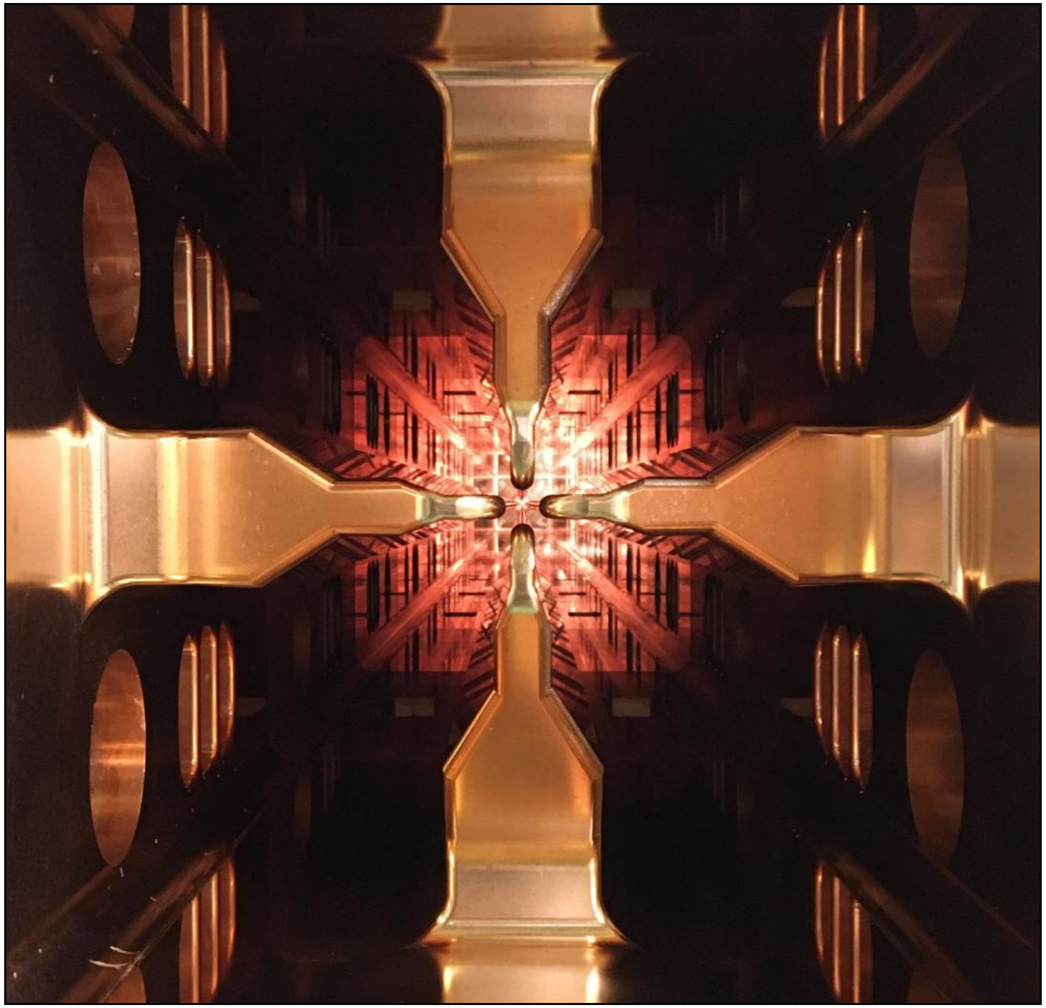


From IFMIF to DONES: European SRF high intensity Linac for fusion material test

Andrea Pisent and Francesco Grespan
INFN

3-4 April 2025 Quarta Giornata Acceleratori-Legnaro (PD)

IFMIF=>DONES

(International Fusion Material Irradiation Facility, Demo oriented Neutron source)

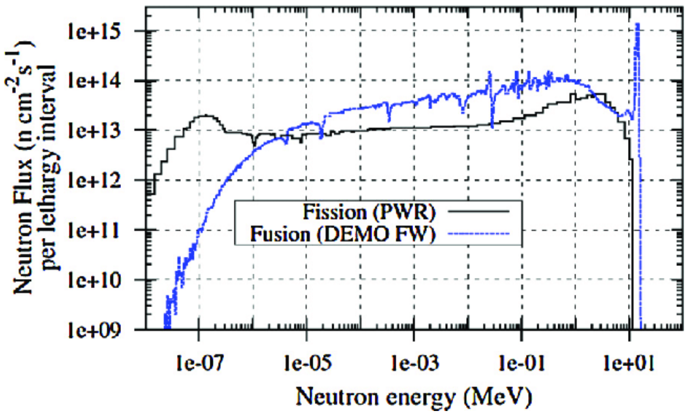
- Motivation
- R&D results (**Broader Approach program**), participation of **INFN** (ENEA and Italian industries, starting from the three sponsor of this ws [*]).
- Construction of a material test facililty in Europe (**DONES**, close to Granada) and INFN in-kind contribution to the accelerator.

INFN 2014 departure of the RFQ to Japan

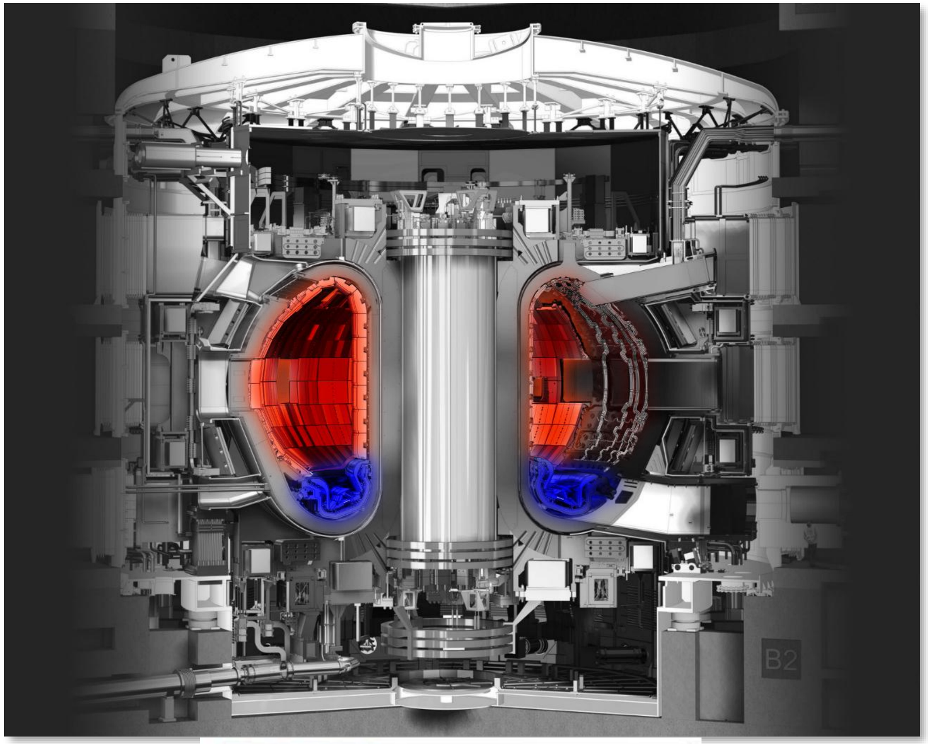
[*] CINEL, dB Science Solutions, Zanon

IFMIF motivation

- In DEMO (and in a tokamak for energy production) internal structures (specially the “first wall”) withstand a high flux of high energy neutrons.



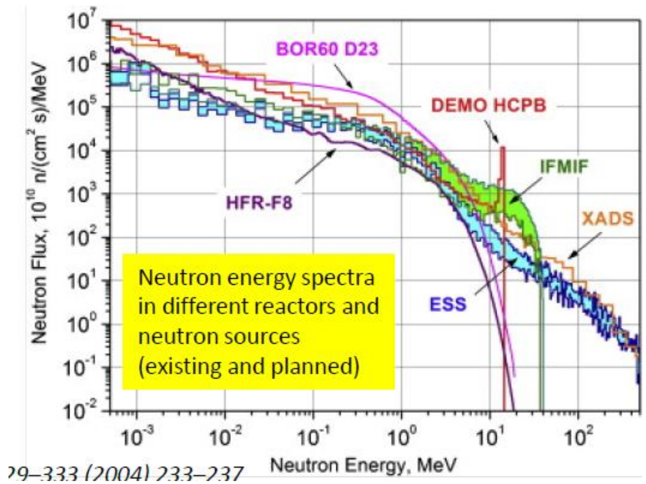
- Deep knowledge of materials in these conditions is needed for design and operation plans.
- **For example the formation of H/He in bulk material with reactions like $^{56}Fe(n,\alpha)^{53}Cr$ with threshold 3.7 MeV**
- Mechanical proprieties like Embrittlement and increase of Ductile-brittle transition temperature, swelling, welding degradation, should be studied at high n flux and different temperatures

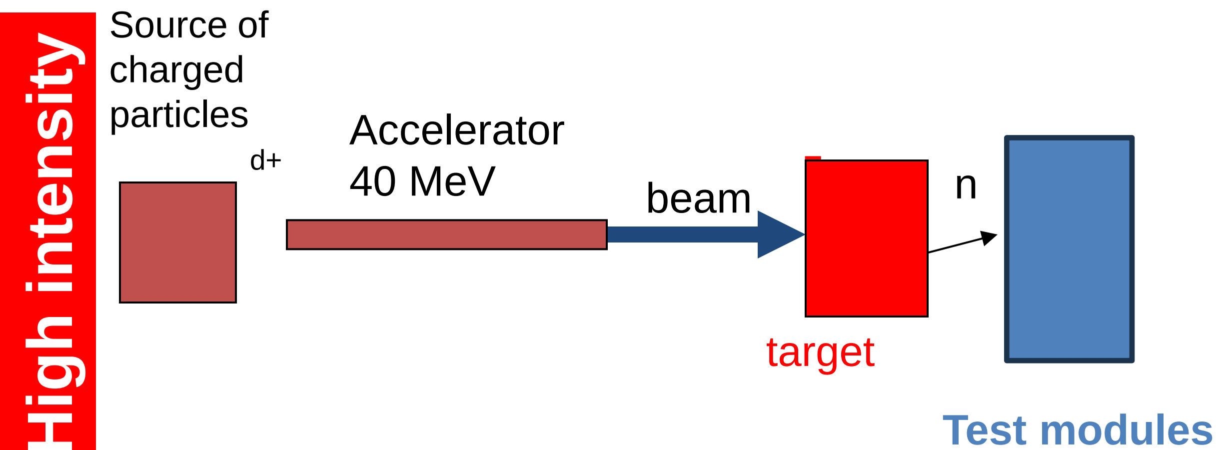


Macroscopic tests, not cross sections

Neutron sources

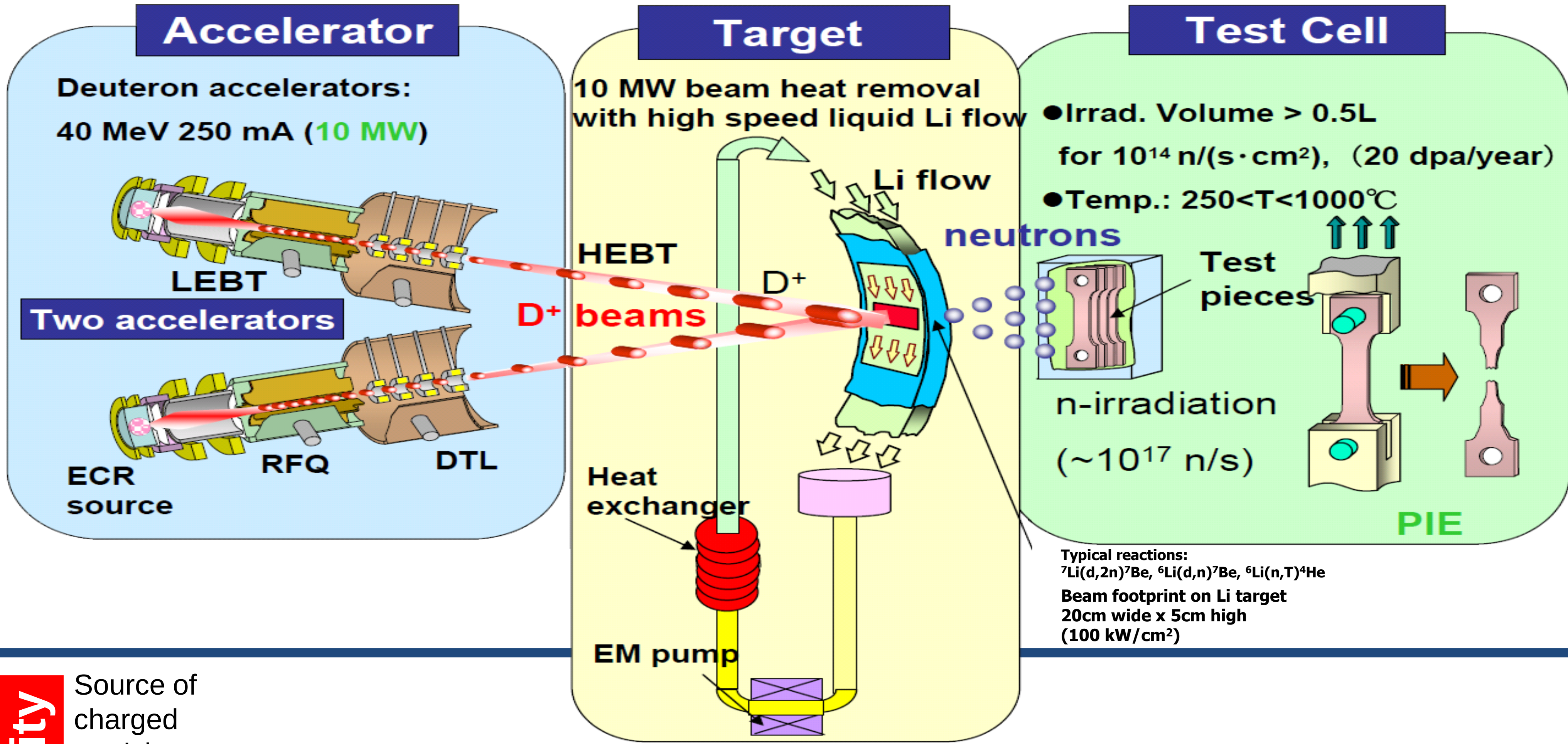
- Fission reaction spectrum is unsuited, the best simulation of fusion spectrum is given by stripping reaction of deuterons (approx. 40 MeV) on lithium.

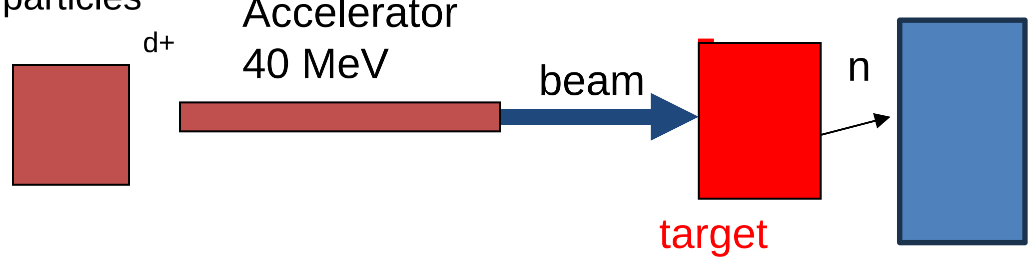


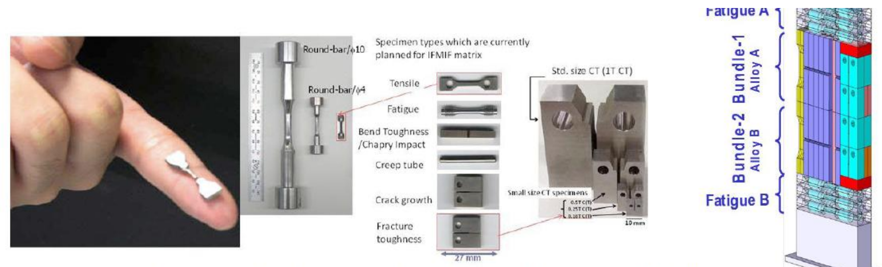


- High power linac (MW)
- **High power target (liquid)**
- **Long exposition time (months)**

High intensity

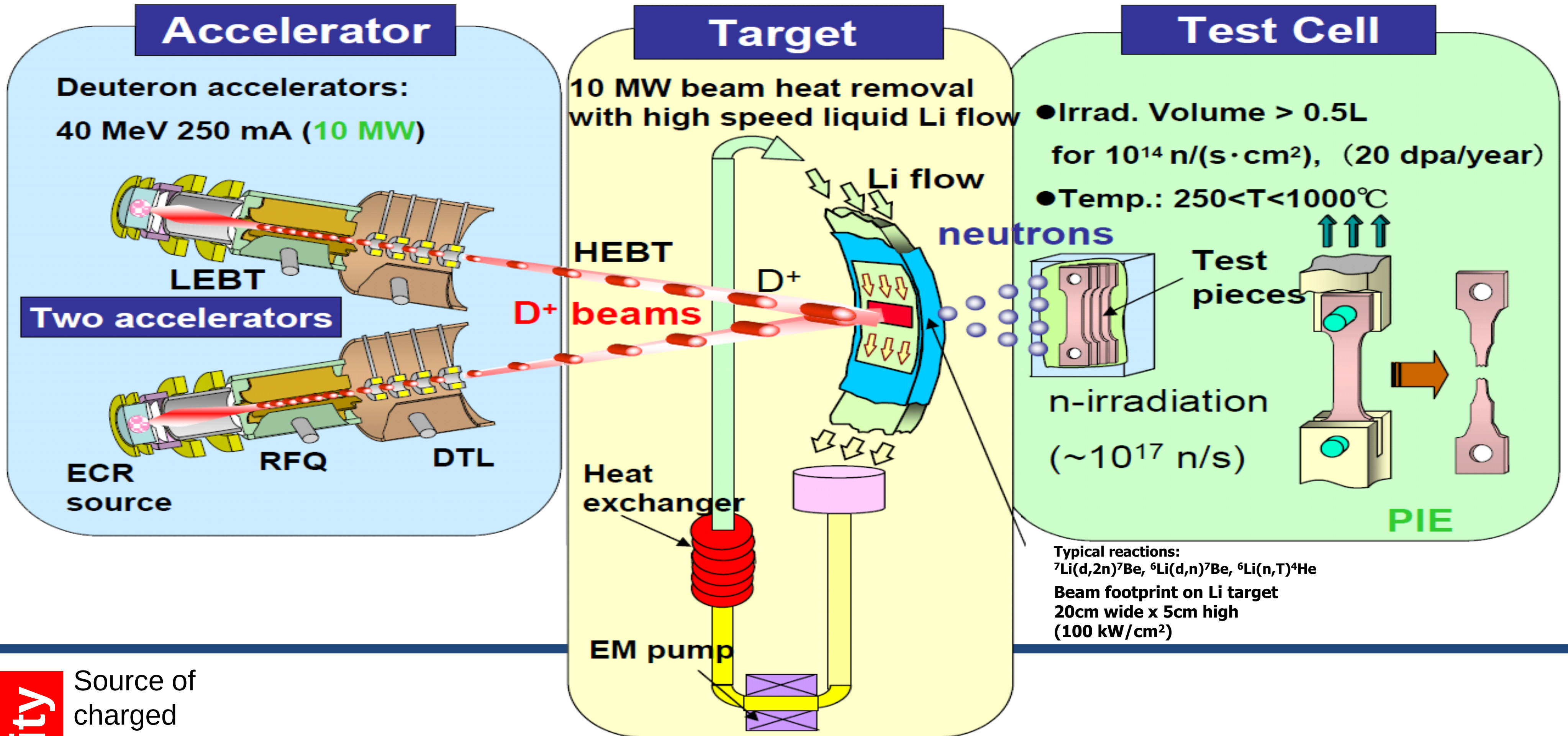




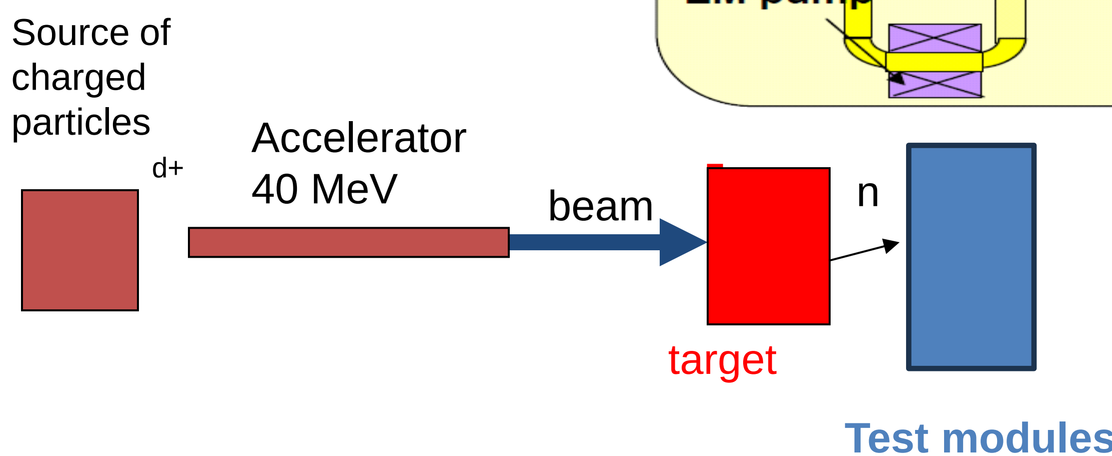


Samples and irradiation modules developed for the IFMIF facility

Test modules

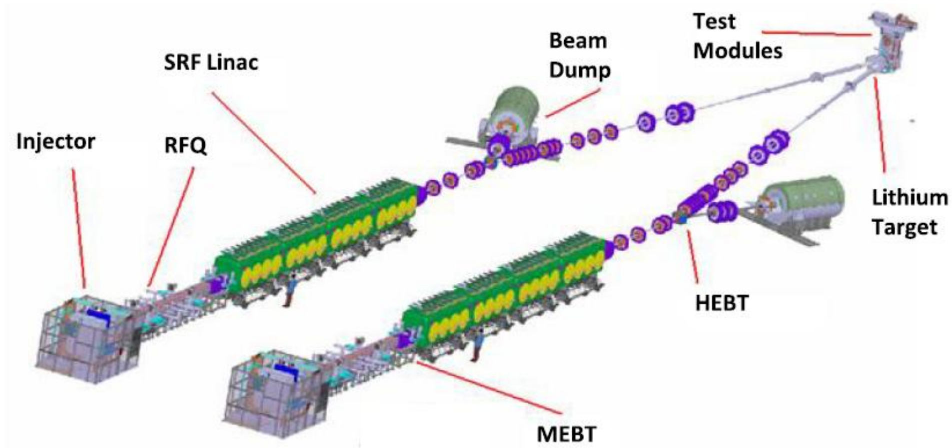


High intensity

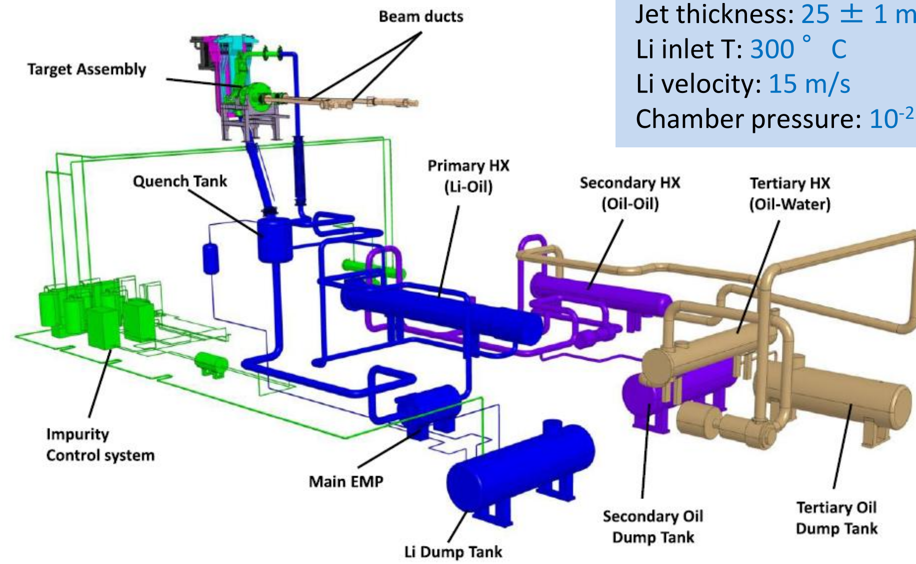


Third DONES Users Workshop, 1-2. Oct. 2024 Zagreb

Plans for H24 use of this half liter for 20 yrs (after 10 yrs construction)

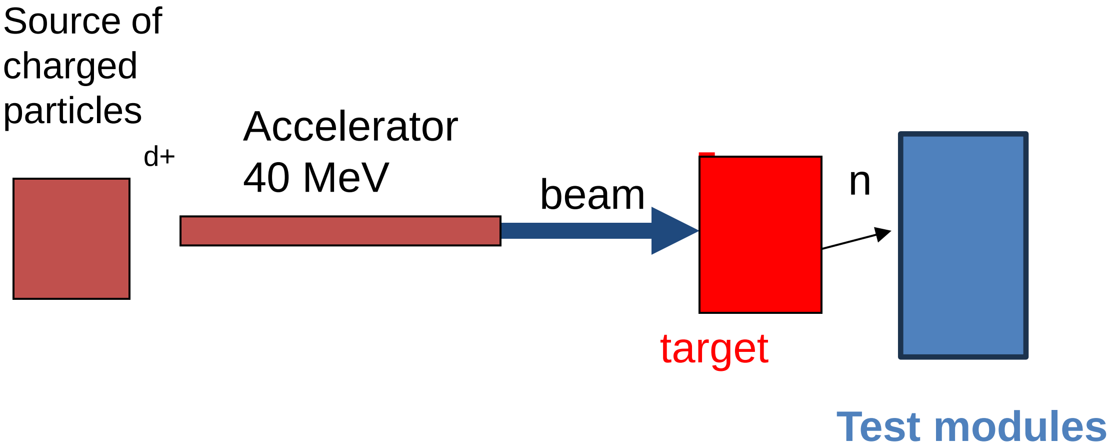


IFMIF concept



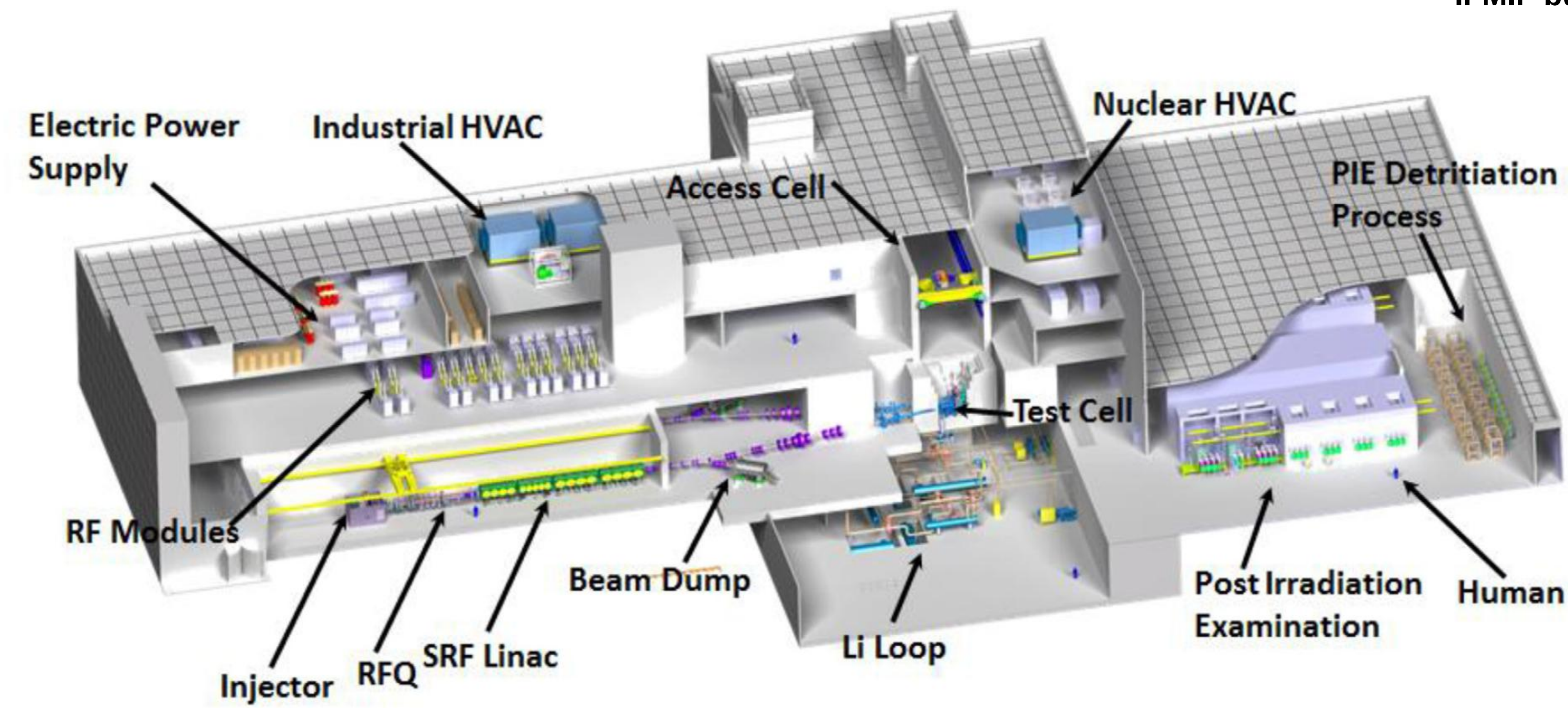
Heat flux: 500 MW/m^2
Jet thickness: 25 ± 1 mm
Li inlet T: 300 ° C
Li velocity: 15 m/s
Chamber pressure: 10^{-2} Pa

High intensity

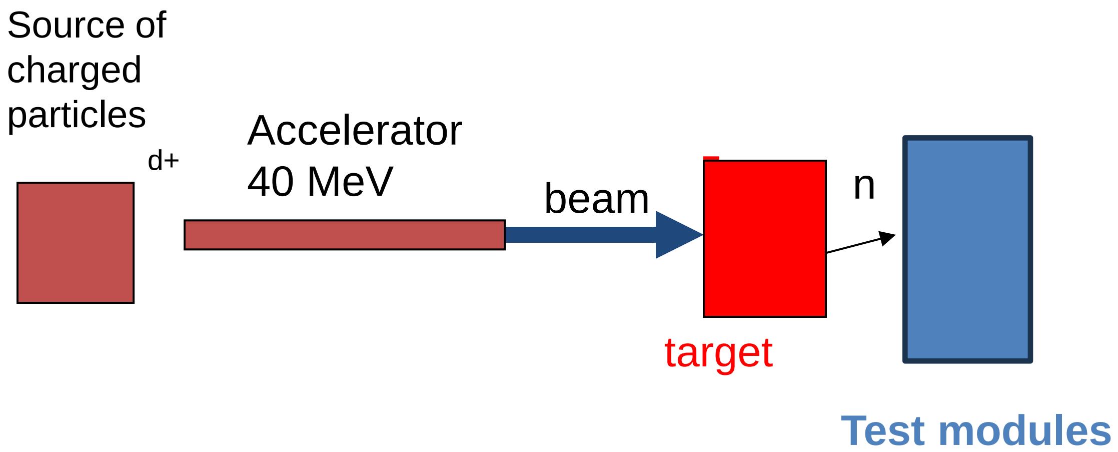


- High power linac (MW)
- **High power target (liquid)**
- **Long exposition time (months)**

IFMIF building idea



High intensity



- High power linac (MW)
- **High power target (liquid)**
- **Long exposition time (months)**

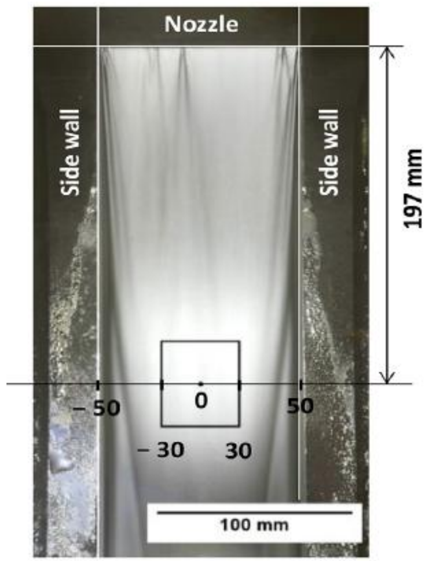
IFMIF EVEDA

(IFMIF Engineering Validation and Design Activities)

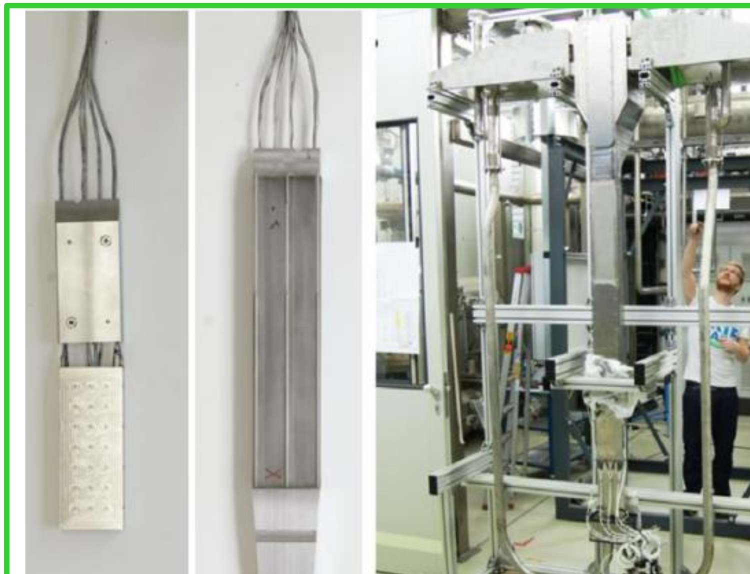
IFMIF-EVEDA project (approved in **2007**, Broader Approach) complementary to ITER includes prototypes of

- **Lithium Loop** prototype
- **Test Facility**,
- **accelerator** (LIPAC) 1.2 MW beam power

And the detailed design of IFMIF. LIPAC is built in Rokkasho (Japan) with European accelerator component and fundamental INFN contribution.



JAEA Oaray, Japan



KIT Karlsruhe, Germany

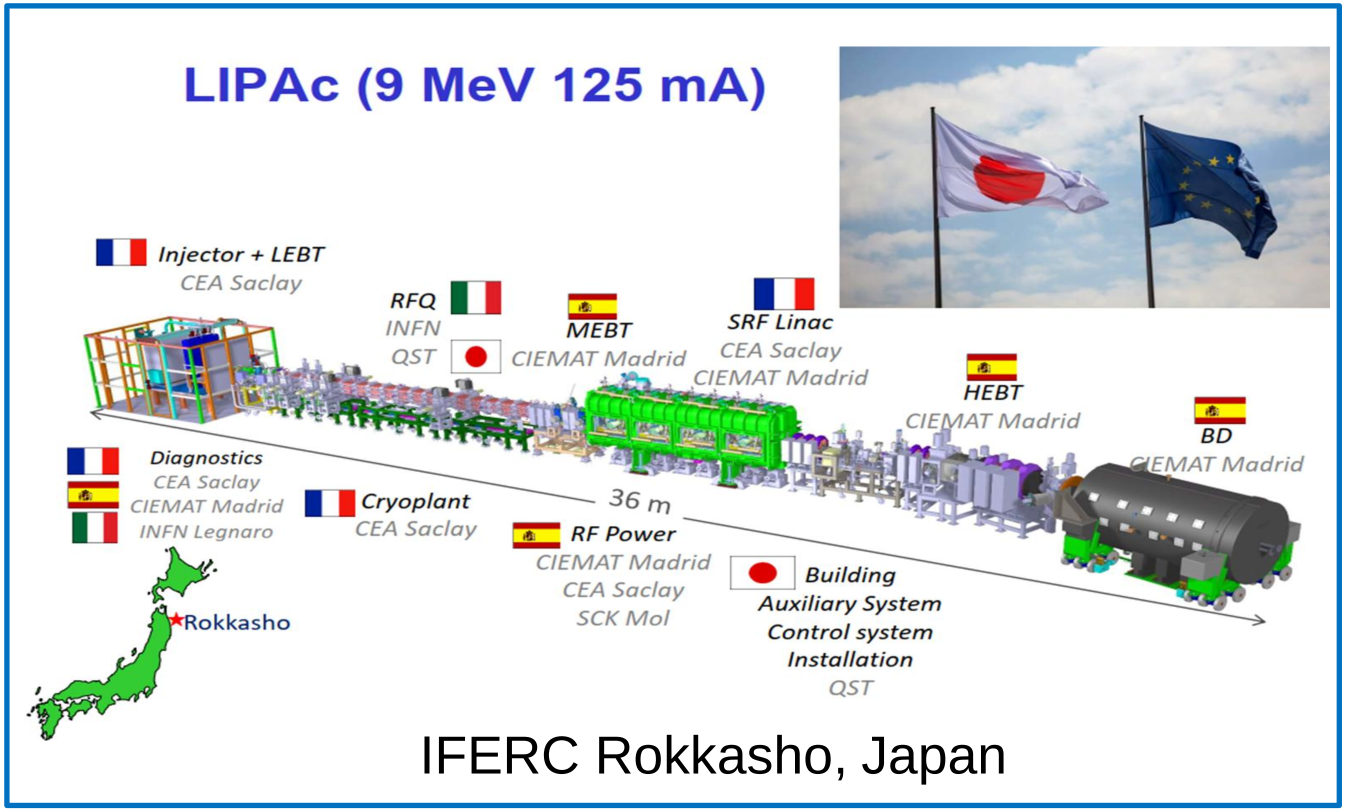
IFMIF EVEDA
(IFMIF Engineering Validation and Design Activities)

IFMIF-EVEDA project (approved in **2007**, Broader Approach) complementary to ITER includes prototypes of

- **Lithium Loop** prototype
- **Test Facility**,
- **accelerator** (LIPAC) 1.2 MW beam power

And the detailed design of IFMIF. LIPAC is built in Rokkasho (Japan) with European accelerator component and fundamental INFN contribution.

- The normal conducting part has been built and commissioned up to 5 MeV full current 9% duty cycle.
- The cryomodule is has been transported into the accelerator voult in March ’25.



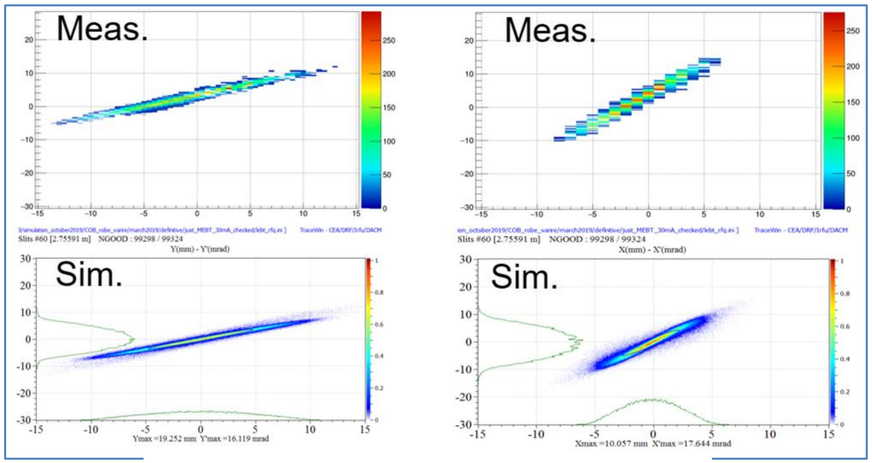
Results with the linac prototype in Japan

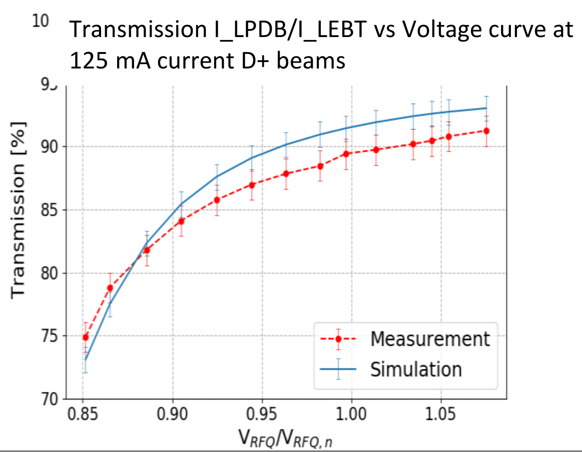
- INFN, with LNL, Bologna, Padova and Torino has realized the RFQ of LIPAc, (125 mA deuterons,100% duty cycle), the most powerful ever.

Full current pulsed beam test

-

For the nominal D+ beam currents, the un-chopped IS pulse length (1.3 ms/1 Hz) overcomes the power limitation of the D-Plate slits, used for the transverse emittance measurements after the RFQ (limit=100 µs/1 Hz at 125 mA)

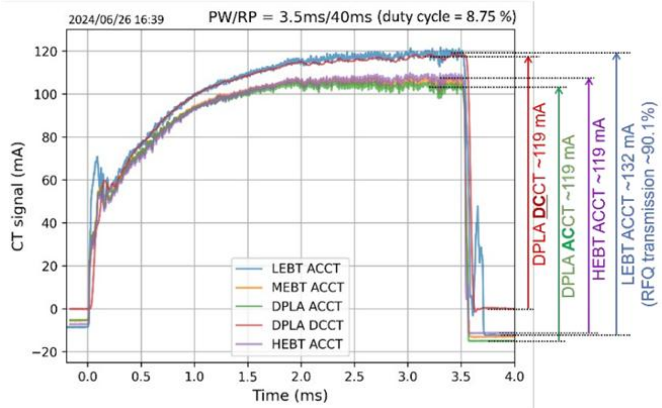




Results with the linac prototype in Japan

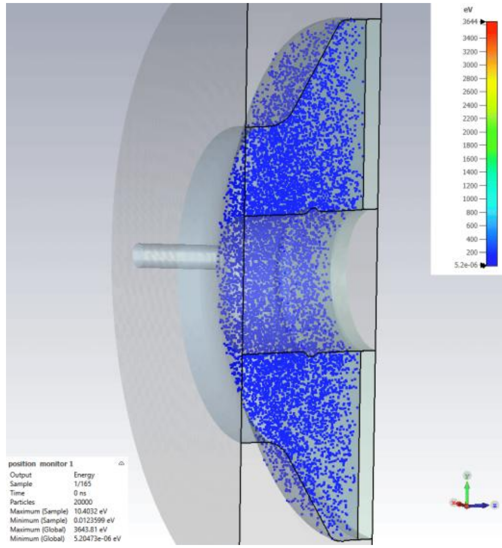
- INFN, with LNL, Bologna, Padova and Torino has realized the RFQ of LIPAc, (125 mA deuterons,100% duty cycle), the most powerful ever.

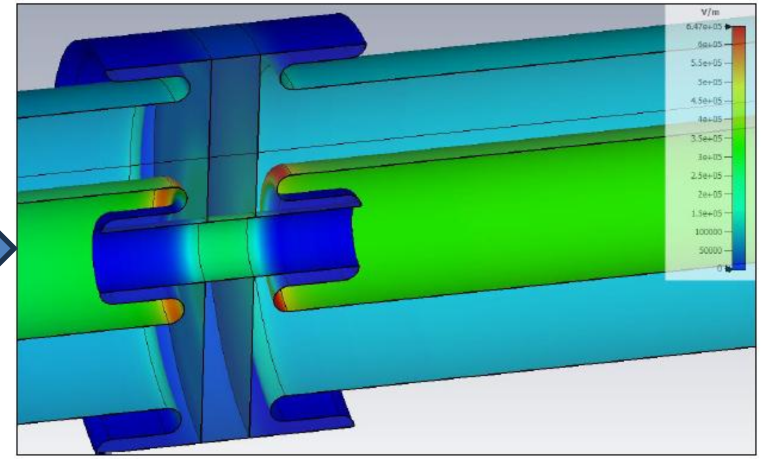
- **Phase B+** (5 MeV Injector+RFQ+MEBT+HEBT+HPBD) was concluded in **June 2024**, **with 8.75% beam duty (pulse width 3.5 ms repetition period 40 ms)**
- **The limitation in power is related to the RF distribution (RF power and couplers) and is object of the consolidation programs by F4E (solid state amplifiers and new brazed couplers).**



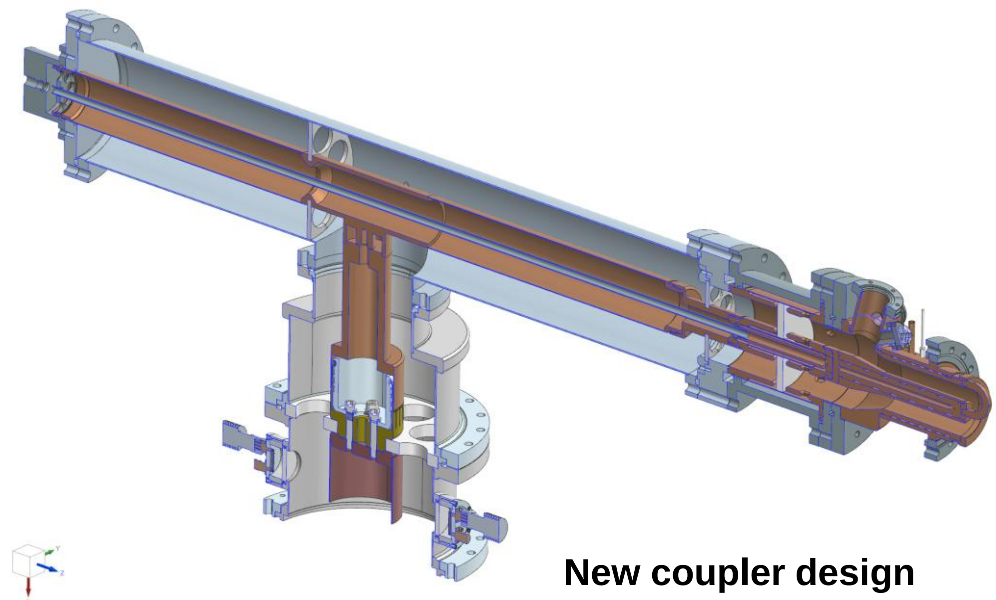
Beam current waveform at duty 8.75%

INFN contract with F4E for new power coupler construction





- New RFQ couplers for LIPAc and DONES (**175 MHz, 200 kW cw**)
- Bulk coupler structure water cooled (like present INFN couplers)
- Brazed alumina window (instead of o-ring), window water cooling.
- Smaller coaxial line in vacuum to avoid multipacting susceptibiity in the operation power range.
- Kick off meeting **June 2024**, final delivery end **2027**



New coupler design

March 2025: The cryomodule was assembled and transported into the accelerator vault

Picture 2-3: Beam line fully assembled

Picture 2-26: Cold mass during lifting test in JR building

Picture 2-25: Beam line out of cleanroom in JR building

9 MeV beam at LIPAc in 2027

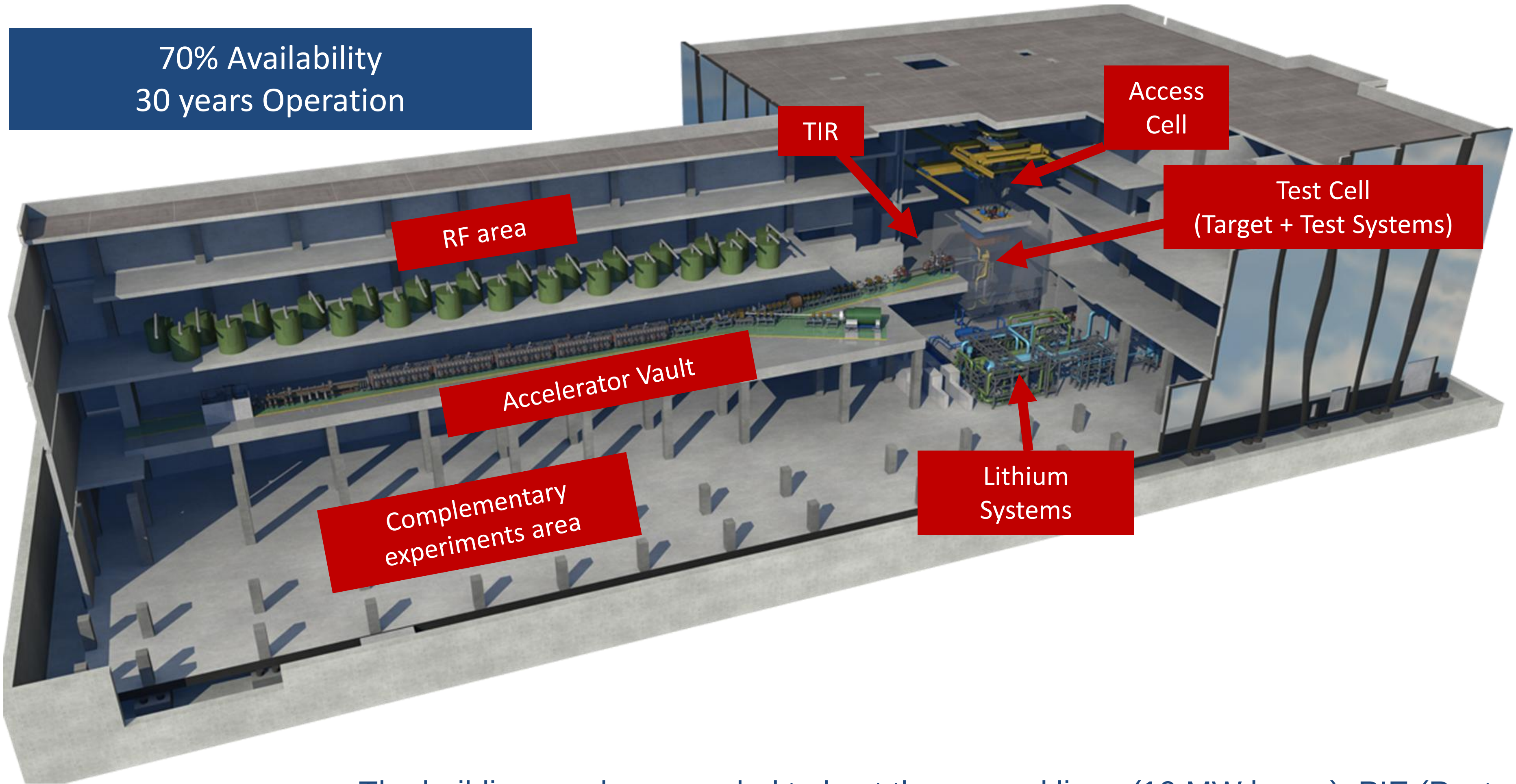
DONES: DEMO oriented Neutron Source

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

Identificata come priorità nella EU Fusion Roadmap
Inclusa nella roadmap di ESFRI* come EU strategic facility
***European Strategy Forum on Research Infrastructures**

IFMIF-DONES Facility

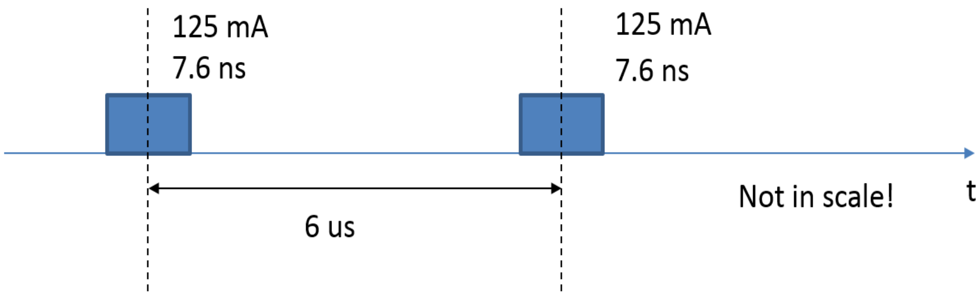
70% Availability
30 years Operation

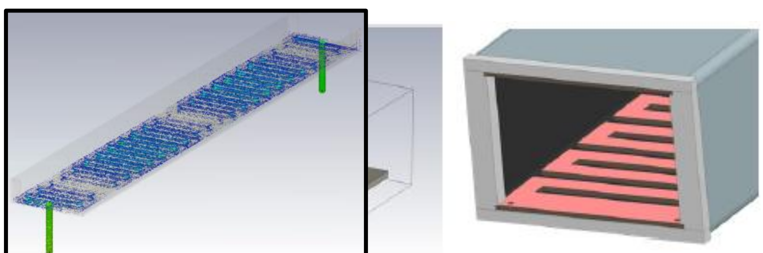


The building can be upgraded to host the second linac (10 MW beam), PIE (Post Irradiation Exams) will mainly take place in the collaborating institutes. Complementary experiments (for example nuclear physics, TOF) are possible in a dedicated vault

Complementary experimental line design

- Meander line choppers are used in other linacs but at such high energy 20 MeV/u (high chopping voltage, 40 kV, and particle speed β=0.2)





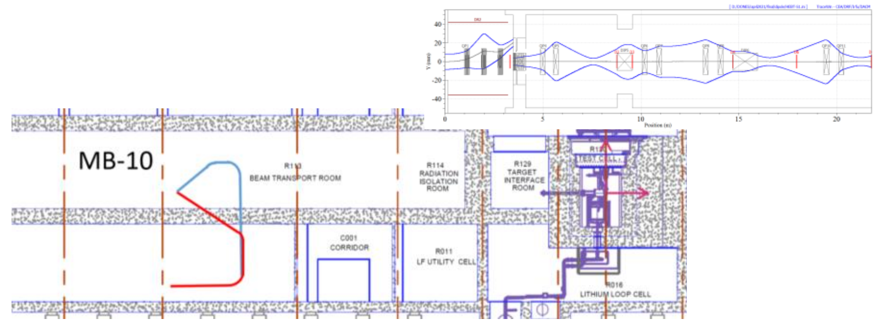
Voltage signal similar to sinusoidal @ 70 HZ

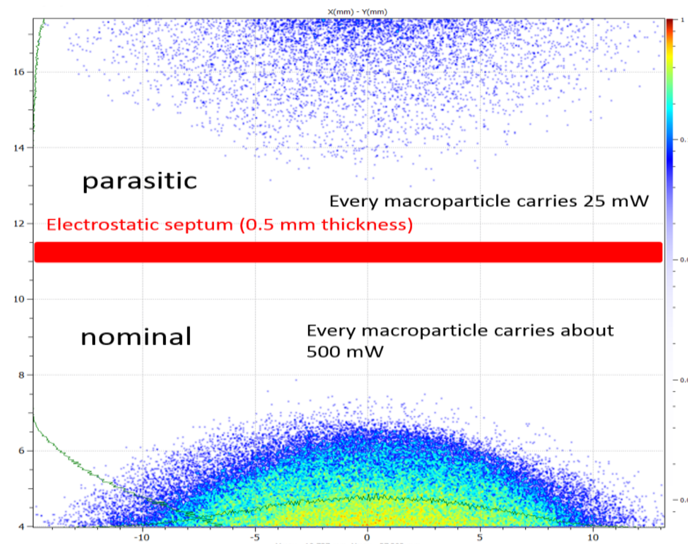
Figure 2: Left: Simplified 3D model of a meander line suspended in vacuum. The main geometrical dimensions are labelled. Right: Meander model inserted in its support.

L. Bellan et al. DONES note, M. D'Andrea et al. Linac 2024

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

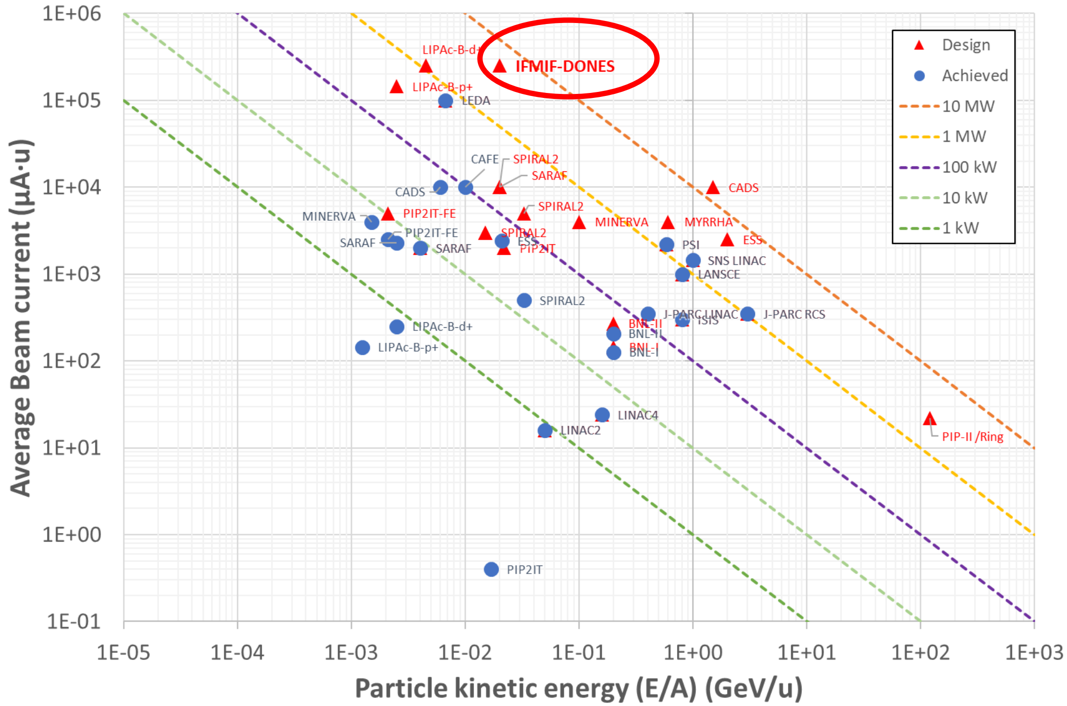
- 1/1000 bunch extracted with a fast meander line chopper for TOF experiments.



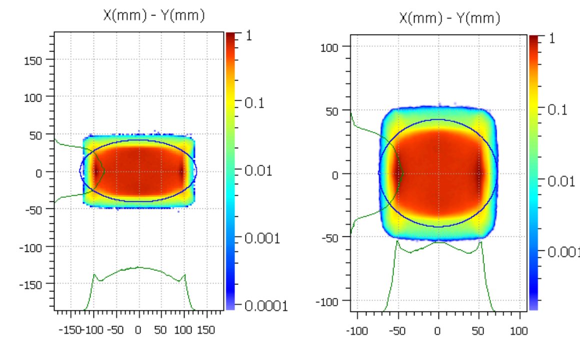


Simulazione della potenza di fascio (principale e parassita) al setto elettrostatico

High power accelerator (5 MW)



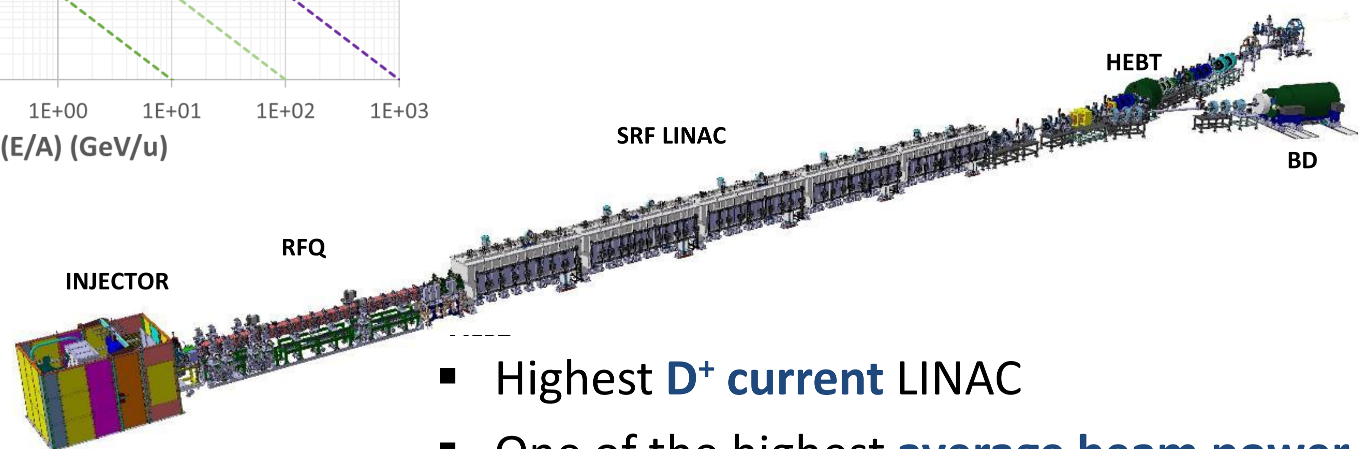
Beam footprint @ target



20x5 cm² footprint (reference)

10x5 cm² footprint (optional)

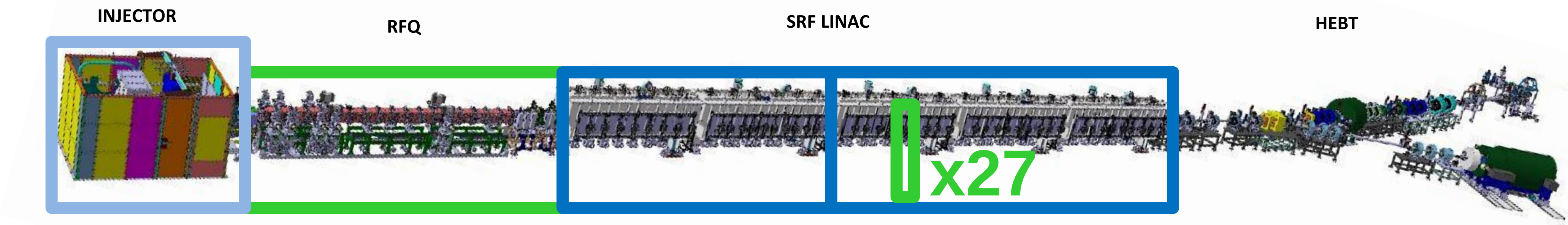
D+ CW 175 MHz SC LINAC
125 mA / 40 MeV → **5 MW**
Total length of ~**100 m**
Windowless liquid **Li target**
20 y, 87% **availability**
Hands-on **maintenance (<1 W/m)**



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

Possible sharing of the accelerator main IKC

The Italian contribution to DONES should be about 8% of DONES cost, approx. 812 M€, i.e. an in-kind contribution of 65M€, 40 M€ ENEA on the target and 25 M€ INFN on the accelerator (this sharing was discussed immediately before Covid, in 2019).

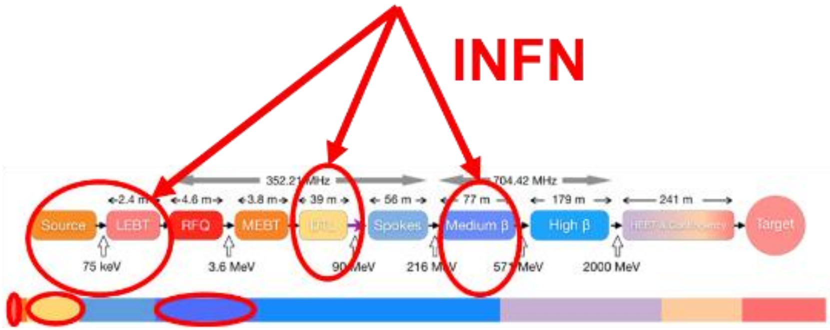


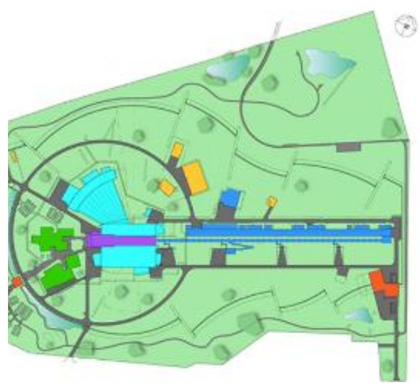
INFN contribution:

- The RFQ
- The 27 HWR superconducting cavities
- A general contribution to computer control, installation, commissioning and management of the accelerator

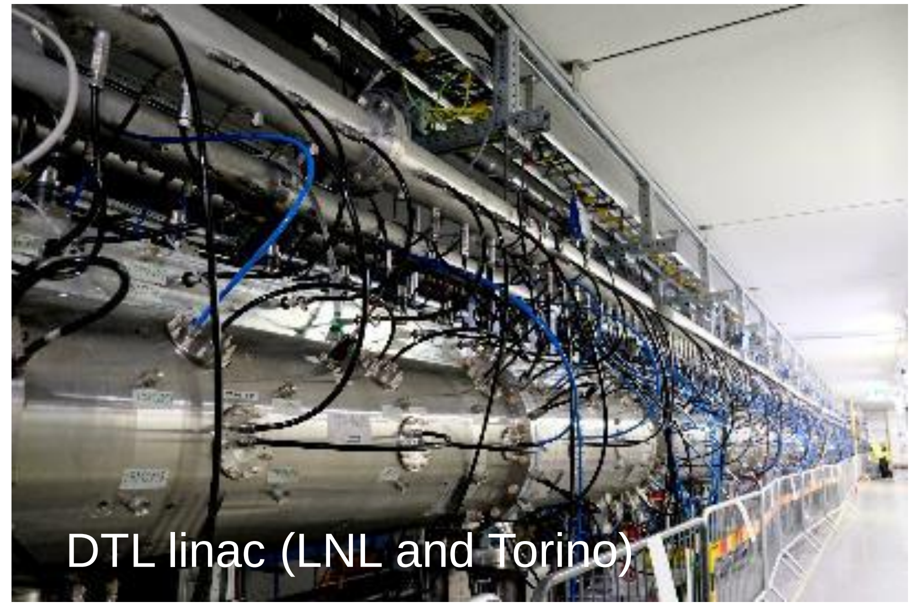
In blu F4E and CEA contributions

Similar IK sharing as done for ESS





- INFN contribution to ESS is now successfully compleated.
- INFN source and DTL have demonstrated beam performances
- All INFN cavities (nc and sc) are RF conditioned and the beam BOT is before summer



DTL linac (LNL and Torino)

6cells MB cavities (Milano)

Opportunities thanks to ESS IKC

- The INFN IKC for ESS, beside a an excellent accelerator, knowledge and skilled young accelerator scientists for the future, created a non negligible budget margin, mainly thanks of the INFN work (LNL and TO for the DTL realization).
- The idea is to invest in a Platform for Accelerator development (LATA or ATIP). The «progettazione definitiva» of LATA was concluded during DB direction and could be now revised and realized

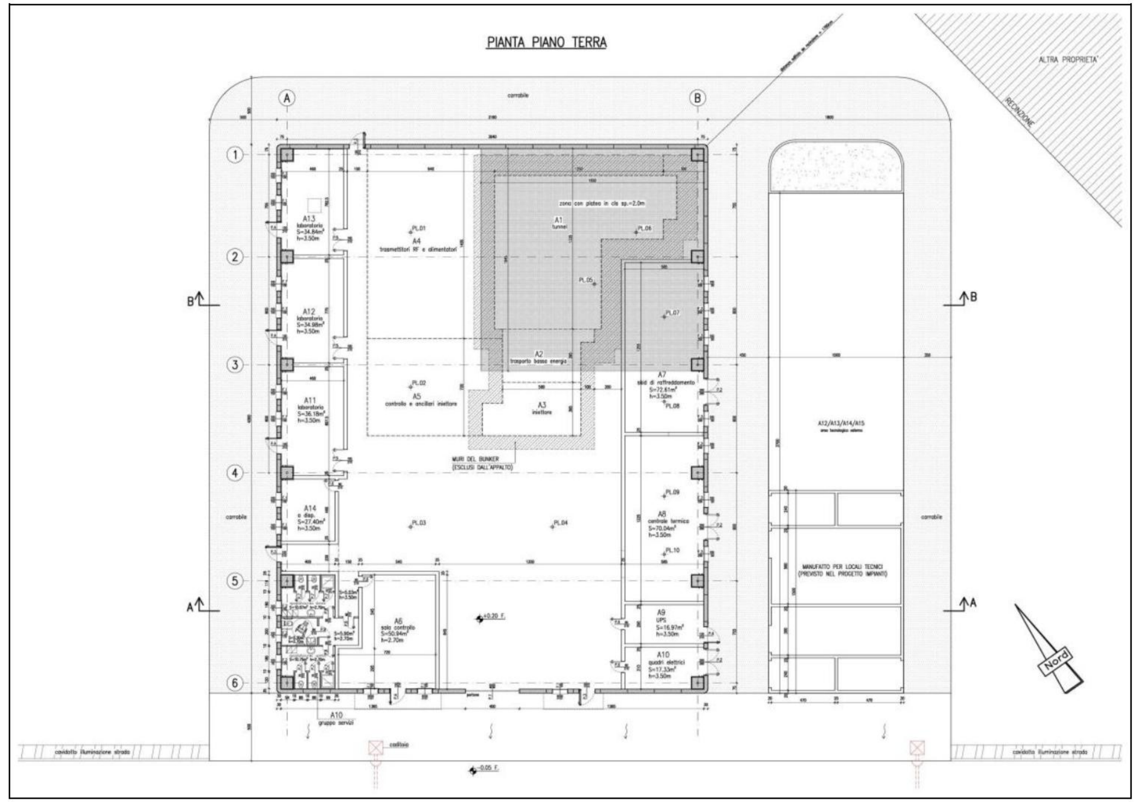
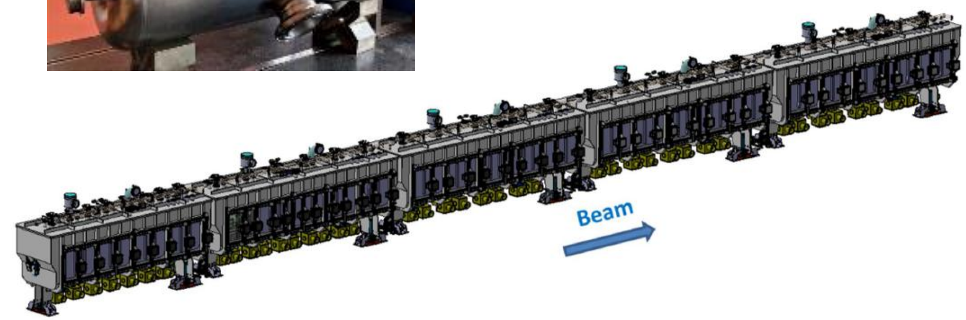


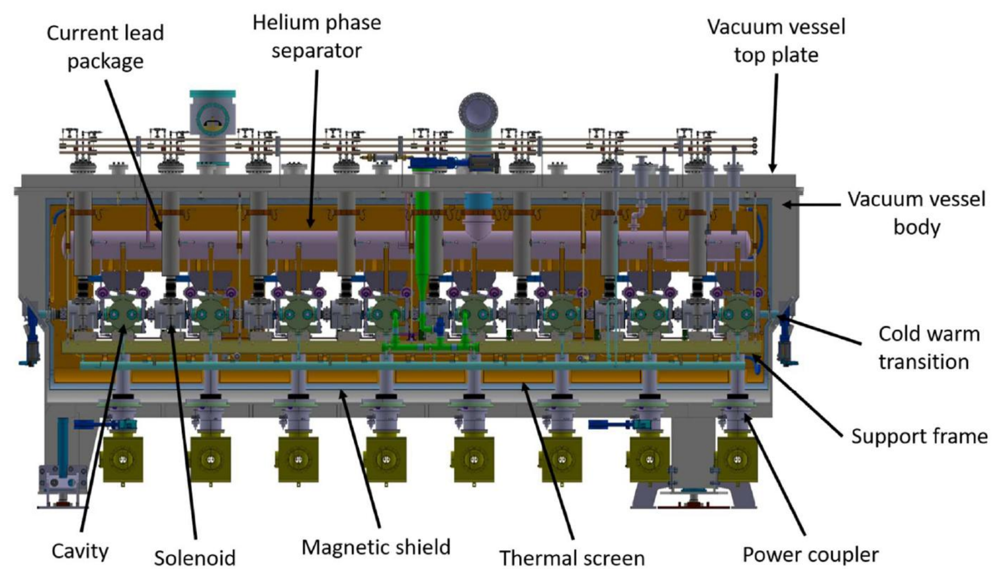
Figura 1 - Pianta piano terra

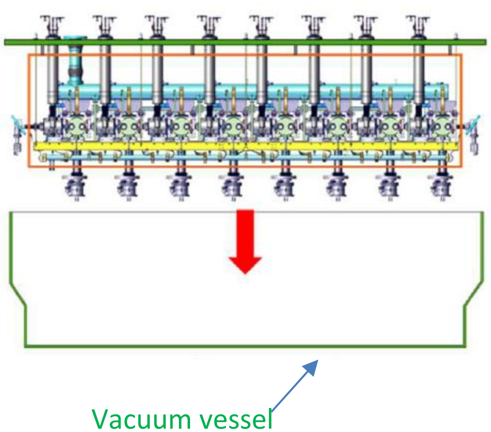
Development of INFN IKC to the accelerator

Superconducting linac accelerator (4deg K, bulk Nb)

- **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**



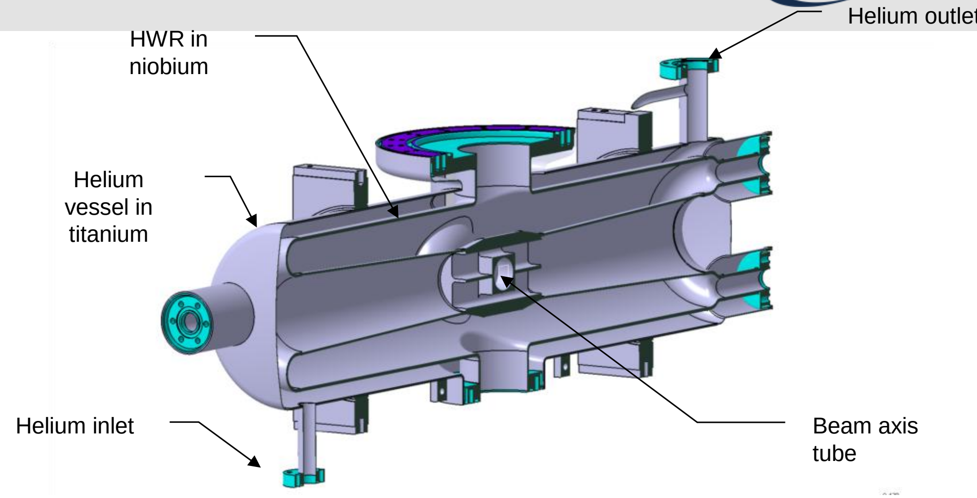




Developed by CEA France, prototype cavity construction by Zanon Italy

Superconducting cavities

- The superconducting linac (cryomodules based on HWR and superconducting solenoids) is developed by CEA
- HWR linac concept is hystorically an evolution of HI superconducting linacs like ALPI
- Cavities for IFMIF EVEDA were fabricated in Italy (Zanon)



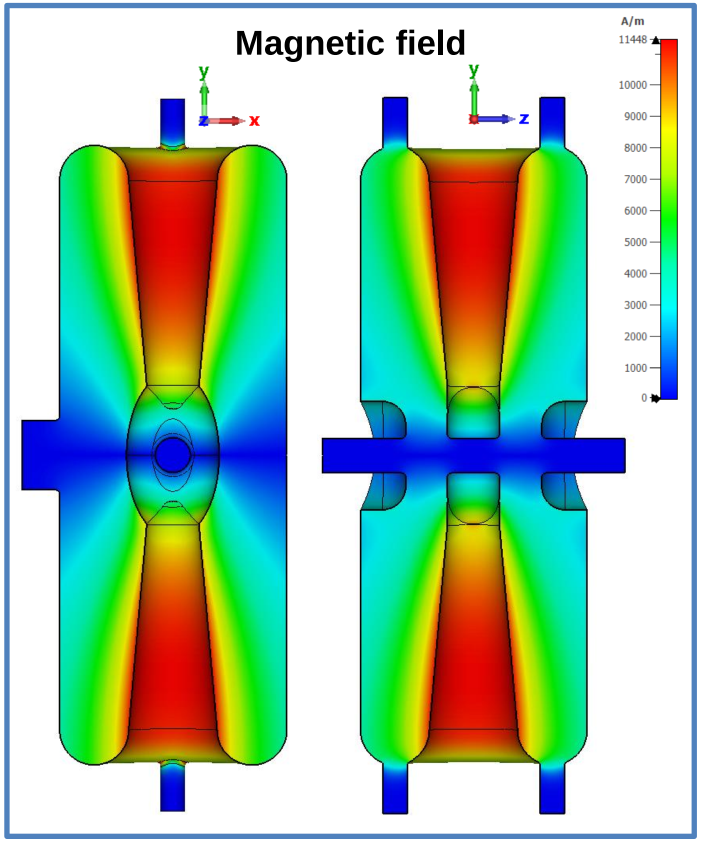
LNL low beta (A. Facco et al)

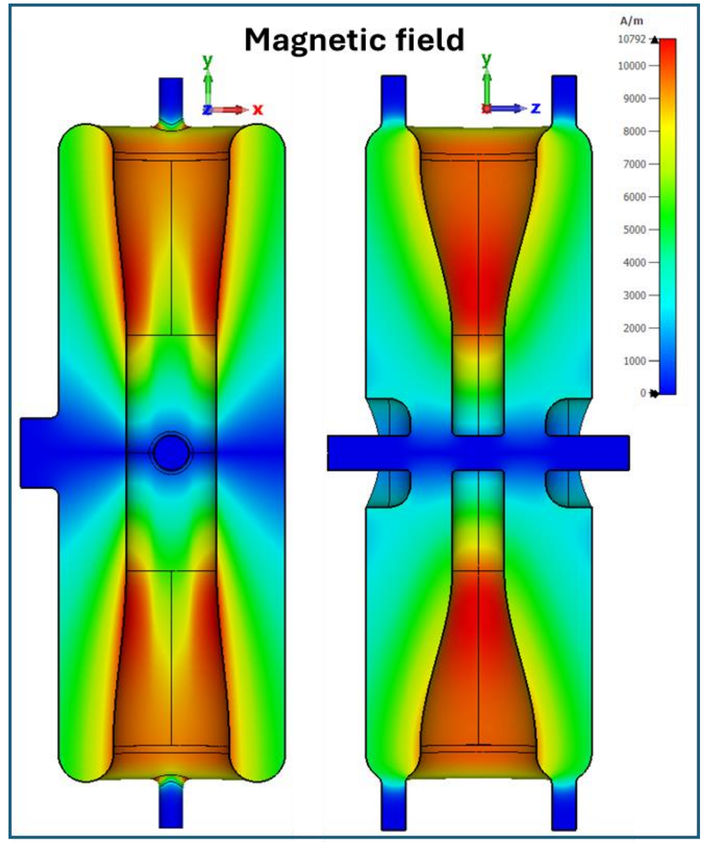
IFMIF EVEDA HWR designed by CEA

The INFN design of the cavity started

- Specifications: 175 MHz, β=.18, Φ_{beam}=50 mm, E_{acc}=4.2 MV/m
- At LNL we started the cavity design: $\frac{E_{max}}{E_{acc}} = 5, B_{max}/E_{acc}$ [mT/(MV/m)]=8-8.5

  two different geometries, ispired by CEA LIPAc and FRIB cavities



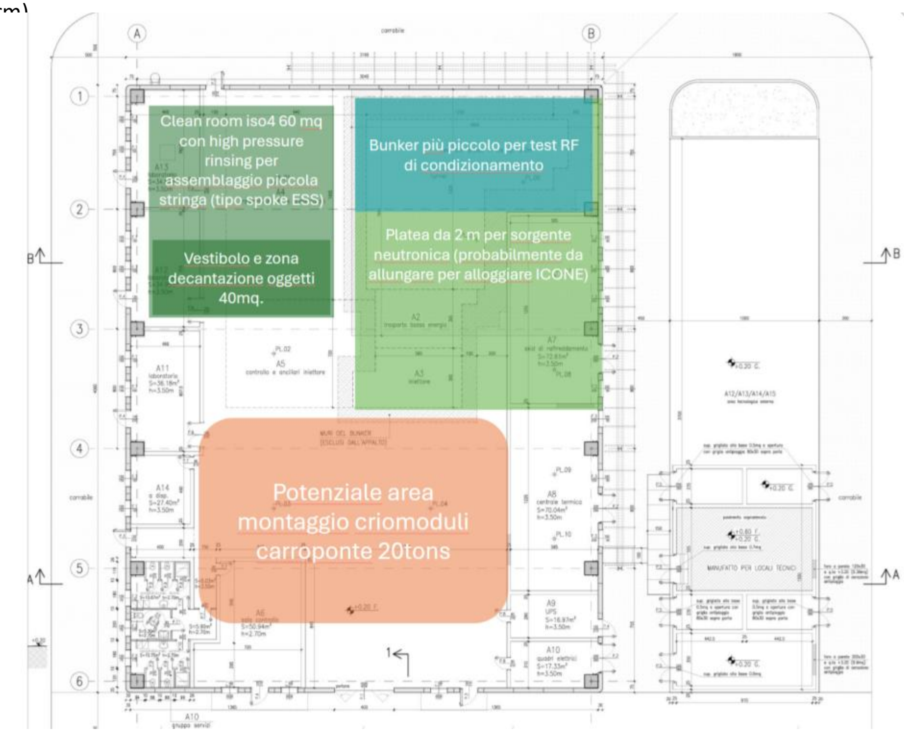


[1] J. Plouin et al., *Design, Fabrication, and Test of a 175 MHz, β = 0.18, Half Wave Resonator for the IFMIF-DONES SRF-Linac*, Proceedings of SRF 2023, link
[2] J. P. Holzbauer, *Superconducting Half Wave Resonators For Heavy Ion Linear Accelerators*, PhD Thesis, Michigan State University, 2011, link

M. D'Andrea, A. Pisent, F. Grespan, A. Palmieri, A. Facco

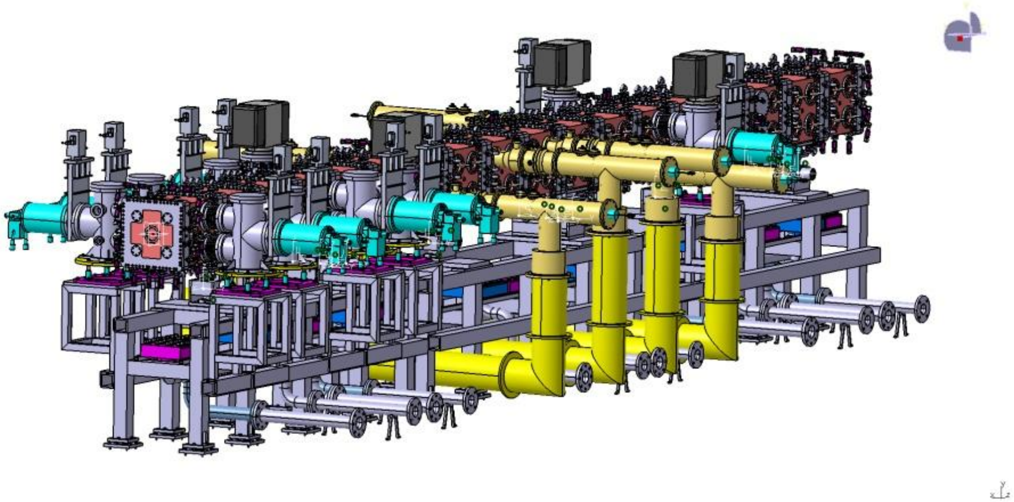
Ideas for the development

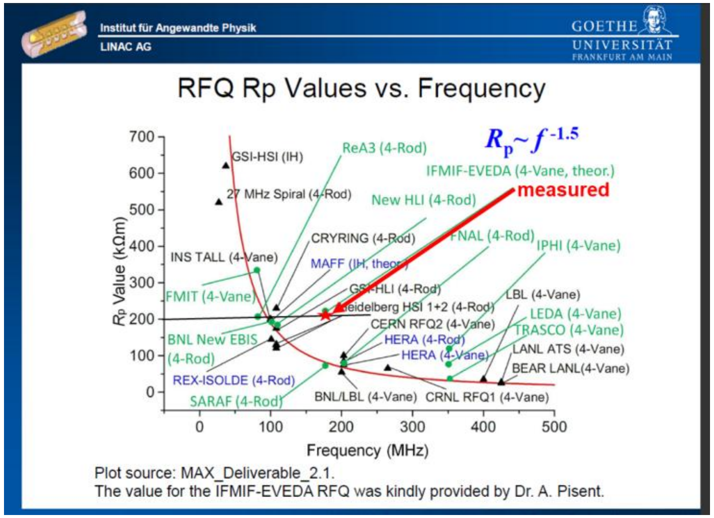
- Participation of LNL, Torino and Milano (open to other contributions)
- All the interfaces need to be compatible with CEA design.
- The prototype can be built with ZANON and characterized in critical coupling with the existing test cryostats.
- The construction of the series need a new cryostat and improved infrastructures, like LATA/ATIP (Accelerator Technology Intgrated Platform)



IFMIF EVEDA RFQ
125 mA, 5 MeV cw

- Delivered in 2014, INFN contribution LNL, Padova, Torino Bologna
- Beam dynamics=>high transmission, high efficiency
- RF design=> high shunt impedance





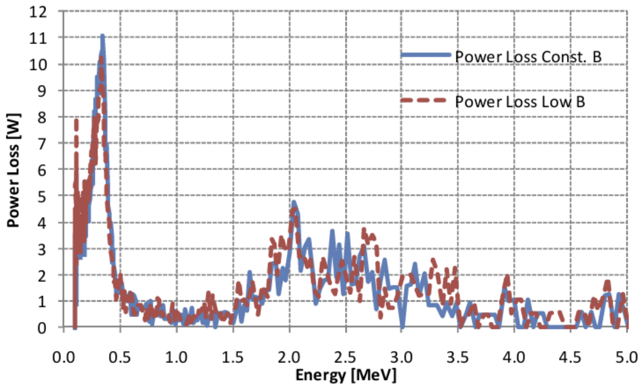
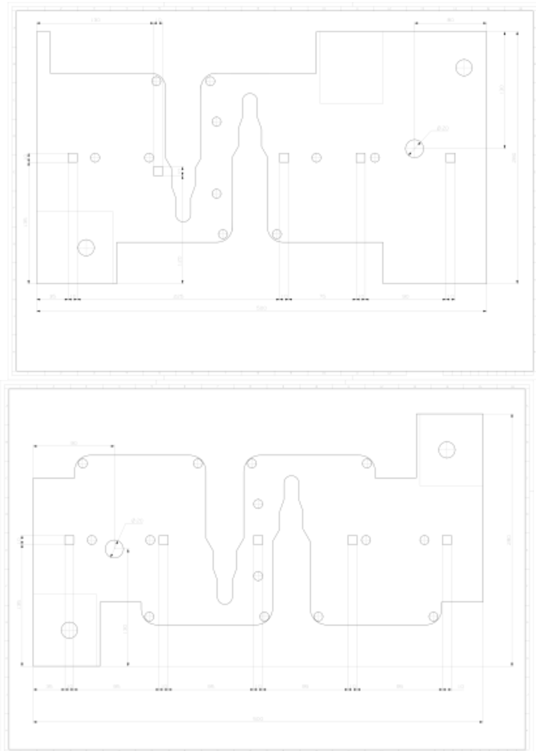
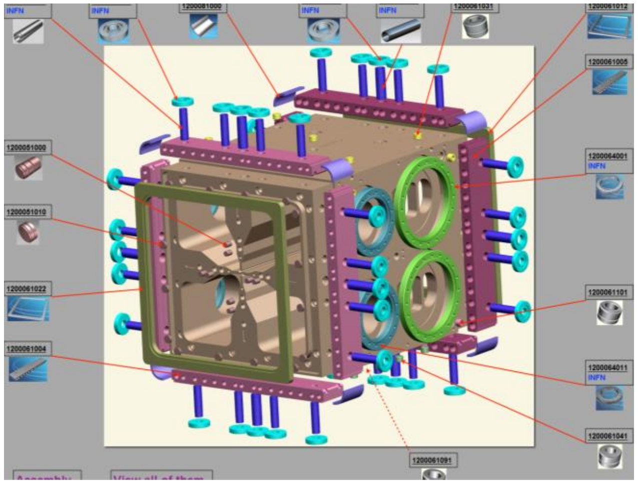


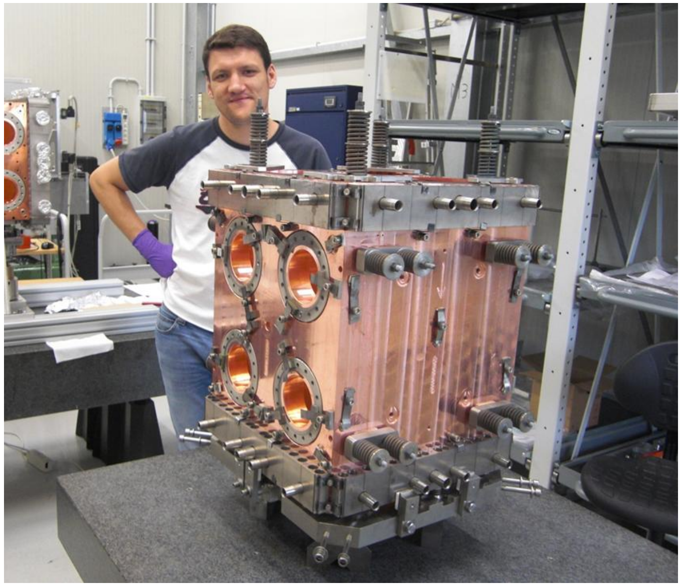
Figure 4: Power Loss as function of the energy.

- Mechanics @ INFN Padova.
  4 sectors, de-couple the mechanical connection towards the leakage tightness.





From forged blocks to modules

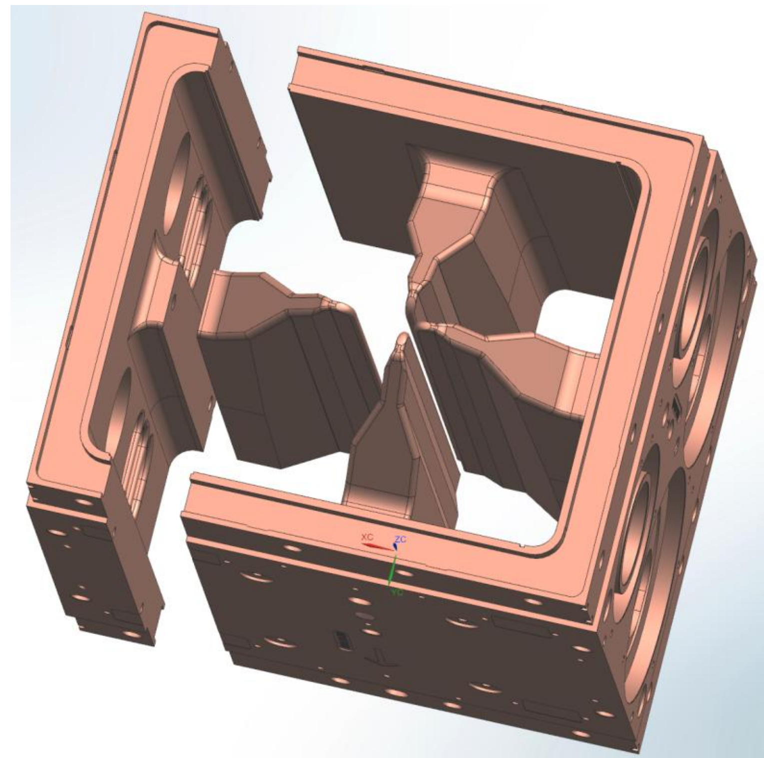


Mechanics in 8 brazed sectors

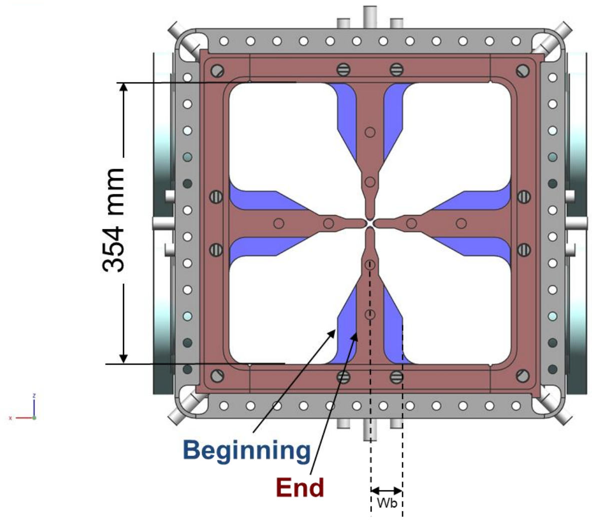
Single step brazing phase already tested of an entire module with the vane brazed to the vessel (M#9 of RFQ IFMIF)

Advantages of using 8-parts modules:

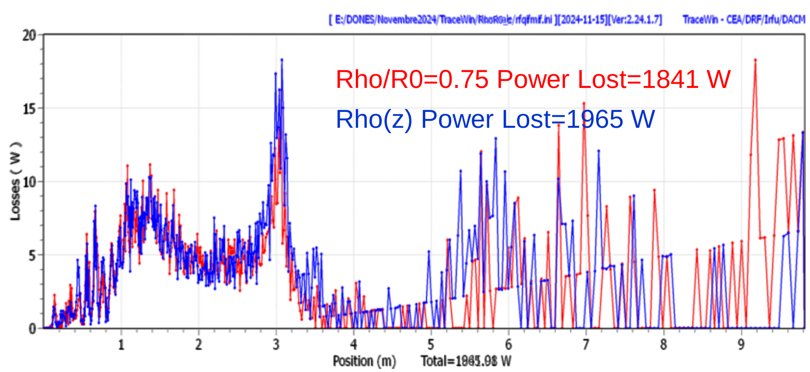
1. EDM machining on big copper Block (difficult to buy and expensive)
   - increasing of the length of the module
   - reduce the number of module assembly interface
   - Reduce the number of module alignment and so increase its positioning reliability
2. Standardize the geometry for vessel and vane components
   - reduce machining/control error due to the standardization of the production phases/quality controls
3. Redistribute tolerances on components that are easier to machine
   - less errors
   - more possibilities to correct machining errors before brazing
4. Raw geometry near to the machined one
   - minor waste of material
   - better quality of the forged material for the tip modulation

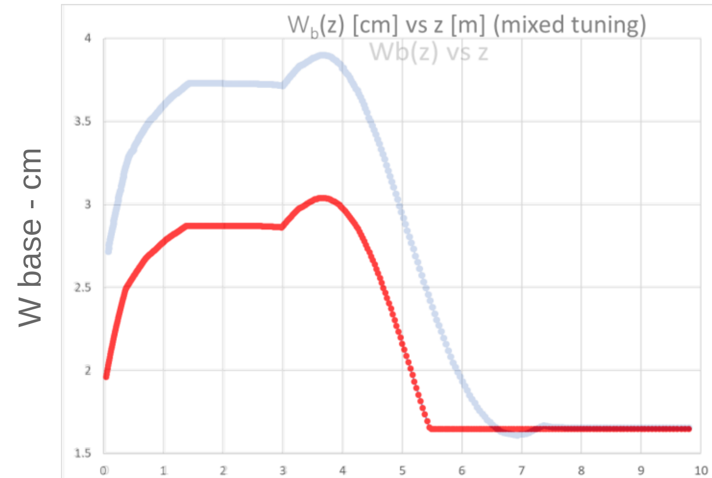


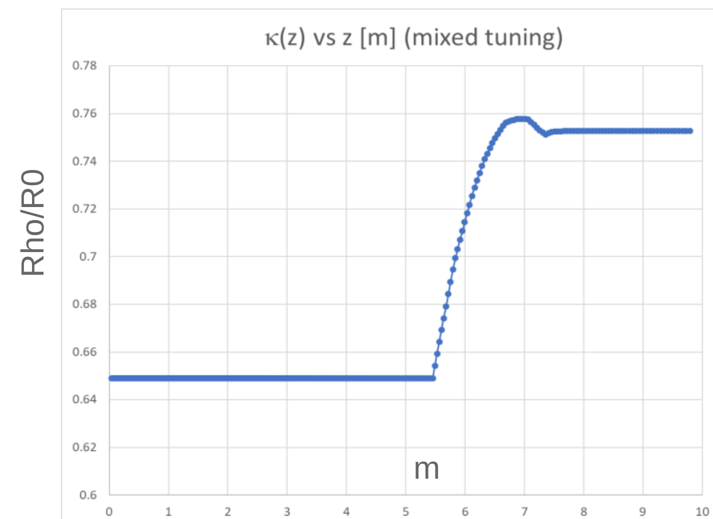
- RF design: mixed tuning on rho/R0 and Wb



- Larger tuners
- Better coupler pumping
- Less weight in the furnace (more furnaces available)







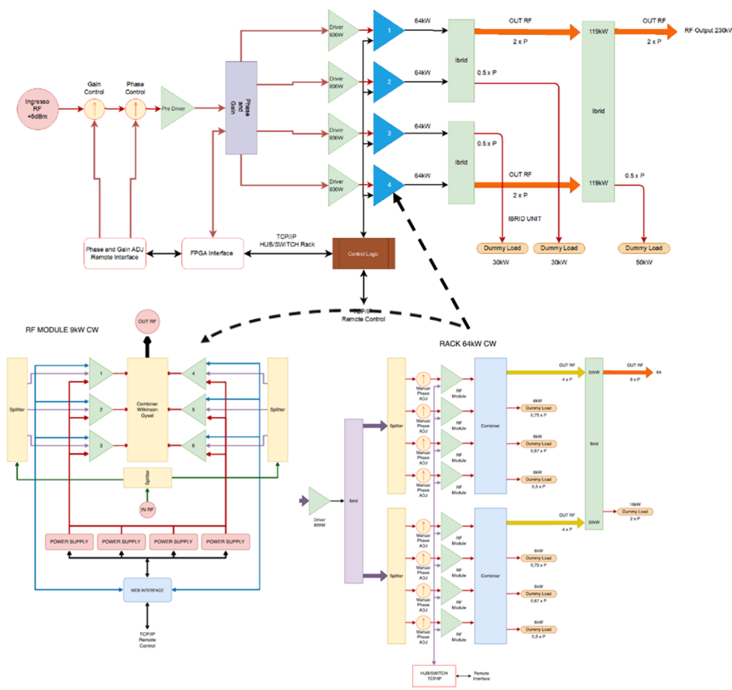
Support for DONES RFQ

Single 3-points final support

SPES RFQ installed at LNL (CW, 100kW, 80 MHz)

Anthem RFQ to be transported on the support assembled to Caserta after tuning and vacuum leak checks. (CW, 600kW, 352MHz)
Support design and integration by INFN-TO.

Other INFN developments: Solid state ampli prototype



RF system should provide 5MW to the beam + 700 kW to the RFQ copper power dissipation.
It is one of the main contributor to the operating cost of the plant.
→ Efficiency is fundamental

The INFN prototype is fully tested and presently ready for power coupler test at LNL.

200kW, 175 MHz , 62% power efficiency.

A fundamental technology where Italian industry is ready to compete for general contracts

Conclusions

- The IKC model was successful for INFN contribution and IFMIF EVEDA and ESS. This second being a user facility is more relevant for DONES.
- The participation of multiple INFN structures is fundamental. For DONES we have the historical core (LNL, Torino and Milano) and additional contributions are welcome.
- The contribution for DONES is centered on **RFQ** and **high beta cavities** (and will include accelerator physics, engineering and management, computer control….)
- For both developments is very important the upgrade of the available technological platform, and in particular the construction of LATA.

Main INFN DONES contributors

LNL A. Pisent. F. Grespan, M. Comunian, A. Palmieri, E. Fagotti. L. Bellan, C. Roncolato, M. D'Andrea, C. Baltador, L. Ferrari, M. Giacchini, M. Montis, L. Antoniazzi, D. Bortolato, P. Bottin, A. Baldo, A. Battistello, A. Colombo (PD), A. Facco, C. Pira

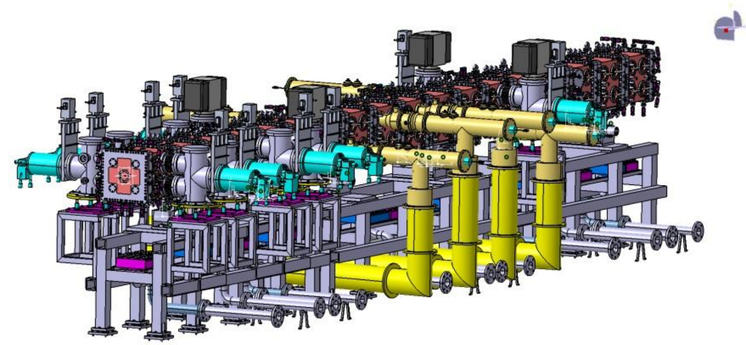
Torino P. Mereu, M. Nenni, C. Mingioni, E. Nicoletti

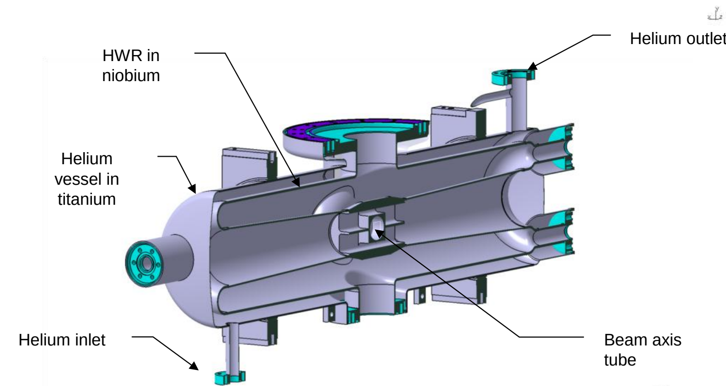
Milano D. Sertore, L. Monaco

Riserva

Possible contribution INFN to DONES

- The Italian contribution to DONES we are speaking about is 8% of DONES cost, approx. 812 M€, i.e. an in-kind contribution of 65M€, 40 M€ ENEA on the target and 25 M€ INFN on the accelerator (this sharing was discussed immediately before Covid, in 2019).
- Main items:
  - RFQ 8-10 M€
  - 27 High beta superconducting cavities10 M€
  - Installation and commissioning 8 M€
- the construction time is approx 5 years for the RFQ and 6 years for SRF cavities after kick off meeting.
- INFN collaboration with a core LNL, Torino, LASA.
- The new accelerator platform (LATA) at LNL is needed for series construction (approx. 2 years from now).





The DONES Programme

1st **DONES Steering Committee** held
the 16th March 2023
Official start of the
DONES Construction Phase

4th DONES steering committee 16 Oct. 2024

- **Spagna e Croazia, menbri del consorzio DONES, gli altri sono observers.**
- **Italia ha un MOU fra ministeri della ricerca scientifica e la trattativa per l'ingresso è in corso (con un contributo ENEA al target e INFN all'acceleratore)**

Granada 16 Mar. 2023

Granada 16 Oct. 2024

The DONES Programme