High Power RFQs

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HIGH POWER RFQs

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Are high duty cycle (generally cw) accelerators for light ions beam power in the range 100-700 kW.

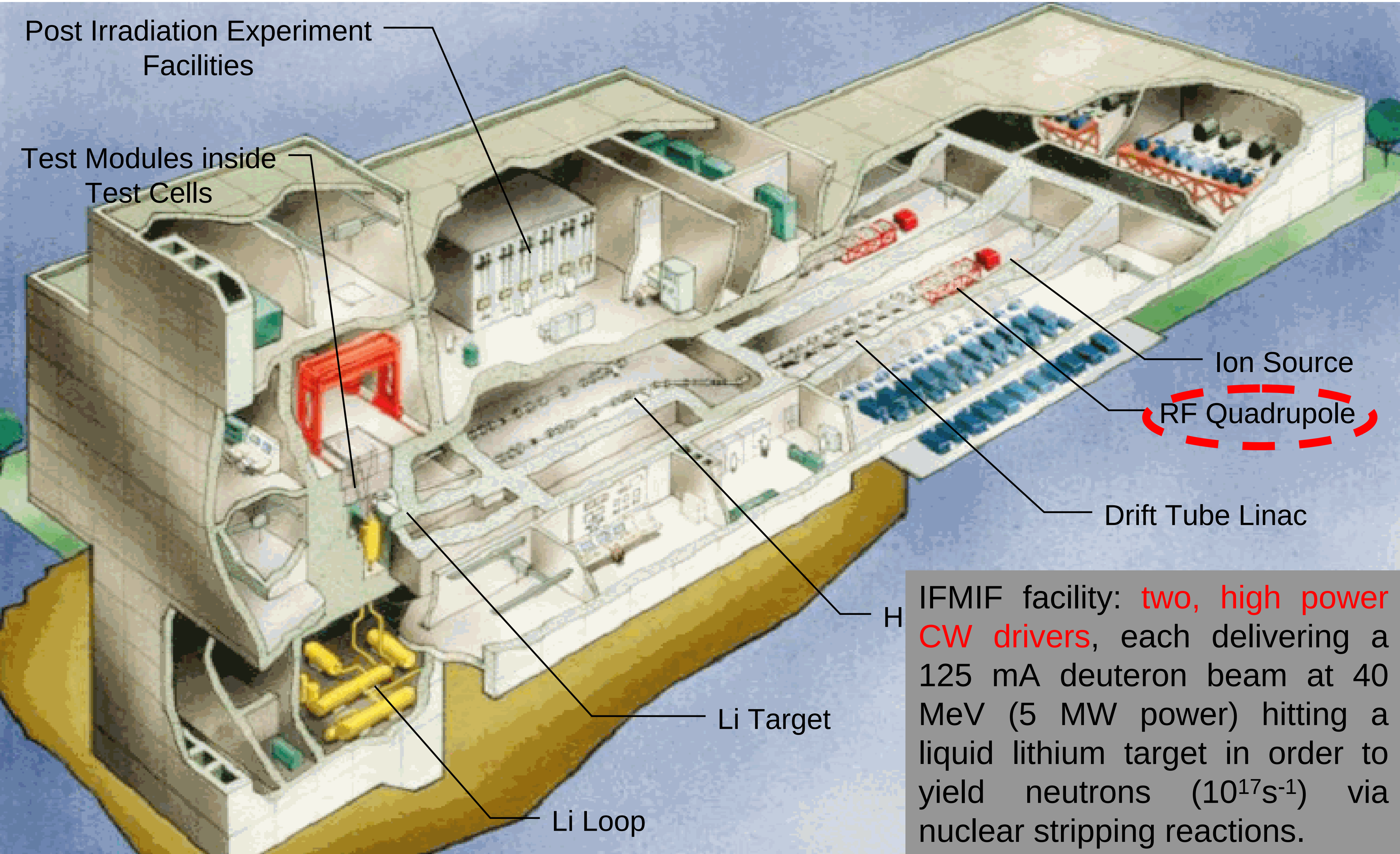
- Applications
- State of the art
- Specific technical issues

Applications of high power RFQs

- Main applications:
  - 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
  - Injector for 40 MeV few mA cw superconducting linacs for neutron and RIBs production
  - Stand alone (e.g. 5 MeV 30 mA) application as neutron source for **BNCT**

IFMIF "Artist View"

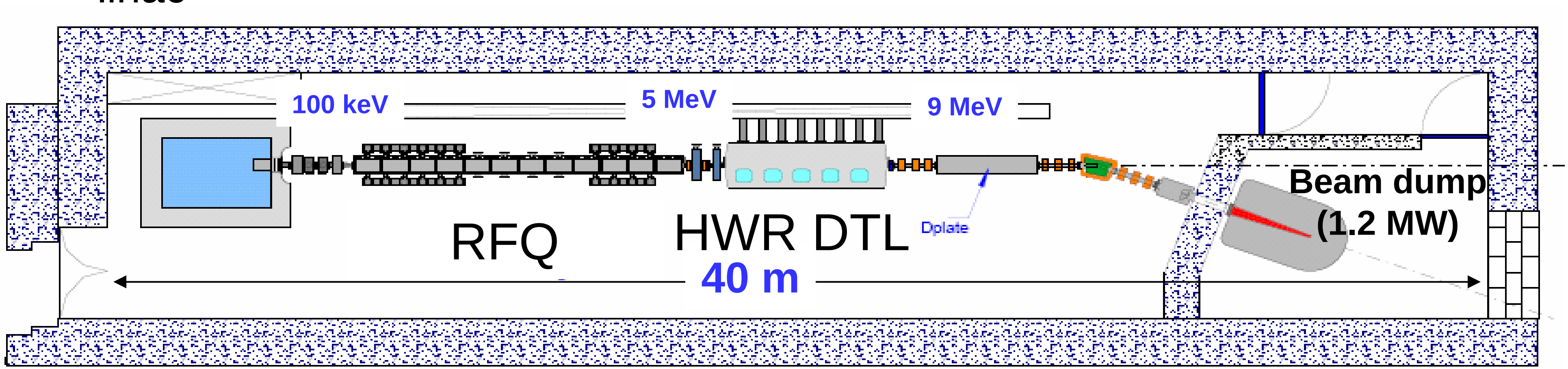
International Fusion Material Irradiation Facility



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



See A. Mosnier TU2RAI01

IFMIF EVEDA

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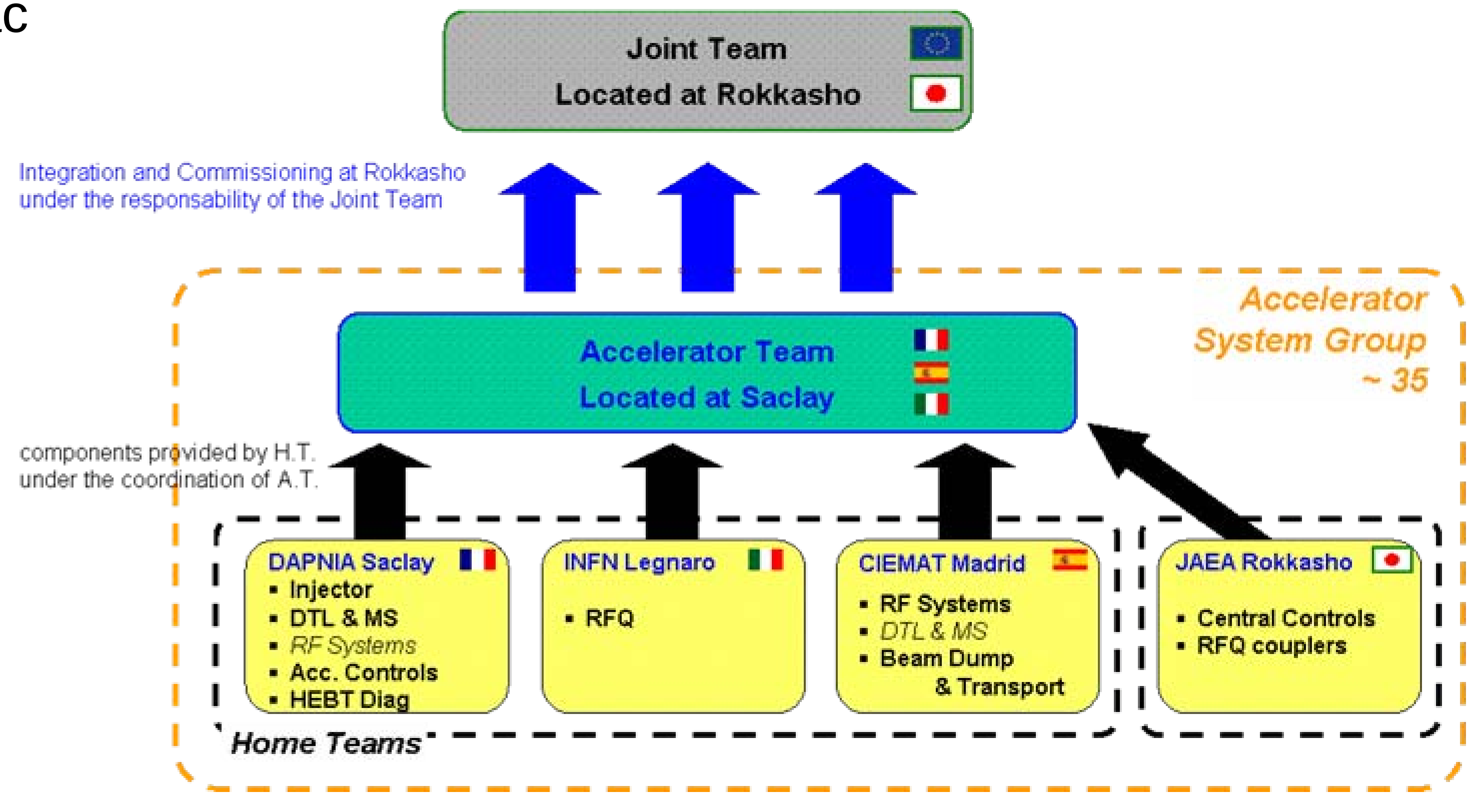
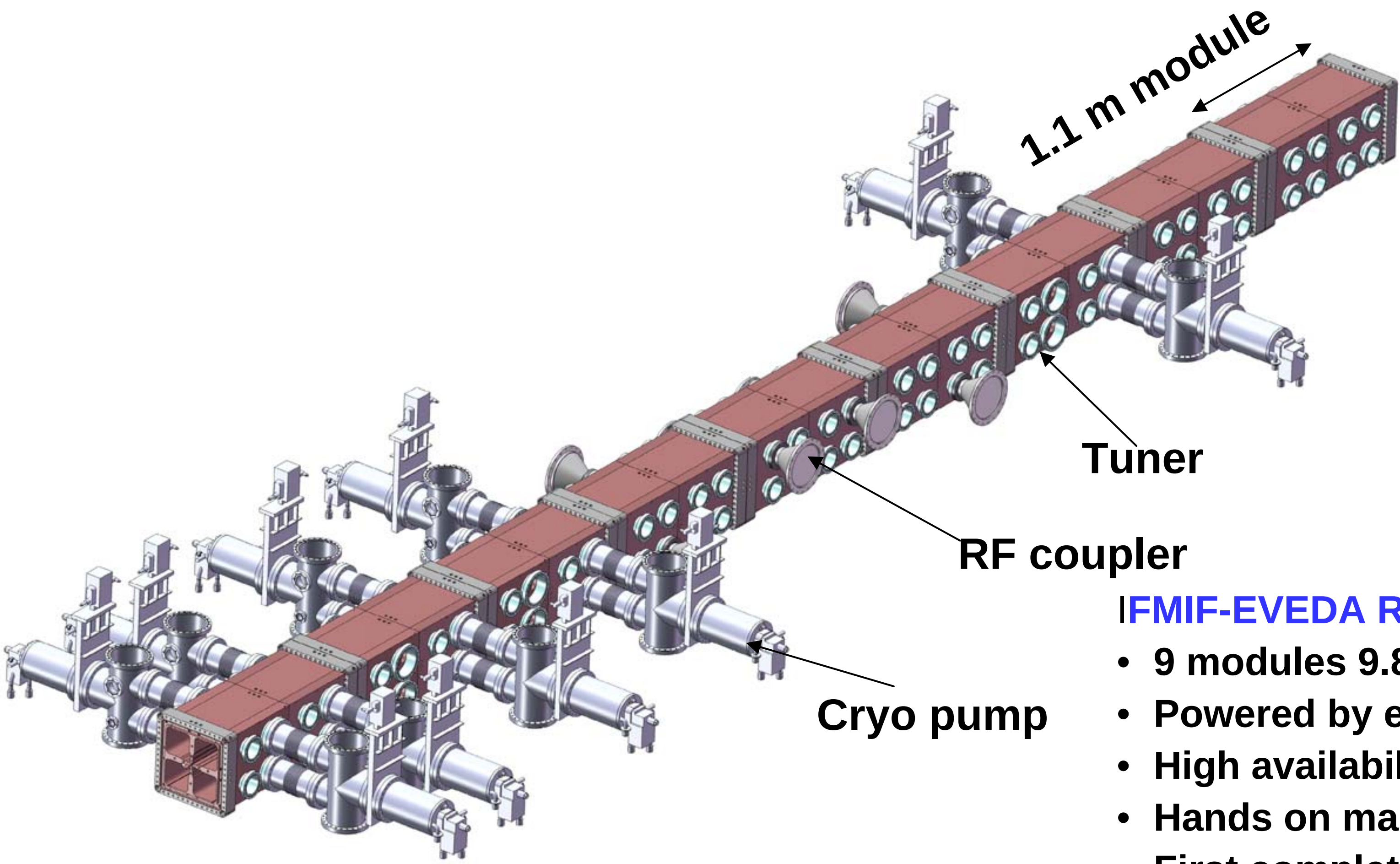


RFQs general parameters

	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**	**30**	**NO**



IFMIF-EVEDA RFQ

- **9 modules 9.8 m**
- **Powered by eight 220 kW rf chains**
- **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!

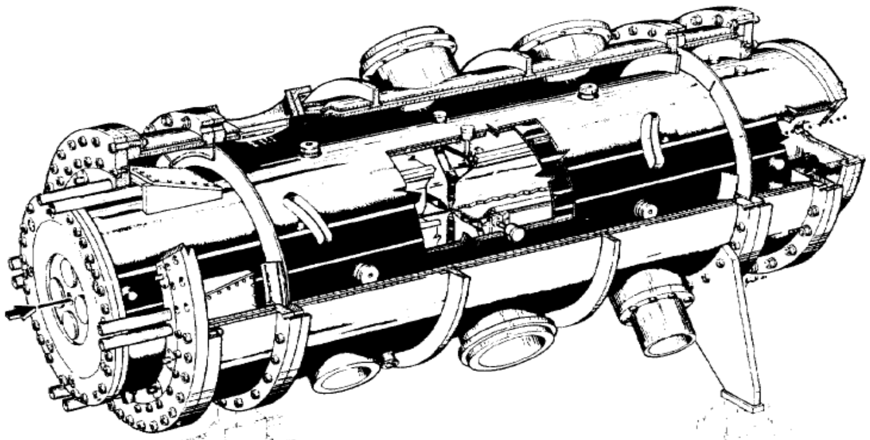
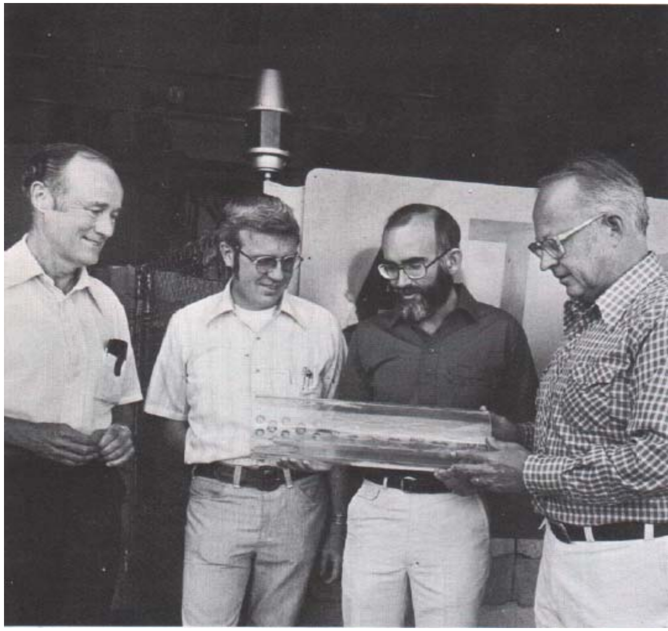


Fig. 1. Initial design of the FMIT RFQ accelerator. The RFQ comprises two coupled, coaxial resonators. The rf power is loop coupled into the outer section. or manifold, which more uniformly distributes the power into the four quadrants of the inner resonator, or core. A 75keV beam is injected (arrow,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

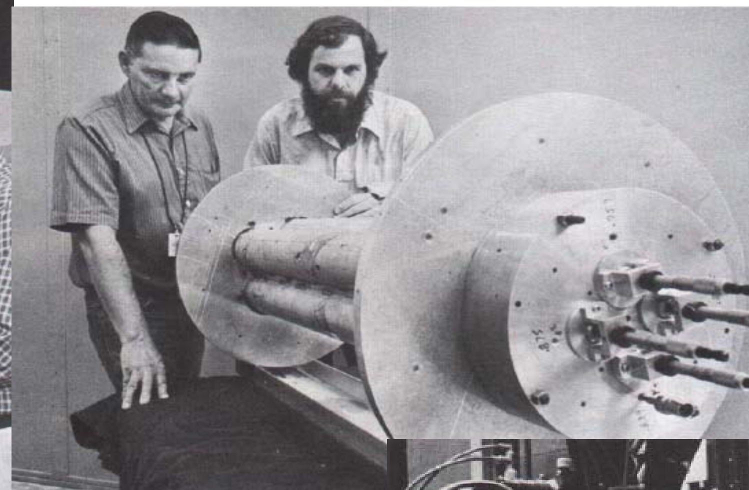
Courtesy of R. Jameson

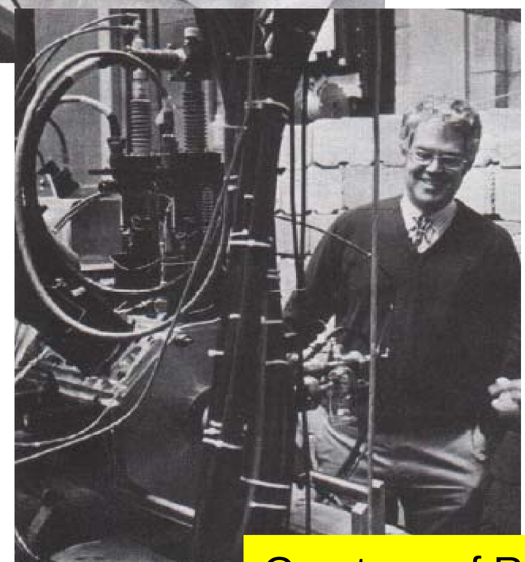
Los Alamos Proof-of-Principle RFQ



Dick Stokes, Bob Jameson, Tom Wangler, Don Swenson

Arlo Thomas, Jim Potter





Ed Knapp

The RFQ is alive and well at the Los Alamos Scientific Laboratory

Los Alamos Scientific Laboratory “atom”, July/August 1980
John T. Ahearne (Ghost-written by R. A. Jameson)

Courtesy of R. Jameson

RFQs general parameters

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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

Mario Weiss (1927 – 2008)

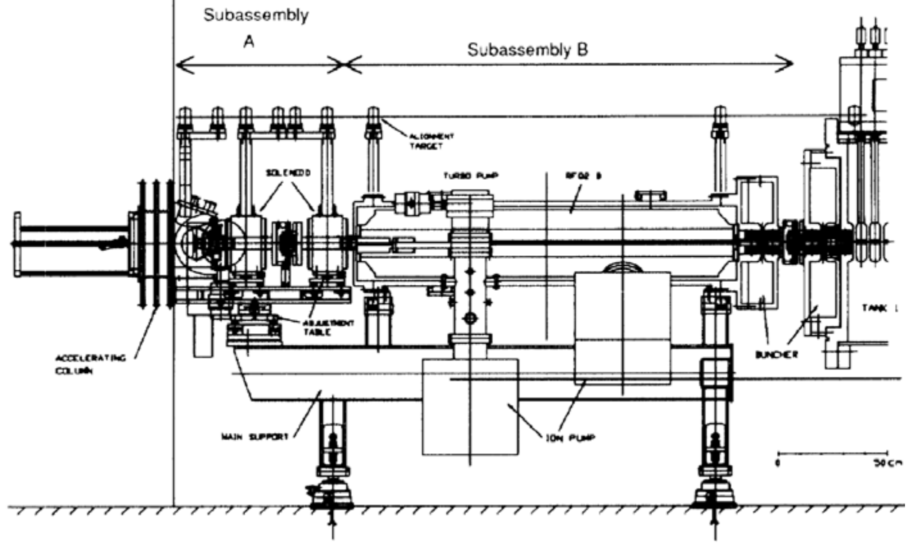
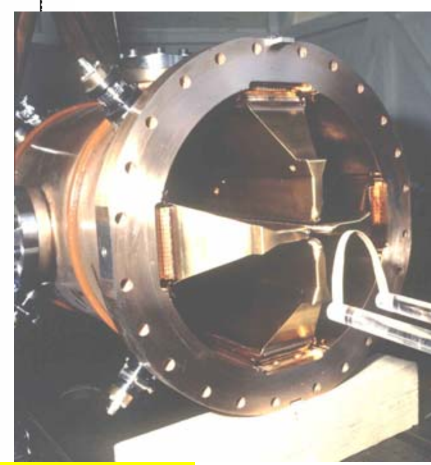


Figure 2. The RFQ2 complex

Main RFQ2 design parameters

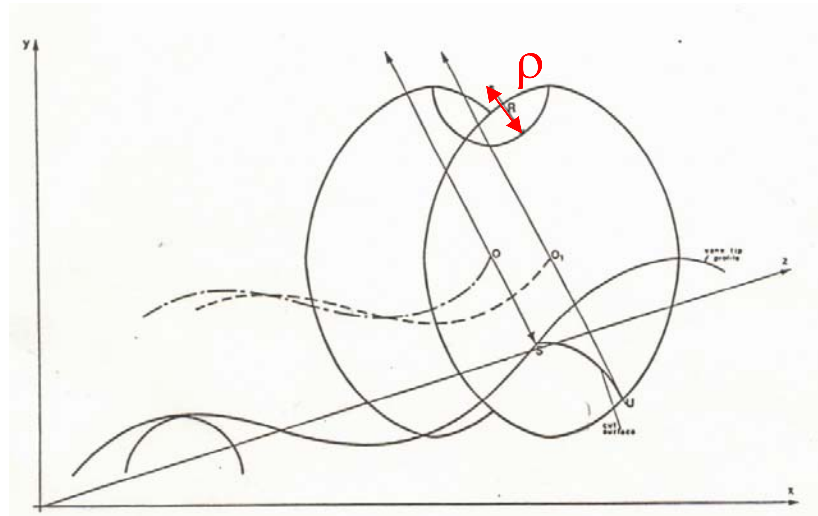
RF frequency	202.56 MHz
Input energy	90 KeV
Output energy	750 KeV
Output current	200 mA
Trapping efficiency	~90 %
Vane voltage	178 KV
Final synchronous phase	-35 °
Modulation factor(max)	1.62
Mean aperture radius	7.87 cm
Cavity length	178.5 cm
Vane length	175.2 cm
Cavity diameter	35.4 cm



In operation since 1992

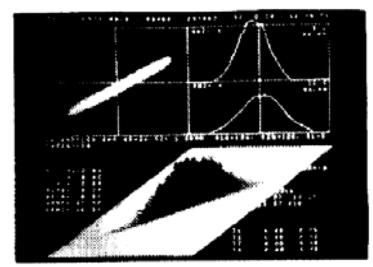
Accelerator Physics challenges solved for RFQ2

- Space charge modeling (especially in the bunching region) for 200 mA beam
- Evaluation of the real acceleration when the geometry of the vane do not follow the perfect two terms potential shape (hyperbolic section with variable tip radius) but has round cross section
- Evaluation of non linear field coefficients (multipoles)

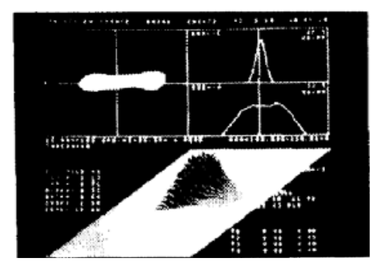


[*] figure from C. Biscari and M. Weiss CERN PS note

Horizontal plane

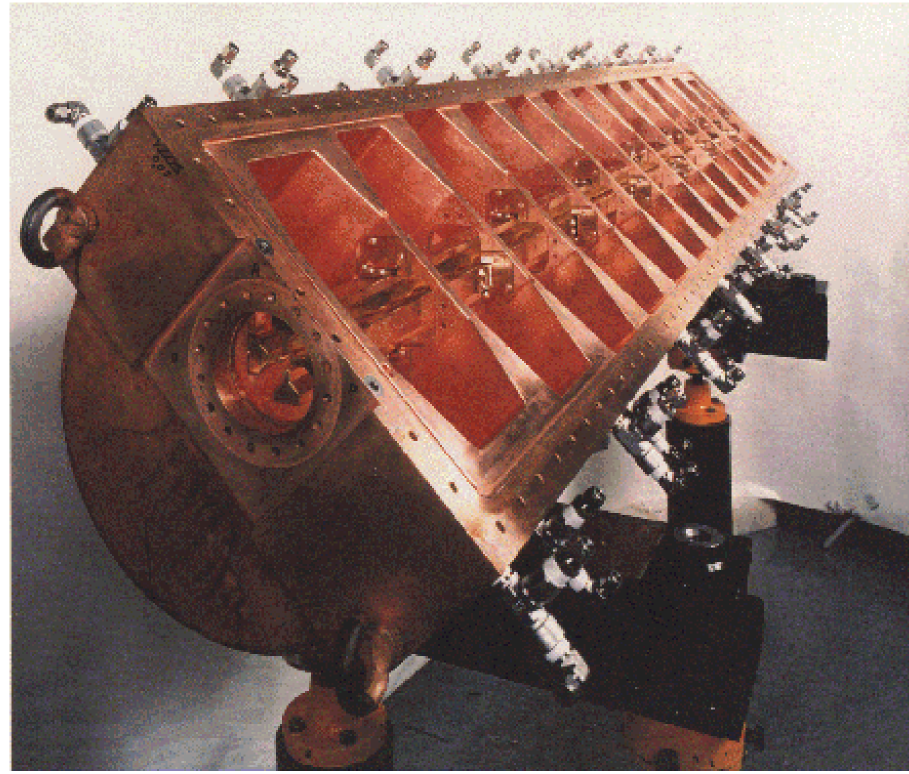


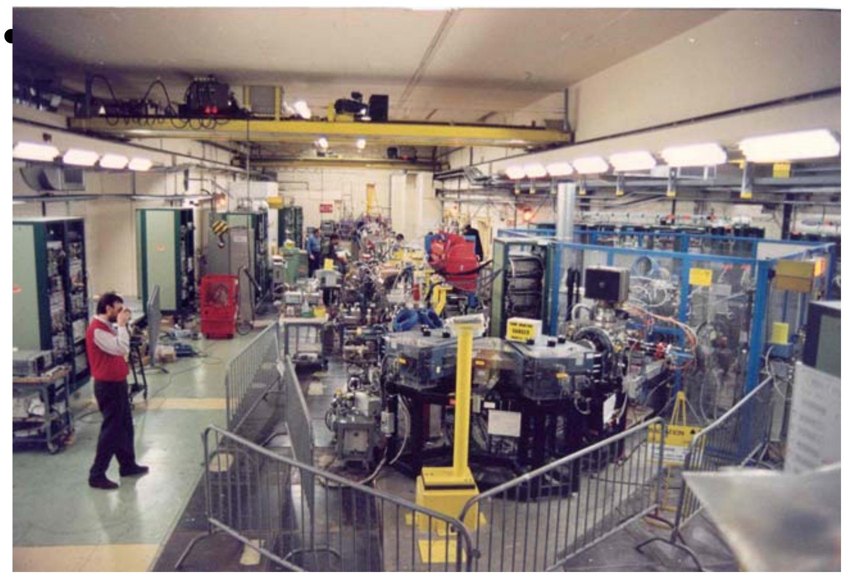
Vertical plane



CERN lead ion RFQ

- 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





- 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

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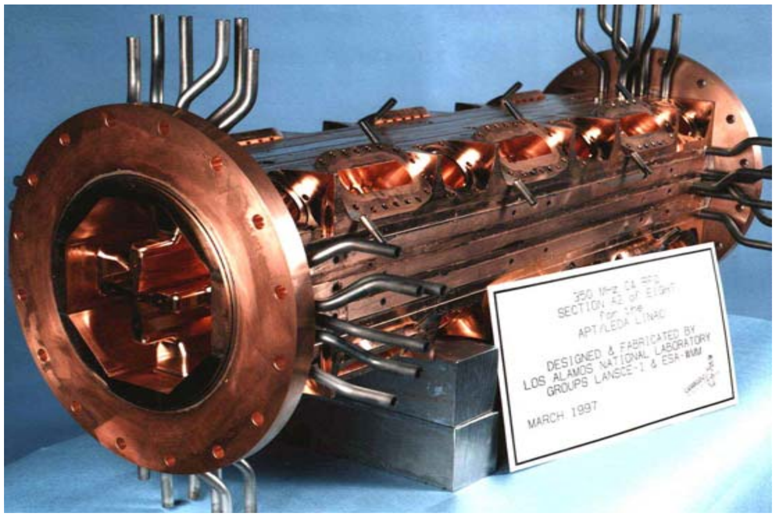
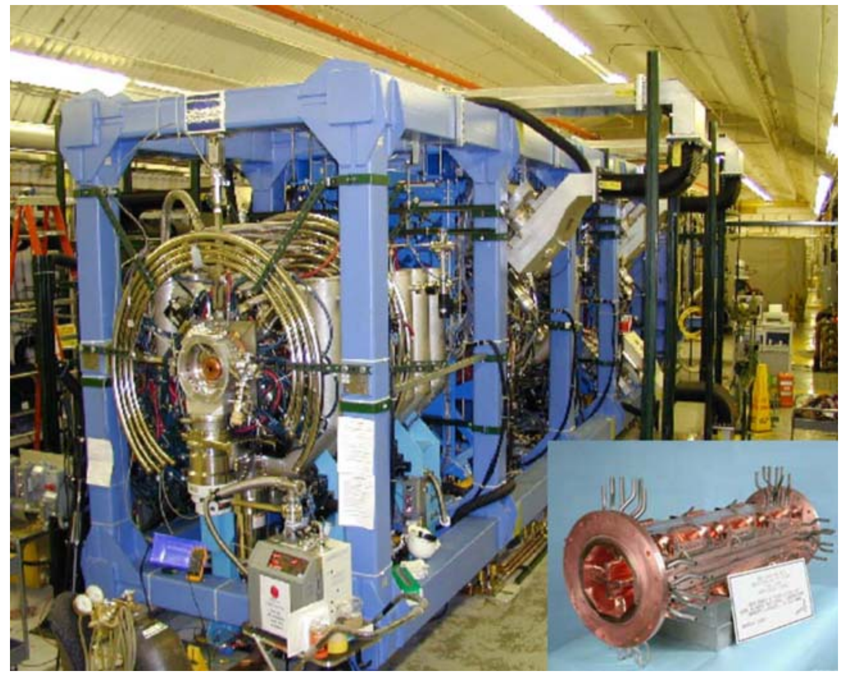
CW	LEDA	LANL	p	6.7	67-117	100	670	1450	350	8	9.3	1.8	11.4	65	*YES*
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LEDA



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



RFQs general parameters

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CW	LEDA	LANL	p	6.7	67-117	100	670	1450	350	8	9.3	1.8	11.4	65	*YES*

LEDA

- Many specific features of HP-RFQ were developed with LEDA-RFQ,
  - LEBT with neutralized beam and electron trap at the RFQ entrance
  - the ramped voltage along the structure,
  - the resonant coupling between RFQ segments, the rods for dipole stabilization.

Research Programs in Europe related to ADS studies

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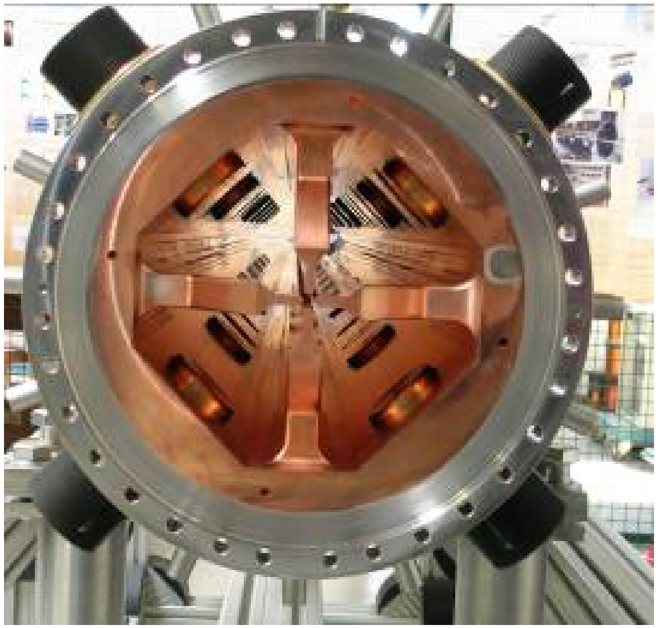
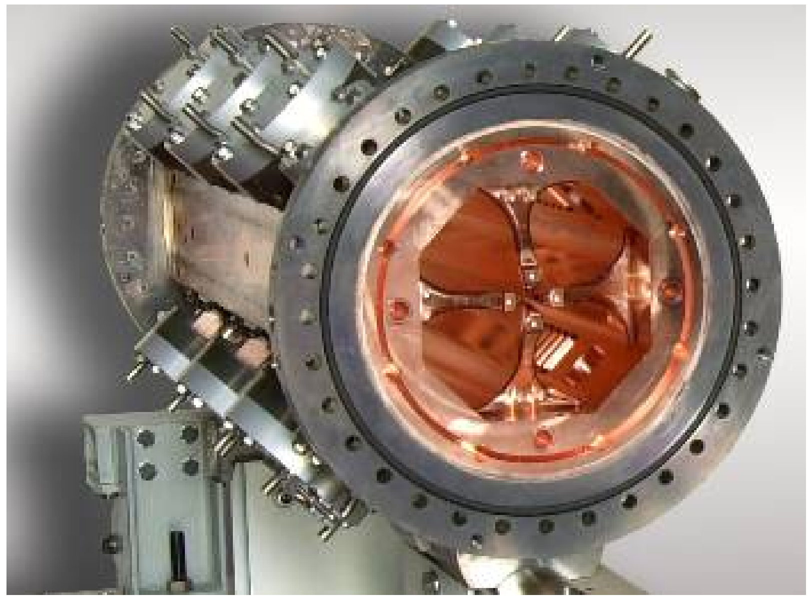
	FMIT	LANL	d	2	185	100	193	407	80	4	1.0	1	0.4		*YES*
high p	IPHI	CEA	p	3	87-123	100	300	750	352	6	7.0	1.7	15	120	*NO*
	TRASCO	LNL	p	5	68	30	150	847	352	7.3	8.6	1.8	6.6	90	*NO*



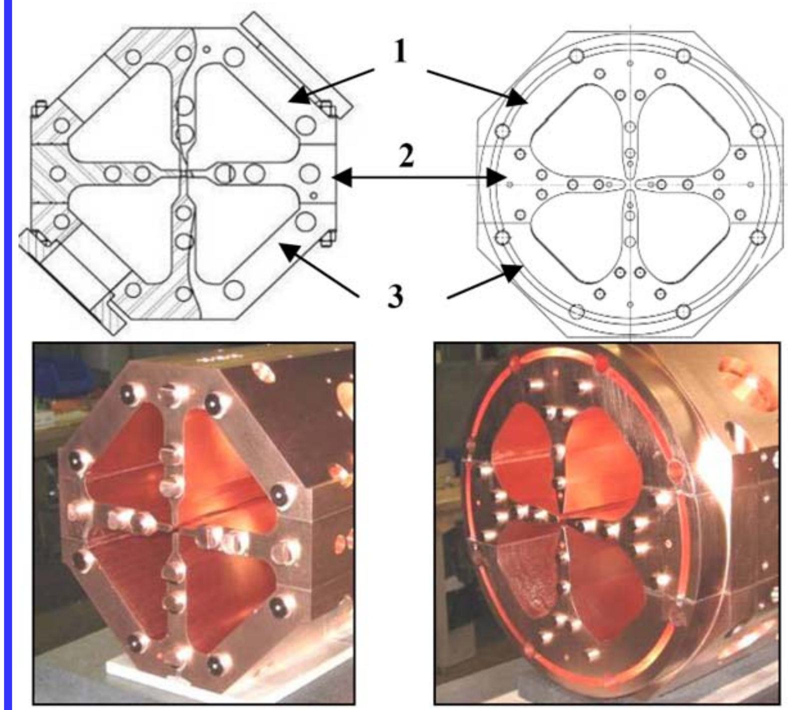
TRASCO@LegnaroINFN



IPHI@Saclay.CEA

Specificity of IPHI and TRASCO RFQ

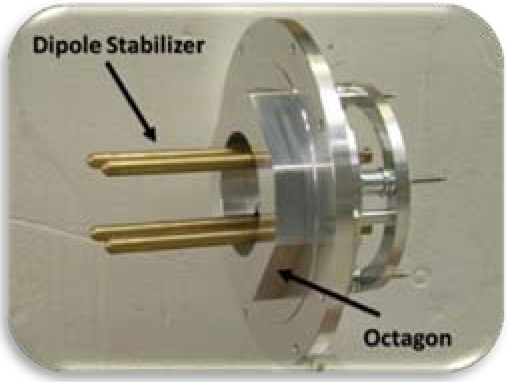
- The design is quite different (also respect to LEDA);
  - IPHI (3 MeV 100mA) is built in six modules (1 m each), has a ramped voltage, a cross section with a specific geometry and has been optimized for a very high transmission (above 98%);
  - TRASCO (5 MeV 30 mA) has constant voltage, 2d vane machining and a cross section simpler to machine; it is built in six modules (1.2 m long, for cost optimization).
- The two RFQs (machined respectively in Italian and French industry) are being brazed at CERN, with the same work sequence and few differences due to the details of the mechanical design and realization.



TRASCO IPHI

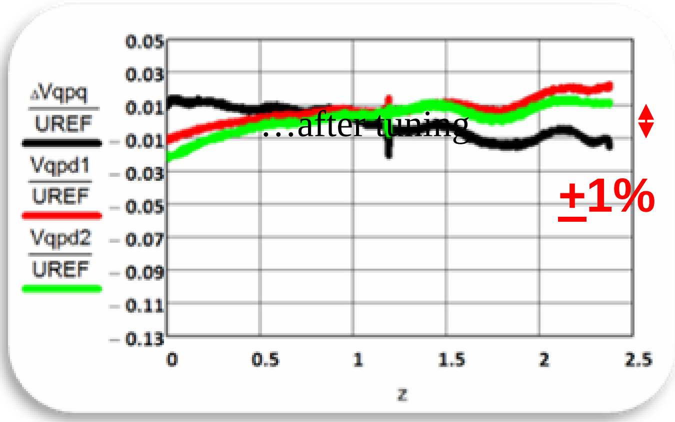
Status of construction

- TRASCO at moment more advanced,



TRASCO: the first two modules

Perturbative quadrupole (black) and dipole (red and green) components after tuning



  - two modules tuned and ready.
  - For the remaining four the brazing in the horizontal vacuum furnace (the most delicate from the point of view of mechanical deformation) is successfully concluded
  - the vertical brazing for the connection of the vacuum flanges are scheduled to be concluded within this summer.
- IPHI two modules have been brazed

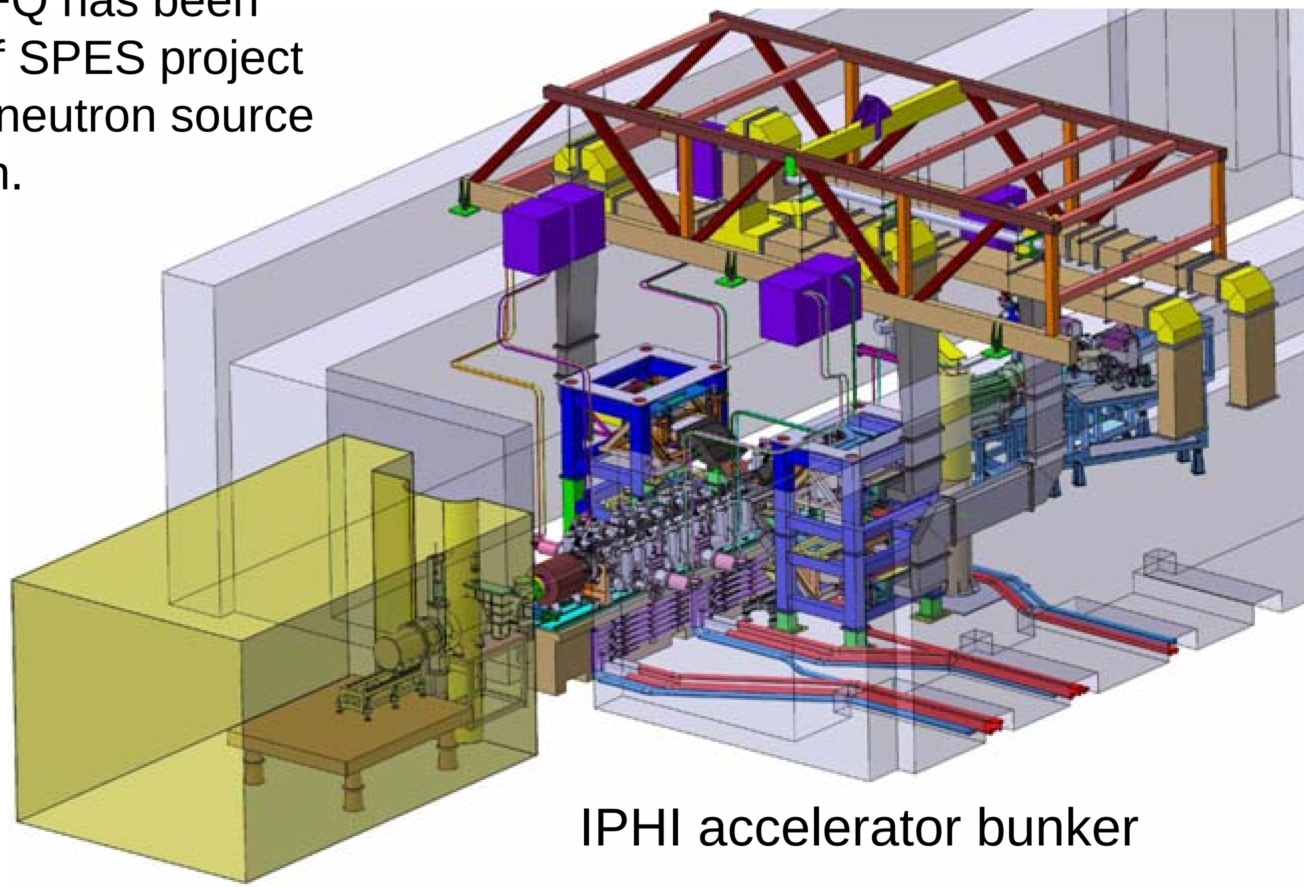
TRASCO: hor and vert. brazing

Status of infrastructures

IPHI site at Saclay is ready (with the ion source tested, two LEP klystrons installed, the cooling system ready

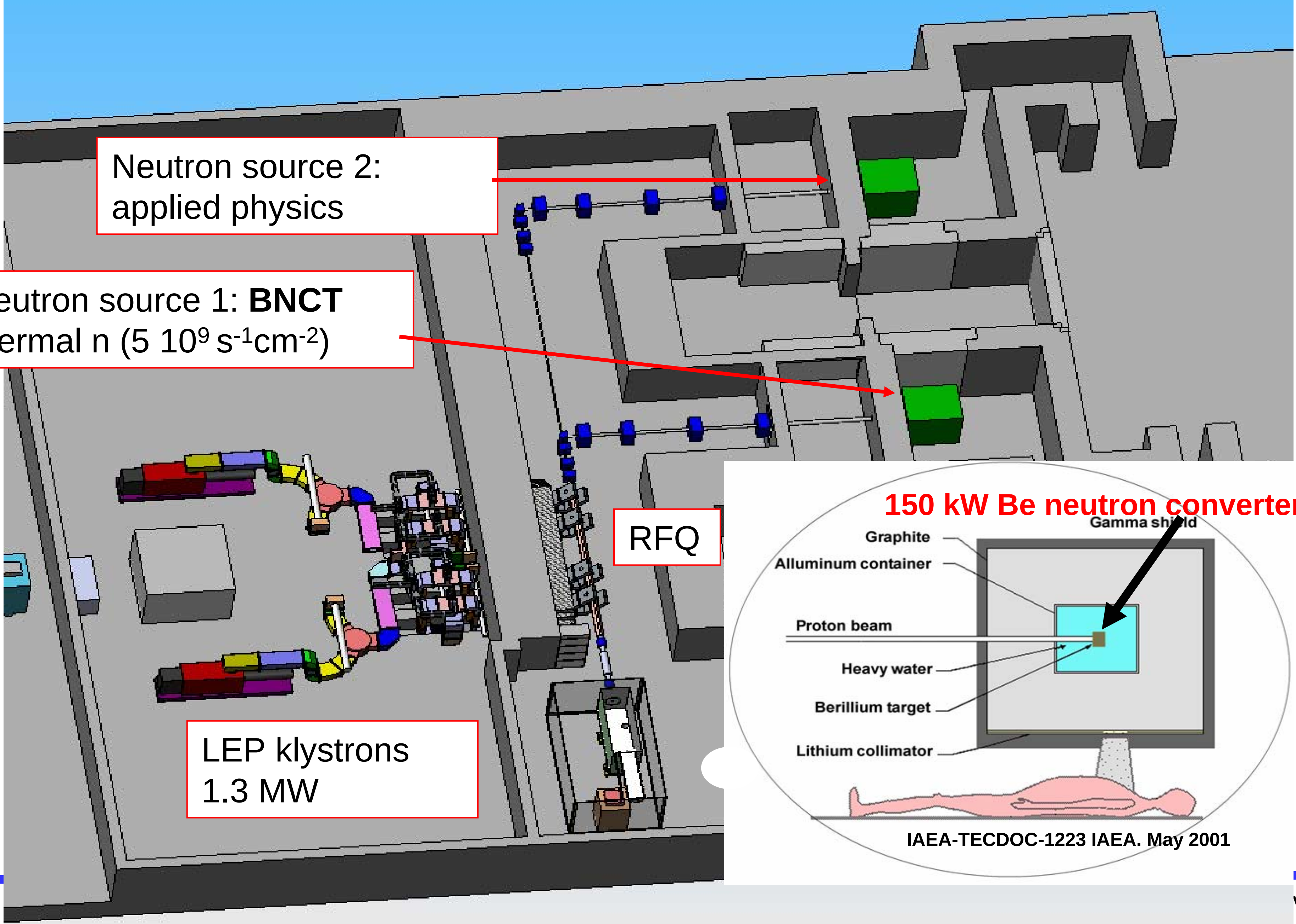
The building for TRASCO RFQ has been recently designed as part of SPES project and should be funded as a neutron source mainly for BNCT application.

IPHI RF system



IPHI accelerator bunker

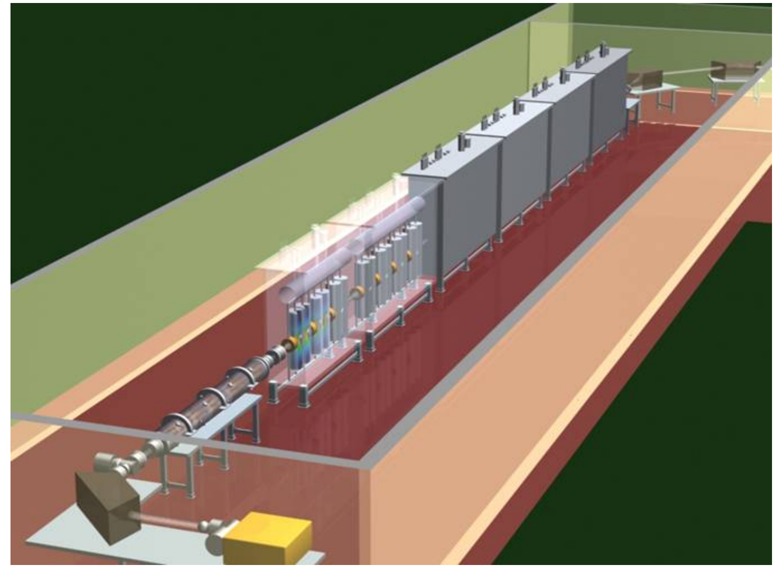
Boron Neutron Capture Therapy at SPES (Legnaro)



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

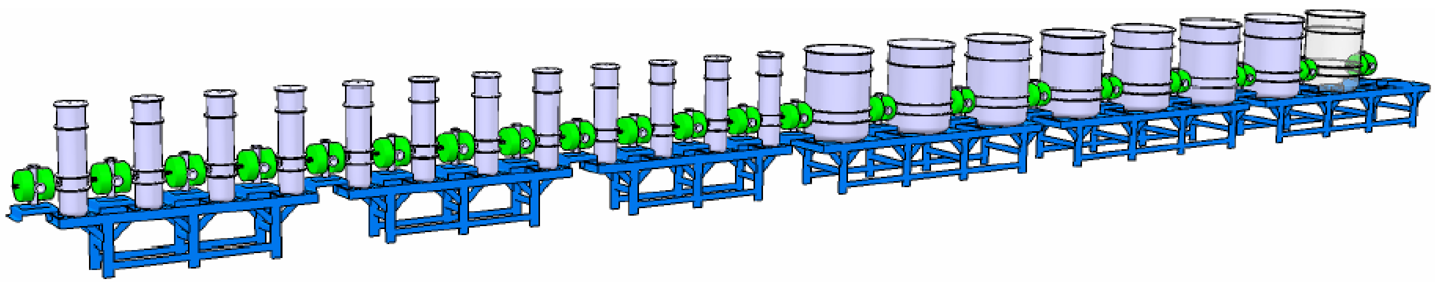
SARAF at SOREQ (Israel)

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

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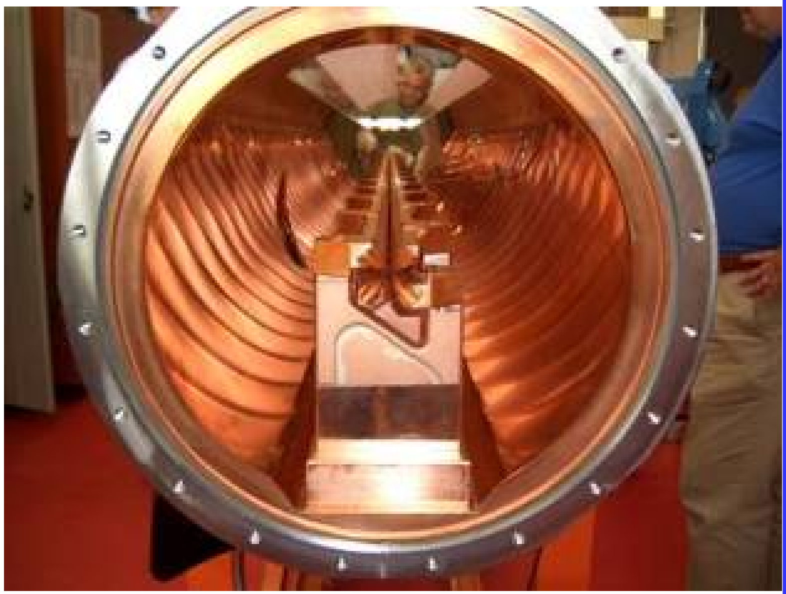
CW	SARAF	NTG	d	1.5	65	4	12	250	176	3.8	2.2	1.4	24	54	*NO*
mid p	SPIRAL2	CEA	A/q=3	0.75	100-113	5	7.5	170	88	5	1.5	1.65	0.6	19	*NO*

SARAF at SOREQ (Israel)



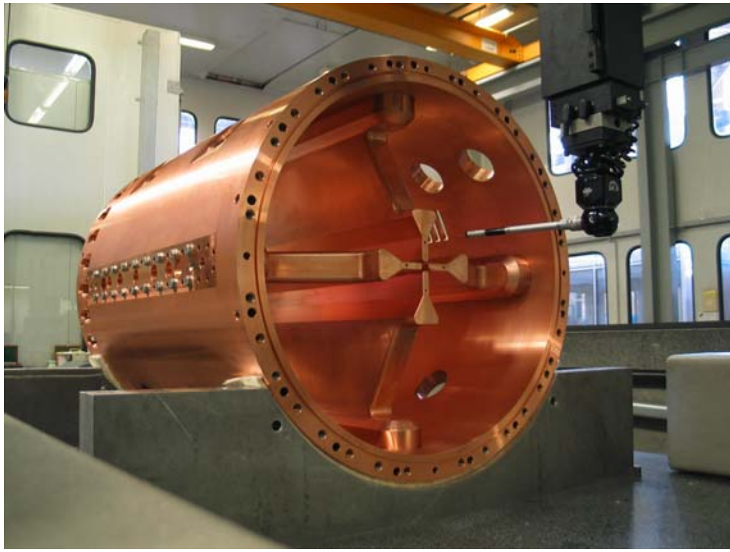
SPIRAL2 at GANIL (France)

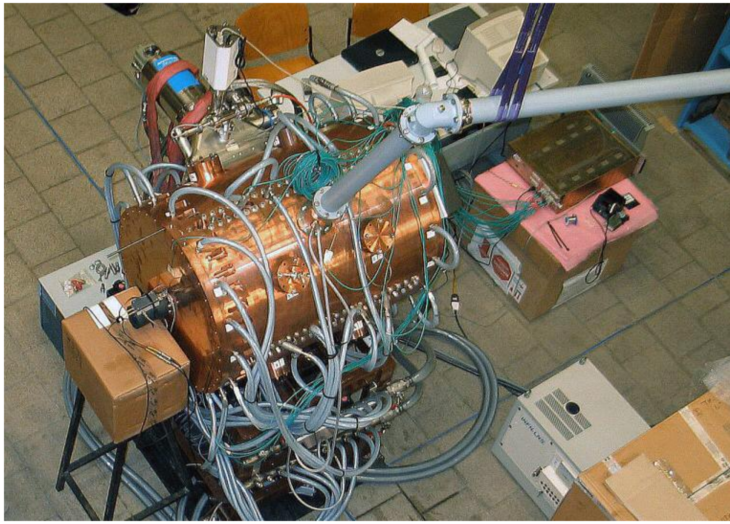
Status of SARAF RFQ

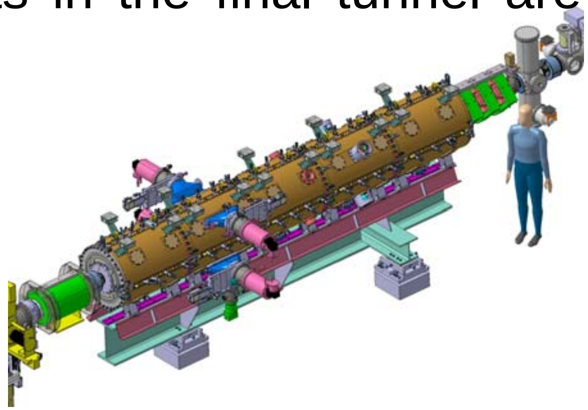
- The SARAF RFQ is a four-rod structure with minivanes, built by European industry.
- This architecture has some advantages in terms of tuning capabilities and cost effectiveness.
- The power density is by far the highest ever designed for a four-rod cavity.
- The RFQ is now installed in the linac tunnel and the conditioning is in progress; presently stable cw operation up to 190 kW (nominal 250 kW for deuteron acceleration) has been reached.

Status of SPIRAL 2 RFQ

- SPIRAL2 RFQ is a four vanes structure, with a novel mechanics concept that avoids the brazing of such a large structure:
- the RFQ is built in solid copper, with the electrodes bolted to the tank (a thick copper tube).
- This RF and thermal contact is sufficient at 22 A/cm surface current density.
- A first 1 m prototype of the RFQ was tested at nominal field at INFN/LNS.
- The order for the entire structure has been placed, and beam tests in the final tunnel are foreseen in 2011.







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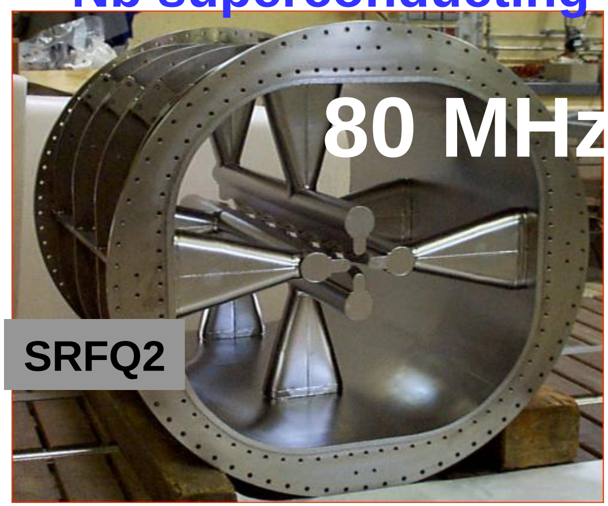
pulsed	CERN linac 2	CERN	p	0.75	178	200	150	440	202	1.8	1.2	2.5			YES
	SNS	LBNL	H-	2.5	83	70	175	664	402.5	3.7	5.0	1.85	1.1	10	*YES*
	CERN linac 3	LNL	A/q=8.3	0.25	70	0.08	0.04	300	101	2.5	0.8	1.9			*YES*
CW	LEDA	LANL	p	6.7	67-117	100	670	1450	350	8	9.3	1.8	11.4	65	*YES*
	FMIT	LANL	d	2	185	100	193	407	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	54	*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



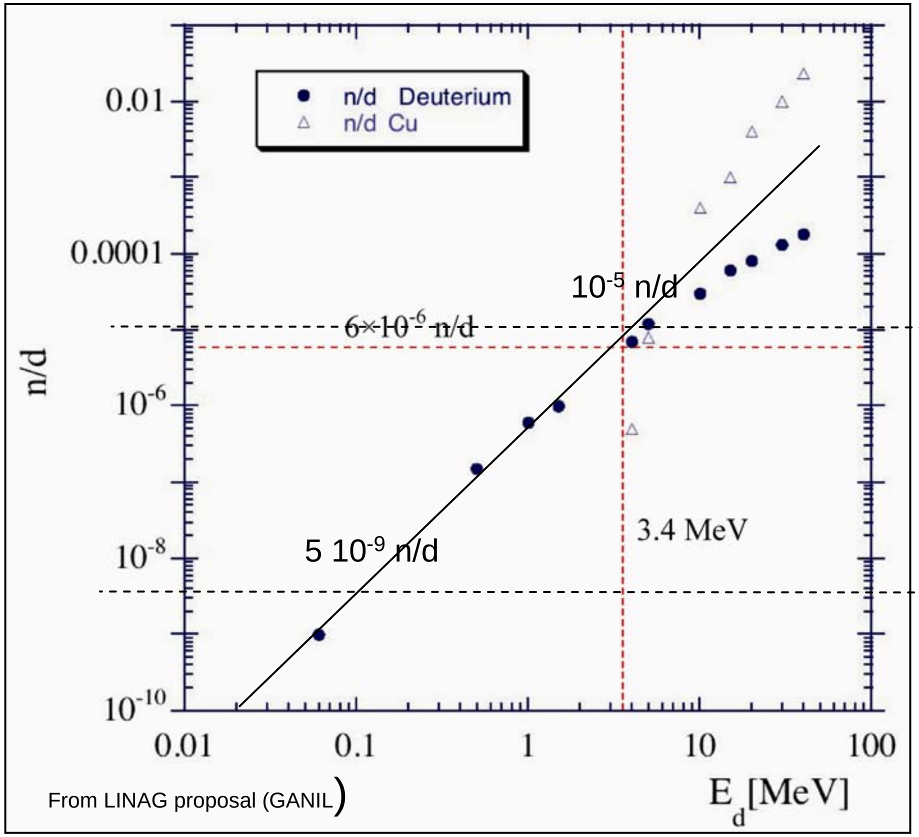
IFMIF RFQ challenges

Beam dynamics

- 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.

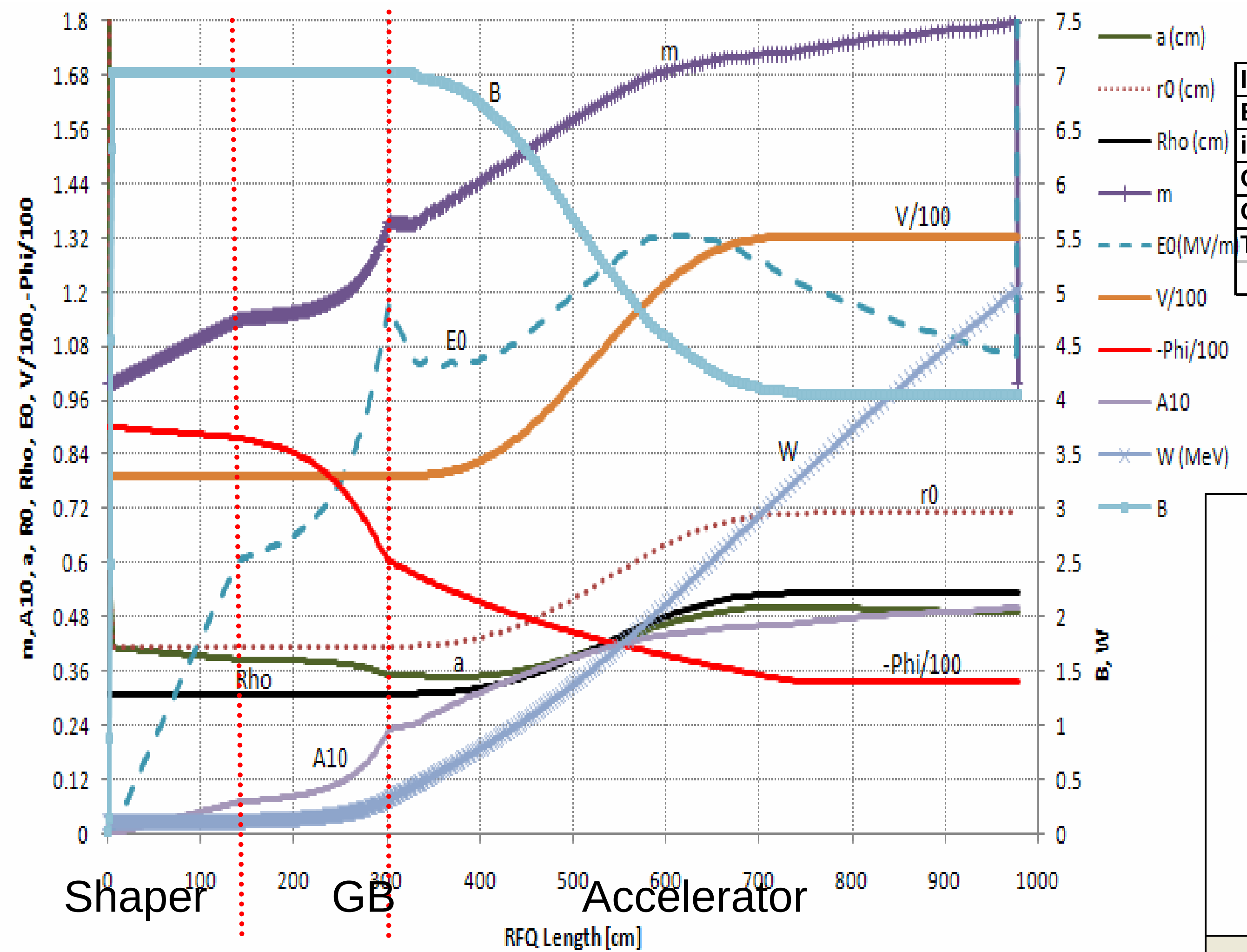


Fit from 0.1 to 5MeV

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

IFMIF modulation design

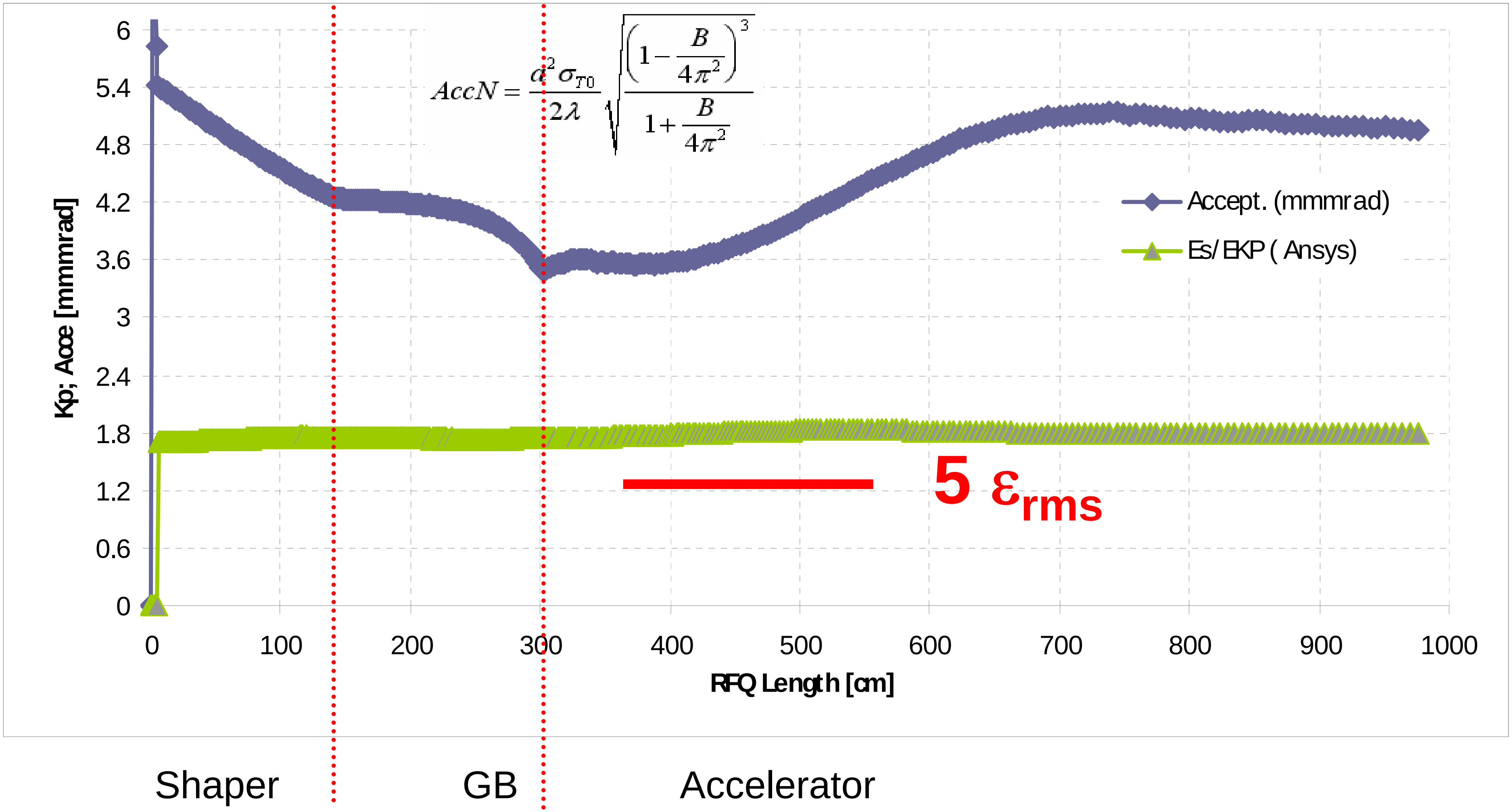
Modulation “m”, average aperture “r0” [cm], small aperture “a” [cm], Voltage/100 [kV] E0 [MV/m], Acceleration factor “A10”, Energy “W”, Focusing “B”,

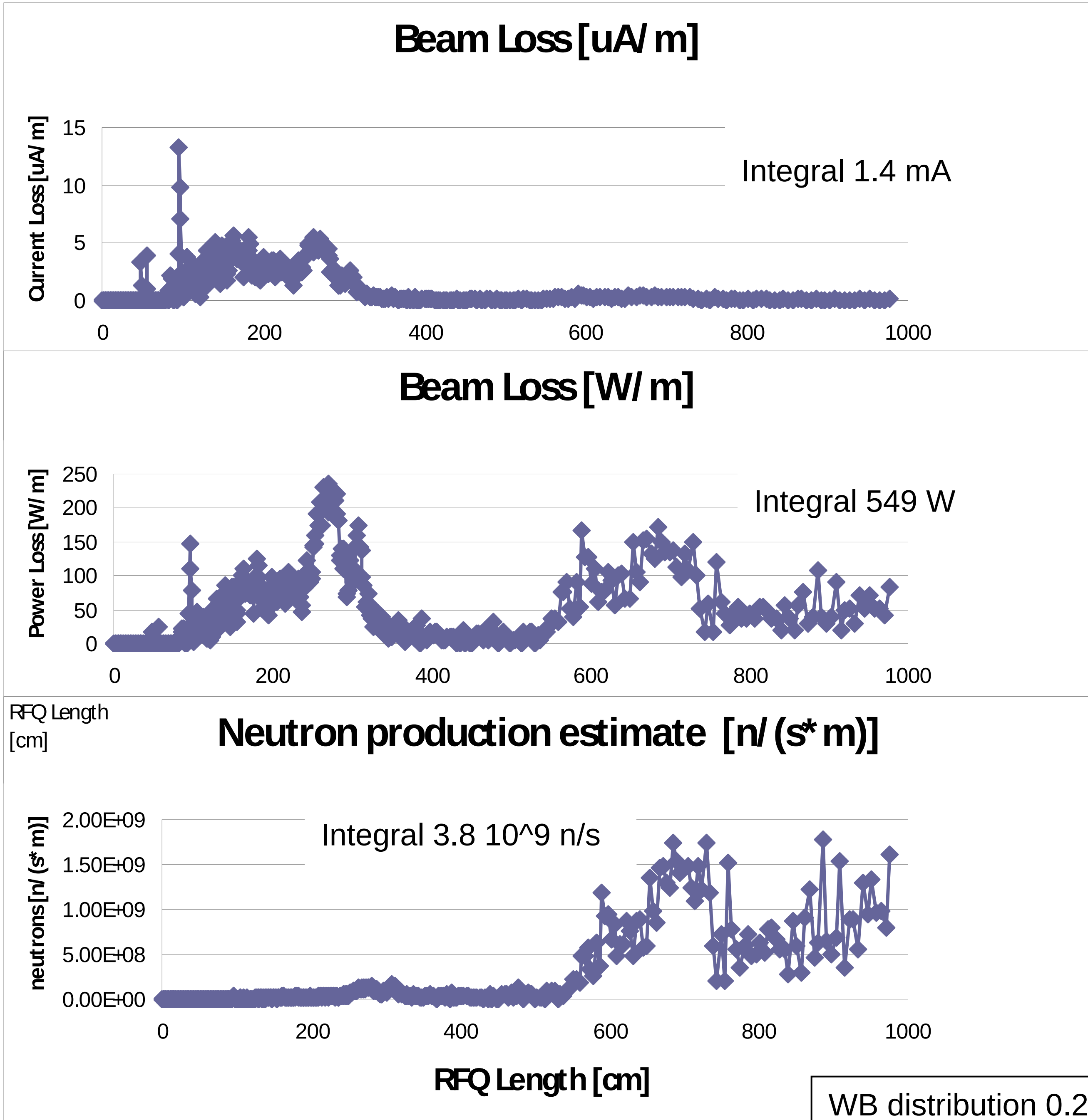


Ions	d	
Energy range	0.1-5	MeV
input-output nom emitt	0.25	mmmrad (rms)
Ouput long emitt.	0.2	MeV deg (rms)
Output current	0.2	
Tansmission	98	% WB distr.
	95	% Gsussian distr.

PhasePLot

Acceptance increase in the accelerator part

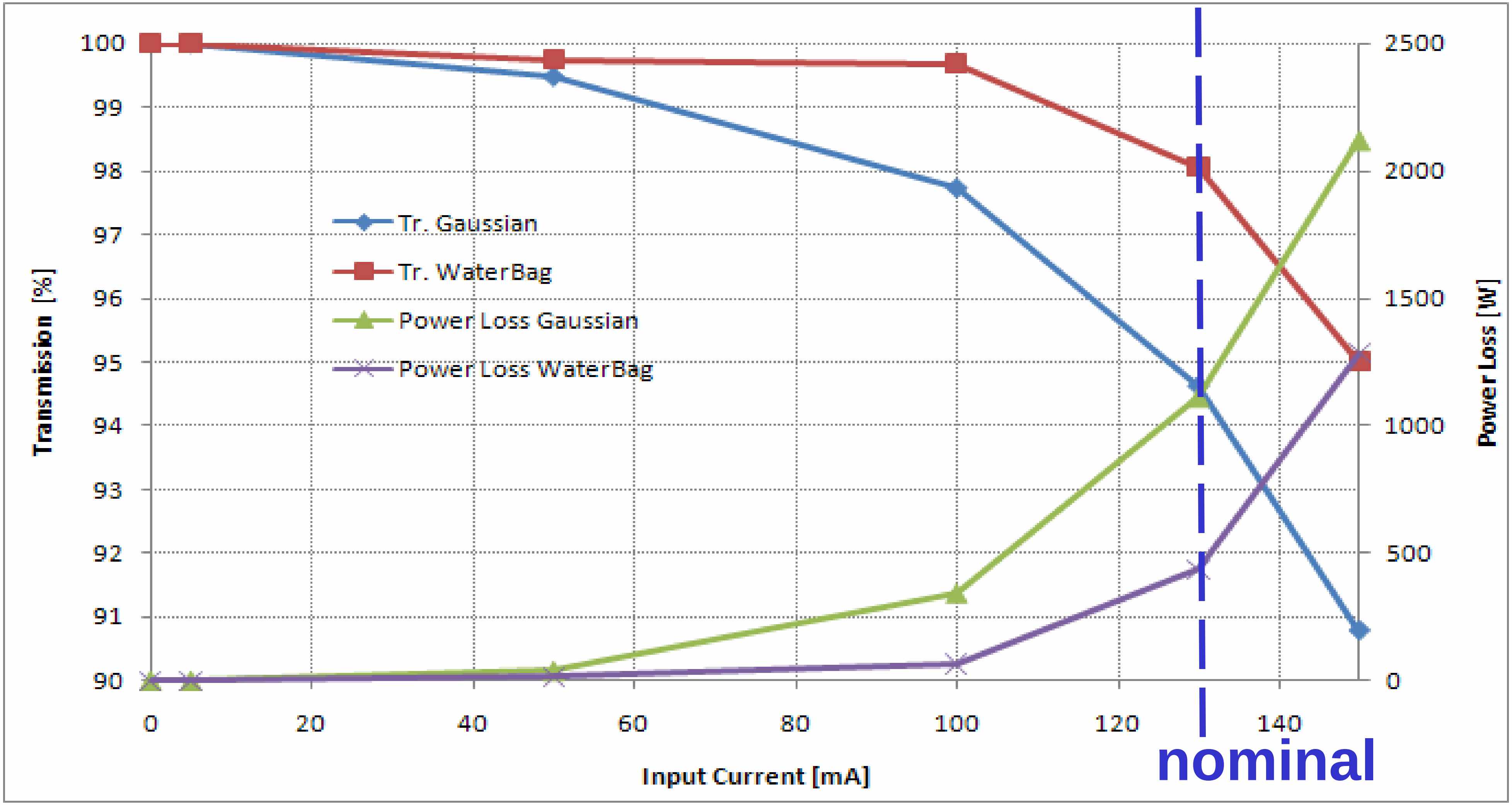




$$n = 5.15 * 10^{-7} N w^{2.1}$$

WB distribution 0.25 mm mrad rms norm

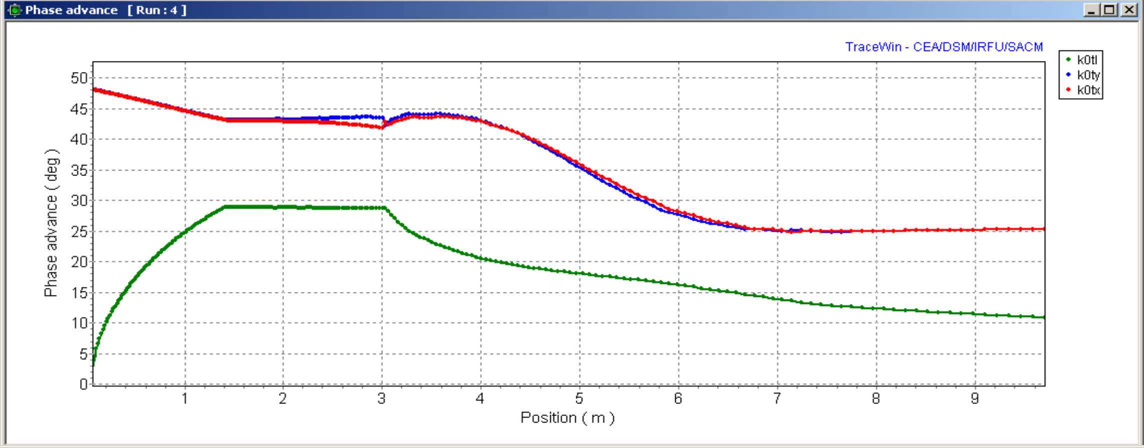
Effect of Input Current and beam distribution



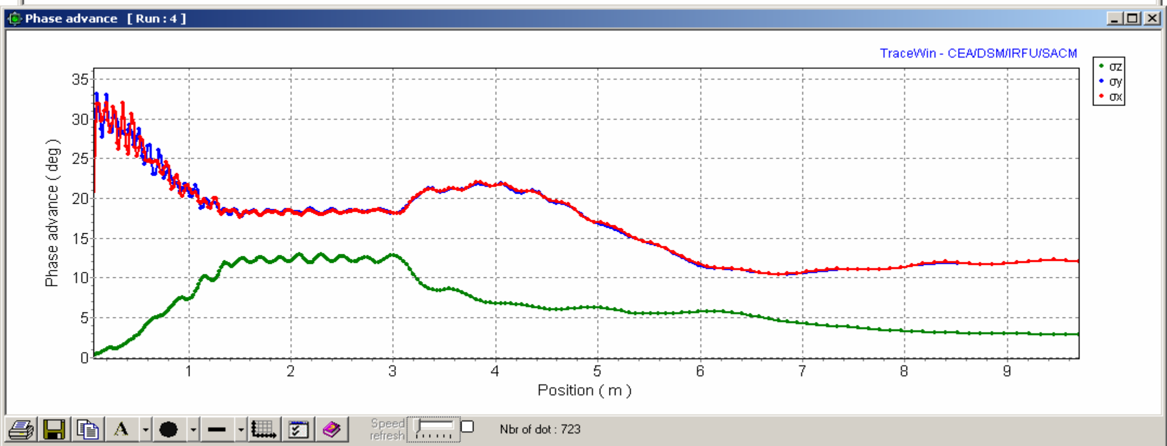
Runs with TraceWin; emit=0.25 mmmrad RMS; Np=100000

The Phase Advance along the RFQ

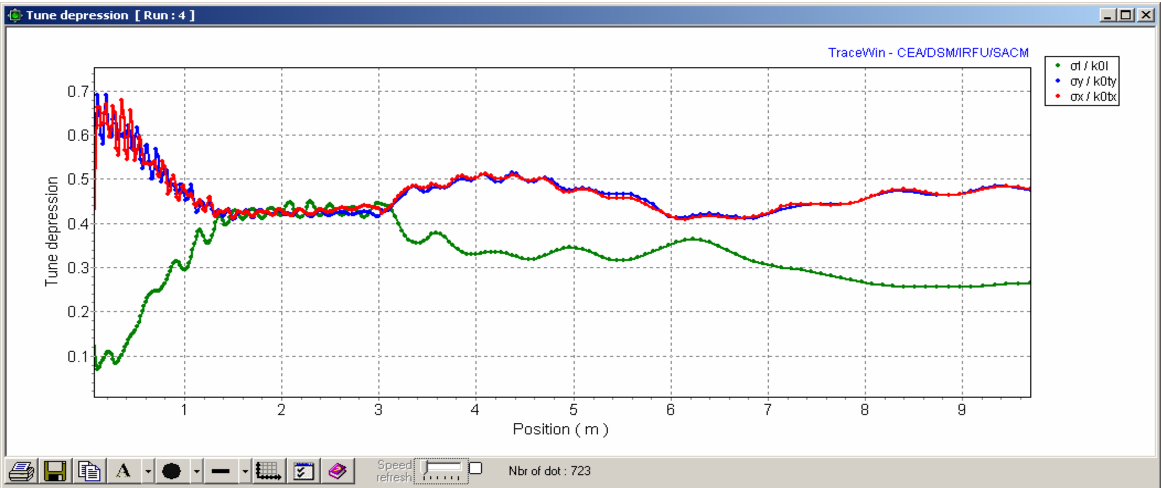
I=0



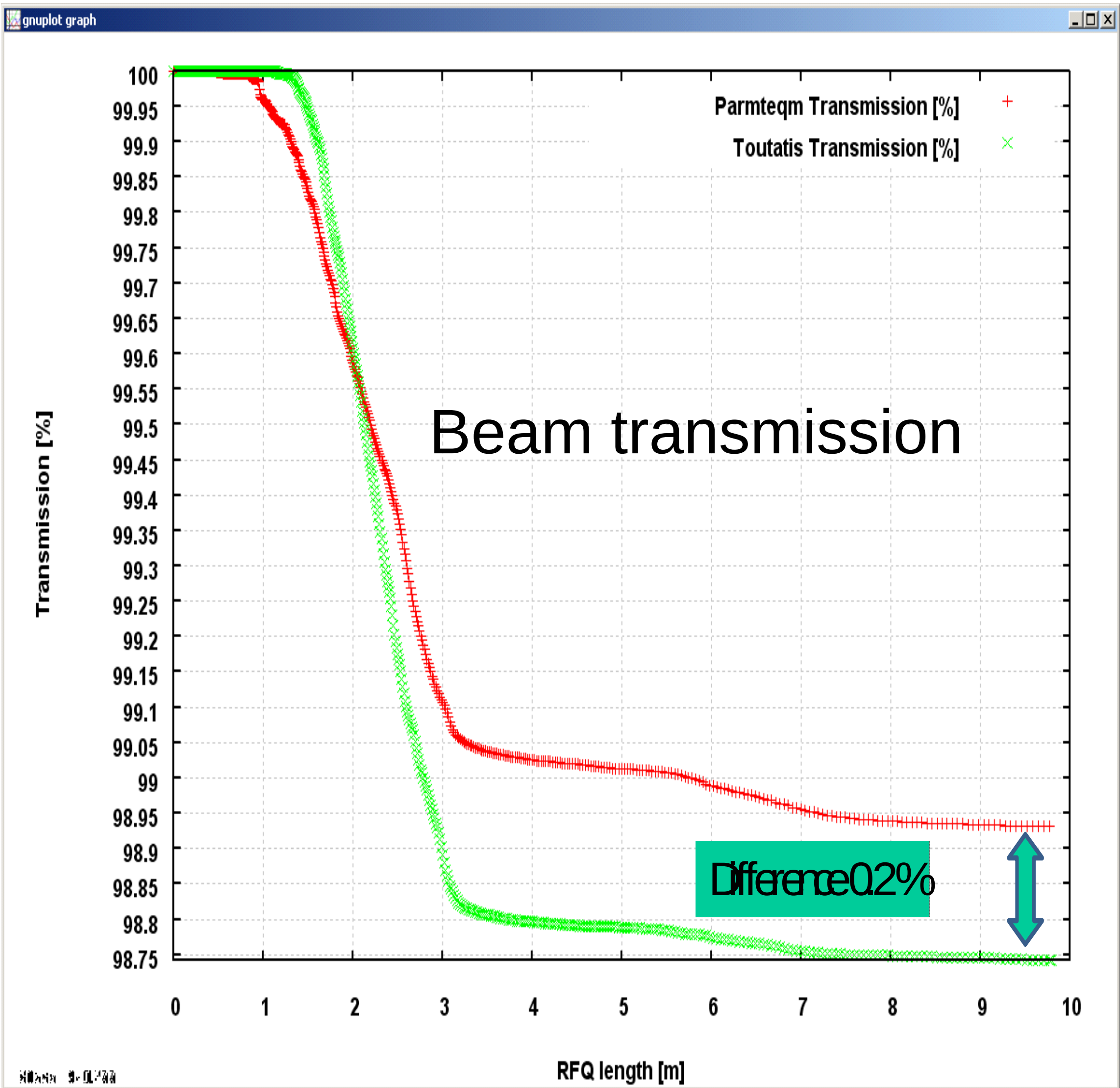
I=130



Tune depression



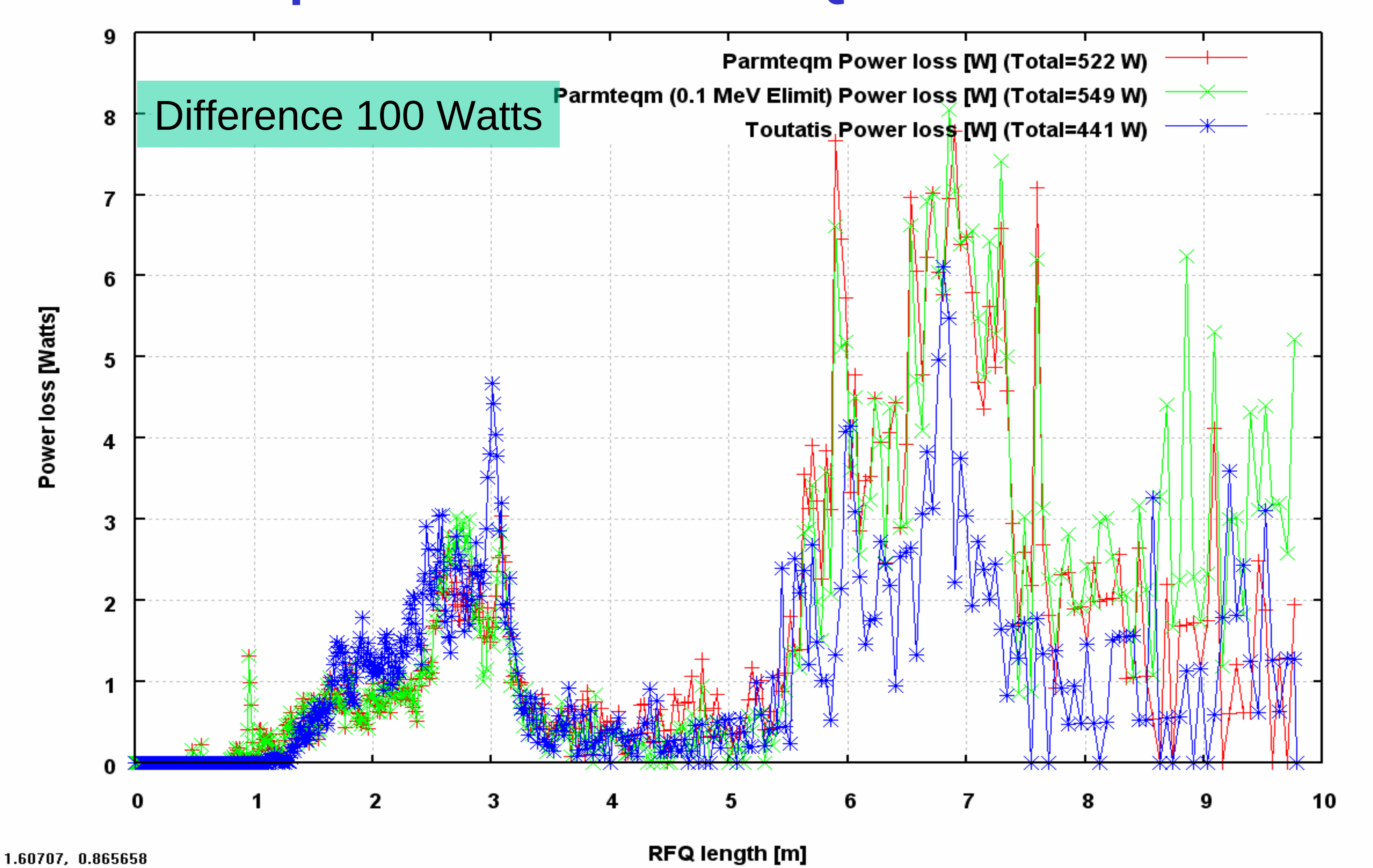
Comparison of PARMTEQM and TOUTATIS



- The two codes are in good agreement with quite different physical description

	PARMTEQM (LANL)	TOUTATIS (CEA)
Integration step	space	time
Space charge	2D SCHEFF with periodic boundary	3D FEM with periodic boundary
Electrodes	Image fields	Solution of Poisson with electrode boundary

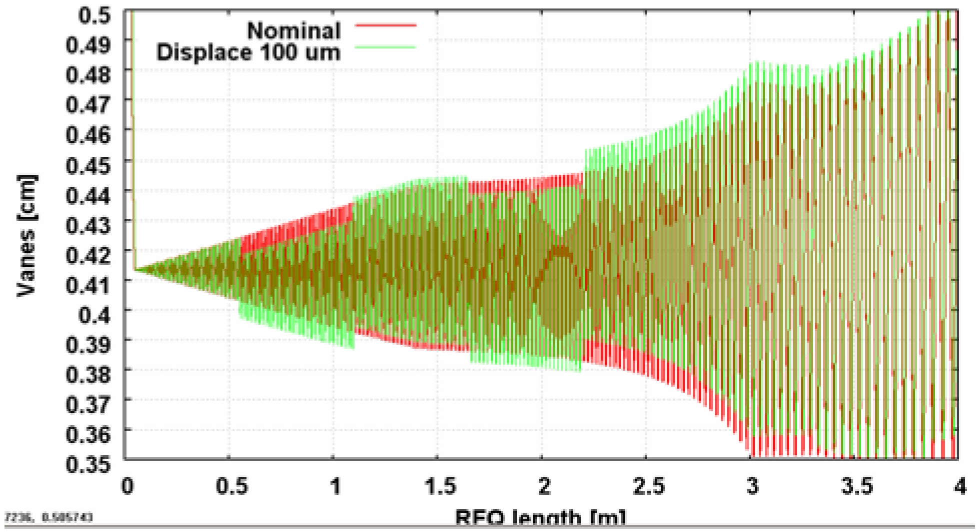
Comparison of PARMTEQM and TOUTATIS

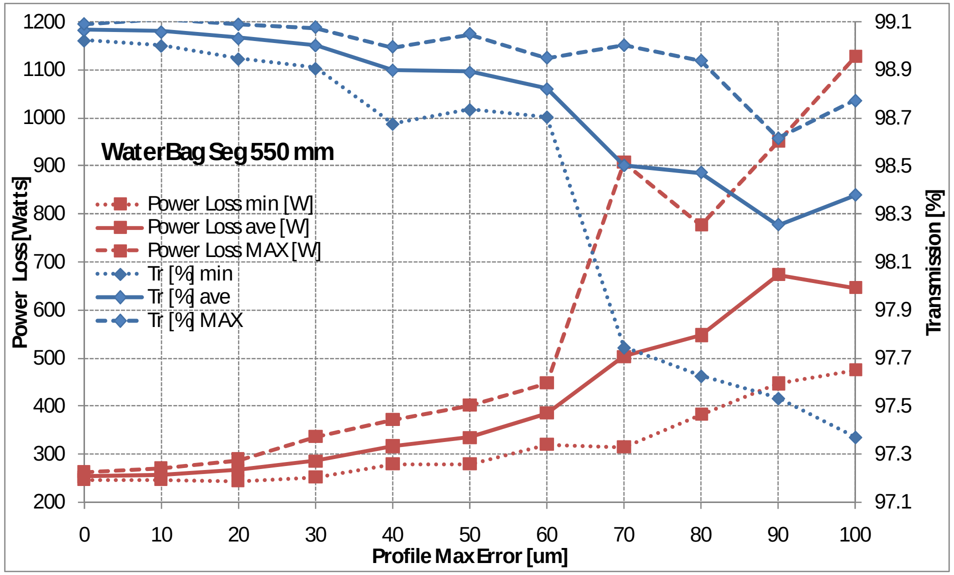


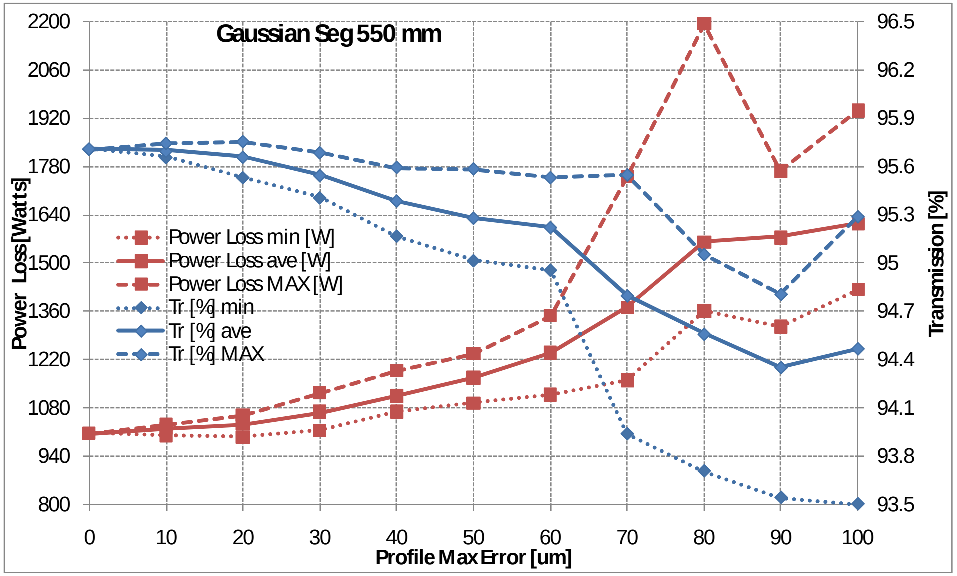
Plot of RFQ Power Loss as function of RFQ length, The toutatis runs are made with 1'000'000 macroparticles.
In this case the 3D Finite Difference poisson solver grid in Toutatis was "65x65x65 and 17x17x17".
The PARMTEQM runs are made with 1'000'000 macroparticles. The 2D (r-z) Scheff grid was "20x40" for the Space charge solver (Image charge on, multipoles on).

Error studies

- The error study shows tolerances in beam alignment and electrode displacements of the order of 0.1 mm, while the RF field law has to be followed with an accuracy of 1-2%.
- Example: displacement between two modules (9 modules)



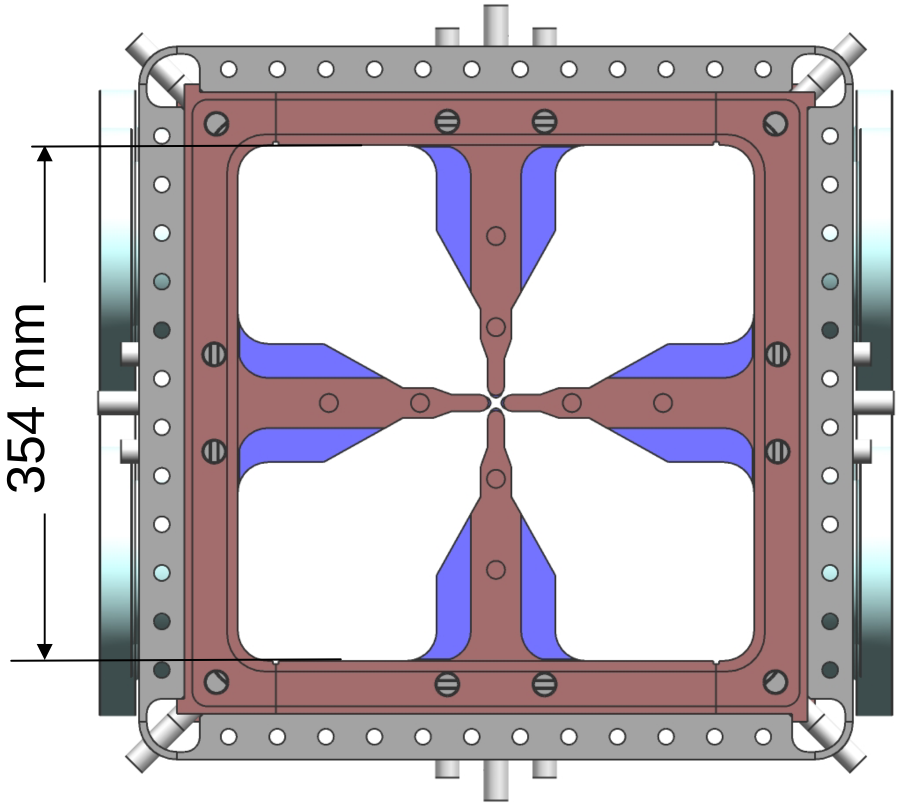




Transmission and Power loss due to the segmentations applied with gaussian and waterbag input beam distribution.**(TOUTATIS)**

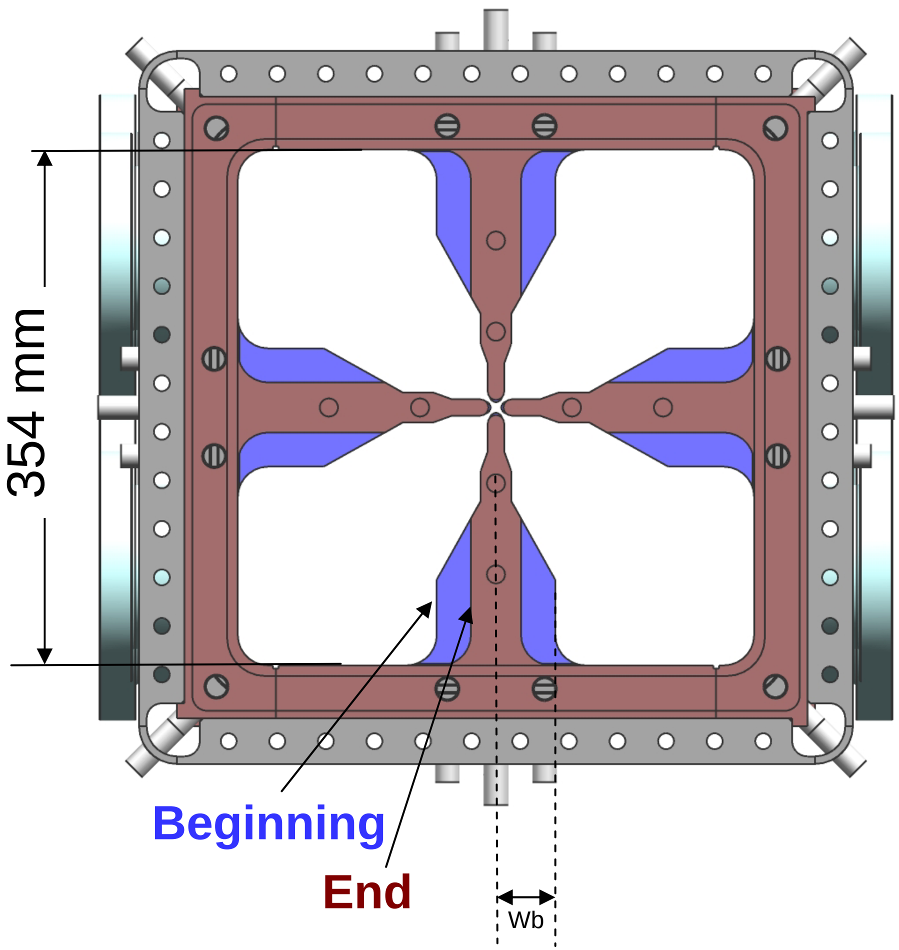
RF cavity design

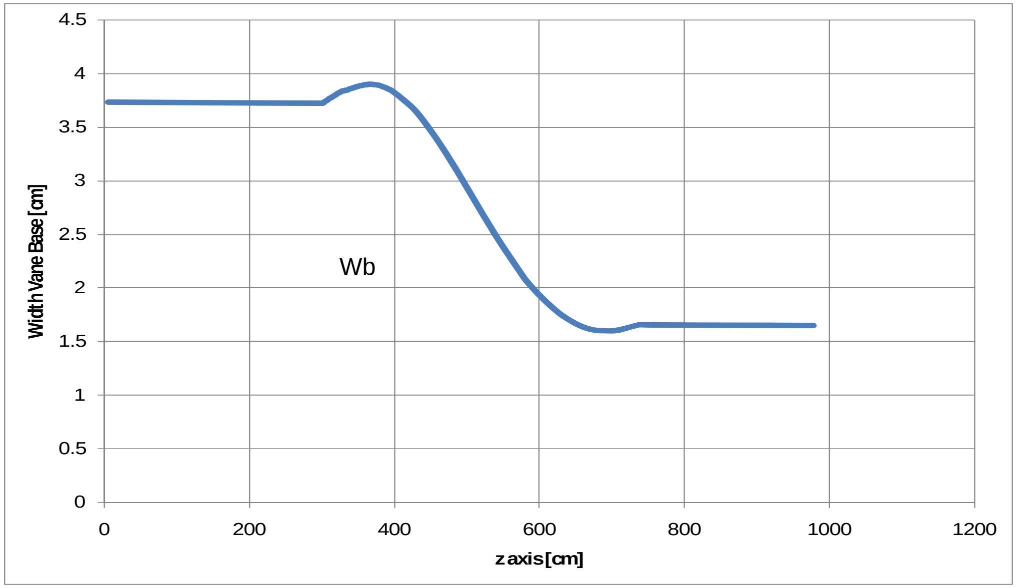
Cavity cross section

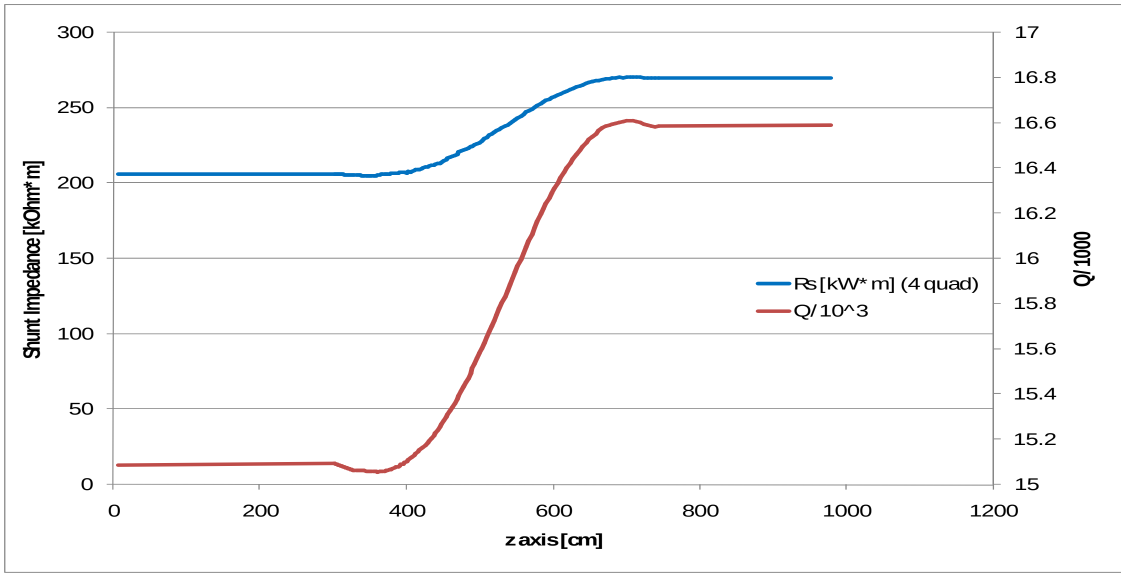


Operating Frequency	**175**	**MHz**
Length	**9.78**	**m**
Vg (min – max)	**79 – 132**	**kV**
R0 (min - max)	**0.4135 - 0.7102**	**cm**
Shunt impedance (min – max)	**206 - 270**	**kΩ*m**
Q (min – max)	**15100 - 16600**	
Total Stored Energy	**6.63**	**J**
Super Fish Copper Power P_{SF}	**450**	**kW**
Beam Loading P_b	**637**	**kW**
Max. RF power to the cavity P_d	**1345**	**kW**
Number of slug tuners	**96**	
Frequency tuning	**Water temp.**	

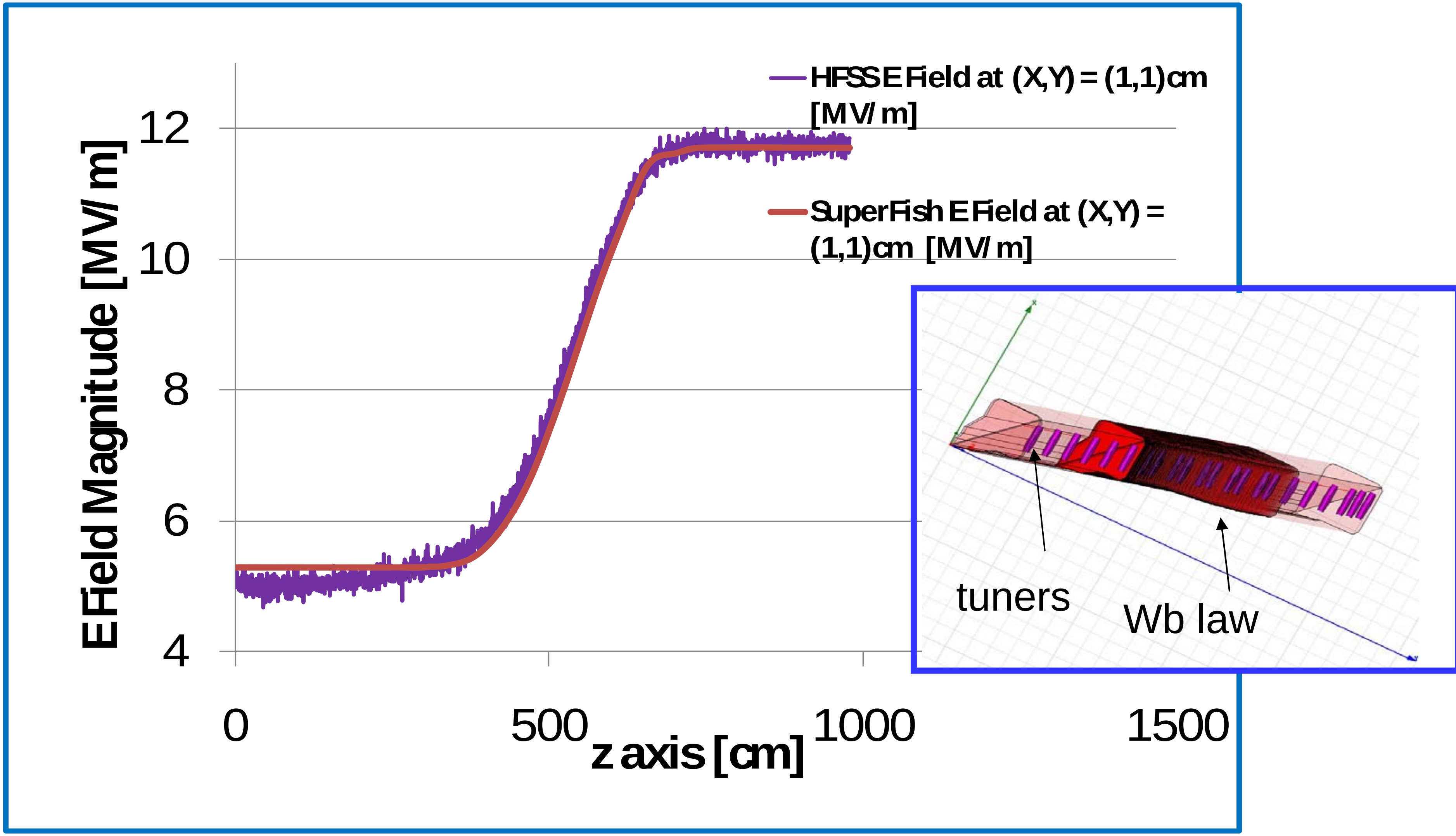
Cavity cross section







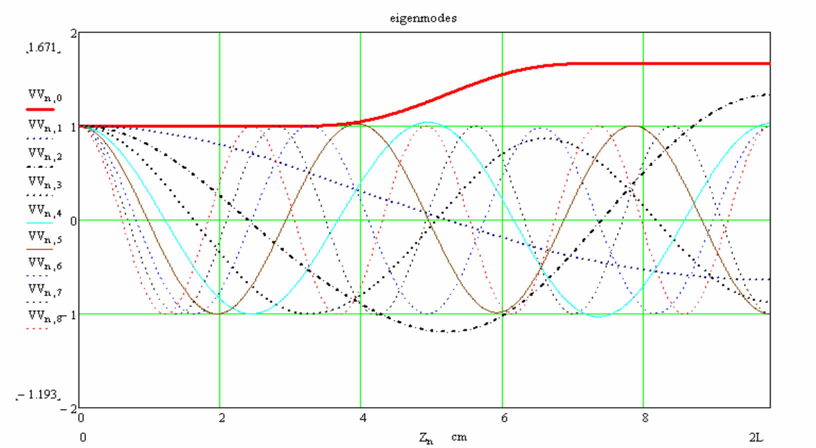
3D simulations with HFSS



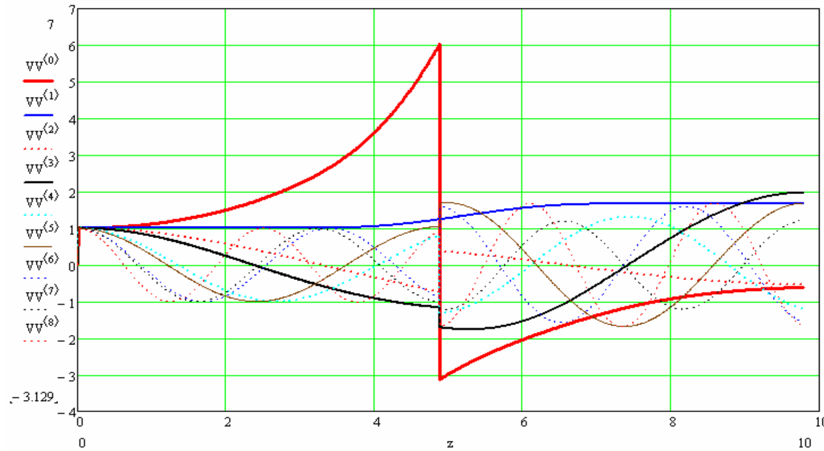
Field Error < 4% in the initial path. F = 174.097 MHz (600000 mesh tetrahedra).

RFQ modeling: transmission line model

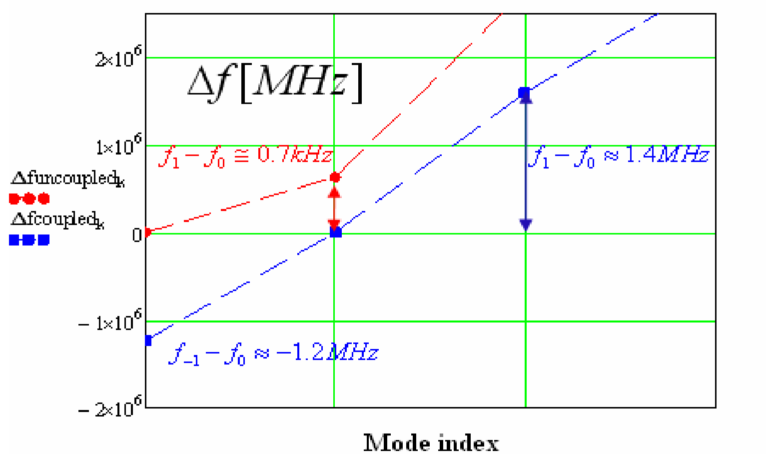
Quadrupole eigenmodes for ideal boundary conditions (s_{ec}=0)



Uncoupled RFQ (Gap and EC matrices are identities)



Coupled RFQ (K=2)



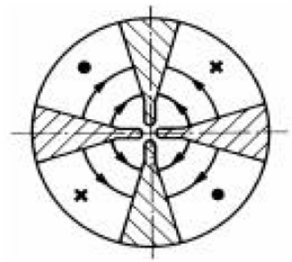
Geometrical tolerances

- The geometrical tolerances for a long RFQ are severe due to the mode contamination from TE21n (spurious quadrupoles) and TE11n (dipole) modes, whose frequencies can be very close to the operating mode.

Perturbation to the nominal geometry ⇨ Accelerating mode is not pure

$$\left|E_{210}^{p}\right\rangle = \left|E_{210}\right\rangle + \sum_{n\neq 0} \frac{\left\langle E_{21n}\middle|P\middle|E_{210}\right\rangle}{\omega_{21n}^{2}-\omega_{210}^{2}}\left|E_{21n}\right\rangle + \sum_{n=0} \frac{\left\langle E_{D1n}\middle|P\middle|E_{210}\right\rangle}{\omega_{D1n}^{2}-\omega_{210}^{2}}\left|E_{D1n}\right\rangle + \sum_{n=0} \frac{\left\langle E_{D2n}\middle|P\middle|E_{210}\right\rangle}{\omega_{D2n}^{2}-\omega_{210}^{2}}\left|E_{D2n}\right\rangle$$

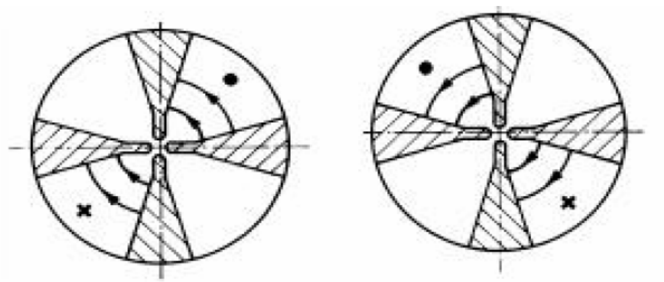
TE_{21n}



Longitudinal dependence: $V(z) = V_0 \cos\left(\frac{n\pi}{l} z\right)$

TE_{11n}

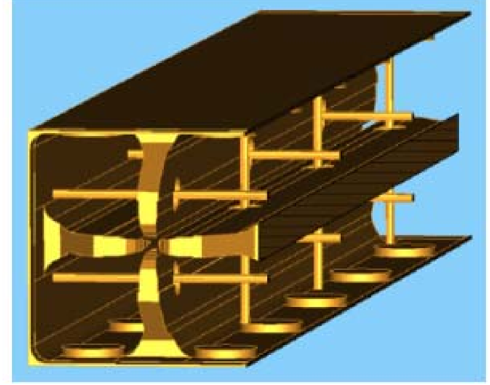
(dipole modes)



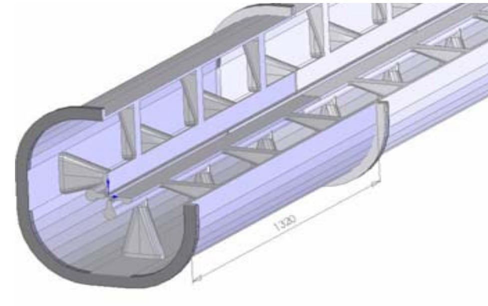
Longitudinal dependence: $V(z) = V_0 \cos\left(\frac{n\pi}{l} z\right)$

Dipole modes

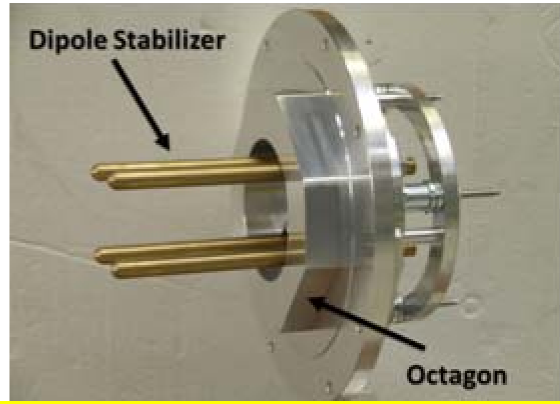
- The TE110 frequency in a pure four vanes is lower than the operating frequency TE210
- this can be corrected increasing the **magnetic coupling between quadrants** (PILs or a four-rod or ladder kind structure) at price of increasing the peak magnetic field and **power dissipation**,
- These approaches are therefore quite un-suited for a HP-RFQ.
- As an alternative one can create a suited **dipole free region** by tuning **rod terminations** of appropriate length in the end regions.
- This approach, used in LEDA, was tested at low power for TRASCO and IPHI, and the well tested tuning algorithms developed by LNL team will be used for IFMIF RFQ .



PILS dipole sabilizers



Ladder kind structure



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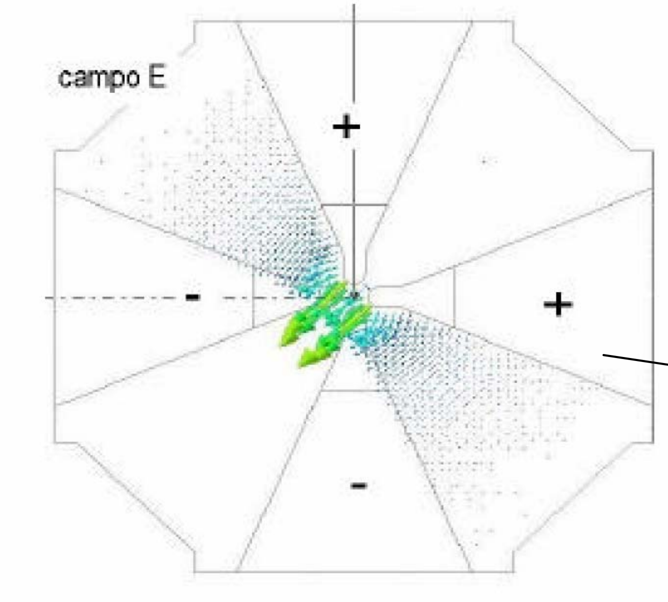
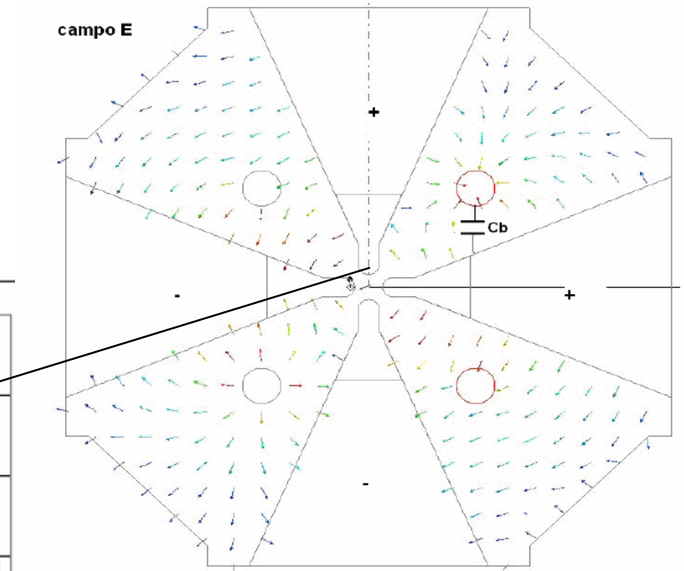
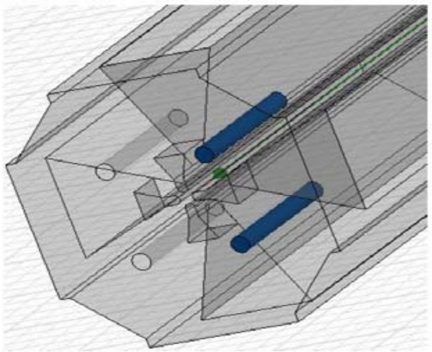
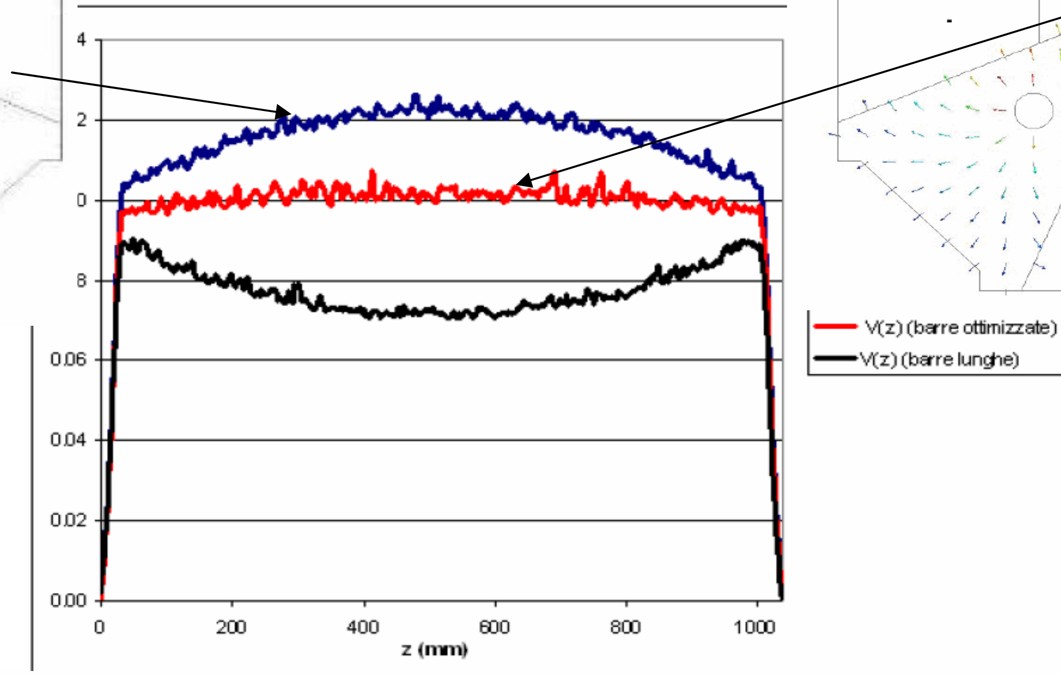
Dipole rod termination

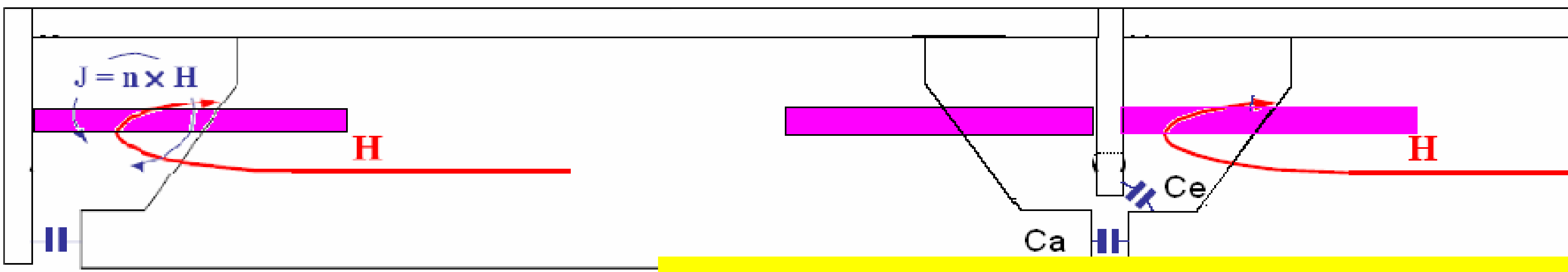
Termination of TE_{110} mode











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λ

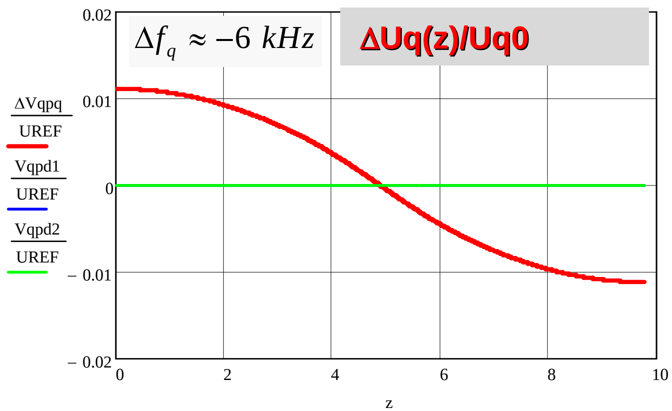
Quad contamination: is resonant coupling necessary?

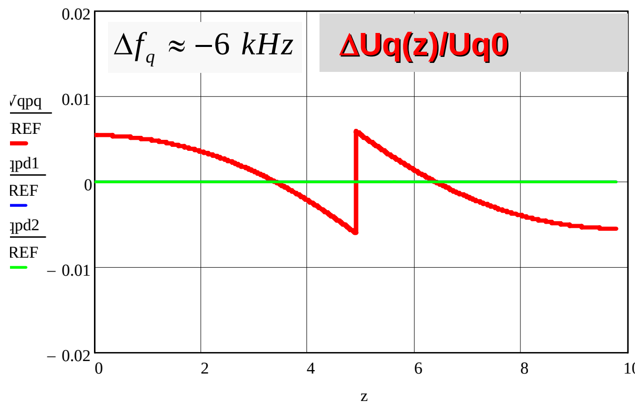
- Concerning TE211 mode, the contamination can be estimated (for pure four vanes or for rods) as:

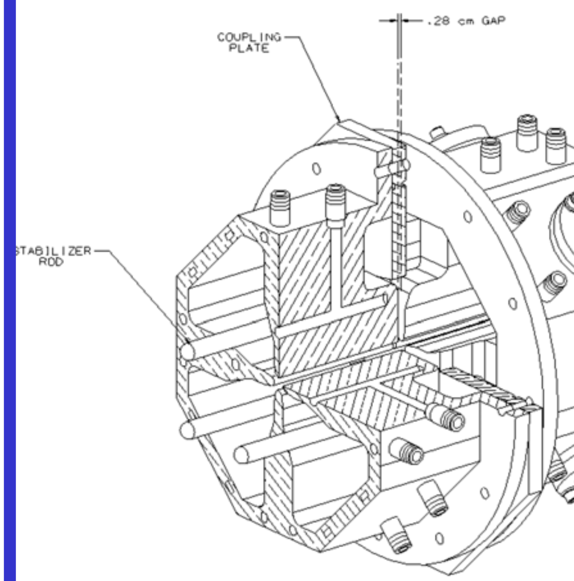
$$a_1 \approx 8\frac{\delta\omega_0}{\omega_0}\left(\frac{\lambda}{\lambda}\right)^2 \approx \frac{8}{3}\frac{\delta R_0}{R_0}\left(\frac{\lambda}{\lambda}\right)^2$$

- For dR0 following for first Fourier component (worst case) 1% contamination corresponds to a tolerance as small 7 kHz or 0.6 um.

For the coupled RFQ the field error is almost half of the uncoupled case



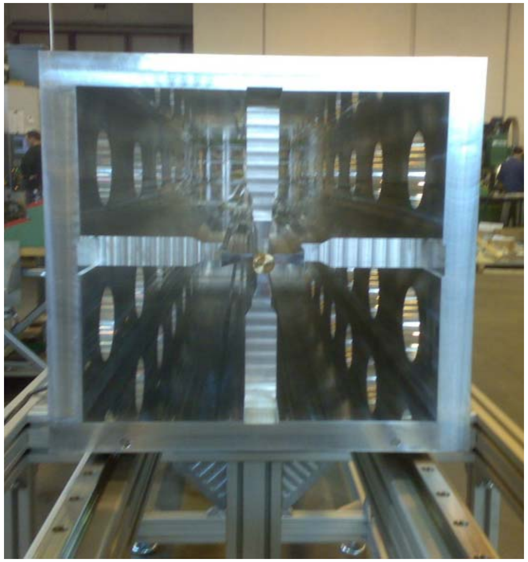


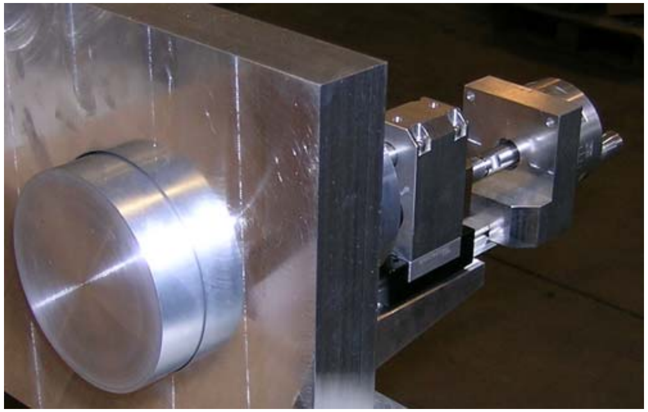


L. Young's schetch

- No evidence of improvement from beam dynamics simulations

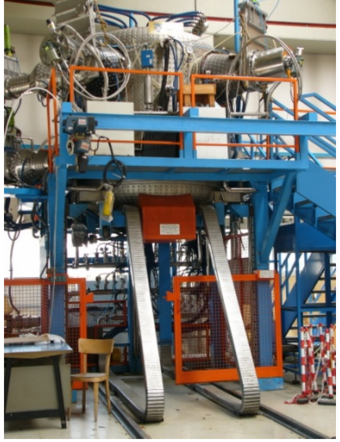
IFMIF-EVEDA: The aluminum real-scale RFQ model



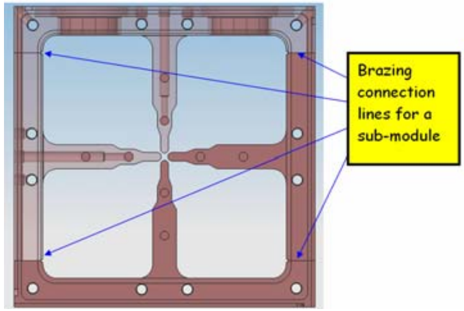


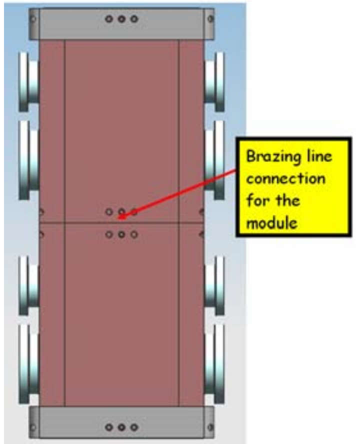
100 dummy tuners "ergonomic"

Mechanics design



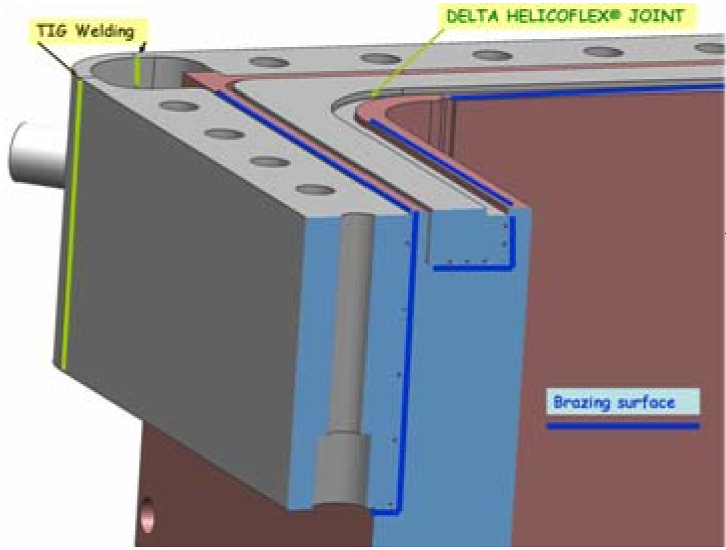
- **Based on vacuum brazing** CERN experience, design compatible with oven at CERN, LNL and in industry;
- Due to the relatively large transverse dimensions of the RFQ, the procurement of the CUC2 raw material blocks is limited by the total mass amount (length **550 mm).**
- **First brazing**, the four electrodes of each block joined in a horizontal oven.
- **Second brazing**, two of such blocks in a vertical oven, together with Stainless Steel head flanges, in order to obtain a mechanical module of **1100 mm for a total weight of about 700 kg.**
- 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 9 of these modules.



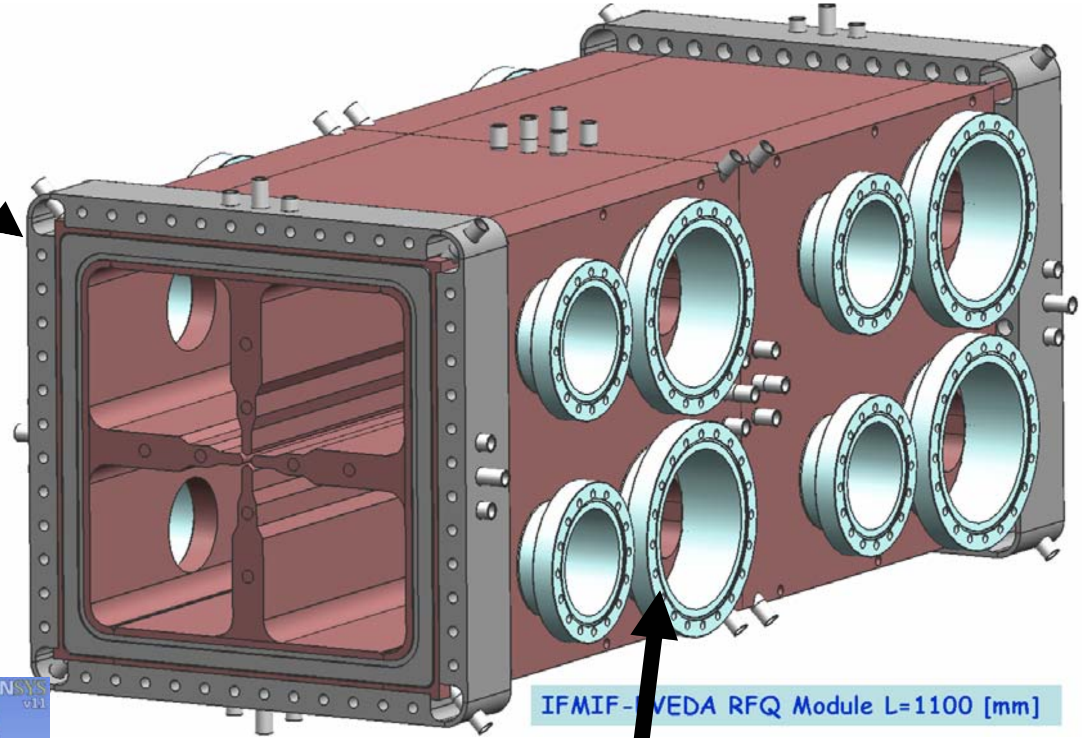


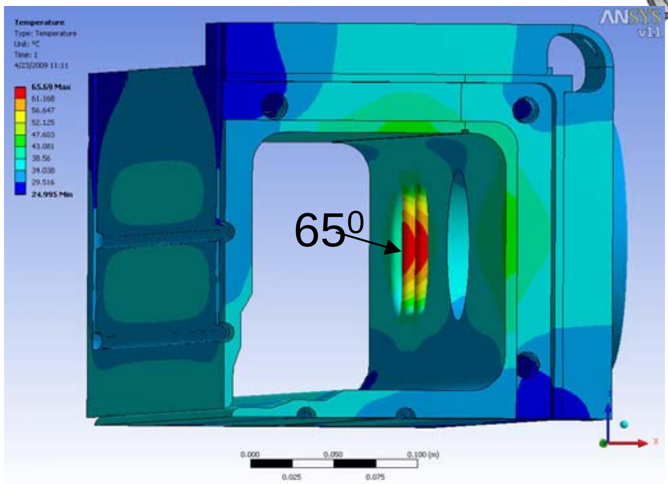
See A. Pepato et al. FR5REP065

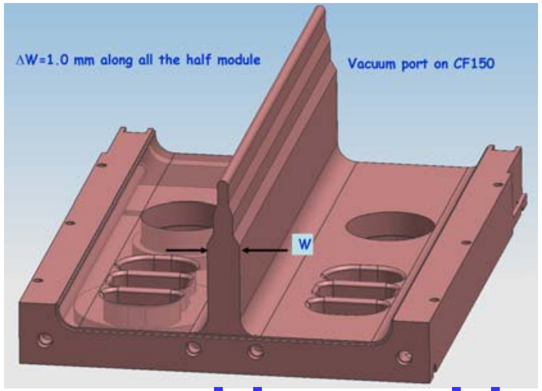
Mechanics details



Head flange

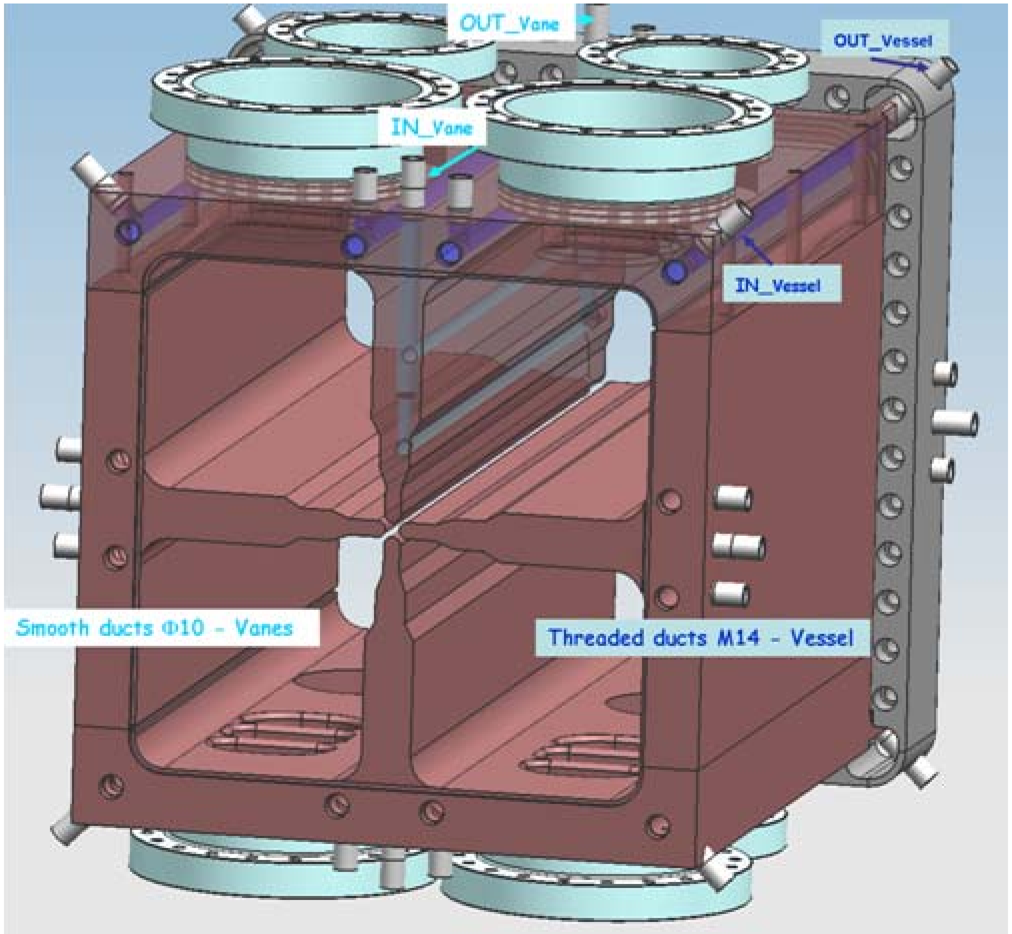


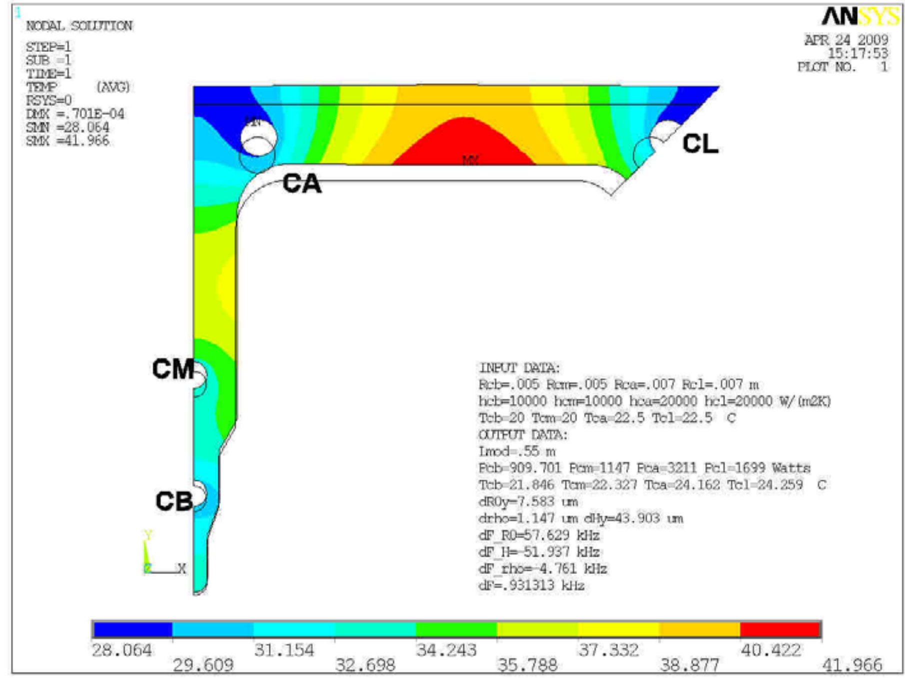




Vacuum grids machined from bulk

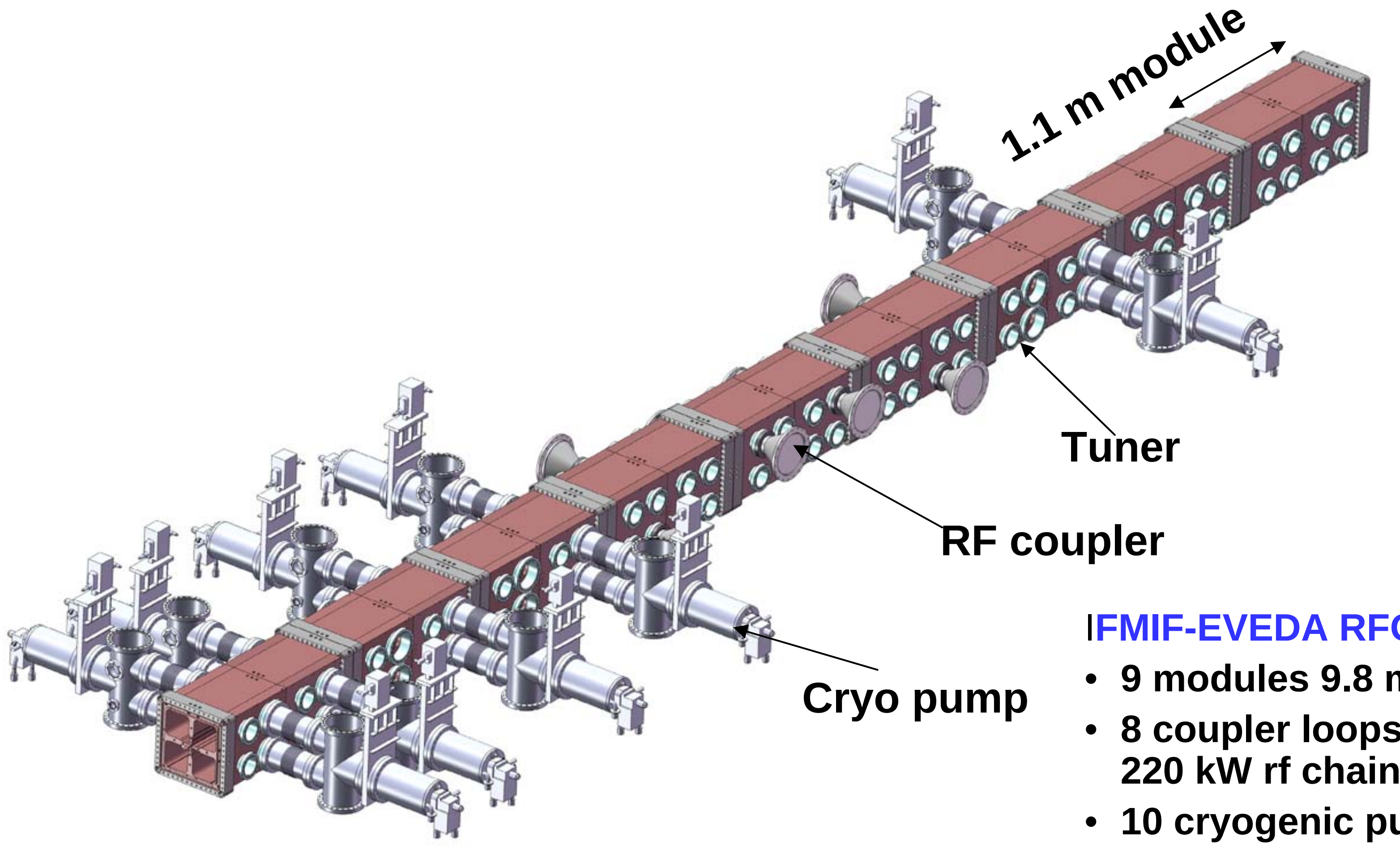
Cooling system and freq. tuning





	R mm	T_{in} °C	v m/s	T_{out} °C	H_c W/m^{2}K	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

Lay out of IFMIF EVEDA RFQ



IFMIF-EVEDA RFQ

- 9 modules 9.8 m
- 8 coupler loops powered by one 220 kW rf chain each
- 10 cryogenic pumps (2000 l/s)
- 5 10-7 mbar with beam

Organization of IFMIF-EVEDA RFQ task

- **INFN LNL**: specific competences on RFQ accelerators, National Laboratory infrastructures
  - – 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**: competences in mechanics for the participation to large experiments, mechanics workshop
  - – Machanical design of the RFQ, production of the modules
- **INFN Sezione di Torino** competences in mechanics for the participation to large experiments, mechanics workshop
  - – supports and tooling, participation to the production modules production
- External competences involved since the beginnig
  - – **CERN**: brazing, chemical treatments, specification and tests of the materials
  - – **Mechanical industries**: Cinel (that had in charge the mechanical design and production of TRASCO RFQ), Mecachrome (IPHI), Zanon,...

RFQ status summary

- Preliminary design: validated by PDR review (chaired by M. Vretenar, CERN) in June 08
- **Prototypes**
  - low power model delivered
  - technological prototype (one module): copper procured, construction started
- Mechanical design: production of the drawings
- Structure support and tooling: preliminary design Cooling system: conceptual design ready
- Vacuum system: preliminary design ready
- Local control system: conceptual design ready
- RF couplers: waiting for the preliminary design from JAEA
- Critical Design Review in Autumn to **start the production**

IFMIF EVEDA
RFQ Preliminary Design Review
Legnaro, 12.06.2008

COMMENTS FROM THE REVIEW COMMITTEE

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General

- the Committee appreciates the careful preparation of all the presentations, and recognises the work done by the RFQ team and the remarkable progress in the last months.
- In particular, accurately following the project milestones had a positive effect on the definition of the different aspects of such a multidisciplinary project.
- The choice of a proven concept for the general RFQ design offers the best chances of success within the time schedule.

Conclusions

- The field of high power RFQs is very lively
- with the recent 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 the recent achievements for cw RFQs are a basis for the success of this project.

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