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Commissioning of Linear IFMIF Prototype Accelerator (LIPAc) RFQ and RF system towards high current and high duty operation

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The Radio Frequency Quadrupole (RFQ) linac accelerating the 125 mA deuteron beam up to 5 MeV is a key component to demonstrate the low energy section of the accelerator system designed for the International Fusion Materials Irradiation Facility (IFMIF). We achieved an unprecedented high current deuteron beam over 125 mA at 5 MeV by using the RFQ and RF system of the Linear IFMIF Prototype Accelerator (LIPAc) in pulsed mode (1 ms per 1 s). The RFQ has eight RF input ports to supply the required RF power (up to 1600 kW) that is provided by an 8-chains RF system. The keys of the success were: (1) tuning each RF chain individually, (2) suppressing the reflection from the RFQ in transient of pulse, (3) holding the stable RF power in the RFQ after intensive RF conditioning, (4) optimizing the beam loading compensation control, (5) tuning the resonance frequency accurately,and (6) injecting a low emittance beam into the RFQ.As consequence of this successful demonstration, the next challenging step is to proceed with the Continuous-Wave (CW) operation of the RFQ and RF system.

The construction of LIPAc is ongoing in Rokkasho Fusion Institute under the Broader Approach Agreement in the field of fusion energy research between Japan and EURATOM[1]. The aim of LIPAc is to accelerate the deuteron beam up to 9 MeV at 125 mA in CW in order to validate the engineering design of the 40 MeV IFMIF accelerator. The major challenge of the large current acceleration is to minimize the beam loss in order to avoid the activation of the accelerator. The control of the beam is difficult because of the strong defocusing due to the large space-charge effect.

The LIPAc RFQ was designed to bring a solution to answer the constraint related to the large current [2]. The RFQ focuses, accelerates, and bunches the beam with the RF electric field resonating at 175 MHz. The input beam of 140 mA generated by the injector is accelerated from 0.1 MeV to 5 MeV by the RFQ with about 90% transmission ratio in CW (Fig. 1). The RFQ requires 560 kW to generate the nominal RF field. For the beam acceleration of 125 mAx5 MeV, an additional 625 kW should be delivered. Therefore, the RF power injected in the cavity to feed the RFQ is at least 1200 kW.

The RF power is delivered to the RFQ from the eight-chain RF system as shown in Fig. 1. Each RF chain is providing 220 kW at 175 MHz. The RF signal generated by the full digital Low-level RF (LLRF) [3] is amplified through a solid-state amplifier and 2 amplifier stage composed by two tetrodes. Each RF power is transmitted by a coaxial waveguide to the accelerator vault and injected into the RFQ through a coupler. To obtain the nominal field in RFQ cavity, the amplitude, phase, and injection timing of the forward waves are automatically synchronized using the timing system and feedback control of LLRFs. In the feedback control, the seven slave RF chains follow the amplitude and phase of the master RF chain. By using the feedback controls, LLRFs automatically increase the forward power when the beam enters RFQ to keep the RF field in RFQ at a constant value. Note that we cannot feed the nominal power of 1200 kW before the beam injection. Otherwise, the RF field exceeds the limit of RF discharge, and could damage the RFQ. The large current beam injection not only requires the synchronized RF power rise, but also causes the resonance frequency down-shift of RFQ by 8 kHz. In order to match RFQ at 175 MHz for the 125 mA beam injection, the resonance frequency of the RFQ is set to be 175.008 MHz during the no beam loading phase. The resonance frequency was adjusted by changing the temperature of RFQ by controlling the cooling water temperature.

The commissioning of the RFQ and the RF power system started in July 2017 [4]. The conditioning was disturbed by the high power reflection when the RF injection was stopped, i.e., the confined energy in the RFQ backflows to the RF sources, which exceeds 100 kW. To avoid the large power reflection, the rise and fall time of the forward power were increased to 20-40 \us, which is longer than the time constant of RFQ (~4 \us). To improve the RFQ conditioning efficiency, the autorearming function recovering from the breakdown was developed. The careful conditioning avoiding large power deposition by the heavy breakdown was continued up to the deuteron acceleration level in pulse operation of 1 ms per 1 s, and the beam acceleration experiment was started. As a first step, prior to the deuteron beam experiment, the proton beam acceleration was tested which requires 1/4 of the power of the deuteron acceleration [5]. RFQ and RF system were validated with proton beam up to about 60 mA at the exit of RFQ. After the confirmation of successful proton beam acceleration, deuteron beam commissioning was started from 10 mA. The control of LLRF was validated in the pulse mode up to 50 mA deuteron beam. The overshoot of forward power was lower than the discharge level. By increasing the current, the feedback control of LLRF became unstable at the beginning of the beam pulse, and the unstable feedback control induced arcs in RFQ. Therefore, we decided to use the open loop (pre-set) at the beginning of the beam pulse. Consequently, no discharge was induced. Finally, the 125 mA deuteron beam acceleration was achieved as shown in Fig. 2. The control properly fixed the RF field in RFQ while the feedback control was activated (0.8-1.3 ms in Fig. 3). The beam energy was 5 MeV, which was determined by means of time-of-flight techniques.

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