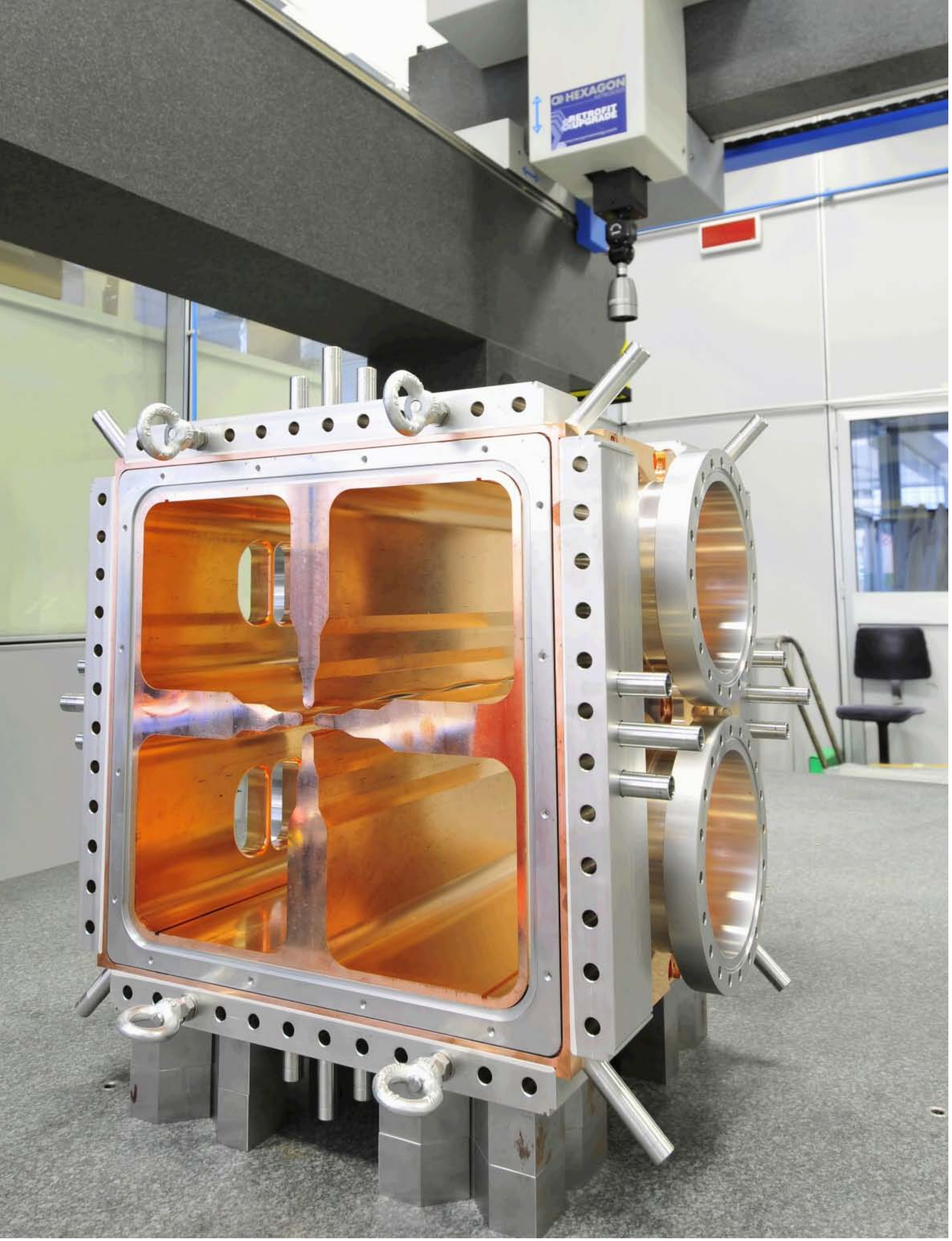
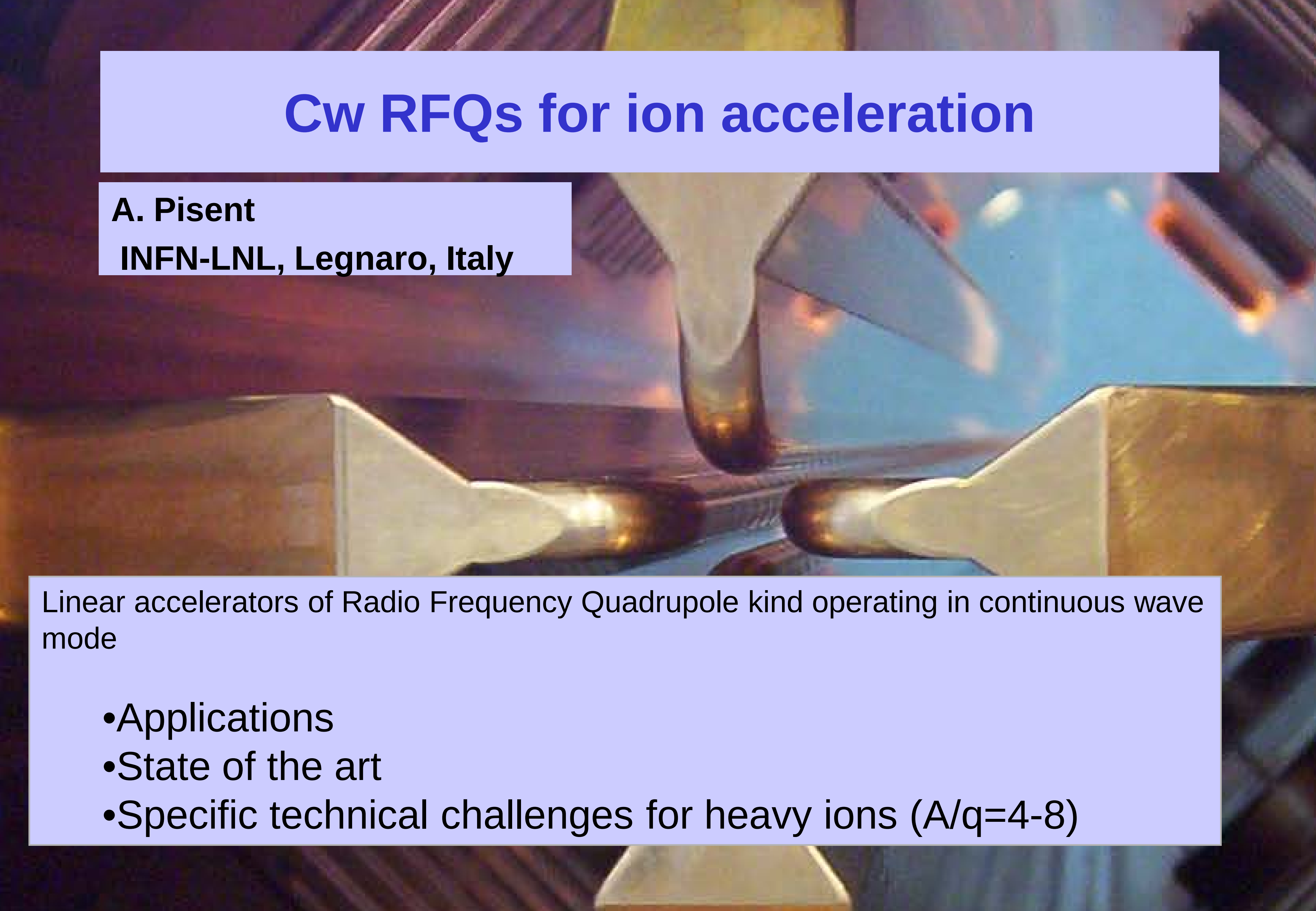


Cw RFQs for ion acceleration

Andrea Pisent
INFN Laboratori Nazionali di Legnaro



Cw RFQs for ion acceleration

A. Pisent
INFN-LNL, Legnaro, Italy

Linear accelerators of Radio Frequency Quadrupole kind operating in continuous wave mode

- Applications
- State of the art
- Specific technical challenges for heavy ions (A/q=4-8)

Applications of cw RFQs

- Main applications (high beam power 100s kW):
  - Injectors of multi MW linacs (protons E>1GeV) for multi MW spallation neutron sources (e.g. **ADS** for nuclear waste transmutation, **radioactive nuclear beams**) or neutrino production
  - Injector for deuteron linac (about 40 MeV) for **Fusion Material Irradiation** tests under large neutron fluxes.
- Lower beam power
  - Cw RFQs are in some cases used as injector of heavy ion linacs for **Nuclear Physics**, like for ALPI at LNL or ISAC at TRIUMF.
  - Injector for 40 MeV few mA **deuteron** cw superconducting linacs for neutron and RIBs production
  - Stand alone (e.g. 5 MeV 30 mA) application as neutron source for **BNCT at LNL (INFN)** or a compact pulsed source (250 kHz) **Astrophysics studies (FRANZ at UNI Frankfurt).**

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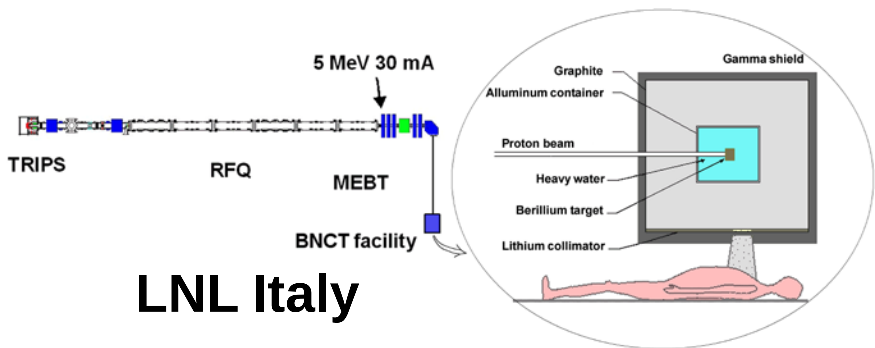
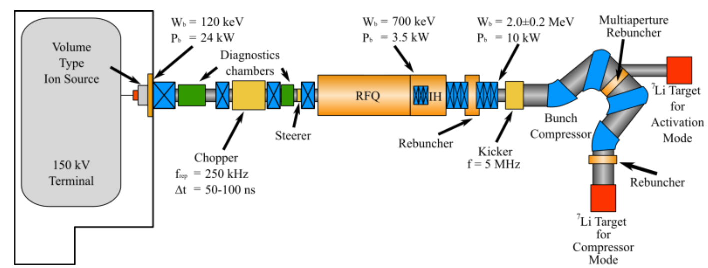


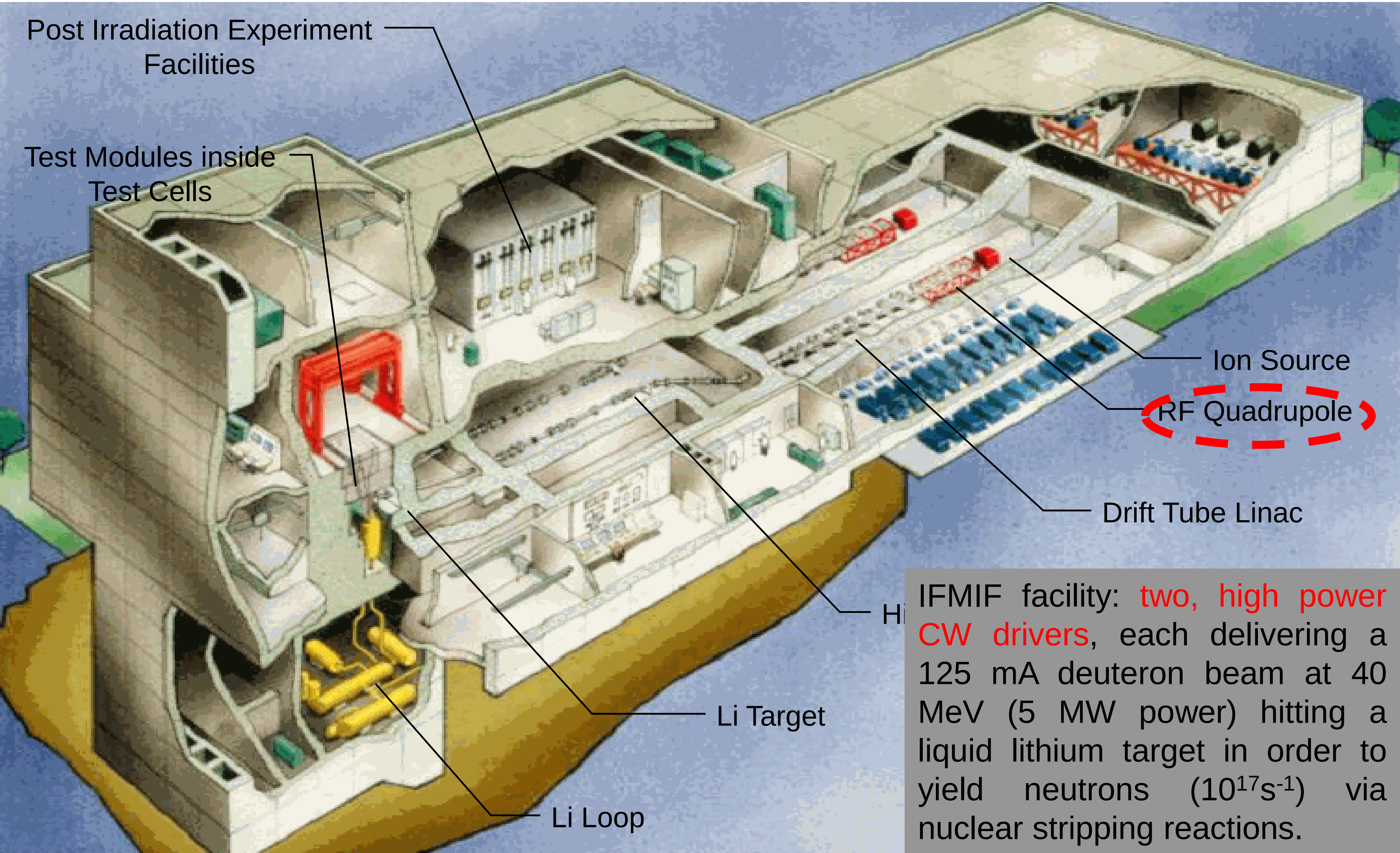
LNL Italy



Uni. Frankfurt Germany

IFMIF “Artist View”

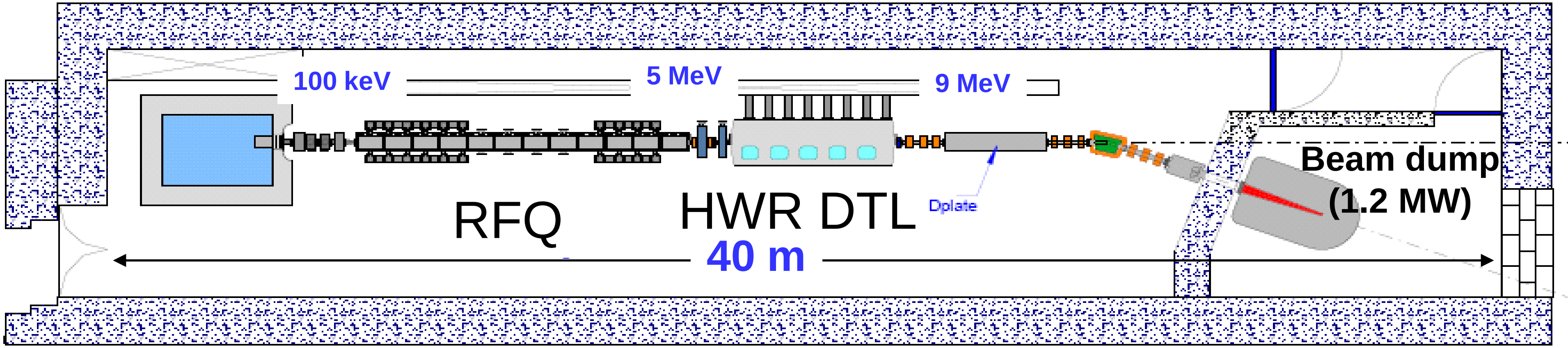
International Fusion Material Irradiation Facility



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.

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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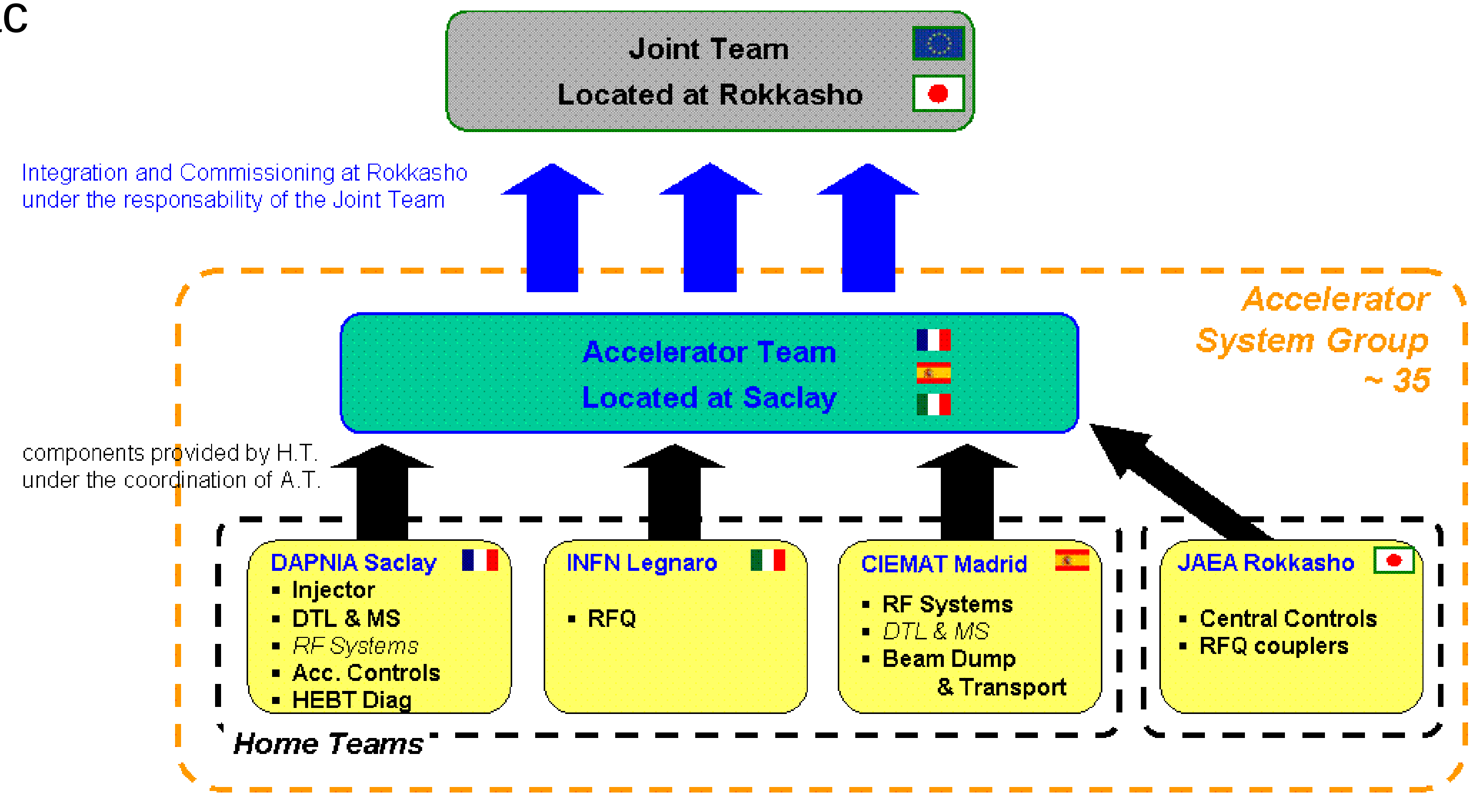
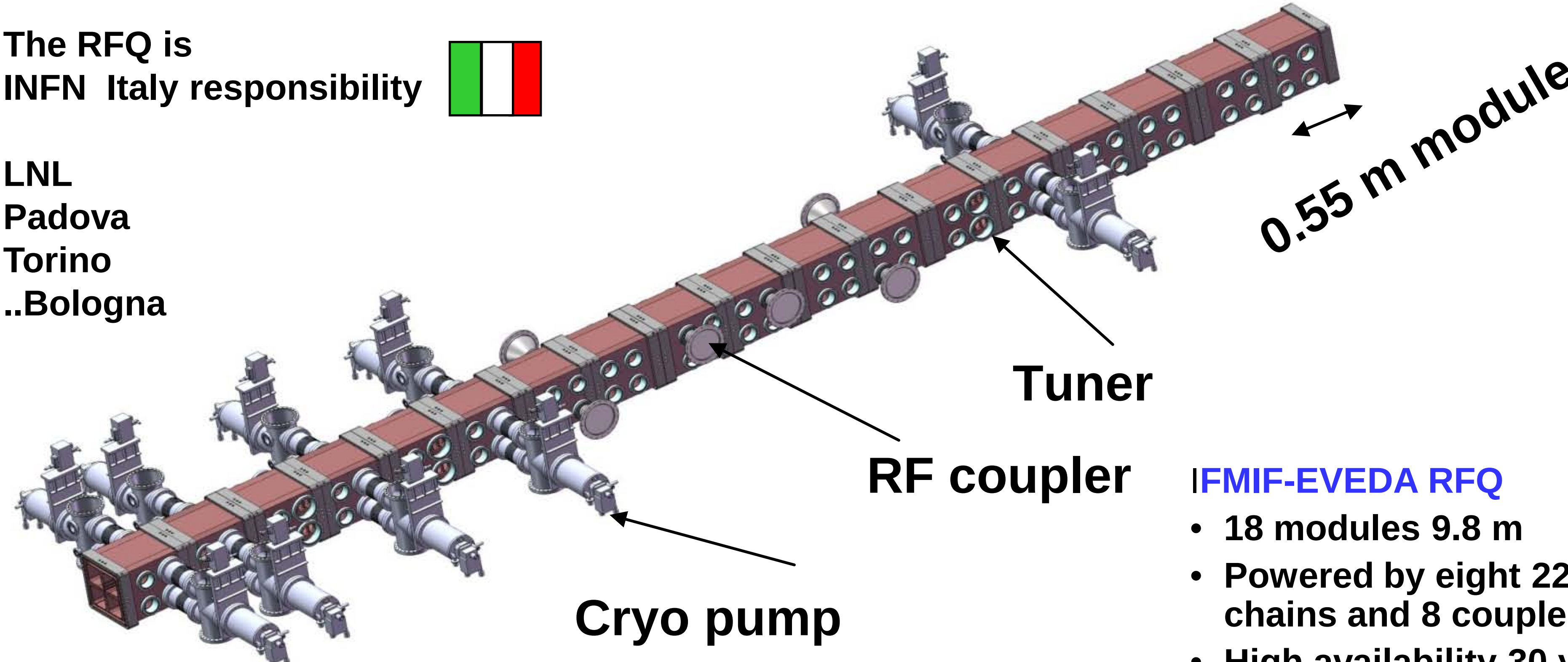


RFQs general parameters

	Name	Lab	ion	energy	vane	beam		RF Cu	Freq.	length		Emax	Power density	
					voltage	current	power	power					ave	max
				MeV/u	kV	mA	kW	kW	MHz	m	lambda	kilpat	W/cm^2	W/cm^2
	IFMIF EVEDA	**LNL**	**d**	**2.5**	**79-132**	**130**	**650**	**585**	**175**	**9.8**	**5.7**	**1.8**	**3.5**	**60**

The RFQ is
INFN Italy responsibility

LNL
Padova
Torino
..Bologna



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**

Fusion Material Irradiation Test Project - FMIT

a US Department of Energy project, accepted as a necessary and vital element for the development of fusion power.

- Construction project approved 1975
- Accelerator construction undertaken by new Accelerator Technology Division at Los Alamos January 1978, after discussions in 1977.
- No IF's - firm budget and schedule, BUT - huge R&D question - injection of 100 mA cw into DTL required several 100 kV DC injector.
- Discovery of Teplyakov RFQ work in Russia.
- Proposal to DOE for RFQ development, approved!

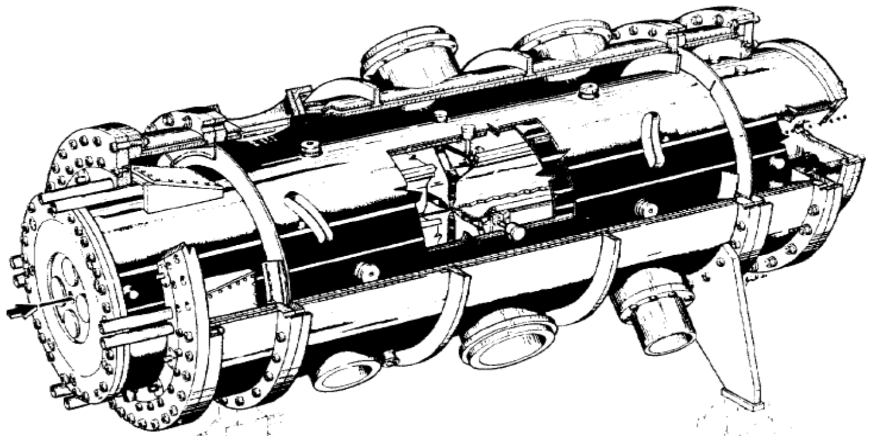
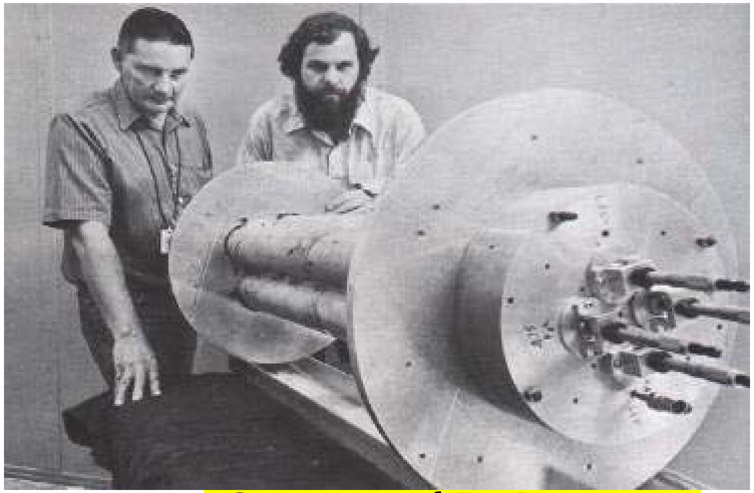


Fig. 1. Initial design of the FMIT RFQ accelerator. The RFQ comprises two coupled, coaxial resonators. The rf power is loop coupled into the outer section. or manifold, which more uniformly distributes the power into the four quadrants of the inner resonator, or core. A 75keV beam is injected (arrow, left in the figure) and accelerated to **2 MeV**.

Arlo Thomas, Jim Potter



Courtesy of R. Jameson

RFQs general parameters

	Name	Lab	ion	energy	vane	beam		RF Cu	Freq.	length		Emax	Power density		operate
					voltage	current	power	power					ave	max	
				MeV/u	kV	mA	kW	kW	MHz	m	lambda	kilpat	W/cm^2	W/cm^2	
	IFMIF EVEDA	**LNL**	**d**	**2.5**	**79-132**	**130**	**650**	**585**	**175**	**9.8**	**5.7**	**1.8**	**3.5**	**30**	**NO**
pulsed	CERN linac 2	CERN	p	0.75	178	200	150	440	202	1.8	1.2	2.5			YES
	SNS	LBNL	H-	2.5	83	70	175	664	402.5	3.7	5.0	1.85	1.1	10	YES
	CERN linac 3	LNL	A/q=8.3	0.25	70	0.08	0.04	300	101	2.5	0.8	1.9			YES

- Since then the experience with CW high power beams from RFQs has been very limited.
- The Radio Frequency Quadrupoles have developed in the following 20 years as the first RF accelerating structure of pused linacs
- This experience (theory, codes, tuning algorithms, engineering tools) is fundamental for the design of a modern high power RFQ,
- Other aspects are specific of the high power application and require dedicated R&D.
- Few examples can be mentioned, chosen in a vast and mature field

CERN RFO2

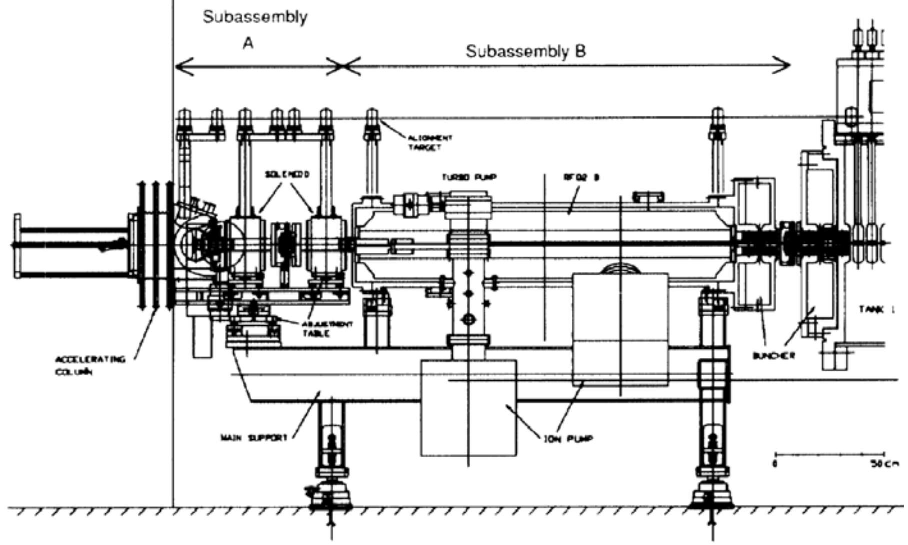
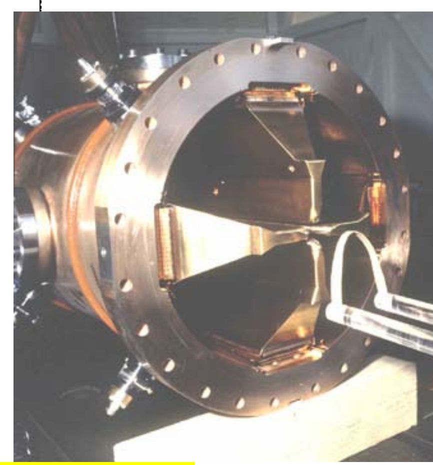


Figure 2. The RFQ2 complex

Main RFQ2 design parameters

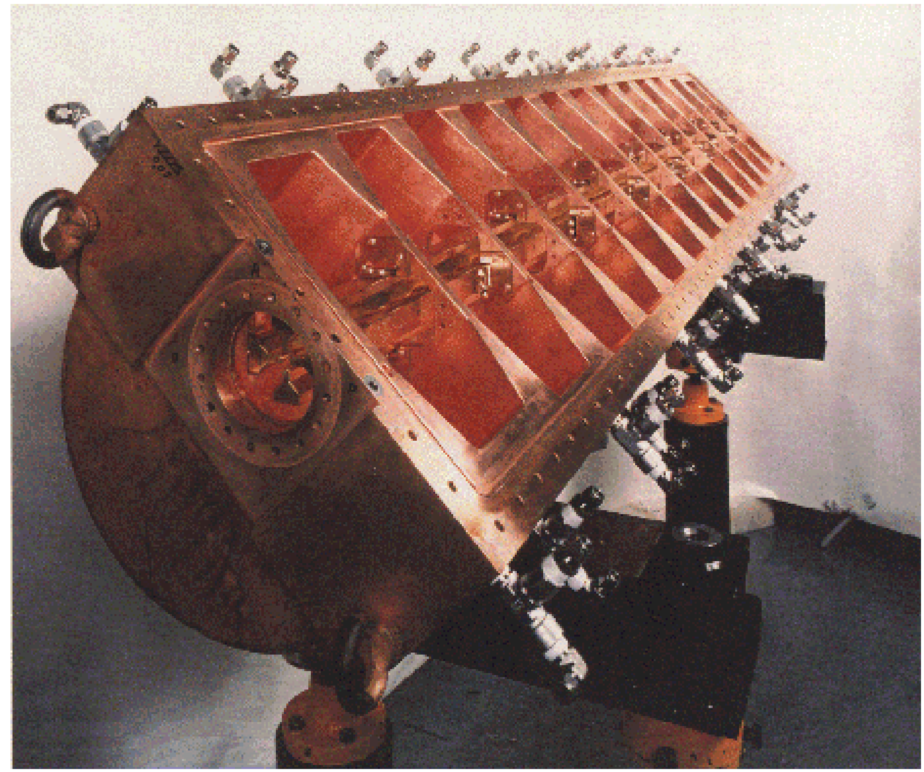
RF frequency	202.56 MHz
Input energy	90 KeV
Output energy	750 KeV
Output current	200 mA
Trapping efficiency	~90 %
Vane voltage	178 KV
Final synchronous phase	-35 °
Modulation factor(max)	1.62
Mean aperture radius	7.87 cm
Cavity length	178.5 cm
Vane length	175.2 cm
Cavity diameter	35.4 cm

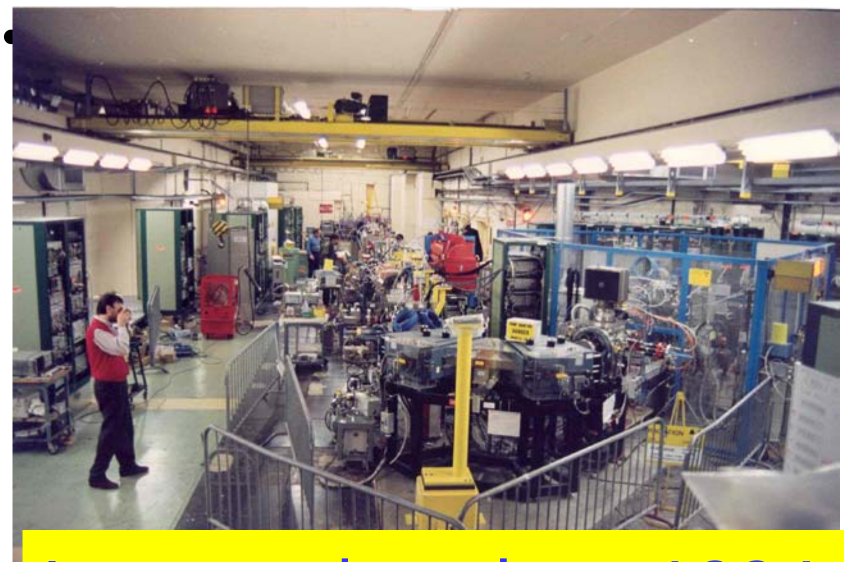


In operation since 1992

CERN lead ion RFQ (Pb injector of LHC)

- A/q=208/25
- 100 uA Pb beam
- Energy range 2.5-250 keV/u
- Transmission 93% with large multipole correction (kR_0=3.3, m=1.1)
- Operational since 1994
- Built in Italy at De Pretto and Cinel





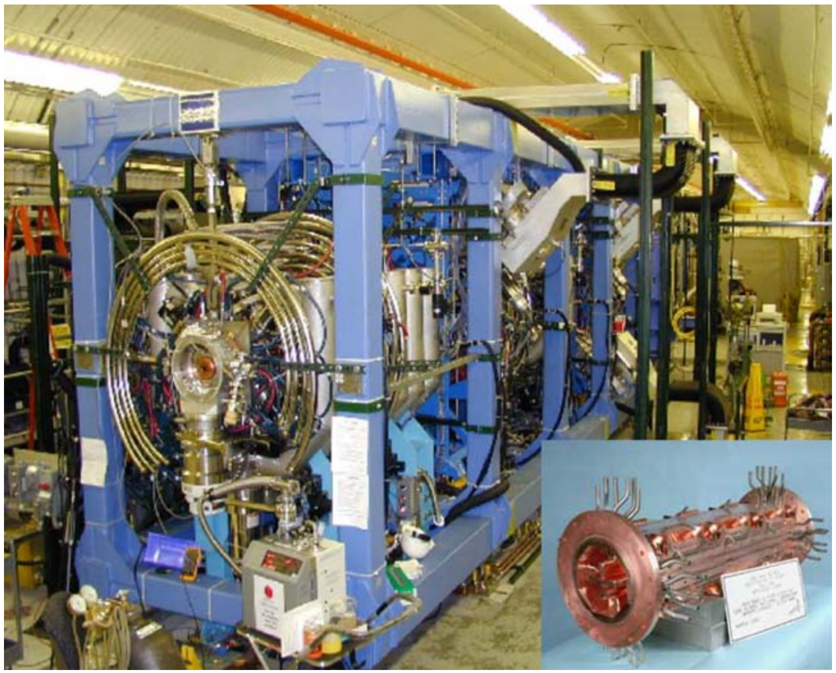
In operation since 1994

- The linac was built by an international collaboration (INFN-GANIL-GSI-CERN).
- INFN LNL delivered in time and in specs the LEBT the MEBT and the RFQ (except the RF, done by GSI)

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}	Power density 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**	**60**	**NO**
CW	LEDA	LANL	p	6.7	67-117	100	670	1450	350	8	9.3	1.8	11.4	65	*YES*

LEDA

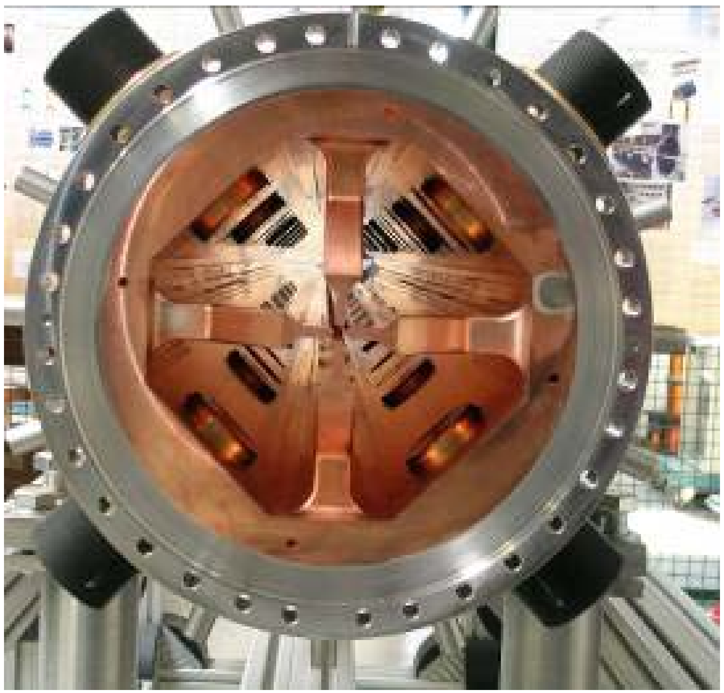


Technology established.
Beam performances reached
About 110 hrs of operating above 90 mA cw

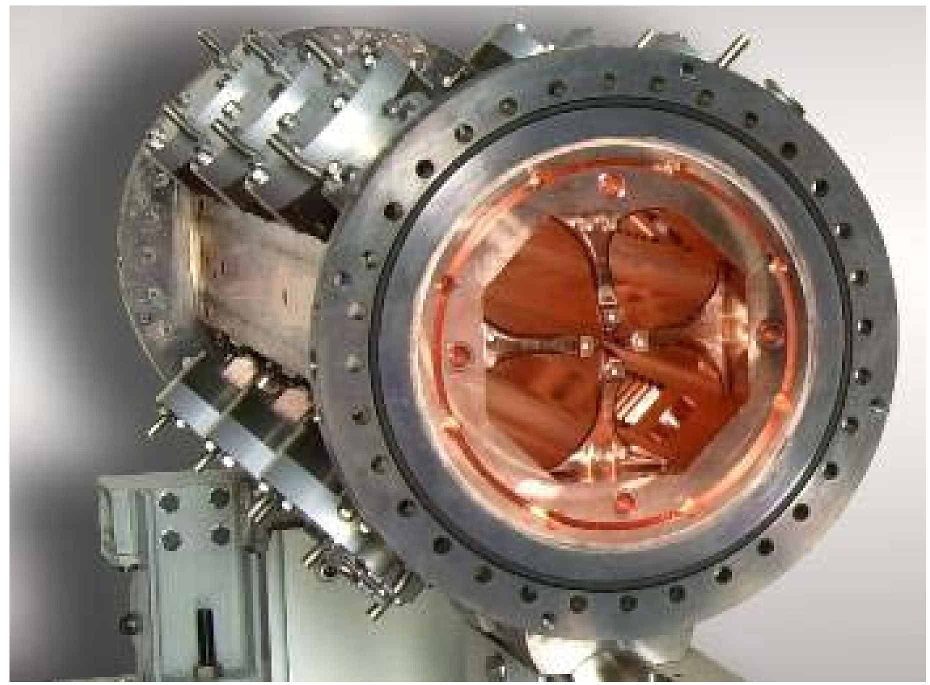
- **Many specific features of cw-RFQ were developed with LEDA-RFQ,**
  - Many modules (8), each module built by brazing
  - the ramped voltage along the structure,
  - the resonant coupling between RFQ segments, the rods for dipole stabilization.
  - LEBT with neutralized beam and electron trap at the RFQ entrance

Research Programs in Europe related to ADS studies

	Name	Lab	ion	energy	vane voltage	beam current	power	RF Cu power	Freq.	length		Emax	Power density ave	max	operate
				MeV/u	kV	mA	kW	kW	MHz	m	lambda	kilpat	W/cm^2	W/cm^2	
	IFMIF EVEDA	**LNL**	**d**	**2.5**	**79-132**	**130**	**650**	**585**	**175**	**9.8**	**5.7**	**1.8**	**3.5**	**60**	**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*



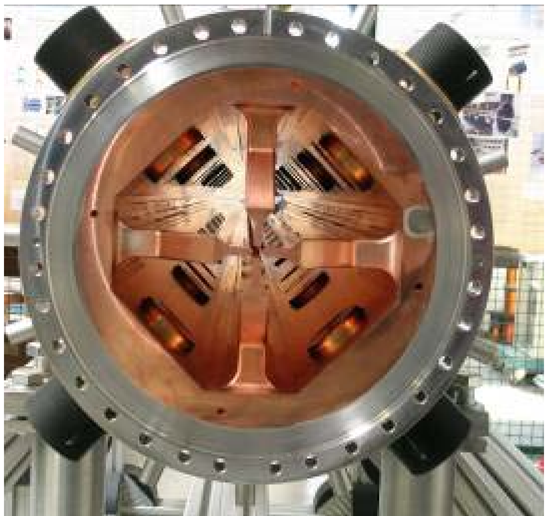
TRASCO@LegnaroINFN



IPHI@Saclay.CEA

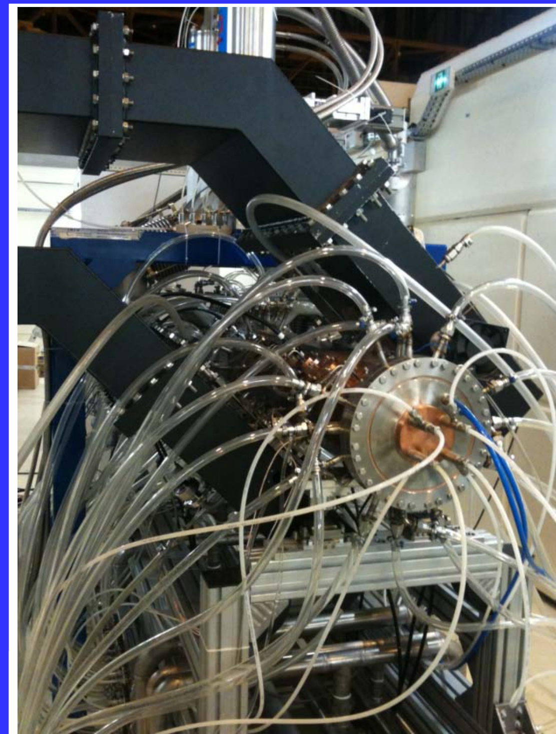
TRASCO RFQ (developed for ADS studies)

	Name	Lab	ion	energy	vane voltage	beam current	power	RF Cu power	Freq.	length		Emax	Power density ave	max	operated
				MeV/u	kV	mA	kW	kW	MHz	m	lambda	kilpat	W/cm^2	W/cm^2	
	IFMIF EVEDA	**LNL**	**d**	**2.5**	**79-132**	**130**	**650**	**585**	**175**	**9.8**	**5.7**	**1.8**	**3.5**	**60**	**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*



TRASCO@LegnaroINFN

TRASCO RF tests @Saclay.CEA

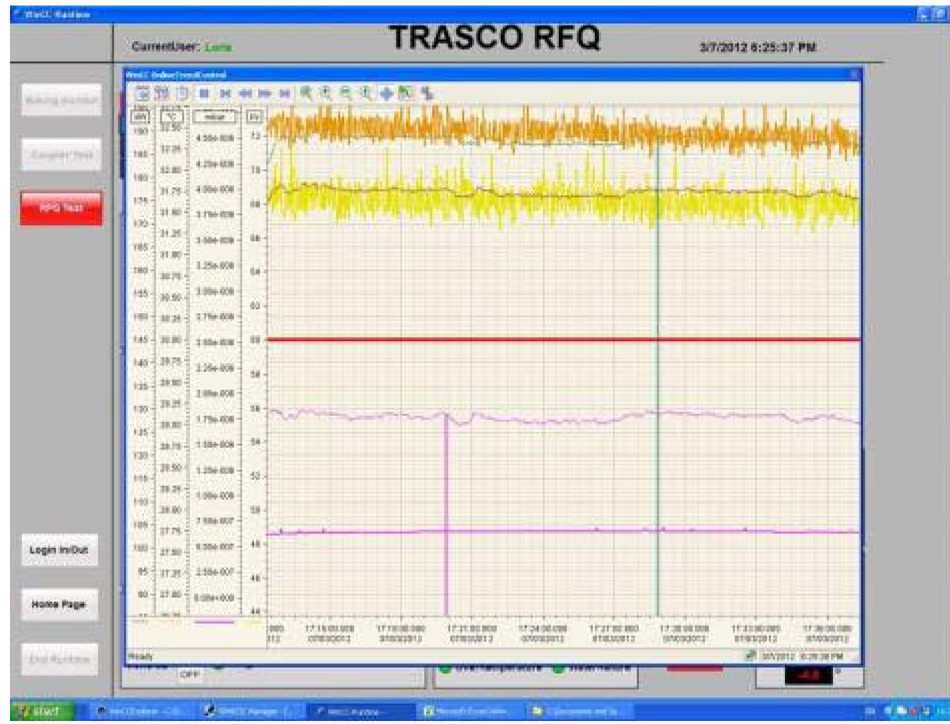


Tested up to 2 Ekp, 80 kW/m
100% duty cycle

RFQ of TRASCO stable condition cw

nominal field

80kW/m, 1.8 Ekp



E. Fagotti et al, results unpublished, off line analysis going on

Nucleare sloveno, polemiche in Friuli-Venezia Giulia

News

ITALIA - Ricerca

21-03-2012

Un acceleratore italiano da record

Se nel campo dell'energia nucleare l'Italia è assente dalla scena internazionale, per quanto riguarda la ricerca nucleare ha e mantiene un ruolo di primo piano a livello mondiale. Ora questa posizione è confermata da **un nuovo record**,

Archivio NEWS

News correlate

Puntare sulla ricerca, per tornare nella serie A del nucleare

Fusione: presentato nuovo laboratorio a Padova

Ancora una vittoria italiana nei bandi per il reattore ITER

ITER parla sempre più italiano

Frascati: esperimento conferma la validità del progetto ITER

Due reattori alle porte di Roma? Sono appena ripartiti

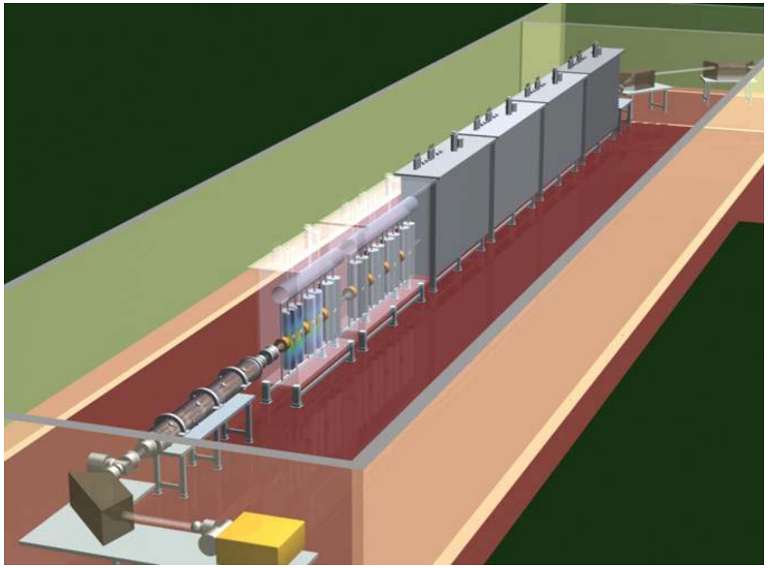
Categorie

- Ambiente e salute
- Bilanci e stato dell'arte
- Commenti
- Energia
- Formazione/Comunicazione
- Industria/Economia
- Nucleare per altri usi
- Politica
- Ricerca
- Scorie
- Sicurezza

CW RFQs for few mA light ion superconducting linacs up to 40 MeV

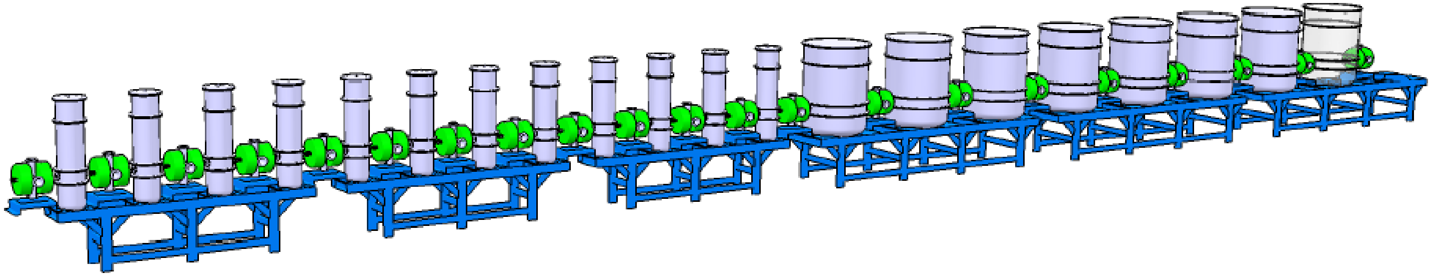
SARAF at SOREQ (Israel)

SARAF (Israel)
40 MeV
4 mA d and p
176 MHz
Status: beam test up to the first cyomodule



SPIRAL2 at GANIL (France)

SPIRAL2 driver (France)
5 mA d and ions up to A/q=3
40 MeV
80 MHz



Status: in construction

RFQs general parameters

	Name	Lab	ion	energy	vane voltage	beam current	power	RF Cu power	Freq.	length		Emax	Power density ave	max	operate
				MeV/u	kV	mA	kW	kW	MHz	m	lambda	kilpat	W/cm^2	W/cm^2	
	IFMIF EVEDA	**LNL**	**d**	**2.5**	**79-132**	**130**	**650**	**585**	**175**	**9.8**	**5.7**	**1.8**	**3.5**	**60**	**NO**
CW high p	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*
	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*
CW mid p	SARAF	NTG	d	1.5	65	4	12	250	176	3.8	2.2	1.4	24	190	*only p*
	SPIRAL2	CEA	A/q=3	0.75	100-113	5	7.5	170	88	5	1.5	1.65	0.6	19	*NO*

SARAF at SOREQ (Israel)

Installed in the tunnel
Cw operation for d and nominal beam transmission not yet reached

SPIRAL2 at GANIL (France)

In construction
Prototype successfully RF conditioned

RFQs general parameters

	Name	Lab	ion	energy	vane voltage	beam current	power	RF Cu power	Freq.	length		Emax	Power density ave	Power density max	operated
				MeV/u	kV	mA	kW	kW	MHz	m	lambda	kilpat	W/cm^2	W/cm^2	
	IFMIF EVEDA	**LNL**	**d**	**2.5**	**79-132**	**130**	**650**	**585**	**175**	**9.8**	**5.7**	**1.8**	**3.5**	**60**	**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*
CW	SARAF	NTG	d	1.5	65	4	12	250	176	3.8	2.2	1.4	24	190	*NO*
mid p	SPIRAL2	CEA	A/q=3	0.75	100-113	5	7.5	170	88	5	1.5	1.65	0.6	19	*NO*
CW	ISAC	TRIUMF	A/q=30	0.15	74	0	0	150	35	8	0.9	1.15	-	-	*YES*
lp	PIAVE	LNL	A/q=7.3	0.58	280	0	0	8e-3 (SC)	80	2.1	0.5	2.1	-	-	*YES*

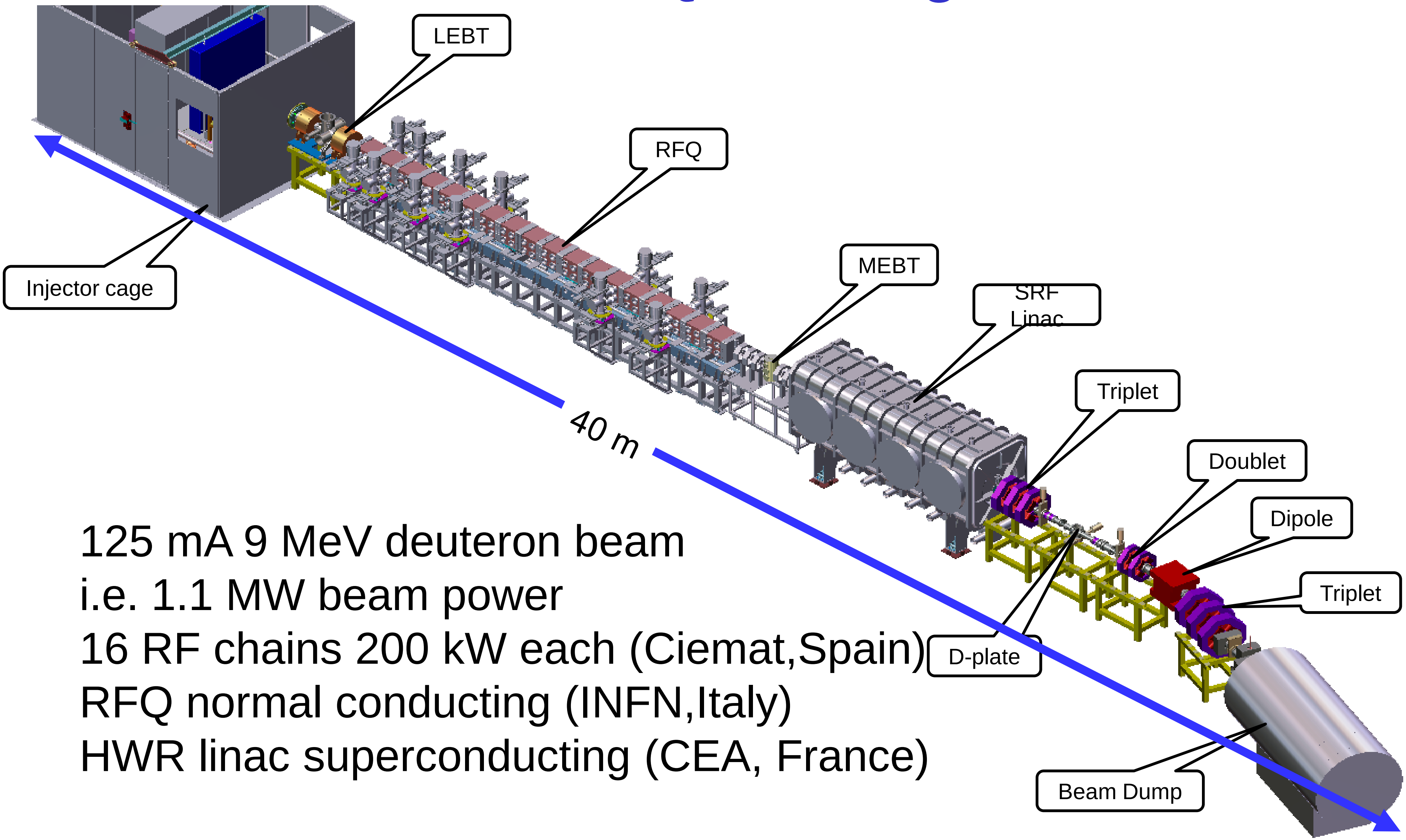
ISAC @TRIUMF (Canada)

PIAVE @LNL INFN (IT)

Nb superconducting

External bunching, 65% transmission (as in simulations) reached

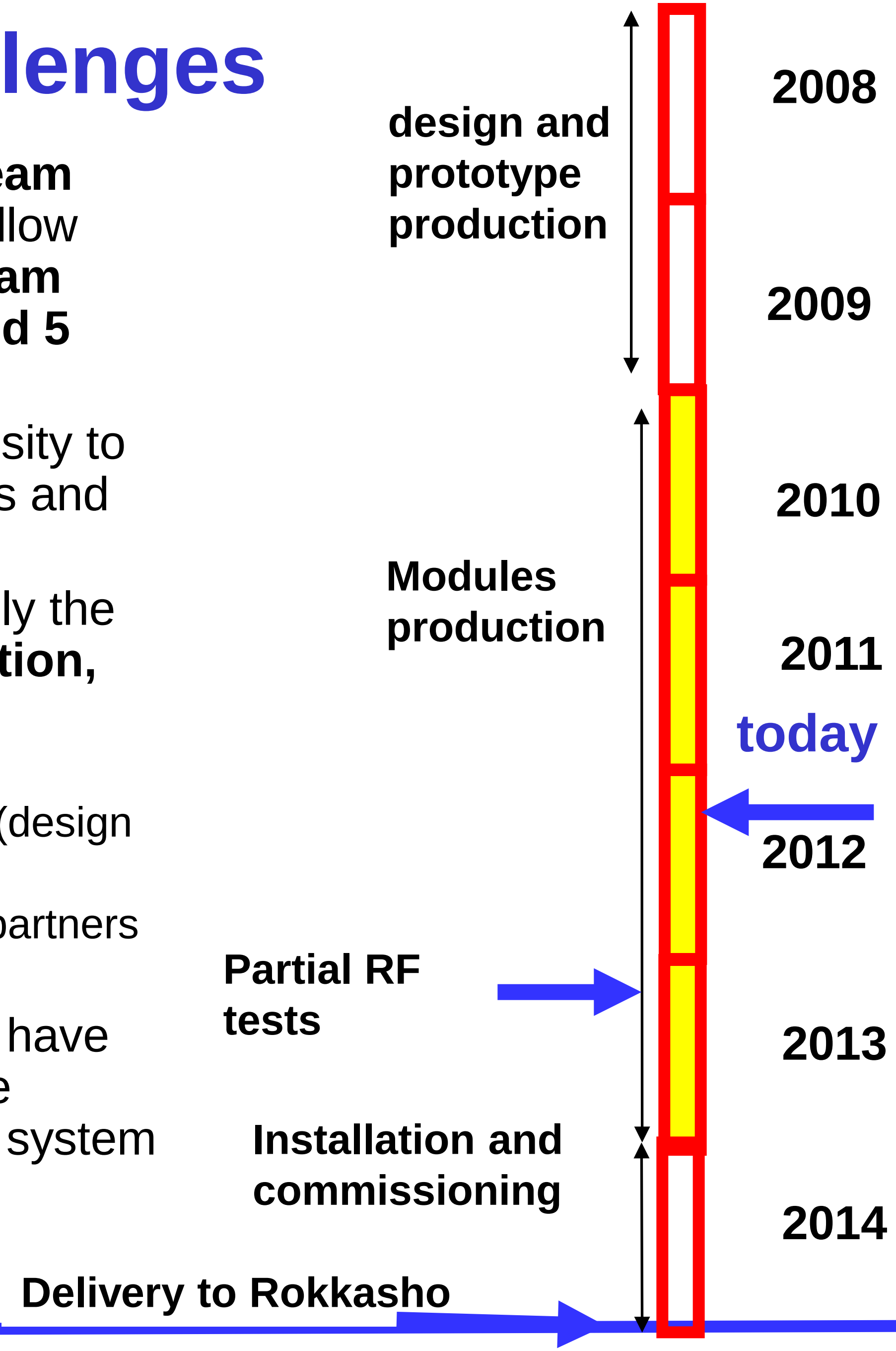
IFMIF RFQ challenges

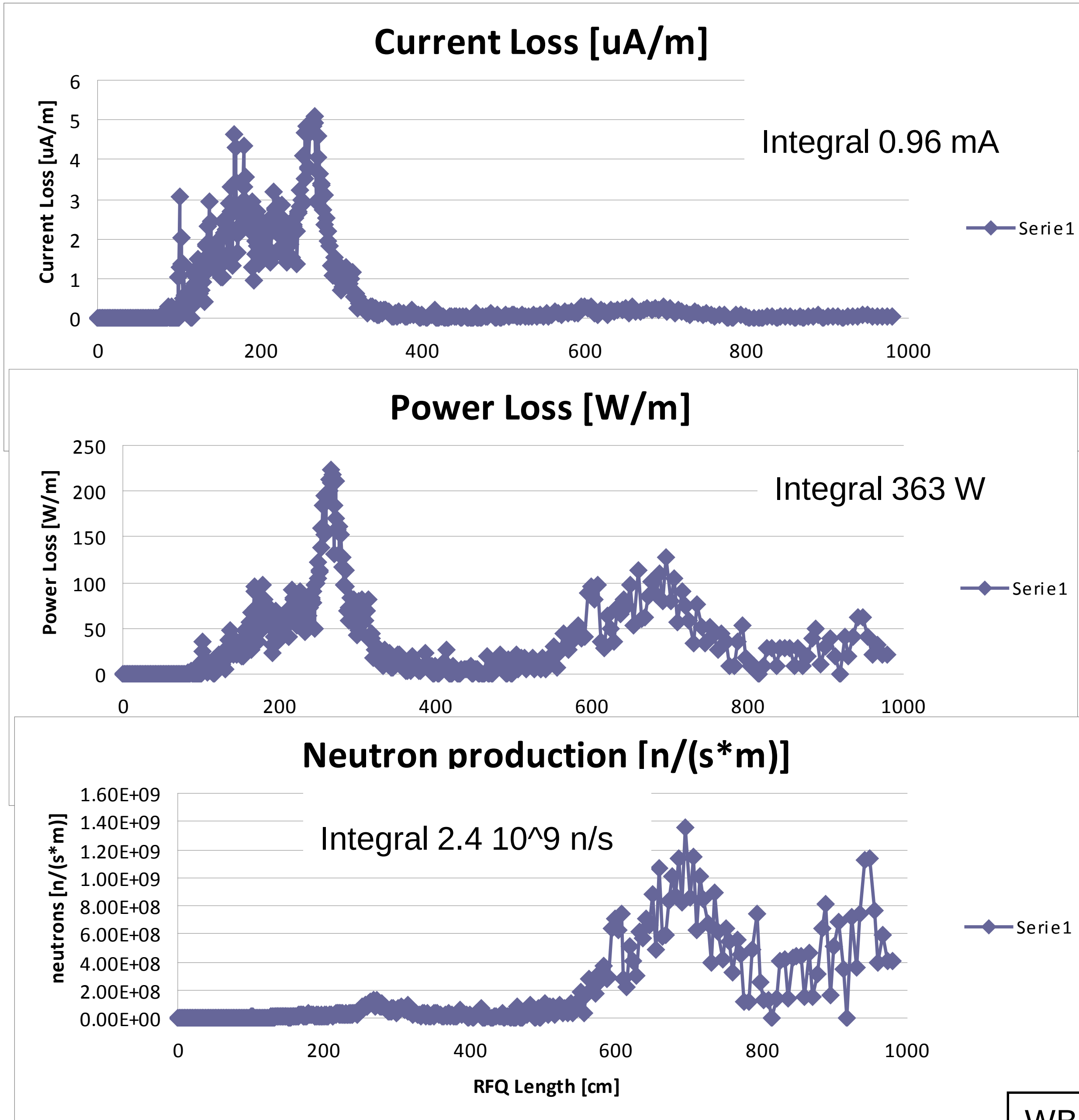


125 mA 9 MeV deuteron beam
i.e. 1.1 MW beam power
16 RF chains 200 kW each (Ciemat,Spain)
RFQ normal conducting (INFN,Italy)
HWR linac superconducting (CEA, France)

IFMIF EVEDA RFQ challenges

- **650 kW beam** should be accelerated with **low beam losses and activation** of the structure so as to allow hands-on maintenance of the structure itself (**Beam losses<10 mA and <0.1 mA between 4 MeV and 5 MeV). (Tolerances of the order of 10-50 um)**
- **600 kW RF dissipated** on copper surface: necessity to keep geometrical tolerances, to manage hot spots and counteract potential instability.
- The RFQ will be the **largest ever built**, so not only the accelerator must be reliable, but also the **production, checking and assembling procedure must be reliable**
  - Fully exploit **INFN internal production capability** (design machining, measurement and *brazing*)
  - Make production accessible for different industrial partners
- At present and **we are in the production of the modules** phase. The construction of 12 modules have been commissioned to industry, 6 modules will be produced internally. Tenders for vacuum, cooling system and other ancillaries are starting.





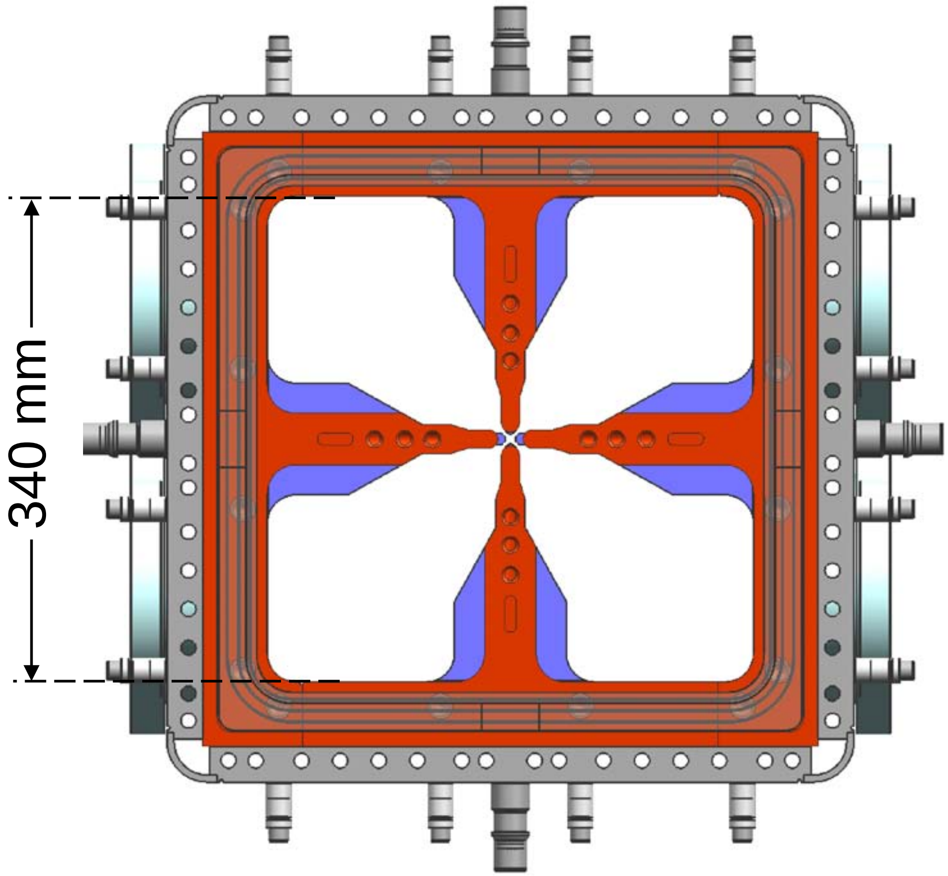
Beam losses

- To achieve Beam losses concentrated in the low energy part is very important since neutron production is proportional to w^2

$$n = 5.15 * 10^{-7} N w^{2.1}$$

WB distribution 0.25 mm mrad rms norm

Cavity cross section

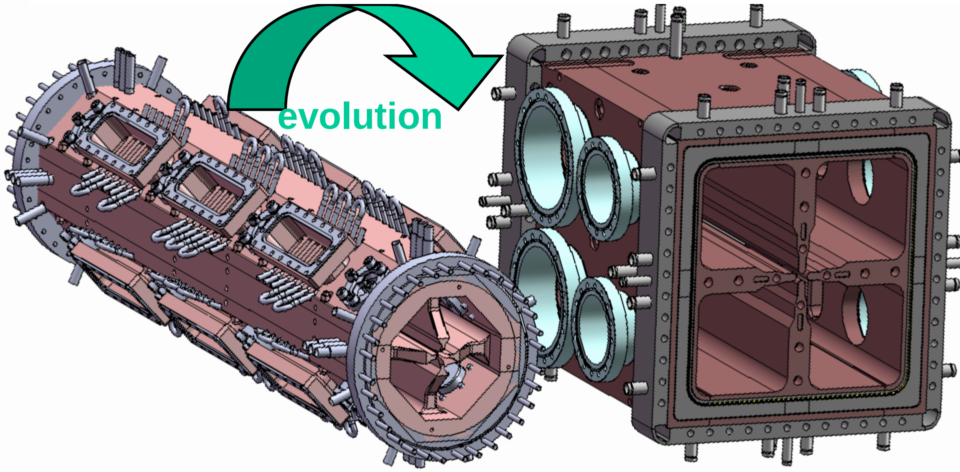


Operating Frequency	175	MHz
Length	9.78	m
Vg (min – max)	79 – 132	kV
R0 (min - max)	0.4135 - 0.7102	cm
Total Stored Energy	6.63	J
Max. RF power to the cavity P_d	1345	kW
Number of slug tuners	96	
Frequency tuning	Water temp.	

Mechanical design

- **Based on vacuum brazing, LNL mechanical experience with TRASCO,** CERN experience for RFQ brazing, 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).**
- 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 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.

Prototype before brazing at CERN

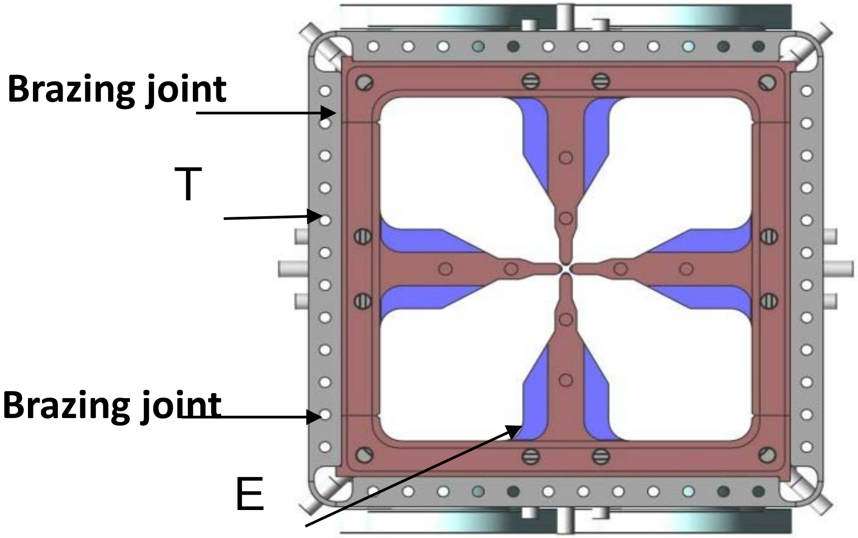


TRASCO and IFMIF module

Mechanical design

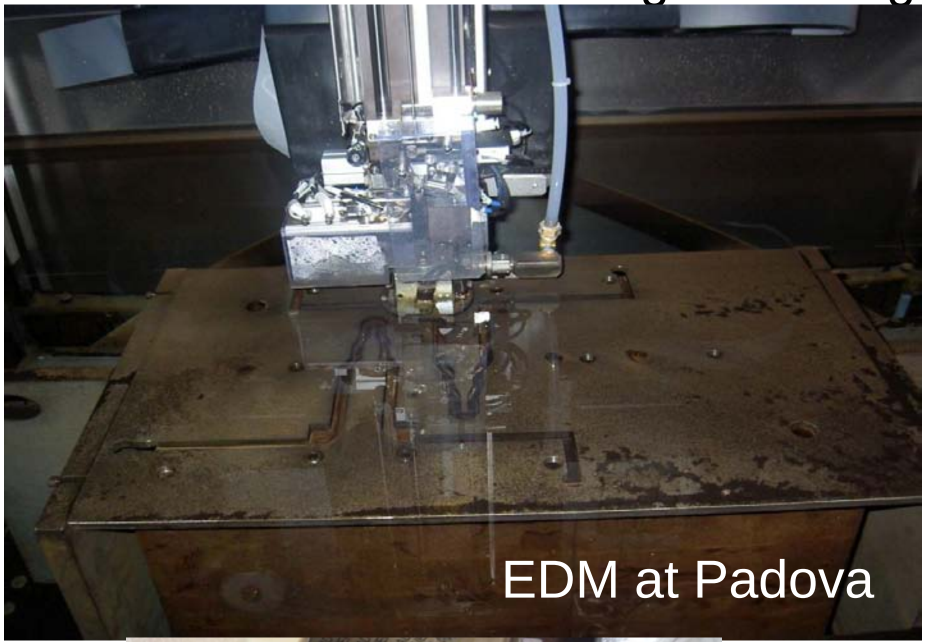
- **Based on vacuum brazing, LNL mechanical experience with TRASCO,** CERN experience for RFQ brazing, design compatible with oven at CERN, LNL and in industry;
- Due to the relatively large transverse dimensions of the RFQ, the procurement of the CUC2 raw material blocks is limited by the total mass amount (length **550 mm).**
- 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 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.

Prototype before brazing at CERN

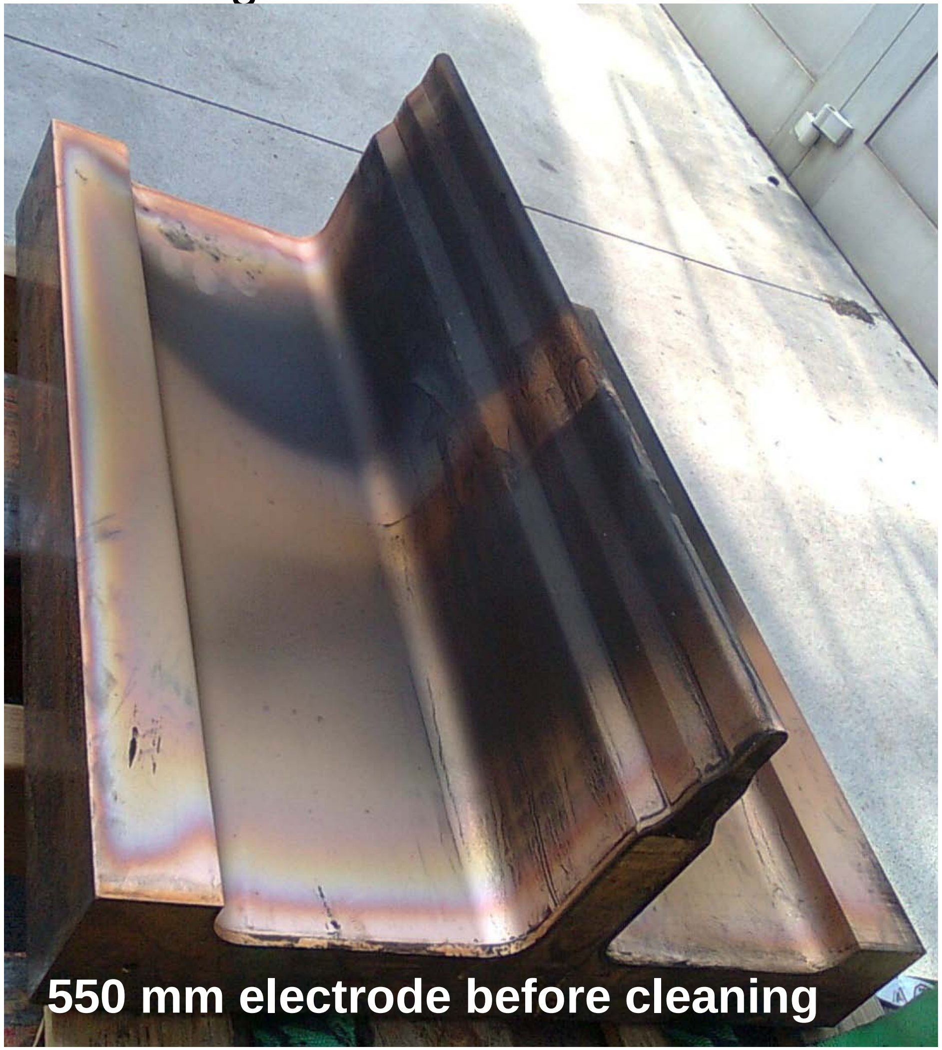


First construction step module n0 16

- Rough machining of block 550 mm long vie EDM for minimal stresses and deformations during annealing and brazing



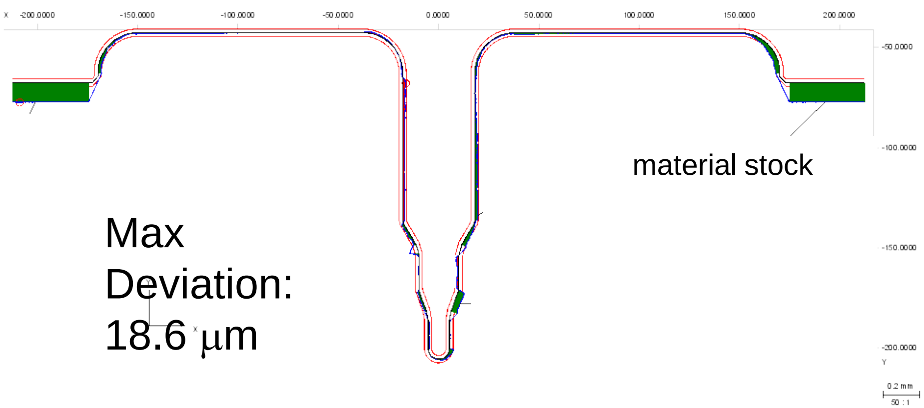
EDM at Padova



550 mm electrode before cleaning

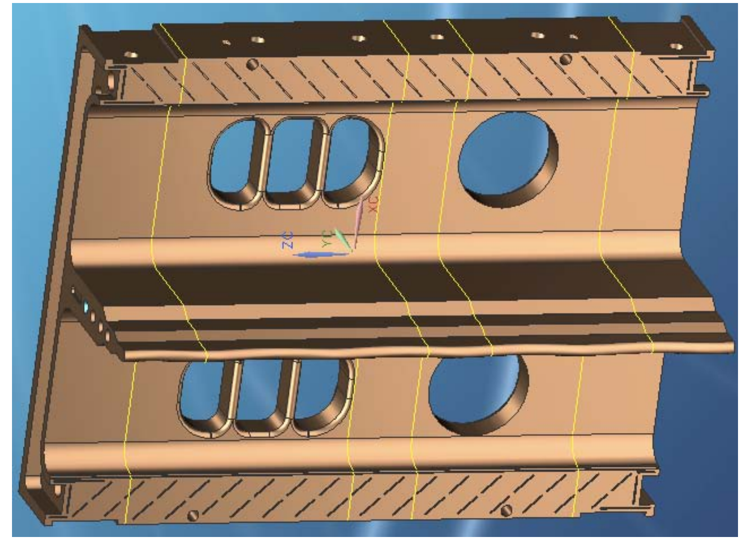
Remaining cupper

Four electrodes of module #16 electrodes (machined by Cinel) in specs

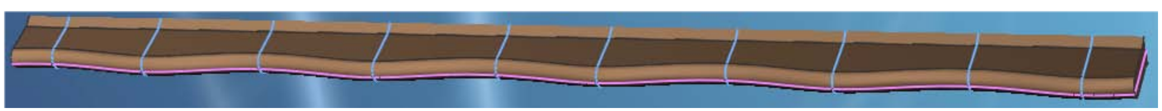


material stock

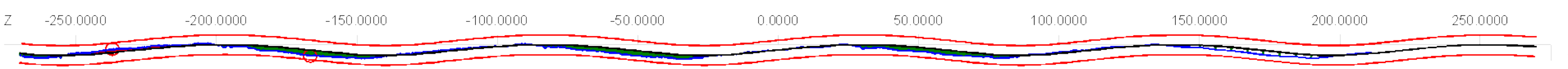
Max Deviation: 18.6 μm



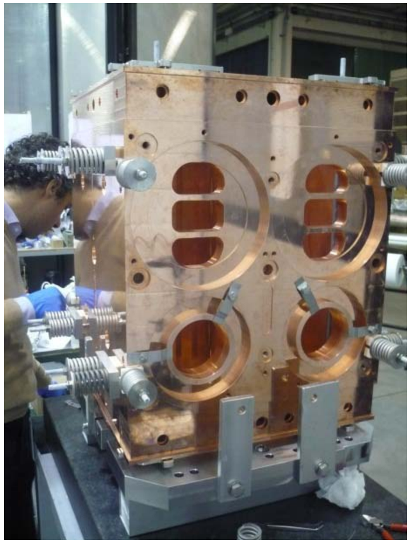
Max Deviation: 10.5 μm

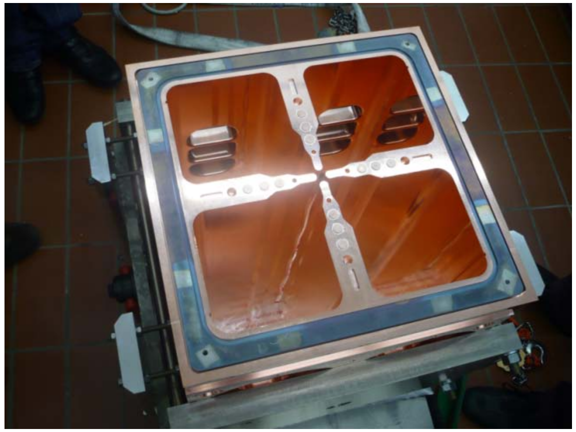


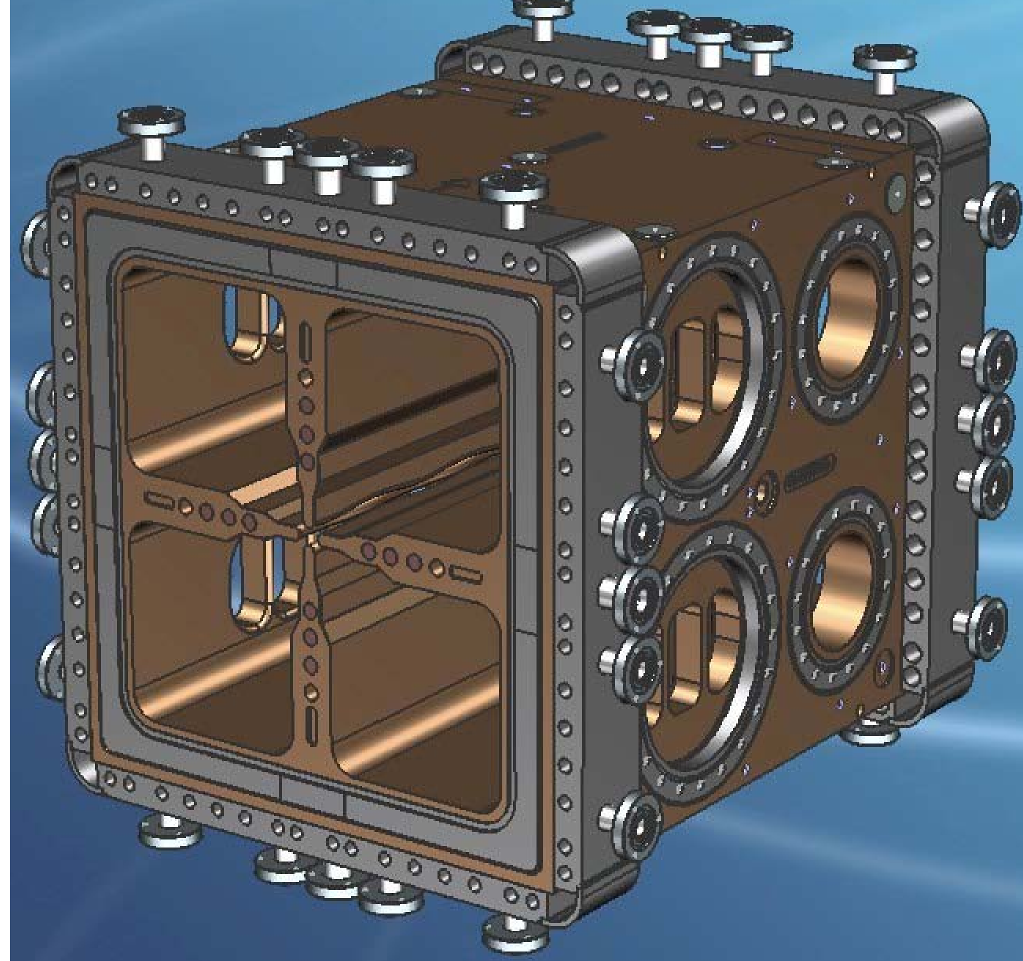
Max Deviation: 6.1 μm

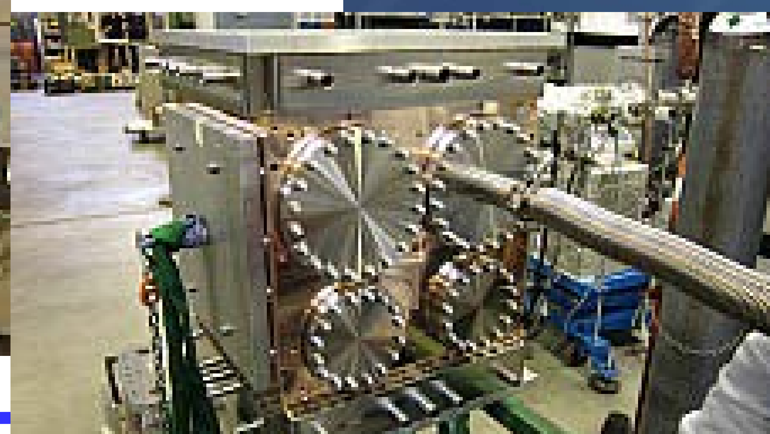


Module 16 construction





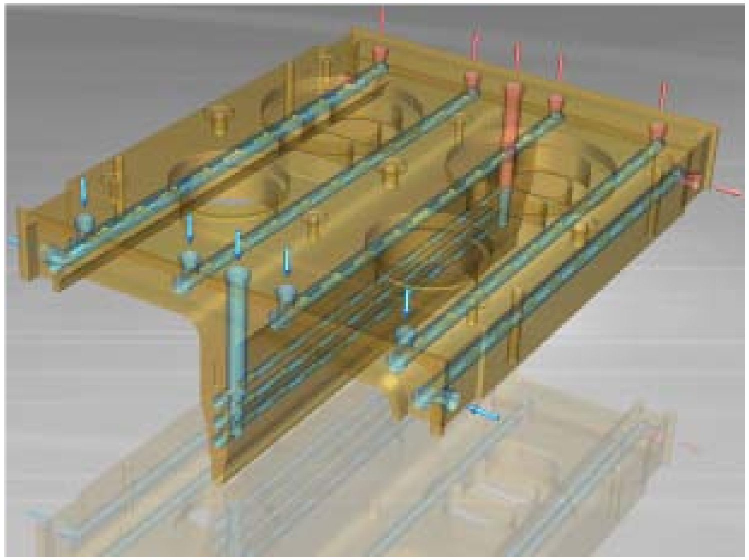


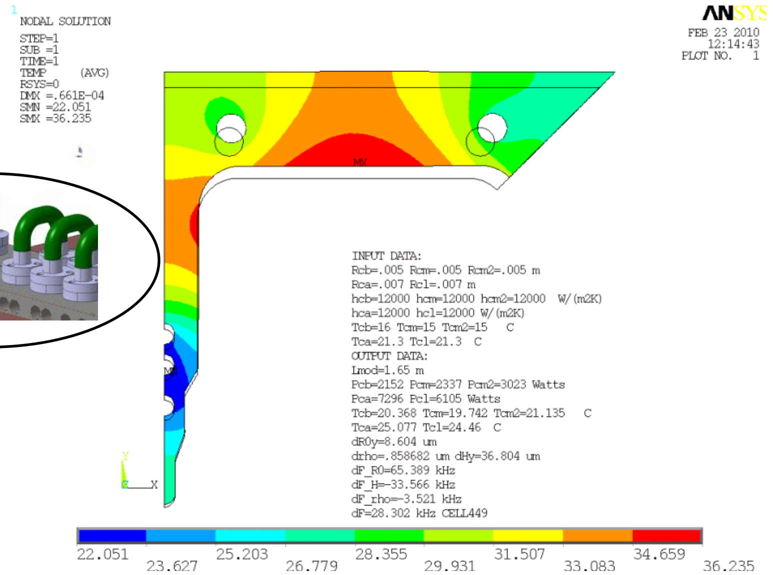


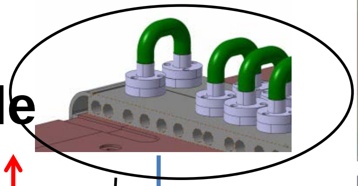
It is hard to keep 50 um accuracy after brazing

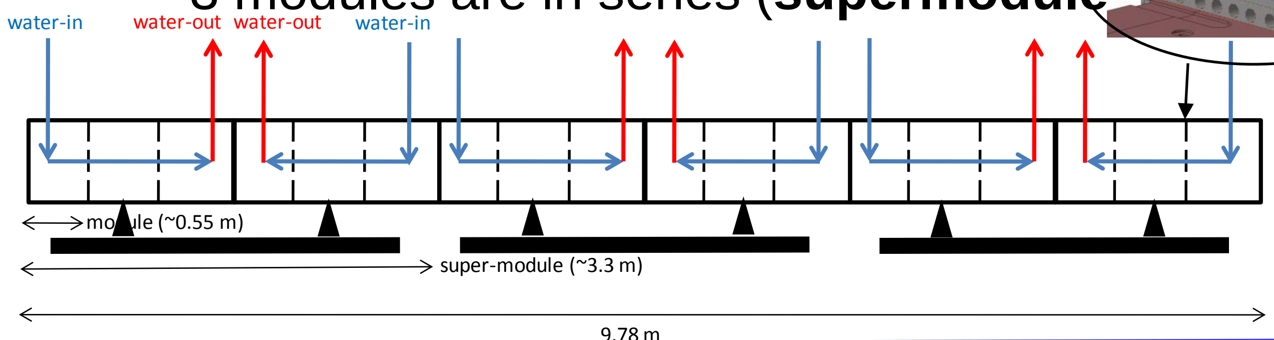
Cooling circuit

- About **600 kW RF power** are removed by means of **28 channels** longitudinally drilled along the RFQ modules; the water velocity is approximately 3 m/s,
- **12 channels at fixed low temperature** on the **vanes**
- **16 channels on the cavity wall** with variable temperature for **frequency tuning**
- the temperature of the channels on the vane and on the cavity wall can be separately tuned so to achieve a tuning range of $\pm$100kHz.
- 3 modules are in series (**supermodule**





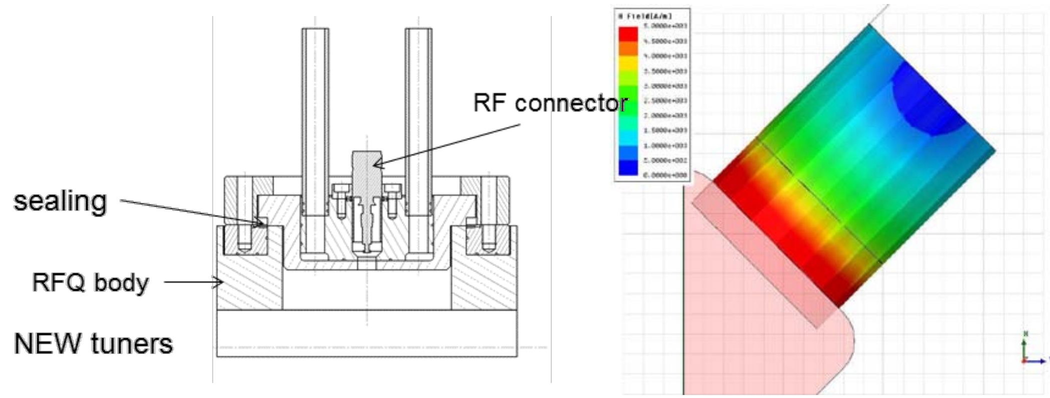




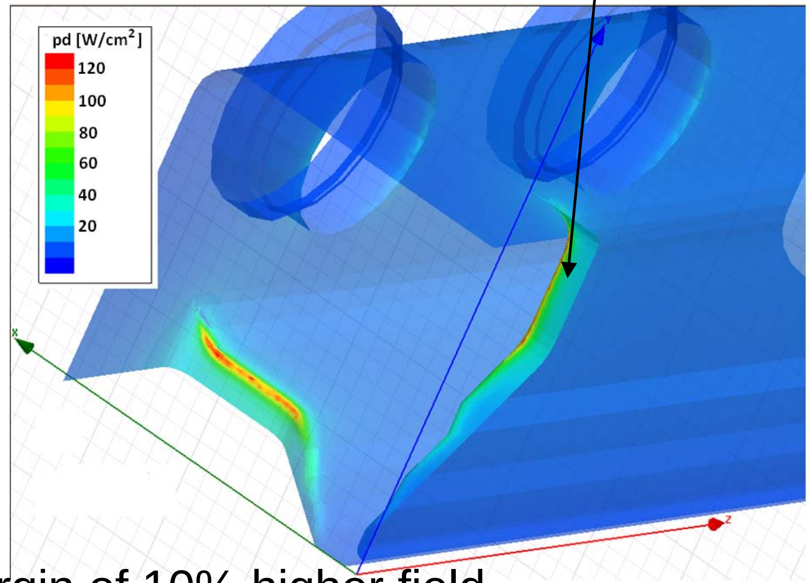
3D details

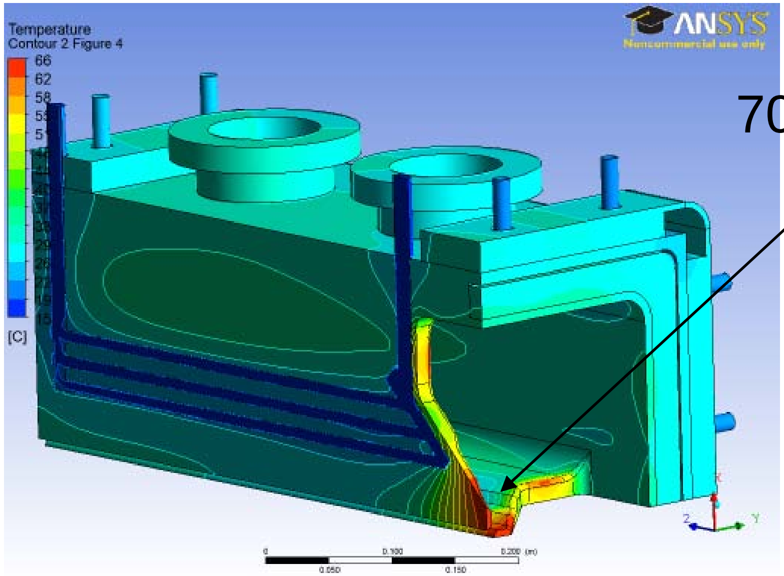
- Dummy tuners, vacuum grids and end cells
- In the end cell the 45° angle of the undercut guarantees the access of the cooling channel as close as possible to the hot spot at the electrode base **(~80 W/cm2*)**, which is the most severe of the entire RFQ
- Deformations of 70 um and field perturbation less than 1%

Slug tuners (CF100)



Tuning range ±1 MHz

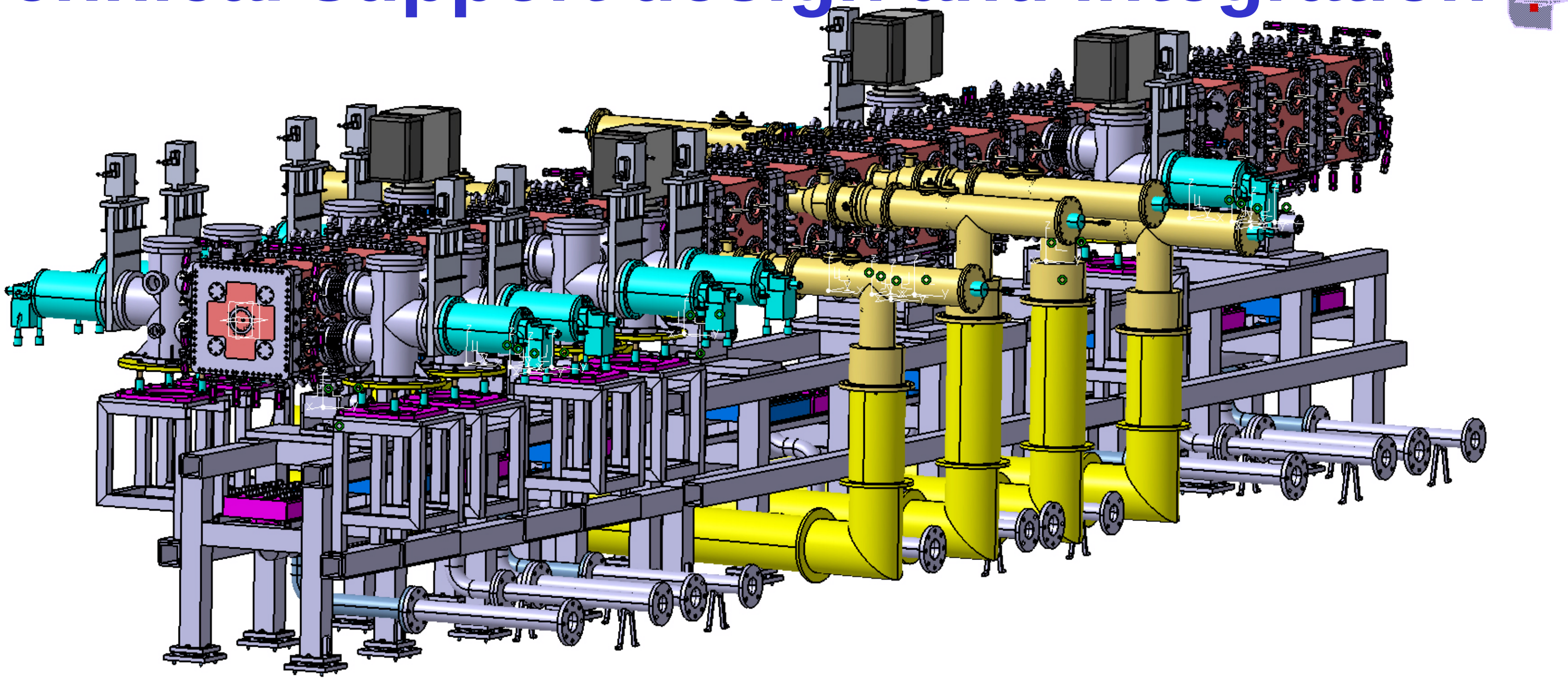


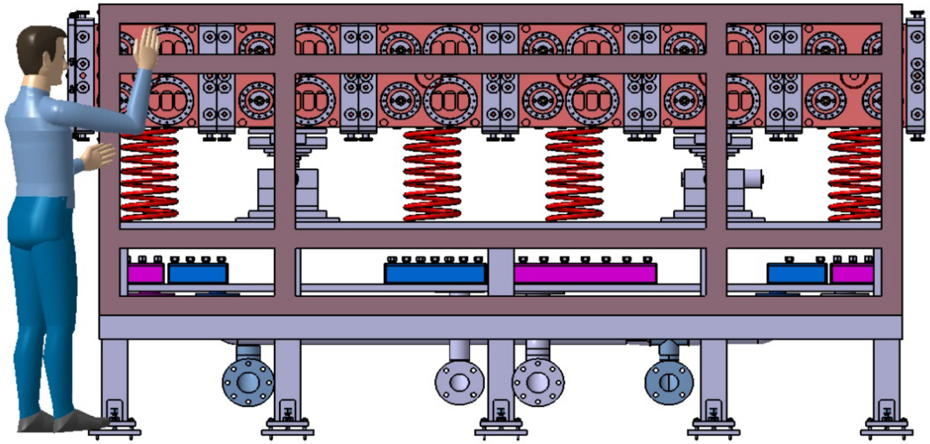


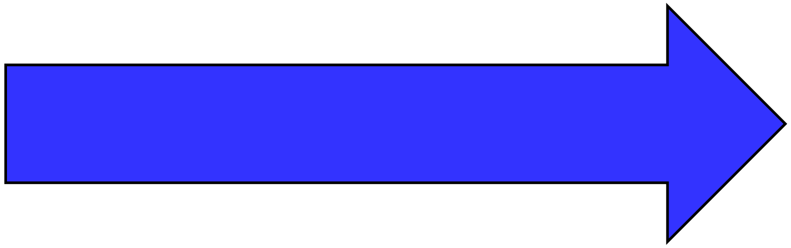
70 deg C

*with margin of 10% higher field

Mechnical support design and integration



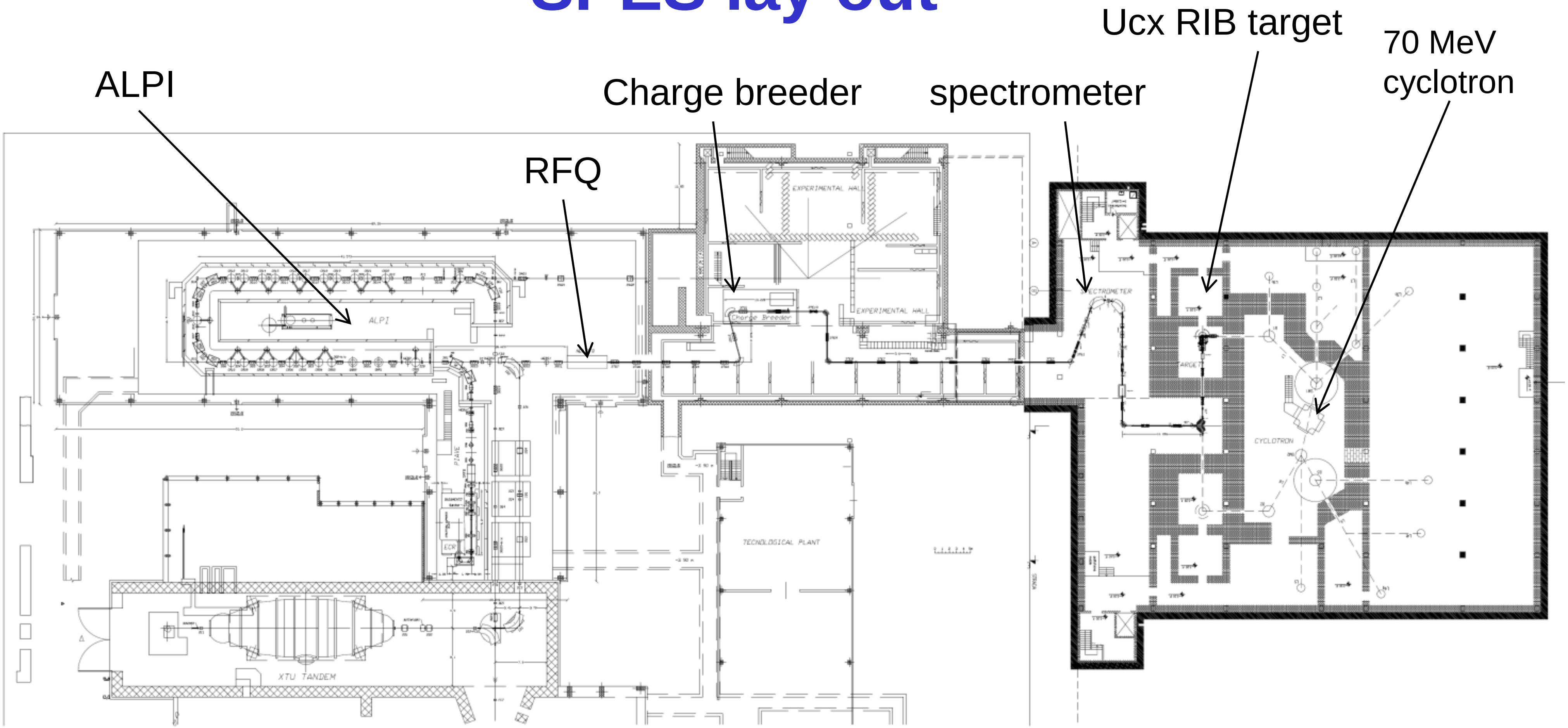




IFMIF/EVEDA Accelerator building by JAEA In Rokkasho (Aomori)

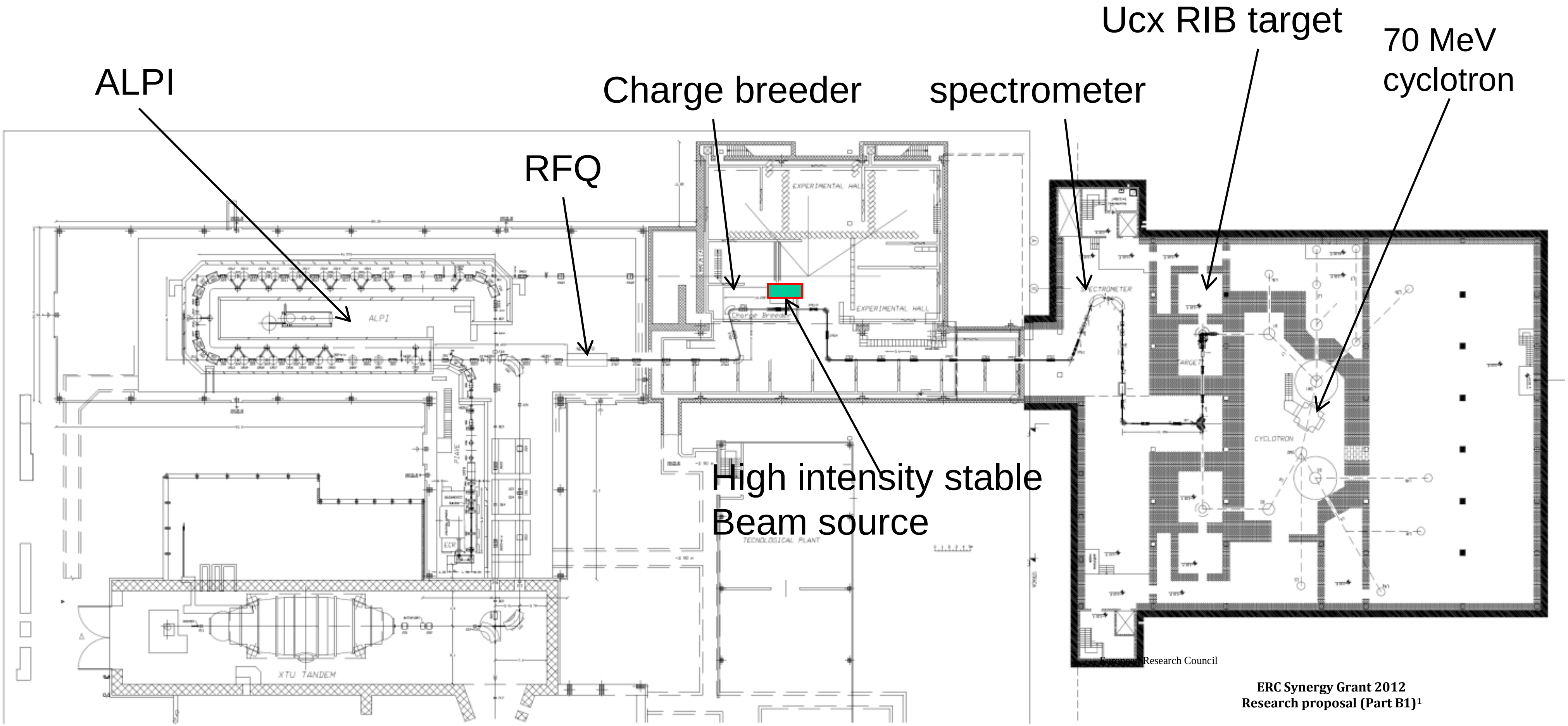
SPES at LNL

SPES lay out



- The new TDR will be based on this lay out, for A/q=7 the extraction voltage is 40 KV, after the breeder the beam is accelerated by a new 80 MHz RFQ

SPES lay out: High intensity capability Pb 10-100



European Research Council

ERC Synergy Grant 2012
Research proposal (Part B1)[1]

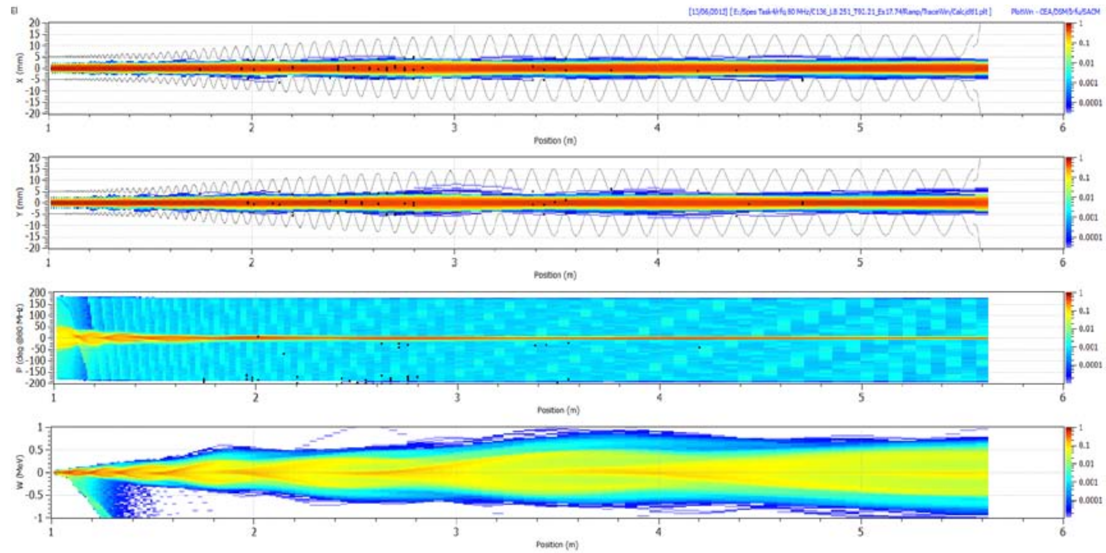
Proposal full title: "Innovative front-end accelerator of a high-intensity stable ion beam, for breakthrough investigations in Nuclear Astrophysics, with applications in Nuclear Medicine, Micro-electronics, Nanotechnology"
PROPOSAL ACRONYM: Pb-10-100

Corresponding Principal Investigator: **Giovanni BISOFFI**
Principal Investigator: **Luigi CELONA**
Principal Investigator: **Adriano PEPATO**
Corresponding Host Institution: **Istituto Nazionale di Fisica Nucleare**
Proposal short name: **Pb-10-100**
Proposal full title: **"Innovative front-end accelerator of a high-intensity stable ion beam, for breakthrough investigations in Nuclear Astrophysics, with applications in Nuclear Medicine, Micro-electronics, Nanotechnology"**
Proposal duration in months: **72**

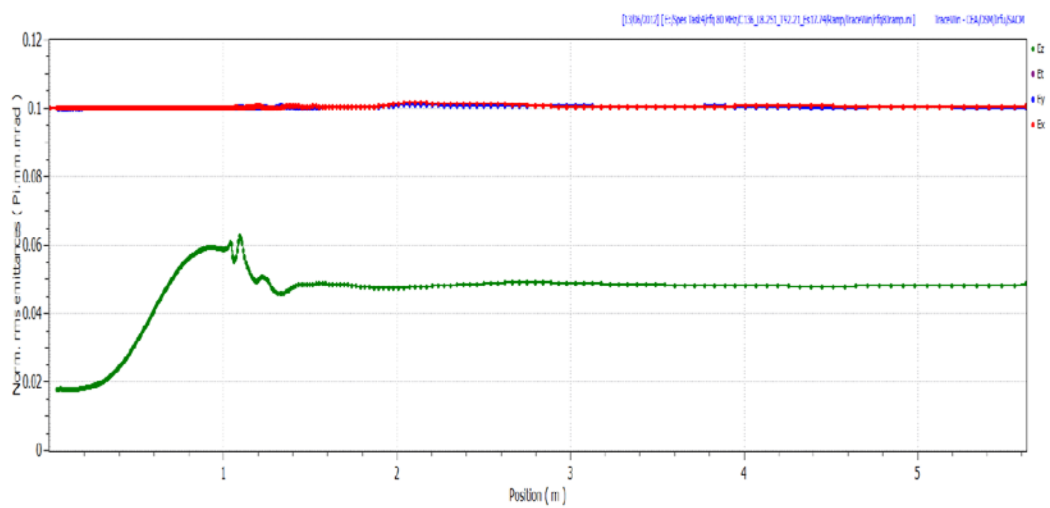
- An ion source (superconducting?) can be added to inject the RFQ and ALPI

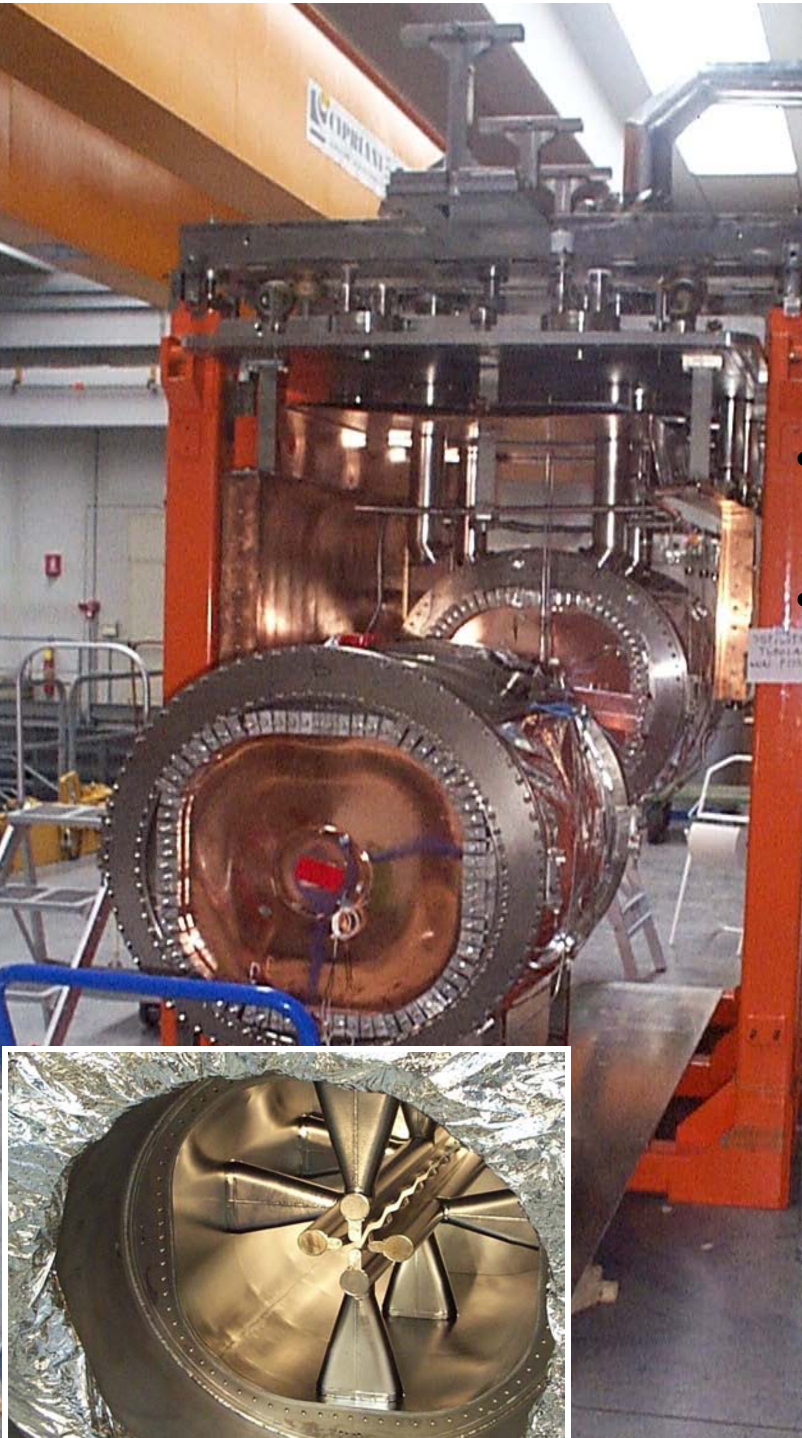
Design for SPES RFQ

Parameter (units)	Value
Operational mode	CW
Frequency (MHz)	80.
Injection Energy (keV/u)	5.7
Extraction Energy (keV/u)	722
Accelerated beam current (μA, typ.)	100
Charge states of accelerated ions (A/q)	7 – 3
Internal bunching section	Yes
Beam transmission	92%
Longitudinal output emittance RMS	4.3 keV/u*deg (0.15 ns keV/u



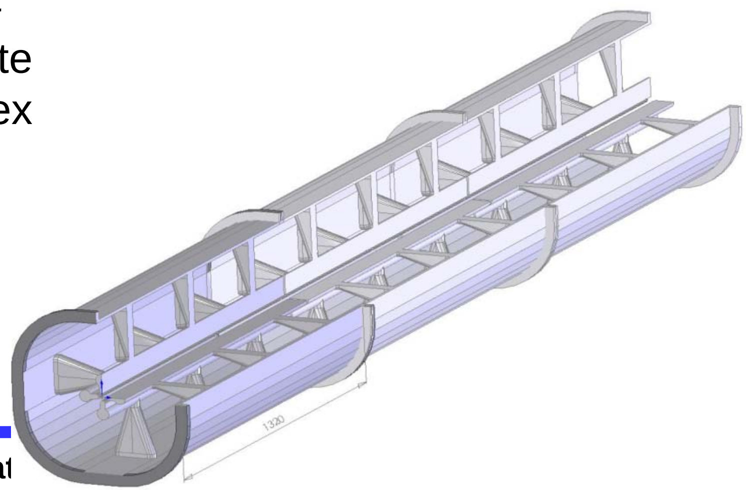
Parameter (units)	
Inter-vane voltage (kV, A/q=7)	63-120
Vane length (m)	5.6
RF power (kW, four vanes structure)	180
Average radius (mm)	5 - 9
Vane radius to average radius ratio	0.8
Modulation factor	1.0-3.2
Total number of cells	293
Synchronous phase (deg.)	-90 - -20
Focusing strength	2.8 - 4.8
Peak field (Kilpatric units)	1.7

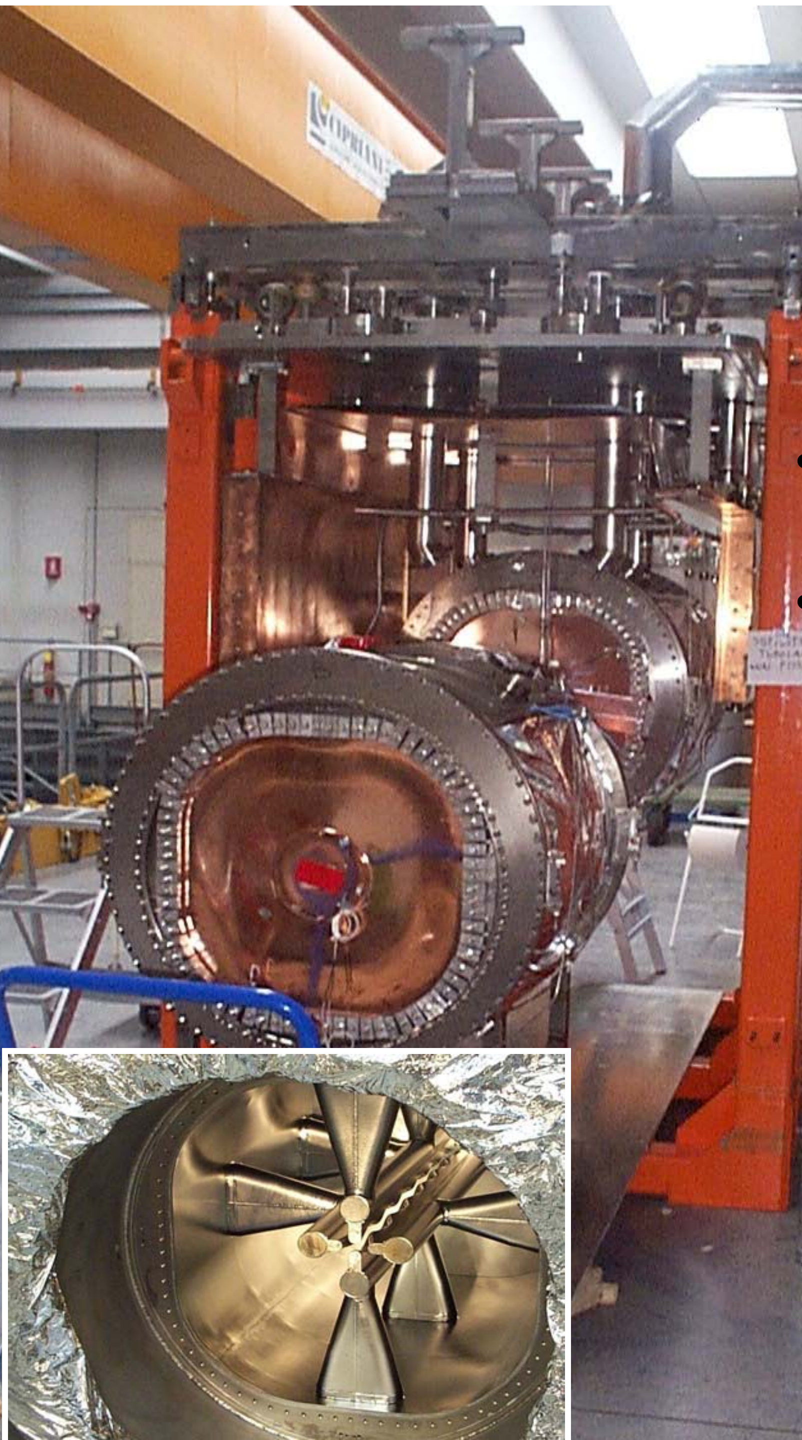




Why not SRFQ ?

- Succesfuly in cw operation since 2006
- But
  - The accelerated beam power is 500 W, beam losses of 10% can be an issue for the cryomodule
  - the new design implies new tank and new cryostat
  - This technology is quite expensive and complex





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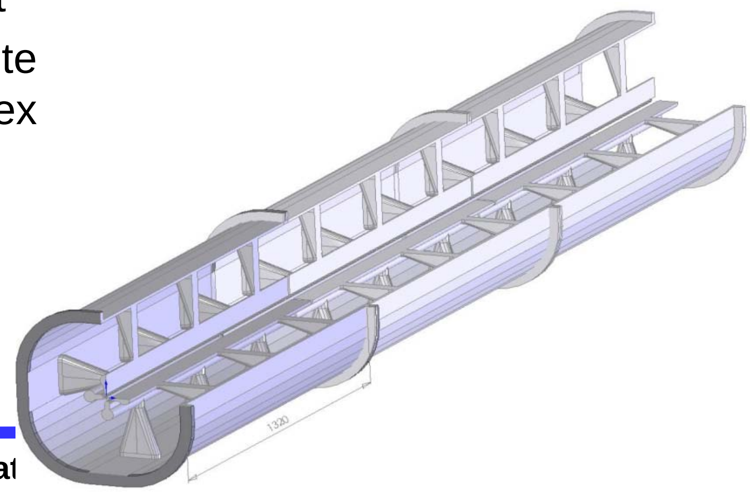

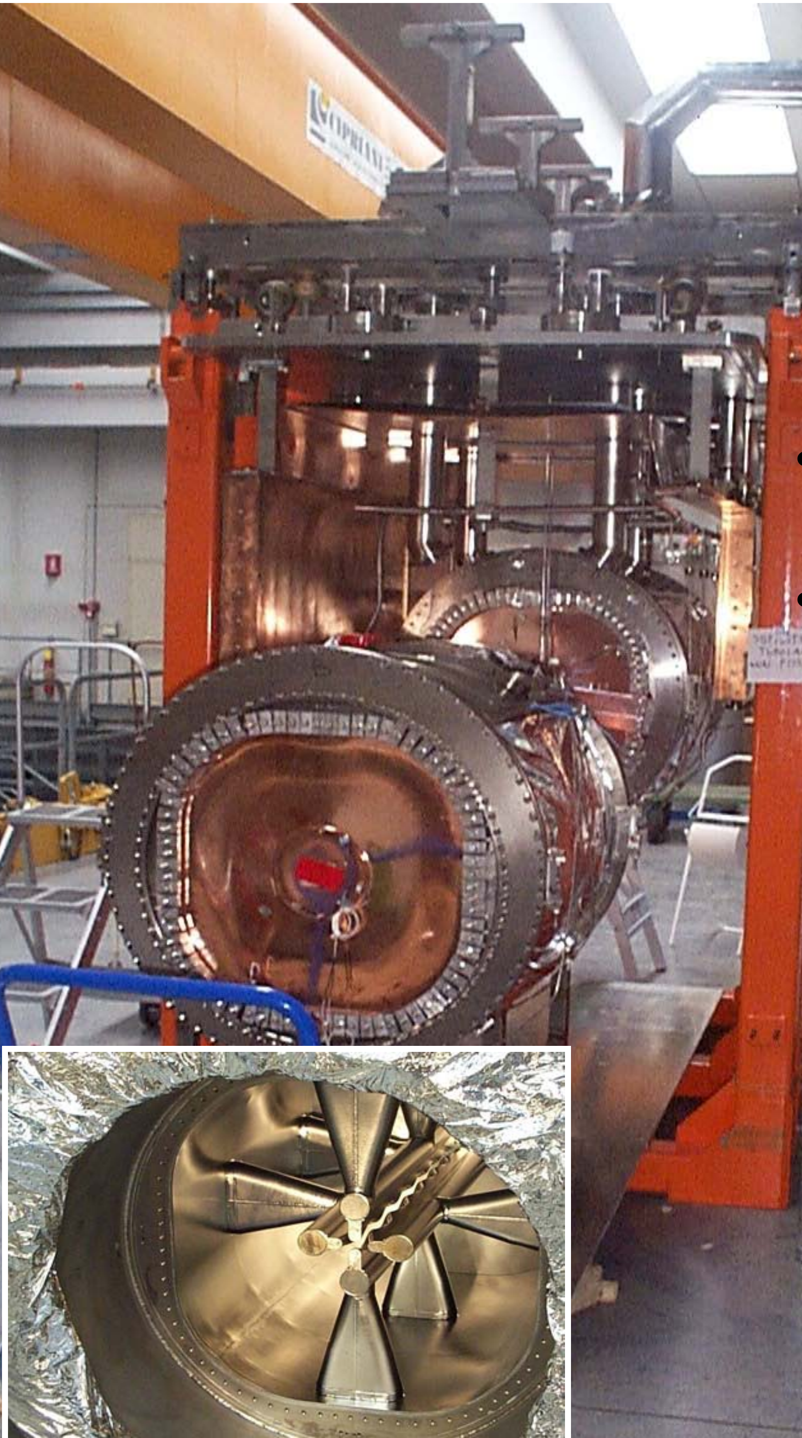

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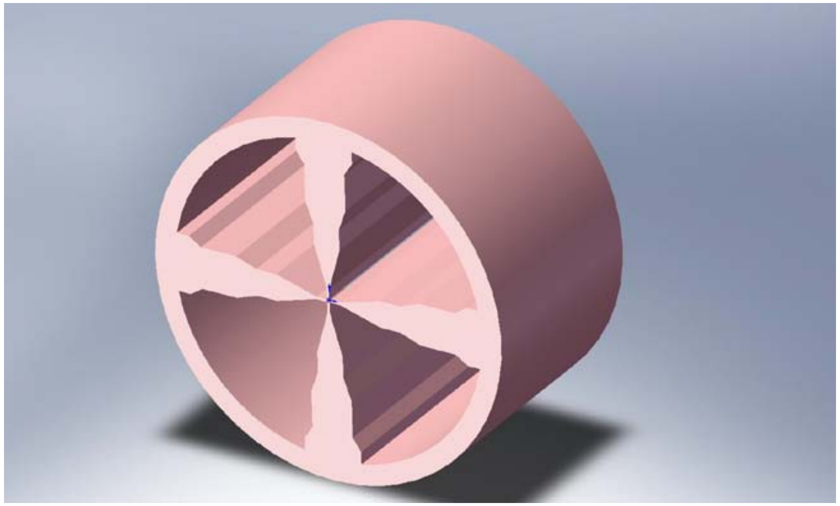
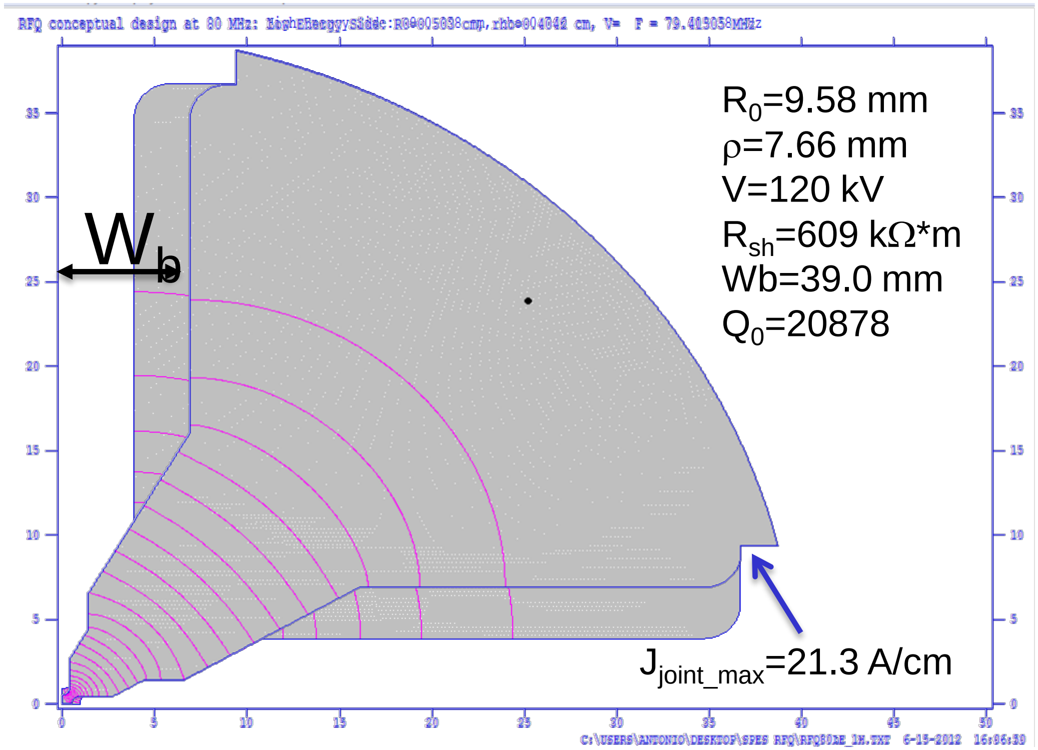
80 MHz RFQ for SPES

2D simulations (SUPERFISH), Rtank=400 mm



R_0=5.03 mm
ρ=4.024 mm
V=63.8 kV
R_{sh}=438 kΩ*m
W_b=69.0 mm
Q_0=18451



$P_{RF}= P_{2D}\cdot\alpha_{3D}\cdot\alpha_{RF}$=120 kW·1.3·1.2=187 kW (power to be delivered from the RF source)

Bolted electrodes, copper plated iron tank, metallic circular joints, brazing of electrodes and other components before assembly

Conclusions

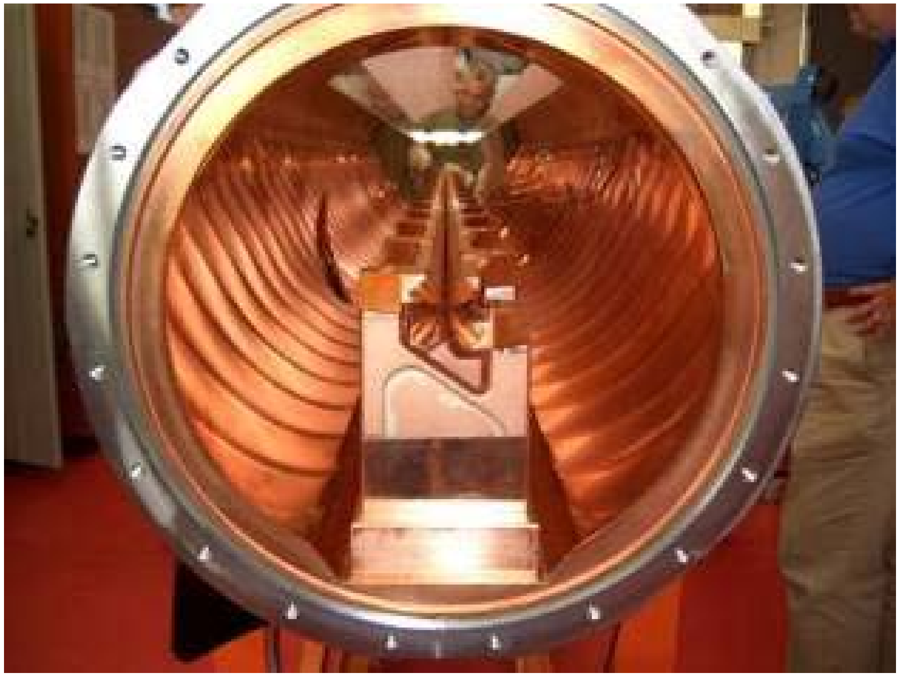
- The field of high power RFQs is very lively
- with the approval of IFMIF EVEDA, the design and construction of an extremely ambitious high power RFQ (5 MeV 125 mA d) has been launched.
- The experience of RFQ construction diffuses between different laboratories and there is in the community the know how necessary for the RFQ necessary for high intensity heavy ions (Pb 10-100).
- Such accelerator is any way very delicate and adequate resources for Physics and engineering design are needed

- **AKNOWLEGMENTS**
- The author wishes to thank R. Ferdinand, J Stovall for very informative discussions. The IFMIF RFQ team has actively participated to the discussion of this paper, and in particular M. Comunian, F. Grespan and A. Palmieri have given an important contribution.

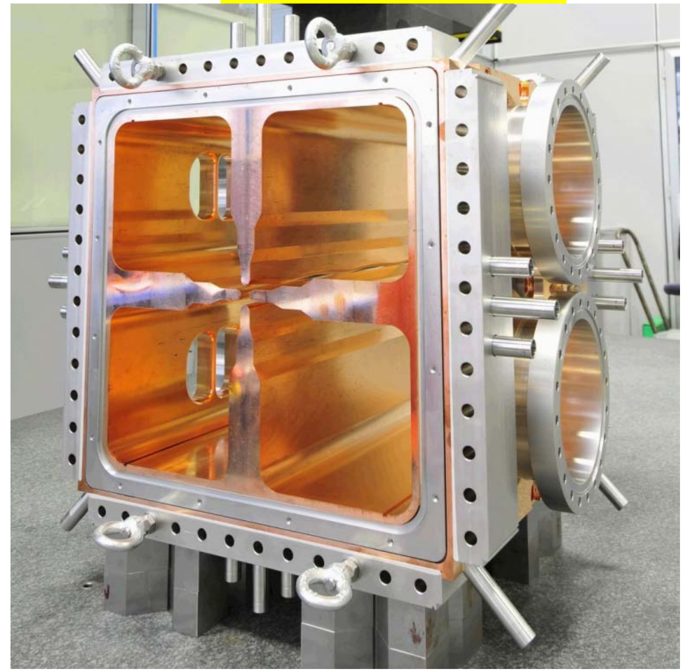
RFQ four rods or four vanes

	Name	Lab	ion	energy	vane voltage	beam current	power	RF Cu power	Freq.	length		Emax	Power density ave	max	operate
				MeV/u	kV	mA	kW	kW	MHz	m	lambda	kilpat	W/cm^2	W/cm^2	
	IFMIF EVEDA	**LNL**	**d**	**2.5**	**79-132**	**130**	**650**	**585**	**175**	**9.8**	**5.7**	**1.8**	**3.5**	**60**	**NO**
CW	SARAF	NTG	d	1.5	65	4	12	250	176	3.8	2.2	1.4	24	190	*only p*

SARAF at SOREQ (Israel)



IFMIF-EVEDA



- Smaller cross section and dipoles at higher frequency.
- Diffused hot spots

- Better shunt impedance, possibility to reach high voltage
- Larger dimensions, dipole stop band to master

RFQ four rods or four vanes

	Name	Lab	ion	energy	vane voltage	beam current	power	RF Cu power	Freq.	length		Emax	Power density ave	max	operate
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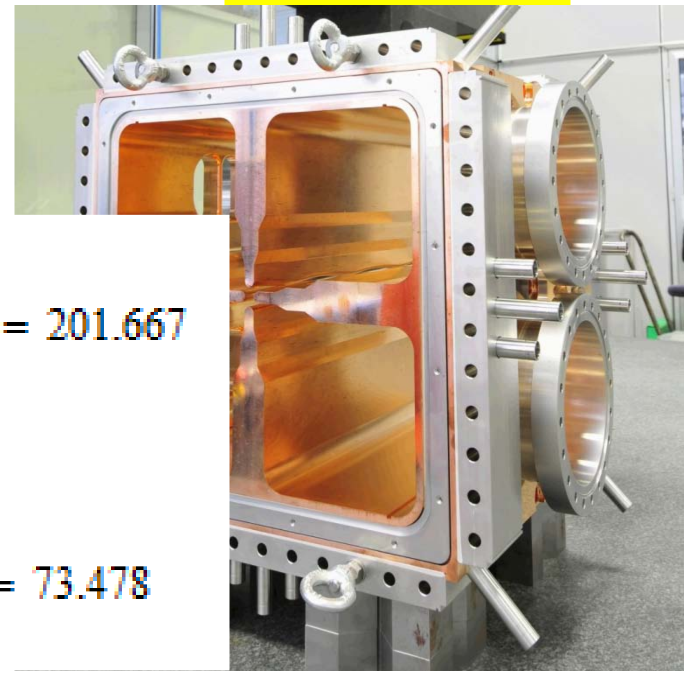

RS IFMIF $\frac{110^2}{600}\cdot 10 = 201.667$

RS SARAF $\frac{65^2}{230}\cdot 4 = 73.478$

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- Better shunt impedance, possibility to reach high voltage
- Larger dimensions, dipole stop band to master