Overview of the Validation Activities of IFMIF/EVEDA: LIPAc, the Linear IFMIF Prototype Accelerator and Lifus 6, the Lithium Corrosion Induced Facility

Presented by M. Sugimoto

FEC2018, 27th IAEA Fusion Energy Conference

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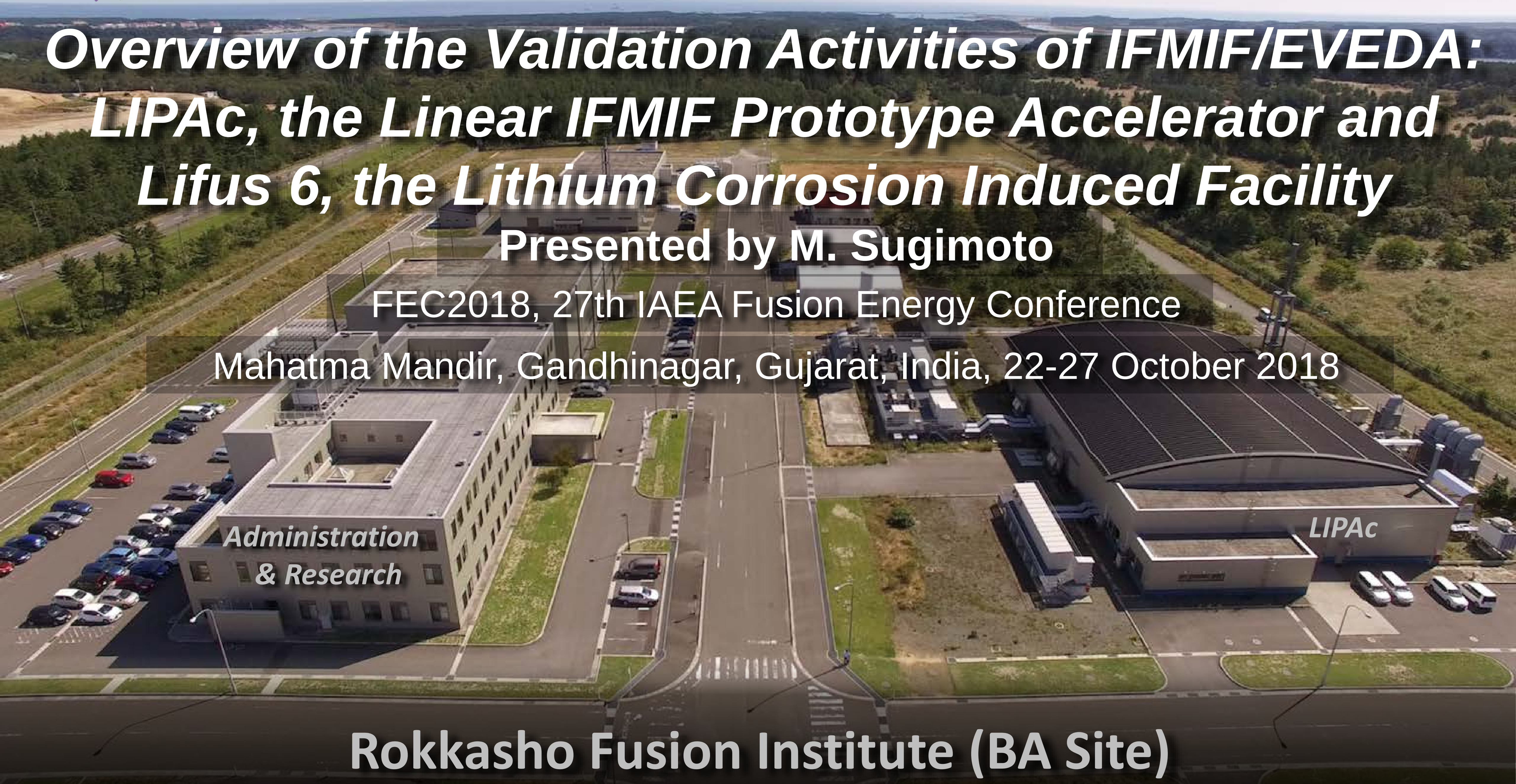

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And many people not shown above have contributed and supported the IFMIF/EVEDA project.

Reference papers and literatures

LIPAc, the Linear IFMIF Prototype Accelerator

- KASUGAI, A. et al., "RFQ Commissioning of Linear IFMIF Prototype Accelerator (LIPAc)", Proc. 27th IAEA Fusion Energy Conf., Gandhinagar, India, 2018. **FIP/P1-13 in this conf.**
- CHAUVIN, N. et al., "Deuteron Beam Commissioning of the Linear IFMIF Prototype Accelerator Source and LEBT", Proc. 27th IAEA Fusion Energy Conf., Gandhinagar, India, 2018. **FIP/P3-19 in this conf.**
- GRESPAN, F. et al., "IFMIF/EVEDA RFQ preliminary beam characterization", Proc. 29th Linear Acc. Conf., Beijing, China, 2018.

Lifus 6, the Lithium Corrosion Induced Facility

- FAVUZZA, P. et al., "Erosion-corrosion resistance of Reduced Activation Ferritic-Martensitic steels exposed to flowing liquid Lithium", Fus. Eng. Design in press.

Contents

1. Introduction
   - *IFMIF engineering design to be validated*
   - *Milestones of IFMIF/EVEDA project*
2. LIPAc, the Linear IFMIF Prototype Accelerator
3. Lifus 6, the Lithium corrosion induced facility
4. Summary

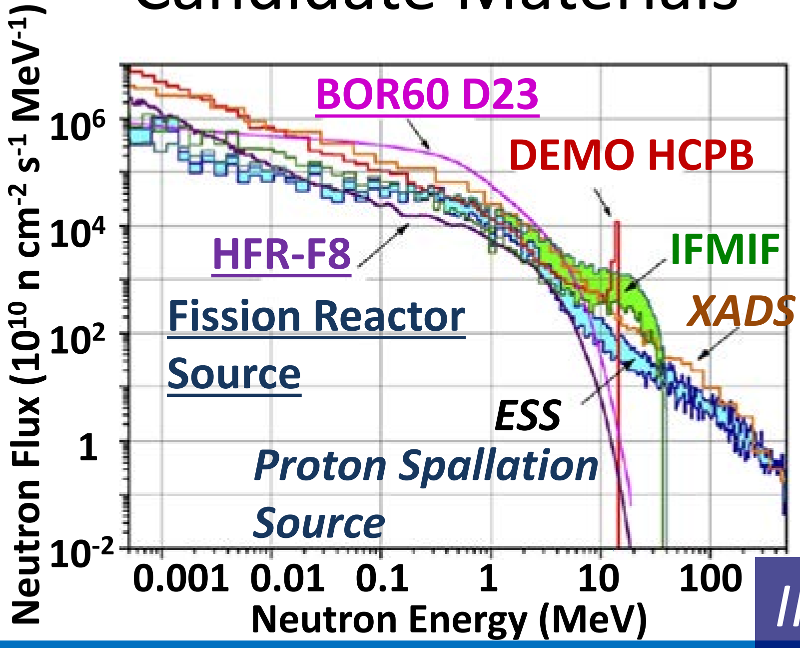
IFMIF Engineering Design to be Validated

3 main activities of IFMIF/EVEDA project were carried out during 2017-2018.

Qualified Materials

Irradiation Tests using Fusion-relevant Neutron Source (IFMIF)

Candidate Materials



Completion of injector Beam Commissioning

Start of RFQ Beam Commissioning

Completion of Li Erosion-Corrosion Tests

Accelerator

40 MeV deuteron, 10 MW CW

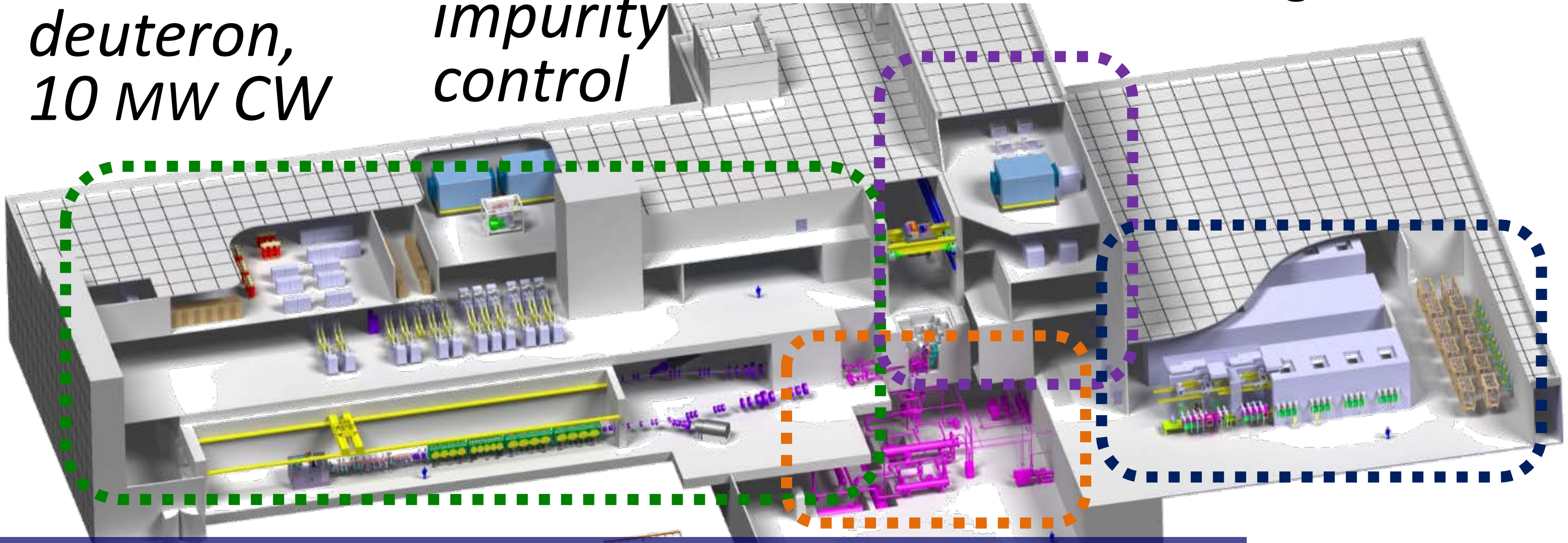
Li Target

15 m/s flow free surface, impurity control

Test Facility

PIE Facility

10^{17} n/s, T_{irrad} control, remote handling, SSTT



IFMIF Intermediate Engineering Design Report (2013)

Milestones of IFMIF/EVEDA Project

Activities	2007 ~ 2016	2017	2018	2019 ~ 2020
Accelerator	LIPAc installation start (2013)	Completion of injector beam commissioning	Start of RFQ beam commissioning	Completion of final beam commissioning
Li Target	EVEDA Li Test Loop operation complete (2015)	Completion of Li erosion-corrosion tests		
Test Facility	HFTM(*1) proto fabrication & irradiation test complete			
Engineering Design	IIEDR(*2) final delivery			

ACCOMPLISHED in 2017

ACCOMPLISHED in 2015

ACCOMPLISHED in 2013

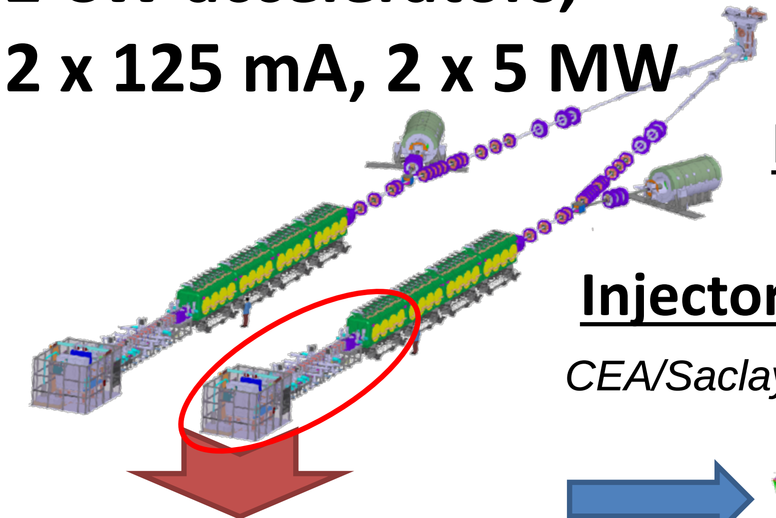
*1 HFTM: High Flux Test Module, *2 IIEDR: IFMIF Intermediate Engineering Design Report

Contents

IFMIF Accelerator Prototype (LIPAc)

Mandate of LIPAc is to validate 9 MeV deuteron beam with 125 mA.

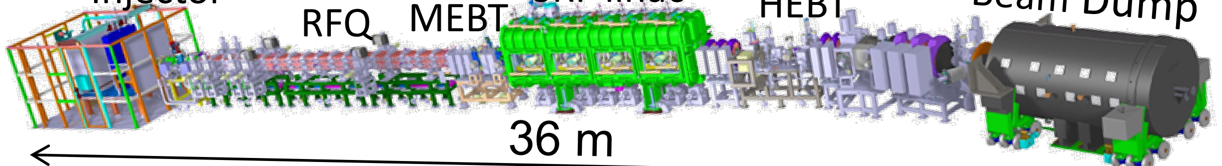
IFMIF
2 CW accelerators,
2 x 125 mA, 2 x 5 MW



Linear IFMIF Prototype Accelerator

to validate low energy section up to 9 MeV (first SRF Linac)

FINAL DESIGN



100 keV **5 MeV** **9 MeV**

Injector
CEA/Saclay

RFQ
INFN Legnaro
F4E Garching
QST Rokkasho

MEBT
CIEMAT Madrid

SRF linac
CEA Saclay
CIEMAT Madrid
F4E Garching

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

Cryoplant
CEA Saclay

HEBT and Beam Dump
CIEMAT Madrid
F4E Garching

Building, Auxiliaries, Infrastructure
QST Rokkasho

Control System
QST Rokkasho
CIEMAT Madrid
CEA Saclay
INFN Legnaro
F4E Garching

Diagnostics
CEA Saclay
CIEMAT Madrid
INFN Legnaro

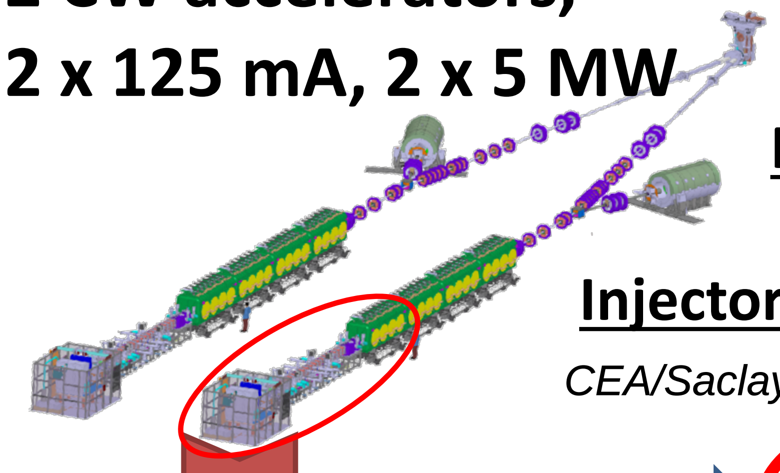
Collaboration with institutes providing components, being integrated at Rokkasho

RFQ: Radio Frequency Quadrupole
MEBT: Medium Energy Beam Transport
SRF: Superconducting RF
HEBT: High Energy Beam Transport

Layout of LIPAc

Mandate of LIPAc is to validate 9 MeV deuteron beam with 125 mA.

IFMIF
2 CW accelerators,
2 x 125 mA, 2 x 5 MW



Linear IFMIF Prototype

A

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up t

SRF linac
CEA Saclay
CIEMAT Madrid
F4E Garching

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

Building, Auxiliaries, Infrastructure
QST Rokkasho

MEBT
CIEMAT Madrid

RFQ
INFN Legnaro
F4E Garching
QST Rokkasho

Cryoplant
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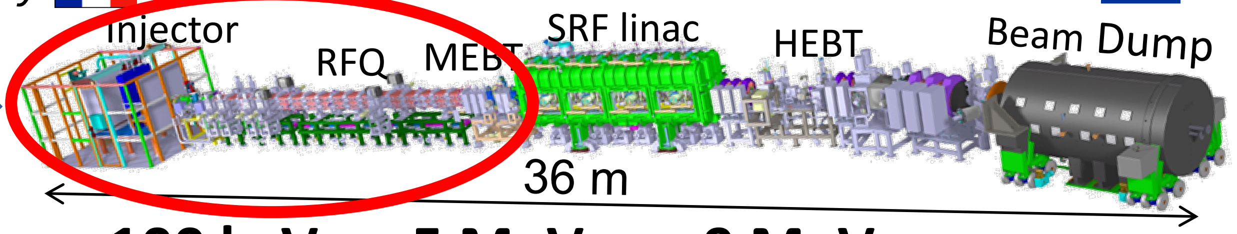
INFN Legnaro

FINAL DESIGN



100 keV **5 MeV** **9 MeV**

…rupole

…m

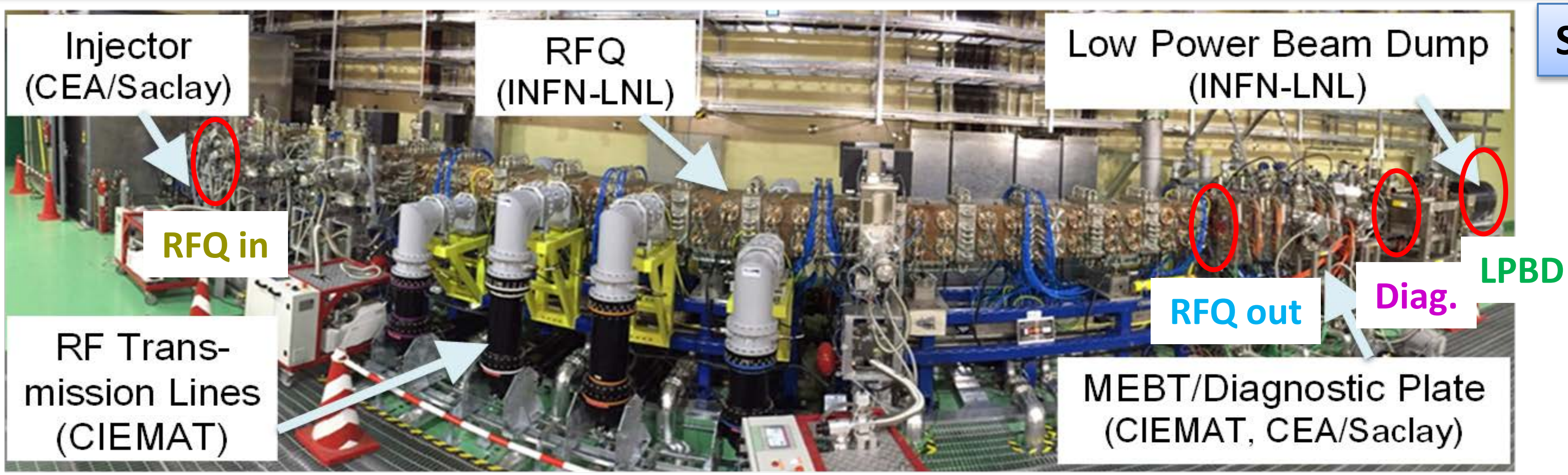
In June 2018, RFQ Beam Commissioning up to 5 MeV (Injector + RFQ + MEBT) with pulse mode was started.

Integrated at Rokkasho

HEBT: High Energy Beam Transport

First beam injection into RFQ

First proton beam (50 keV, 0.3 ms pulse) was injected into the RFQ on 13 June 2018.



See poster FIP/P1-13 by A. Kasugai et al.

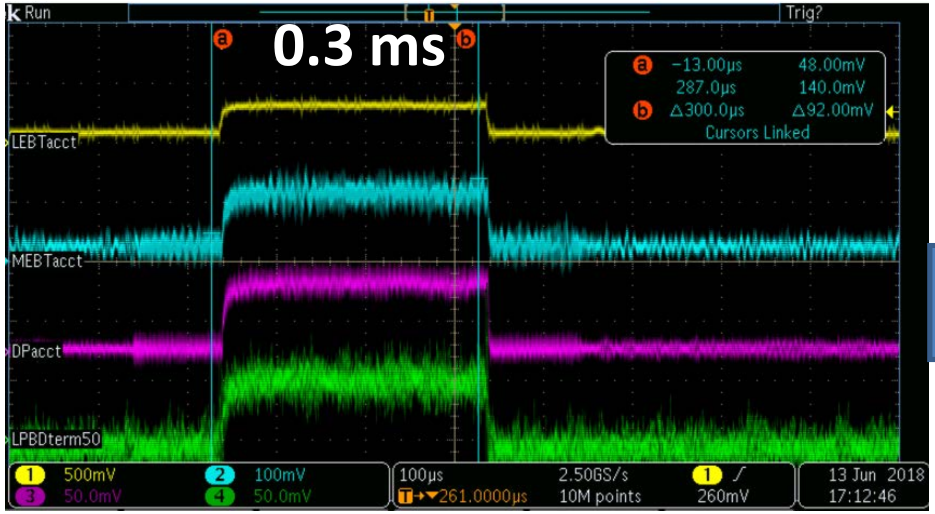
Current measurements for the first beam

RFQ in

RFQ out

Diag.

LPBD



Stable beam was achieved after adjustment

All of 4 pulse heights (beam currents) became high & almost same amplitude.

RF Power Injection and Control

RF power form 8 independent RF power sources are successfully injected at the same time into a single RFQ cavity (length of 9.8 m and resonant frequency of 175 MHz).

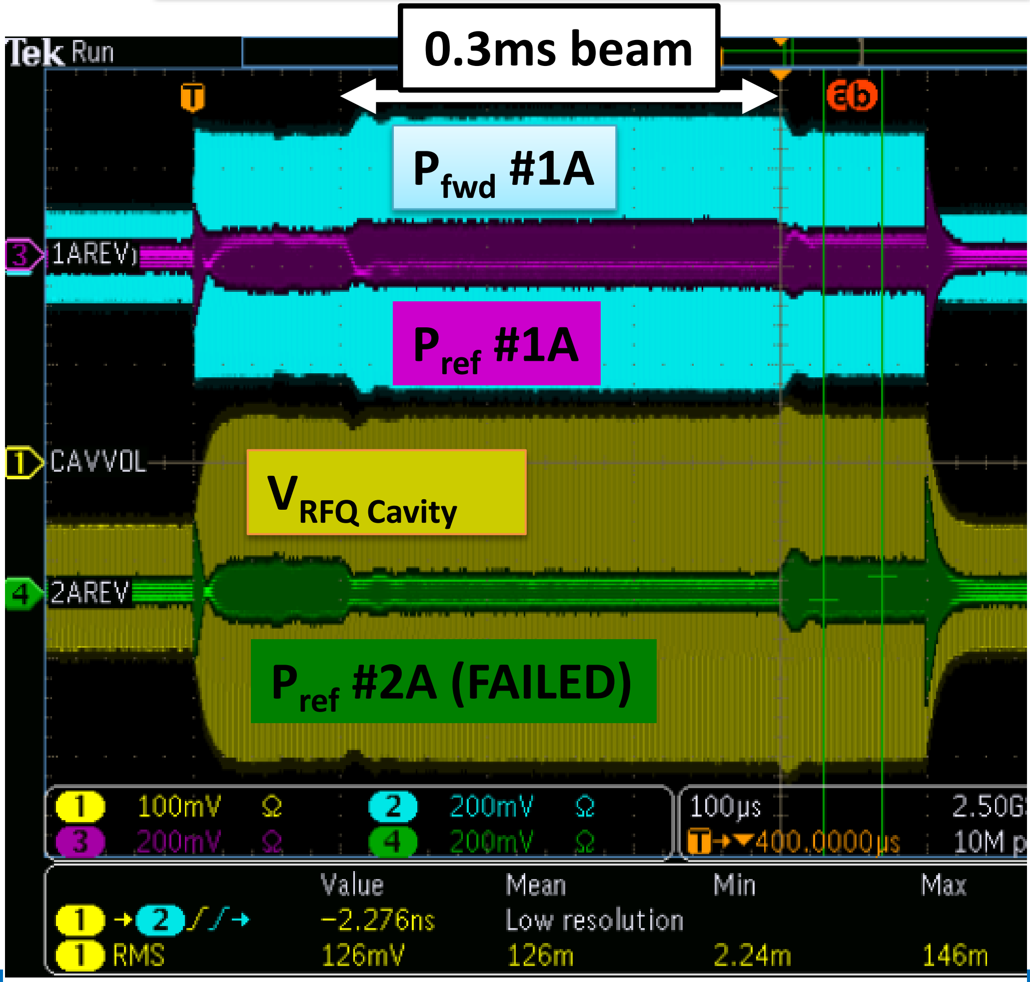
This is a world first trial. Synchronization with White Rabbit technology is a new application.

See poster FIP/P1-13 by A. Kasugai et al.

Beam loading compensation with 7-RF chains operation

In the case of 1 of 8 RF chains was failed to operate, it was possible to continue the beam commissioning using the rest of 7 RF chains.

- *P_{fwd} is increased during beam pulse to compensate the beam acceleration power.*
- *$V_{RFQ\ Cavity}$ is kept nearly constant, which means beam acceleration condition is kept.*
- *P_{ref} of #1A is unchanged while #2A (failed chain) is decreased due to change of impedance.*

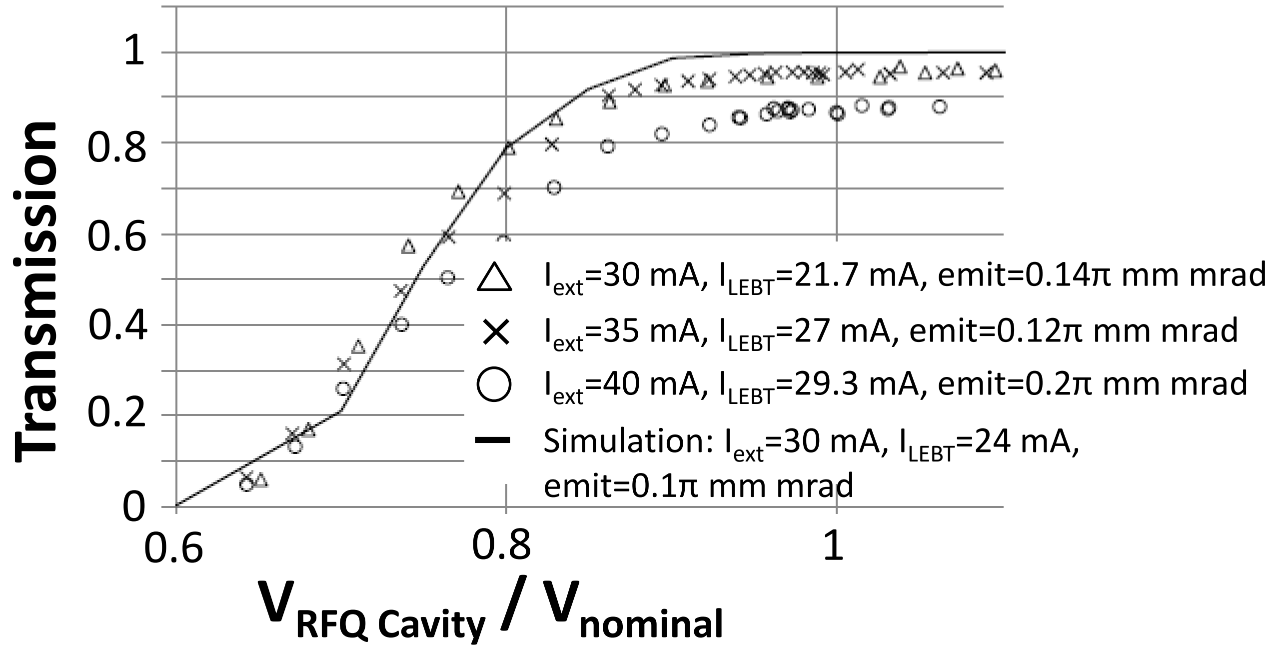


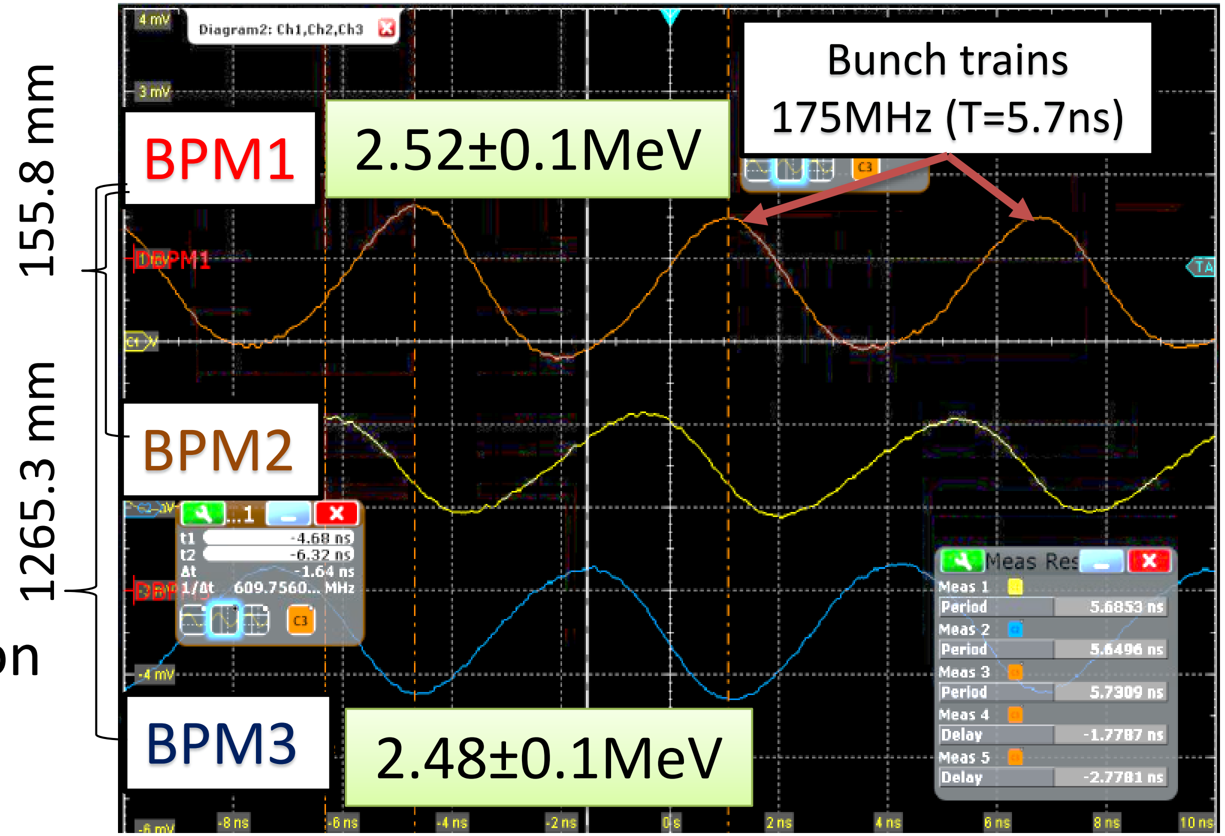
Beam Transmission and Energy Measurements

See poster FIP/P1-13 by A. Kasugai et al.

Transmission (ratio of current at LPBD to RFQ input current) was measured by varying voltage applied to the RFQ cavity. Compared with beam dynamics simulation was made.

Beam energy was measured by using TOF among 3 Beam Position Monitors (BPM) and agreed with design value, 2.5 MeV.





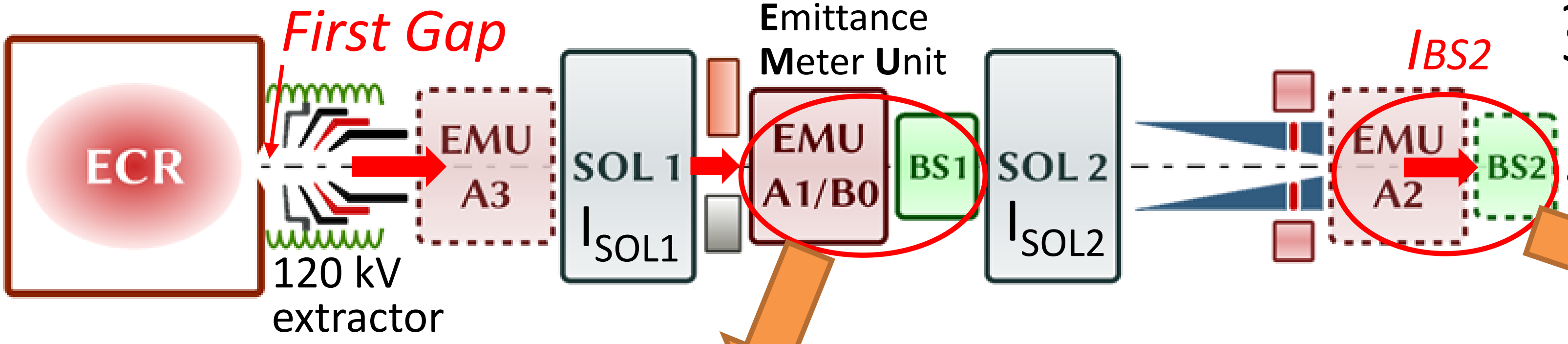
Differences between measurements and simulation

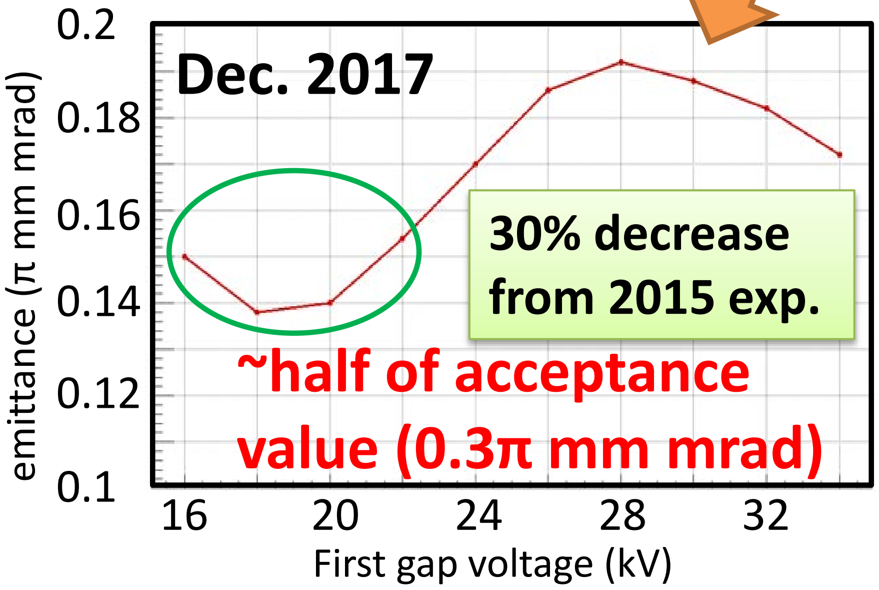
- Contaminant molecular beams
- Error in injection beam alignment

High Quality Deuteron Beam for RFQ Injection

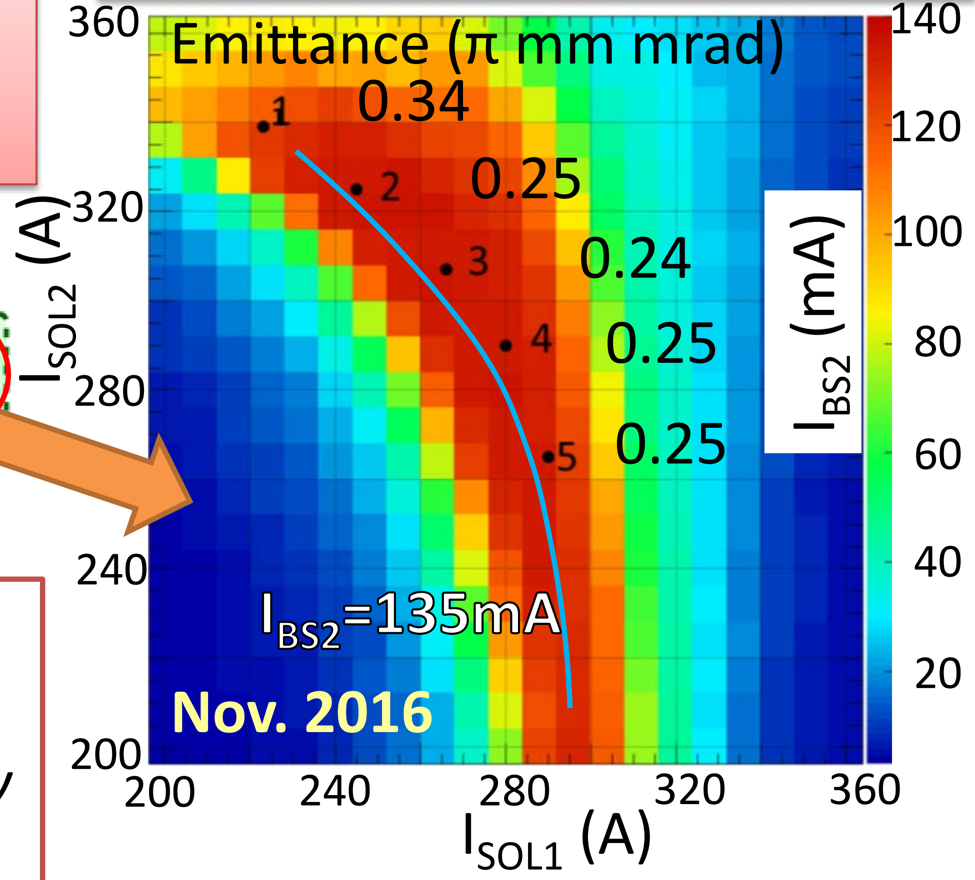
Deuteron beam with 100 keV/140 mA required for RFQ injection is ready for beam commissioning with a sufficient margin of the quality, i.e. beam emittance.

See poster FIP/P3-19 by N. Chauvin et al.





First gap voltage is an important parameter to control the beam quality from ion source plasma. Extractor electrodes should be clean/smooth and aligned.

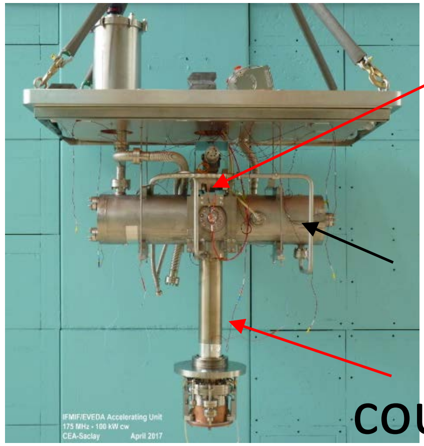


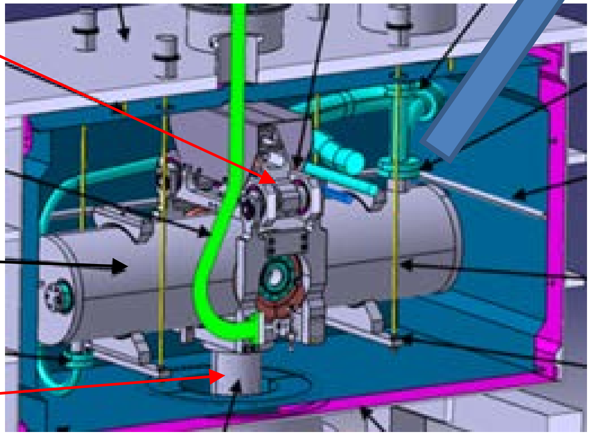
Emittance varied according to the 2 focusing solenoid magnet currents. Locus of maximum transmission to BS2 is observed.

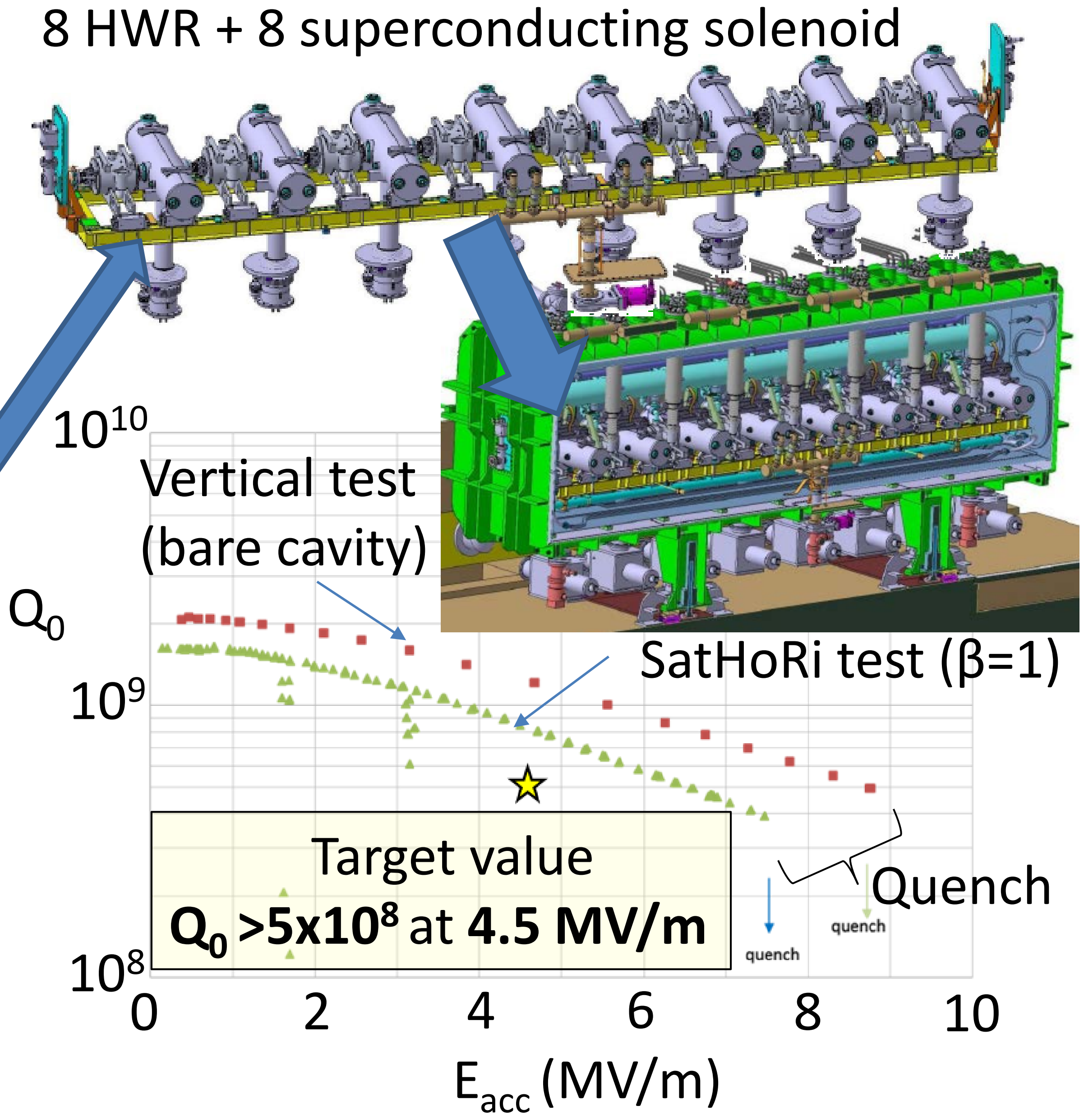
SRF Linac Half Wave Resonators performance

2 HWRs satisfied the required performance: $Q_0=8\times10^8$ at $E_{acc}=4.5$ MV/m, frequency tuning range of tuner > 50 kHz. All of 8 HWRs were manufactured and ready to deliver in Rokkasho.

High power and tuner function test
@ CEA/Saclay (SatHoRi test stand)

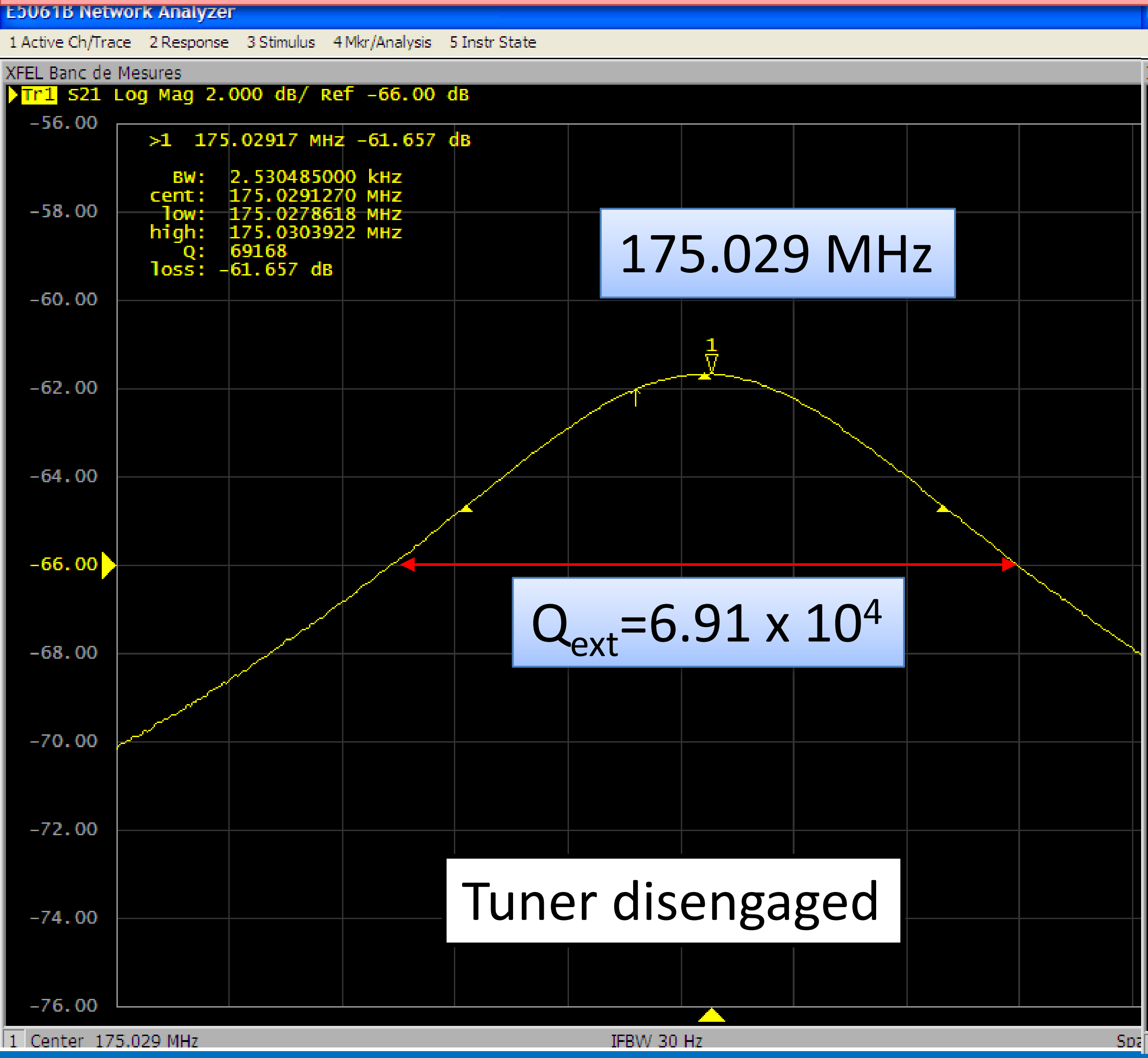


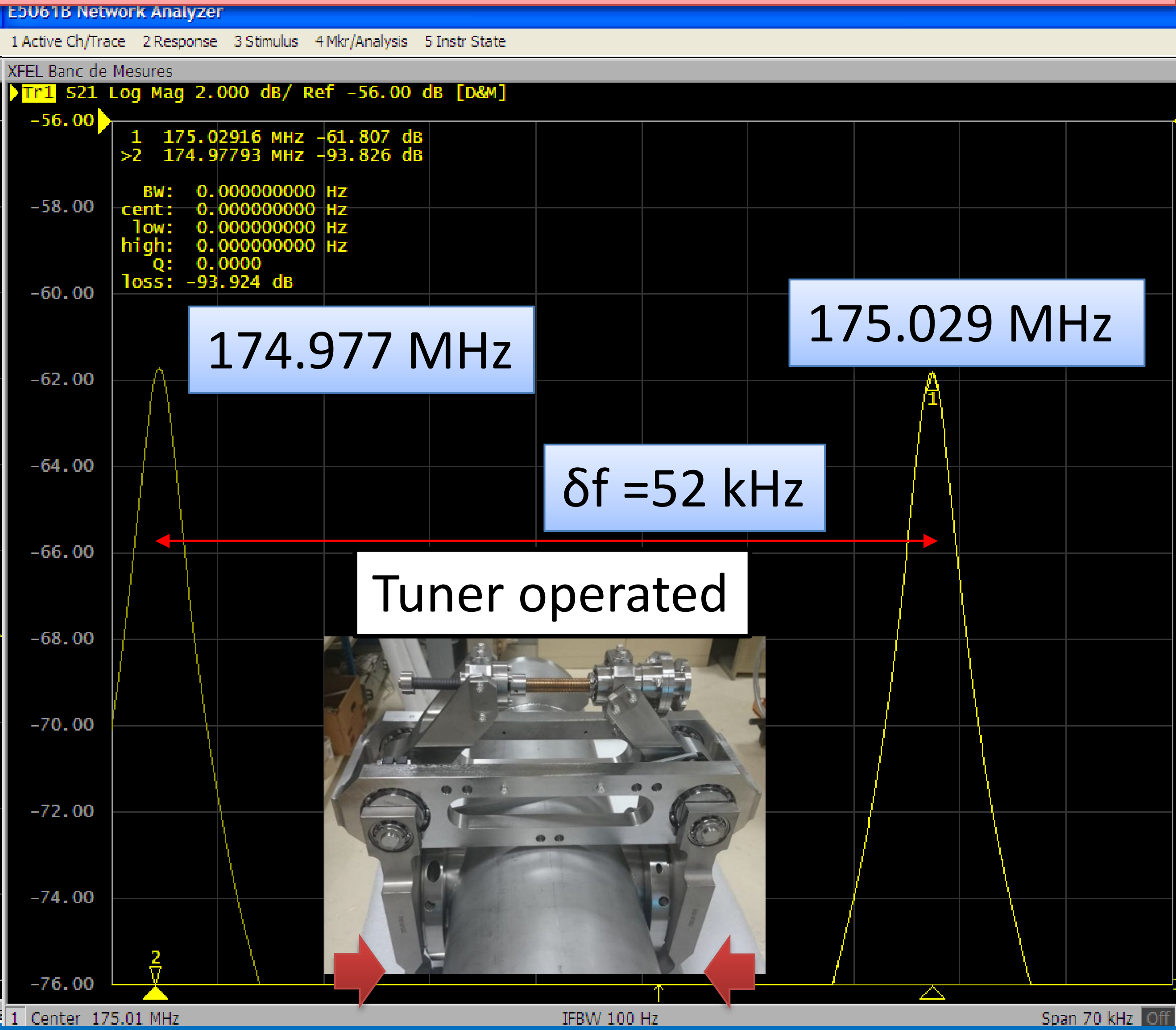




SRF Linac Half Wave Resonators performance

Resonant frequency and its tuning range were confirmed with #3 HWR cavity.





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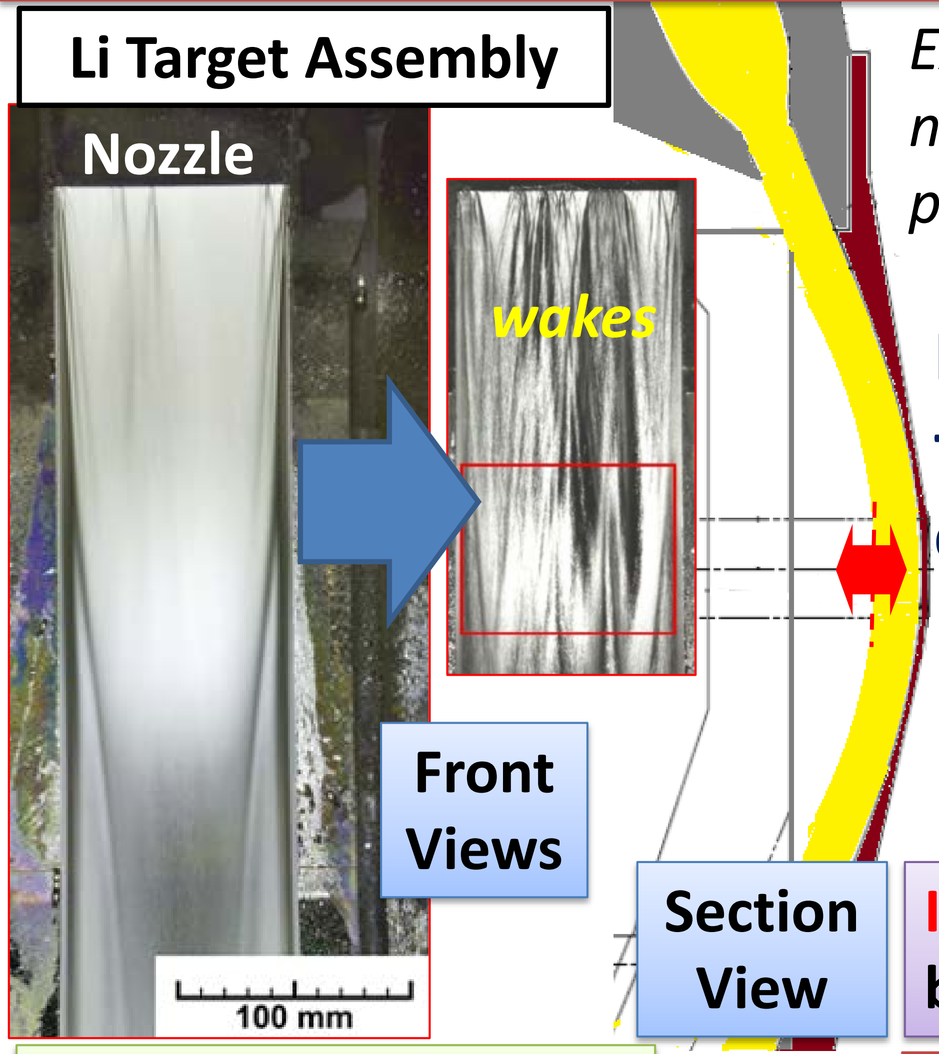
Lithium Erosion-Corrosion Effects

Stability of surface of Li flow is a major issue to cause the flow breakup in the extreme case.



Experiment in 2014

Example of instability: wakes found in EVEDA Li test loop nozzle made of 316L stainless steel, caused by the chemical products attached to the edge.

In long term operation, erosion-corrosion effects on the target structural material (RAFM steel) is a main concern to cause the similar instability.

Preliminary test in 2007 (Lifus3): corrosion rate **~3.2 µm/y** for Eurofer 97

Nitrogen concentration ~ 300 wppm is a main reason.

IFMIF Design Requirement: corrosion rate <1 µm/y (could be achieved by the purified Li with low nitrogen <30 wppm).

Lifus 6 was constructed to verify this up to 4000 h exposure.

Layout of Lifus 6 Facility

ENEA Brasimone

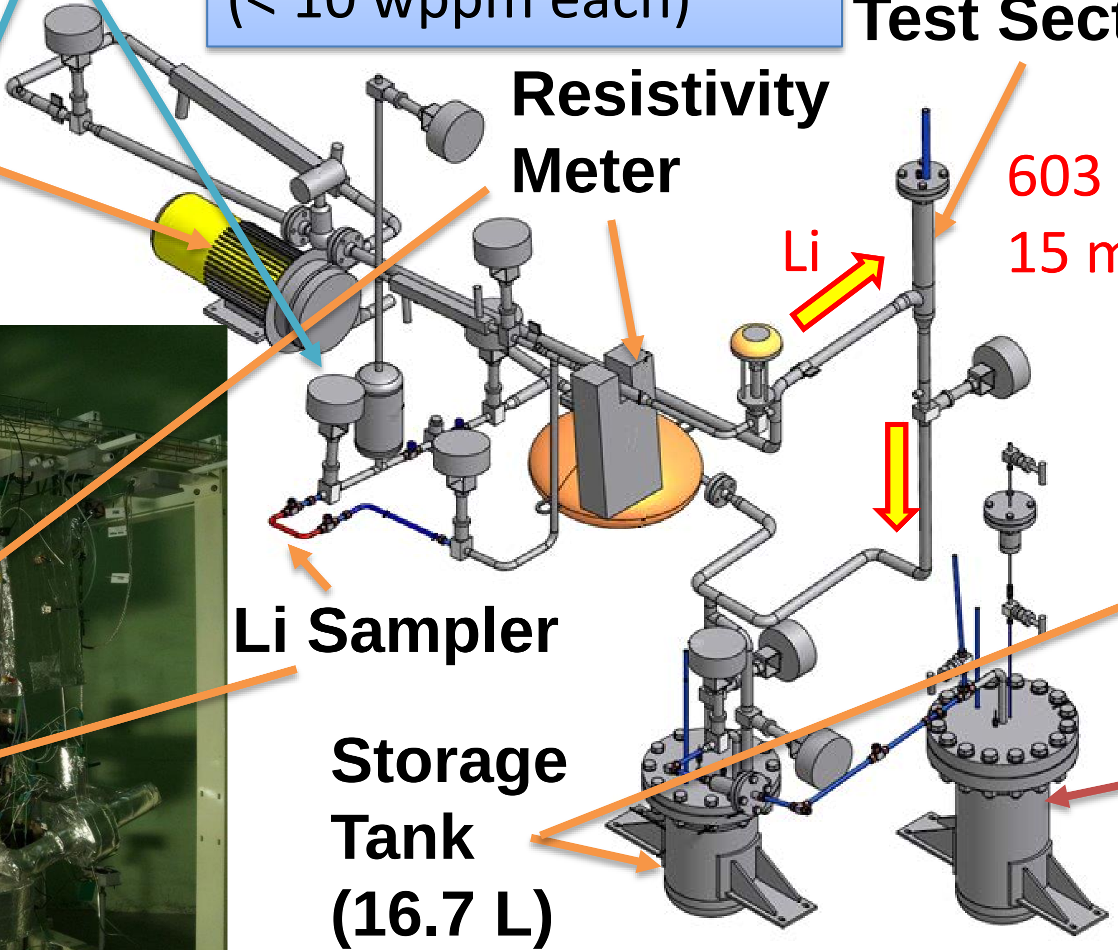
Cold Trap

473 K to remove C, O and metallic impurities (< 10 wppm each)

Main Electro-magnetic Pump

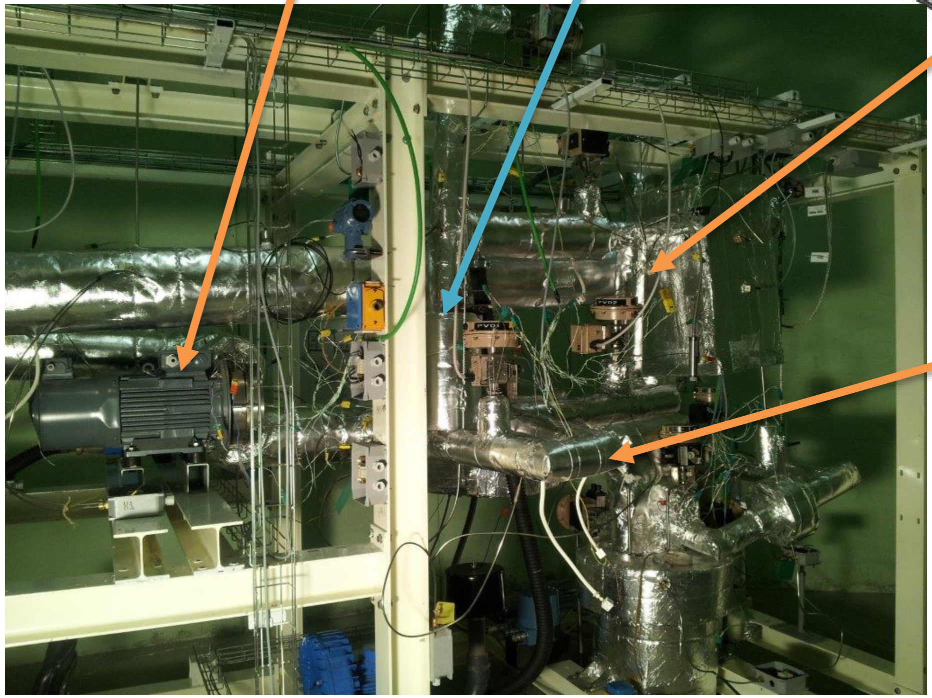
Test Section

Resistivity Meter



Li Sampler

Storage Tank (16.7 L)



Hot Trap (Ti sponge)

823 ~ 873 K to remove N impurity (< 30 wppm)

Corrosion Rate Measurements

Comparison of erosion-corrosion rates for F82H and Eurofer97 caused by flowing lithium

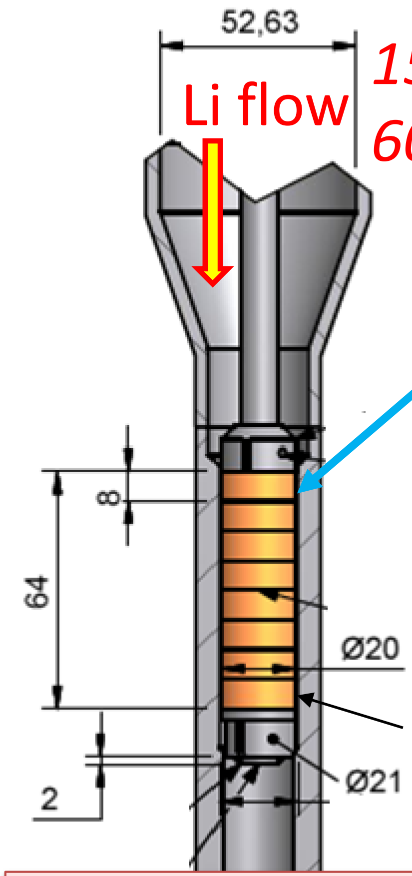
See ref. FED in press by P. Favuzza et al.

IFMIF requirement: |thickness change rate| ≤ 1 μm/y

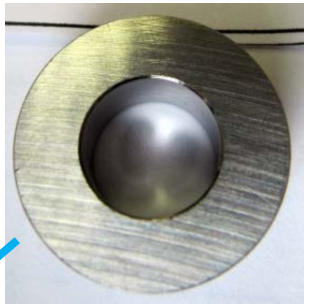
Test section

Li flow

15 m/s, 603 K

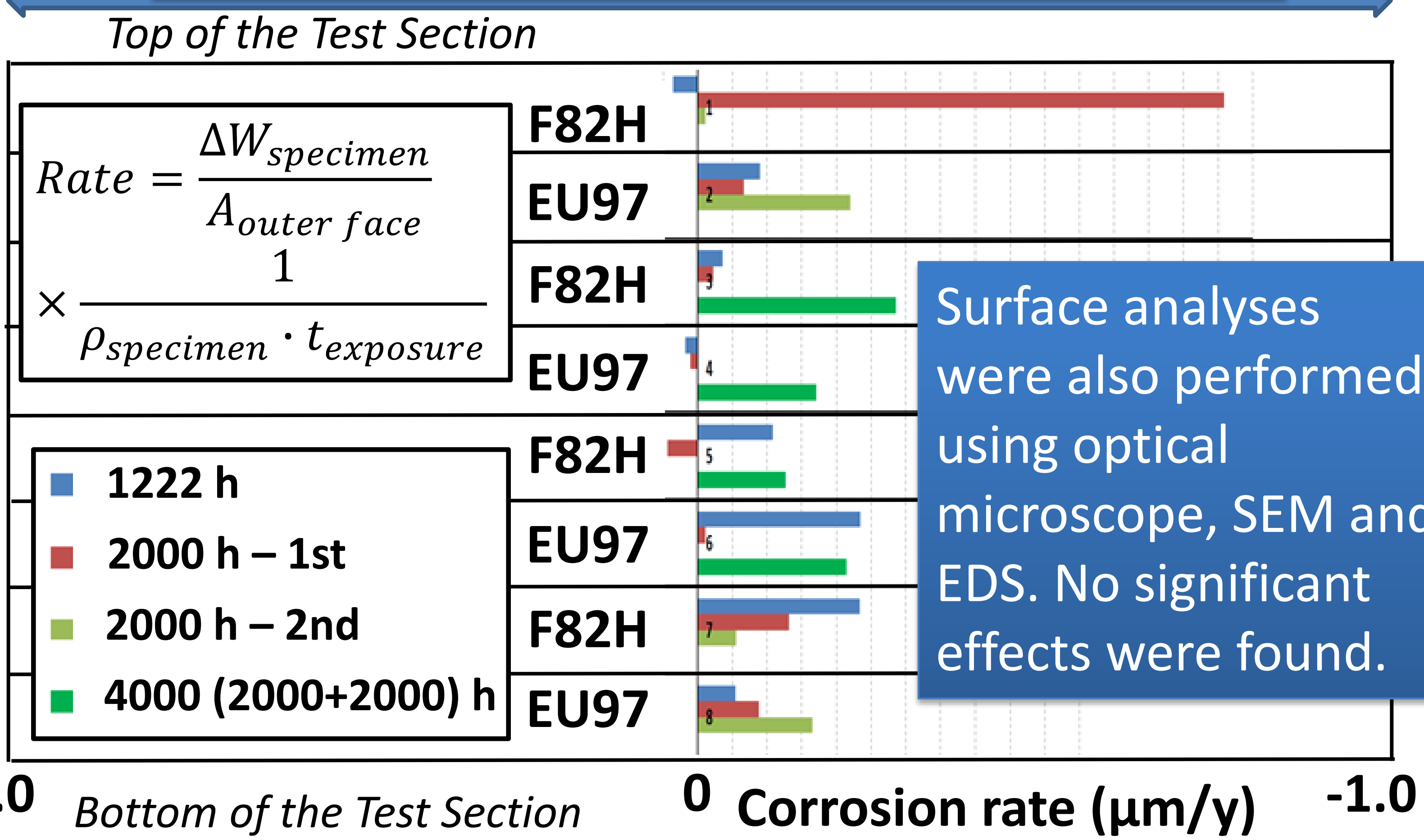


Specimen



d_{ext} = 20 mm
d_{int} = 10 mm
h = 8 mm

d_{int} = 21 mm



Surface analyses were also performed using optical microscope, SEM and EDS. No significant effects were found.

No relevant differences are seen between 2 materials, and the absolute rates are < 1 μm/y.

Summary

LIPAc

- RFQ beam commissioning is started with 50 keV proton, and the initial measurements of RFQ transmission (96% at maximum) and beam energy (2.5±0.2 MeV) gave a good sign of RFQ design validity.
- Injector commissioning with 100 keV/140 mA deuteron beam was completed successfully with twice better than acceptable emittance.

IFMIF design on RFQ was validated for pulsed 50 keV proton and that on injector was verified for pulsed 100 keV deuteron.

Lifus 6

- Corrosion rate requirement <1 μm/y for RAFM steels was achieved with controlled nitrogen impurity (about 30 wppm using Ti hot trap).

Lithium erosion-corrosion effects on RAFM steel can be managed if the impurity in Li is controlled properly (esp. N < 30 wppm) and the design requirement of corrosion rate (<1 μm/y) is achievable.