Subsidiary materials for Rapporteur

IFMIF Concept and LIPAc

IFMIF (International Fusion Materials Irradiation Facility) :

Accelerator based neutron source using Li(d,n) reactions: 125mA x2, CW, deuteron

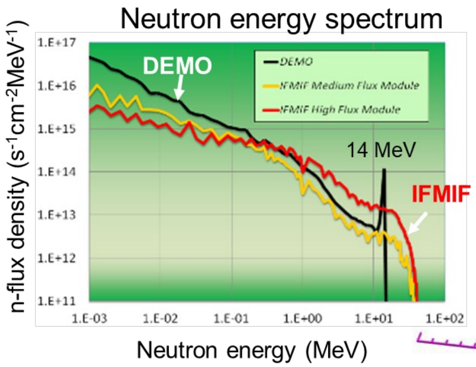
For material irradiation database for design, construction, licensing, and operation of Fusion DEMO.

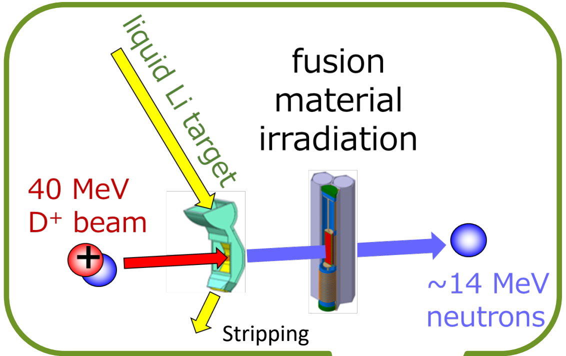
EVEDA (Engineering Validation and Engineering Design Activities)

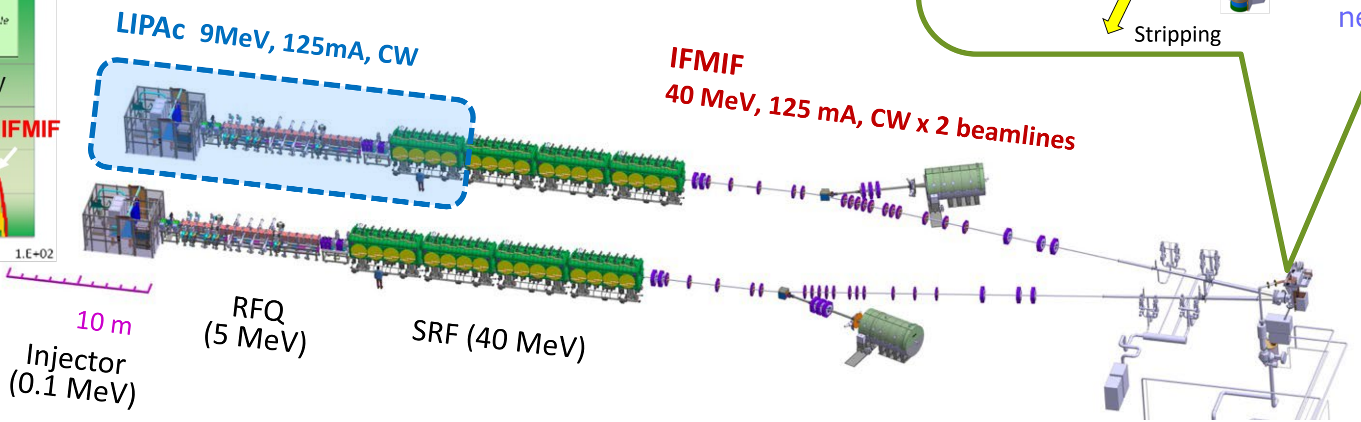
- **Providing the Engineering Design of IFMIF**
- **Validating the key technologies**

The low energy part of accelerator: LIPAc

(Liner IFMIF Prototype Accelerator)

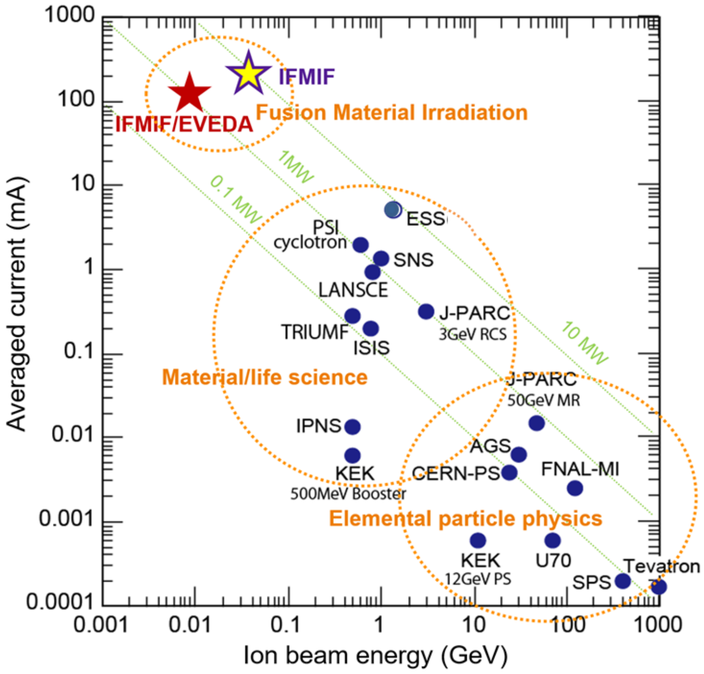






Challenges of LIPAc

IFMIF: the world's highest beam current (125 mA x 2), highest power (5 MW x 2)



Average beam Current vs. Energy

Challenges of LIPAc (IFMIF/EVEDA)

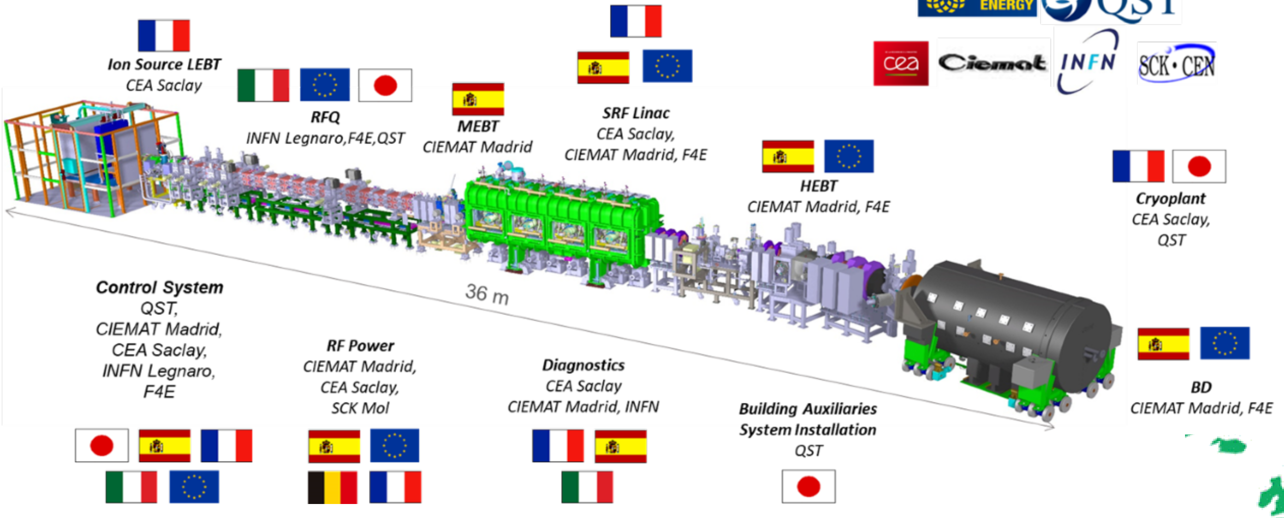
- **High Current: 125 mA, Deuteron, high space charge**
- **High Duty Cycle: 100 % (CW)**

Challenges

- **Injector: high current, low emittance, CW**
- **RFQ: the world's most powerful, longest, CW**
- **RF source: 200 kW x8, CW, synchronized injection**
- **SRF: the highest current for hadrons**
- **Beam diagnostics: pulse to CW, no interceptive**
- **Low beam loss, space charge mitigation**
- **Heat removal, temperature control**

etc.

Linear IFMIF Prototype Accelerator (LIPAc) : EU/JA Collaboration

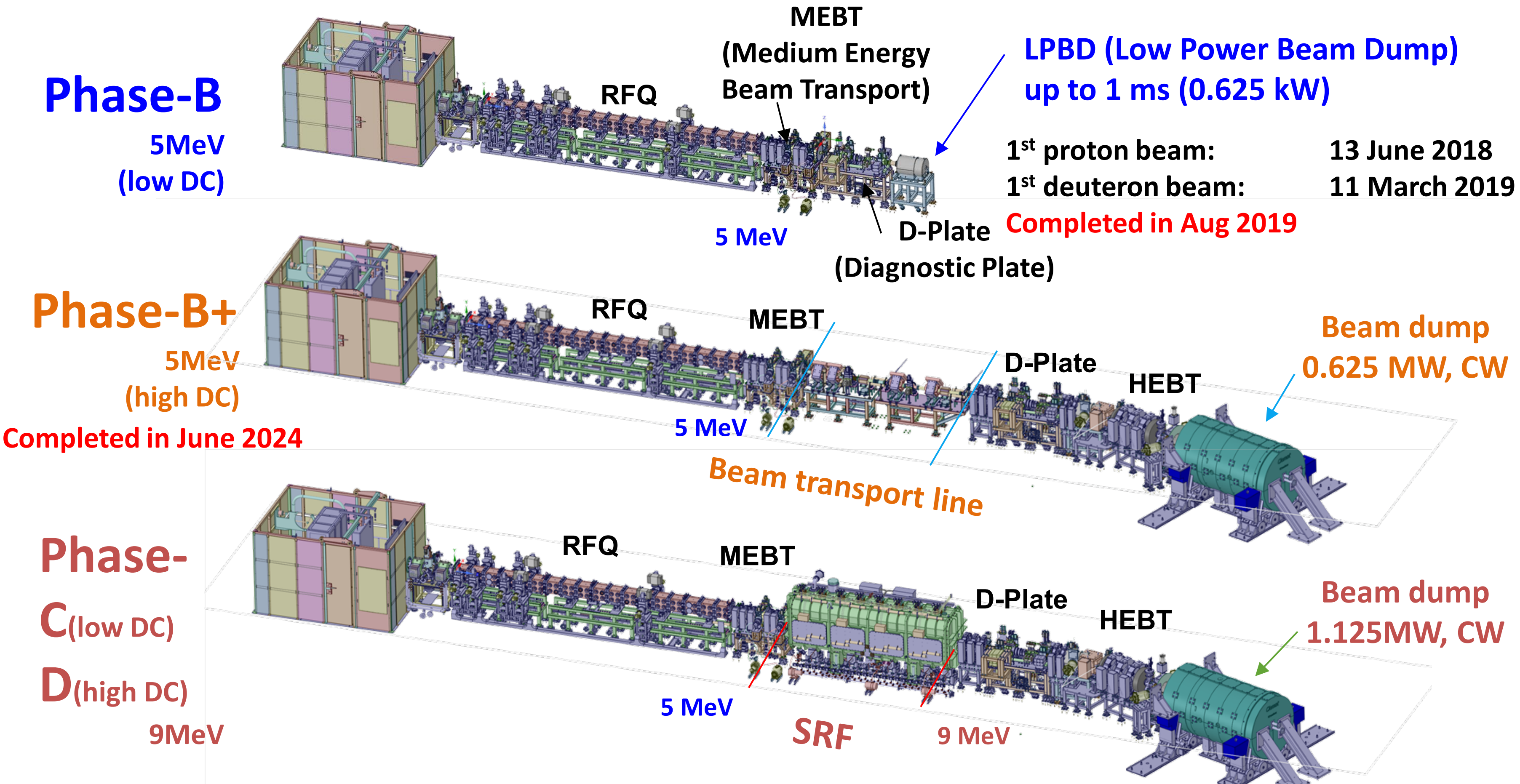


Equipment designed and constructed in Europe,

installed and commissioned in Rokkasho, Japan.

Central Control Room in Rokkasho
Remote participation to LIPAc operation from Europe

Staged Approach Toward 9MeV/CW



Phase B+: High-duty deuteron beam test

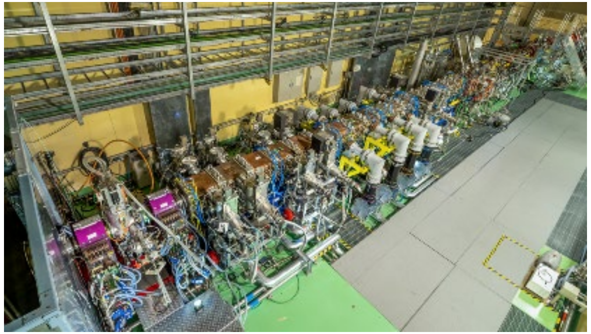
Phase B+ commissioning consists of three stages

- **Stage 1: Low current, low duty H+/D+ beam (probe beam) → Completed December 2021** Checking electromagnets, beam dumps, and diagnostics
  → Overheating and vacuum leak happen on RFQ RF couplers. Some measures were taken.
- **Stage 2: Rated current (125 mA), low-duty D+ beam → Started in August 2023 and ended in December**
  Testing and beam characterization of various beam transport modes (different buncher settings), BPM optimization, longitudinal emittance measurement, non-destructive profiler testing, etc.
- **Stage 3: Rated current (125 mA), high duty D+ beam → Started in December 2023 and finished in June 2024**

Over 8 months beam study

2023/8～12
2024/3～6

Start with 1~5% Duty and increase Duty to CW if possible
Duty limit range and maximum value are determined by looking at RFQ RFQ conditioning and coupler thermal behavior



LIPAc in Phase-B+

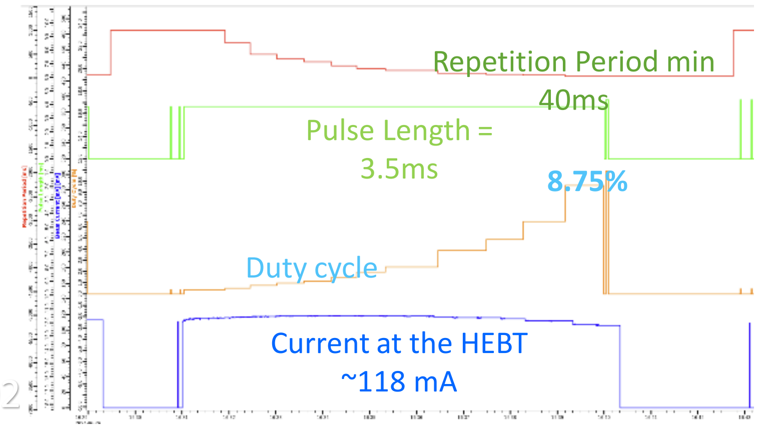
CCR during operation

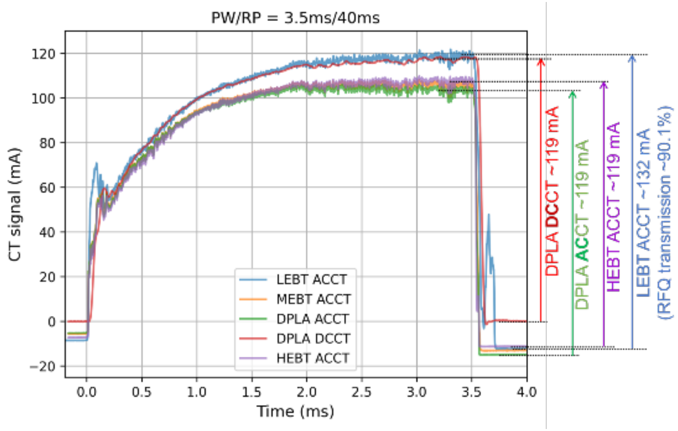
High duty operation: duty 10% operation

Completed high duty deuteron beam test at the end of June 2024

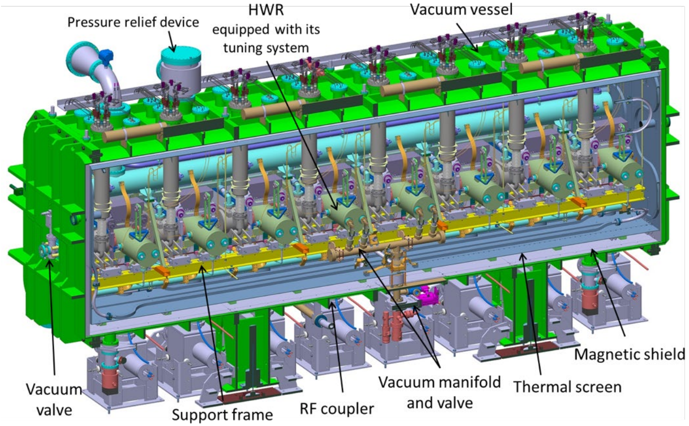
Stage 3 : Rated Current (125 mA), High Duty (<10%)

- **The maximum duty of beam acceleration is 8.75 % (pulse width 3.5 ms, pulse repetition period 40 ms, duration approx. 1 minute) The vacuum and temperature of the RFQ are almost constant. The beam current is approximately 119 mA, and the RFQ beam transmittance is 90.1%.**
- **RFQ average beam power: 40~45kW**
- **The RFQ cavity conditioning reached CW at about 80% of the deuteron acceleration voltage and the duty of 27% at the deuteron acceleration voltage, but the overheating of the couplers happened.**
- **It became clear that the current RF coupler is the bottle neck to increasing duty further.**

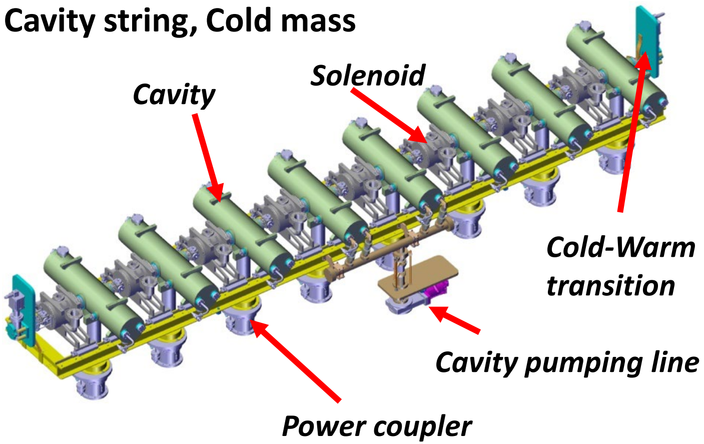




Preparation for Phase-C/D LIPAc Cryomodule



Cavity string, Cold mass

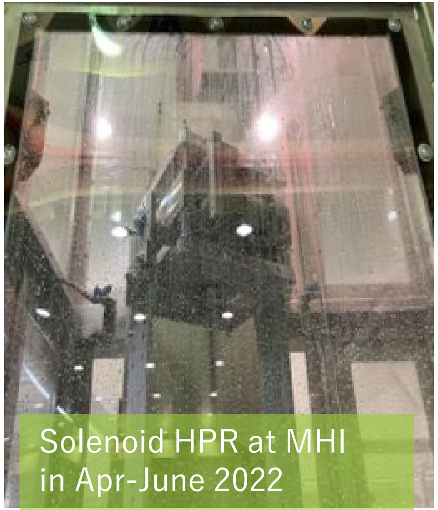


- Overall design and procurement by CEA/Saclay
- Eight half-wave resonators
  - 175 MHz, β=0.094
  - $E_{acc\text{-}nom}$ = 4.5 MV/m, $Q_0 \geq 5 \times 10^8$
  - Operating temperature: 4.4 K
- Power Couplers
  - Designed to handle 200 kW CW
  - 70 kW CW maximum on LIPAc
- Eight superconducting solenoid packages designed and procured by CIEMAT.
  - Two-nested solenoids to focus the beam (6T) with reduced fringe field (20 mT on cavity flange)
  - Two steerers for horizontal and vertical orbits
  - Beam position monitors (BPM) and micro loss monitors

Cryomodule Assembly

- **Most of the cryomodule components (cavity, power coupler, and cryostat) were delivered to Rokkasho by March 2019, and the solenoids arrived by the end of 2021.**
- **QST are taking the responsibility to prepare the infrastructure and F4E to assemble the Cryomodule with the support of the experts from CEA and KEK. HPR conducted in Japan.**
- **Entry ban due to COVID was an obstacle of assembly, but resumed in Aug 2022.**


Cryostat arrived at Rokkasho in Feb. 2018


Solenoid HPR at MHI in Apr-June 2022


Cavity-coupler connection completed in Sep 2022

SRF Assembly at Rokkasho

- **In September 2024, the String Assembly (connection work and vacuum leakage test of all equipment such as cavities and solenoid coils that make up the beam line) was completed in the clean room.**
- **After being taken out of the clean room, the helium piping was assembled.**
- **In January 2025, the insertion of the cold mass into the cryomodule was successfully completed.**

Connecting a cavity in the clean room

Assembled string

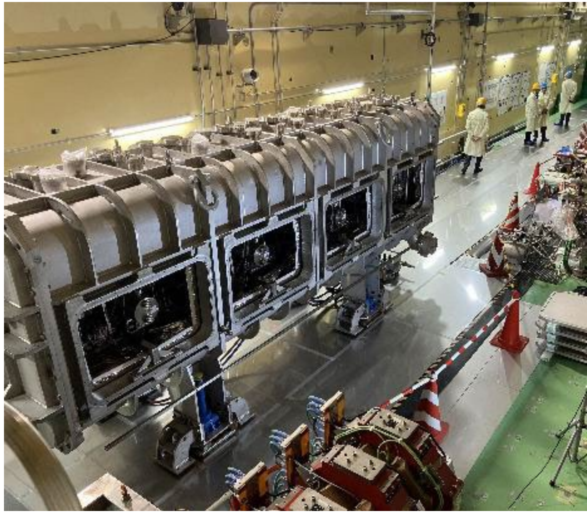
Insertion of cold mass into the cryomodule

SRF cryomodule transportation

- **Transportation from the Assembling Building to the IFMIF/EVEDA Acclerator Building was carried out on March 18, 2025.**
- **Moving between buildings is carried by hanging it with a rough terrain crane and loading it on a trailer.**
- **Electric chill rollers are used to move from the front of the IFMIF building to the accelerator vault.**
- **It is planned to move to the final location of the beamline around the end of September and carry out cable wiring and refrigeration piping work.**
-

Moving from the Assembling Building

Unloading to the LIPAc Building

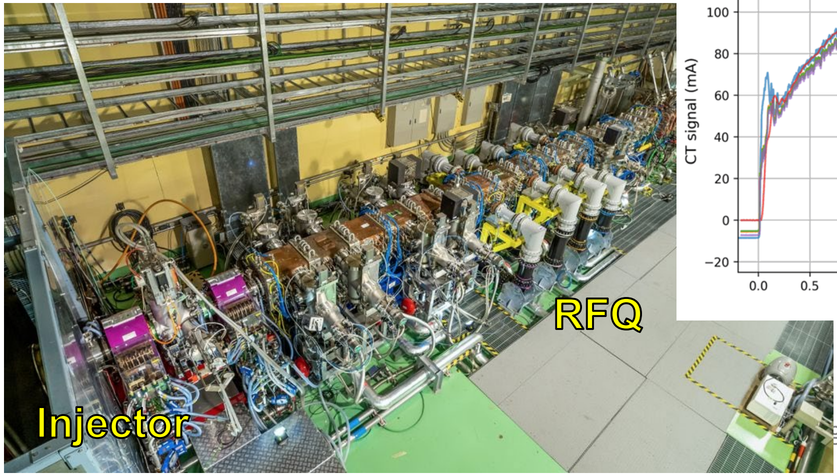


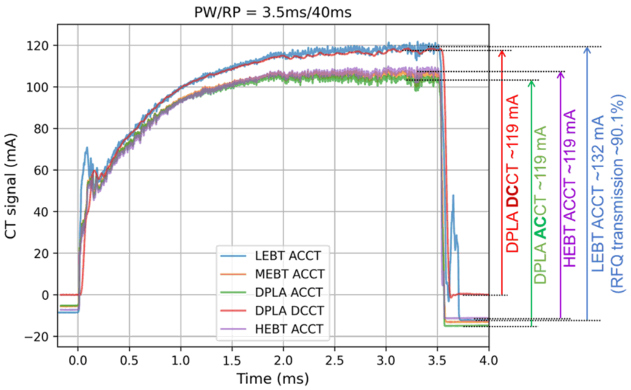
Transported to the accelerator vault

Progress of LIPAc

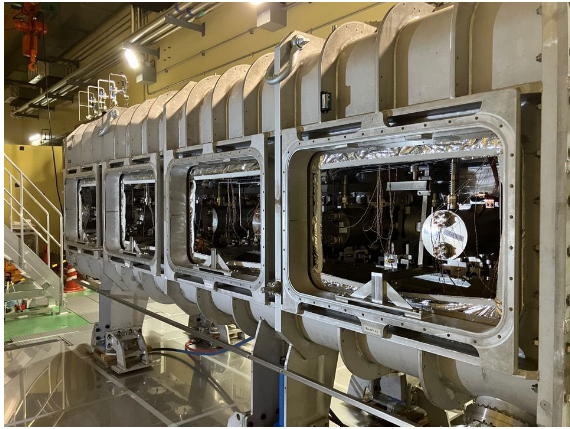
Completion of the RFQ long pulse D+ beam operation

- Deuteron beam acceleration up to 5 MeV by RFQ has been succeeded in achieving a maximum duty ratio of 8.75 % with a current of approximately 120 mA in June 2024.
- Assembly of the SRF beam vacuum section was completed in September 2024, and transportation of the cryomodule to the accelerator vault was completed in March 2025. The assembly is currently in the final stage.





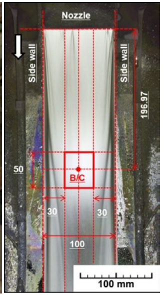
SRF Linac in the vault



FNSD in IFMIF/EVEDA Phase I

- **Engineering Design Activities (EDA) completed in July 2013**
  - **IFMIF Intermediate Engineering Design Report:** Plant Design Description Documents with design guidelines, 3DMU, safety and RAMI studies, licensing scenarios and beam dynamic studies including comprehensive cost and schedule
- **Engineering Validation Activities (EVA)**
  - **Target Facility – Completed April 2017**
    - ✓ **In Japan (Oarai):** World largest Li loop, Construction completed on 19-Nov. 2010, Test on 31-Mar 2015 (operated stable for 571h), Dismantlement on Mar. 2017
    - ✓ **In Europe (Brasimone, Italy):** test stands for LIFUS6 dedicated corrosion/erosion and bayonet backplate remote handling
  - **Test Facility – Completed April 2015**
    - ✓ **High Flux Test Module** (HFTM) at KIT (Karlsruhe, Germany) and SCK CEN (Mol, Belgium)
    - ✓ **Medium Flux Test Module** (MFTM) at EPFL (Lausanne, Switzerland)
    - ✓ Small Specimen Testing Technologies (CEA, CIEMAT, KIT, SCK CEN, IAEA)
    - ✓ HELOKA-LP helium loop at KIT (Karlsruhe, Germany)
  - **Accelerator Facility (LIPAc) – 2 phases were completed**
    - ✓ **In-kind contributions of EU and JA to build this prototype**
    - ✓ Phase A: injector commissioning – 140 mA D+ Beam at 100keV
    - ✓ Phase B: RFQ commissioning – 125mA at RFQ exit, pulse mode, 5MeV

Lithium Target Loop in Oarai, Japan



HELOKA facility and Test Modules

Engineering Design Activity

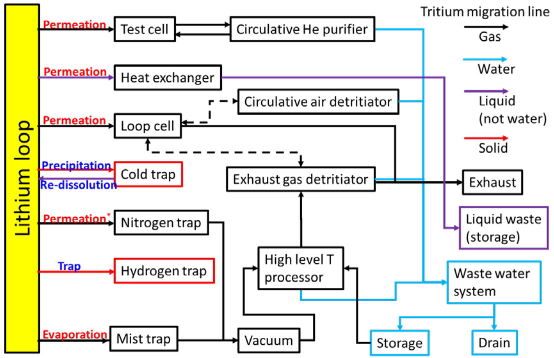
JA activities related to Engineering Design have primarily implemented the following:

- Evaluation of tritium generated at neutron source facilities and the environmental impact of tritium release has been verified with a developed code. This code has been compared with a past tritium diffusion experiment and corresponded with the experimental data.

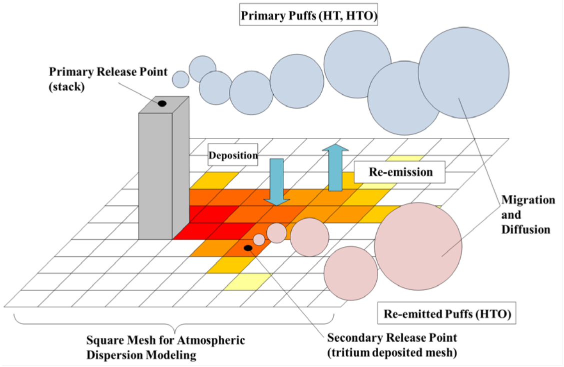
- The following items through LIPAc beam operations (LIPAc as test facility):
  - Testing of radiation-based beam diagnostics
  - Neutron field verification and activation・LIPAc nuclear analysis
  - LIPAc RAMI

Especially for neutronics in Phase B+ of LIPAc, JA and EU collaborated on implementation, with JA (QST) conducting the experiments and EU performing the analysis. They compared neutron fields using activation foils and performed the validity of the analysis methods.

Tritium and Safety assessments



A tritium migration model from lithium loop under steady operation of FNS (JA).

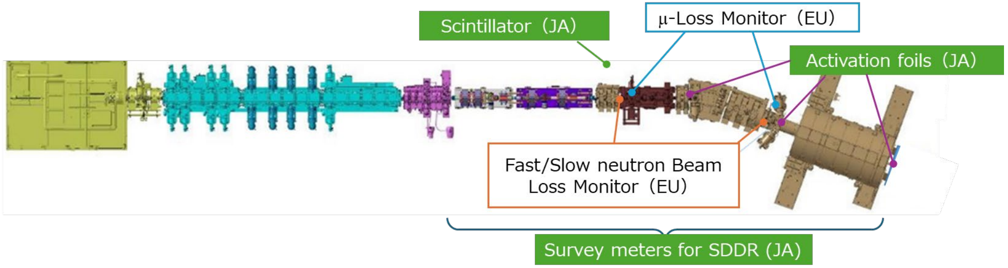


Physical Model Schematic of Developed Tritium Environmental Diffusion Code ROPUCO (JA)

S. Kenjo et al. on this conference (POSTER)

Radiological safety assessments for fusion neutron source in engineering design activities under IFMIF/EVEDA Project

LIPAc as test facility (Diagnostics and Neutronics)



In Phase B+, Activation foils (Ni and Au) for neutron field verification has been use and measured the shutdown dose rate by using some kinds of survey meter.

K. Kumagai et al. on this conference (POSTER)

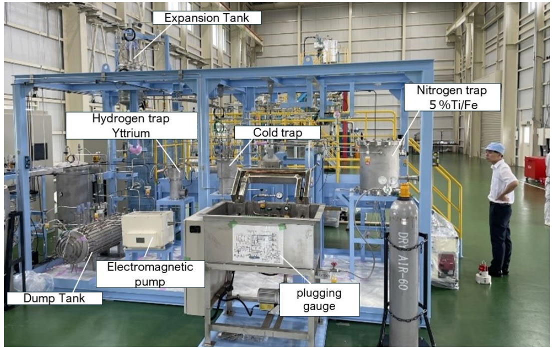
Quantitative Evaluation of Beam Loss Based on Radiation Detection in High-Duty Beam Commissioning of LIPAc RFQ

Lithium Target Facility Activity

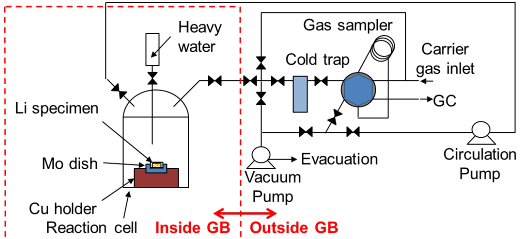
EU-JA activities related to Lithium Target Facility Activities implemented the following:

- Development of impurity removal testing and concentration analysis methods for nitrogen-Hydrogen impurities using a compact Lithium Purification System Equipment **LIPSE**. LIPES has already been operated from Dec. 2024 to verify the specification on FNS target loop system.
- Development of a diagnostics on free surface lithium has been carried out to measure the thickness of lithium target with laser device and lithium-loop facility of Osaka-Univ. **Remote diagnostics from 10-m distance** has been succeed within 1-mm measurement error. JA also investigates the **allocation design** of the laser diagnostics considering the radiation analysis.
- The experimental study on lithium fire protection has been performed in QST (JA). Characterization of high temperature lithium has been investigated with an experimental apparatus. The condition on the **lithium ignition** has been clarified and the **method of extinguishing** has been considered with Ar gas.

Lithium purification validation

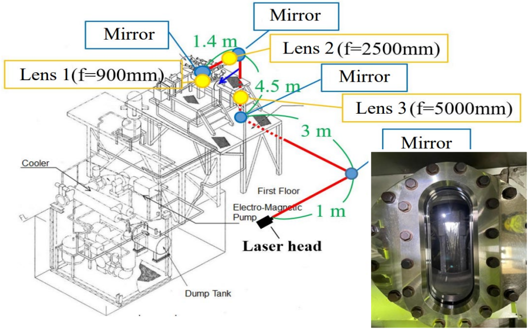


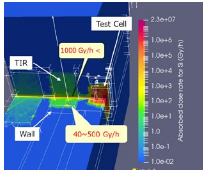
Lithium Purification System Device LIPSE (JA-QST).



Schematic view of concentration analysis apparatus for nitrogen and hydrogen in lithium.

Lithium surface diagnostics





Remote Diagnosis Using Laser Methods with Lithium flow (Osaka-Univ.) and Dose Analysis for Laser Diagnostic Equipment allocation (JA).

Lithium Fire Protection

Experiment of lithium ignition and extinguishing. The ignition temperature was around 600 degree under

EU-FNSD activities at a glance

2021 — ED/LF06-1 (Preparatory phase)

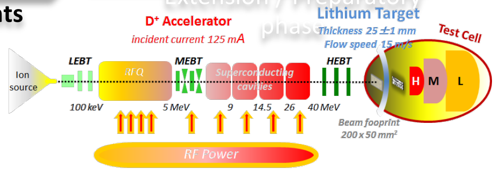
2022 — ED/LF06-2 **Start of activities** 2 Deliverables released

2023 — ED/LF06-2 4 Deliverables released

2024 — ED/LF06-2 3 Deliverables released

2025 — ED/LF06-2 7 Deliverables released — **PA Amendments**

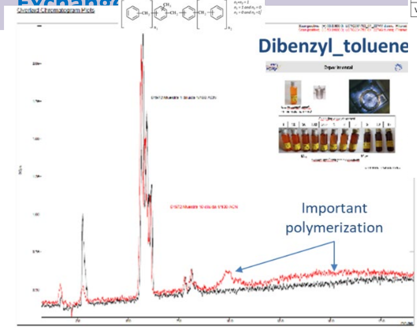
2026 — …06 (JA)/LF06-2 (JA-EU) 1 Deliverables released — Extension / Preparatory phase



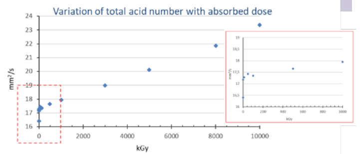
- Since **2021, the EU and JA have been developing different approaches to FNS facilities**
- With a budget of more than 8 KBAUAs, accomplishing up to 18 deliverables (EU) in 2 PAs
- **Common Europa (EU)-Japan (JA) FNS design activities have been defined in the frame of the Broader Approach Phase Two (BA-II),** in addition to IFMIF Engineering Validation and Engineering Design Activities (IFMIF/EVEDA)
- **Several EU Engineering Design (ED) and Lithium Facilities (LF) design activities** required for advancement in an FNS design are being developed from **2022 to 2025** under two Procurement Arrangements (PAs):
  - ✓ EU & JA FNS are developing **5 main activities inside ED06-2** based on the engineering, modelling, calculation, and experimental activities of FNS: i) **Tritium migration estimation**, ii) **Erosion/deposition modelling** in the li loop, iii) **Accident analysis in Safety**, iv) **Optimization of the Li-oil heat exchanger**, v) **The use of LIPAc (9 MeV & 125 mA) as a key testing facility** for future FNS construction, testing new diagnostics, making neutronic and activation studies, and use for the analysis of the operational experience reliability data collection (RAMI)
  - ✓ EU & JA FNS activities include **5 main activities inside LF06-2** based on experimental and modelling activities in Li: i) **Li purification system validation activities** by means of pilot plants 1:1, ii) **Li target diagnostics** design and validation by laser for Li thickness measure, iii) **Erosion/corrosion analysis and modelling** on the materials of the **EVEDA Lithium Test Loop (ELTL)**

EU-FNSD_Engineering Design activities (ED06-2)

Study and design on the optimization of the Li-Oil Heat Exchanger



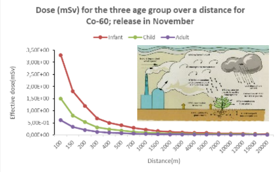
Absorbed dose	KGy	0	1	10	50	100	500	1000	3000	5000	8000	10000
Viscosity@ 40 ºC	mm^2/s	16,4	17,18	17,27	17,43	17,34	17,65	17,94	18,98	20,11	21,89	23,39



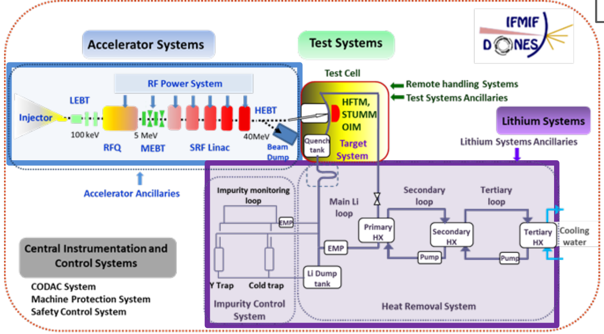
Important polymerization (free radicals) occurs at the beginning of irradiation.

Increase of Density and Viscosity

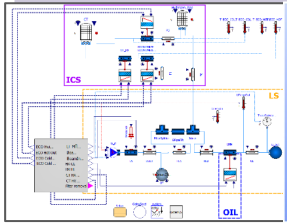
Accident analysis in

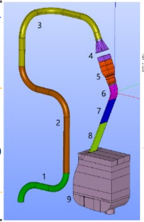


Dose during the 1st year Vs distance, produced by an acute release in Nov of 1010 Bq of Co-60

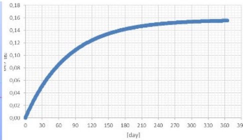


Erosion/deposition modelling in the Lithium loop



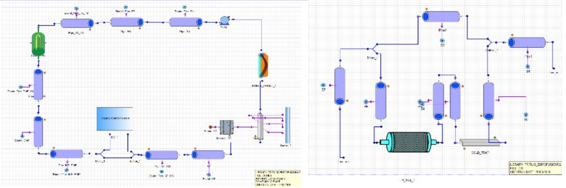


Neutronic calculation ACPs&EAPs



Equilibrium inventory of Be7 in ENS-DONES

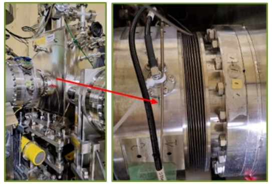
Tritium migration in the Li loop



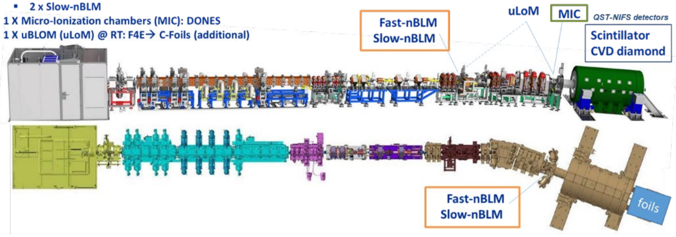
Model for Target System and purification system in EcosimPro

Use of LIPAc as a testing facility

Validation of sensors and diagnostics of DONES at LIPAc

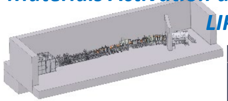


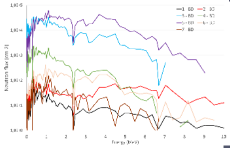
- Neutron Beam Loss Monitors Micromegas (nBLM): CEA
  - 2 x Fast-nBLM
  - 2 x Slow-nBLM
- 1 X Micro-Ionization chambers (MIC): DONES
- 1 X uBLOM (uLoM) @ RT: F4E→ C-Foils (additional)



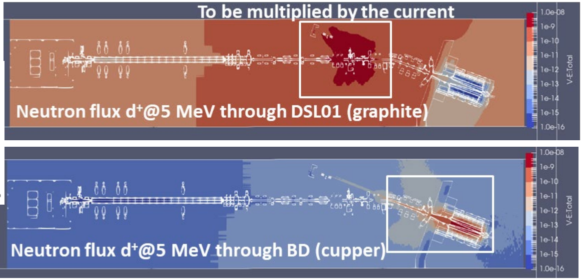
Materials Activation and validation of Neutronic calculations at LIPAc

The first full detailed nuclear model



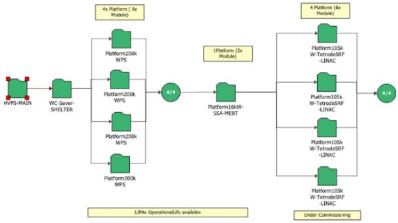


Neutron flux received by foils in the different selected positions



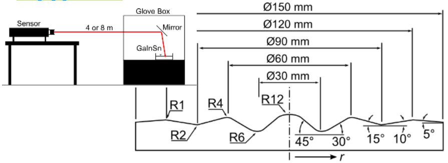
RAMI data from LIPAc exploitation

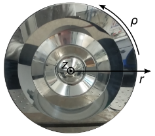
The RAMI performance of the LIPAc RFPS system resulted in ***67.51%***

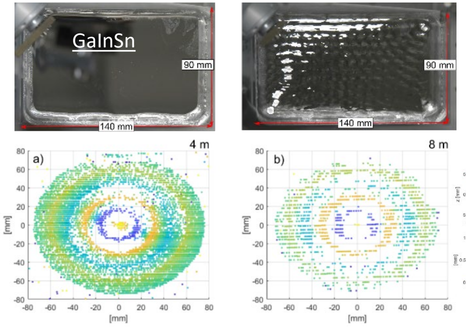


EU-FNSD_Lithium Design activities LF06-2)

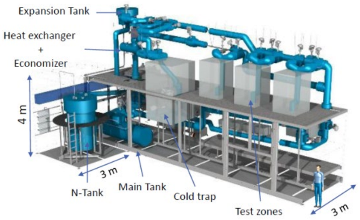
Li target diagnostics design and validation in EU

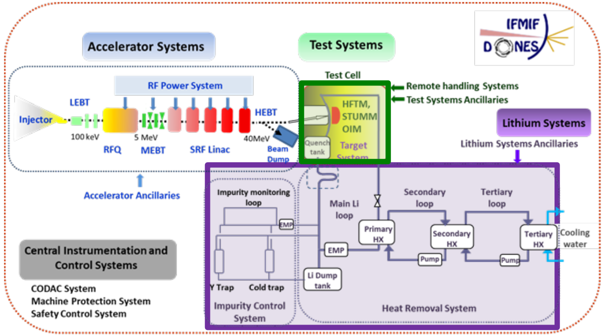






Measurements with IVVS were conducted. The vertical resolution is within the required <0.3 mm

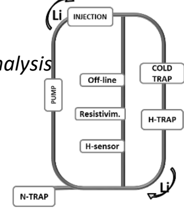




Li purification system validation activities in EU

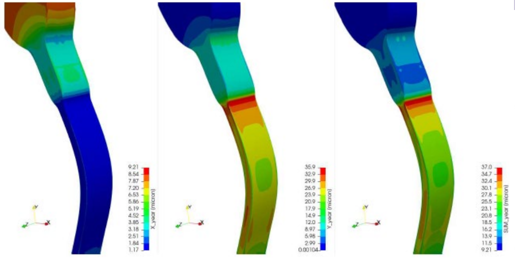
Commissioning plant (Sep2025):

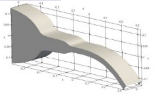
1. *Off-line analysis. To check the composition of the Li after several hours of LITEC operation*
2. *Impurities addition -- Off-line analysis*
3. *Cold-trap - Plugging meter online + offline analysis*
4. *N-trap – resistivimeter + offline analysis*
5. *H-trap - H-sensor + Off-line analysis*
6. *Cold trap + H trap operating in series*
7. *Optimizations/upgrades*

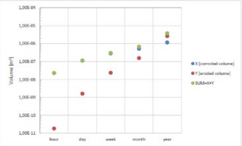


Erosion/corrosion analysis on ELTL materials in EU

Thickness reduction between ~25 µm & ~37µm after a year



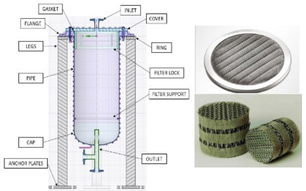




Corroded thickness (X), eroded thickness (Y), and their sum (SUM) after 1y

Nitrogen trap

Cold trap



Hydrogen trap