Fasci di alta potenza per il test dei materiali dei futuri reattori di Fusione: il progetto IFMIF

International Fusion Material Irradiation Facility

Andrea Pisent
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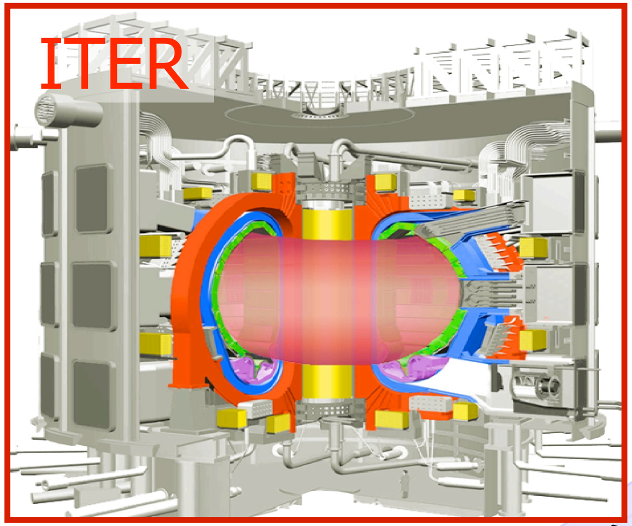
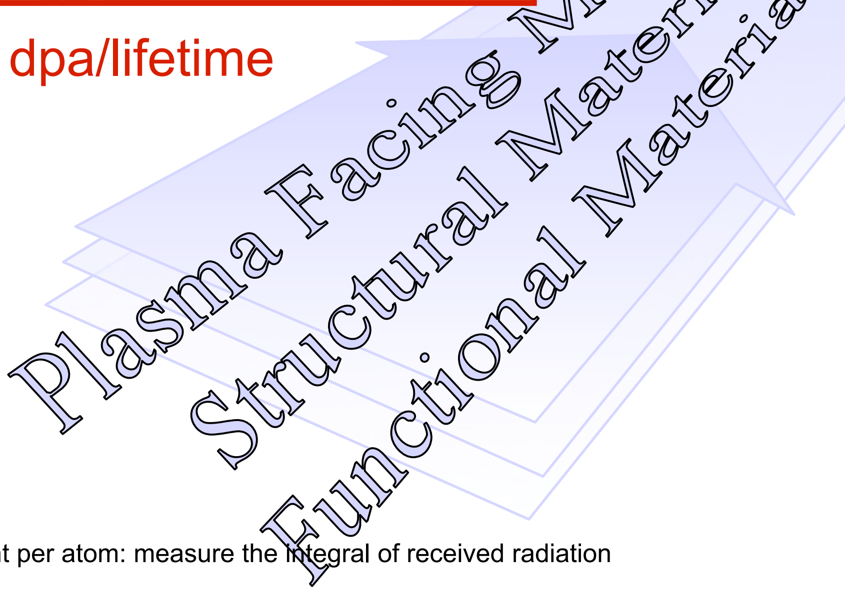
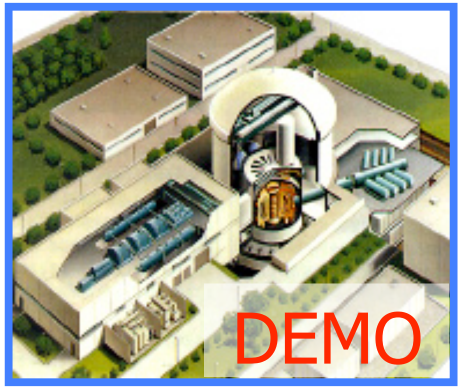
Nuclear Fusion International Road Map

Advanced Materials are at a critical path

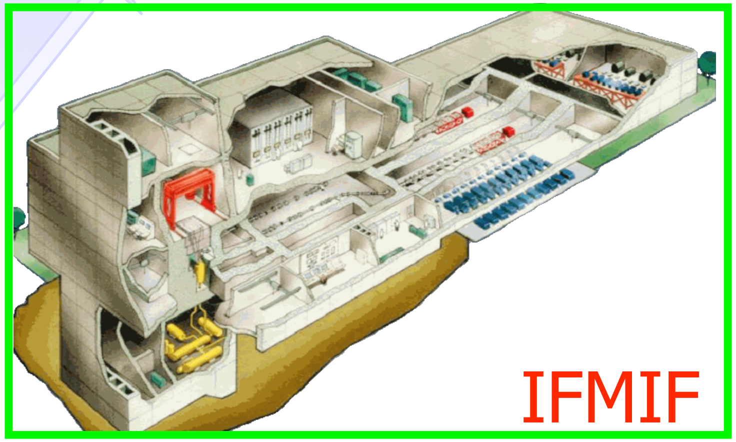


1-3 dpa/lifetime





< 150 dpa



20-40 dpa/year

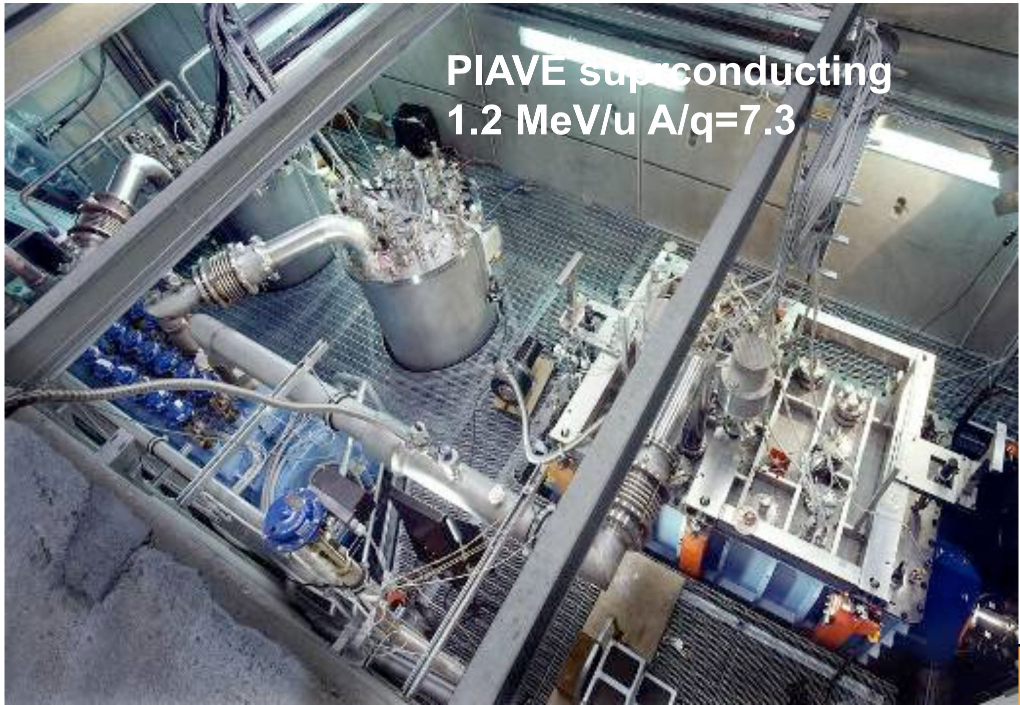
International Fusion Materials Irradiation Facility

Dpa: displacement per atom: measure the integral of received radiation

Applications of high power beams

- Light ion beams from particle linear accelerators beam power MW range
- Main applications:
  - Nuclear fusion: **Fusion reactors Material Irradiation** tests under large neutron fluxes (IFMIF) 40 MeV, 250 mA deuterons
  - Nuclear fission: **nuclear waste transmutation**, i.e. processing of the nuclear reactor fuels to eliminate (ideally) long lived radiactive components, material science Fundamental Physics (above 1 GeV protons)
- Contribution of **Particle Accelerators** to the development of clean nuclear power
- Contribution from **High Energy Physics and Nuclear Physics** community (and INFN in particular)

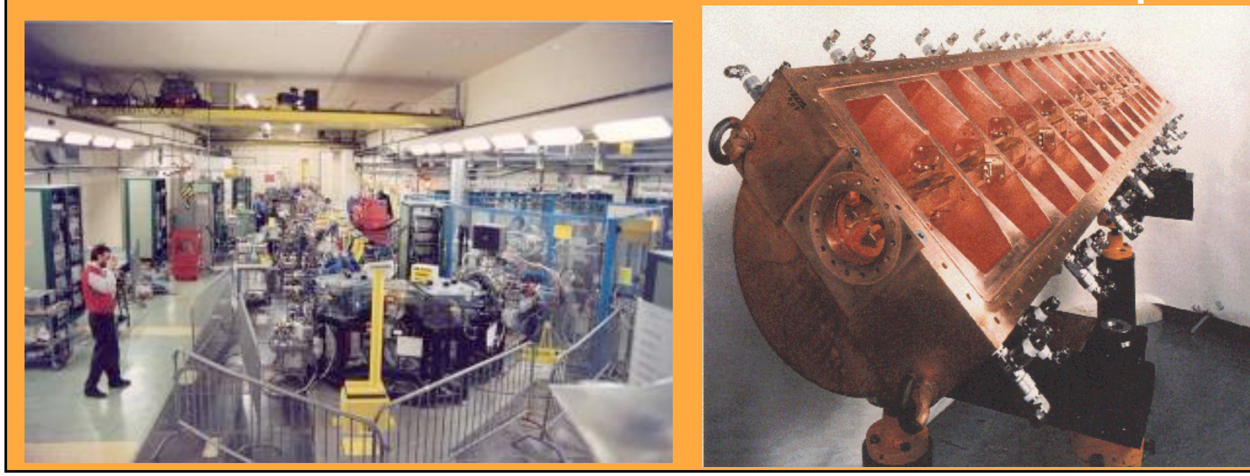
Linear Accelerators by INFN Legnaro



PIAVE su[illegible]conducting
1.2 MeV/u A/q=7.3

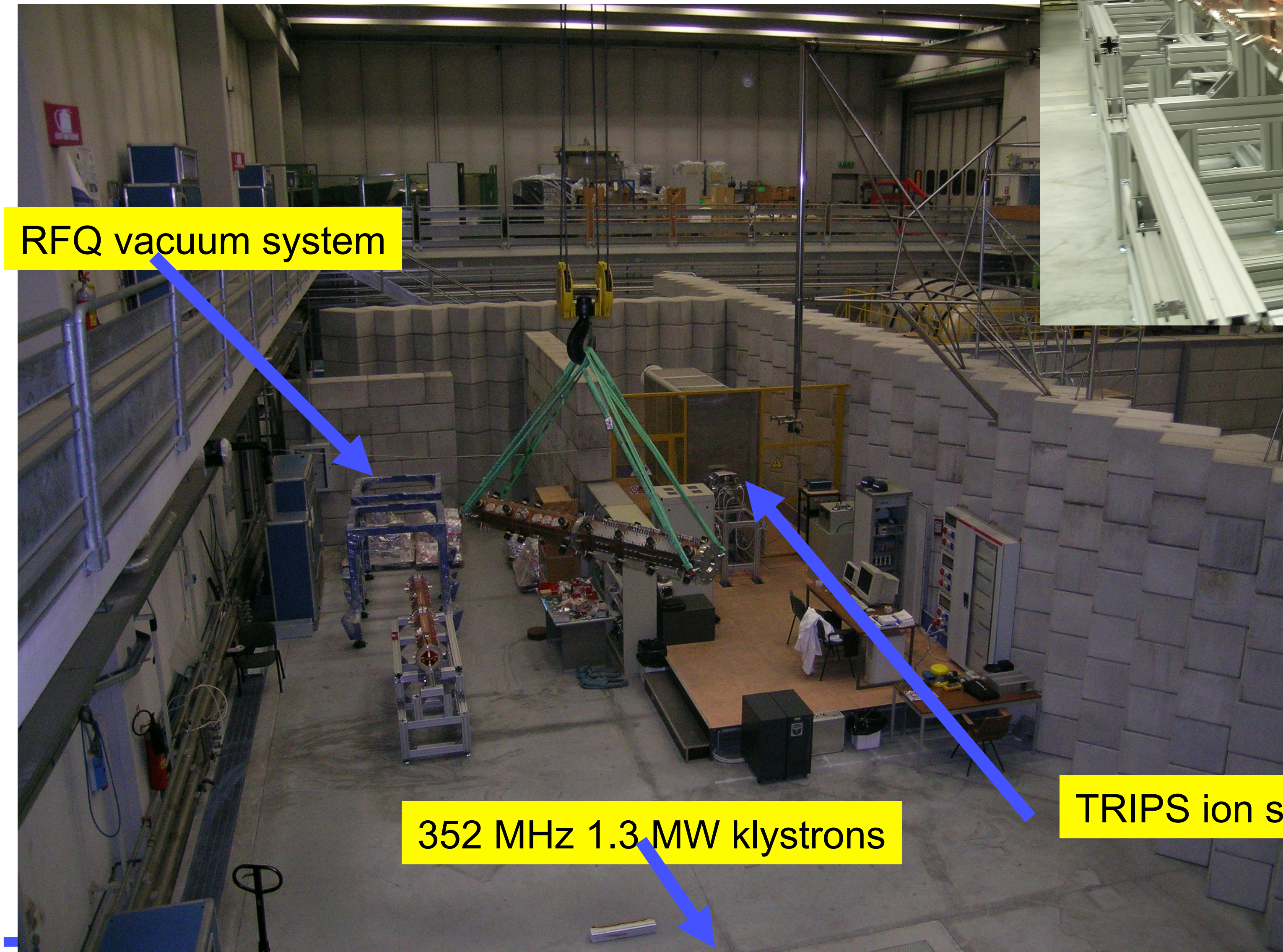
ALPI suprconducting
7 MeV/u A/q=7.3

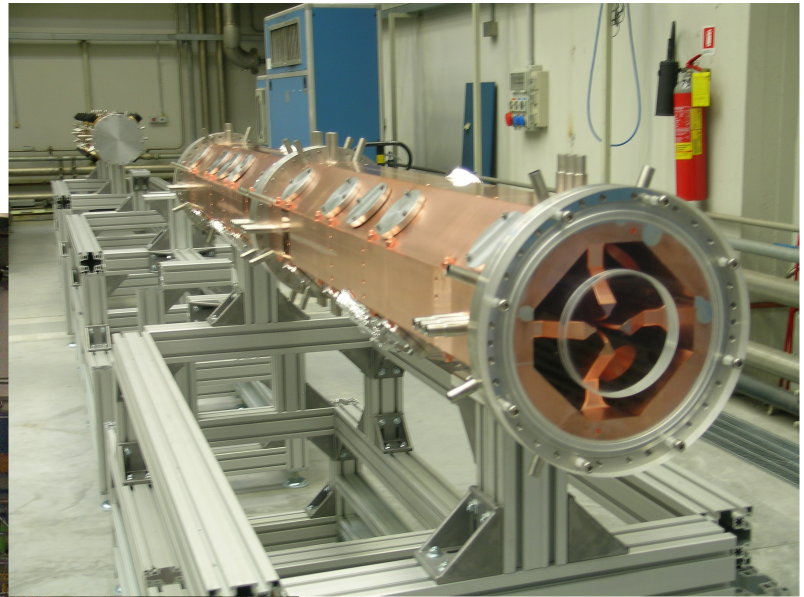
First SC RFQ in the world



CERN Linac 3 RFQ nc 250 keV/u A/q=8

High intensity experimental area at LNL during TRASCO-RFQ delivery

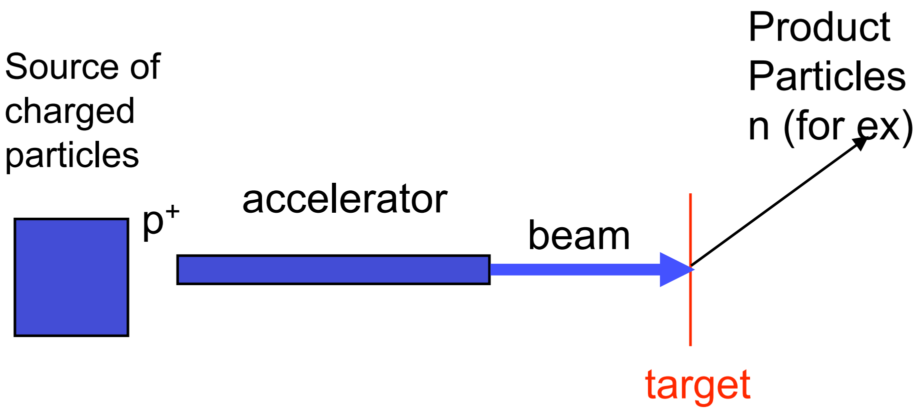




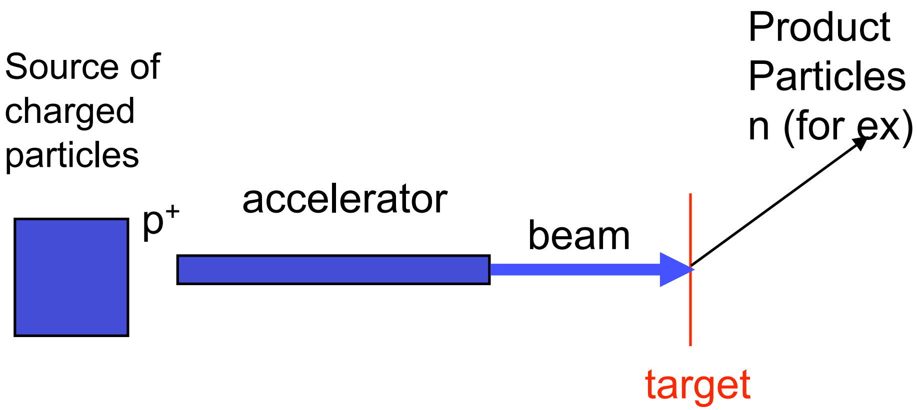
Energy range: 0.08 - 5 MeV
Beam current: 30 mA CW
Beam Power: 150 kW
Frequency: 352 MHz
7.2 meters long
1000 kW RF power injected (1 Klystron)
8 Couplers
4500 Liter/min water cooling
33 MV/m Surface field
Transmission: 98%

Introduction: High intensity

Scheme of experiment with accelerated particles



Scheme of experiment with accelerated particles



- If the target is thin (i.e. if multiple scattering has low probability) neutron production rate is

$$\frac{dN_e}{dt} = \sigma \left[\frac{N_d}{S} \frac{dN_i}{dt} \right]$$

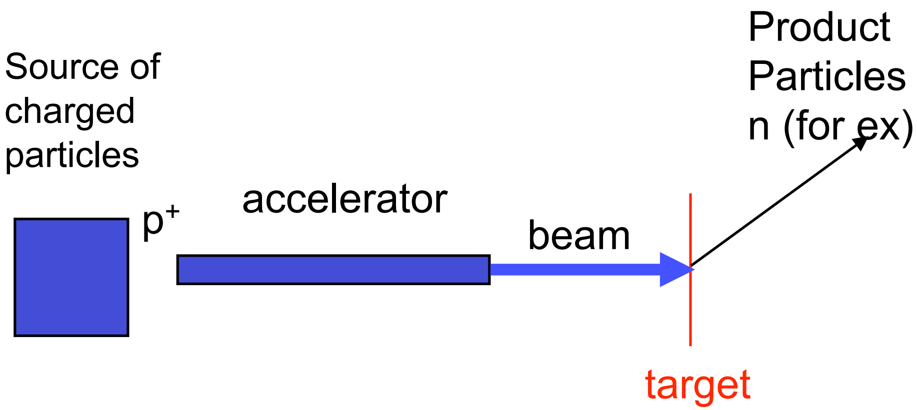
Cross section (σ)

Target thickness (N_d / S)

Beam current (dN_i / dt)

Scheme of experiment with accelerated particles

Low intensity



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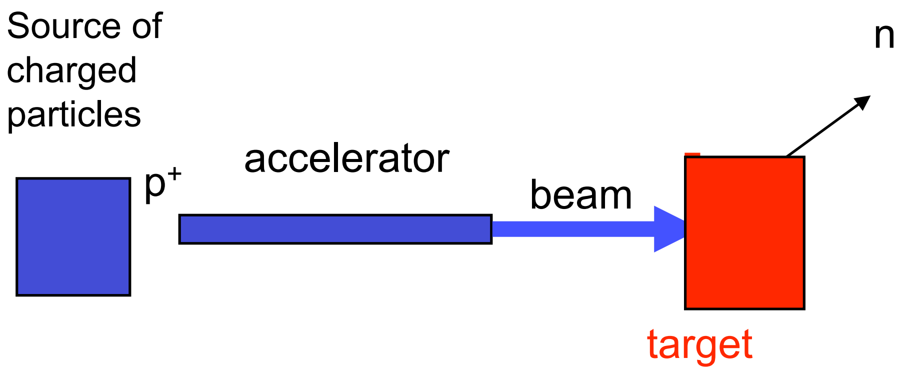
$$\frac{dN_e}{dt} = \sigma \left[\frac{N_d}{S} \frac{dN_i}{dt} \right]$$

Cross section

Target thickness

Beam current

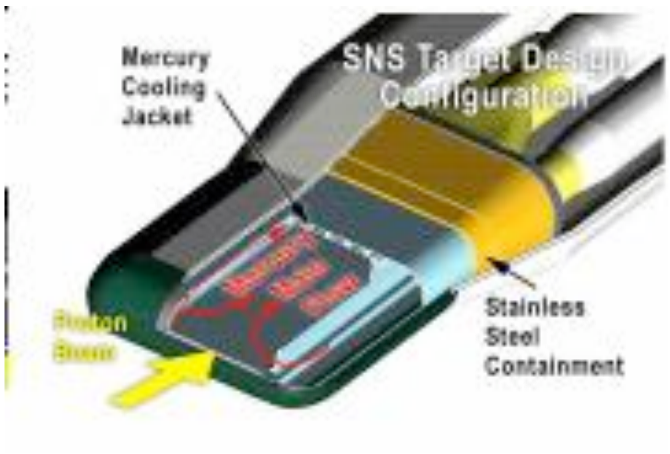
High intensity



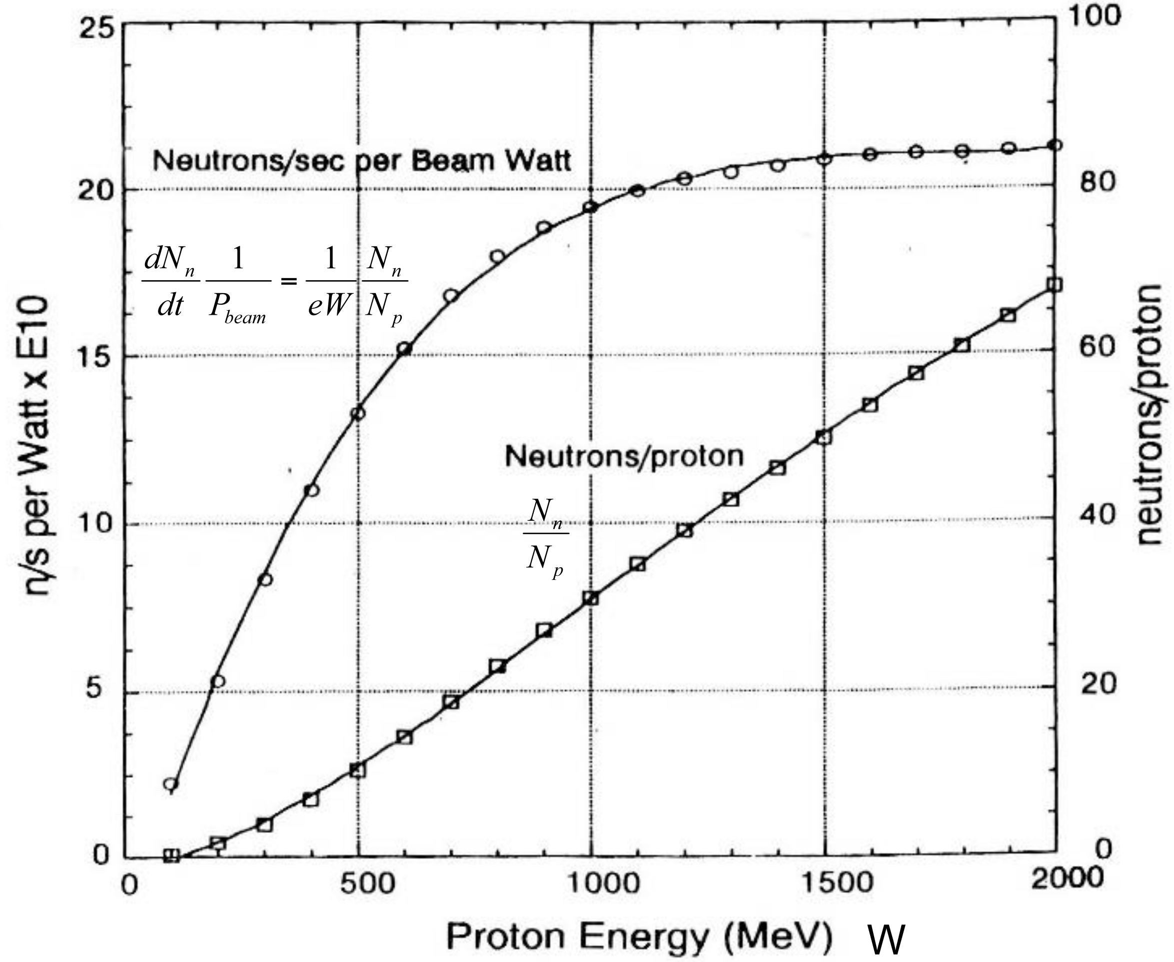
- To increase the production of particles (for given conditions or fixed σ) one needs
  - **High power** beam
  - **Thick target**. The beam power is (almost) completely dissipated in the target mainly with electromagnetic scattering into the electrons in the material.

beam-target choices neutron production (1/2)

- 1-3 GeV protons with high Z solid or liquid metal **spallation** target



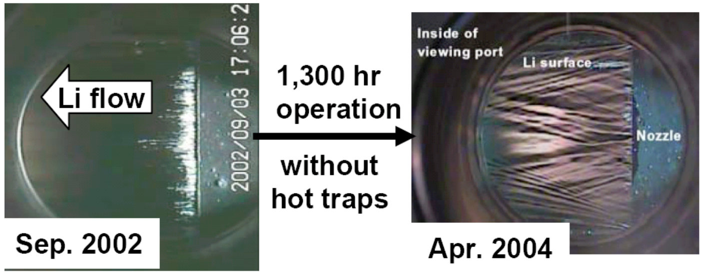
SNS mercury target



Important alternative the **Pb Bi** target developed for TRASCO (10-30 MW)

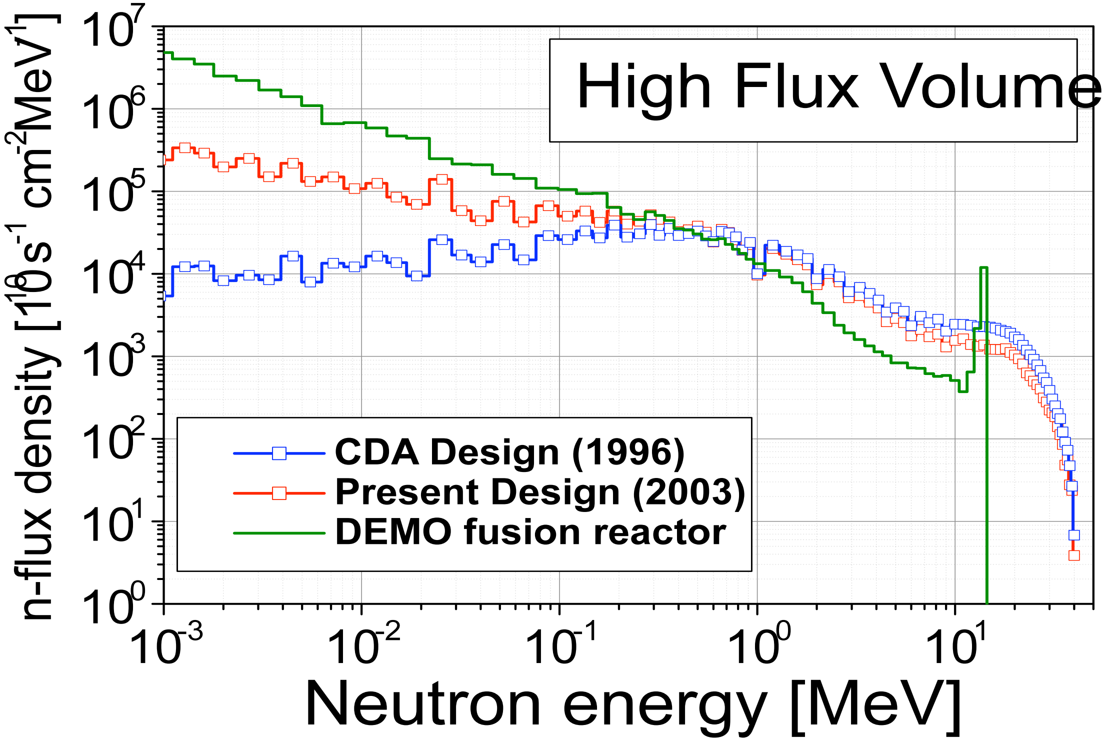
Three beam-target choices neutron production (2/2)

- **40 MeV deuterons** with Li target **nuclear stripping reaction**



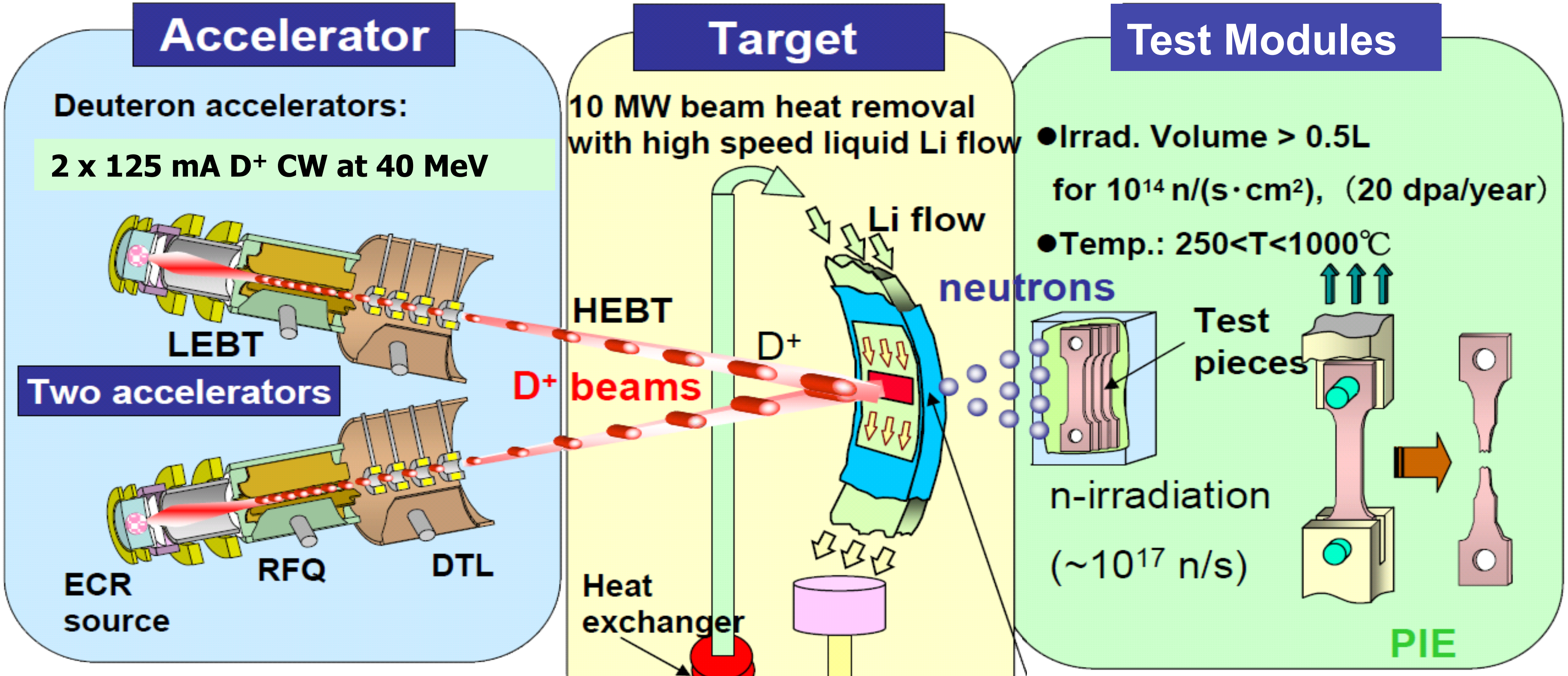
Li free-surfaces at nozzle exit

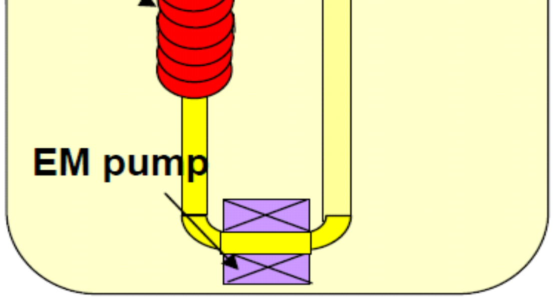
IFMIF-EVEDA tests of LI flux



- 10 MW about 10^{17}n/s and 10^{10} n/s per W or 0.06 n/d
- Typical reactions
- ^{7}Li(d,2n)^{7}Be and ^{6}Li(d,n)^{7}Be

IFMIF Principles





Accelerator based neutron source using the D-Li stripping reaction ⇒ intense neutron flux with the appropriate energy spectrum

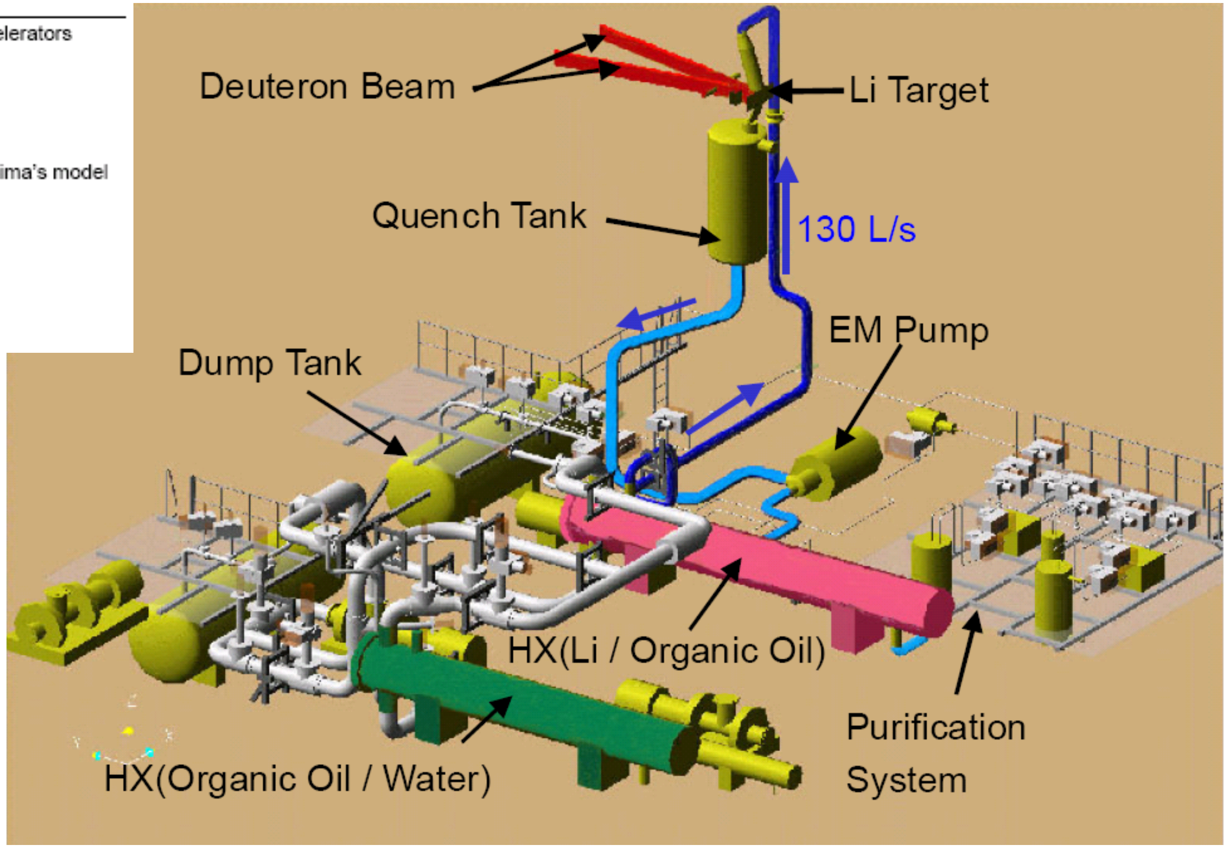
Typical reactions:
^{7}Li(d,2n)^{7}Be, ^{6}Li(d,n)^{7}Be, ^{6}Li(n,T)^{4}He

Beam footprint on Li target
20cm wide x 5cm high
(1 GW/m^2)

The Li target concept

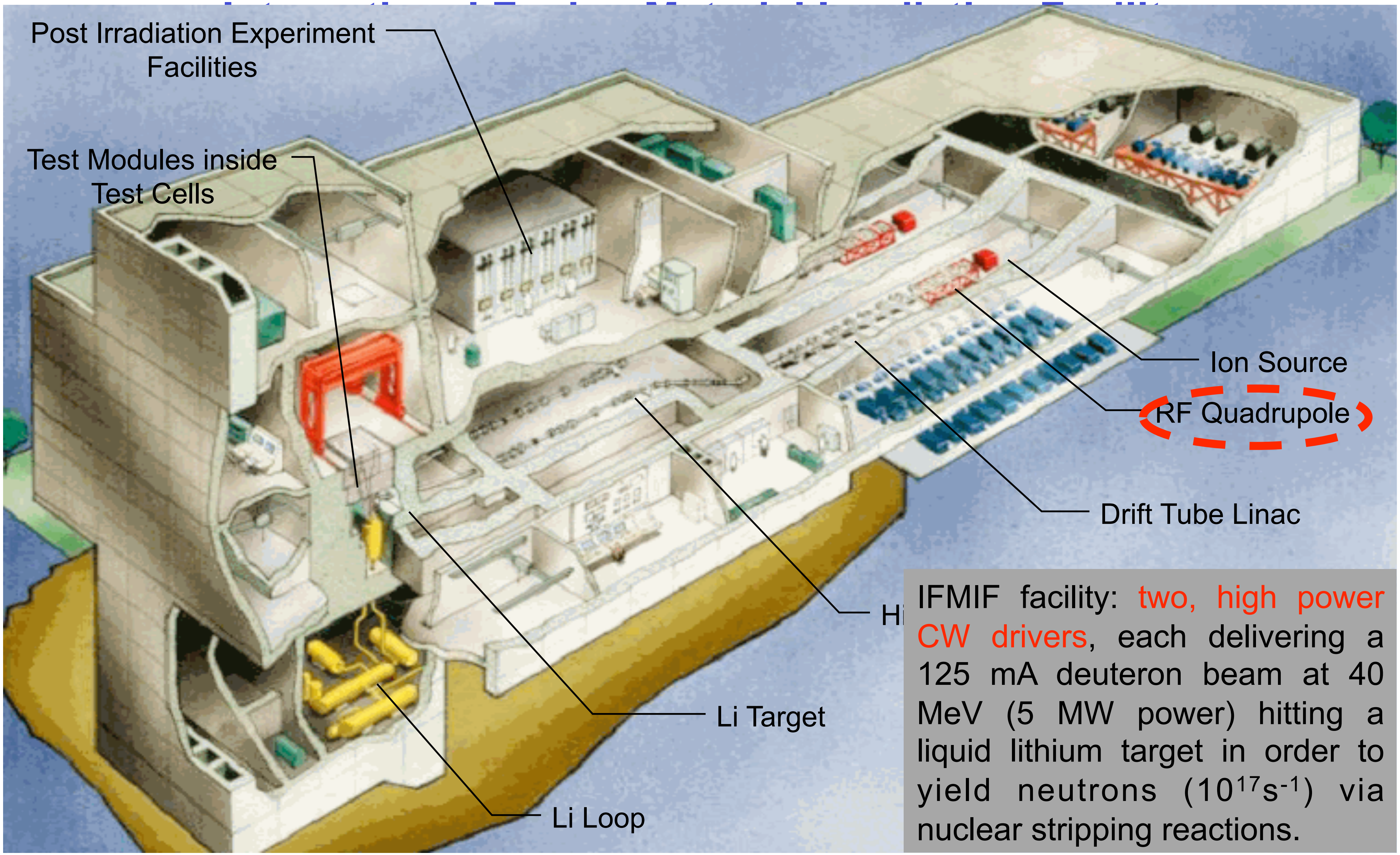
Table 3.2-1. Major design requirements of the IFMIF target facility.

Items	Parameters
Deuterium beam energy/current	40 MeV / 125 mA (nominal) x 2 accelerators
Averaged heat flux	1 GW/m^2
Beam deposition area on Li jet	0.2 m^W x 0.05 m^H
Jet width / thickness	0.26 m / 0.025 m
Jet velocity	15 (range 10 ~ 20) m/s
Nozzle geometry	Double-reducer nozzle based on Shima's model
Nozzle contraction ratio	10 (4 : 1st nozzle, 2.5 : 2nd nozzle)
Surface roughness of nozzle	< 6 µm
Curvature of back wall	0.25 m
Wave amplitude of Li-free surface	< 1 mm
Flow rate of Li	130 l/s (at target section)
Inlet Temperature of Li	250°C (nominal)



10 MW
Li solidification about 180 deg C
Li boiling about 1000 deg C

IFMIF “Artist View”

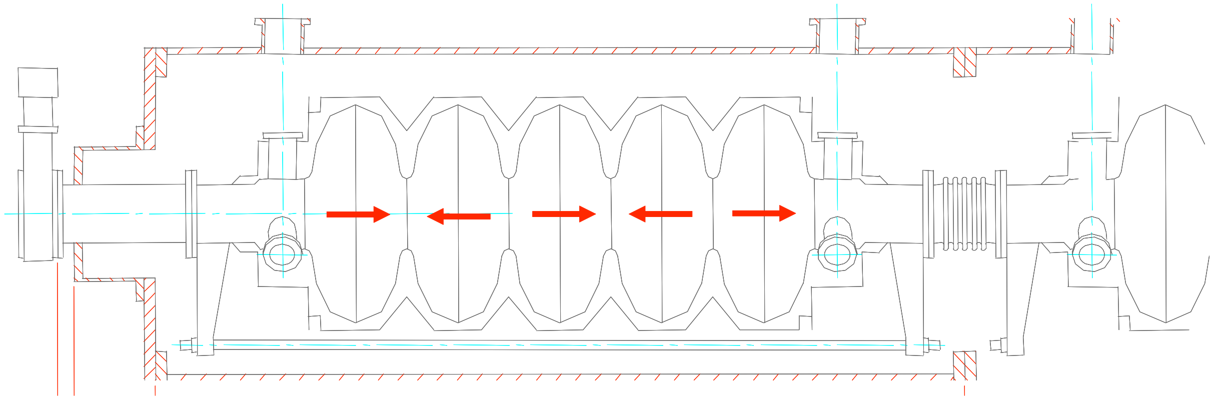


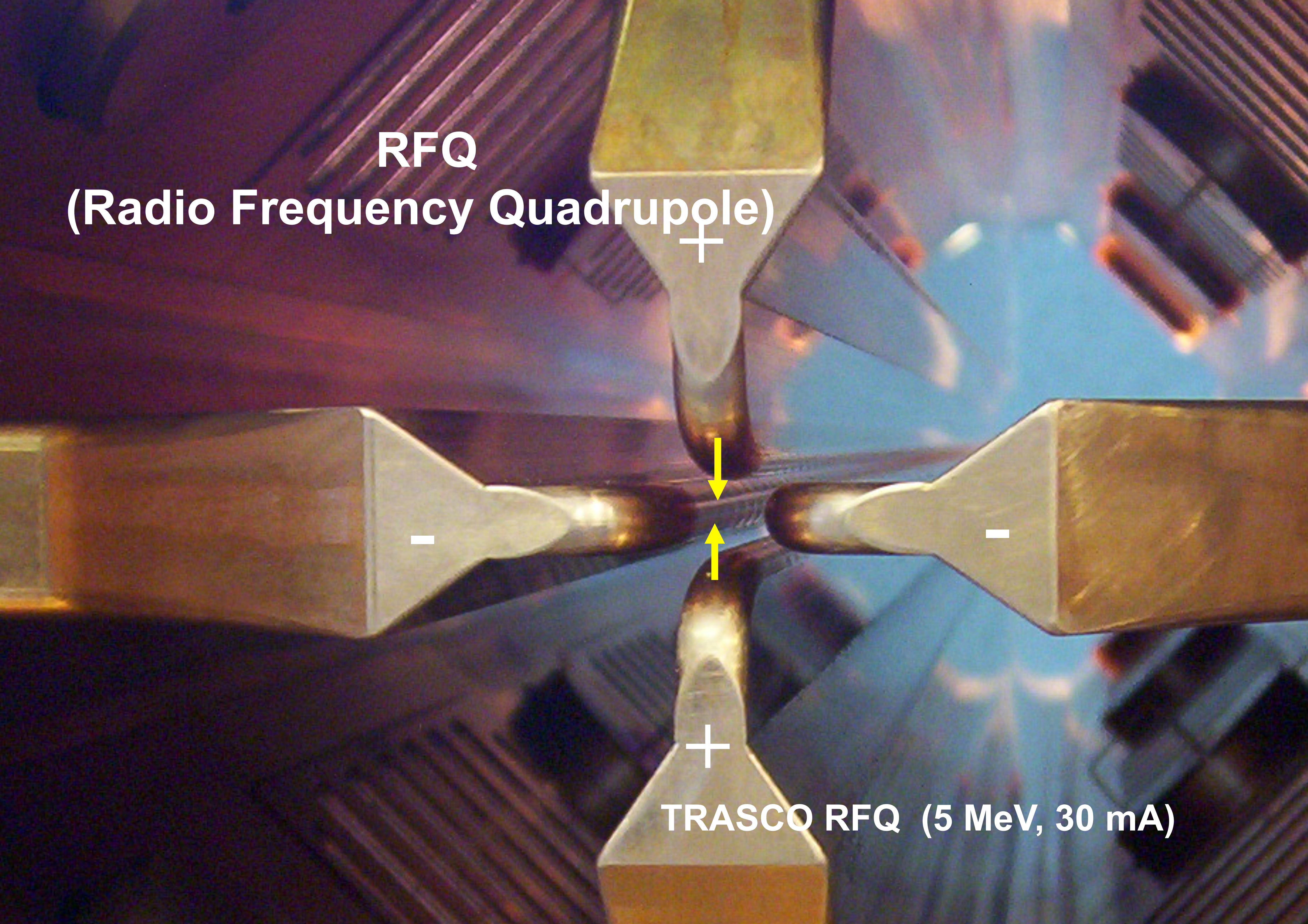
IFMIF facility: two, high power CW drivers, each delivering a 125 mA deuteron beam at 40 MeV (5 MW power) hitting a liquid lithium target in order to yield neutrons ($10^{17} s^{-1}$) via nuclear stripping reactions.

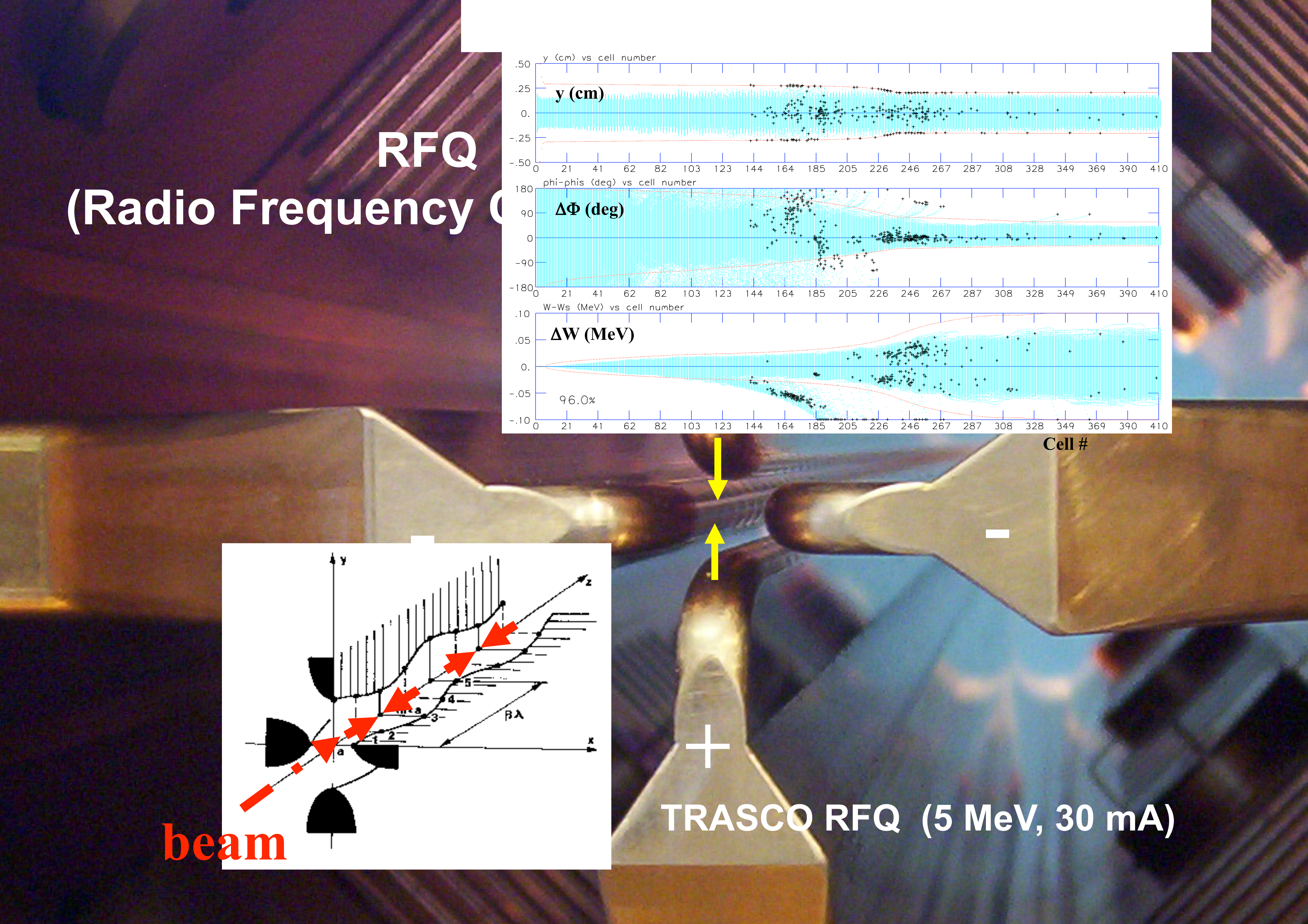
Small losses are a fundamental feature of linear accelerators of MW class

- **low losses (1 W/m, i.e. 10^{-6}) are specific of linear accelerators.**

- Linear path without extraction devices
- Large beam aperture in the main superconducting structures
- Very precise beam distribution formation in the ECR source and RFQ bunching system, and consequent control of beam halo formation



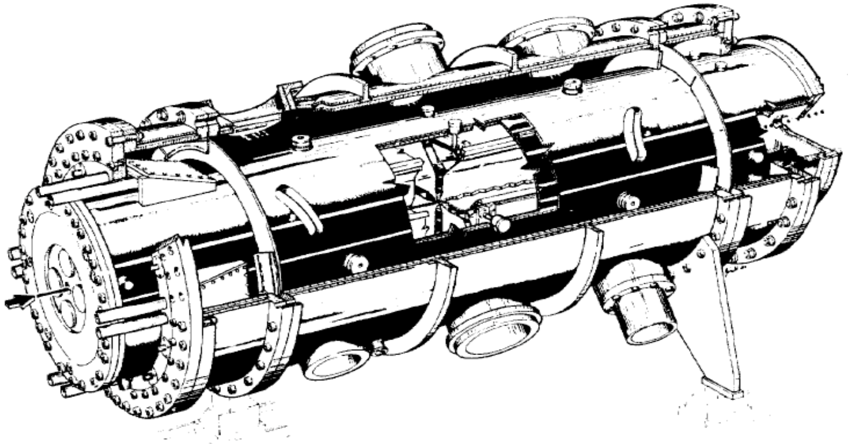

RFQ
(Radio Frequency Quadrupole)
+
-
-
+
TRASCO RFQ (5 MeV, 30 mA)

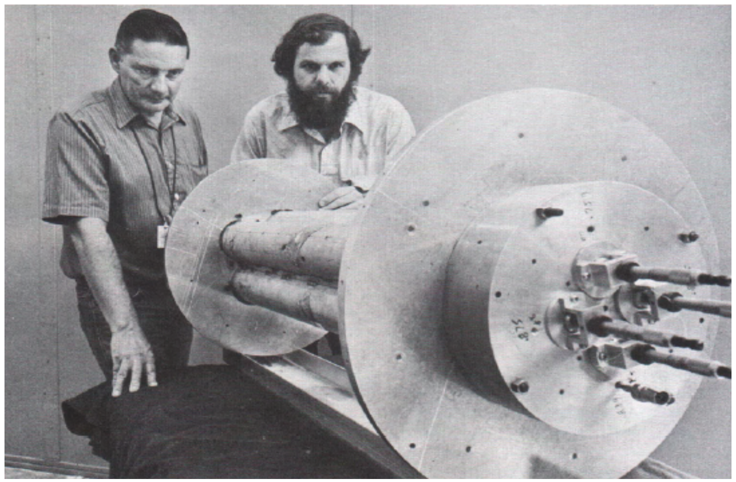

RFQ
(Radio Frequency
y (cm) vs cell number
y (cm)
phi-phis (deg) vs cell number
ΔΦ (deg)
W-Ws (MeV) vs cell number
ΔW (MeV)
96.0%
Cell #
-
+
βλ
beam
TRASCO RFQ (5 MeV, 30 mA)

Test of materials for Fusion Reactors: History

- The idea of the Fusion Material Irradiation facility based on a high intensity accelerator has been floating for many years.
- Fusion Material Irradiation Test Project - FMIT
  a US Department of Energy project, Construction project approved in 1975
- It was for example **at the basis of the RFQ developement at Los Alamos** on the basis of the idea of Kapchinsky and Teplyakof

Los Alamos Proof-of-Principle RFQ

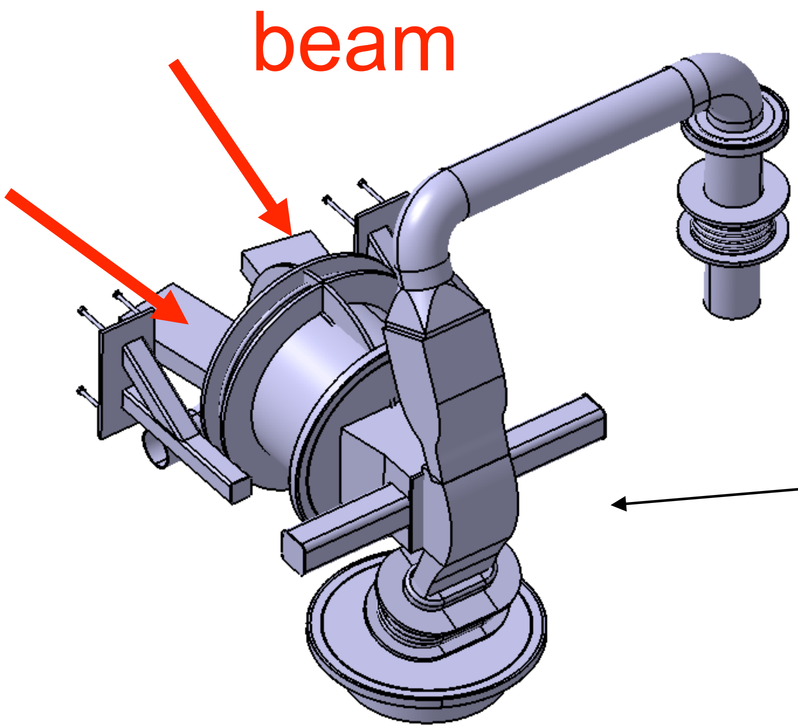


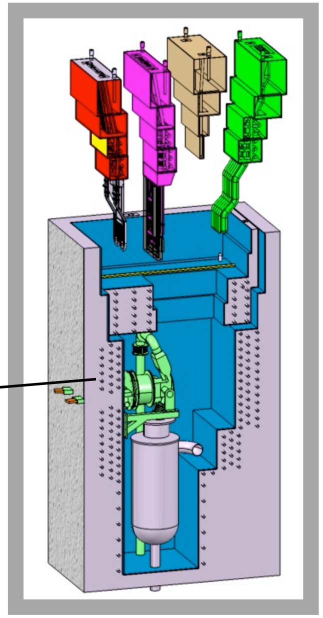


IFMIF EVEDA
(IFMIF Engineering Validation Engineering Design Activities)

- **Within the BA (Broader Approach to fusion agreement) the IFMIF EVEDA activities have been launched in 2007 following three programs**

- Prototype of the Lithium target circuit
- Experimental facility definition
- Prototype Accelerator



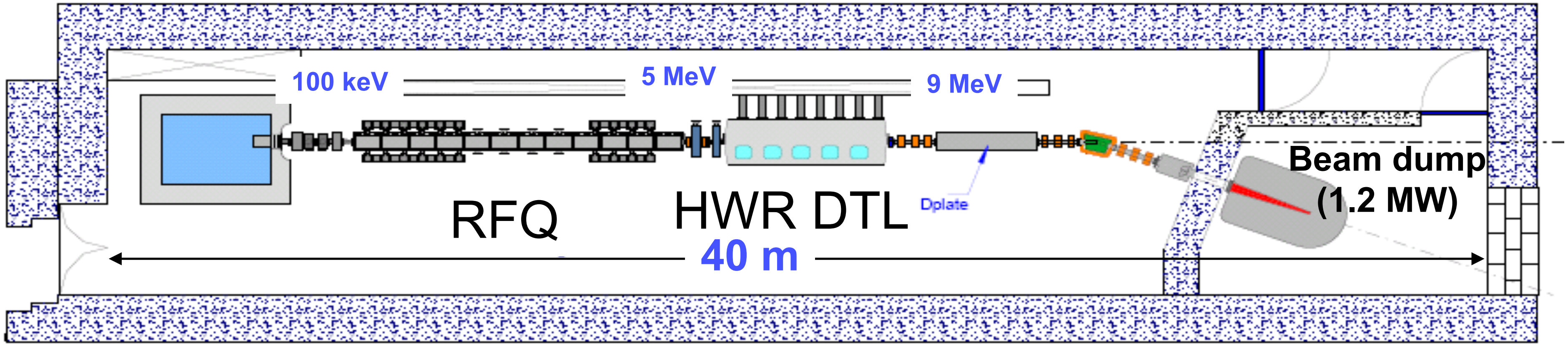


Li target assembly

Experimental assembly

IFMIF EVEDA

- Recently funded within the Broader Approach to Fusion: construction of **a 9 MeV 125 mA cw deuteron accelerator** (to be built in Rokkasho, Japan) based on a high power RFQ followed by a superconducting linac



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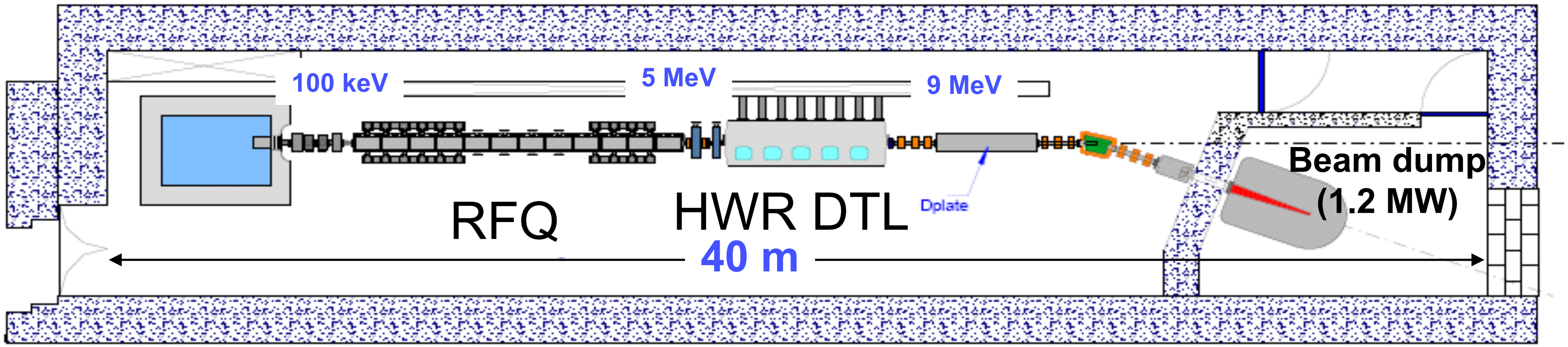

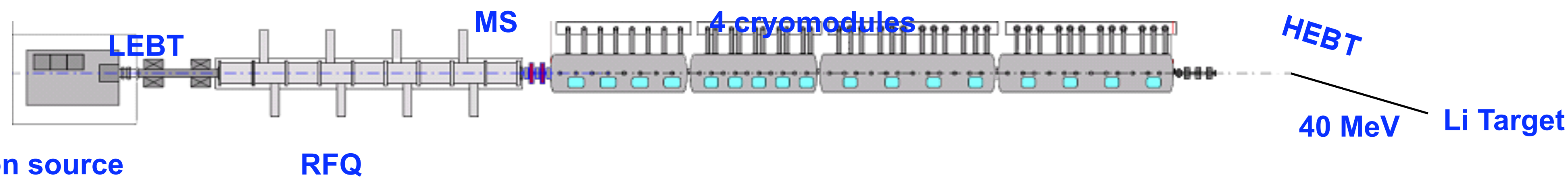

IFMIF EVEDA accelerator prototype

IFMIF EVEDA

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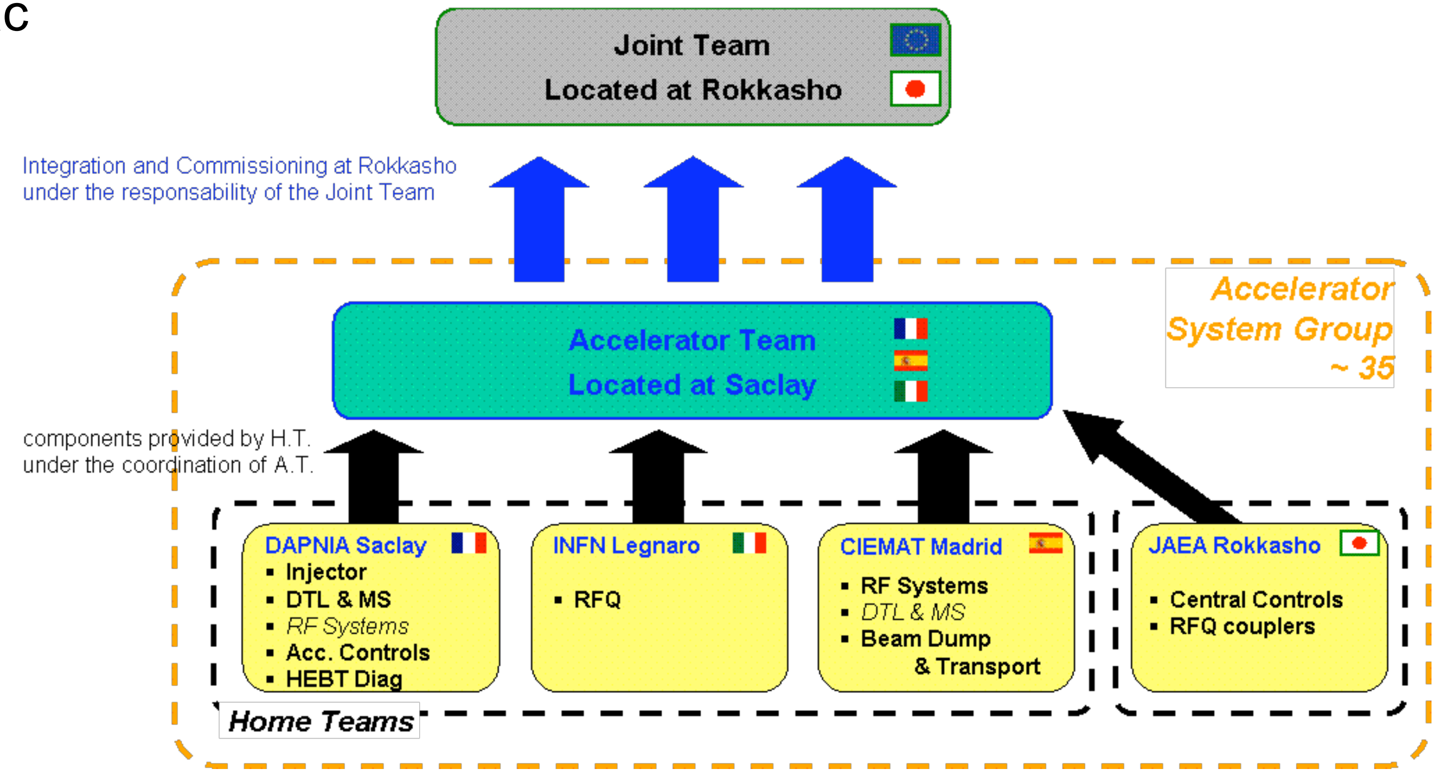
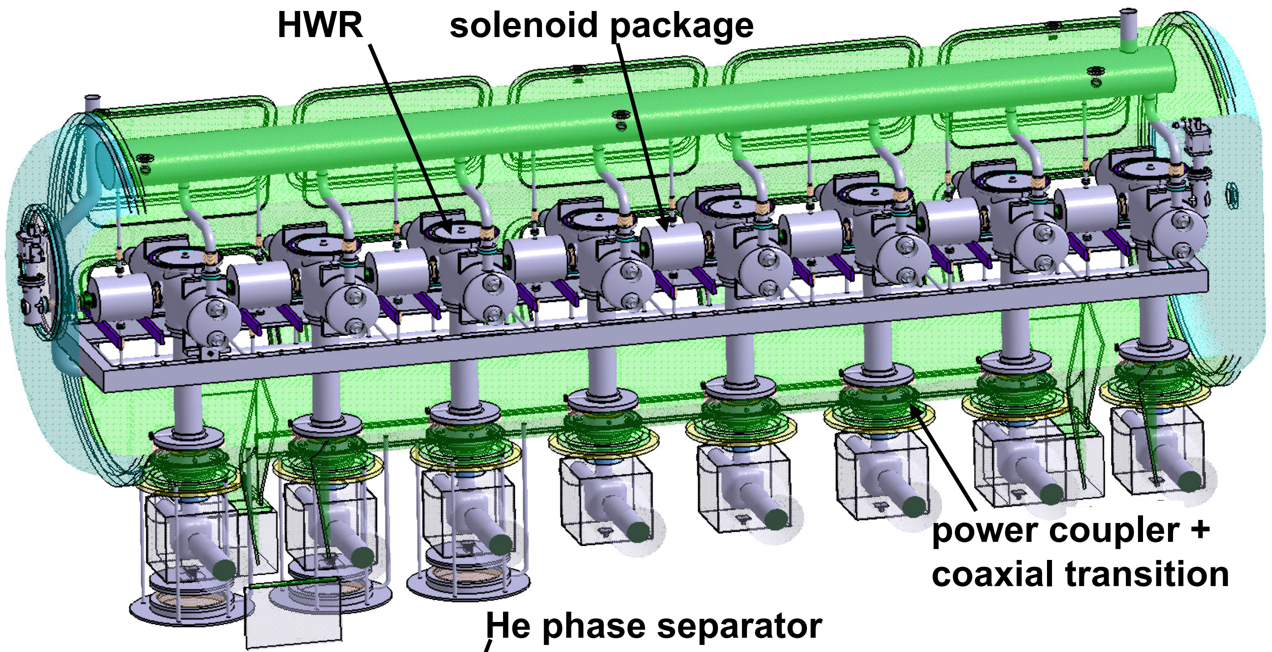
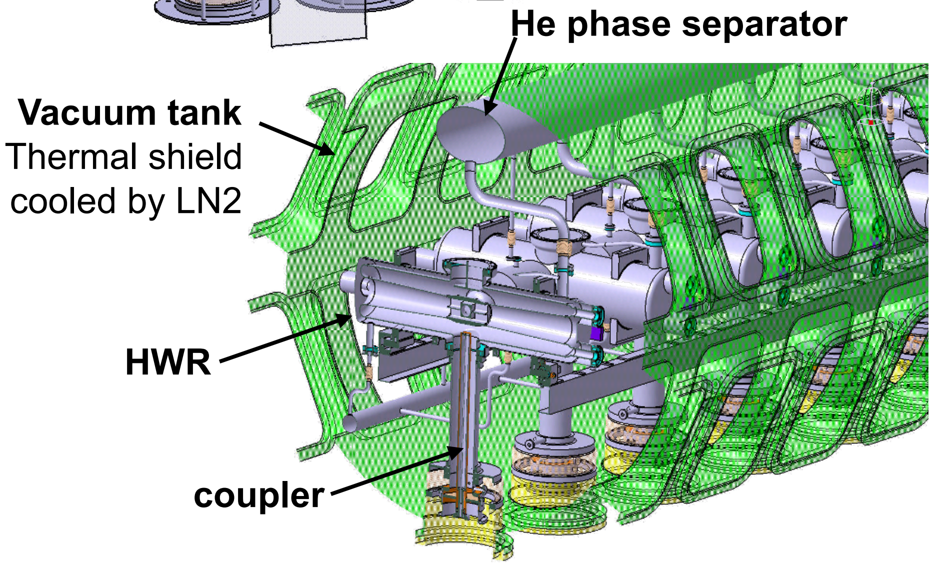


The accelerator components are in kind contribution from European countries

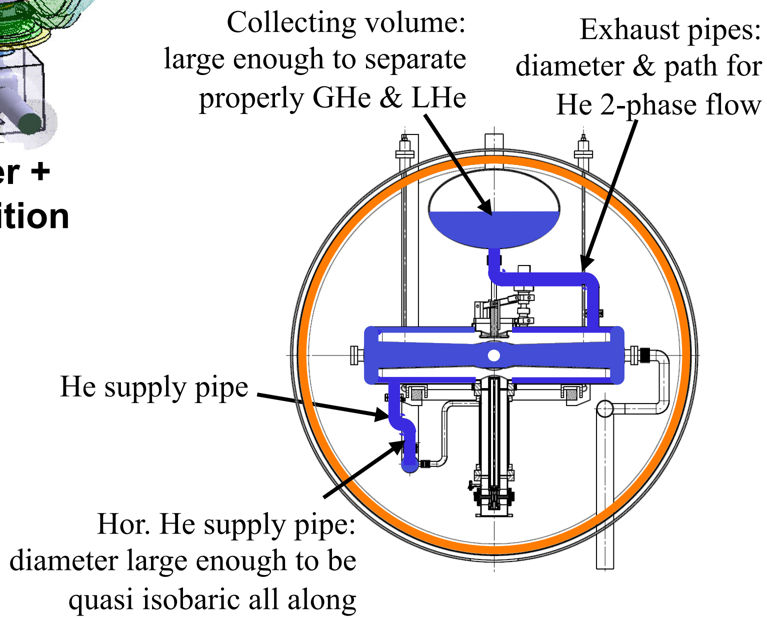
CEA France responsibility

Cryomodule Conceptual design





- **Conceptual design for:**
  cold mass support, alignment system, cryogenic pipes, vacuum pipes, interfaces, connections with all services



- **Conceptual design for:**
  He cooling (forced flow mode)

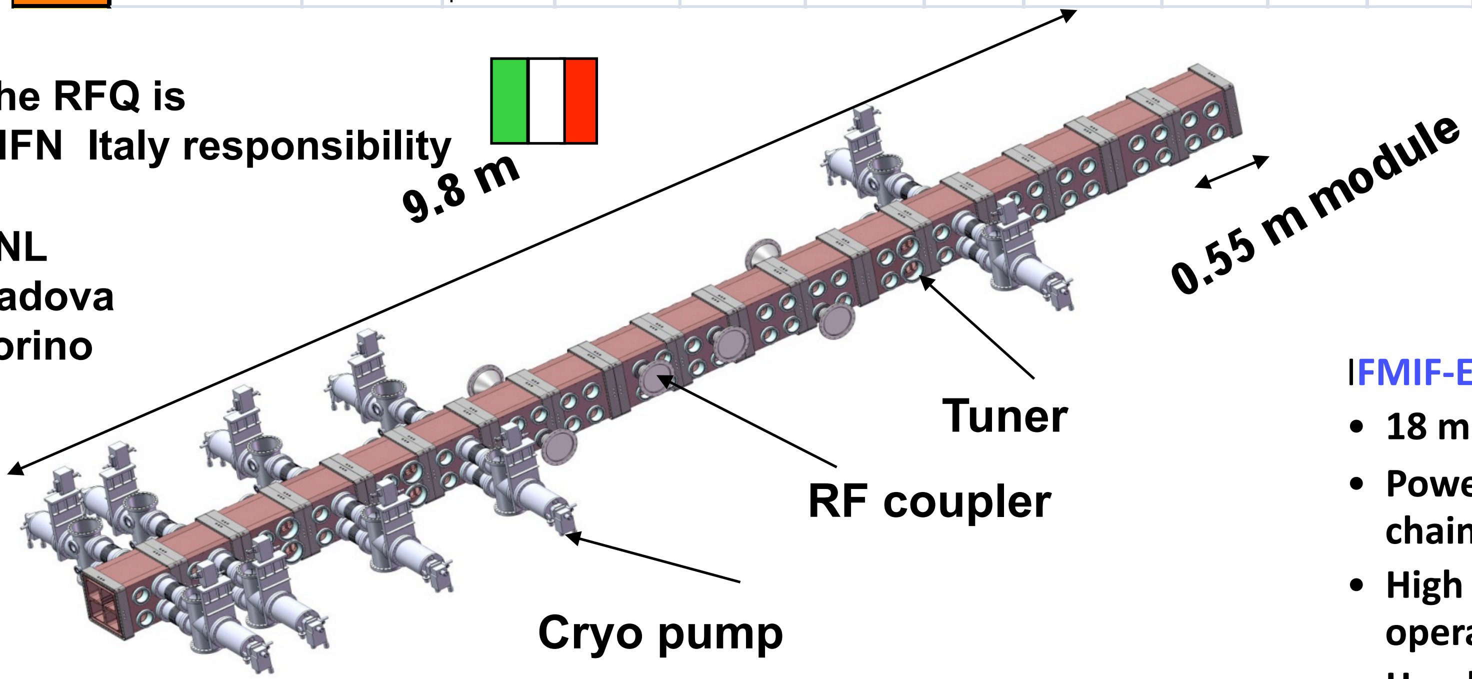
Alban Mosnier, PAC 09

RFQs general parameters

	Name	Lab	ion	energy MeV/u	vane voltage kV	beam current mA	power kW	RF Cu power kW	Freq. MHz	length m	lambda	Emax kilpat	Power density ave W/cm 2	max W/cm 2	operated
	IFMIF EVEDA	**LNL**	**d**	**2.5**	**79-132**	**130**	**650**	**585**	**175**	**9.8**	**5.7**	**1.8**	**3.5**	**30**	**NO**
CW	LEDA	LANL	p	6.7	67-117	100	670	1450	350	8	9.3	1.8	11.4	65	*YES*
	FMIT	LANL	d	2	185	100	193	407	80	4	1.0	1	0.4		*YES*
high p	IPHI	CEA	p	3	87-123	100	300	750	352	6	7.0	1.7	15	120	*NO*
	TRASCO	LNL	p	5	68	30	150	847	352	7.3	8.6	1.8	6.6	90	*NO*

The RFQ is INFN Italy responsibility

LNL
Padova
Torino



IFMIF-EVEDA RFQ

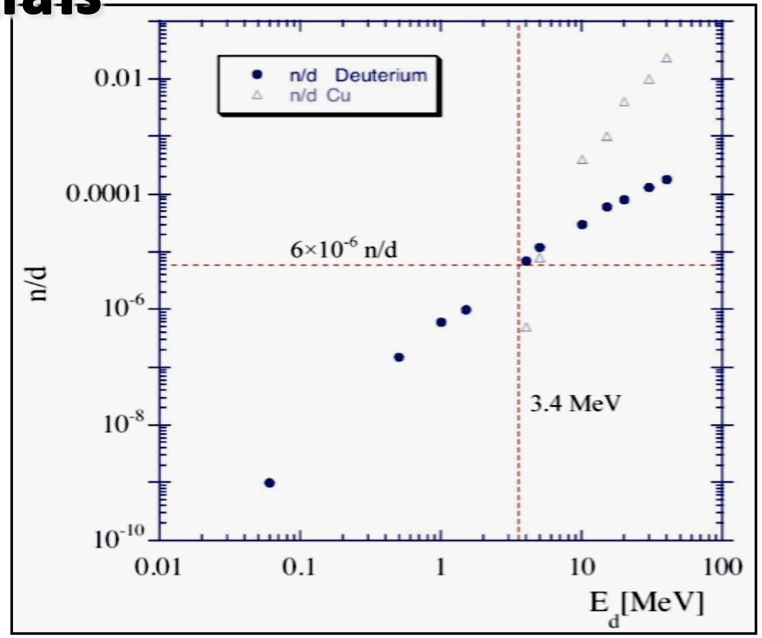
- **18 modules 9.8 m**
- **Powered by eight 220 kW rf chains and 8 couplers**
- **High availability 30 years operation.**
- **Hands on maintenance**
- **First complete installation in Japan**

Organization of IFMIF-EVEDA RFQ task

- **INFN LNL**:
  - Physics design (beam dynamics, RF design, general conception, thermal and chemical treatments, brazing, RF test of the final assembly, vacuum and cooling system
- **INFN Sezione di Padova**:
  - Machanical design of the RFQ, production of the modules, QA procedure
- **INFN Sezione di Torino**
  - supports and tooling, integrationparticipation to the production of modules
- External competences involved since the beginnig
  - **CERN**: brazing, chemical treatments, specification and tests of the materials
  - **Mechanical industries**:with specific experience

- **ASG deputy leader** *A. Facco*
- **Responsible of the task** *A. Pisent*
  - Administrative responsible: *R. Battistella*
  - Planning: *J. Esposito*
- **Physical design and beam dynamics**: *M. Comunian*
  - Radio frequency: *A. Palmieri*
  - High power tests: *E. Fagotti*
  - Controls: *G. Bassato*
  - Vacuum system and technological processes *C. Roncolato*
- **Mechanics design and construction** *A. Pepato*
  - Engineering integration and preparation to installation *P. Mereu*
  - Quality assurance: *R. Dima*

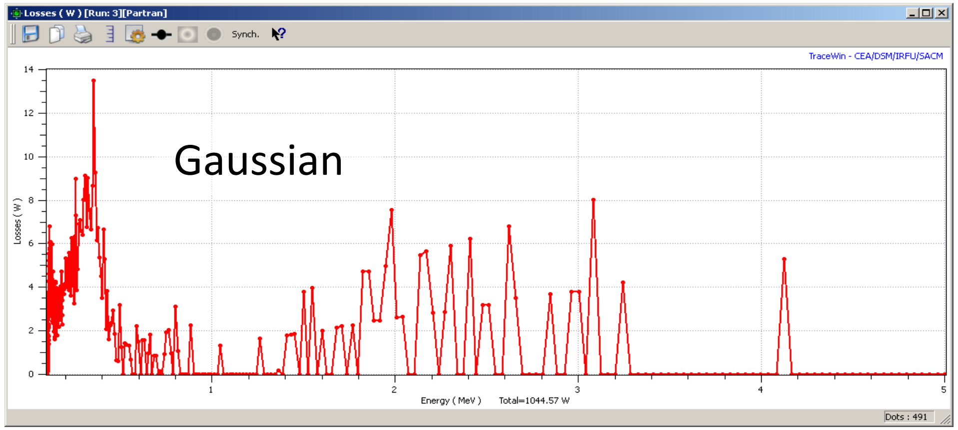
Beam dynamics essentials



- The beam dynamics design should minimize the activation by beam losses in the RFQ (Hands-on maintenance)
- prepare a high quality beam for a clean transport in the following superconducting linac.
- It is important to consider that the neutron production *n* at low energy (caused mainly by the fusion d-d reaction up to about 5 MeV) scales approximately as:

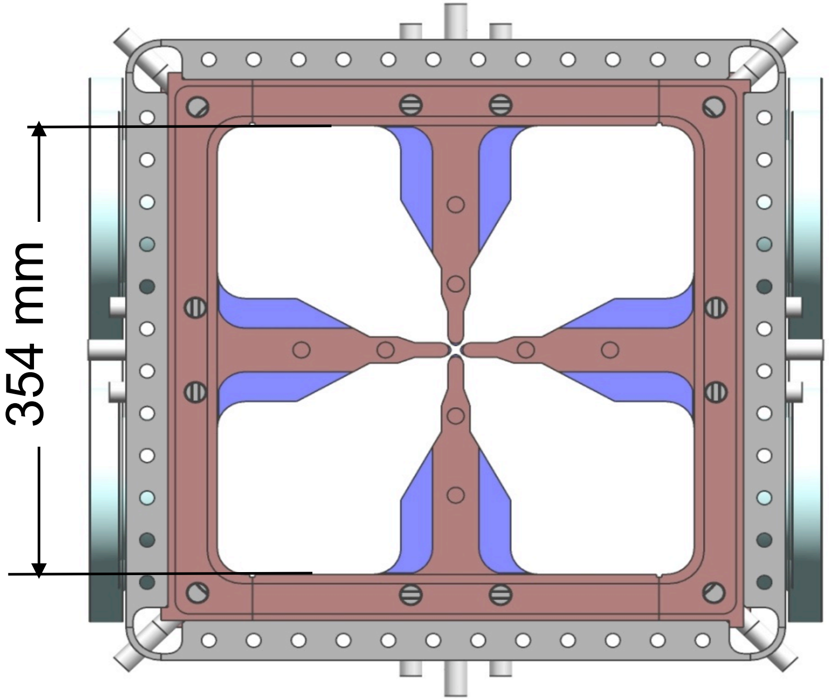
$$n \propto N w^2$$

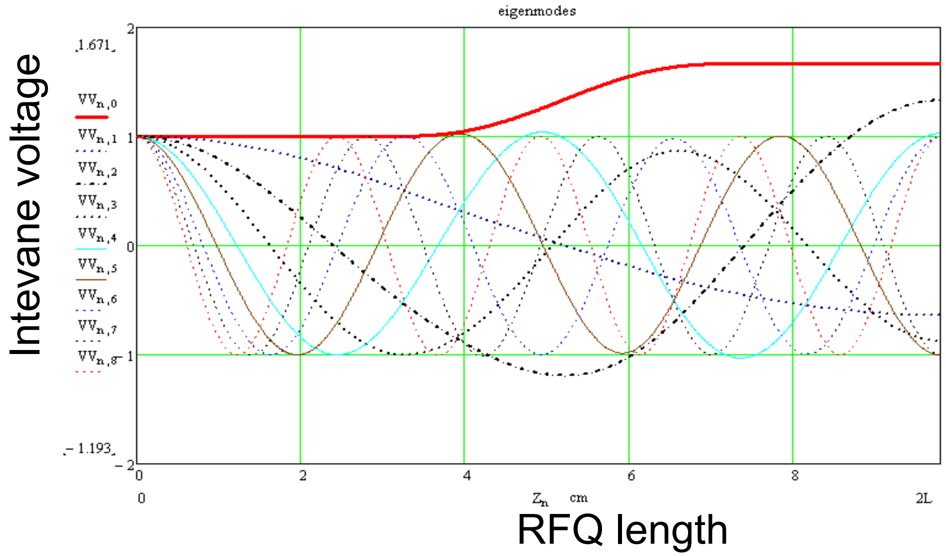
- This means that, one has to concentrate the beam losses at low energy.
- 96% transmission (gaussian) requires $\pm$2% homogeneity of the intervane voltage



Power loss as function of energy (130 mA @ 0.25 mmmrad): the main part of the losses is below 1MeV

Geometric tolerances





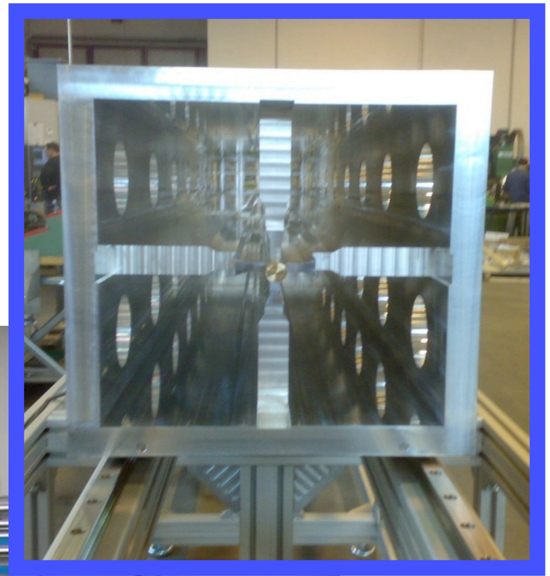
Perturbation to the nominal geometry ⇨ Accelerating mode is not pure

[illegible]

Geometrical tolerances: about 1 um

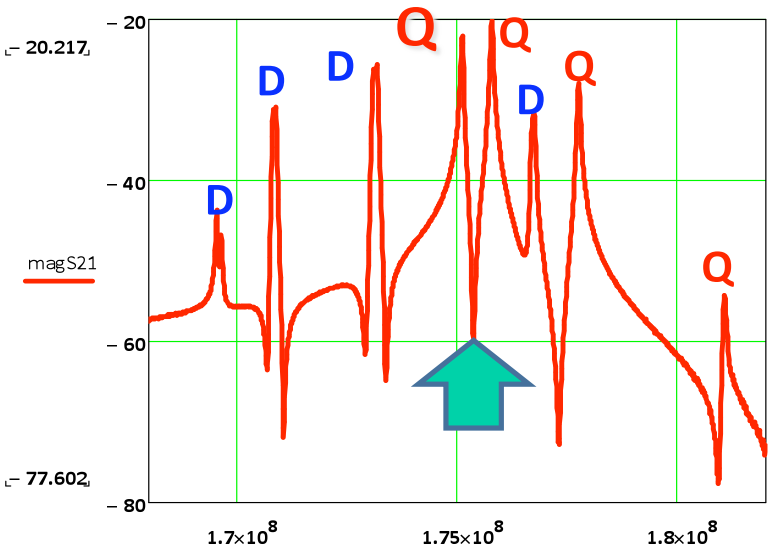
Mechanical constructionl tolerances: about 20 um

The aluminum real-scale RFQ model

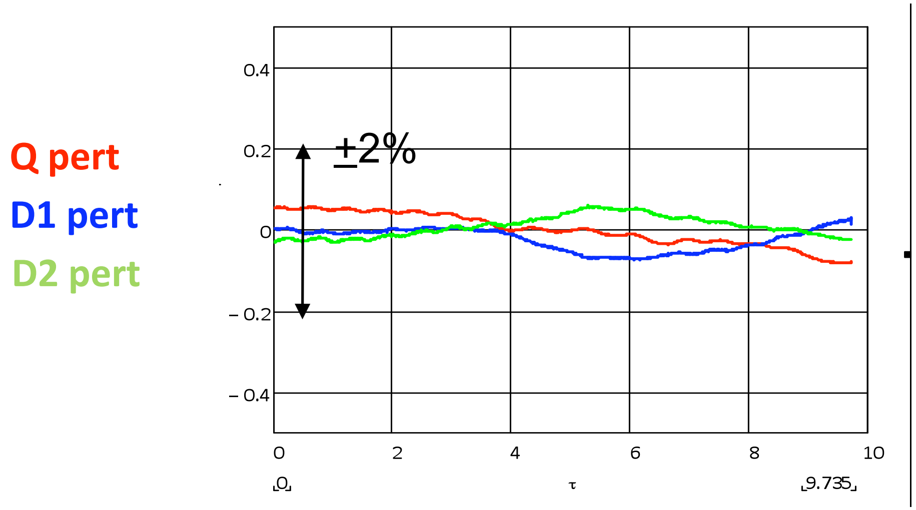


The RFQ model set up at LNL for measurements and equipped with tuners, feeds, dummy plugs and end cells (23/06/09)

The aluminum real-scale RFQ model : Preliminary bead pull measurements



175 MHz
Operating mode



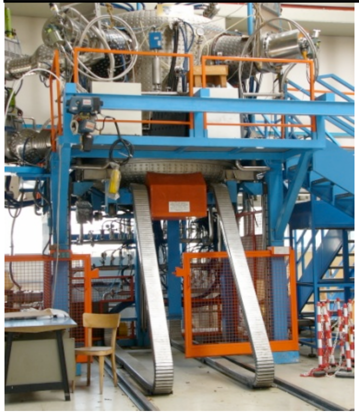
Measurement after 1st iteration. fq=175.1 MHz

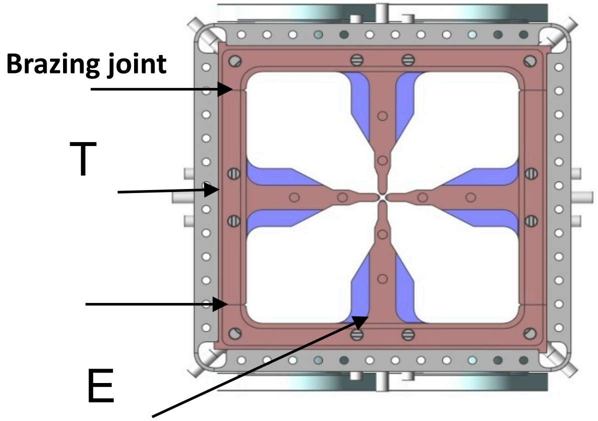
Mode spectra after tuner settings: dipole free region around operational mode keeps almost symmetric [-1.9 MHz, 1.6 MHz]

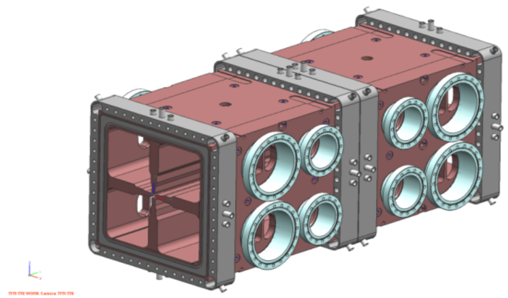
Mechanical design

- **Based on vacuum brazing** CERN experience, design compatible with oven at CERN, LNL and in industry;
- Due to the relatively large transverse dimensions of the RFQ, the procurement of the CUC2 raw material blocks is limited by the total mass amount (length **550 mm).**
- **First brazing**, the four electrodes of each block joined in a horizontal oven, copper plugs for cooling channels.
- **Second brazing**, in a vertical oven, together with Stainless Steel head flanges cooling tubes and lateral flanges**.**
- To minimize the use of Ultra-pure CUC2 and to limit the induced stresses on the raw material, a rough-cut of the shape of the sub-module components from a starting block of about 500x280x570 mm will be performed, by using a **EDM** (wire electroerosion).
- The accelerator is composed by 18 of these modules.

LNL brazing oven

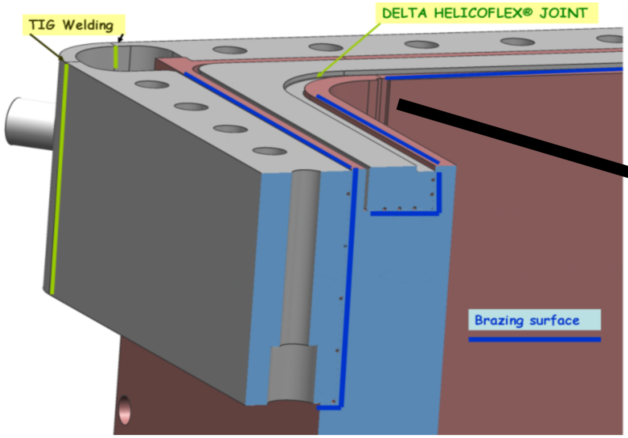




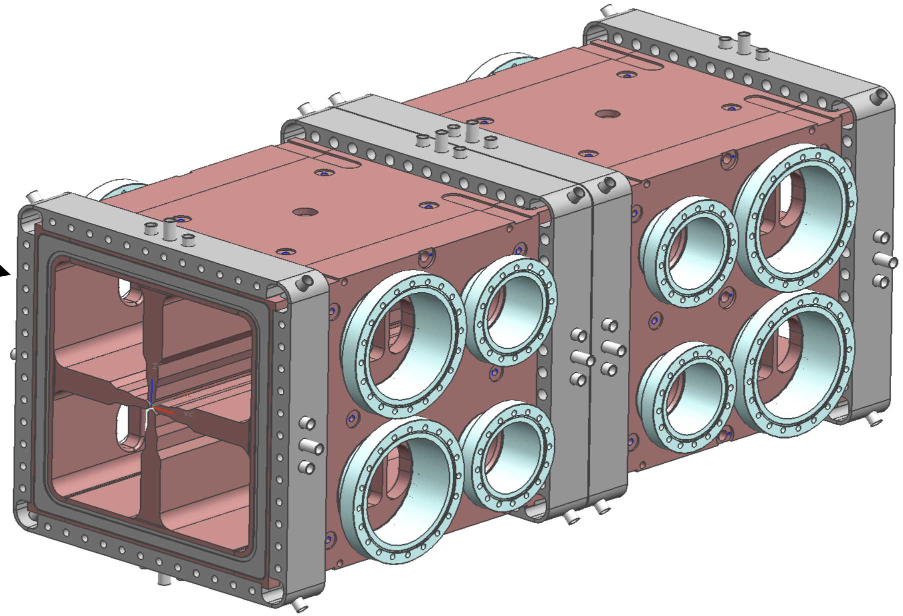


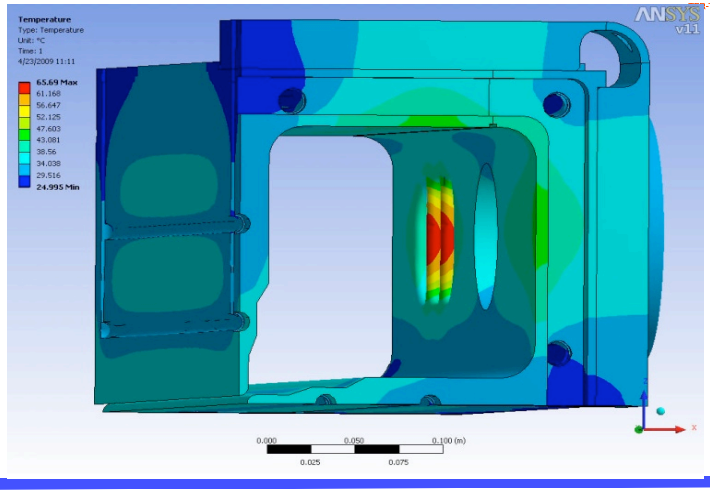
Two modules

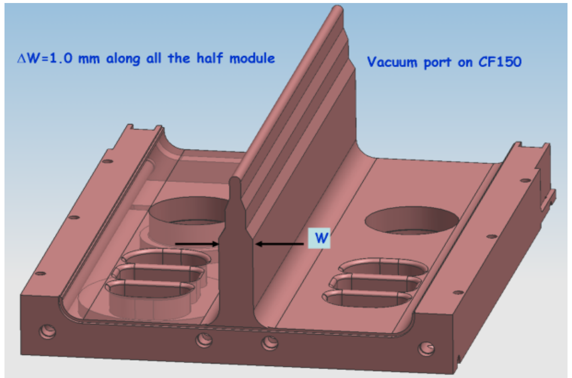
Mechanical design (2)



Head flange

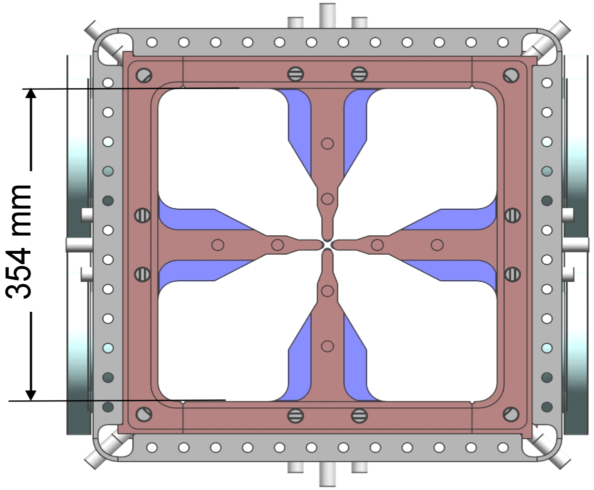


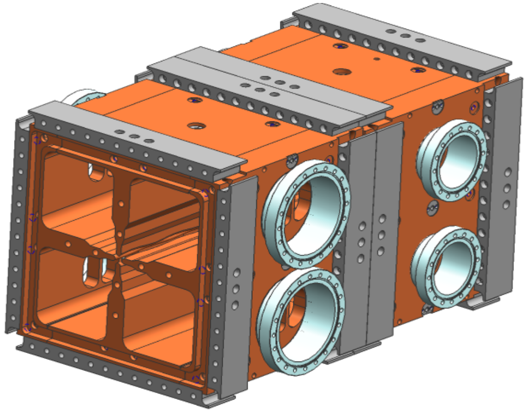


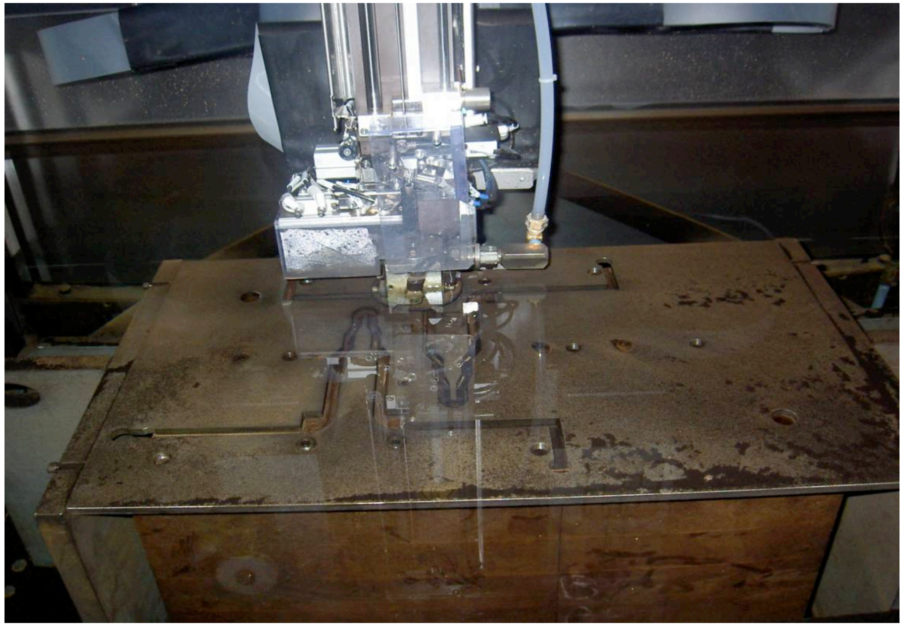


Vacuum grids machined from bulk

RFQ prototype: construction status

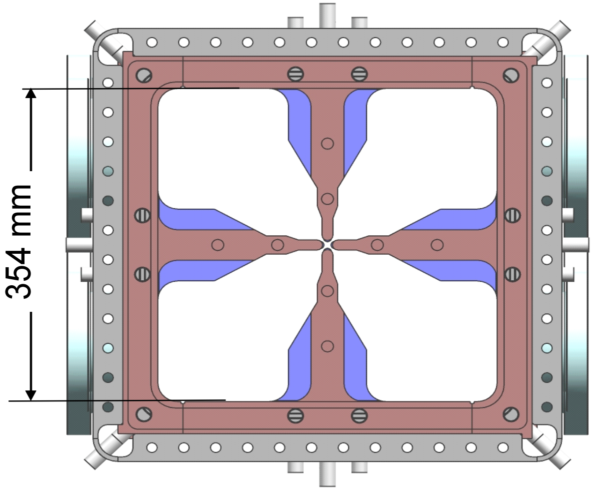


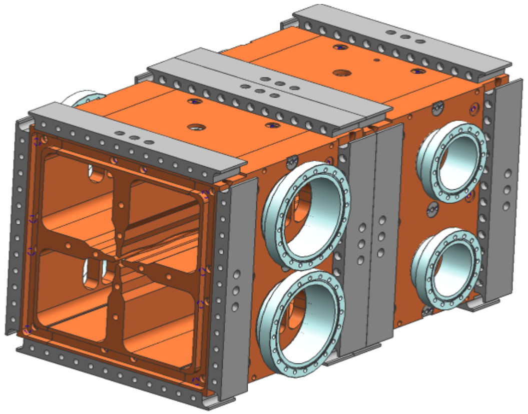




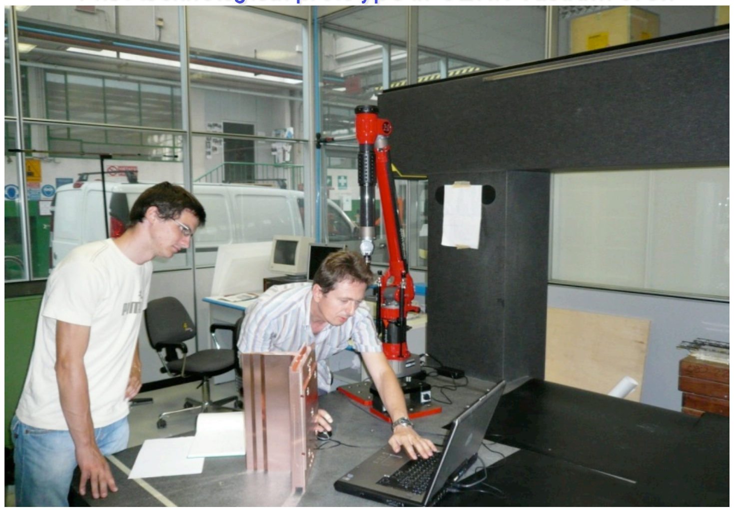
First technological prototype during EDM cutting at INFN Padova

RFQ prototype: construction status



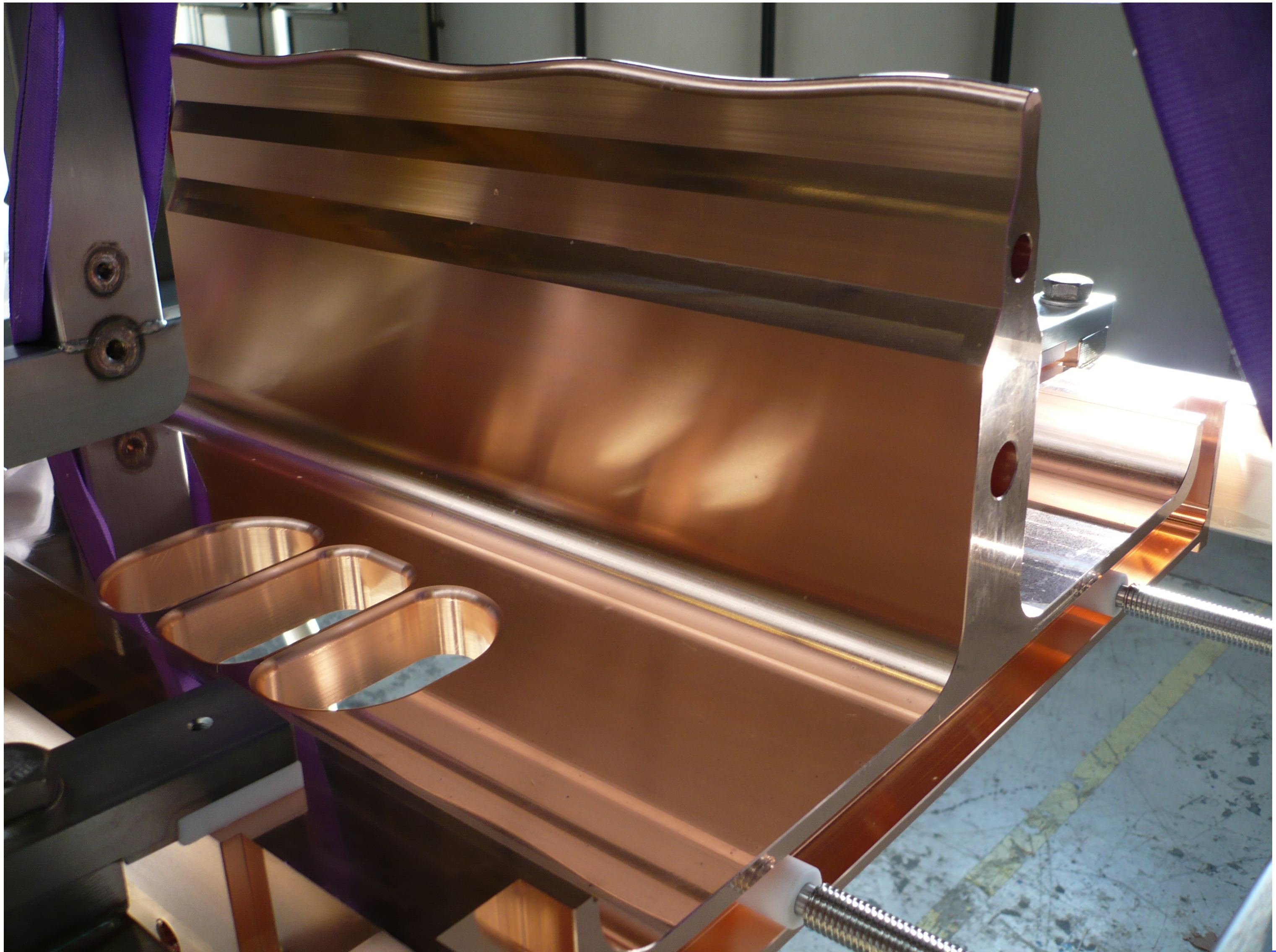


First technological prototype in CERN vacuum oven



First technological prototype mechanical measurements at INFN TO

E electrode machined at INFN Torino after 800 deg annealing in LNL vacuum oven

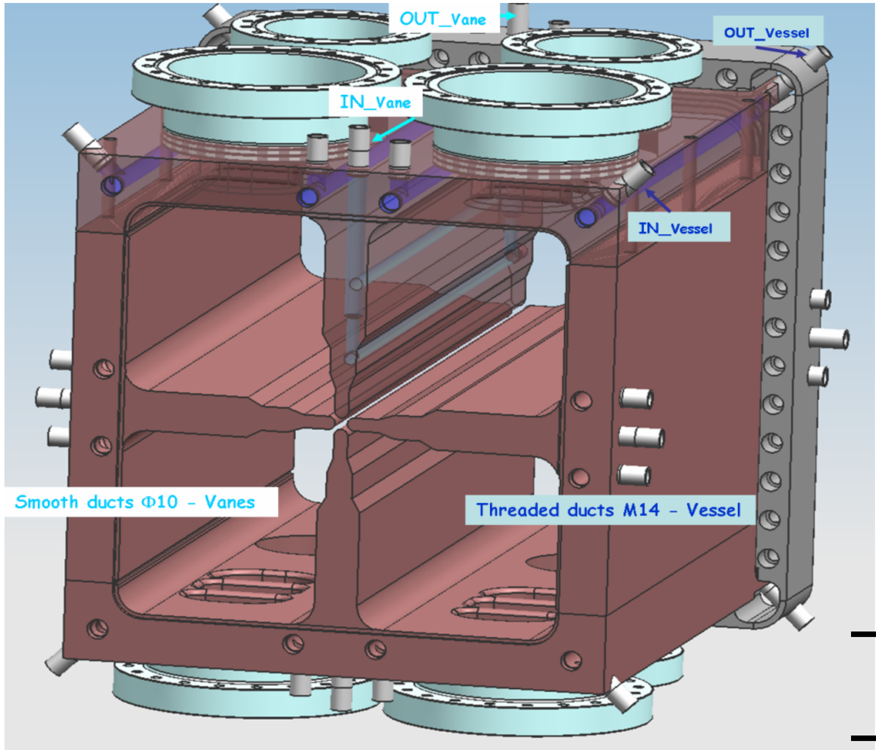


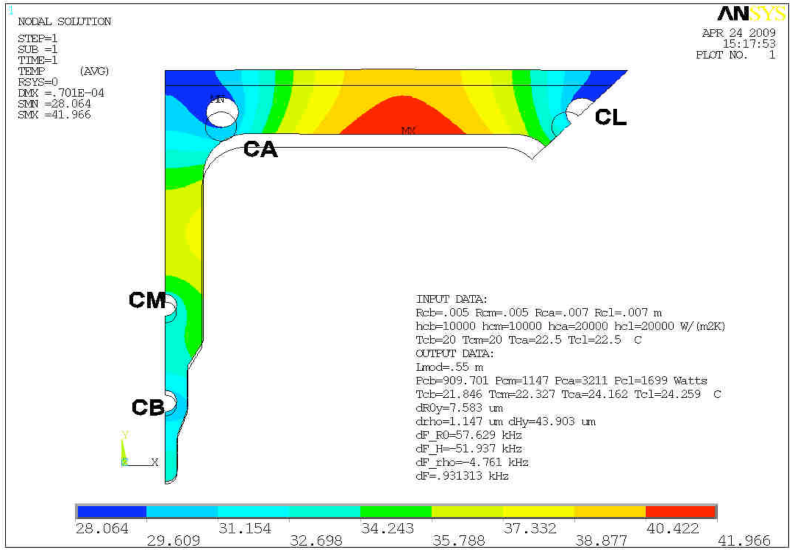
E electrode machined at INFN Torino after 800 deg annealing in LNL vacuum oven

Assembly of the first module this week in Torino for brazing at CERN in January

Cooling system and frequency tuning

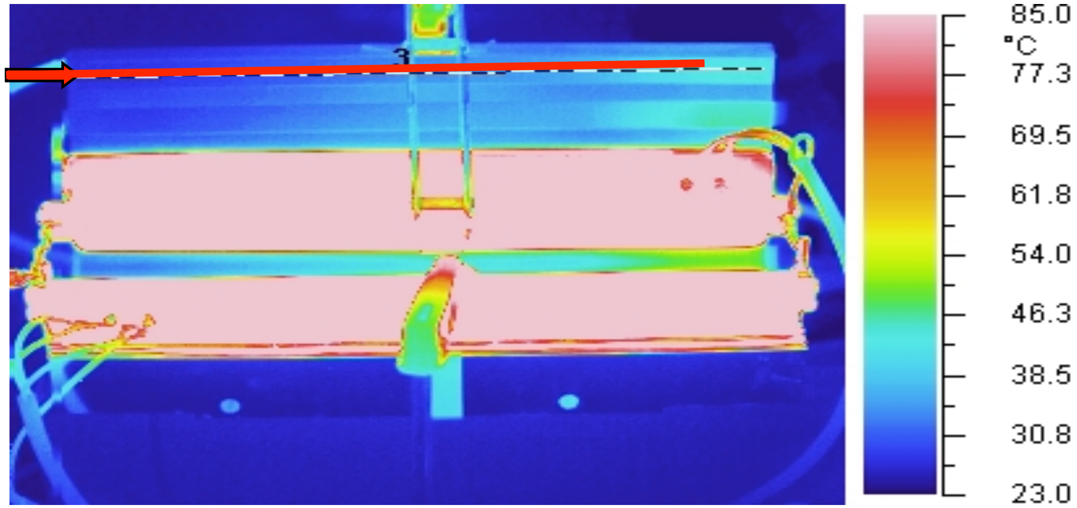
(700 kW must be evacuated keeping 1 um geometrical tolerances for vane tips)

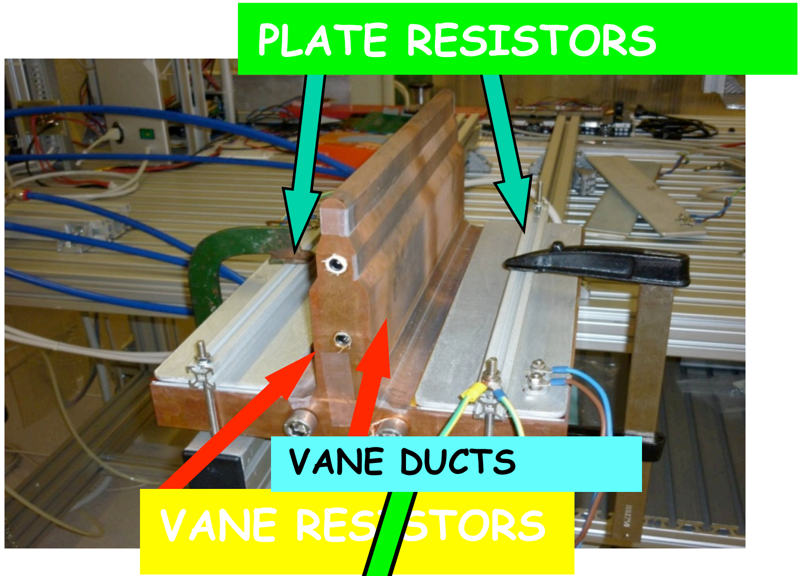


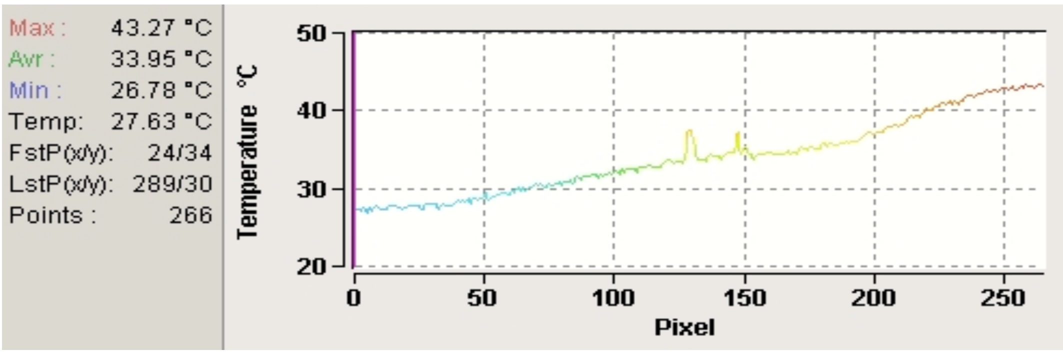


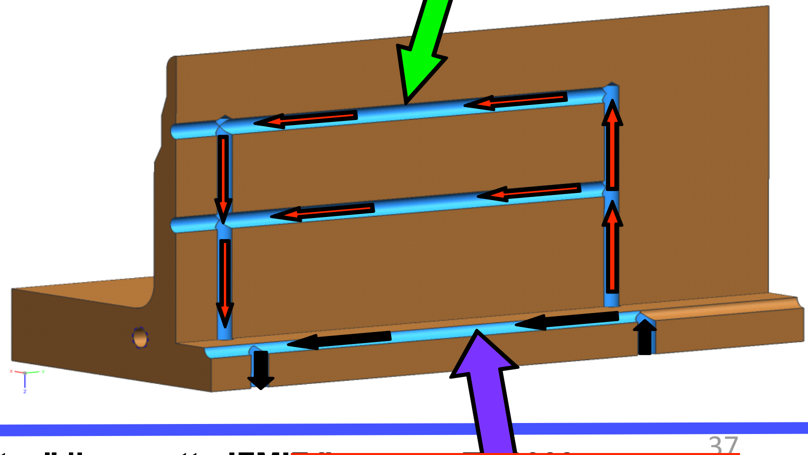
	R mm	T_{in} ^{o}C	v m/s	T_{out} ^{o}C	H_c W/m^2K	P_c W
CB	5	20.0	3	21.8	10000	909.7
CM	5	20.0	3	22.3	10000	1147
CA	7	22.5	3	24.2	20000	3211
CL	7	22.5	3	24.3	20000	1699

Thermal test facility: preliminary results

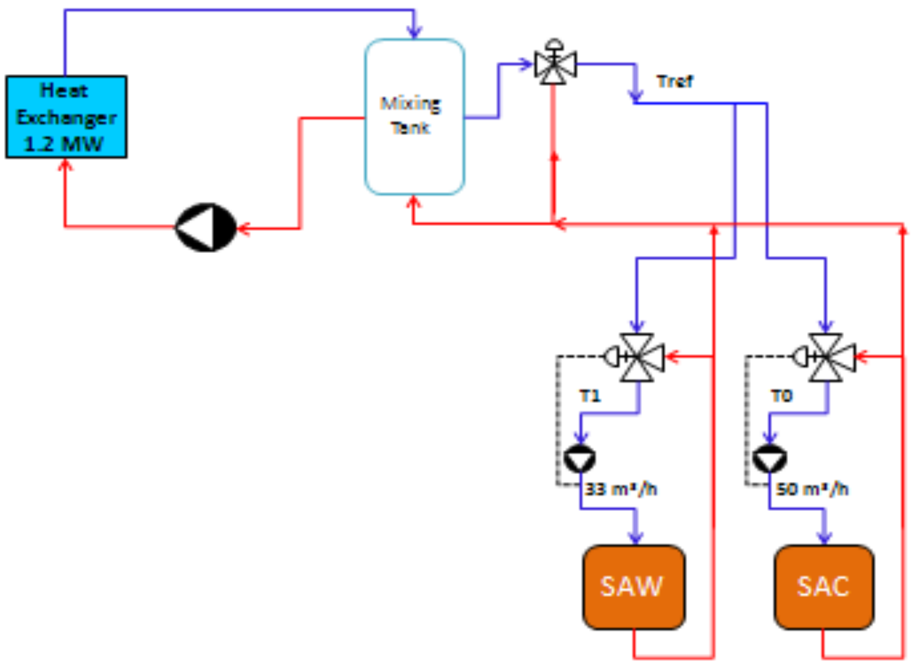




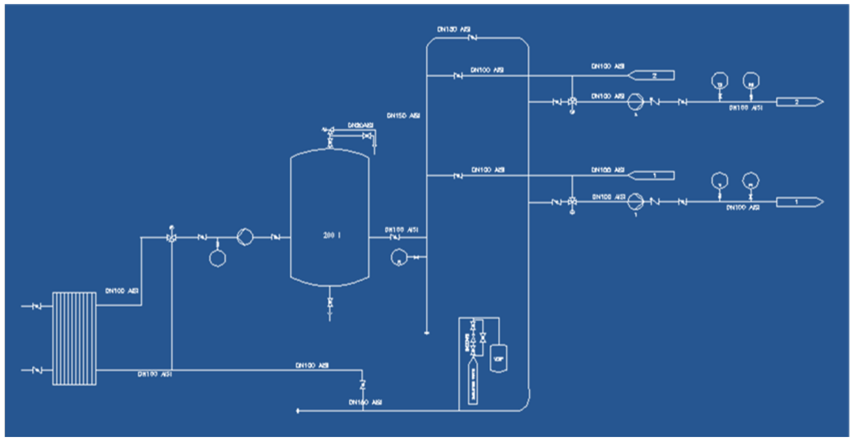




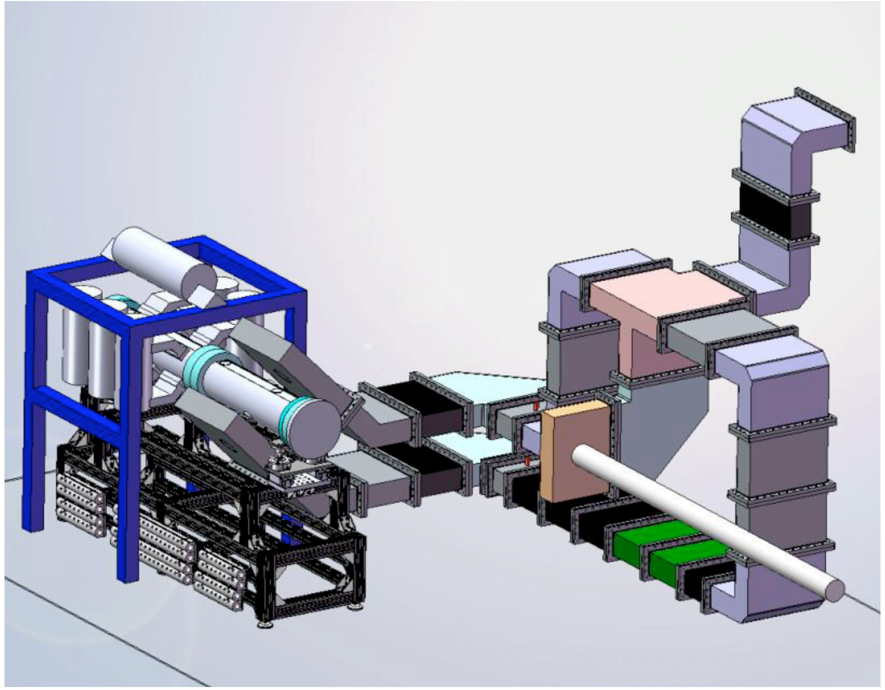
Prototype of the cooling skid



- Two independent cooling circuits (different temperatures for freq. tuning)
- Cooling power 300 kW



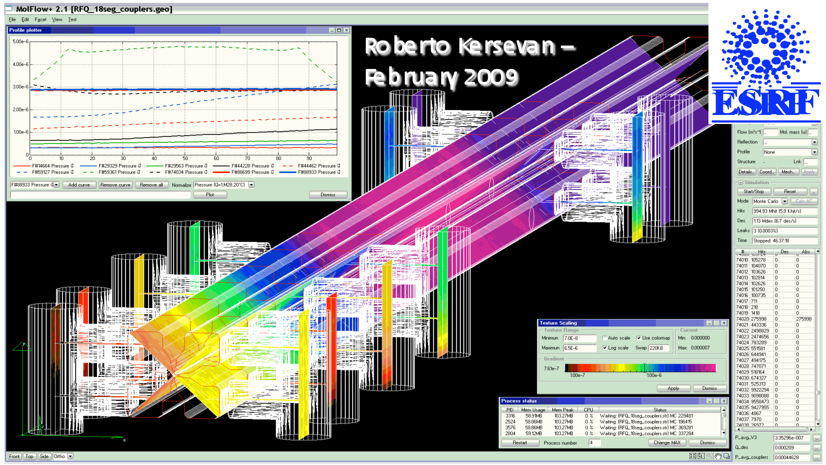
Test of the high power operation with water temperature tuning on existing INFN RFQ (TRASCO RFQ modules)



Frequency	352.2	MHz
RF Power	300	kW
Time structure	Up to cw	
Length of the Cavity	2.3	m
Number of couplers	2	
Approximate dimensions and weight	2.2m X 3m X 2m; 1500 kg	
Cooling water power	300	kW
Max temperature at heat exchanger	20	Celsius Deg
Cooling system (interface with our skid)	Heat exchanger 300 kW 7-12 deg	
Dimension of the skid	2m X 2m X 2m	
Vacuum system	Cryogenic pump 2000l/s	
Mode of control	LNL-CERN tbd	

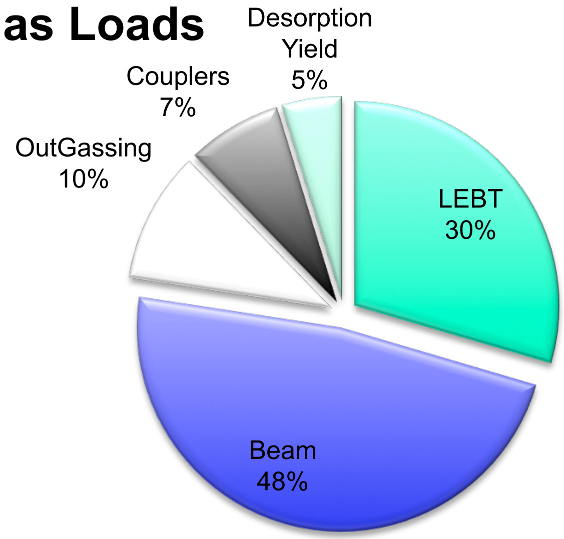
Vacuum System

Numerical simulations

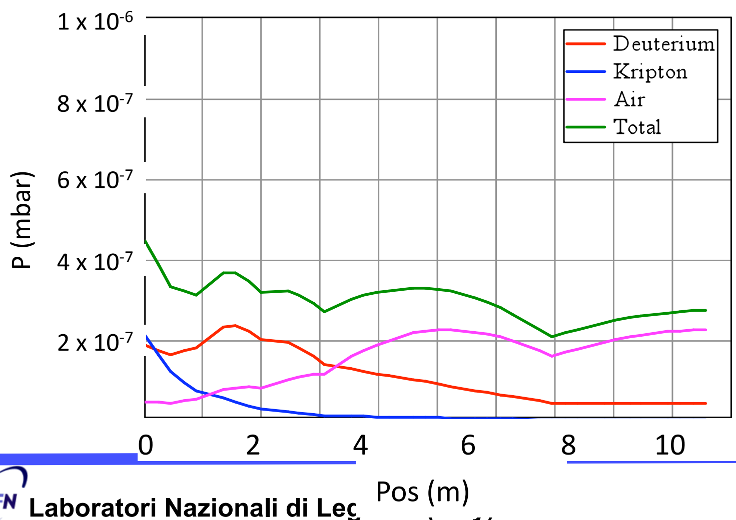


Losses	Gas	Load (mbar Lt / s)
LEBT	De + Kr	8.26E-04
Beam	De	1.34E-03
OutGassing	Air	2.90E-04
Couplers	Air	2.09E-04
Des. Yield	Air	1.33E-04

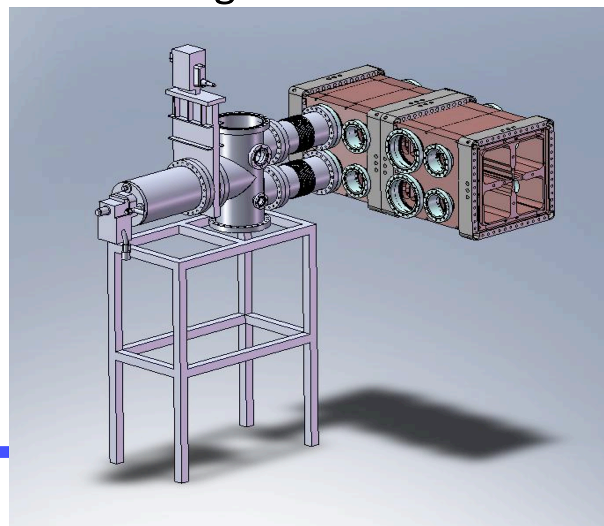
Gas Loads



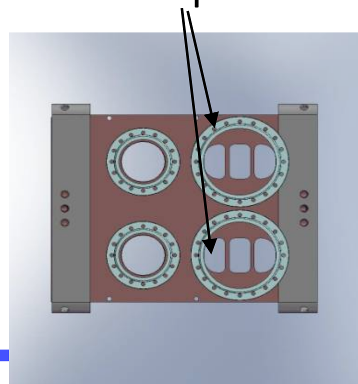
Pressure Profile



Design of manifolds



Vacuum ports

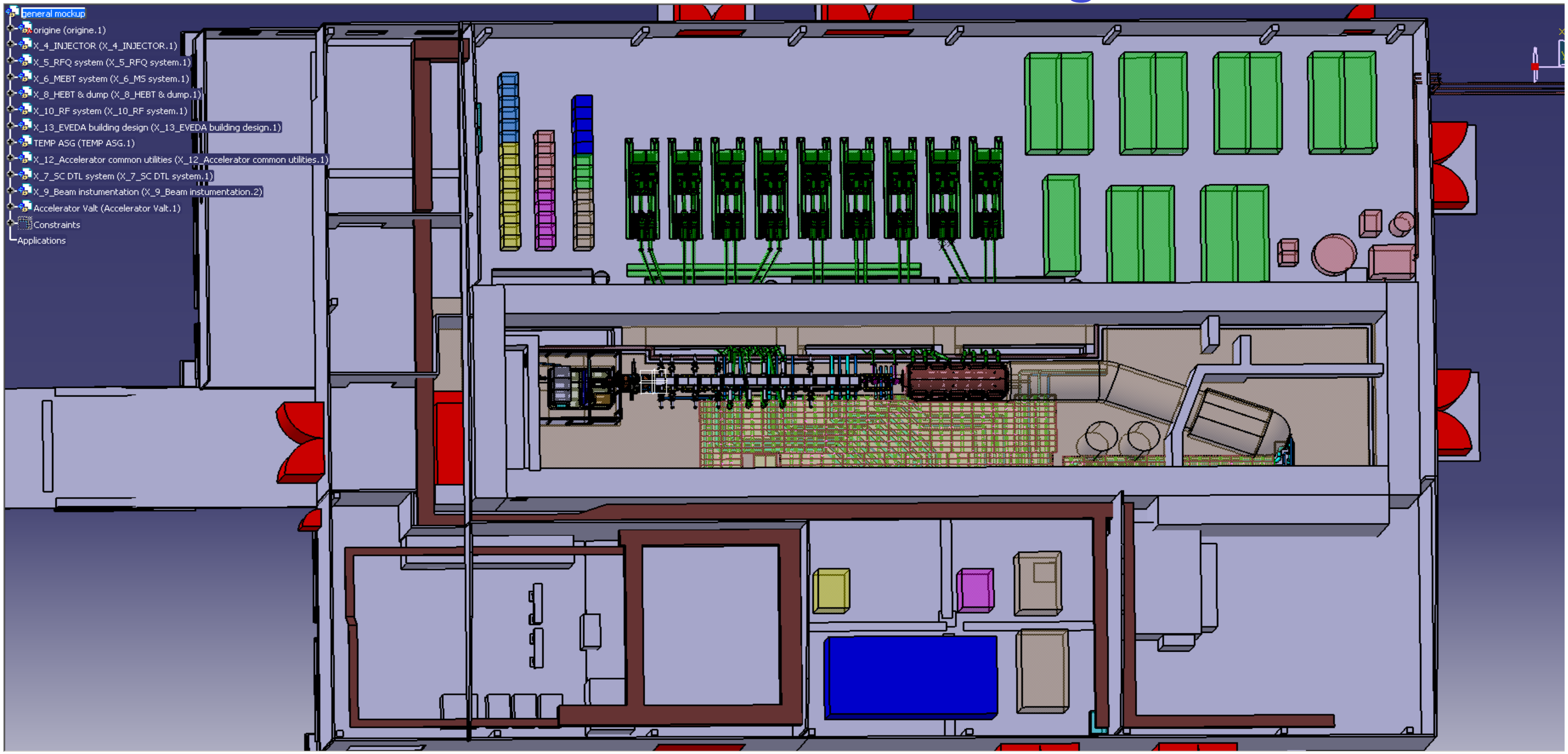


IFMIF/EVEDA building (Rokkasho)

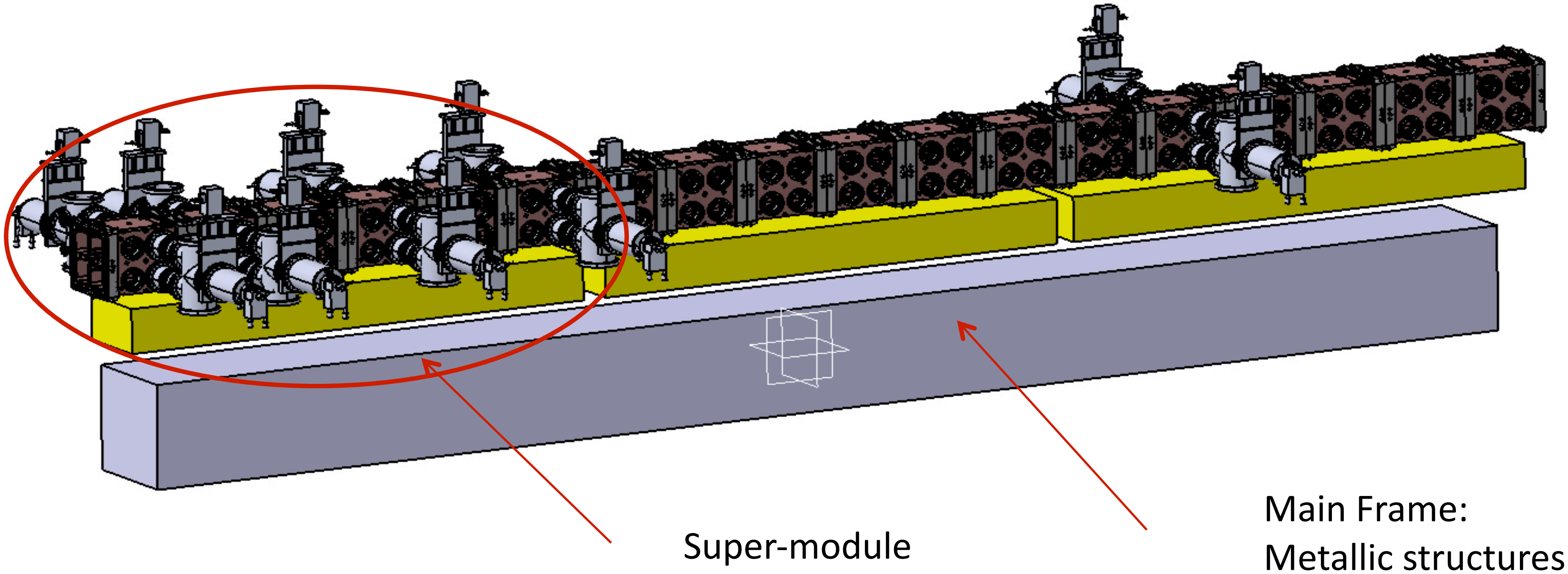
Foundations of the building at Rokkasho...

RFQ in the building

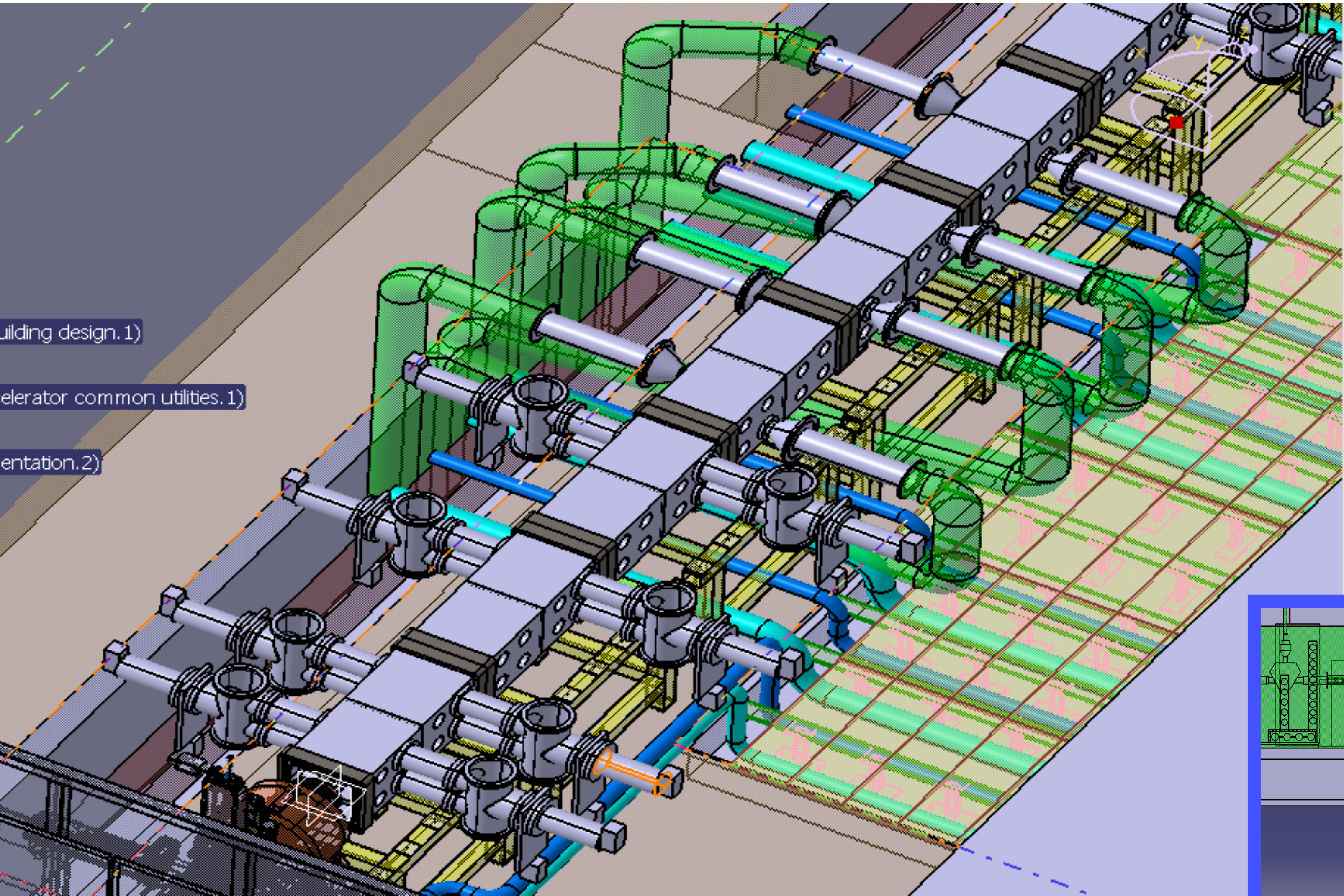
RFQ in the building



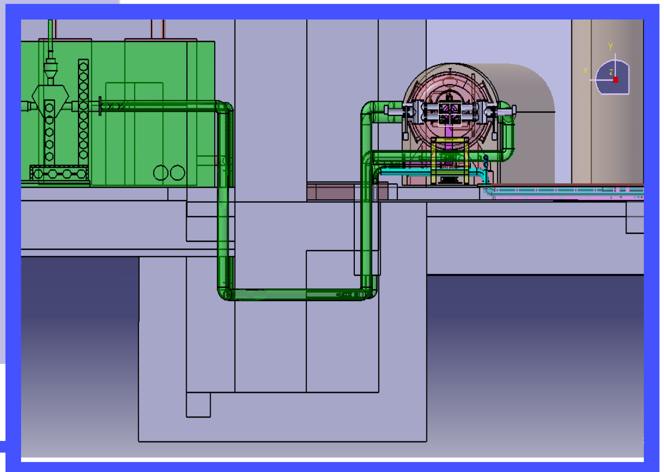
Preliminary support layout



RFQ installed in the tunnel

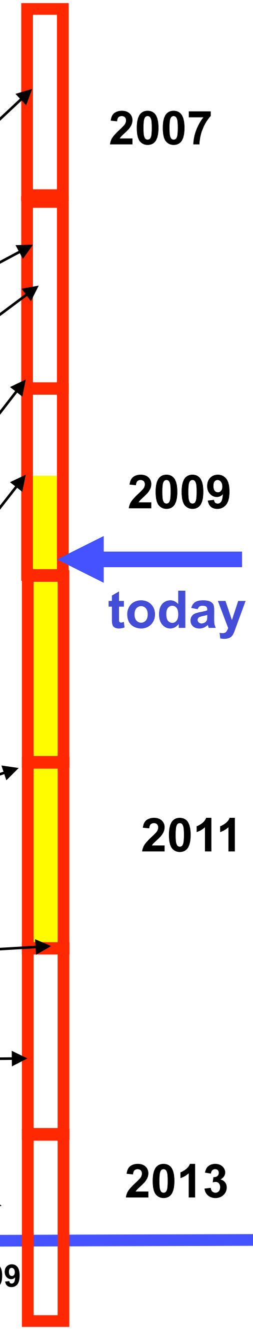


RF Pit



IFMIF EVEDA: RFQ Milestones

- ✓1st June 2007: Input parameters frozen (matching to LEBT and DTL)
- ✓Beam Dynamics frozen Feb 2008 and choice of the construction technology May 2008
- ✓Specs ready for tendering of copper procurement August 2008
- Specs ready for structure machining and technological processes. February 2009
- Beginning of fabrication August 2009
- Last part of the RFQ ready for high power RF tests at CEA Jannuary 2011
- Fabrication finished. Modules ready for assembly and low power tests at LNL Jannuary 2012
- Shipment to Japan September 2012
- RFQ ready for beam operation in Japan March 2013



Reviews

- **PDR Preliminary design review 12 June 2008:**
  - Approval of the sub system main design choices and specifications: all elements ready for the Procurement Arrangements (PA)
- **DDR Detailed design review January 2010**
  - Approval of the detailed engineering design (design justification, details about integration, safety aspects, standards). All elements ready for the production

Conclusioni

- Il test dei materiali sotto un alto flusso di neutroni veloci rappresenta una componente essenziale della road map verso i nuovi reattori di fusione (DEMO).
- La facility IFMIF si basa sull'utilizzo di due acceleratori lineari di alta intensità (40 MeV 125 mA di deutoni ciascuno).
- Il prototipo dell'acceleratore (sino a 9 MeV piena corrente) è in costruzione in Europa e verrà installato a Rokkasho (Giappone) fra 2012 e 2013.
- La prima componente di questo acceleratore, l'RFQ, che forma il fascio di alta qualità e intensità e lo accelera sino a 5 MeV, costituisce una sfida tecnologica di assoluta frontiera, e viene costruito in Italia sotto responsabilità dell'INFN (Legnaro, Padova e Torino).