

CONFERENCE PRE-PRINT**REPETITIVE GENERATION OF HYDROGEN
NEGATIVE ION BEAMS WITH INITIAL TARGET
PARAMETERS FOR THE ITER HNB**

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Abstract

Long-pulse acceleration of MeV-class ITER-relevant hydrogen negative ion (H^-) beams ($0.87\text{ MeV}/230\text{ Am}^{-2}$) has been pursued in Mega-volt Test Facility (MTF) in QST. Stability of such high-energy and high-intensity beam is primarily constrained by lifetime of filaments used for plasma generation and voltage holding capability. To extend filament lifetime, FPGA-based fast cuoff system has been installed to promptly terminate abnormal discharges that cause severe damage on filaments. Surge protection circuit has been integrated to prevent FPGA from malfunction induced by electrical breakdowns. In parallel, high-voltage conditioning procedure has been reexamined to suppress temporal variations in dark current and vacuum pressure. As a result of these modification, repetitive generation of ITER-relevant H^- beam at 0.87 MeV for 50 s was successfully demonstrated. Furthermore, the beam pulse length was extended to 110 s with stable H^- current and beam divergence maintained below the ITER requirement of 7 mrad .

1. INTRODUCTION

In the heating neutral beam injector (HNB) of ITER, acceleration of high-power beams of 0.87 MeV and 46 A (230 Am^{-2}) H^- and 1 MeV and 40 A (200 Am^{-2}) deuterium negative ion (D^-) are required [1]. The beam pulse length is planned to be progressively extended up to 1000 s for H^- and 3600 s for D^- . During the initial operation of the ITER HNB, the H^- beam is required to be accelerated with beam energy of 0.87 MeV and current of 46 A for 50 s . These target parameters of ITER significantly exceed the performance achieved in existing devices such as the HNBs of JT-60SA and LHD [2, 3]. For instance, JT-60SA negative-ion-based NB is designed to deliver H^-/D^- beams with an energy of 0.5 MeV and current of 22 A (130 Am^{-2}) for 100 s [2].

To develop the ITER negative ion accelerator, long-pulse beam acceleration experiments have been conducted at Mega-volt Test Facility (MTF) in QST using a filament-arc-type negative ion source and an electrostatic accelerator configured identically to the ITER one. One of the primary challenges in achieving stable long-pulse acceleration is the degradation of the H^- current due to excess heating of plasma grid (PG). In negative ion sources for fusions, the H^- ions are produced via surface conversion of hydrogen atoms and/or positive ions on cesium (Cs) coated PG surface. The efficiency of the H^- production is highly sensitive to work function of the PG surface, which is strongly influenced by PG temperature. For filament-arc-type negative ion sources, the optimal temperature range is approximately $200\text{--}300\text{ deg. C}$. However, during long-pulse operation, the PG temperature gradually increases due to the heat flux from plasmas and exceed 300 deg. C , resulting in deterioration of the H^- current. To address this issue, an air-cooled PG has been developed at QST, enabling stable acceleration of the H^- beam at 0.275 MeV for 300 s and 0.5 MeV for 100 s [4]. Nevertheless, long-pulse operation at higher beam energy remains challenging due to limited filament lifetime and electrical breakdowns in the accelerator. Filaments are vulnerable to damage from abnormal discharge, which are more likely occur under high discharge power conditions required for producing high density H^- ions to satisfy perveance matching at high beam energy over 0.7 MeV . Additionally, the voltage holding capability had been insufficient to sustain the beam acceleration at more than 0.7 kV , preventing operation at the target beam energy of 0.87 keV . To overcome these limitations, a series of technical improvements have been implemented. A filament protection system was introduced to promptly terminate abnormal discharges. A surge protection circuit was integrated to avoid malfunction of the protection system caused by electrical surges. Furthermore, the voltage holding capability has been improved by a new high-voltage conditioning procedure. This paper reports the recent progress in long-pulse acceleration at QST, demonstrating the feasibility of ITER-relevant operation through these modifications.

2. MEGA-VOLT TEST FACILITY (MTF)

Figure 1 shows the schematic illustration of MTF at QST, comprising a negative ion source, an electrostatic accelerator, and a beamline equipped with beam diagnostic systems. The negative ion source plasmas are generated via filament-arc discharge using six tungsten (W) filaments. Cesium (Cs) vapor is introduced into the discharge chamber to enhance negative ion production from the PG surface. The air-cooling system is implemented to actively control the PG temperature. The H^- ions are extracted by the potential difference between the PG and an extraction grid (EXG), and are subsequently accelerated by a prototype accelerator for ITER, so-called MeV accelerator. MeV accelerator is the five-stage and multi-aperture accelerator with a geometrical configuration identical to that of the ITER accelerator. Specifically, the aperture interval is 20 mm x 22 mm, acceleration gap length is 88 mm, and aperture diameters of the acceleration grids are 14 mm (A1G-A2G) and 16 mm (A3G-GRG), respectively. The number of apertures is limited to nine due to the capability of the acceleration power supply (1 MV/0.5 A in rated values). The heat load on each acceleration grid is evaluated from the temperature increment of the cooling water. The accelerated H^- beams are dumped onto a water-cooled beam dump, and the H^- beam current is evaluated from the increment of the cooling water temperature. The beam divergence is one of the important parameters to determine the beam quality for HNB. To enable non-destructive measurement of the beam divergence during long-pulse beam accelerations, a visible camera is installed 2142.5 mm from the GRG to observe the H^- beams from the side [5], which emits the H-alpha light by the collisions with the residual gas along its trajectory. As shown in Fig. 1, only three beamlets are visible in the camera image, since three beamlets in each row overlap with each other from the side-view perspective. The beamlet width (w_{beam}) is obtained by applying a multi-Gaussian fit to the line profile of the light intensity extracted from the camera image. The beam divergence is then evaluated using the formula $\tan^{-1}((w_{\text{beam}}/2)/L)$, where L is the distance between the camera and the GRG. For the plasma diagnostics, the optical emission from the plasmas is observed from the top of the discharge chamber.

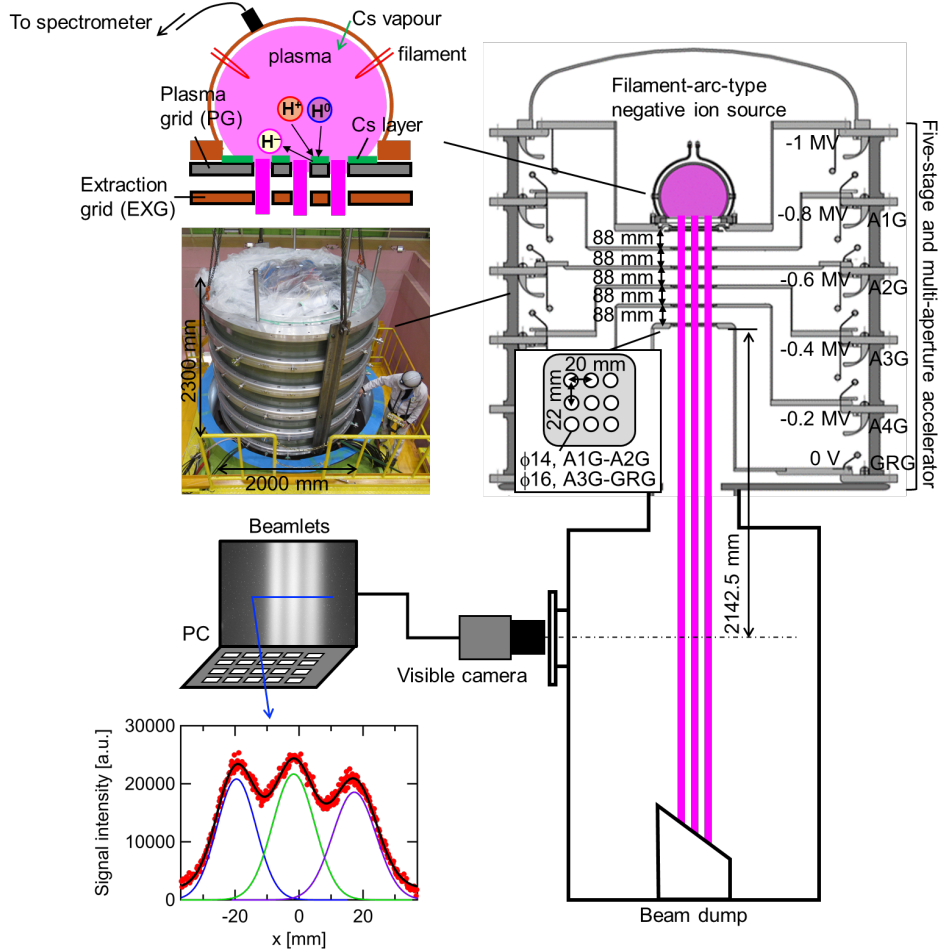


FIG. 1. Schematic illustration of MTF.

3. FAST CUTOFF OF ABNORMAL DISCHARGE UNDER HIGH VOLTAGE

Abnormal discharges, commonly referred as arcing, tend to occur with increasing the discharge power required for generating high-density H^- ions. Such events cause serious damage to the filaments and significantly limit the operational lifetime of filament-arc-type negative ion sources. To enable immediate detection and termination of the arcing, a FPGA (Field-Programmable Gate Array) based fast cutoff system has been developed [6] as shown in Fig. 2(a). In previous experiments, the arcing was detected when the discharge current exceeded a predefined threshold. However, this method posed a limitation in reducing the detection time as depicted in Fig. 2(b). The arcing occurring during the ramp-up phase of the discharge current is particularly difficult to detect promptly, since the threshold must be set higher than the discharge current at steady state to avoid false detections. Moreover, the intermittent noises superimposed on the current signal further necessitates raising the threshold, resulting in delay of the detection. Due to these constraints, conventional detection logic requires approximately 1 ms to terminate the arcing, whereas the cutoff time below 0.343 ms is essential to keep the filaments from being severely damaged [6]. To address this, the FPGA has been programmed to calculate the time derivative of the discharge current and evaluate whether it exceeds a predefined threshold within a given time interval. False detections are effectively suppressed, since intermittent noises typically have a shorter time constant than the arcing. As a result, the cutoff time has been successfully reduced to less than 0.1 ms.

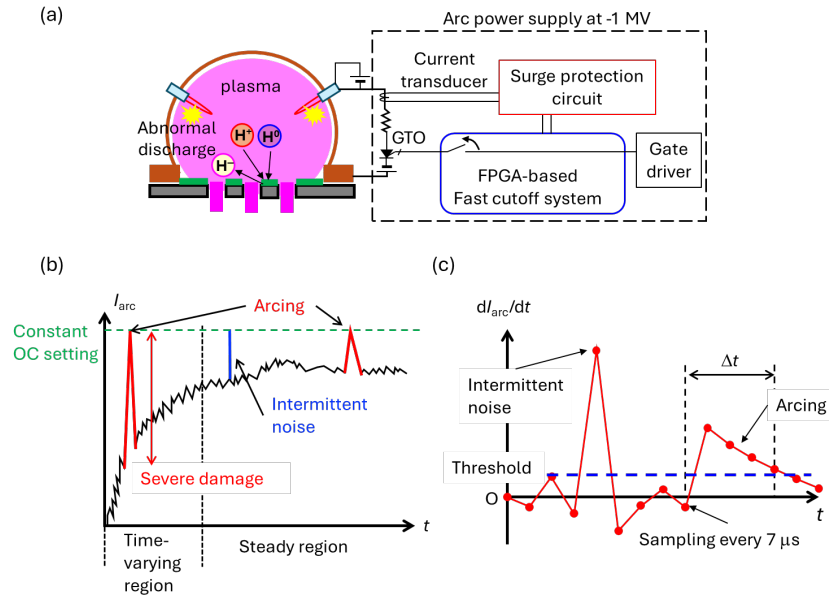


FIG. 2 (a) Schematic diagram of arc power supply with surge protection system and FPGA-based fast cutoff system, and illustrations of time evolutions of (b) discharge current, and (c) its time derivative.

Nevertheless, implementing this system under high voltage circumstances presents a challenge due to electrical surges associated with electrical breakdowns in the accelerator. The electrical surges may lead to malfunction of the FPGA. To mitigate this risk, a surge protection circuit was installed between a current transducer and the FPGA as shown in Fig. 2(a). Figure 3(a) shows the equivalent circuit of the protection system, which consists of bypass capacitors and a ferrite core. The bypass capacitors eliminate the high frequency components originated from the surge to the ground. To suppress the common mode currents while minimizing interference with the measurement signals, the cables from the current transducer are wound around the ferrite core. Figure 3(b) shows the result of a verification experiment for the protection circuit. It was confirmed that the surge voltage induced in the fast cutoff system was suppressed to one-tenth by implementing the surge protection circuit. As a result of this countermeasure, the fast cutoff system has been stably operated without incurring any damage from high voltage breakdowns. Consequently, the filament lifetime was extended by a factor of three, and the total plasma discharge duration became longer by seven times in the particular case of discharge power of more than 25 kW, which is necessary to meet perveance matching at more than 0.7 MeV.

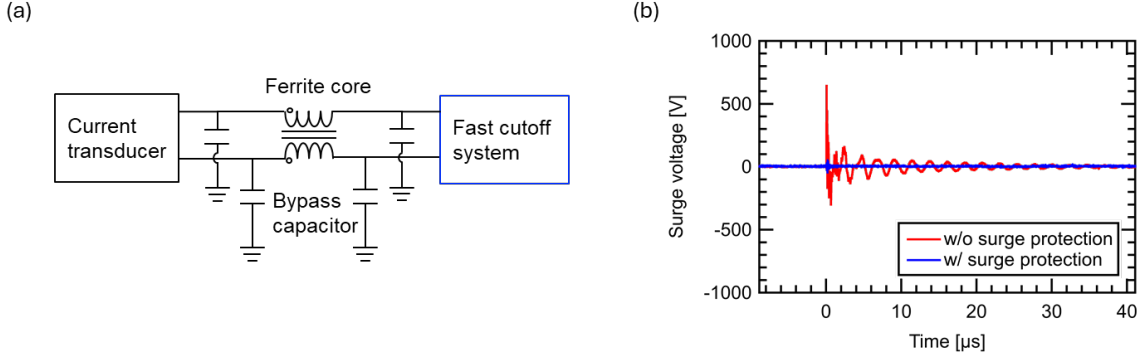


FIG. 3 (a) equivalent circuit of surge protection and (b) result of verification test.

4. IMPROVED HIGH VOLTAGE CONDITIONING PROCEDURE

The electrical breakdown in extraction and acceleration gaps is another issue for the long-pulse beam acceleration. To further improve the voltage holding capability for long-pulse operation at more than 0.7 MV, the high voltage conditioning procedure was reexamined. During high voltage conditioning in vacuum, the rapid increases in the dark current flowing through the acceleration gaps and the vacuum pressure in the beamline are observed intermittently, especially pronounced spike is evident before the electrical breakdown. Then, these temporal variation in the dark current and the vacuum pressure were used as an index of the progress of the conditioning, and the procedure to suppress them effectively was developed. Figure 4 shows the representative example of high voltage conditioning conducted in MTF in a day. After each breakdown event, the high voltage application was resumed, and the results from six consecutive trials were aggregated. During the initial phase of conditioning, pronounced intermittent spikes were observed in both the dark current and vacuum pressure, limiting the high voltage hold time to less than 500 s. In the third trial, these temporal variations were significantly reduced, and the acceleration voltage was stably maintained at 0.922 MV, which is higher than the target beam energy of 0.87 MeV, for over 1000 s without the dark current. As a subsequent step, the extraction voltage was applied sequentially for 1 s every 30 s while maintaining the acceleration voltage at 0.922 MV. Although the dark current reappeared and increased with the extraction voltage, it was ultimately suppressed to several mA through repeated application. In addition to the conditioning in vacuum, the underperveant beam was intentionally extracted by applying the extraction voltage higher than the optimal value. This approach aimed to sputter the Cs deposited on the EXG surface with the divergent beam components, since the Cs seems to cause the enhancement of the secondary electron emission and to contribute to the electrical breakdowns in the extraction gap during the beam extraction. The high-voltage conditioning procedures described above may also be applicable to the ITER HNB equipped with the multi-stage and multi-aperture accelerator and the Cs-seeded negative ion source.

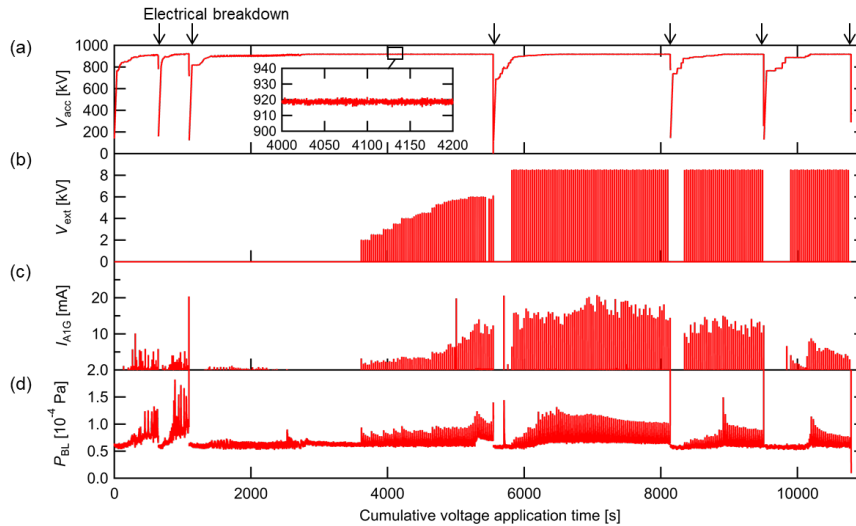


FIG. 4. History of high voltage conditioning: (a) acceleration voltage, (b) extraction voltage, (c) dark current flowing through A1G, and (d) vacuum pressure in beamline.

5. LONG-PULSE ACCELERATION OF ITER-RELEVANT H^- BEAM

Following modifications to the plasma generation and high voltage conditioning, long-pulse acceleration of the ITER-relevant H^- beam was successfully achieved. Figure 5(a) shows the history of beam pulse length and amount of Cs introduced into the plasma chamber during the experimental campaign, where the temperature of the Cs reservoir was kept at 180 deg. C and the Cs flux was regulated with a pneumatic valve. In the early phase of the campaign, the H^- beams were accelerated at relatively low beam energy (~ 0.275 MeV), since the H^- ion density was insufficient to satisfy the perveance matching condition required for higher beam energy. As the Cs conditioning progressed, both the beam energy and plasma discharge power increased. In the later phase of the campaign, when sufficient Cs conditioning had been achieved, corresponding to approximately 1.5 g of Cs introduced in the discharge chamber, the beam energy reached 0.87 MeV. Long-pulse acceleration at 0.87 MeV was performed following the optimization of the beam parameters such as the beam current density, the beam divergence, and grid heat loads through the adjustment of the extraction voltage and discharge power. As a result, the repetitive generation of the H^- beam at 0.87 MeV for 50 s, corresponding to the target at initial operation of ITER HNB, was successfully demonstrated for the first time. Here, the pulse length refers to the net beam acceleration time, excluding intervals of plasma termination caused by the arcing during each trial. Although the arcing occurred, the acceleration voltage was stably maintained for 50 s without the electrical breakdown. The H^- current density was comparable to the ITER requirement, and the total heat load on the acceleration grids remained below the allowable level of 15% throughout all long-pulse trials, as shown in Fig. 5(b).

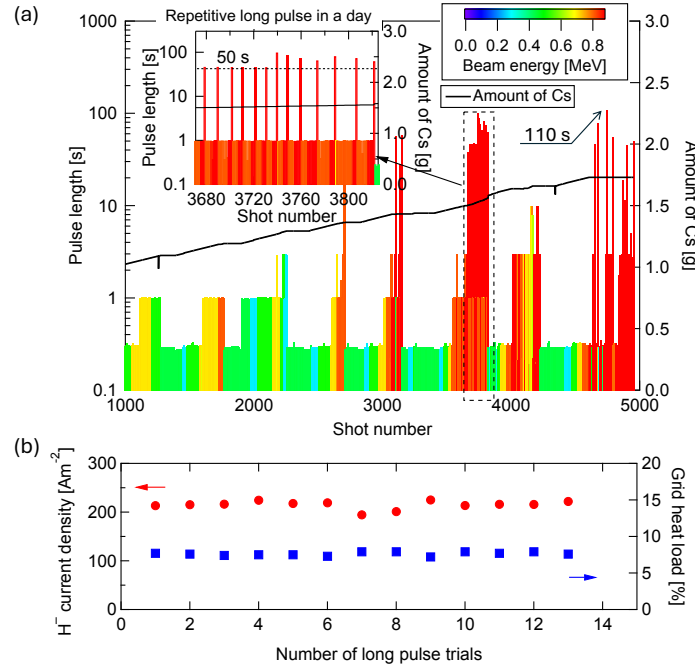


Fig. 5. shot summary of beam pulse length and (a) Cs consumption and (b) current density and grid heat load in long-pulse trials.

Further long-pulse generation of the ITER-relevant H^- beam was conducted in pursuit of the final ITER target for hydrogen operation, namely, 1000 s. Figure 6 shows the time evolutions of the beam parameters such as acceleration current, electron current, and beam divergence during the long-pulse acceleration. Here, the electron current was evaluated from the difference between the drain currents measured in the extraction and acceleration power supplies. During this pulse, the air-cooling system for the PG was not activated, since the PG temperature remained around 300 deg. C, which is still within the optimal temperature range for efficient negative ion production from the PG surface. The arcing occurred in the hatched area, leading to abrupt termination of both plasma discharge and beam extraction. Nevertheless, thanks to the protection provided by the fast cutoff system, the beam extraction resumed after short interval without the filament break and was sustained for 110 s in total. The beam acceleration was ultimately halted by the electrical breakdown. Throughout the pulse duration, both the H^- and electron currents remained stable. This would be attributed to the stable condition of the Cs in the plasma

chamber as well as the proper PG temperature since the degradation of the currents was previously observed in conjunction with steep increase in the optical emission of the Cs [2]. In contrast, no significant change was observed during this pulse as shown in Fig. 6(d). In addition to current stability, the beam divergence was maintained below the ITER HNB target of 7 mrad without degradation. Figure 7 shows the time evolution of the increment in the cooling water temperature in the acceleration grids and the beam dump during 110 s beam pulse. The observed variation in the water temperature on the beam dump after 50 s was attributed to the beam termination caused by the arcing. The flow rate of the cooling water in acceleration grids was approximately 10 L/min, which is comparable to that of the ITER accelerator when normalized per aperture. The maximum temperature rise in the grid cooling water was suppressed to less than 10 deg. C and reached thermal equilibrium at around 40 s. This implies that the ITER accelerator can tolerate the grid heat load during the long-pulse operation. The overall progress of long-pulse beam acceleration is summarised in Fig. 8. The beam energy reached 0.87 MeV following improvements to the high-voltage conditioning procedure, and the pulse duration was extended to beyond 100 s through prompt cutoff of the arcing under the high-voltage conditions. Although the beam pulse length is still limited by electrical breakdowns, the acceleration power supply of the ITER HNB is designed to resume operation after breakdown events and to be able to withstand up to 200 breakdowns per hour [7]. Hence, the achievement in this study provides strong evidence supporting the feasibility of long-pulse beam acceleration under ITER-relevant conditions.

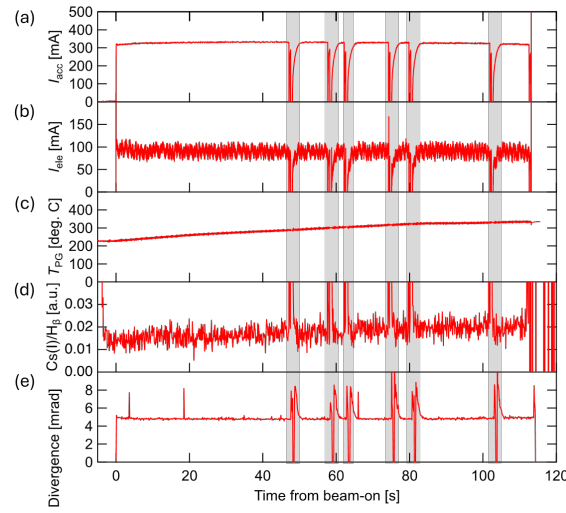


Fig. 6. Time evolution of (a) acceleration current, (b) electron current, (c) PG temperature, (d) optical emission intensity of Cs atom normalized by H-beta, and (e) beam divergence.

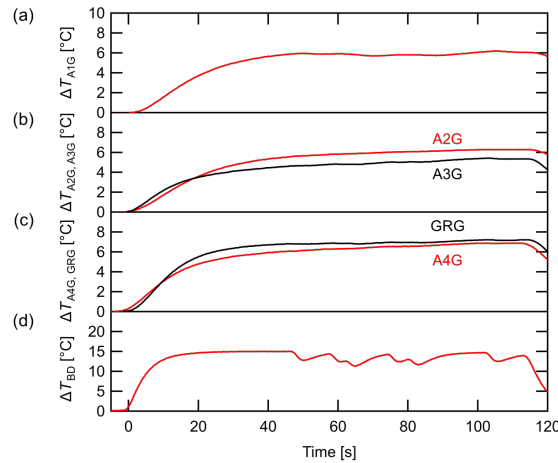


Fig. 7. Time evolution of increment of cooling water temperature on (a) A1G, (b) A2G and A3G, (c) A4G and GRG, (d) beam dump.

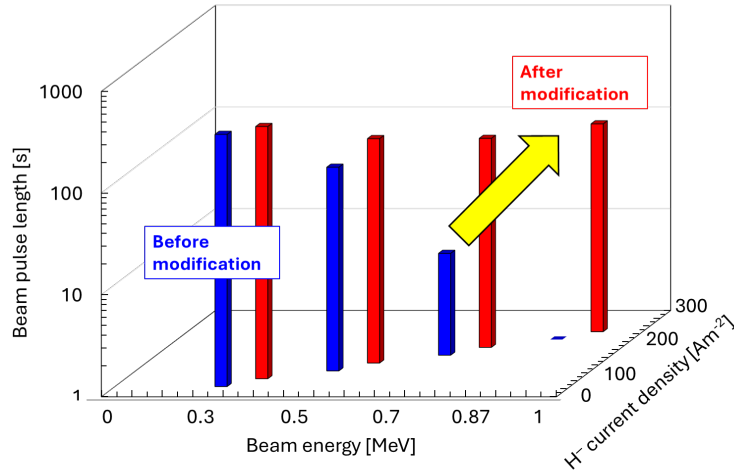


Fig. 8. Progress of long-pulse beam acceleration.

6. SUMMARY

Long-pulse acceleration of ITER-relevant H⁻ beams was successfully demonstrated at MTF following improvements in plasma generation and high-voltage conditioning. The surge protection circuit was integrated into the FPGA-based fast cutoff system to suppress the risk leading to severe damage. Owing to this, the fast cutoff system effectively mitigated damage to filaments from the arcing under high-voltage conditions, resulting in extended filament lifetimes and improved operational reliability. High-voltage conditioning procedures were reexamined to suppress the temporal variations in the dark current and vacuum pressure, enabling stable beam acceleration at 0.87 MeV. As a result, repetitive generation of ITER-relevant H⁻ beams with ITER initial target was successfully achieved. Furthermore, the beam pulse length was extended to 110 s at 0.87 MeV, during which the cooling water temperature reached thermal equilibrium. This demonstrates the feasibility of long-pulse operation under ITER-relevant conditions.

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