

Symposium 2019 on the ITER/BA Activities Fusion Energy Forum of Japan

## Frontier of Fusion Energy -Development of the world's highest-intensity accelerator-

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GQST

FUSION FOR ENERGY

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Symposium for 2019 on ITER/BA, ITO INTERNATIONAL RESEARH CENTER, The Univ. of Tokyo, Dec. 19, 2019 Development of the world's highest-intensity (=current) accelerator for DEMO 🎆 🎆 🥩 QST

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#### Challenge and difficulty for the highest-current accelerator









<u>(1) Development of the world's longest-RFQ</u>

The solution is to develop the 9.8 meters long RFQ which accelerates and focuses the large current deuteron beam (125 milliamp) with the RF electric field. It's so challenging because the RF field is about the theoretical limit of discharge.

#### **(2)** Development of the world's largest number of RF power chains

The solution is to develop the eight-chain large RF power system with synchronization and feedback control system, which feds the large RF power to RFQ (1600 kilowatt max.).





### Challenge for the development of the large beam current RF 🕸 🎆 🦪 QST

install RFQ (18 modules)

9.8m

The difficulty of developing the world's longest RFQ is to generate the RF electric field as intended along the 9.8 meters long. We challenged to overcome it by dividing the RFQ into 18 modules, which is the largest number of modules in the world.

machine four vanes with cooling channels



braze module



High-accuracy and -precision

machining: 30 microns brazing: 50-100 microns installation: 100 microns High-accuracy and –precision machining, brazing, and installation are required for realizing the 9.8 meters RFQ.

## INFN (National Institute for Nuclear Physics, Italy) developed the 18 modules 🌼 🎆 🥝 QST

The high-accuracy and –precision machining of vanes was performed with a five-axis milling machining center and 3D measuring instrument. The four vanes were brazed in a furnace in once after the pre-assembly of vanes satisfied the requirement of displacement. The quality control was also well managed. Finally, INFN succeeded in machining and brazing the all RFQ modules within the high accurate and precise requirement in 2016.

machining (all 18 modules are different shapes)



brazing (four vanes in once)





#### High-accuracy and –precision installation of RFQ



The high-accuracy and –precision 3D measurement technique with the laser tracker and algorithm (SA<sup>®</sup> Ultimate) was established. With the technique, we succeeded in installing the all RFQ modules at the beam line within the requirement of 100 micron in displacement.

High-accuracy and –precision installation (with the laser tracker and algorithm)



# View from the entrance to exit of RFQ after the installation





## High-accuracy tuning, and completed

The resonance frequency and voltage profile were tuned with 108 of tuners, which took about 1 day for 1 tuning. We obtained the design value of the resonance frequency (175 MHz) and voltage profile (98% accuracy) after about 30 times of tuning.



19/12/19

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For large RF power: Development of the cutting-edge device of synchronization and feedback control

The cutting-edge device for the synchronization and feedback control of the eightchain RF system was newly developed by CIEMAT (Spanish Public Research Institution dependent on the Ministry of Economy and Competitiveness, Spain). The special function was realized with the high-precision synchronization technology (WHITE RABBIT) developed in CERN and integrated circuits (FPGA).

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## Completion of the eight-chain large RF power system 🍪 🎆 🦃 QST

We verified that the each chains amplified 200 kW, which was absorbed by a dummy load. It indicated that the eight-chain large RF power system satisfied the requirement of the large RF power of 1600 kW in total.

Installed eight-chain large RF power system in Jun., 2017



Finally, the eight-chain large RF power system was completed after seven years.

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## Success of RF power injection from RF system to RFQ IIII GOST

#### The first RF injection to RFQ from the eight-chain RF power system was successfully performed. The detector showing the first RF injection to RFQ, and LIPAc Unit Team



The commissioning of eight-chain RF power system and RFQ started for the large deuteron beam current acceleration commissioning.

## LIPAc Unit Team overcame the commissioning of RF system and RFQ I BODY CONT

The commissioning of RF system and RFQ was not straight forward because three tough tunings must be performed in parallel: tuning of more than 100 parameters of synchronization and feedback control (PID etc.), RF conditioning of RFQ, and tuning of RF components. It was struggle, but LIPAc Unit Team got through it, and RF system and RFQ became ready for the deuteron beam commissioning.

Tuning of more than 1000 parameters



Tuning of synchronization Tuning of feedback control





#### Challenge for the large deuteron beam current: **Tuning of RF system from low current**



The idea of beam commissioning procedure was starting from low current proton beam. It can reduce the risk of damaging RFQ because we can tune the beam loading control of RF system from the low beam loading. The beam current to the RFQ entrance was increased step-by-step by replacing the plasma electrode at the injector.

Beam loading = Beam current  $\times$  Beam energy

Adjust the beam current by changing the electrode diameter



## Success of RF system tuning at low current proton beam 🌼 🎬 🦃 QST

The beam loading control of RF system was successfully tuned at the low current proton beam by monitoring the overshoot of power at the beam injection, and we succeeded in the first beam acceleration with the eight-chain RF power system in Jun., 2018.



#### We succeeded in the first beam acceleration



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Achieved the goal of the world's largest-current deuteron beam acceleration!

We succeeded in the acceleration of the world's largest current deuteron beam at 125 mA in the pulse operation (1ms per 1s) in Jul. 24, 2019. We achieved the world's largest-current

Beam current at the entrance and exit







An unprecedented achievement!



## **Achievement and future**



The key elements of IFMIF proto type -the world's longest-RFQ and largest-number of RF power chains- had been developed, commissioned, and validated in the pulse operation of deuteron beam.



Validation of RFQ and RF system in pulse

Next challenge

Validation in long pulse

Final challenge

Validation of SRF + continuous wave (CW) operation



The achievement is a major step toward the completion of IFMIF prototype accelerator.

Three important things learned from first hand experiences through the project 🌼 👯 🥝 QST

#### PASSION

## HARMONY Important things are PATIENCE PASSION, HARMONY, and PATIENCE

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