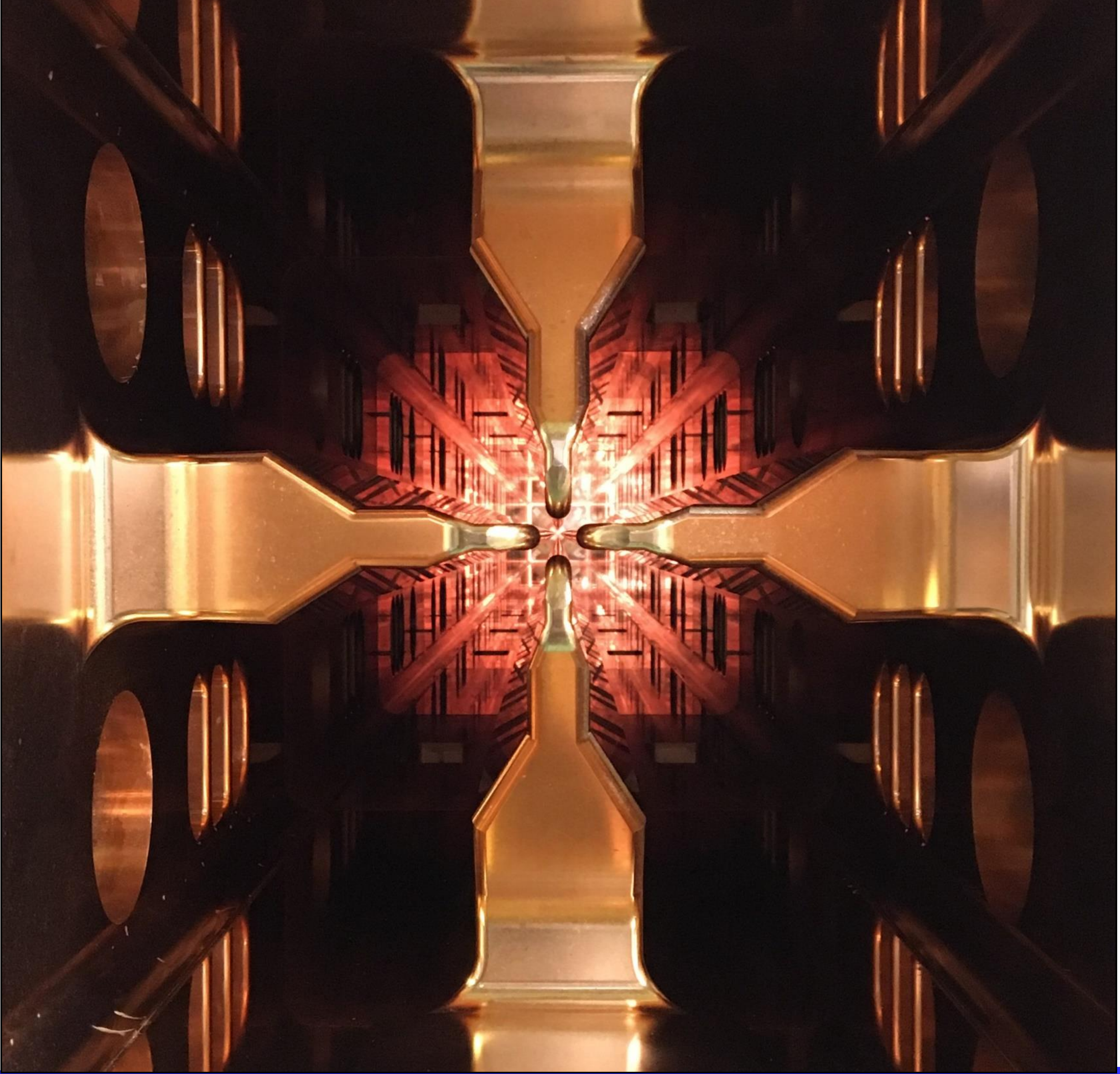
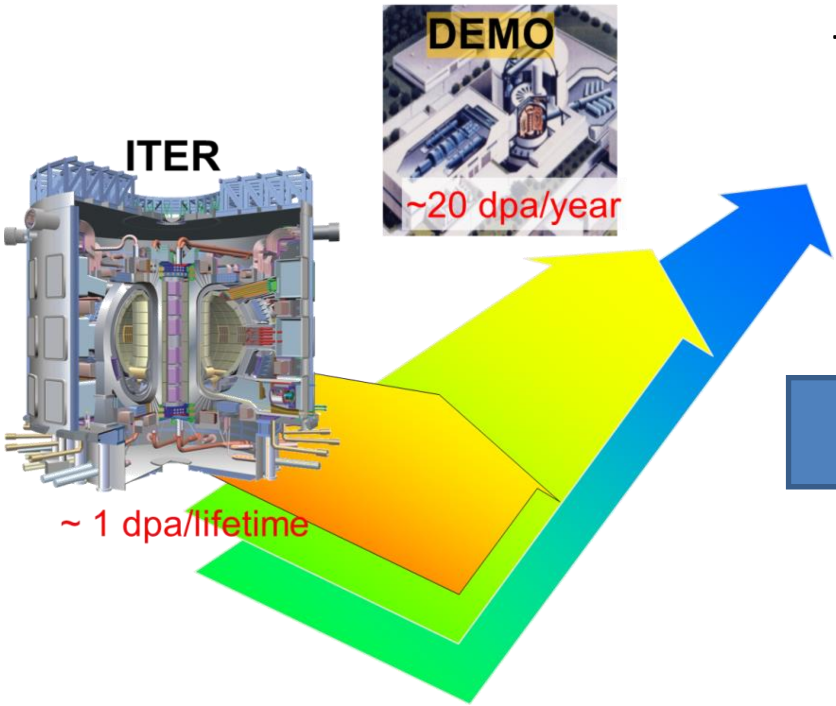


DONES stato e prospettive

A. Pisent- INFN
Laboratori Nazionali di Legnaro

DONES

- DONES, Demo Oriented Neutron Source, is the European version of IFMIF, i.e. a facility based on high intensity linear accelerator, for the test of fusion reactor structural materials.
  This in view of DEMO, that will be the first fusion reactor for electrical power production

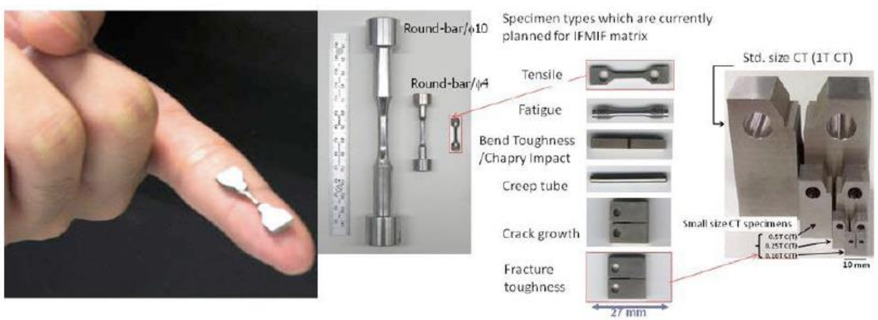


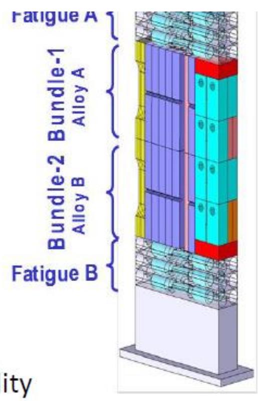
One of the main differences between ITER and DEMO is the radiation dose: at DEMO more that two orders of magnitude higher

DONES: DEMO oriented Neutron Source

Material degradation in Typical Fusion Reaction Conditions

- Neutrons interact with the plasma facing walls and with the structural material behind them (Special steels, W, Cu, SiC, Be, Li ceramic, and others)
  - elastic collisions cause displacement of the atoms in the lattice
  - Neutron capture cause transmutation and generation of He and H inside the material
- Macroscopic phenomena observed:
  - Embrittlement, and increase of the Ductile to Brittle Transition Temperature (DBTT)
  - Swelling
  - In general, modification of mechanical properties
- Main parameters determining mechanical properties evolution:
  - **Type of material**
  - **Neutron energy** distribution
  - Average number of **displacements per atom (dpa)** accumulated, and ratio of **appm He/dpa**
  - **Temperature** of the irradiated material
- Experimental data: available at a **few dpa** (sufficient for low duty cycle research reactors) but largely missing for **10-100 dpa** or more, expected infusion power plants (~**150 dpa**)

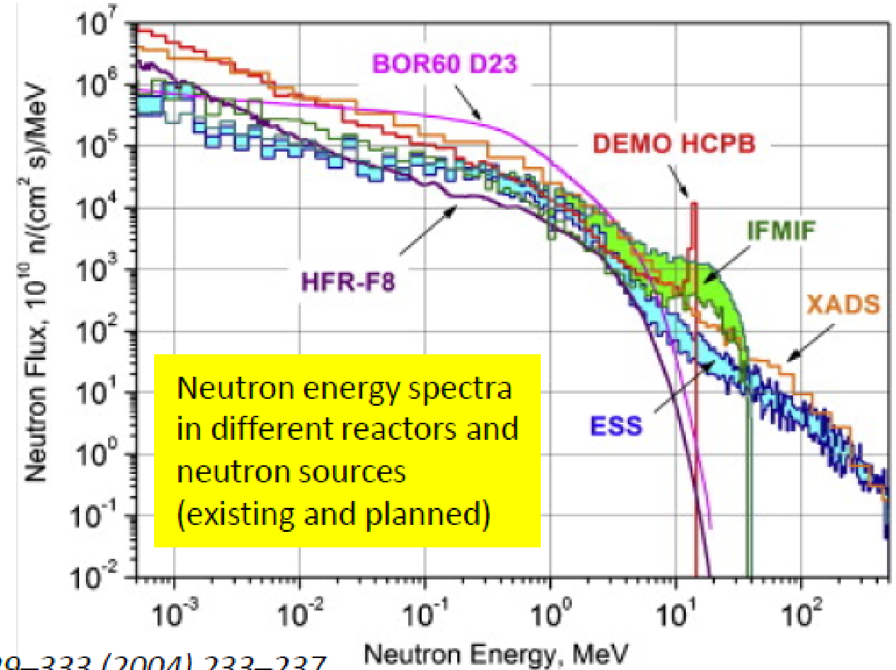




Samples and irradiation modules developed for the IFMIF facility

Neutron Source Comparison

- Fission reactors deliver high flux, but neutrons have too low energy compared to fusion ones
- Spallation neutron sources energy spectrum has a high energy tail which produce different material modifications
- Existing fusion reactors can deliver a similar energy spectrum, but not the dose
- To fulfill fusion reactor program needs a Li stripping n source (IFMIF) was designed



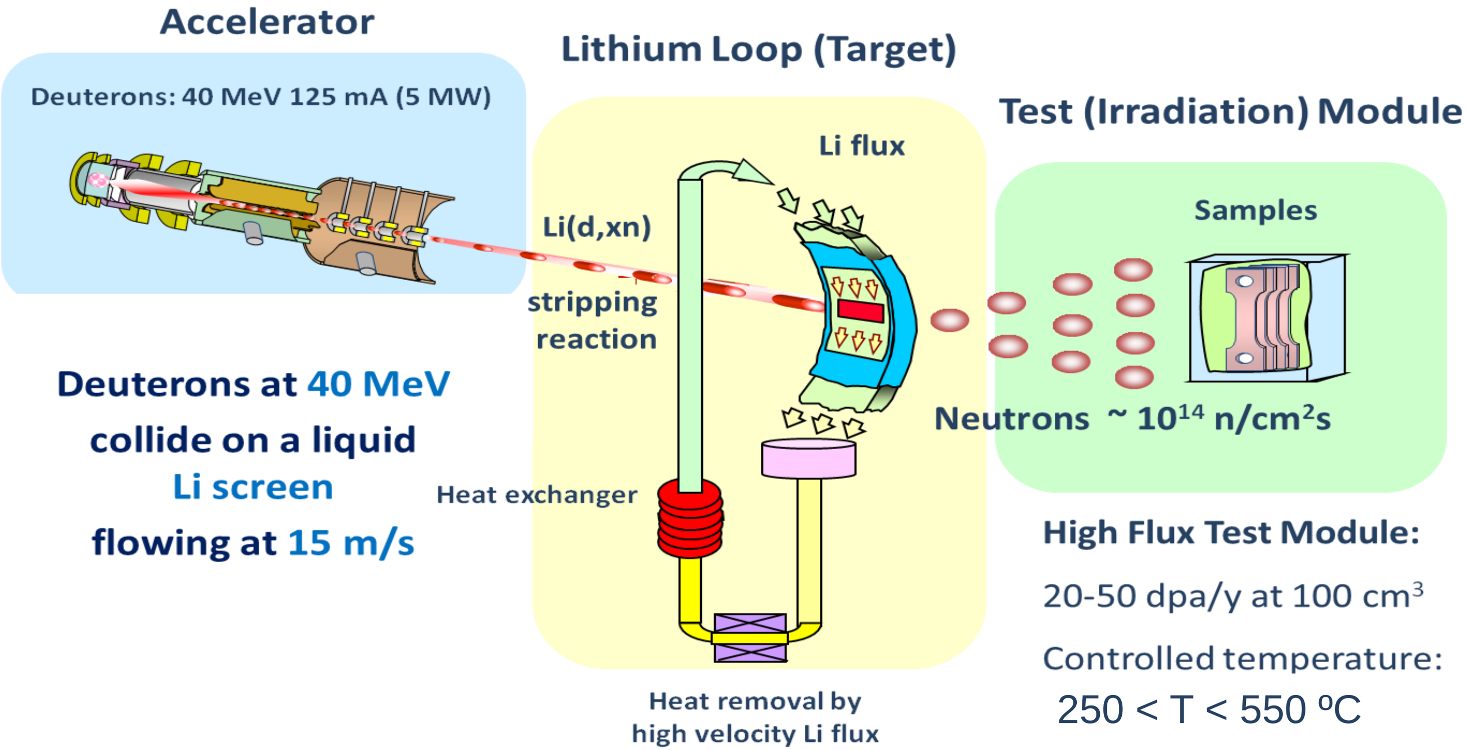
From P. Vladimirov, A. Moeslang / Journal of Nuclear Materials 329–333 (2004) 233–237

Irradiation parameter	Demo power plant W/m²	IFMIF HFTM	ESS	XADS 1 MW	HFR (reactor)	BOR60 (reactor)
Total flux, n	**$1.3 \cdot 10^{15}$**	$5.7 \cdot 10^{14}$	$6.5 \cdot 10^{14}$	$1.2 \cdot 10^{15}$	$3.8 \cdot 10^{14}$	$2.3 \cdot 10^{15}$
$cm^{-2}\ s^{-1}$ p	**0**	0	$2.5 \cdot 10^{12}$	$2.7 \cdot 10^{14}$	0	0
Damage, dpa/fpy	**30**	20–55	5–10	38	2.5	20
H, appm/fpy	**1240**	1000–2400	160–360	16 250	1.9	14
He, appm/fpy	**320**	250–600	25–60	1320	0.8	5.8
H/dpa	**41**	35–54	33–36	430	0.8	0.70
He/dpa	**11**	10–12	5–6	35	0.3	0.29

Displacement damage and gas production in iron for several neutron irradiation environments

What is IFMIF-DONES?

A neutron flux of ~ 10^{14} $cm^{-2}s^{-1}$ is generated with neutron spectrum up to 50 MeV energy



Identified as high priority in the EU Fusion Roadmap
Included in the ESFRI Roadmap as a EU strategic facility

DONES overall framework

The need for a facility of this type was identified long time ago and work has been carried out by using different frameworks

In the last 15 years, some key projects has been contributing. Presently more relevant ones are:

- **IFMIF/EVEDA** (included in the BA)
- **WPENS** –including specific Industry contract- (EUROfusion WP) extended in 2022

DONES-PRIME
DONES-UGR

- **DONES-PreP** (ESFRI preparatory phase, EURATOM CSA, 2019-21)
- **DONES-Cons2** (ESFRI consolidation phase, EURATOM CSA, i2023-25)
- **DONES-PRIME** and **DONES-UGR** (Spanish funded projects)

Institutions and main contributors to DONES design

S. Becerril, M. García, A. Ibarra, M. Luque, M. Weber
B. Bolzon, N. Chauvin, S. Chel, A. Madur, J. Marroncle, L. Seguí
F. Arranz, D. Jímenez, F. Martín-Fuertes, C. de la Morena, C. Oliver, D. Regidor
D. Bernardi, M. Cappelli, G. Miccichè, F.S. Nitti, T. Pinna
J.C. Marugán, J. Gutiérrez, C. Prieto
P. Cara, D. Duglue, H. Dzitko
W. Królas
L. Bellan, M. Comunian, A. Palmieri, A. Pisent
L. Macià, M. Sanmarti
F. Arbeiter, V. Hauer, Y. Qiu
M.J. Ferreira, A. Jansson, M. Eshraqi, C. Martins
T. Tadic
J. Aguilar, J. Díaz, J. Maestre, A. Moreno, R. Lorenzo, D. Sánchez-Herranz, C. Torregrosa
J. Castellanos

+ the whole WPENS IFMIF-DONES Team!!

INFN involvement in DONES design

- **General accelerator physics**: A. Pisent (DT),E. Fagotti (1T)
- ***Beam dynamics:*** M. Comunian (R), L. Bellan (TD), C. Baltador (AR)
- ***Diagnostica del fascio***. M. Poggi (1T)
- ***Radio frequenza***: A. Palmieri (T), F. Grespan, (T), A. Baldo (CTER TD)
- ***Progettazione Meccanica e prototipi*** L. Ferrari (TD), P. Bottin T (CTER); F. Scantamburlo (congedo F4E a Rokkasho),
- ***Computer control*** L. Antoniazzi(T), M. Montis(T), M. Giacchini
- ***Inoltre, principalmente impegnato nei progetti IFMIF e ESS***
  - M. Giacchini,, A. Battistello (CTER ESS), A. Colombo (INFN PD), D. Conventi, R. Panizzolo (CTER ESS),
- Sia per ESS che per IFMIF è attiva un'intensa collaborazione con INFN TO, Gruppo guidato da P. Mereu (1T) [*]

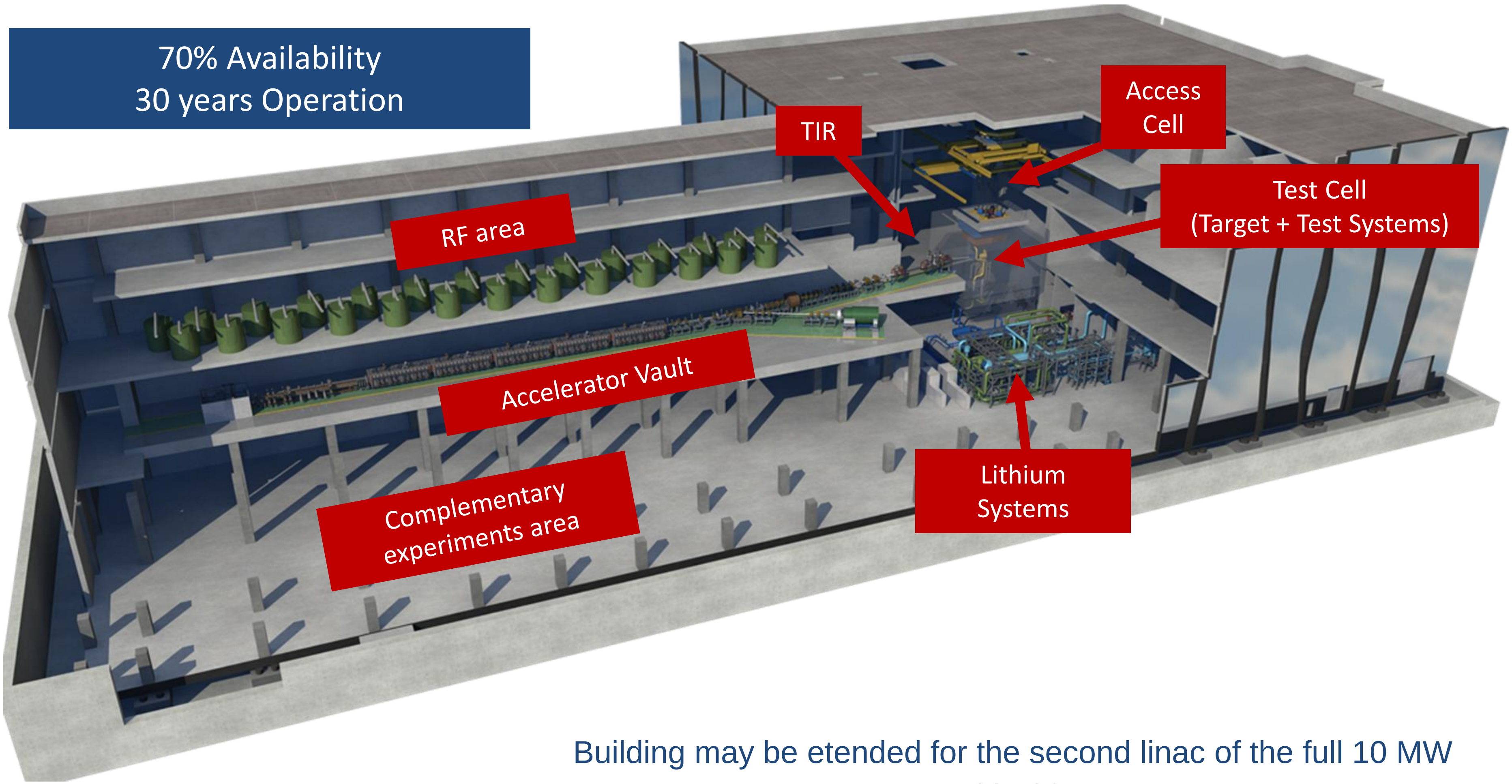
[*] situazione attuale, in passato anche sezione di Padova (A. Pepato et al.) e Bologna (A. Margotti et al.)

IFMIF-DONES Facility

The site is located at Escúzar -18 km southwest from Granada city- Spain

IFMIF-DONES Facility

70% Availability
30 years Operation



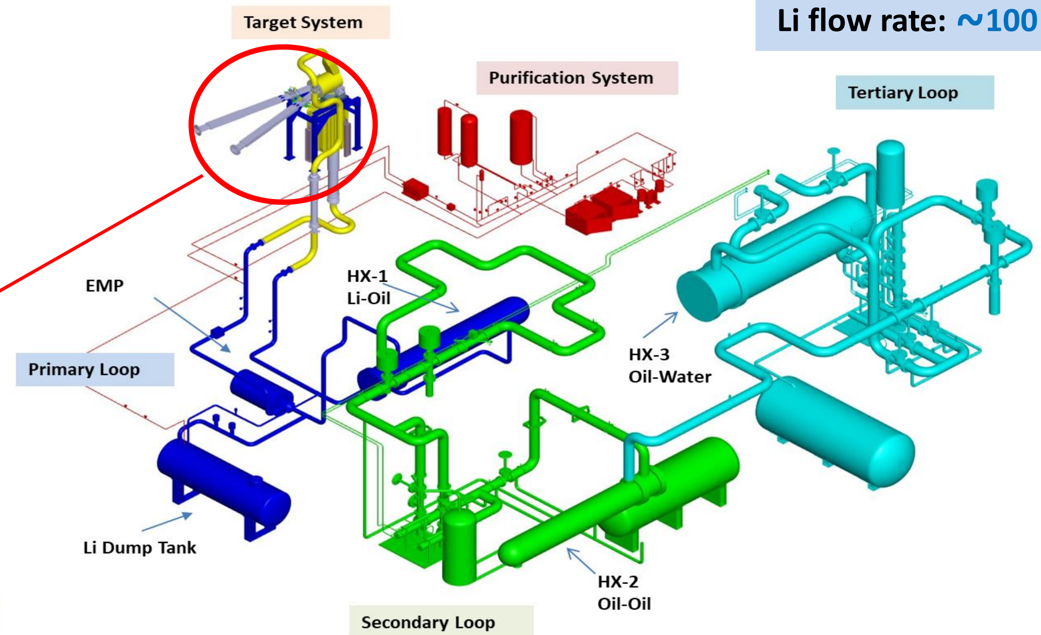
Building may be etended for the second linac of the full 10 MW power

Lithium Systems

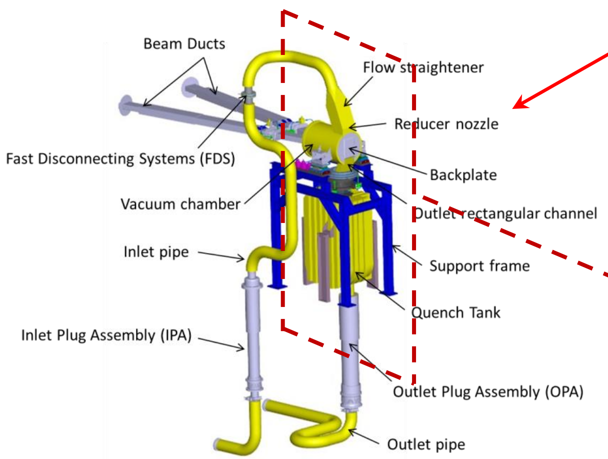
Lithium System (LS) main functions:

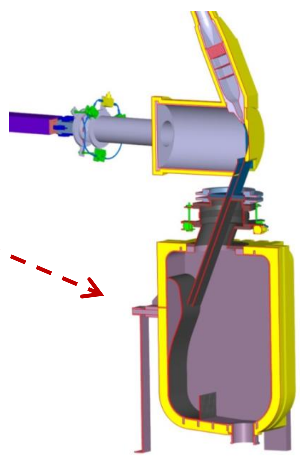
- 5 MW power handling
- Li flow stability
- Li impurities control and monitoring
  - Corrosion issues (affected by N content)
  - Radioactivity inventory (Be-7, Tritium, ACP…)

Li volume ~14 m^3
Li flow rate: ~100 l/s



Target Assembly (TA)



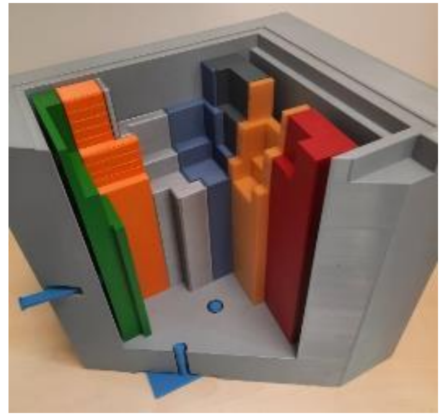


Heat flux: 500 MW/m^2
Jet thickness: 25 ± 1 mm
Li inlet T: 300 °C
Li velocity: 15 m/s
Chamber pressure: 10^{-2} Pa

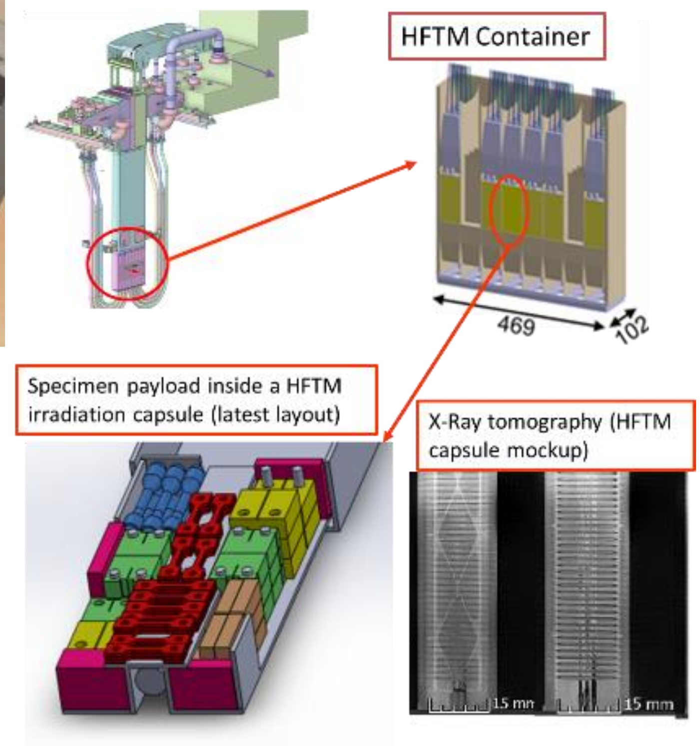
IFMIF/EVEDA ELTL validation results implemented in the design

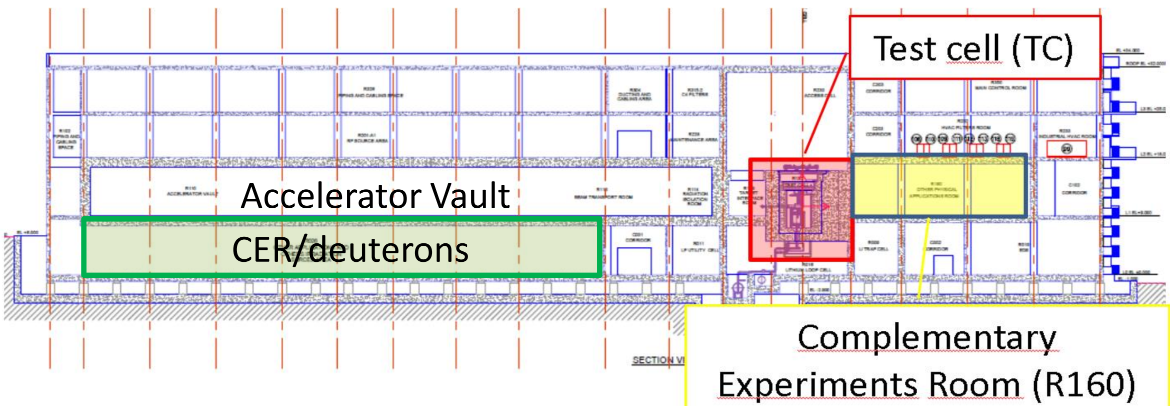
Test Systems

- Main test area: behind Target Assembly inside Test Cell →
  High Flux Test Module (HFTM)
- Test Cell Maintainable → HFTM removed periodically (1/year)
- Other modules under assessment
- Other experimental areas:
  - Room for other applications using Test Cell neutrons downstream the Test Cell (R160)
  - Room for other applications using HEBT deuterons (nuclear physics, medicine, industry,…) below the Accelerator Vault



Optimization of the design to maximize the number of small specimens

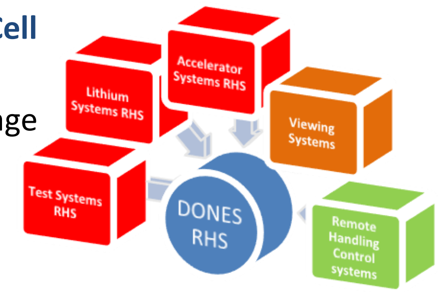


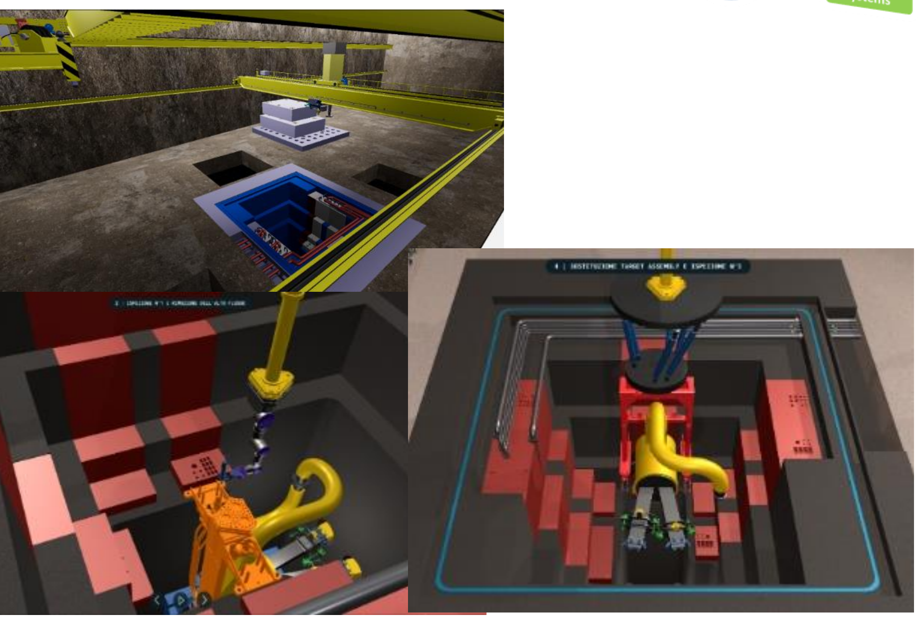


More than 850 specimens can be hold in the HFTM !!

Remote Handling

- Main RH Equipment in **Access Cell** HROC and ACMC
- Access Cell big enough for storage of all components
- Other RH in AS and LS





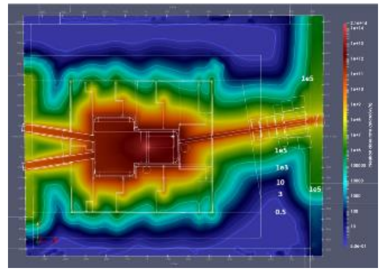
Logistics & Maintenance

- Compatibility of architectural features with **Flow of Materials** for replacement and maintenance of plant equipment (shipping bays, elevators, casks, OMV's…)
- Maintenance Matrix, harmonization equipment and Asset Management
- Development of **Virtual Reality tools** for analysis of installation and maintenance operations

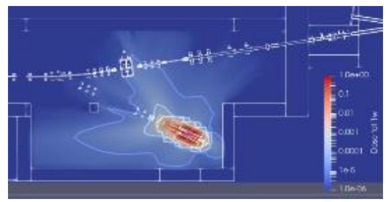
Safety activities

Safety

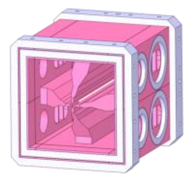
- **Safety Analysis Report** issued and continuously updated
- Analysis of the **accidental events** and the mitigation measures (MELCOR simulations)
- Identification & development of specific **safety requirements** for components
- Staged **Licensing s**trategy



Test Cell neutron dose rate



BD neutron dose rate



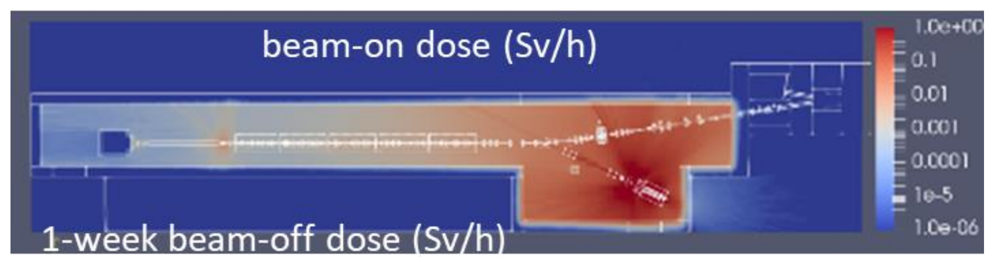
RFQ neutronics model

Neutronics

- **Nuclear Data Handbook** issued
- **Detailed model** developed of AS
- Data on prompt doses, residual dose rate
- Design and optimization of shielding barriers
- Analysis water and vacuum products activation
- Integrated doses during critical maintenance activities under analysis
- Standard codes and libraries (MCNPX, McDelicious, McUNED, ACAB, FISPACT…)

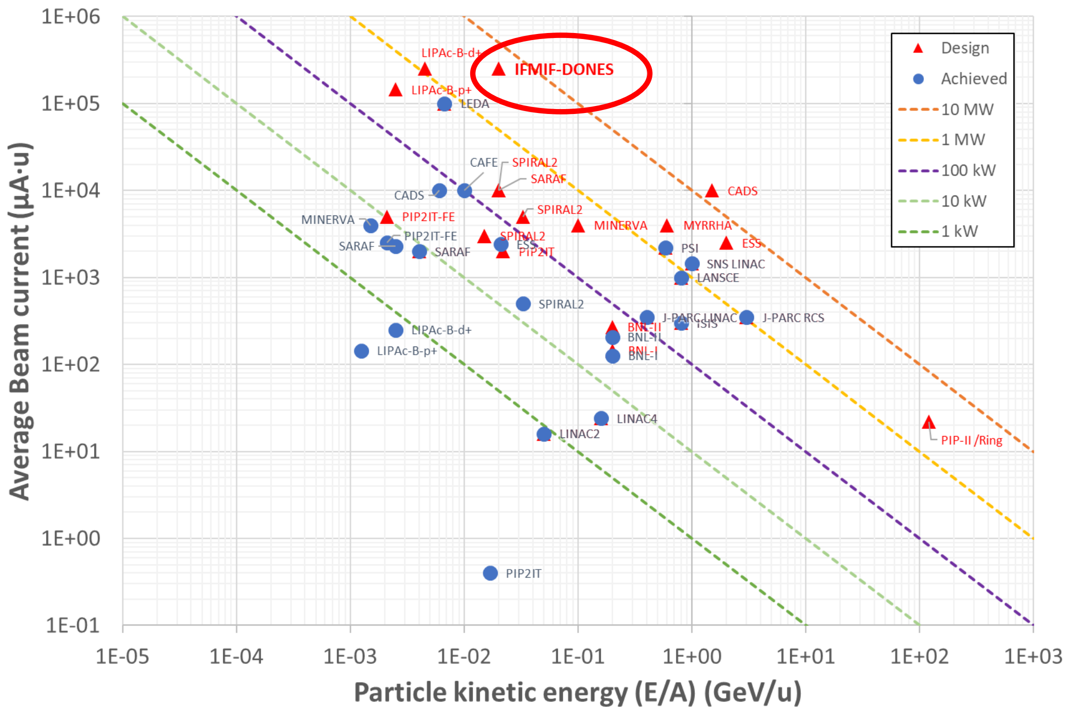
RAMI

- **Top-down** simulation with availability allocation for each group of system (87% AS)
- **Bottom-Up** simulations using BlockSim under analysis to improve performance for each system



IFMIF-DONES 5 MW Accelerator Design

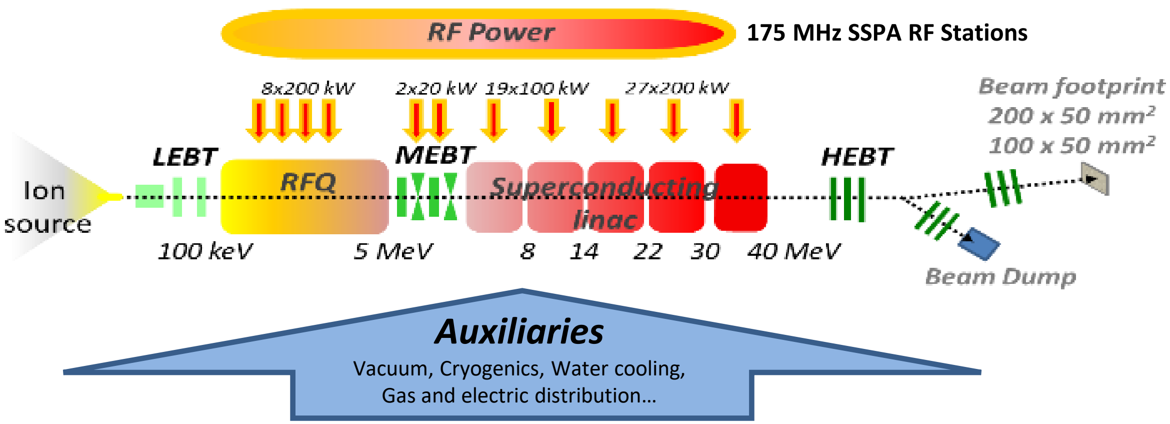
40 MeV / 125 mA CW / 5 MW SC LINAC



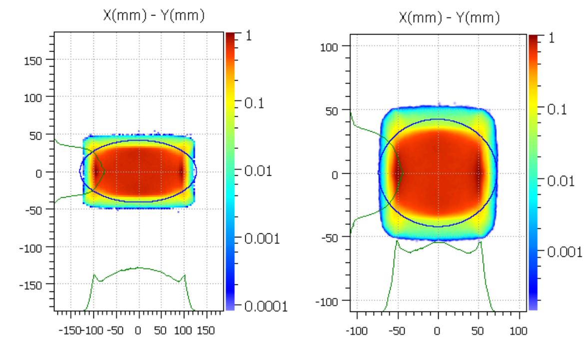
- Highest **D⁺ current** LINAC
- One of the highest **average beam power**
- Longest **RFQ**
- Record of light hadrons current through **SC cavities**
- Highest **Beam perveance**

IFMIF-DONES 5 MW Accelerator Design

Accelerator based on IFMIF design with
Beam incident at 9° angle →
possibility to upgrade to IFMIF with 2nd mirror accelerator (10 MW)



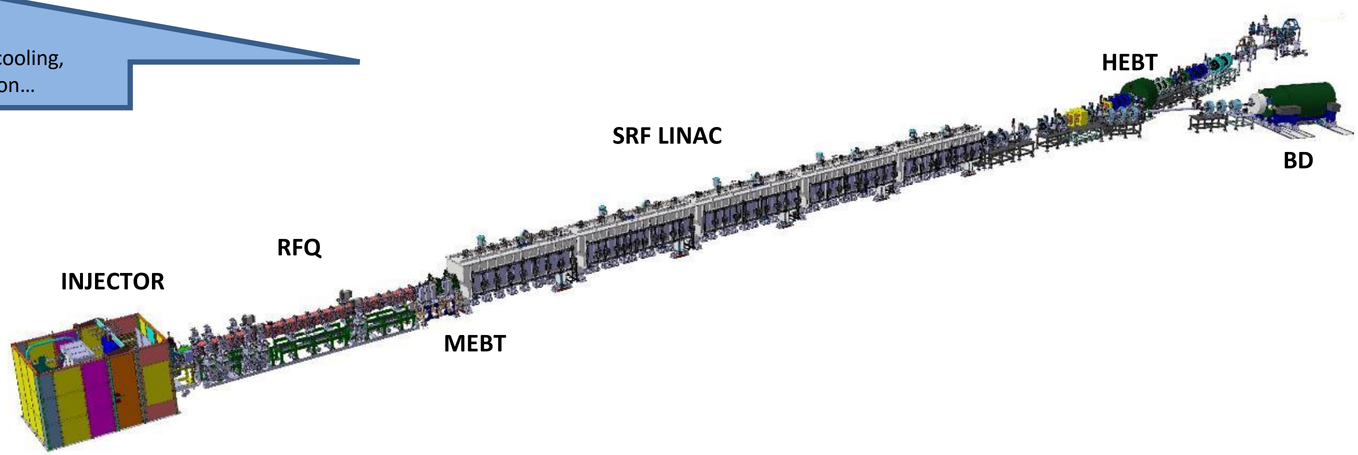
Beam footprint @ target



20x5 cm² footprint (reference)

10x5 cm² footprint (optional)

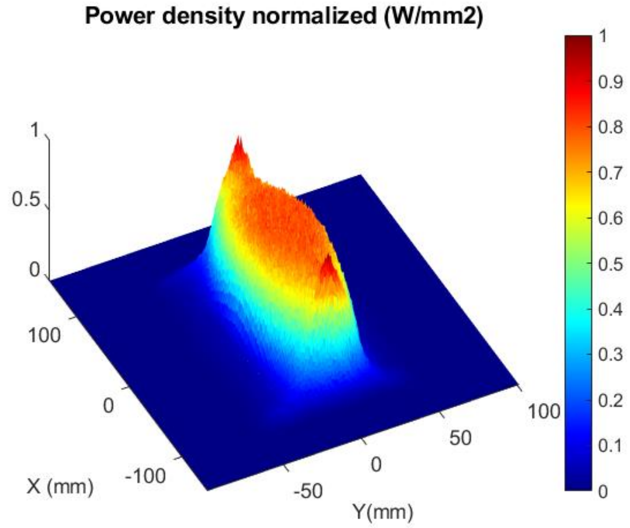
D+ CW 175 MHz SC LINAC
125 mA / 40 MeV → **5 MW**
Total length of ~**100 m**
Windowless liquid **Li target**
20 y, 87% **availability**
Hands-on **maintenance (<1 W/m)**

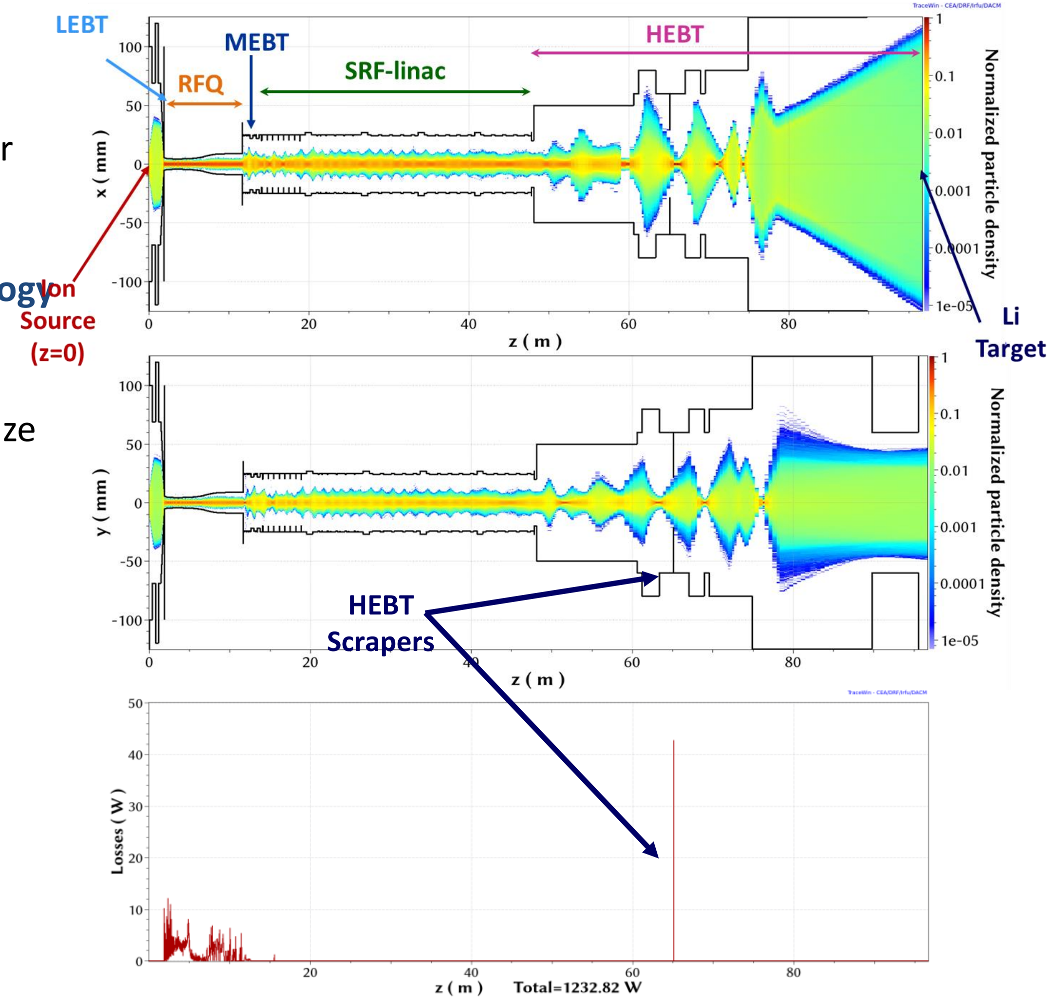


IFMIF-DONES 5 MW Accelerator Design

Major **Upgrades**:

- Number of **SRF cryomodules** increased from 4 to 5 for enhanced flexibility, increased operational margins
- 200 kW Tetrodes replaced by **Solid State (SS) technology** in the RF Power System
- **Flexibility on the target beam footprint** (horizontal size and size of side peaks)
- Enhanced **Availability**

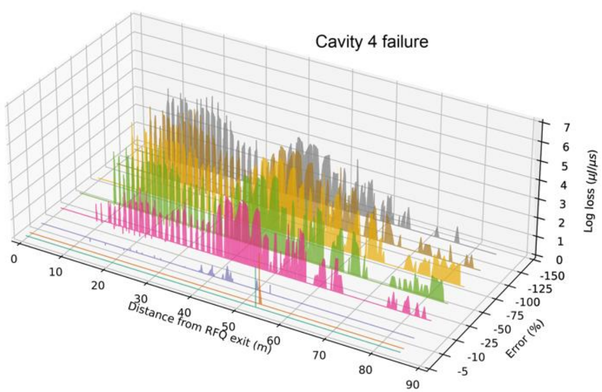




Beam dynamics design

Start to end error study

- Assessment of possible and realistic errors of the beam line (mechanical, ripple, static, dynamic) from ion source to target
- Correction scheme (steerers – BPM)
- Monte-Carlo simulations



+ Studies of the **beam scattering** due to residual gas near the target

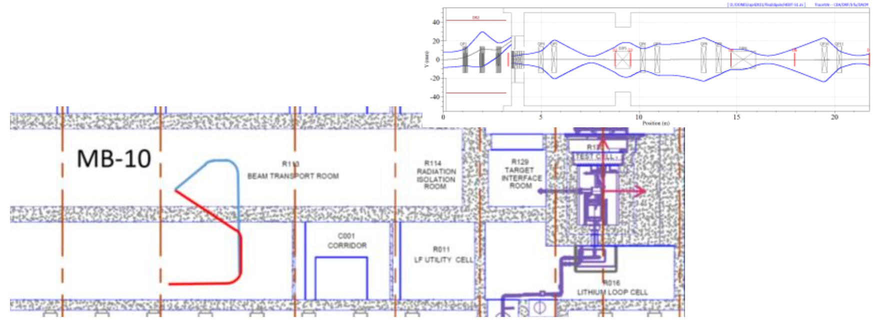
+ Extraction of **parasitic beam** (0.1%) to experimental area

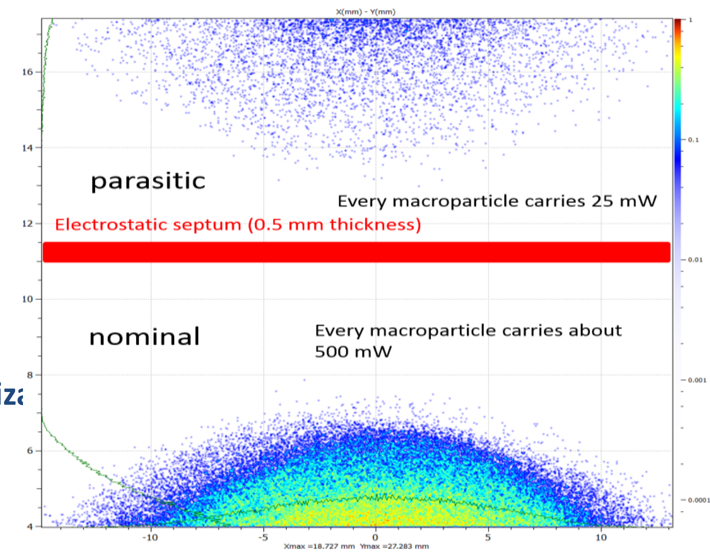
+ Coupling of beam dynamics/neutronics simulations for **irradiation optimiz**

+ Uncertainty Quantification analysis

Design and simulation of parasitic line for interdisciplinary users (INFN)

- 1/1000 bunch extracted with a fast meander line chopper for TOF experiments.

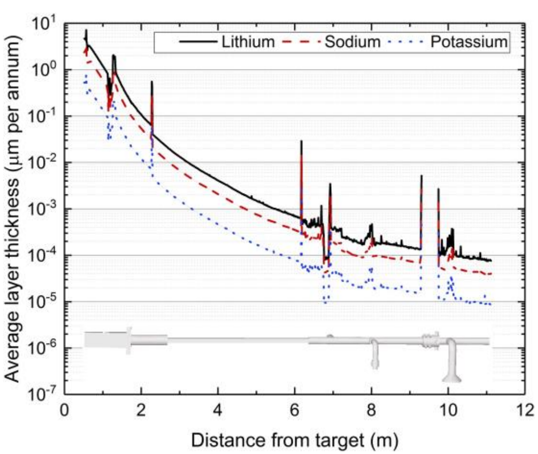


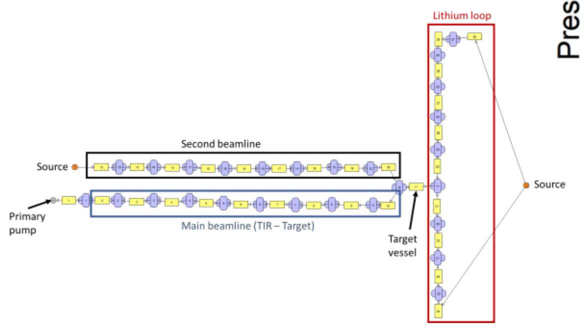


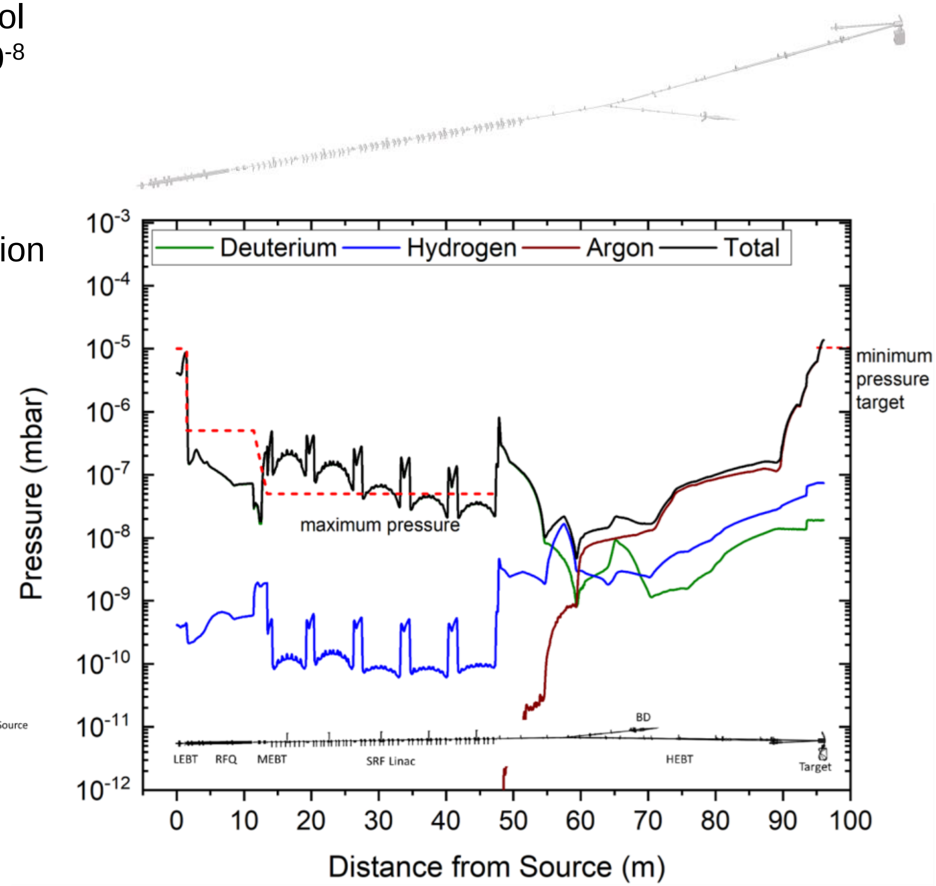
Simulazione della potenza di fascio (principale e parassita) al setto elettrostatico

Vacuum design

- **Differential vacuum profile** near the target with gas injection control (Ar), pressure between 10^{-4} to 10^{-5} hPa in the target and below $5 \cdot 10^{-8}$ hPa in the SRF LINAC (Molflow+)
- Use of **Slow Pumping Systems** in the SRF LINAC area
- Pumping in the SRF LINAC area to be optimized
- **Fast valves** for mitigation of accidental events and machine protection
- **Primary pumps** outside the vault
- **Equipment harmonization** to improve maintenance
- Quantification of the **lithium vapour deposition** along the line
- Simulations of the **lithium loop** (ITERVAC)
- **Vacuum Handbook**





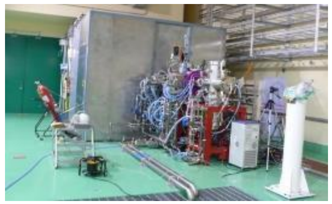


Injector/RFQ/MEBT

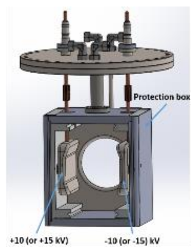
Based on LIPAc design +

Injector

- New **Chopper** for high intensity D^+ beam



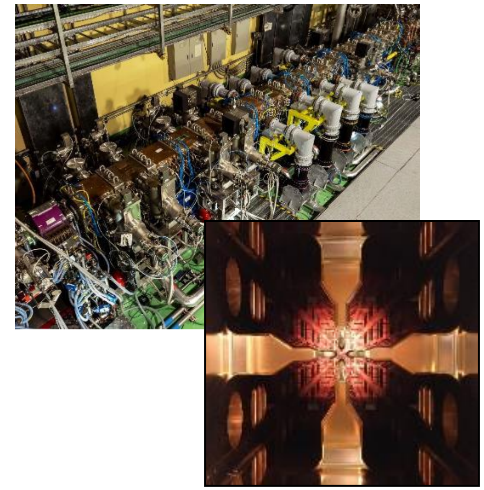
- Experimental plan of study of **dielectric disks** inside the ion source for improving/optimizing injector and Facility availability (Boron Nitride disk)



- Injector enhancement based on **LIPAc operational feedback** and enhancement programme performed in the frame of the IFMIF/EVEDA BA-I and BA-II (respectively)

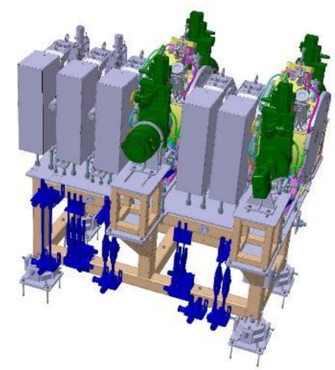
RFQ

- **Vanes erosion model** based on sputtering. Other phenomena under study (ion implantation, …)
- **RFQ mechanical engineering upgrade** to ease the maintenance
- **Power coupler with brazed windows**



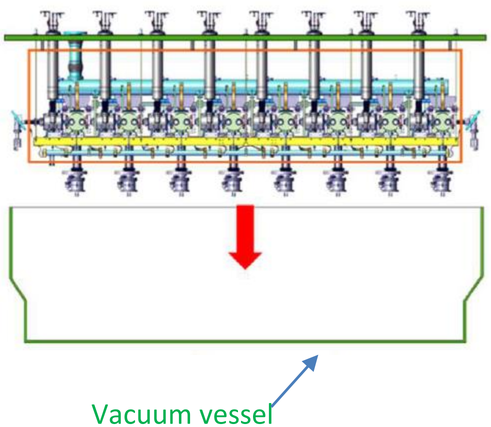
MEBT

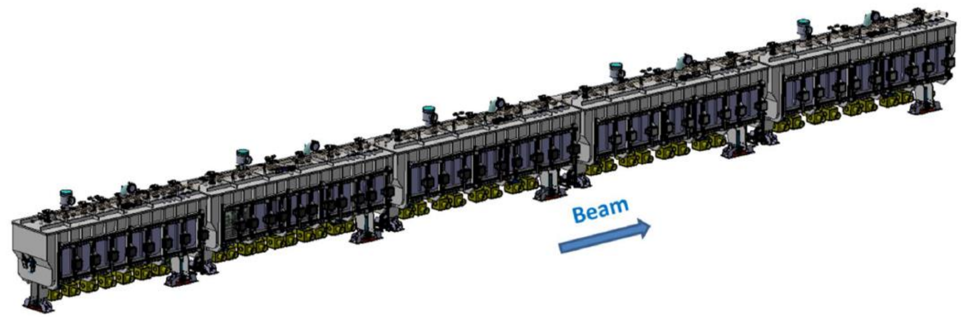
- Modifications introduce to improve the **maintainability**
- Enhancement of the **Beam Diagnostics** (DC measurement) and **Vacuum package**

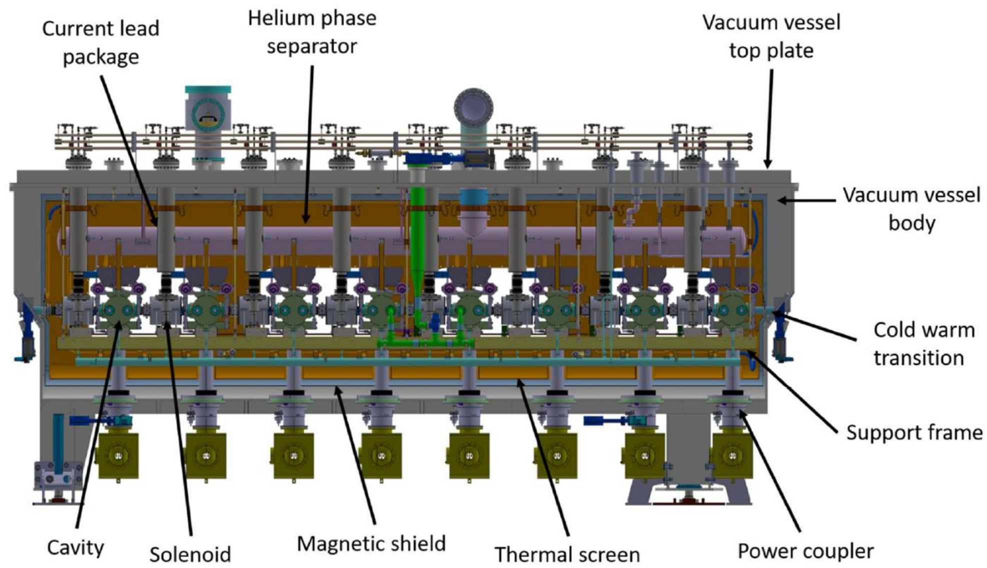


IFMIF-DONES: SRF LINAc

- **Five Cryomodules** top-loaded → integration in the vault
- Two types of HWR's cavities: 19 x low-β and 27 x high- β
- <200 kW RF couplers. Biased T-box design
- **29 x solenoids packages** (with steerers, BPM's & BLM's)
- **4 x Short Warm Sections**
- **Valve boxes** in a parallel room to ease maintenance
- Complete study of **cryogenic hazards**

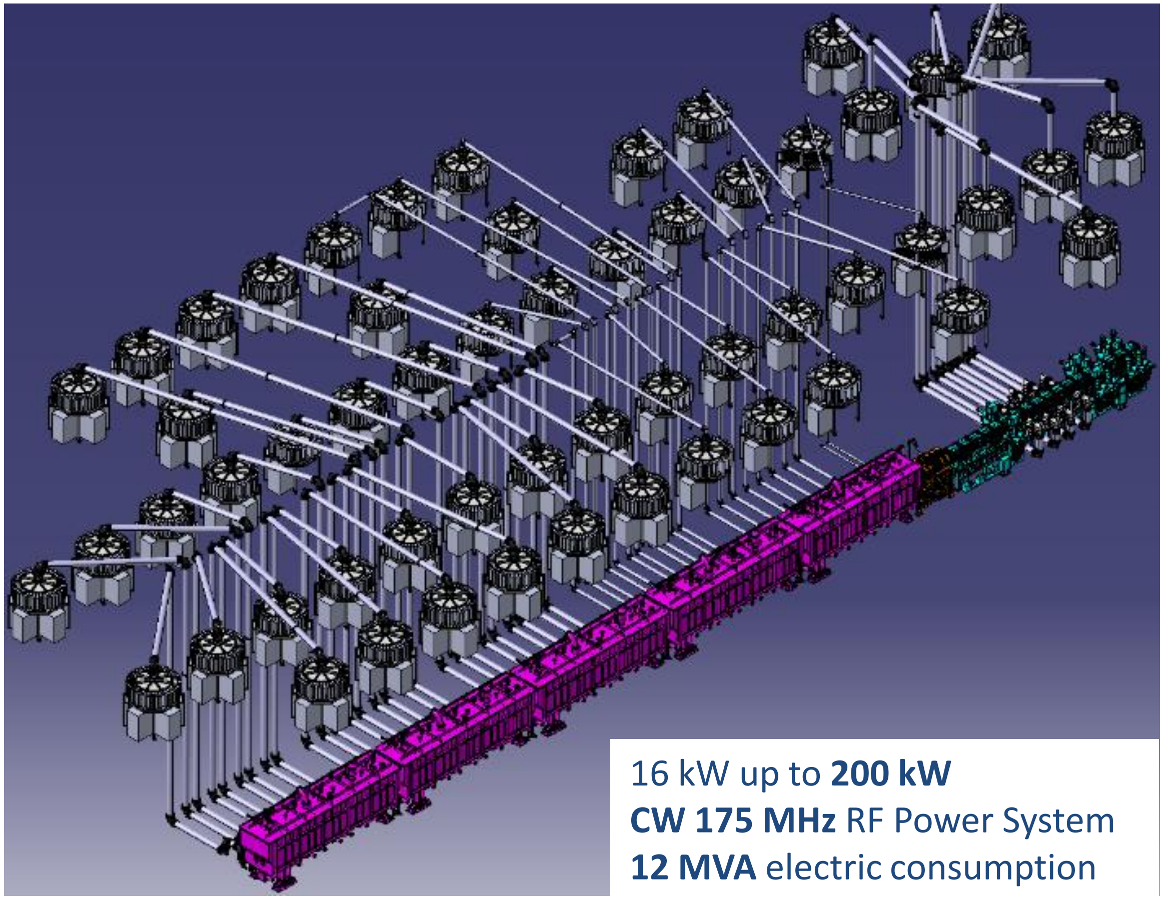






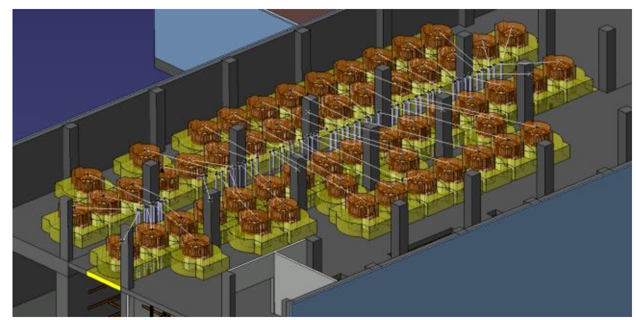
RF Power System

56 RF Stations to supply the RFQ (8), MEBT (2) & SRF (8;11;9;9;9) cavities including the respective coaxial lines



16 kW up to **200 kW**
CW 175 MHz RF Power System
12 MVA electric consumption

- Based on **SSPA** (LIPAc Tetrode Based) to improve the reliability and maintainability
- The design of the RF System well advanced by improving the **efficiency** (>60%) and architecture with respect to the LIPAc one
- Requirements for a powerful **LLRF** based on LIPAc experience
- Challenging design of the **coaxial lines**
- Assessment of **circulator** requirements and **transistors** technologies

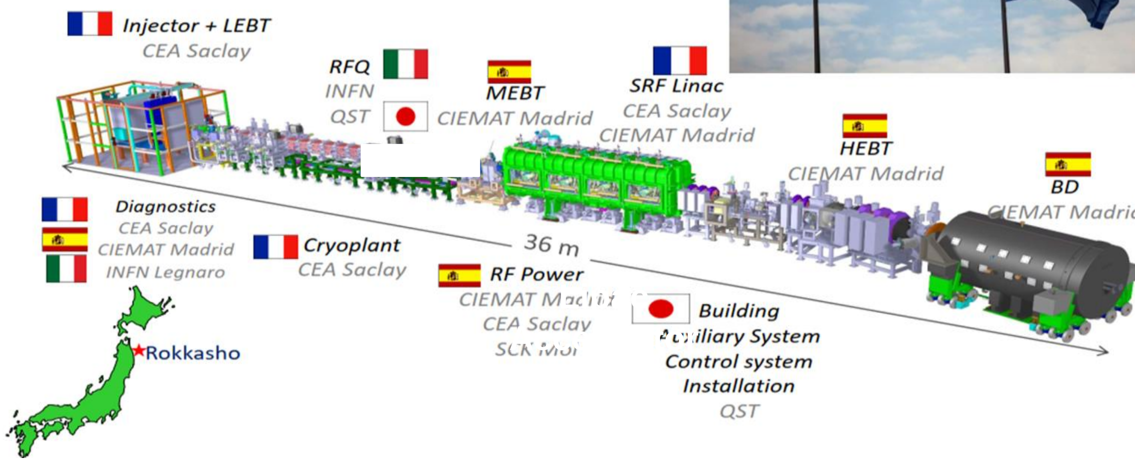


Prototype of DONES linac

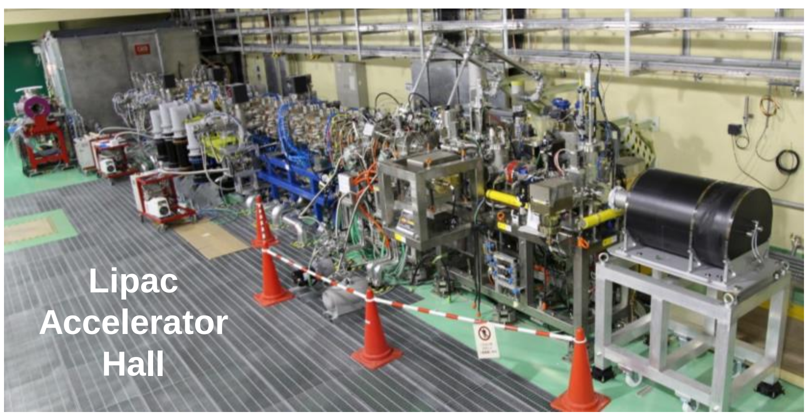
IFMIF EVEDA RFQ

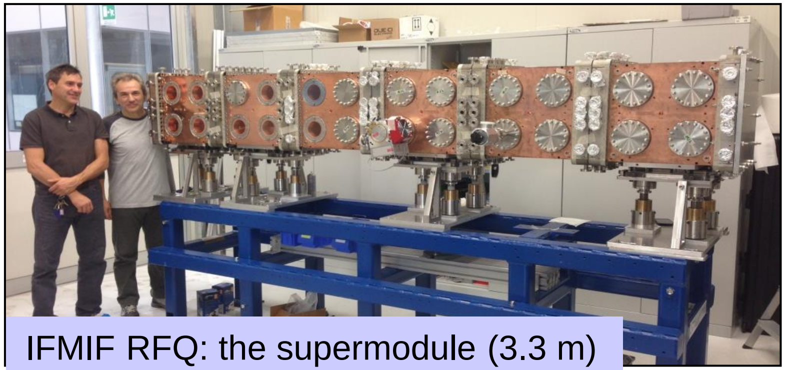
International fusion material irradiation facility, engineering validation and engineering design activity

LIPAc (9 MeV 125 mA)



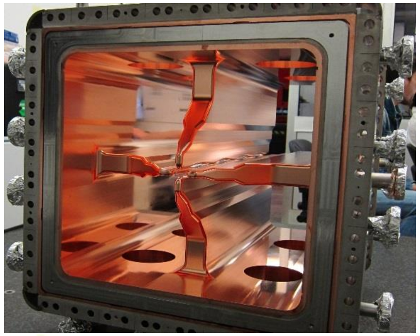
In-kind contribution through INFN 24 M€

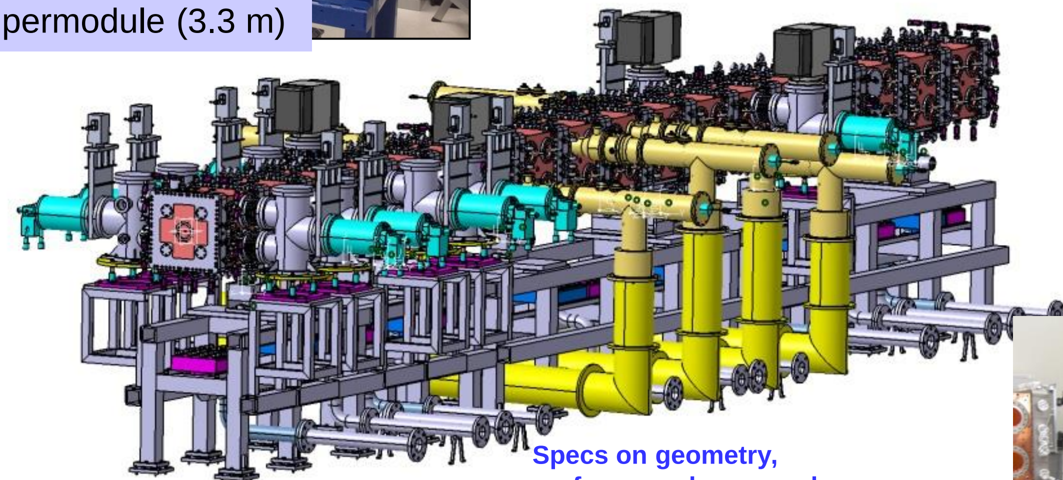




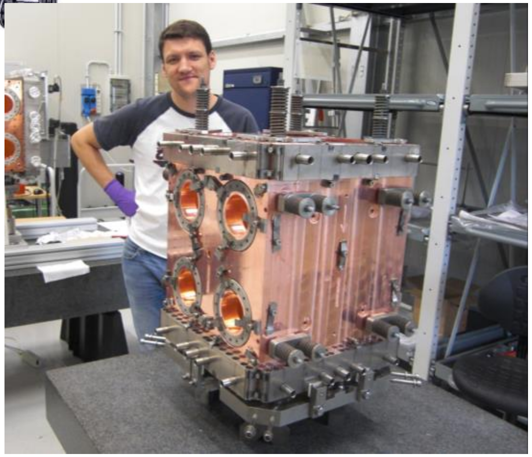
IFMIF RFQ: the supermodule (3.3 m)

RFQ construction





Specs on geometry, surface roughness and quality, vacuum tightness….
Field and beam performances under INFN responsibility



INFN development for Brazing

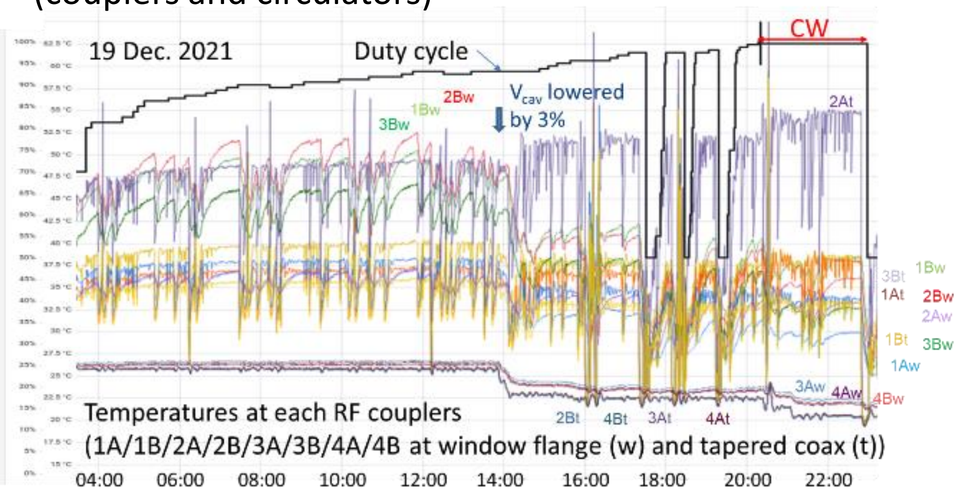
18 modules in three supemodules

- High energy SM built by Cinel, Padua (Italy),
- Intermediate energy built internally by INFN,
- Low energy attributed to RI Koln (Germany), concluded by INFN

LIPAc (the prototype accelerator in Japan)

Hardware commissioning

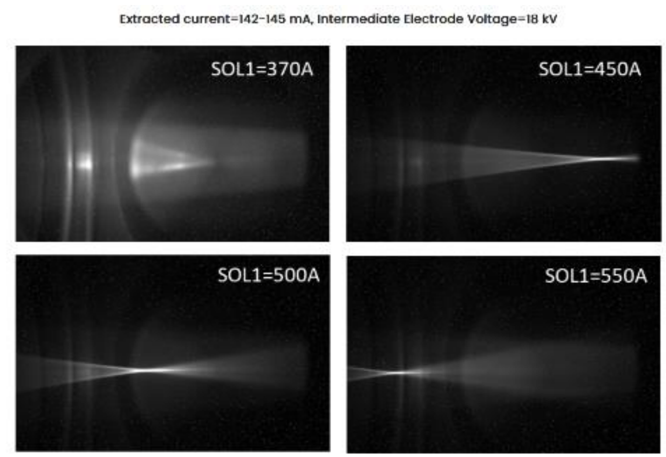
- **RFQ beam performances full current pulsed mode reached**
- **RFQ conditioning** reached 105 kV CW tested (80% nominal)
- **RFQ water frequency tuning loop** tested
- To restart later soon after solving issues with **RFPS/RFQ** (couplers and circulators)



INFN has realized the full performance protype, and temporary couplers (funded by F4E) used until now, brazed final couplers were in charge to QST (Japan).

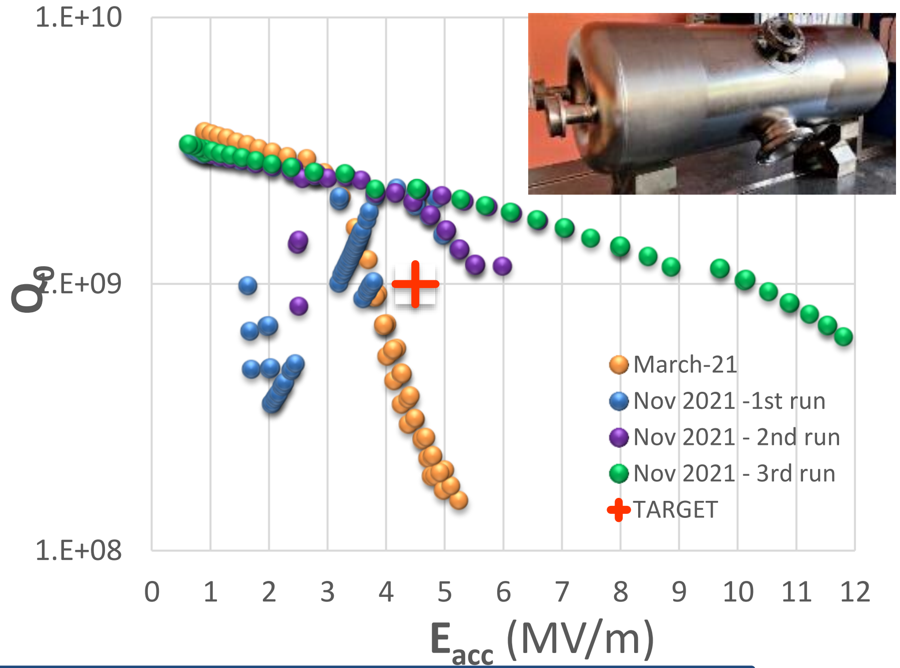
Beam commissioning

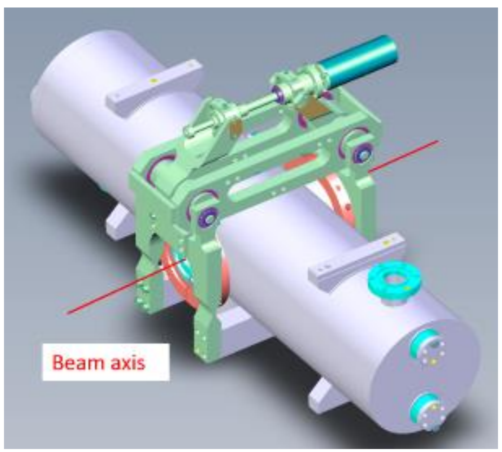
- **Deuteron 125 mA** / 0.1% achieved during Phase B (5 MeV)
- Long and comprehensive **Injector CW campaign**:
  - **140 mA CW** achieved stably for several hours (~12 h) with 11 mm electrode. Up to 155 mA achieved with 12 mm electrode. Campaigns ongoing to check the best electrode for CW operation.
  - Damage of BN disk (~3 months) and insulators under analysis, as well as current jitter and emittance degradation along the run.
- **Phase B+** (Injector+RFQ+MEBT+HEBT+HPBD) to restart soon



Superconducting HWR's

- High Beta naked cavity designed, manufactured and tested with margins related to the specification
- Design of the Tuning system adapted from LIPAc and SARAF
- Complete Cavity under design and manufacturing





Tuning force along the beam axis (LIPAC/IFMIF - DONES)

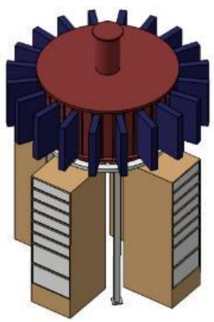
- Assembly of the LIPAc SRF LINAC ongoing
  → essential input to be integrated in the final design

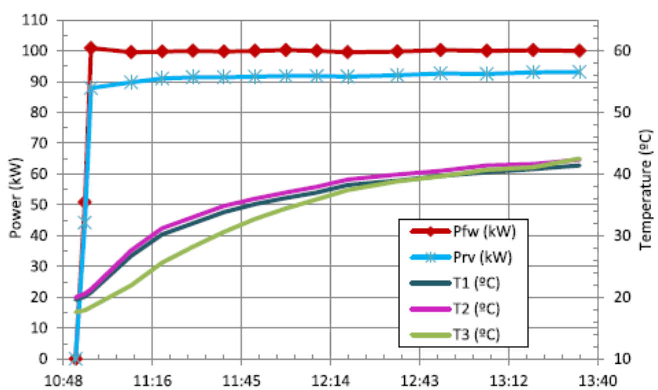
- The commissioning is expected to start in 2024
  → Validation of the low-beta cavity and its tuning system,
  → Validation of the cryomodule integration.

200 kW CW 175 MHz SSPA RF stations

Two prototype alternatives under manufacturing and testing

1) Based on **Single cavity combiner**
   - **160-cavity combiner** tested up to **100 kW CW**
   - Amplifier modules under manufacturing

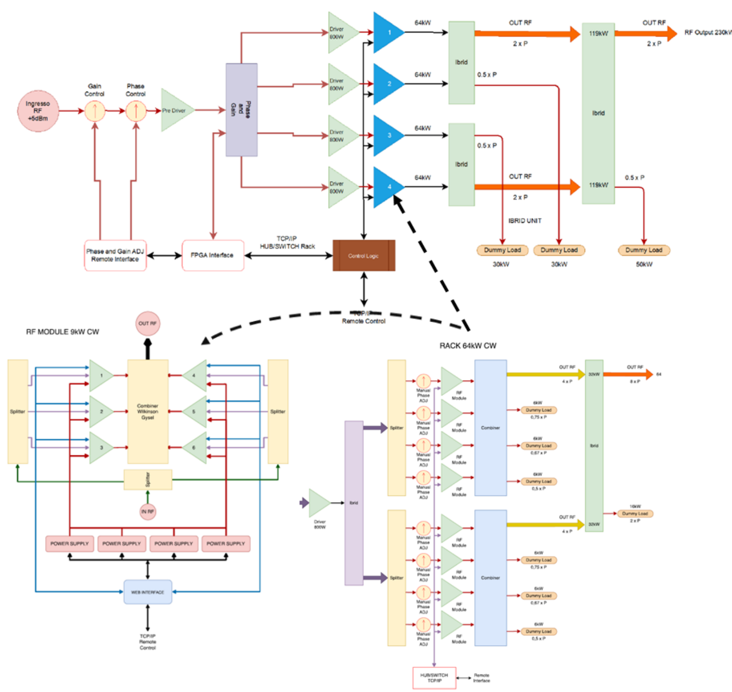




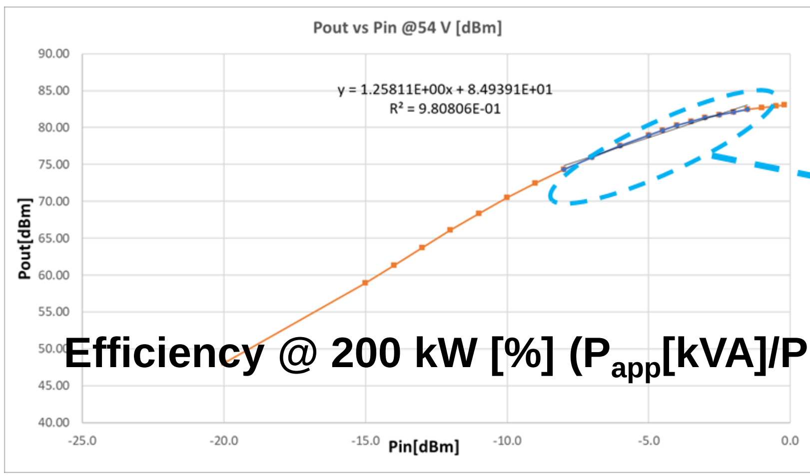
2) Based on **Progressive and hybrid combiners**
   - **RF Station** tested successfully up to **200 kW full duty cycle**
   - **Total efficiency exceeded 60%**

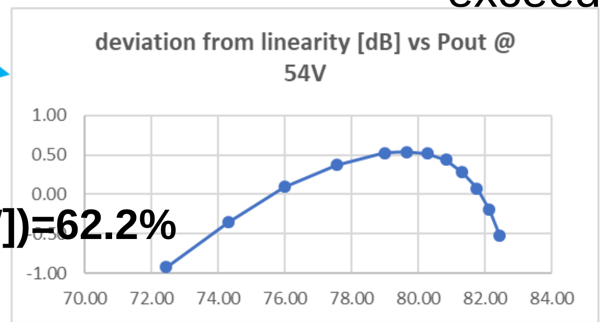
+ Feedback from **LIPAc** 16 kW SSPA stations and **enhancement** of LIPAc RFQ stations (based on the feedback of IFMIF-DONES prototypes)

The INFN solid state (200kW, 60% power efficiency)



as presented by A. Palmieri at the WPENS technical meeting **13/12/2023** the INFN prototype for the solid state amplifier, so called alternative 2, produced by the Italian companies DB and associated, has reached the nominal performances; in particular for a long run test has kept for various days the 200 kW power level and shown a power conversion efficiency exceeding 60%.





Efficiency @ 200 kW [%] (P_{app}[kVA]/P_{RF} [kW])=62.2%

The DONES Programme

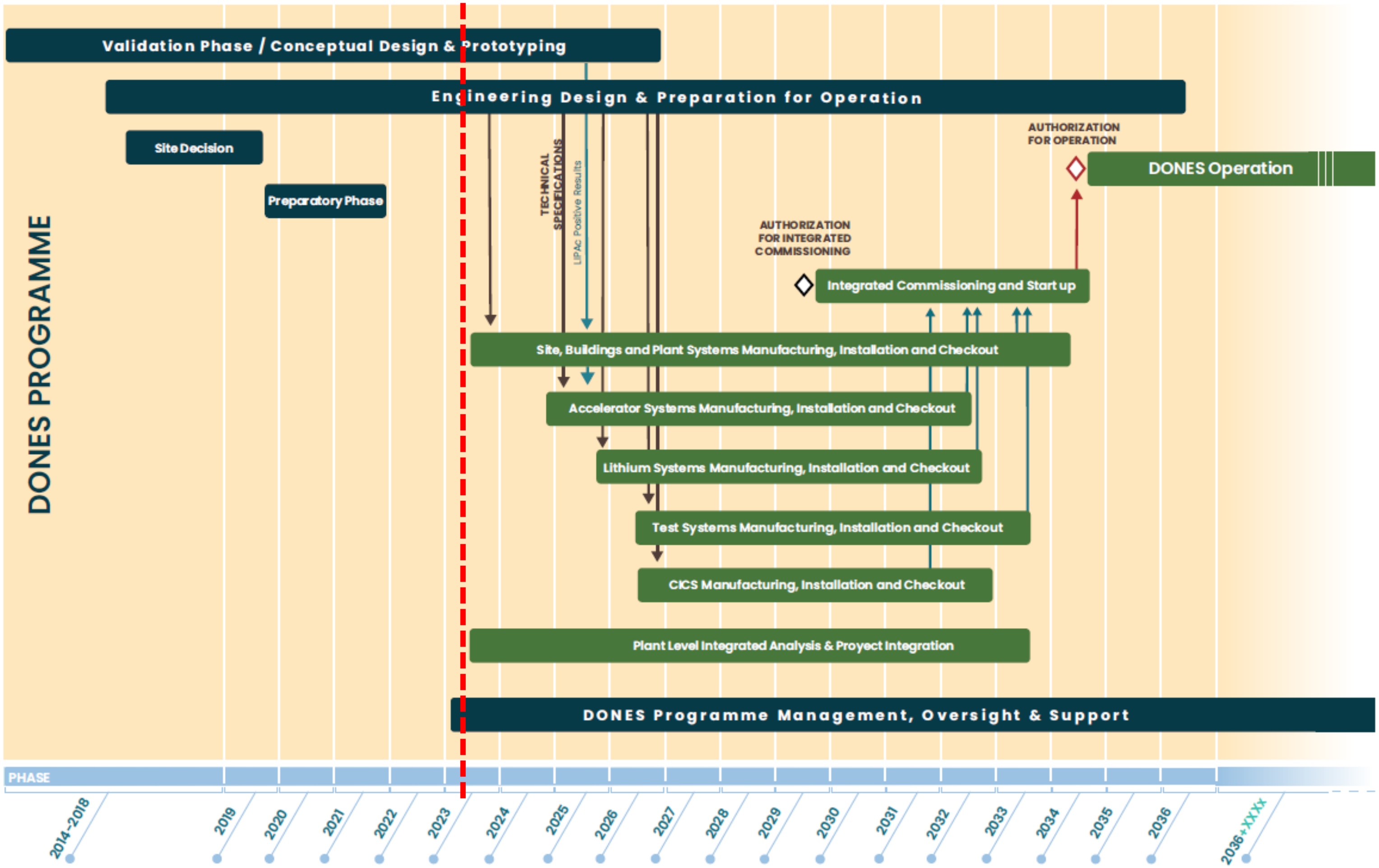
1st **DONES Steering Committee** held the 16th March 2023

Official start of the
DONES Construction Phase

Next steps:

- Project construction phase ramp-up
- Consolidation of current baseline
- Handover of the design from other projects
- Start procurements
- Widen the Users Community to non-fusion apps

The DONES Programme



Construction of First Auxiliary Buildings

Conclusions (DONES point of view)

The **DONES Programme** has entered into its **Construction Phase**

The work carried out during these last years within the framework of the **EUROFUSION WPENS** Project has consolidated the design of the **IFMIF-DONES Facility** and its accelerator, started with the design of IFMIF from 2007 within the Broader Approach activities

Although some engineering validation activities are still ongoing **no showstoppers have been identified**

The strategy implemented to find synergy with **similar facilities** (e.g. ESS, CERN, MYRRHA, SPIRAL2,…) in addition to **LIPAc** is an important asset to minimize/mitigate the risk and will be pursued,

Strengthening the collaboration with the whole accelerator scientific and industrial community is key for the success of IFMIF-DONES and the next generation high current linear accelerators

Updated Cost Estimate (May 2021)

Last update (2021) based on industrial quotations for conventional systems and BA expertise for high-technology ones

WBS N°	Task Name	*Low Value (M€)	Base Value (M€)	*High Value (M€)
5.0.0.0.0.	Task Name. DONES Construction, Installation, Test and Systems Commissioning	526,77	643,03	819,85
5.1.0.0.0	Design integration	2,99	3,33	3,82
5.2.0.0.0	Plant Level Integrated analysis	7,61	8,45	9,72
5.3.0.0.0	Site, Buildings and Plant Systems manufacturing, installation and checkout	282,94	332,87	416,08
5.4.0.0.0	Test Systems Manufacturing, Installation & Check out	21,80	29,07	39,25
5.5.0.0.0	Lithium Systems Manufacturing, Installation & Check out	27,69	36,92	49,85
5.6.0.0.0	Accelerator Systems Manufacturing, Installation & Check out	113,72	151,62	204,69
5.7.0.0.0	Project Management	56,68	62,98	72,42
5.8.0.0.0	Central Instrumentation and Control Systems Manufacturing, Installation & Check out	13,34	17,79	24,02
6.0.0.0.0	DONES Integrated Commissioning and Start-up	34,74	40,87	51,09
7.0.0.0.0	DONES Operation	960,84	1130,4	1.413
8.0.0.0.0	DONES Decommissioning	158,33	211,11	285,00

(*) Class 3-4 according to AACE Cost Estimate Classification System

Italian participation in DONES accelerator (discussion in progress)

- In the next phase of DONES, the INFN could provide, in addition to the **RFQ**, the entire **injector** (ECR source, LEBT line, chopping system) having all the necessary skills and excellent contacts with highly qualified Italian industries.
- Integrating the **RF system** and **injector** under the INFN responsibility would simplify the management of two interfaces between different components that have proved to be very complex in the LIPAc experience.
- Moreover we can participate to the realization of the **SRF linac**, INFN and Italian industry. For example one cavity family

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Survey on possible contributions to the DONES Program

Fields marked with * are mandatory.

Answers to the survey should be given by Country Representatives involved in the DONES Working Group. Answers should by no means be seen as commitments from the represented countries, but rather as informative indications. The main objective is to develop an informed overall view on the possible future contributors to the DONES Program.