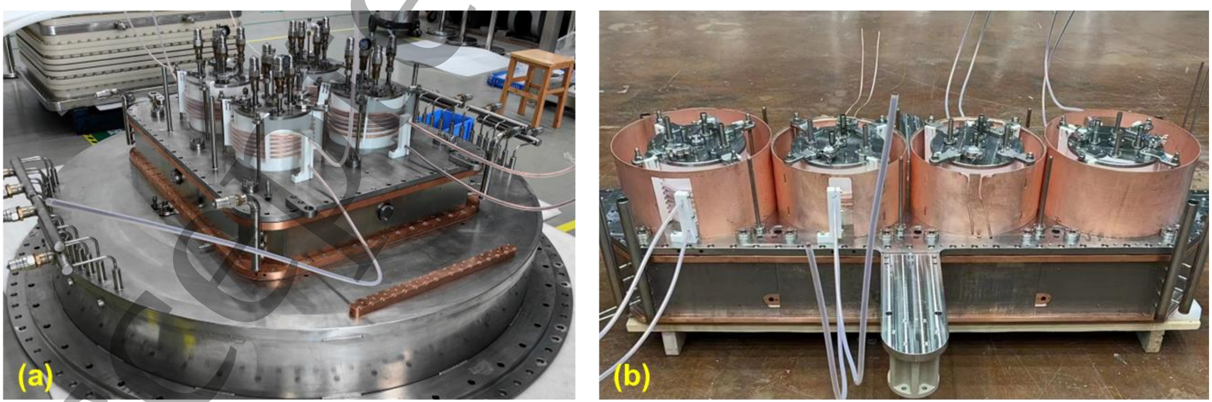

Figure 8. (a) Assembly of 2×2 driver plasma source, (b) assembly of 1×4 driver plasma source.

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3. Results in first operations

3.1. Commissioning

A whole system commissioning was carried out in the first operations of the CRAFT NNBI facility, to test and debug the problems when all the sub-systems working together. By using the acceleration voltage power supply, both of HONOR HV platform and CANBE HV tank could hold a high voltage of 200 kV for 100 s.

Until now, both of 2-unit and 4-unit cryopumps have been installed on the HONOR as design; a full-size cryopump with 8 units has been installed on CANBE, but another one just has 2 units due to the deferred delivery. The cryopump with only 2 units in either HONOR or CANBE vacuum vessel was tested to have a pumping speed of > 100,000 L/s, as shown in figure 9. The gas was puffed into from the negative ion source. The pumping speed reduced a bit with the increasing gas inflow.

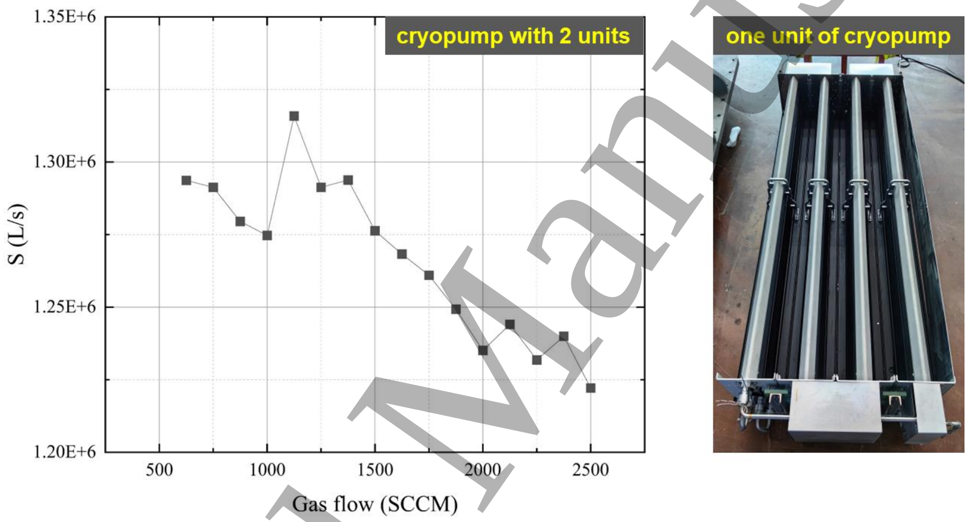

Figure 9. Measurement of pumping speed of the cryopump with 2 units.

During the commissioning, a high-power and long-pulse RF plasma discharge (140 kW for 110 s) was obtained via the dual-driver negative ion source; a H^- beam current of ~ 1 A was successfully extracted for 10 s in the volume mode (i.e., without Cs seeding). The design parameters of the dual-driver negative ion source are listed in table 2.

Table 2. Key designs of the dual-driver negative ion source.

Items	Design value
RF power	140 kW
RF frequency	1 MHz (±5% adjustable)
RF driver	Φ 24 cm, 16 cm (height)

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Expansion chamber	90 (length) × 50 (width) × 20 (depth) cm^3
PG aperture	Φ 14 mm, 6×16×4
Extraction voltage	−8 kV
Acceleration voltage	50/200 kV
Ion current	15 A (~ 255 A/m^2)
Pulse duration	> 100 s

3.2. Operations on HONOR

The dual-driver negative ion source of CRAFT is based on the design and experimental results of the single-driver negative ion source. In order to demonstrate the physical designs and operation methods for a RF driven negative ion source, the dual-driver negative ion source is required to replicate the results of single-driver source that is long-pulse negative ions extraction. Hence, the dual-driver negative ion source was equipped with a 50 keV accelerator at first [81]. The experiments were carried out with the 2-unit cryopump only in the HONOR.

A long-pulse extraction of H^- has been achieved repeatably and the typical waveforms are shown in figure 10. The RF coils were connected in series between two drivers and the RF power was 50 kW in this shot. The filling pressure was 0.4 Pa, the bias voltage was 14 V, and the PG current for magnetic filter was 1,000 A. The extraction voltage was 5.4 kV, the acceleration voltage was 50 kV. The bias voltage was generally applied 3 s leading the beam extraction pulse. Because the bias voltage was already lower than the floating potential, the bias current should be negative, but the unipolar power supply could not display the negative current. Note that, the floating potential was not measured simultaneously during the beam extraction because it requires the high-voltage isolation. But it was measured during the shots of the plasma only.

Here, the current load on the extraction grid (EG), I_{EG}, was regarded as the co-extracted electron current, because almost all the electrons could be deflected onto the EG [82]; the current output of the acceleration voltage power supply, I_{ACC}, was regarded as the extracted H^- current, although it included part of stripping electrons (assumed to be < 10% of the acceleration current). There were 20 times of breakdown (i.e., the burrs of the acceleration voltage signal, V_{acc}) during the pulse duration of 105 s and the pause before the restart of beam extraction was 200 ms. The breakdowns were all due to the over-current of the high voltage power supply, which were the sparks between two grid electrodes essentially. But the over-current signals were not displayed in the waveforms because the high-speed data acquisition system was not ready [83]. Among them, 17 times were related to the extraction voltage and 3 times were due to the acceleration voltage. Furthermore, the breakdowns were more frequent after 45 s and the reasons were not determined (maybe outgas from the grids by particle bombardment or Cs pollution

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on the grids). The I_{EG} was gradually increased from 0.8 A to 1.1 A and I_{ACC} was increased from 7.3 A (~ 123 A/m^2) to 8 A (~ 135 A/m^2), which induced an electron-to-ion ratio of < 0.15.

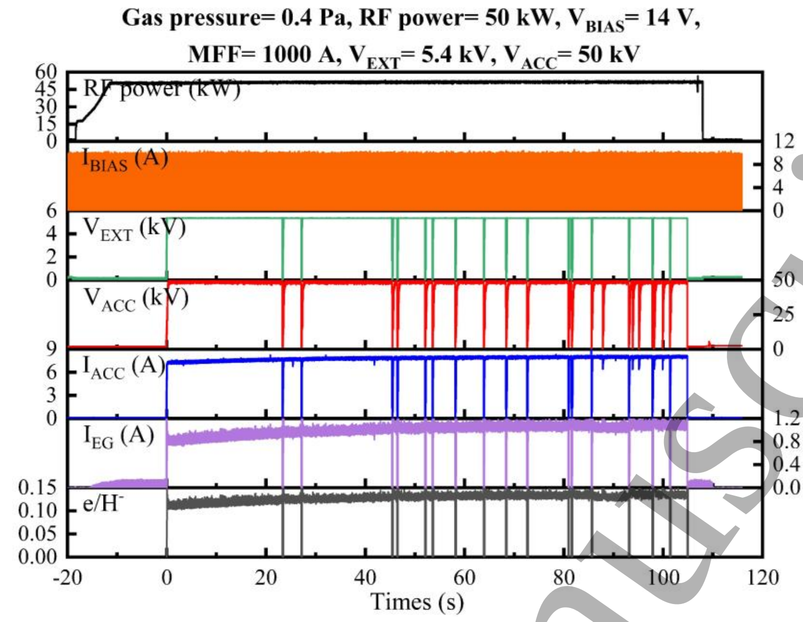

Figure 10. Typical waveforms of the long-pulse extraction of negative ions.

By increasing the RF power and extraction voltage, a high-current extraction of negative ions was also tested. The typical waveforms are shown in figure 11. The RF power was 97 kW, the filling pressure was 0.4 Pa, the bias voltage was 15 V, and the PG current for magnetic filter was 1,100 A. The extraction voltage was 8.0 kV, the acceleration voltage was 47 kV. The I_{ACC} was almost constant at 14.7 A (~ 248 A/m^2) and I_{EG} was below 6.0 A, which induced an electron-to-ion ratio of < 0.41. There were 9 times of breakdowns during the pulse duration of 30 s and all of them were related to the extraction voltage. Note that, only the room-temperature water was used for the PG in these experiments. For Cs seeding, the temperature of the Cs delivery pipe was constant at a value between 220 ℃ and 260 ℃ in general, the temperature of the Cs oven was increased in the step of 10 ℃ when the electron-to-ion ratio was almost unchanged [84].

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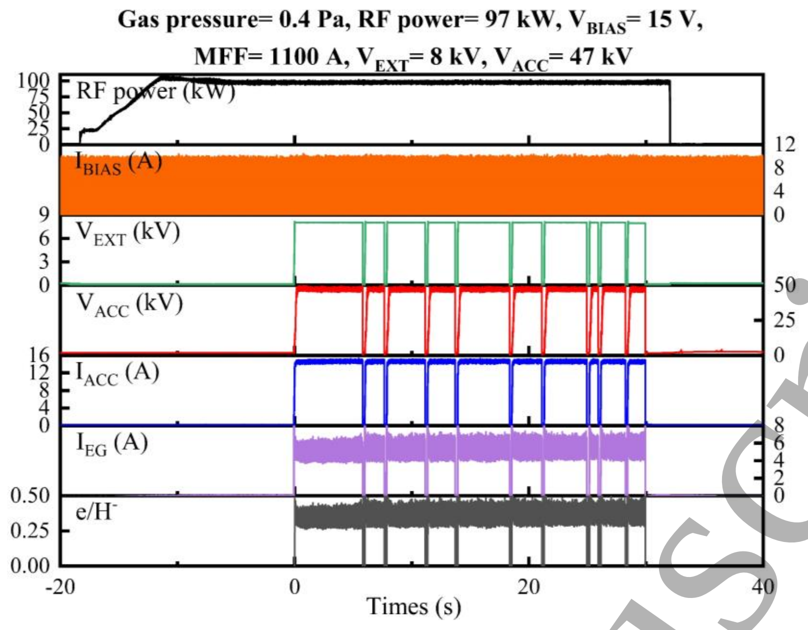

Figure 11. Typical waveforms of the high-current extraction of negative ions.

Since the extraction of negative ions has been verified, the dual-driver negative ion source was upgraded with 200 keV accelerator. The major differences were that the acceleration gap was enlarged from 20 mm to 90 mm and the height of main insulator was increased from 100 mm to 400 mm. The target was to achieve a high-energy and high-power negative ion beam. The waveforms of the highest beam power in the first operations of HONOR are shown in figure 12. The RF power was 69 kW, the filling pressure was 0.4 Pa, the bias voltage was 16 V, and the PG current for magnetic filter was 1,100 A. The extraction voltage was 5.9 kV, the acceleration voltage was 130 kV. The I_{ACC} was constant at 8.9 A and I_{EG} was 5.0 A. There were 2 times of breakdowns during the pulse duration of 10 s, and the pause before restart of beam extraction was changed to 1 s during the high energy operation. Because the breakdown rate was hardly below 0.2 count/s (breakdown rate = number of breakdown / pulse duration), the long-pulse and high-energy acceleration of negative ions was not attempted.

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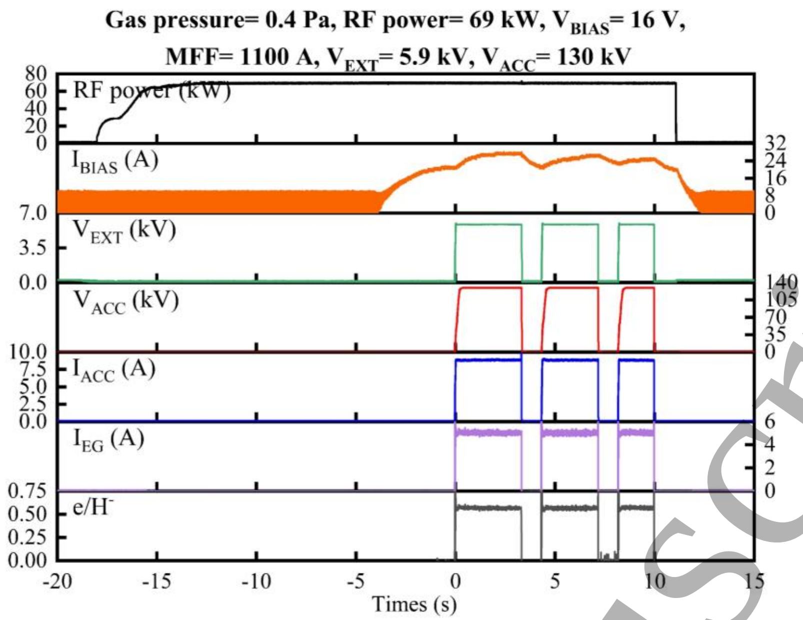

Figure 12. Typical waveforms of the high-energy acceleration of negative ions.

Until the end of the first operations on HONOR (from July 2023 to November 2023), the acceleration voltage of the dual-driver negative ion source was hardly higher than 140 kV even decreasing extracted ion current. Several creepage paths were found on the outside surface of the insulator between PG and EG. But the reason of the limited acceleration voltage was not sure. After upgrading to 200 keV accelerator, the electron-to-ion ratio of the dual-driver negative ion source showed a general increase in different levels of extracted ion current, even with a higher heating temperature for the Cs injection system. The reasons were not determined. But one guess was that the back-streaming ions with higher energy changed the Cs re-distribution or impurities released from the back plate of the source.

3.3. Operations on CANBE

Considered the performance of the dual-driver negative ion source hitting a bottleneck, the first operations of HONOR were closed and the source was installed on CANBE for its first operations. The target was to demonstrate a whole operation process of negative ion based neutral beam injector. The operation value of acceleration voltage was limited to 120 kV to avoid too much breakdowns. The cross section of either beam channel of the neutralizer was changed to 0.6 m × 0.18 m to match the beam profile from the dual-driver negative ion source. However, the structure of ERID was hard to be changed, which caused the width of beam channels of ERID (0.31 m) being larger than that of neutralizer. To ensure the removal of the residual ions, the ERID with 3 m in length was used. As mentioned above, the experiments could be carried out only with a 2-unit cryopump on CANBE. It resulted in the accelerated beam current being hardly higher than ~ 6 A when the ERID was on work, because the HV breakdown on the ERID became frequent.

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The typical waveforms of the neutral beam purification with the ERID are shown in figure 13 (displaying three shots: Nos. 2496, 2498 and 2499). The operation parameters of negative ion source were the same in these three shots. The RF power was 42 kW, the filling pressure was 0.4 Pa, the bias voltage was 25 V, and the PG current for magnetic filter was 2,000 A. The extraction voltage was 4.5 kV, the acceleration voltage was 105 kV. The I_{ACC} was 3.4 A and I_{EG} was 1.5 A. For No. 2496 and No. 2498, the ERID was off work and on work, respectively. For No. 2498 and No. 2499, the ERID was both on work, but the gas input from the neutralizer was 0 and 100 sccm, respectively.

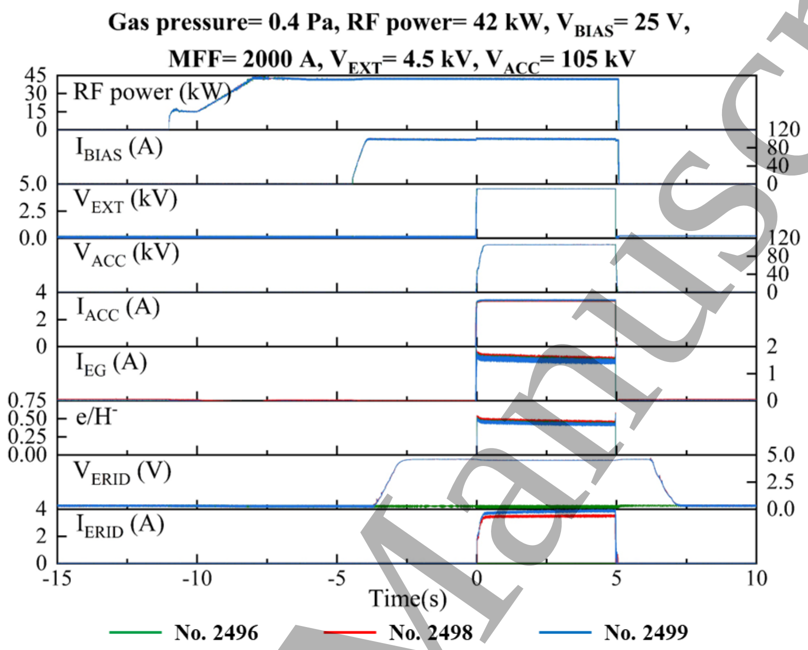

Figure 13. Typical waveforms of the neutral beam production: shot No. 2496 without ERID on work, shot No. 2498 with ERID on work and without adding gas from neutralizer, and shot No. 2499 with ERID on work and with adding gas from neutralizer of 100 sccm. The gas inlet rates to negative ion source were all 1750 sccm.

The applied voltage to ERID V_{ERID} was gradually increased to 4.6 kV to ensure that the residual ions were fully deflected onto the ERID. The judgement was that the power load on the beam dump had little increase when raising the V_{ERID}. Generally, the ratio of the power loads on the beam dump (i.e., calorimeter) with and without the removal of residual ions (i.e., with and without the V_{ERID} here) was used to evaluate the neutralization efficiency [85–88], and then, the average neutralization efficiency was 35.7% without the makeup gas and 43.1% with gas input of 100 sccm from neutralizer. Note that, the gas input to the negative ion source was constant at 1750 sccm.

The ERID current I_{ERID} (i.e., the output current of the ERID power supply) was already higher than the I_{ACC}, which was the solid evidence of the production of secondary plasma inside the ERID. Because the maximal residual ion beam current could not be higher than the initial ion beam current even if there was no neutralization. Moreover, when adding the gas from the neutralizer (shot No. 2499), the I_{ERID} was increased but the neutralization efficiency was higher (i.e., less residual ions)

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comparing to the shot without gas from neutralizer (No. 2498). Therefore, the increased I_{ERID} was due to the secondary plasma. Just because of the increased I_{ERID}, the breakdowns became frequent when trying to raise the gas inlet rate from neutralizer.

Although no higher beam energy or beam power and no maximal neutralization efficiency was achieved, the first operations of CANBE (from November 2023 to January 2024) were closed to modify and assemble the large cryopumps.

4. Conclusion

This paper gives an overview of the CRAFT NNBI facility, called CRANE, and its two testbeds: HONOR for the negative ion source research and CANBE as the CFETR NBI injector prototype. CRANE also hosts some necessary supporting systems for the testbeds, such as high voltage power supply, cryogenic plant, cooling plant. The most outstanding features of HONOR are the flexible assembly and the various diagnostics for source plasma and beam. The CANBE is designed to have a comparable size and full working process to the CFETR NBI injector, especially the unconfirmed technique of the electrical removal of powerful residual ions.

The CRANE building construction was started in 2019 and completed in 2021. The component integration and commissioning of HONOR and CANBE were finished in 2022 and 2023, respectively. The power supply, vacuum pumping, diagnostics and control have been implemented and tested. Both of two testbeds have possessed the experimental ability of negative ion beam acceleration.

The CRAFT dual-driver negative ion source was applied to the first operations of HONOR and CANBE. By using a 50 keV accelerator, the long-pulse and high-current extractions of negative hydrogen ions have been achieved on HONOR, and the typical values were 55.4 keV, 7.3 A (~ 123 A/m^2), 105 s and 55.0 keV, 14.7 A (~ 248 A/m^2), 30 s, respectively. The results demonstrated the physical design of the dual-driver negative ion source which was transplanted from the CRAFT single-driver negative ion source. By replacing with a 200 keV accelerator, the MW-class negative ion acceleration has been achieved on HONOR, and the typical values were 135.9 keV, 8.9 A (~ 150 A/m^2), 8 s. However, the acceleration voltage could not raise above 140 kV.

By installing dual-driver negative ion source on CANBE, a whole operation process of negative ion production, neutralization and purification has been demonstrated, and the typical values were 109.5 keV, 3.4 A, 8 s with a neutralization efficiency of 43.1%. The electrical removal of powerful residual ions was applied to an NNBI injector for the first time. However, a problem of frequent HV breakdowns on the ERID was exposed when the large cryopump was not fully on work.

According to the results of the first operations of CRANE and the acceptance target of the project (200–400 keV, 2 MW, 100 s, H^0), several tasks will be carried out in the next step. The dual-driver negative ion source needs to resolve the HV breakdown problem on the accelerator and has to attain a long-pulse and MW-class negative ion beam. The Cs pollution, beam

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optics, stray charged particles could be the causes of the HV breakdown or spark down. In future, we will detect the reason and further improve the beam parameters. Two different quad-driver negative ion sources will be assembled and tested. For HONOR, several diagnostic systems need to support the research on the plasma and beam uniformity in the next campaign. For CANBE, the large cryopumps should be fully on work at first.

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