PNRR ANTHEM/BNCT
Status and perspectives

F. Grespan

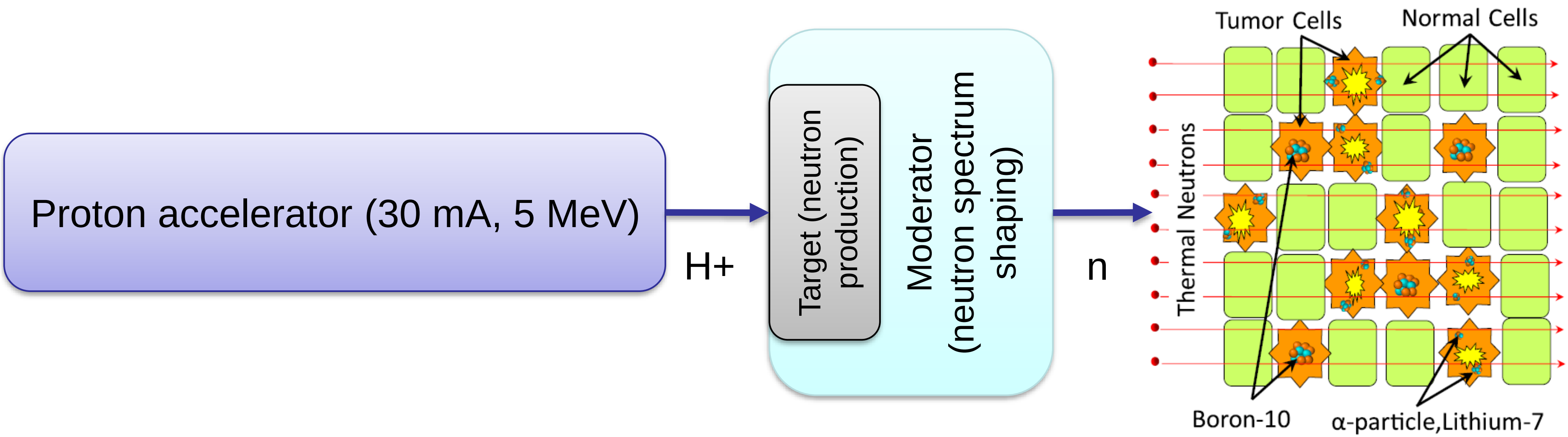
Terza Giornata Acceleratori

4–5 Aprile 2024 INFN Frascati National Laboratories

Contents

- Building
- Accelerator line
- Ion Source: refurbishment plan and last results
- LEBT line
- RFQ: cavity, tuning, support and integration, high power couplers
- RF system: architecture, test and procurement
- MEBT line studies and procurements
- Target

A-BNCT concept



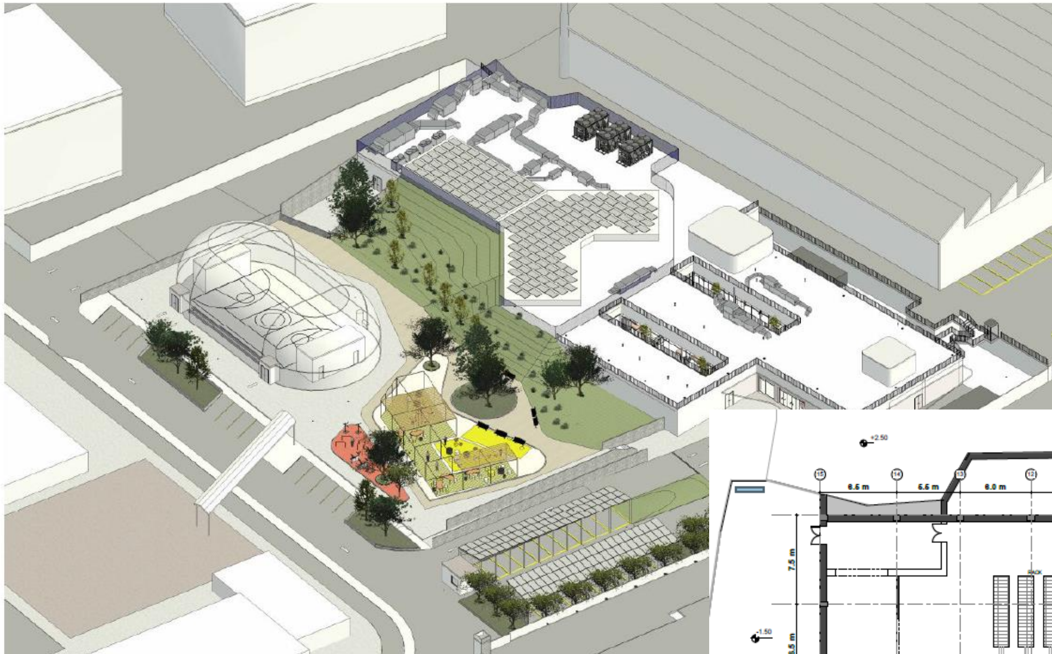
INFN Structures involved in the BNCT LINAc construction

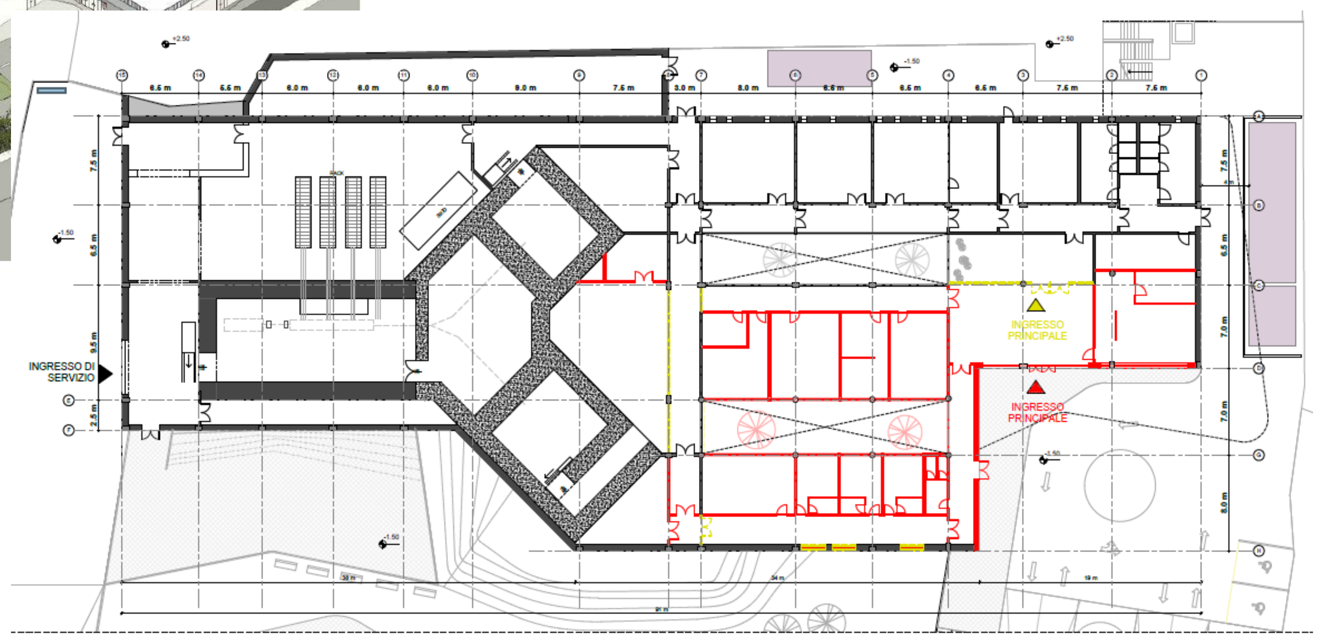
- **Pavia** design and construction of the BSA (beam shape assembly)
- **LNL**, accelerator, RF system, diagnostic, micro-dosimetry, production target, beam tests (source), RF tests and neutron production tests (electrostatic accelerator)
- **Torino**, mechanical development of the accelerator, transfer line and integration with the building, documentation management and QA/QM procedures.
- **Napoli** (sezione and Unicampania) accelerator development, integration with of the building, administrative coordination, tenders.
- **LNS** technical and administrative participation to main tenders

- **INFN – Laboratori Nazionali di Legnaro**
  - F. Grespan, C. Baltador, L . Bellan, A. Bianchi, D. Bortolato, M. Comunian, V. Conte, J. Esposito, E. Fagotti, L. Ferrari, M. Montis, Y. Ong, A. Selva, A. Palmieri, A. Pisent
- **INFN – Sezione di Napoli**
  - M.R. Masullo, A. Passarelli, L. Gialanella, L. Bagnale, D. Pistone, G. Porzio
- **INFN – Sezione di Pavia**
  - S. Bortolussi, I. Postuma, S. Fatemi, R. Ramos, B. Marcaccio, A. Kourkoumeli, A. Lanza, V. Vercesi – Principal Investigator INFN
- **INFN – Sezione di Torino**
  - Paolo Mereu, Carlo Mingioni, Marco Nenni, Edoardo Nicoletti

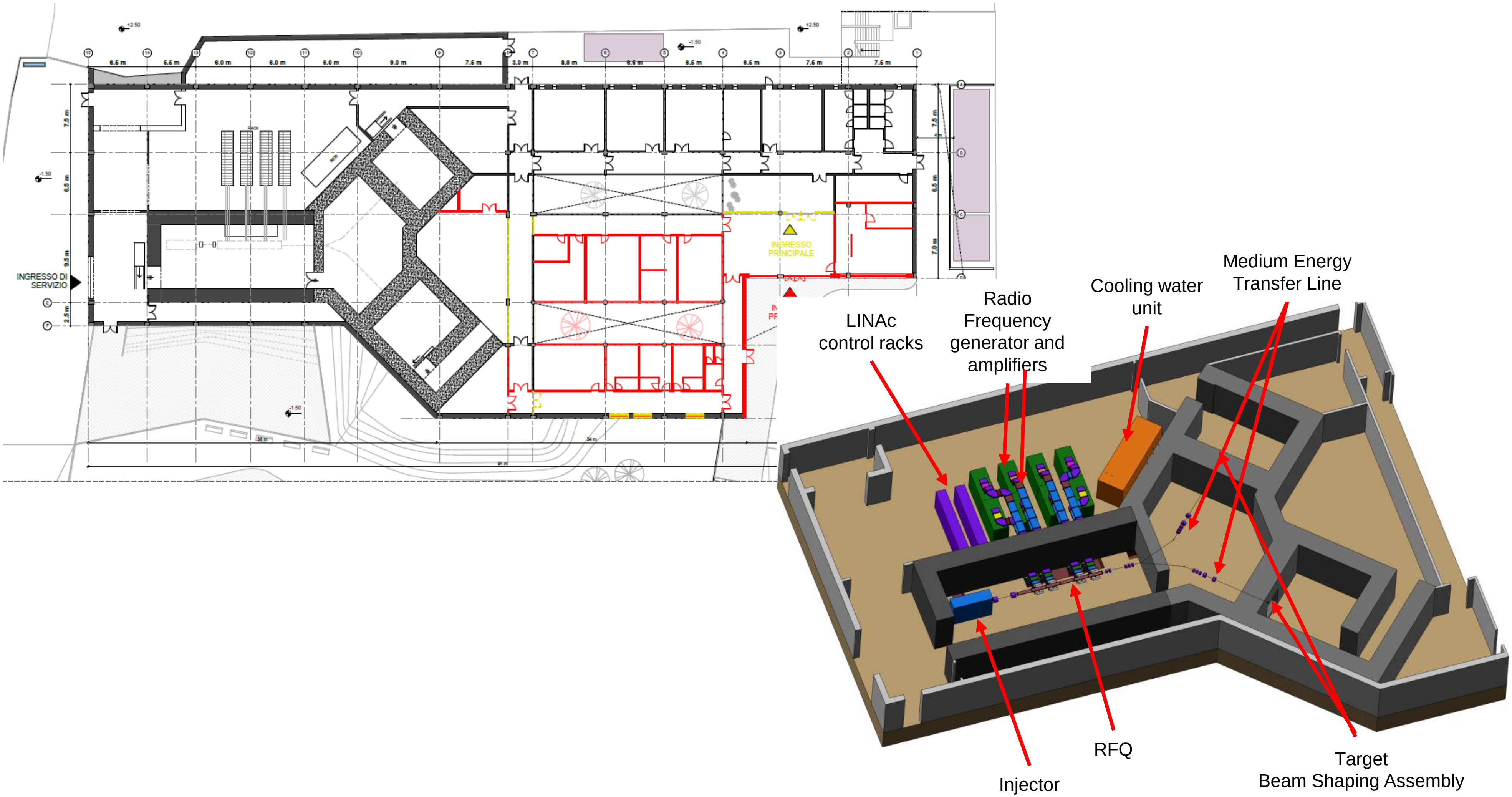
Building

RENDERING VIEW – PHASE 2





Building



INGRESSO DI SERVIZIO
INGRESSO PRINCIPALE
LINAc control racks
Radio Frequency generator and amplifiers
Cooling water unit
Medium Energy Transfer Line
Injector
RFQ
Target
Beam Shaping Assembly

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Laboratori Nazionali di Legnaro

The accelerator line

Anthem
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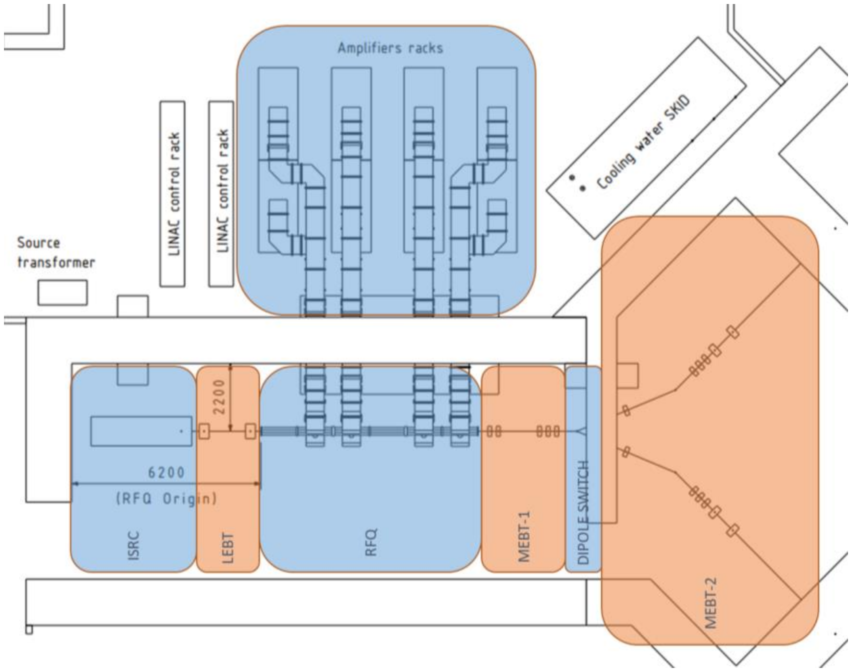
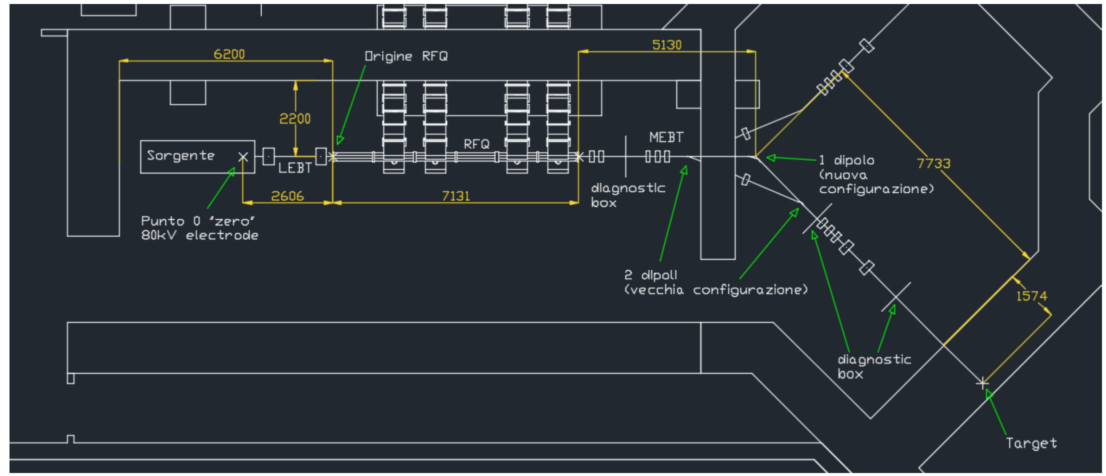




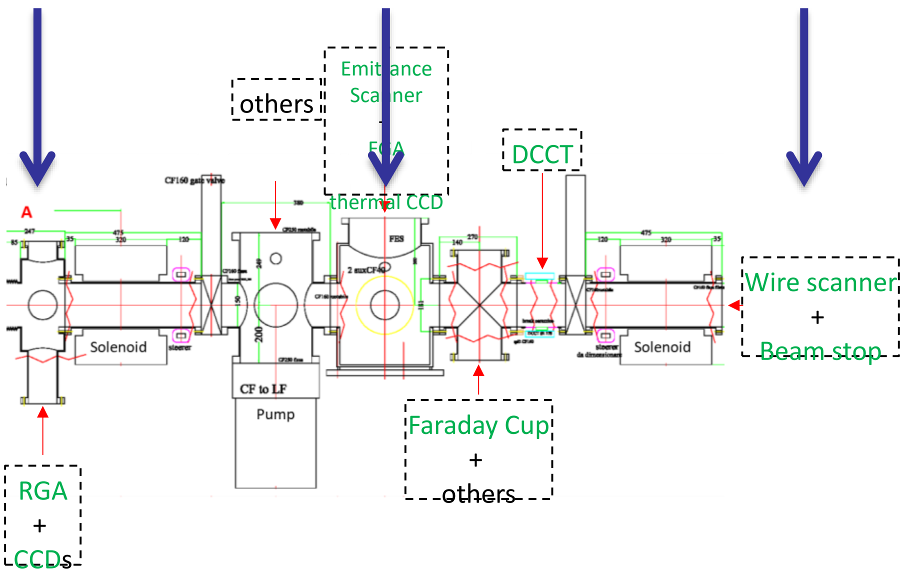
Parameter/Item	Value	Unit
Ion Source	Microwave plasma source	
ISRC proton current	> 35	mA
Duty cycle	100	%
RFQ input energy	0.8	MeV
RFQ output energy	5	MeV
RFQ RF system	8×125=1000	kW - solid state amplifiers
RFQ structure type	4-vane, resonantly coupled	(3rd or 4th case)
RFQ Length	7.12	m
$P_{TOT} = (P_{cu} + P_{beam}) \cdot 1.15$	$(600 + 150) \cdot 1.15 \approx 870$	kW - 15% margin for LLRF

Ion source

- **TRIPS Refurbishing process:**
  - HV platform and faraday cage restoration
  - New transformer (with status check via control sys.)
  - New and re-arranged connections under false floor
  - Complete source dismantling for repairs and cleaning operations.
  - Laser tracker alignment
  - PPS updated
  - General replacement and improvement of source components, electronics, connections, cooling.
- Further upgrade to 50 mA H+ could be beneficial for power saving.
- Indeed according to IBNCT (Tsukuba) data, the average current necessary for half an hour treatment is around 10-15 mA. It already allowes reducing the duty cycle to 50 %.

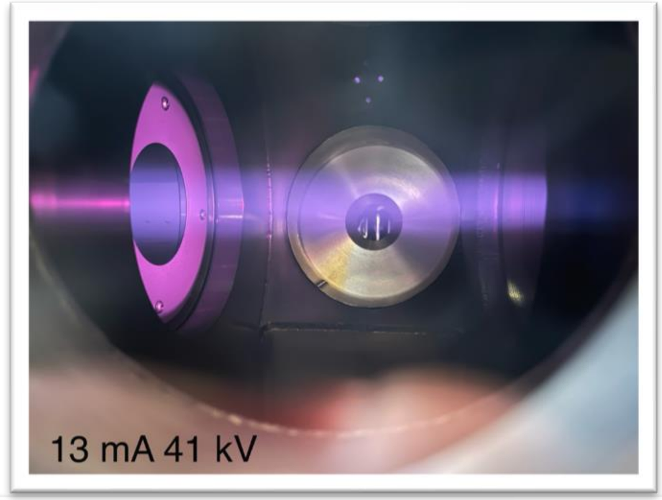
Ion source

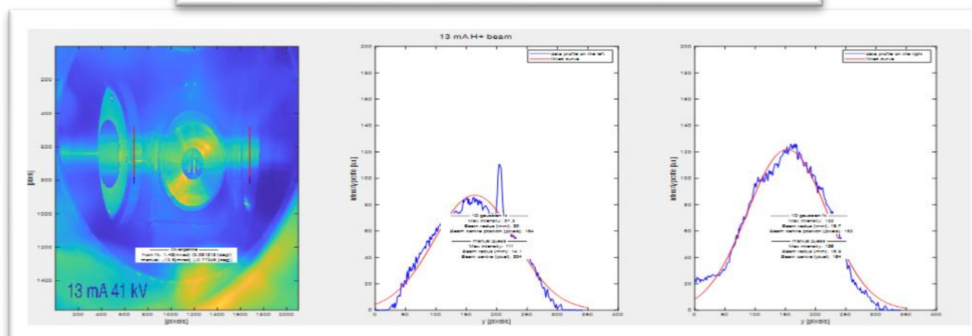
LEBT configuration for testing at LNL, with 3 characterization points.



From recent experiences @ IFMIF and ESS: (reliability of simulation codes) + (understanding of Space Charge)
→ H+ beam characterization sufficient just with FC after extraction.

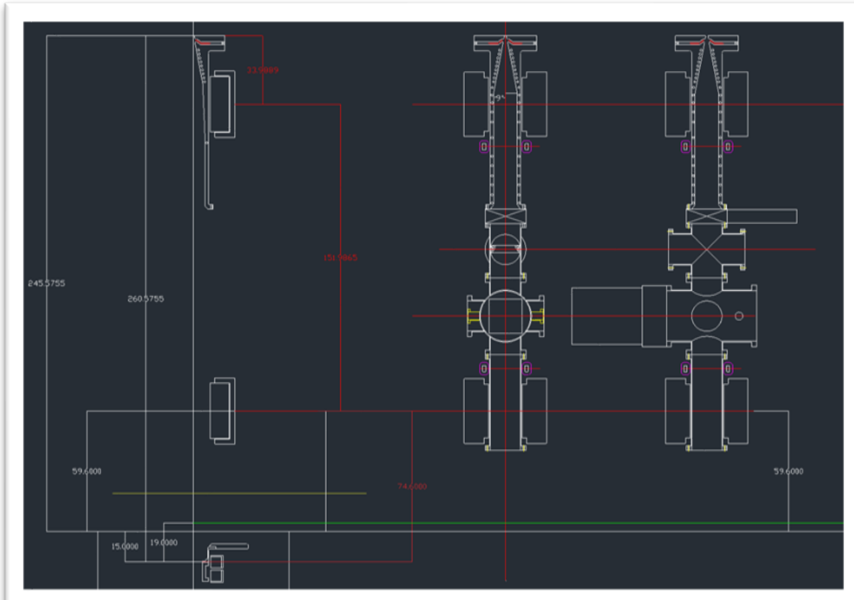
Bellan et al., "SPACE CHARGE AND ELECTRON CONFINEMENT IN HIGH CURRENT LOW ENERGY TRANSPORT LINES.", Linac22 proceedings.

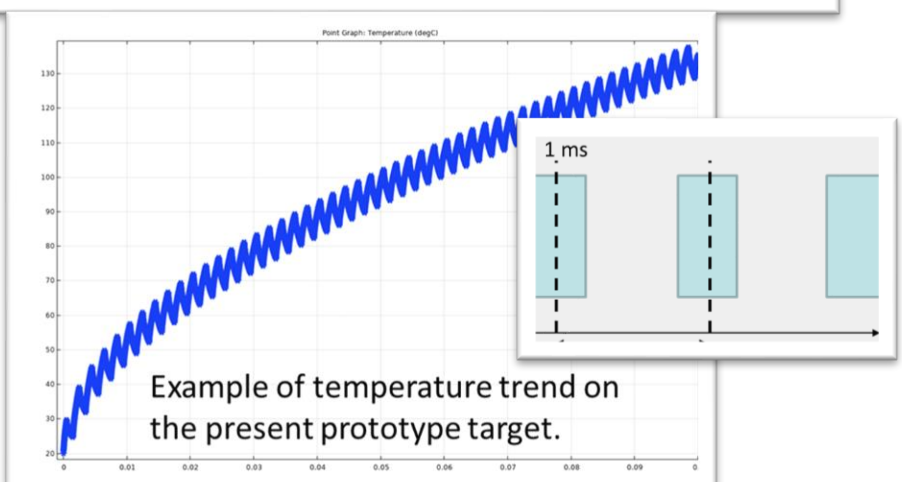




March 2024: beam from TRIPS restarted after some years. Conditioning on going.

LEBT





Example of temperature trend on the present prototype target.

Installed LEBT shorter than the test LEBT. (2.6 m)

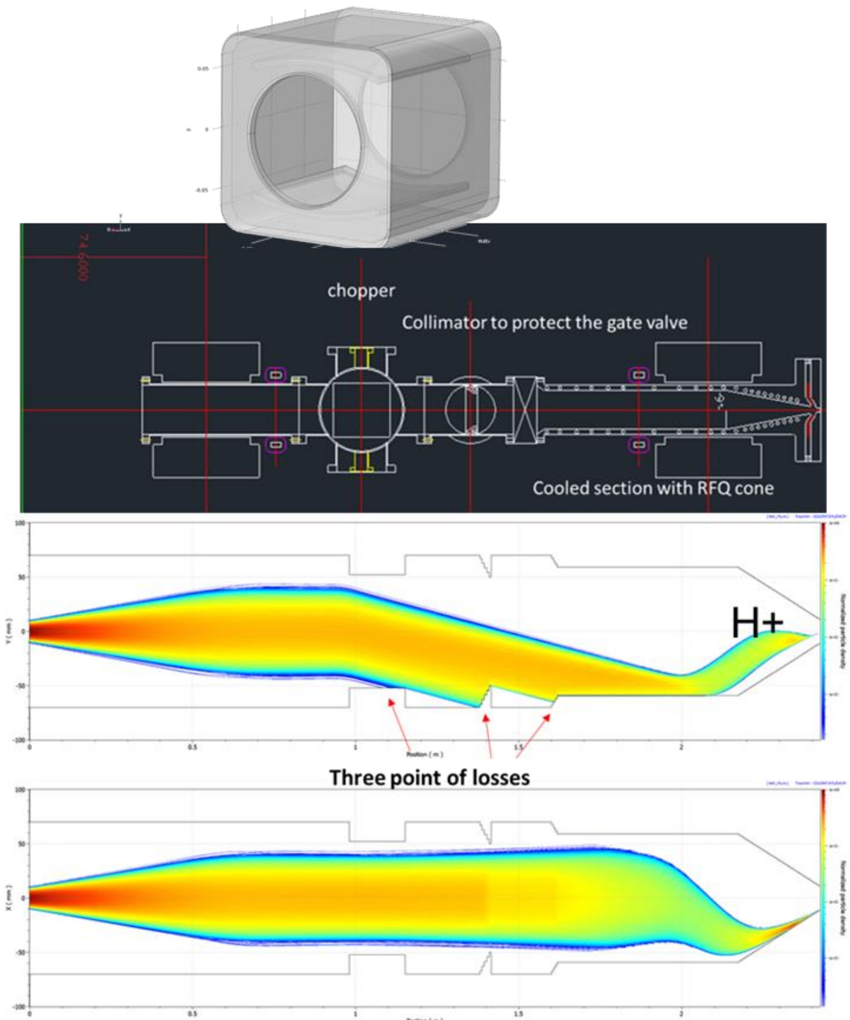
Less diagnostics (DCCT, ACCT, FC)

Chopper for pulsed operation at 50 mA, 50% DC.

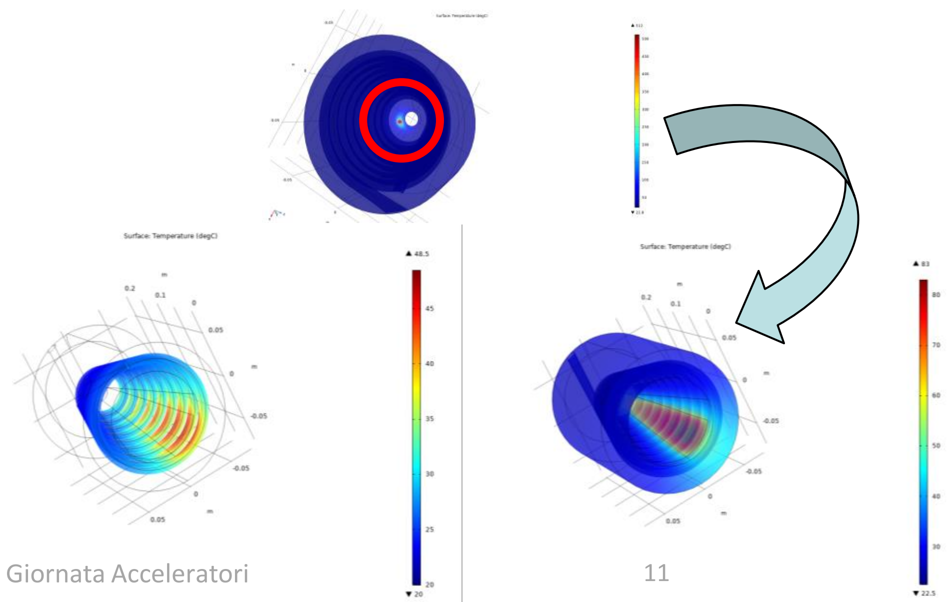
The temperature trends on the target and the rise time of the IS plasma restrict the possible timing to 1msON-1msOFF with CW ion source.

This requirements has been applied to the RF systems.

LEBT

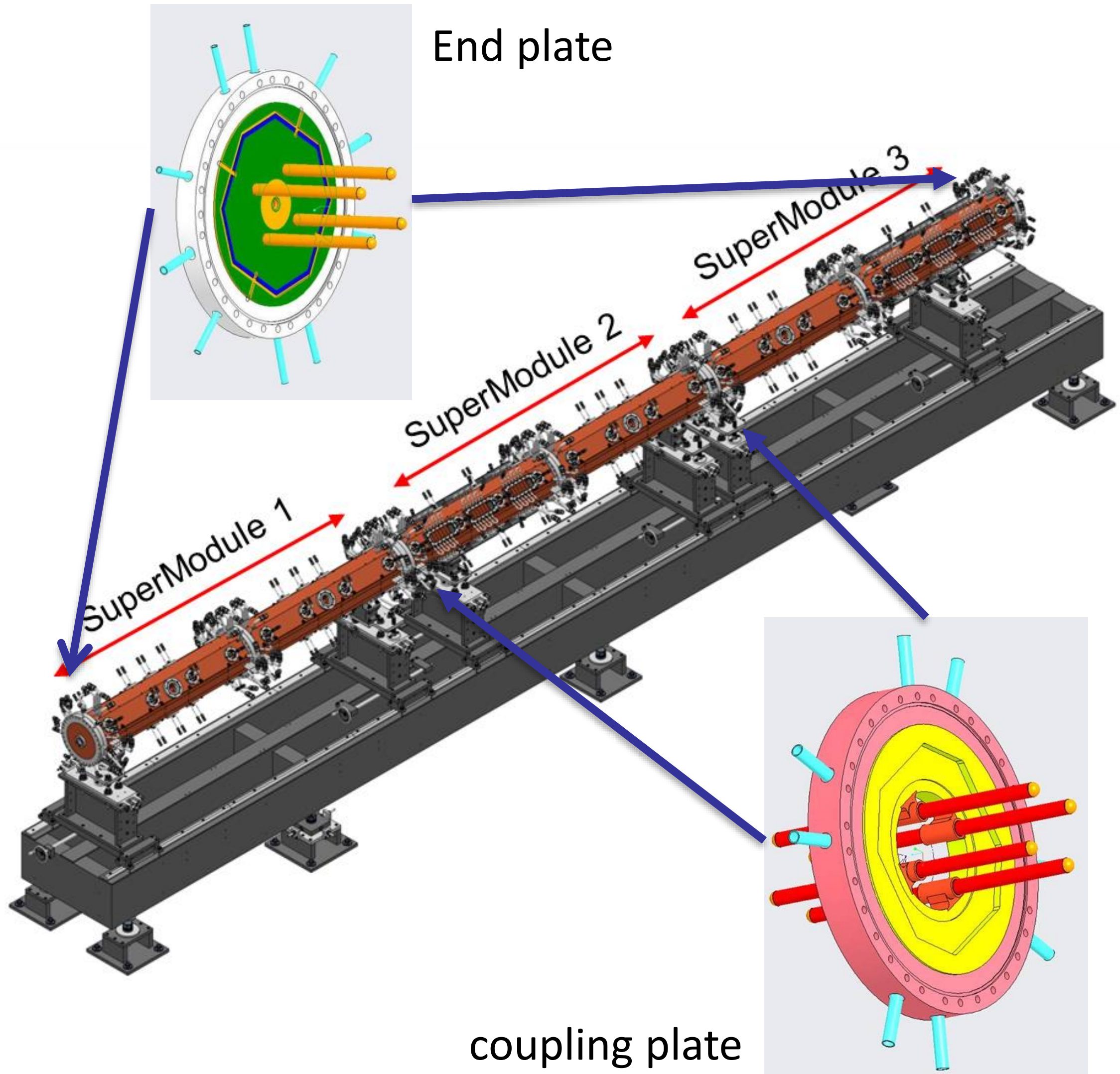


- Chopper included, without LEBT length changed.
- Beam line cooled
- Several design of chopper tested: for now, the best one is given by two vertical rounded plates which can sustain up to 11 kV each.
- The realistic simulation models (SpaceChargeCompensation, solenoid fringe fields, contaminants) fundamental to obtain a manageable power density on the RFQ cone, otherwise difficult with sharp edges and linear dynamics.



RFQ: cavity

- 6 brazed modules → 3 SuperModules
- Each supermodule is an EM segment, coupled with the neighbors (resonant coupling → stability)
- EM boundary conditions are given by 2 Endcells + 2 Coupling Cells, equipped with dipole stabilizers
- Local frequency adjustment by slug 96 tuners
- Tuning process will be performed at LNL on the final support frame.
- Cavity tuned and vacuum tested will be shipped to final destination



RFQ: tuning

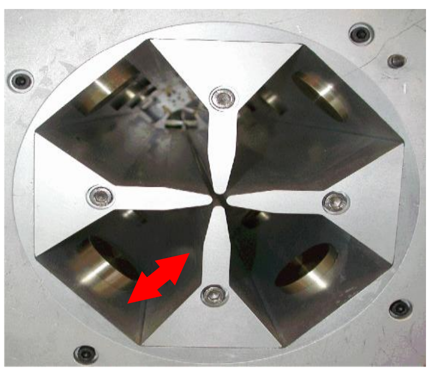
Tuning algorithms:

1. $\frac{dV(z)}{dz} = \frac{dV(L)}{dz} = 0$ for end cells and coupling plate thickness
2. Dipole dispersion curve symmetric with respect to fquad for dipole stabilizer rods
3. Central region: slug tuners to compensate local frequency errors developed in eigenfunction basis, obtained from Fourier analysis of the voltages. PERTURBATION ANALYSIS ON A FOUR-VANE RFQ

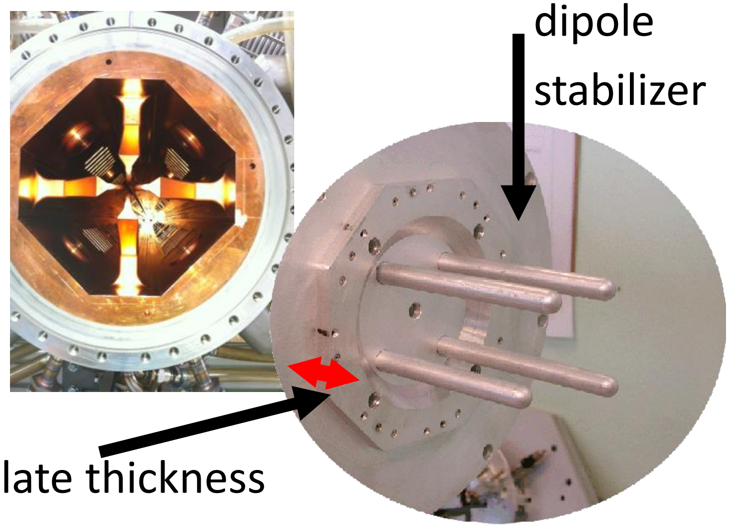
$$\left[c^2\frac{d^2}{dz^2} - \left(\omega_0^2\bar{\bar{A}} + \overline{\overline{\Delta\omega^2}}(z)\right)\right]V(z) = -\omega^2 V(z) \rightarrow \frac{1}{4}\left[\Delta\omega_1^2(z) + \Delta\omega_2^2(z) + \Delta\omega_3^2(z) + \Delta\omega_4^2(z)\right] = \sum_{n=1}^{N}\beta_n^q\varphi_n^q(z)$$

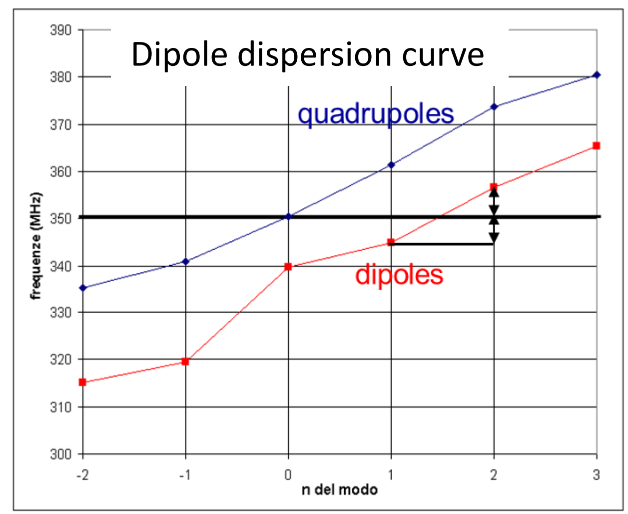
Central region

Slug tuners



End regions

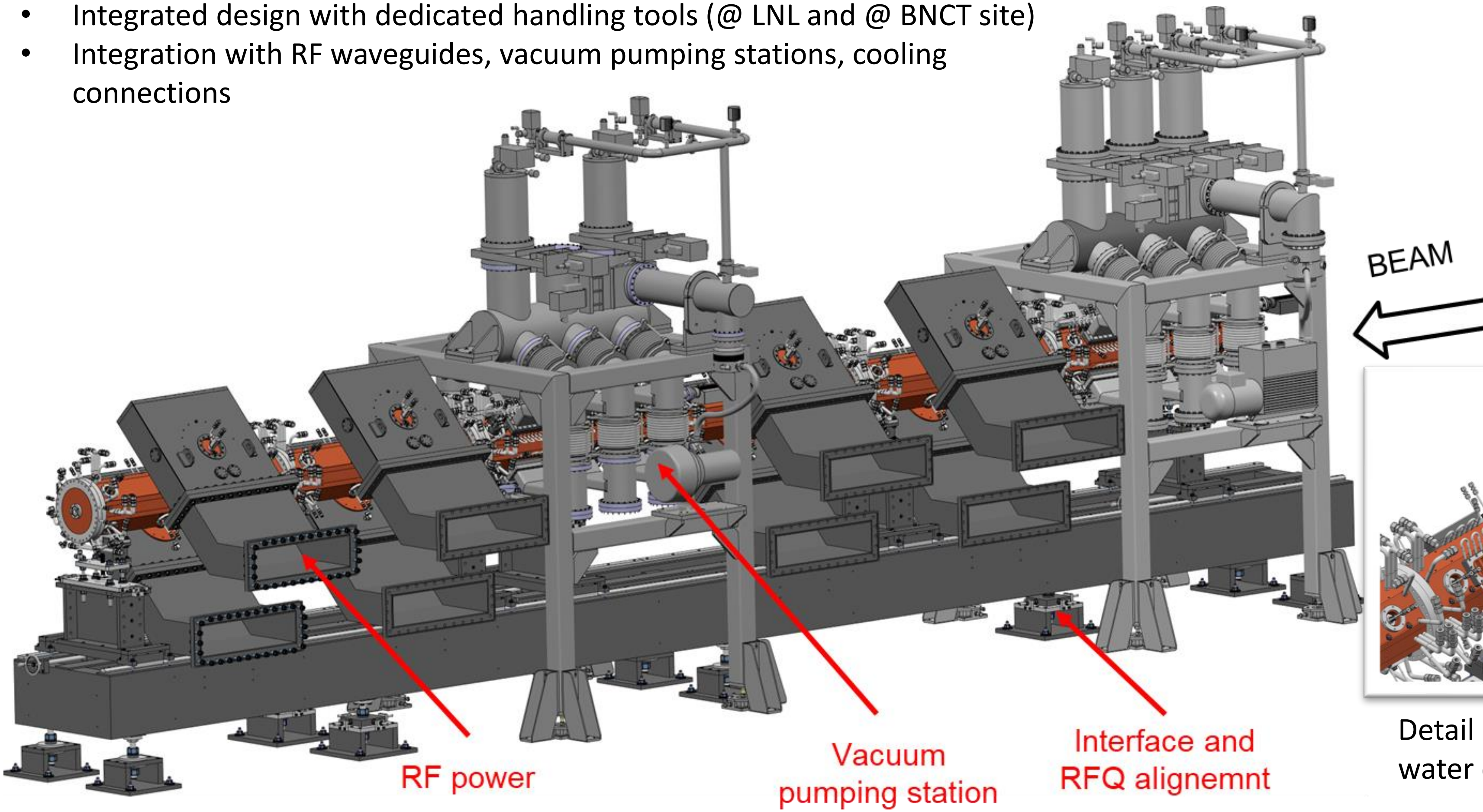


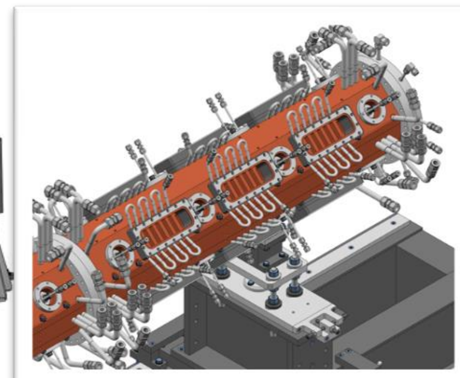


RFQ support and integration

RFQ mechanical support frame

- Integrated design with dedicated handling tools (@ LNL and @ BNCT site)
- Integration with RF waveguides, vacuum pumping stations, cooling connections





Detail of the cooling water distribution design

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Attivita' RFQ a LNL: power coupler conditioning

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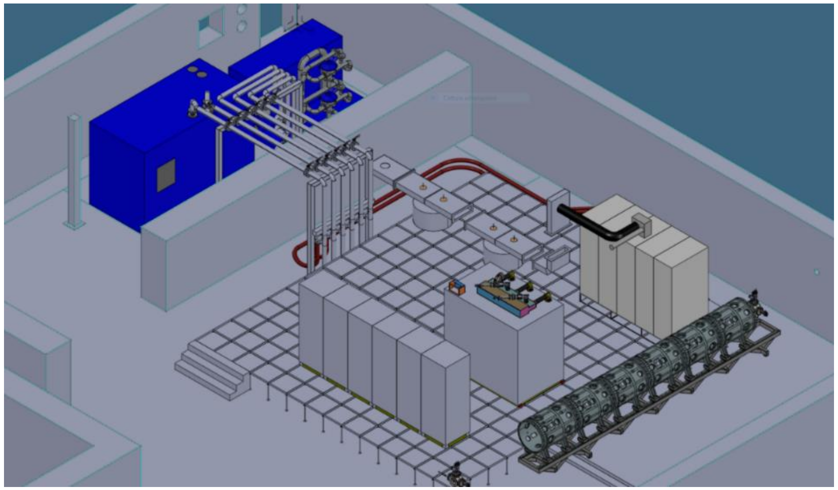


- Two already produced and tested in 2012 to full power (CEA-Saclay 140 kW cw) and used for RFQ test.
- We need to produce and test @ LNL (with INFN solid state amplifiers) 8 new couplers.
- Bridge cavity (see A. Passarelli talk)

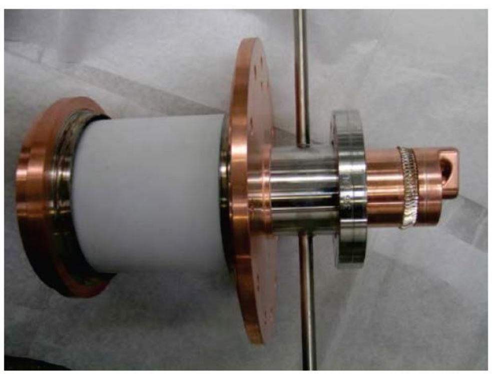
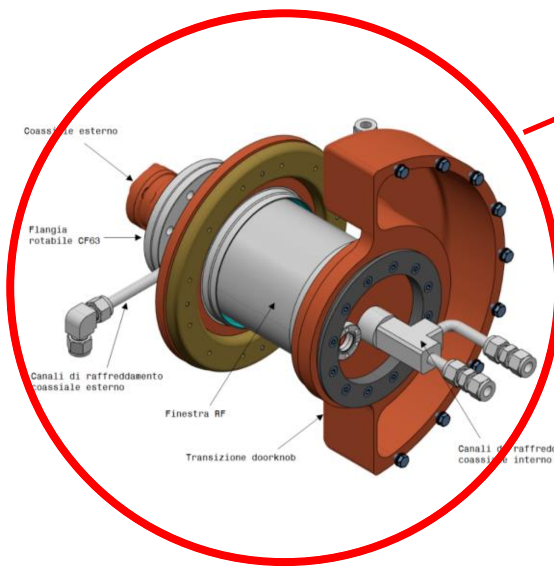
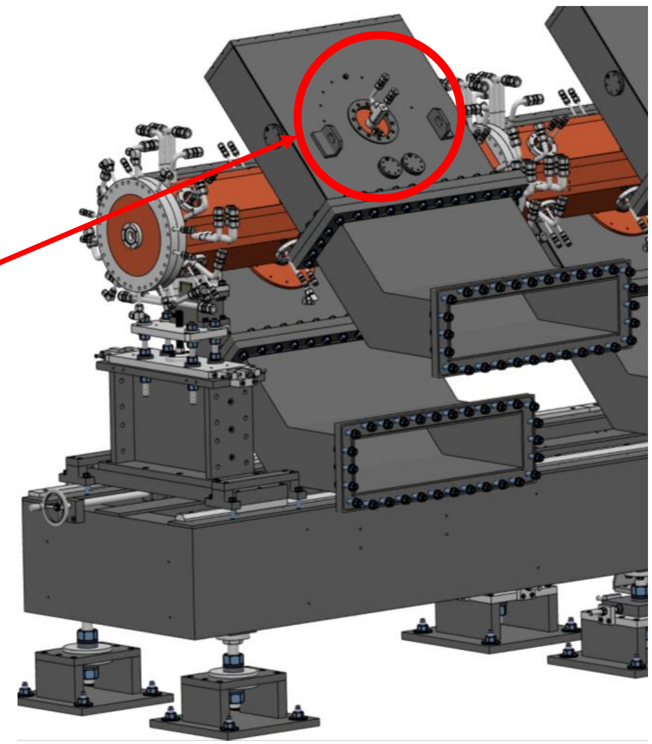


Figure 1: RF coupler system with loop, coaxial transmission line and coaxial alumina window.

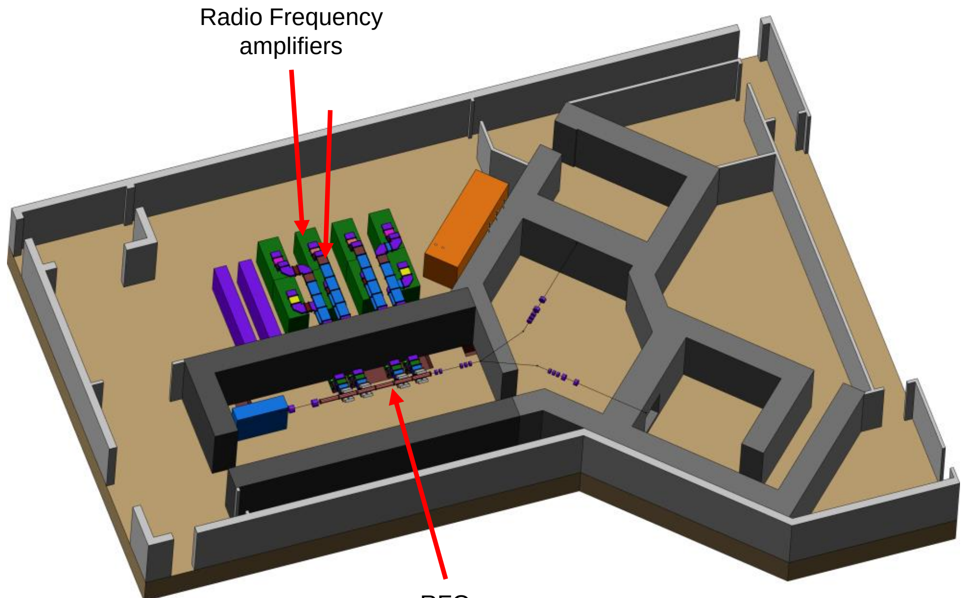




RF amplifiers

Eight independent 125 kW amplifiers (one per RF coupler). 5 available and tested to full power on RF load.

Each amplifier needs 5 racks (including power supply)



The 3 missing RF systems tendered in 2023, the 5 to be updated in the same contract.

Advantages respect to a klystron:

- Lower operating costs (cost and duration of components)
- Availability e reliability (no stop operation in case of components failure)
- Absence of high voltages very important for the operation in a hospital

RF amplifiers

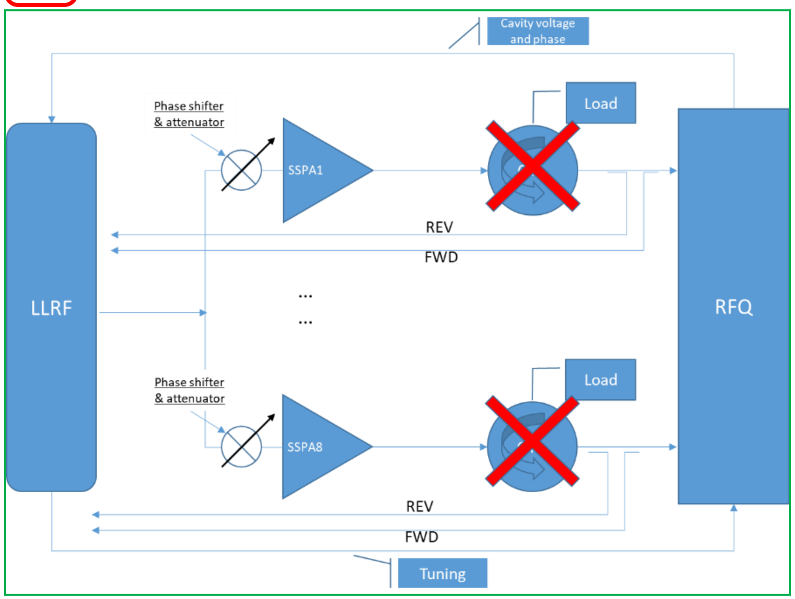
Peculiarities of Anthem RF system:

1. 8 RF system connected to the same cavity (IFMIF) → RF cross talk trough the cavity
2. No circulators →bus bar protection
3. Single LLRF input splitted to the 8 RF chains → error study on the requirements about amplitude and phase balance

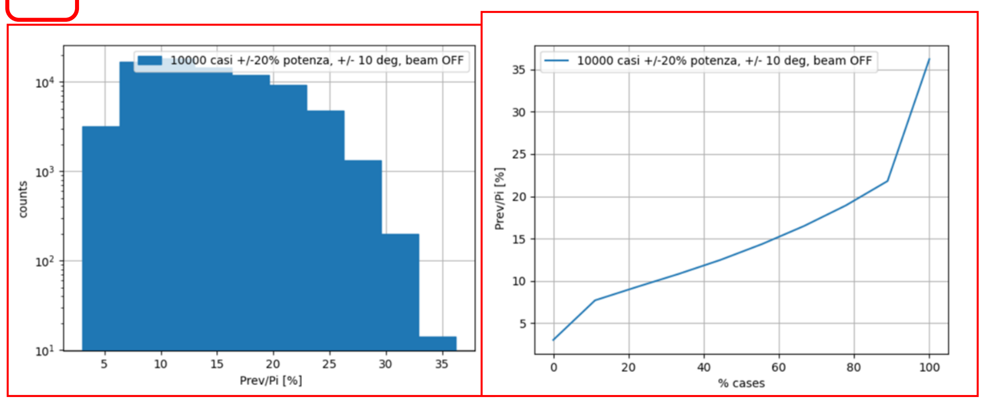
1

N. Amplifiers ON	P reverse back to each amplifier ON	P reverse back to each amplifier OFF
1	70.3%	2.1%
2	50.4%	8.4%
3	31.9%	18.9%
4	17.7%	33.6%
5	7.6%	52.5%
6	1.7%	75.6%
7	0.0%	103%
8	2.5%	-

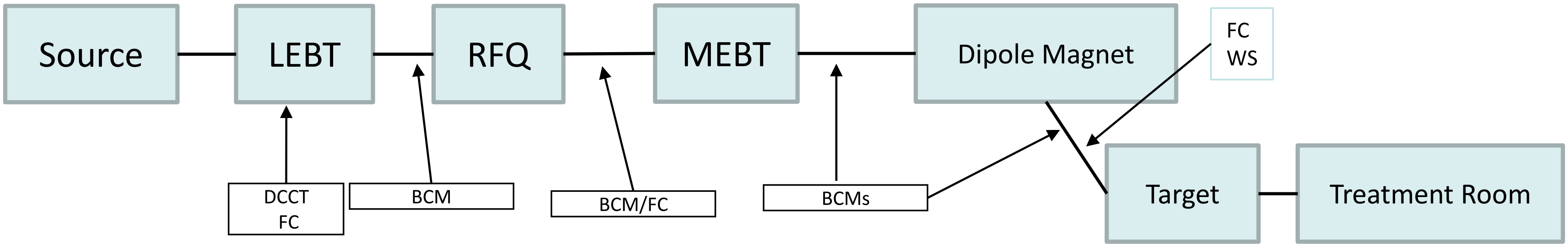
2



3



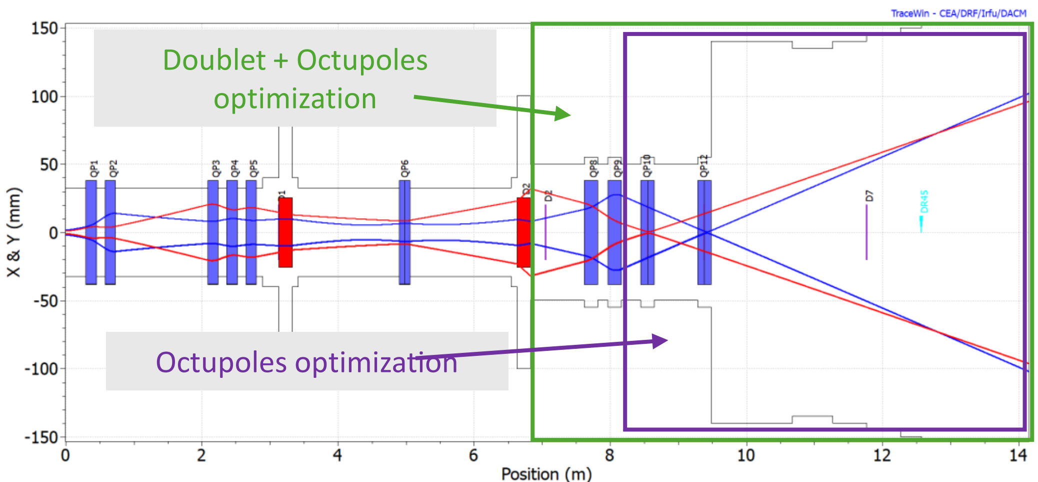
Anthem Accelerator Controls

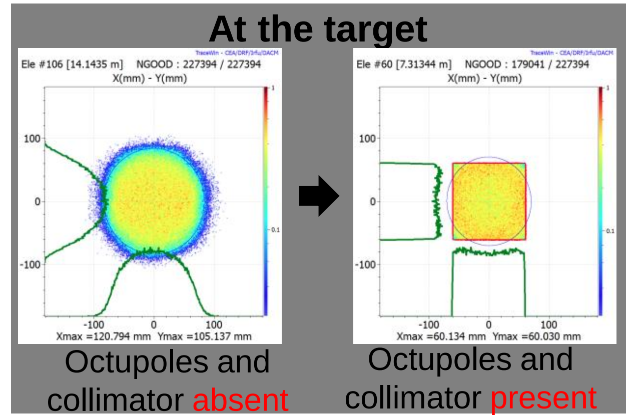


Accelerator Control System:

- **Ion Source**: HV platform and ground PLCs updated to Siemens family – software upgrade WIP; MPS update REQUIRED; FUG PS communication upgrade DONE, direct interface to high-level control (EPICS) WIP; no beam profile used; DCCT to be integrated in high-level control (EPICS); cooling system upgraded required
- **LEBT**: lens PS based on CaenELS HW (already used in ALPI) - SW already available, minor modifications; FC requires integration to MPS system, PS upgrade for Repeller with CaenELS HW; DCCT and ACCT to be integrated in high-level control (EPICS)
- **RFQ**: logic and algorithms inherited by IFMIF controls (high-level logic); vacuum upgrade with actual SPES HW and SW – devices (pumps, etc.), logic update and configuration required; cooling skid based on ESS DTL controls, integration logic required (migration from ESS to Anthem SW standards).
- **RF system**: LLRF developed at LNL. Connected to MPS. RF acquisition system upgrade (based on uTCA technology)
- **MEBT:** lens PS based on CaenELS HW, SW already available.
- **Dipole Magnets:** device control must be interfaced to high-level control (EPICS)
- **Target:** cooling, temperatures, venting,
- **Fast acquisition** technology based on microTCA boards.
- **MPS**: 2 BCMs for beam losses and target temperatures.→ Fast Beam Inhibition: IS magnetron, RF system.

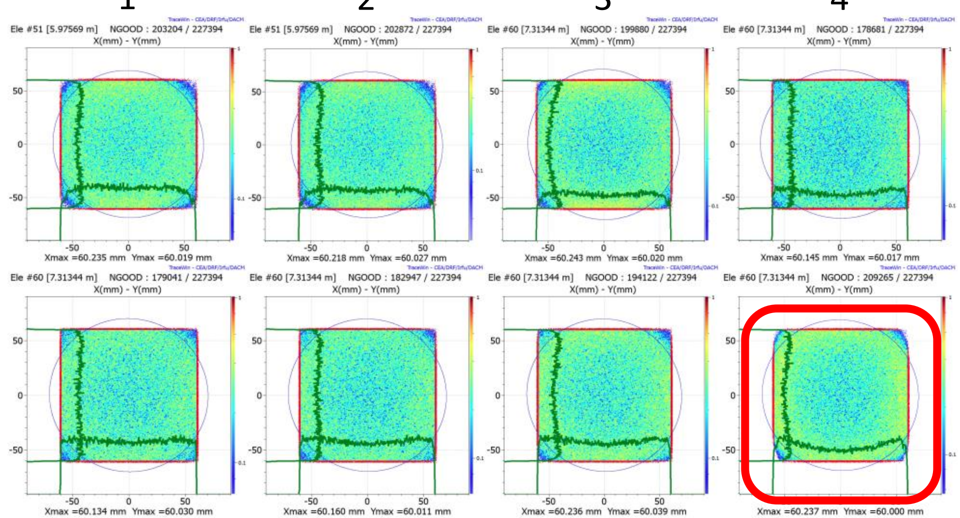
MEBT layout: losses and uniformity





Losses

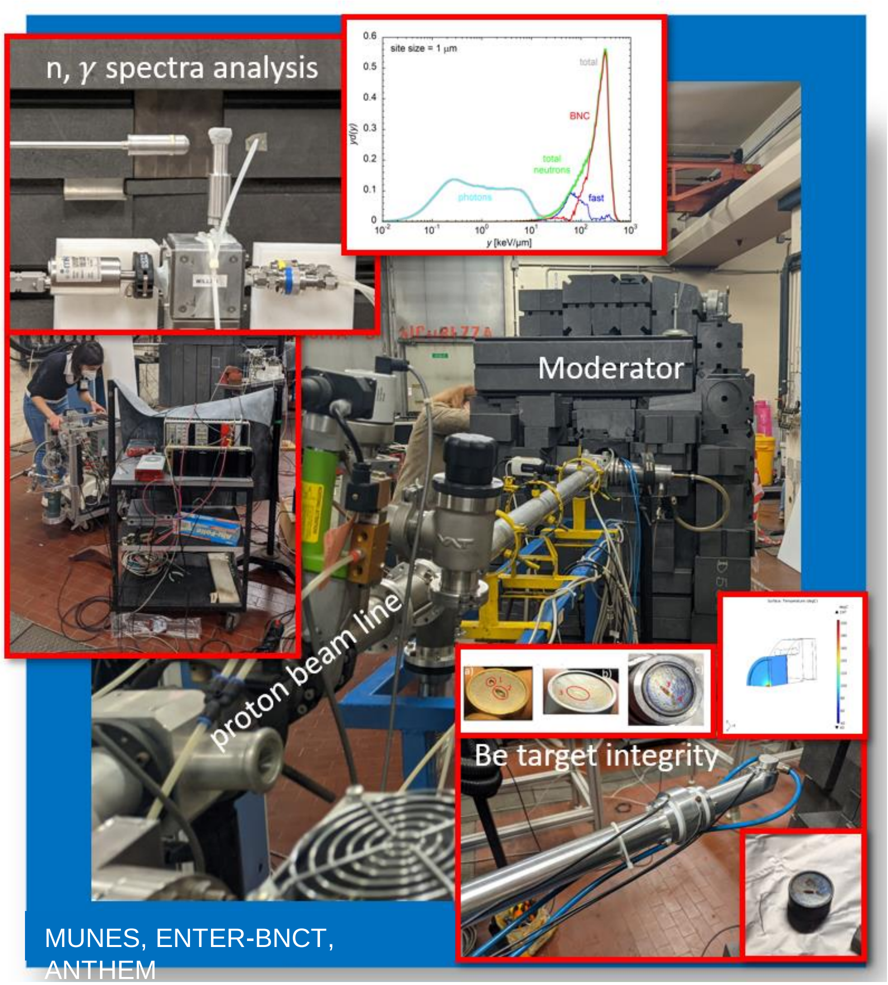
1 2 3 4



5 6 7 8

Distribution Uniformity

Target compositions and neutron spectra: testing activities



5 MeV, 5 uA proton accelerator at LNL is used to test target compositions and neutron spectras.
Two lines are used with Be targets:

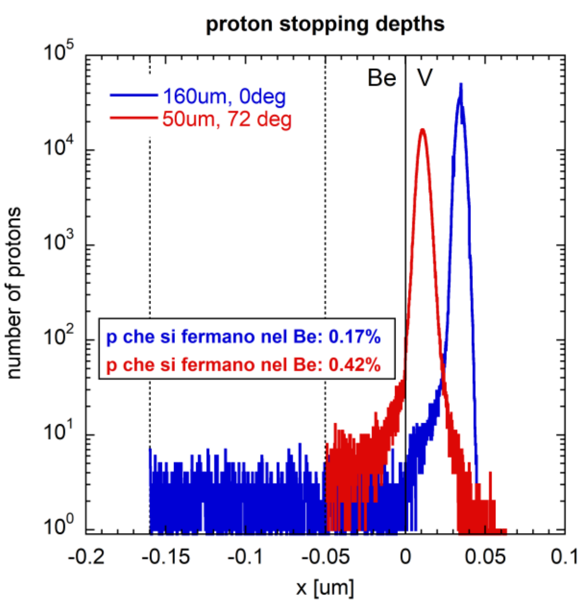
- MUNES line equipped with thermal neutrons heavy water graphite moderator, **4.5×10^5 n $s^{-1}cm^{-2}$, 96% thermal fraction**
- BELINA line equipped with TOF for neutron spectra measurements **3.6×10^6 n cm^{-2} s^{-1}** (@ 20 cm), peaked at 1.2 MeV, with maximum 3.2 MeV, **broad-spectrum energy** (without moderator)

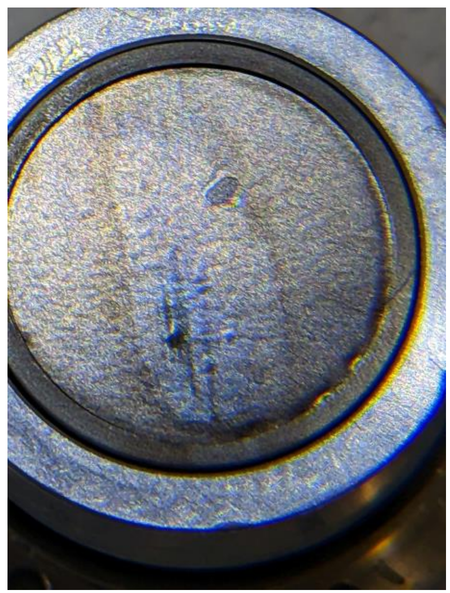
- ➢ Developed several water-air cooled prototype target assemblies, capable of sustaining up to 2.5 kW/cm^2 over 0.5 mm radius spot, with different impact angles.
- ➢ Micro-dosimetry and neutron spectra measurements with/without thermal moderator

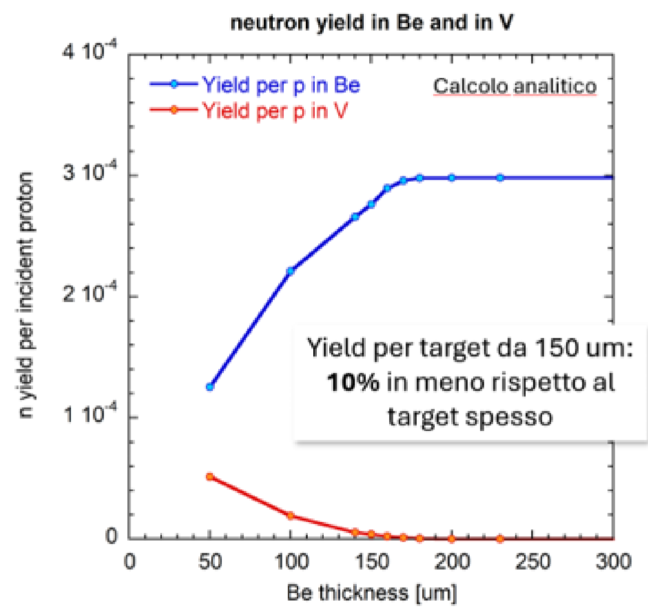
Target: orientation and thickness

Analyzing the last experimental data at LNL-CN (BeVCu), the conclusion is to use a target orthogonal to the beam:
→different thickness
→similar neutron production
→1/3 of proton stopping on BE layer (blistering)
→higher power density

TARGET ID	turno	Data	Angolo [deg]	Dens pot [W/cm^2]	Durata [h]	FLUENZA [cm^-2]	BLISTERING
BeVCu 1	6	mar 2022	72	393	77.5	1.4E+20	sì
BeVCu 1	7	lug 2022	72	393	11	1.9E+19	
BeVCu 2	8	lug 2022	72	27	95	1.2E+19	sì
BeVCu 2	9	dic 2022	0	637	48	1.4E+20	no

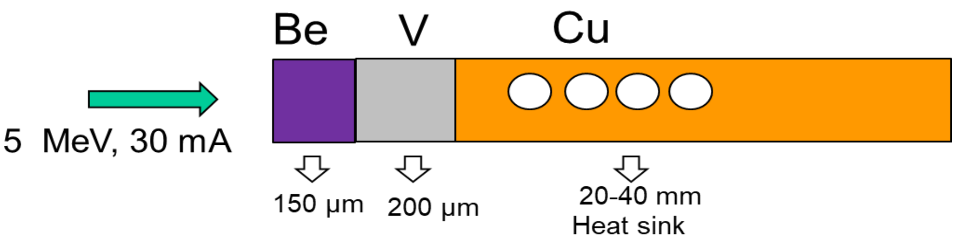


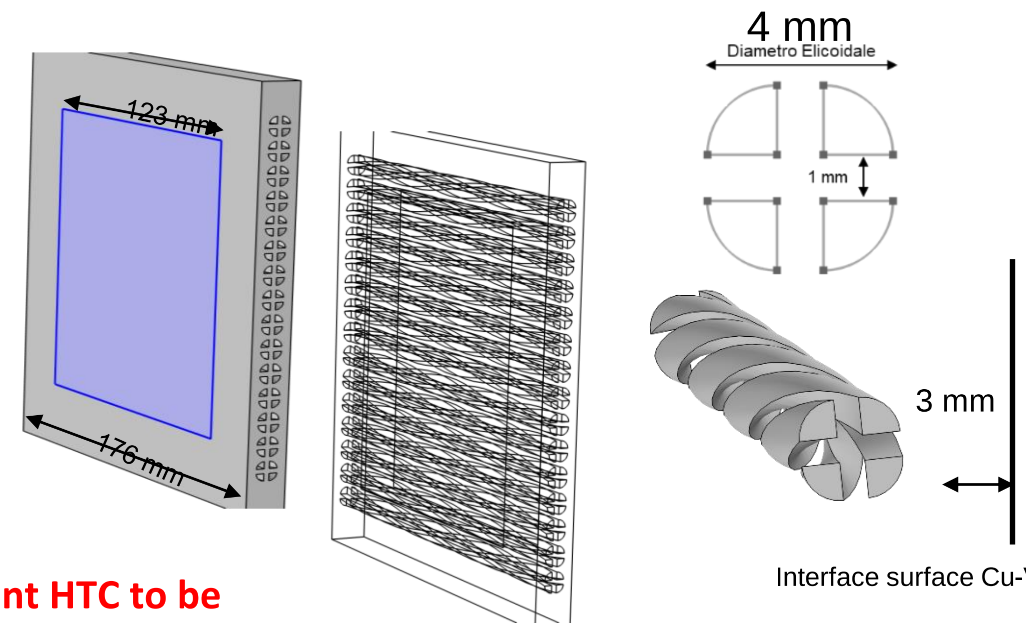




Target: general concept

The proposed Be/V/Cu target configuration:



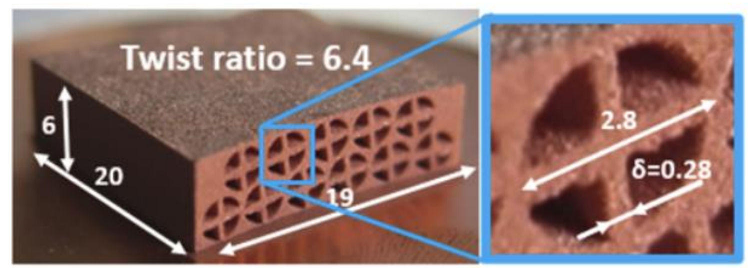


Interface surface Cu-V

Produced by **additive manufacturing (Cu-OFE)**

- **operation with 1 kW/cm2 ➔ heat transfer coefficient HTC to be maximized h > 5•10^4 W/m^2 K)**
- New heat dissipator configurations unavailable with traditional techniques
- Microchannels (different geometries) to improve water cooling
- Cu-OFE powder technology now very well known with leading-edge Additive Manufacturing

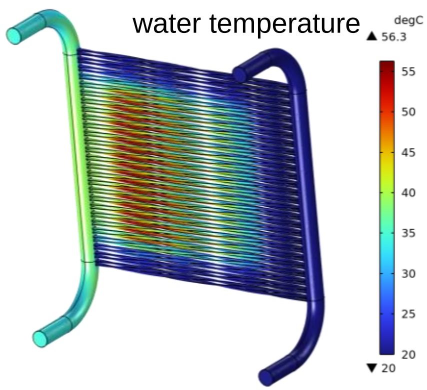
Be and V coating deposition with Hot Isostatic Pressure (HIP) process

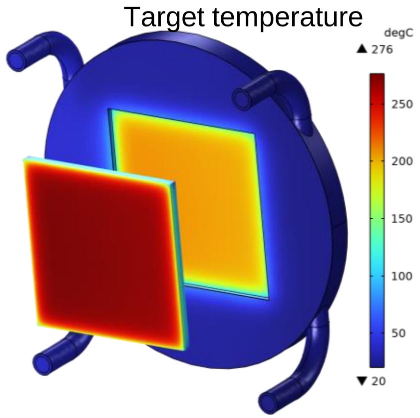


J. Esposito et al. "Experimental and numerical characterization of pure copper heat sinks produced by laser powder bed fusion" Materials & Design Volume 214, February 2022, 110415

Target: thermal studies, sampling and integration

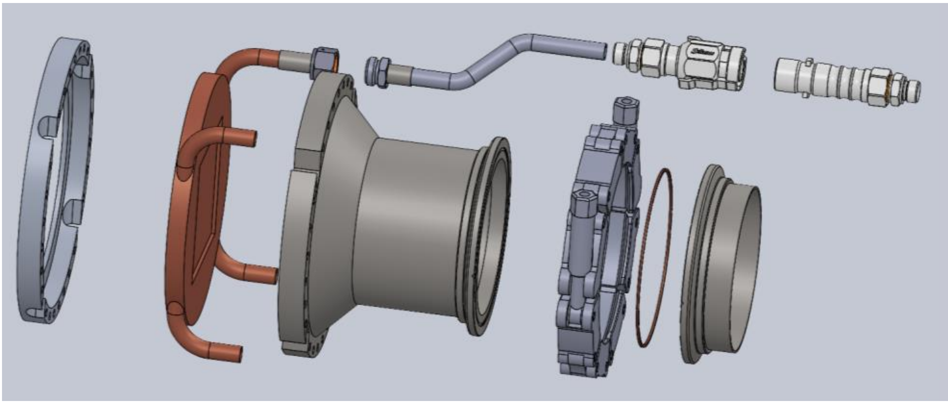
flow [l/min]	Reynolds	velocity [m/s]	pressure drop [bar]	Cu surface temp [°C]	Hc global [W/(m²·K)]	Max water Temp [°C]	Max wall Temp [°C]	Average exit water Temp [°C]
80	11155	7,5	1,9	224	48935	81	124	47
100	13931	9,4	3,0	212	51997	71	112	42
120	16741	11,3	4,2	203	54579	64	103	38
150	20798	14,0	6,3	193	57798	56	93	35



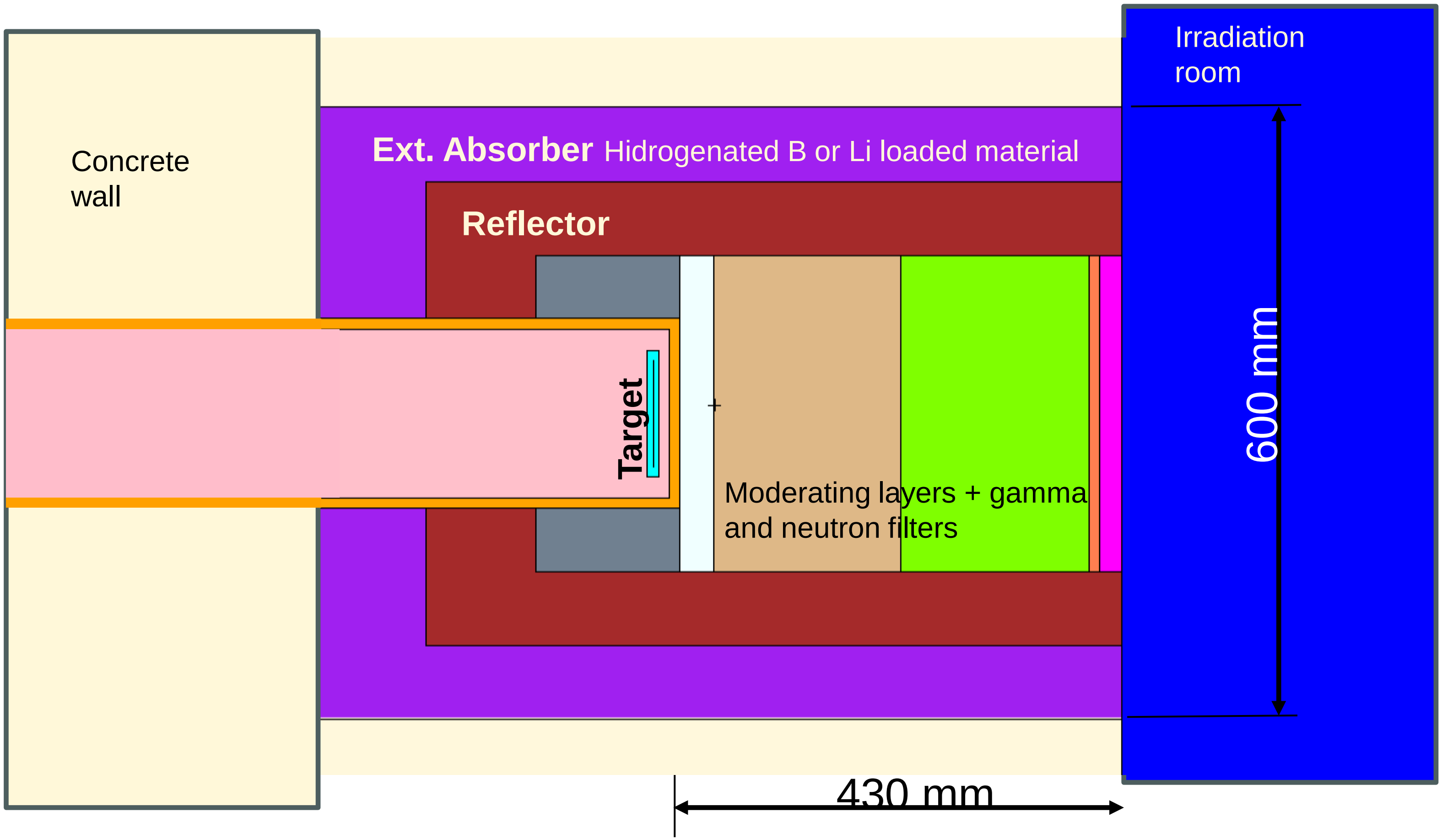


Thermal maps of the Be-V-Cu target
maxT(Be)-aveT(Cu) = 82° C
MaxWater temperature 56° C

- HIP and AD process under sampling with dedicated industrial partners
- Target integration in a Aluminum vacuum chamber (low activation) with fast clamping to the beam line
- Integration of the inlet and outlet hydraulic manifold with the target and the vacuum chamber
- Hydraulic hoses with fast connectors



Moderator or BSA



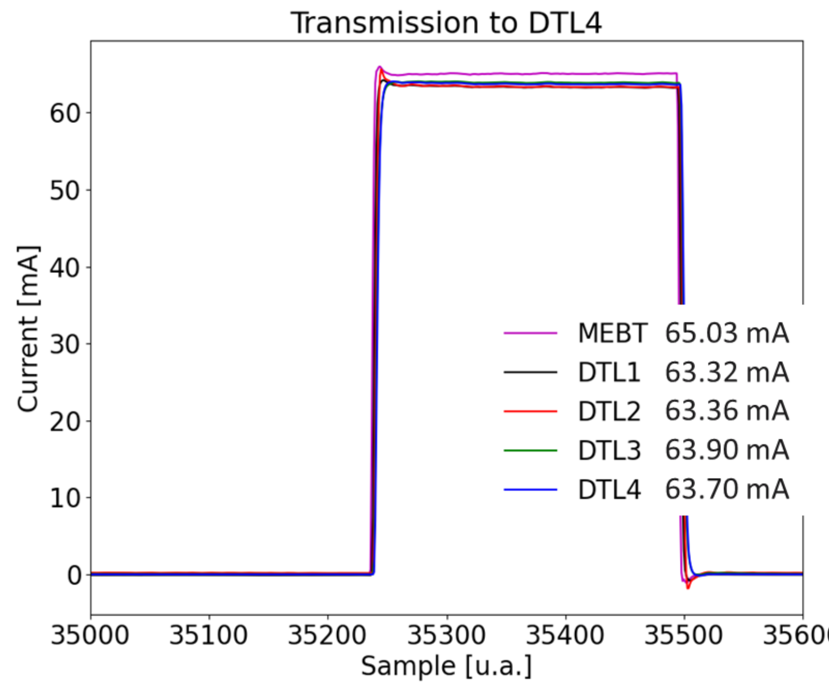
Reflector: to concentrate the neutron flux to the central bulk of the BSA (Pb)
External Absorber: boron loaded polyethilene layer to absorb neutron not reflected back by the reflector
Moderator: various layers to shape the neutron spectra from fast to epithermal (AlF_3 or MgF_2), and to filter thermal neutron (LiF) and photons (Pb or Bi)
Collimator: specially tailored aperture to give the neutron beam the proper shape to match the clinical requirements

Conclusions

- Use of existing main components still at technology frontier.
- Participation of LNL, LNS, Pavia, Torino and Napoli INFN sections.
- Procurement of main components with Napoli and LNS.
- Experimental test at LNL of accelerator, BSA and target components
- Commitment for design, integration, production, installation and commissioning of the full LINAc at Caserta site.
  - ✓ Ion source restarted
  - ✓ RF amplifier tender assigned
  - ✓ Main tender for RFQ ancillaries to be assigned in 2024
  - ✓ RFQ refurbishment on going
  - ✓ Transport lines designed; magnet procurement started
  - ✓ High power target design close to finalization, sample procurement already started (Additive Man. and HIP technology)
  - ✓ Cooling skid refurbishment on going

ESS update

- 5^{th} DTL installed in Sept 2023
- DTL5 conditioning and commissioning from October 2024.



DTL1 to 4:
- Full power RF conditioning
- Full beam current transmission

ESS update

RF windows arcing

After some weeks of full power operation, the DTL2 an DTL3 RF windows start arcing.

All windows have been successfully high power tested at CEA.

On going activities:

→ repetition of RF test to reveal performance degradation

→ Deep analysis of the design and production (coating, RF, Multipacting)

→ refurbishment of existing window with original company (TiN coating improvement)

→ consultancy of worldwide experts to identify all possible weak points (coating, MP, vacuum, conditioning process,…)