

RFQ FOR CW APPLICATIONS

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Abstract

CW RFQs requires solid design since they have to deal with design challenges and technological limitations. This talk overviews the recent performances of some of the most powerful RFQ cavities. Development, industrialisation and commissioning results of CW RFQ are describe and discussed, with recent update on two emblematic designs: IFMIF and TRASCO.

INTRODUCTION

The term cw RFQs indicates linear accelerators of Radio Frequency Quadrupole operating in continuous wave mode. Such accelerators are able to accelerate (light) ions for high beam power (about 670 kW reached up to now).

The main application of these devices is related to their possible use as injectors of multi MW superconducting linacs able to accelerate cw proton beams above 1 GeV. This will allow the development of multi MW spallation neutron sources for nuclear waste transmutation, radioactive nuclear beams production and other applications. Proton linacs with higher energy could be used for the production of pions, muons and neutrinos.

As a second application cw RFQs can be used as injectors of deuteron linacs (about 40 MeV) for Fusion Material Irradiation tests. The International Fusion Materials Irradiation Facility (IFMIF) [1] project aims at producing an intense (about 10^{17} s^{-1}) neutron source facility, with spectrum up to about 14 MeV, in order to test the materials to be employed in the future fusion reactors. The facility will be based on two high power CW accelerator drivers, each one delivering a 125 mA deuteron beam at 40 MeV hitting a liquid lithium target (10 MW power) to yield neutrons via nuclear stripping reactions.

Concerning proton applications, a high intensity injector was prototyped at Los Alamos with LEDA with important results [2], but the extension above 7 MeV was not funded. New linac based ADS studies are pursued in UE, India and China.

For the second application instead the IFMIF-EVEDA [3] project has been funded in the last years, with the task to validate the IFMIF design with test a number of prototypes, including a high-intensity CW deuteron accelerator for a beam power exceeding 1 MW. INFN, mainly through the LNL labs, Padua, Torino and Bologna sections, will design, build and test with beam the high intensity deuteron RFQ [4]. The RFQ will be installed in the JAEA site at Rokkasho (Japan) as the main accelerating structure of the IFMIF prototype accelerator sketched in Fig. 1 (9 MeV 125 mA). The other elements of the Accelerator System, namely the ion source, one superconducting linac cryomodule, the RF system, the beam transport lines and the beam dump, are provided by

the other two main European partners, CEA (France) and CIEMAT (Spain).

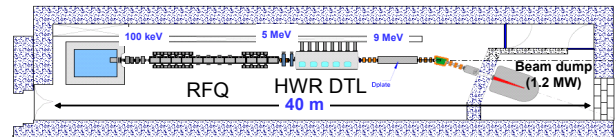


Figure 1: Schematic lay-out of the IFMIF-EVEDA prototype linac (125mA, 9 MeV deuterons).

Concerning low beam power applications cw RFQs are almost always used as injector of heavy ion linacs for Nuclear Physics, like for ALPI at LNL or ISAC at TRIUMF. The optimization of the beam time structure is in this case dictated by the continuous low current from the source and by the superconducting linac characteristics (many two-gap independent cavities driven by solid state amplifiers) so that one has a cw beam with negligible space charge.

An evolution of these applications are related with the development of new medium power superconducting cw linacs (energy about 40 MeV). Deuteron currents of few mA are accelerated for neutron and RIBs production. Two projects with comparable parameters are SARAF in Israel [5] and the SPIRAL2 driver in France [6]. The two projects are respectively in commissioning phase (up to the first cryomodule) and in construction.

Finally, the stand alone application of cw RFQs for compact neutron sources should be mentioned. This is the case of the proposed application of TRASCO RFQ (5 MeV 30 mA) at LNL [7], as a thermal and epithermal neutron source for Boron Neutron Capture Therapy, making use of a 150 kW beryllium target, or the case of the project FRANZ (2 MeV p onto Li target) at Frankfurt University [8], with an integrated RFQ-IH cw structure for a pulsed neutron source (250 kHz) for nuclear measurements of astrophysical interest.

LANDSCAPE

Concerning the historical origin it is interesting that the first activities in the field of RFQs outside Russia were related to the Fusion Irradiation Facility application, that is now very topical. For FMIT project (back in the seventies) the new ideas of Teplyakov and Kapchinsky were really a possible solution of the huge R&D questions for a high current (100 mA) high voltage injector into the cw DTL. The first RFQ operated cw was FMIT RFQ accelerating up to 2 MeV a H_2^+ beam [9]. Since then, the experience with CW high power beams from RFQs has been very limited.

Important development with cw RFQ came much later; the RFQ of LEDA is probably the most important high power RFQ, with the record of accelerated beam power, total dissipated power, dissipated power density and

length in lambda units (indicator of the RF field stability). Most of these figures were more challenging than those to be reached by IFMIF RFQ.

Many features specific of high power RFQ were developed within this project, like the construction in several modules flanged together (8 modules each brazed in Hydrogen furnace); the modules were organized in four segments resonantly coupled. The TE mode configuration in the four vane RFQ allows the subdivision in many modules since significant currents cross the RF joints only at the end coupling cells. Other important characteristics of LEDA RFQ were the LEBT with

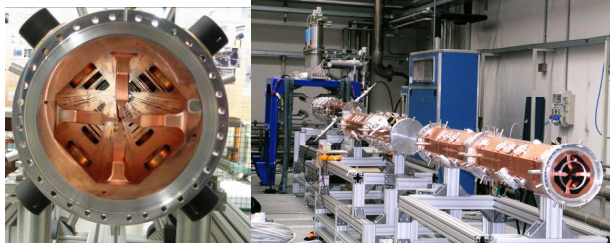


Figure 2: The six modules of TRASCO RFQ.

neutralized beam and electron trap at the RFQ entrance, the ramped voltage along the structure, the rods for dipole stabilization. Unfortunately the project ended with a quite limited beam operation experience (about 110 hr above 90 mA cw).

In Europe two R&D programs based on cw 352 MHz RFQs were launched within ADS studies, namely IPHI at CEA Saclay and TRASCO at INFN Legnaro (Fig. 2). The design is quite different (also respect to LEDA); IPHI [10] is built in six modules (1 m each), has a ramped voltage, a cross section with a sophisticated geometry and has been optimized for a very high nominal transmission (above 98%); TRASCO [11] [12] is optimized for 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).

Both RFQs are brazed under vacuum. The six TRASCO RFQ modules, designed by INFN and built in Italian industry, have been brazed at CERN [13] and, after some delay, are now ready for high power tests. The brazing of IPHI modules are being completed in French industry.

Concerning the infrastructures, IPHI site at Saclay is ready (with the ion source tested, two LEP klystrons installed, the cooling system ready) while the building for TRASCO RFQ is not yet funded. A first test at high power at CEA site is foreseen for Autumn 2010 using TRASCO RFQ modules

Concerning medium intensity applications the two RFQs of SPIRAL2 and SARAF projects (Fig. 3) are both designed to accelerate deuterons, with low beam losses.

Table 1: General Parameters of Various RFQs (→ means “non operated”)

RFQ (design by...)		Ion (A/q)	Final energy	Vane Voltage	Beam current	Beam power	RF power	Freq.	Length		E _{max}	Av. Power density	Max. Power density
			MeV/u	kV	mA	kW		MHz	m	λ	kilp.	W/cm ²	
→ IFMIF EVEDA (LNL)		d	2.5	79-132	130	650	585	175	9.8	5.7	1.8	3.5	70
CW high p	LEDA (LANL)	p	6.7	67-117	100	670	1450	350	8	9.3	1.8	11.4	65
	FMIT (LANL)	d	1	185	100	193	407	80	4	1	1	-	-
	→ IPHI (CEA)	p	3	87-123	100	300	750	352	6	7.0	1.7	15	120
	→ TRASCO (LNL)	p	5	68	30	150	847	352	7.3	8.6	1.8	6.6	90
CW med. P	SARAF (NTG)	d	1.5	65	4	12	250	176	3.8	2.2	1.4	24	190
	→ SPIRAL2 (CEA)	3	0.75	100-113	5	7.5	170	88	5	1.5	1.65	0.6	19
CW low p	ISAC (TRIUMF)	30	0.15	74	0	0	150	35	8	0.9	1.15	-	-
	PIAVE (LNL)	7.3	0.58	280	0	0	8e-3 (SC)	80	2	0.5	2.1	-	-



Figure 3: Front view of the SARAF RFQ (176 MHz four rods) and SPIRAL2 RFQ (88 MHz four vanes).

SPIRAL2 RFQ [14] 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 [15]. The order for the entire structure has been placed, and the final machining of first module is almost completed.

The SARAF RFQ [16] is a four-rod structure with minivanes, built by European industry. This architecture promises some advantages in terms of cost effectiveness, but power density at the stem bases is very high. The RFQ is now installed in the linac tunnel, the conditioning is in progress and first beam tests have been performed; up to now neither cw operation at nominal power (250 kW for deuteron acceleration) nor the nominal transmission could be reached.

Finally, there are cw RFQs for low current heavy ions, that have a long operational experience and give routinely beam to the Nuclear Physics experiments. The ISAC RFQ at TRIUMF [17] is a quite long (8 m like LEDA) low frequency structure, PIAVE at LNL [18] is based on a single cryomodule (about 2.5 m long) with two superconducting RFQs; PIAVE RFQ is currently operated with $A/q \leq 7$, ($A/q=8.5$ by design). The nominal transmission (60% with external beam bunching) has been reached.

THE RFQ OF IFMIF-EVEDA PROJECT

The specifications of IFMIF-EVEDA RFQ are very challenging, since the 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 in total and < 0.1 mA between 4 MeV and 5 MeV are allowed.

A dissipated power of approximately 600 kW (100 kW/m at high energy end) has to be removed while keeping extremely strict geometrical tolerances, with the necessity to manage hot spots and counteract potential thermal instabilities. Moreover this 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 and possibly accessible to different producers and specific technical solutions. To face these challenges the maximum use of previous experience has been made (TRASCO including brazing at CERN), INFN internal production capability has been exploited (design, machining, measurement and brazing),

a design such to make production accessible for different industrial partners has been chosen.

At present the design phase is concluded, including the construction of prototypes for crucial items, and the production of the modules has begun.

Beam Dynamics

The beam dynamics design [19] achieved a consistent reduction of the structure length (about 20%) with respect to the CDR case, with lower RF dissipation and beam losses. This has an important impact on RF stability and construction aspects.

The design approach followed the standard subdivision in Shaper (approx 1.5 m), Gentle Buncher (approx 1.5 m) and Accelerator (approx 7 m). The accelerator (with a linear synchronous phase variation from -60° to -32°) is optimized cell by cell, keeping the maximum surface field and increasing the acceptance up to a large value (2 mm mrad norm.). A strong focussing factor ($B=7$) is necessary in the gentle buncher section in order to keep the tune depression above 0.4 so to avoid the main space charge driven resonances. Following reviewers recommendations the focusing in the shaper raises now from $B=4$ to $B=7$ to allow an input beam with smaller divergence and an easier matching from the LEBT.

The intervene voltage in the accelerator section is ramped using a law $V(z)$ in closed-form and continuous up to the 2nd derivative; it is possible in this way to have continuous cut-off frequency variations along the RFQ, as well as limited frequency excursions, keeping at the same time the maximum surface field below 1.8 kV. Along the structure. As a result beam losses and the estimated neutron production along the RFQ follows the curves in Fig. 4; the importance of the acceptance maximization in the second part of the RFQ is really evident.

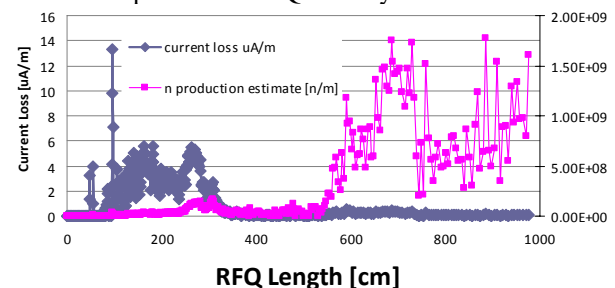


Figure 4: Simulated beam losses along IFMIF RFQ for a 130 mA water-bag distribution, 0.25 mm mrad r.m.s normalized, simulated by PARMTEQM; the integral losses amount to 1.4 mA, corresponding to 550 W beam power and estimated neutron production of 3.8×10^9 n/s.

Systematic simulations have been performed with the two codes PARMTEQM and TOUTATIS with 10^6 particles; the good agreement between the two codes (that are both benchmarked with experimental data following quite different physics description of the accelerator) is the best possible verification of our design. 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 2-4%.

Cavity Design

The resonator of IFMIF EVEDA RFQ [20] is a four-vane structure with variable average aperture R_0 profile and ramped voltage (from 79 to 132 kV). The necessary tuning of the cut off frequency is achieved increasing the magnetic field region along the structure; in this way the shunt impedance is higher where the voltage is larger.

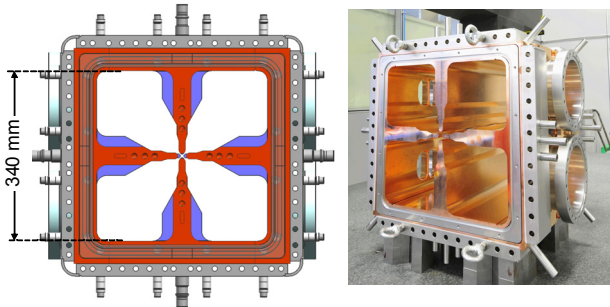


Figure 5: Left; cross section of IFMIF-EVEDA RFQ; the 28 cooling channels and the shape variation can be seen. Right: technological prototype of the same RFQ.

The choice of the “square” cross section has mechanical advantages like well accessible planar surfaces to machine, it allows good accessibility for the apertures (tuners, couplers, vacuum ports..) and has a favourable area over perimeter ratio for each quadrant (beneficial for shunt impedance).

The geometrical tolerances for a long RFQ are severe due to the mode contamination from TE_{21n} (spurious quadrupoles) and TE_{11n} (dipole) modes. Dipole modes could be moved to higher frequency increasing the magnetic coupling (PILs [21] or a four-rod or ladder kind structure) with a severe increasing of complexity and peak power dissipation. It was therefore decided to keep the pure four vanes structure with the possibility to maximize the 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 [22]

Concerning TE_{211} mode, the contamination (both for pure four vanes or four rods) scales as $\left(\frac{\ell}{\lambda}\right)^2$, RFQ length

expressed in λ units. The possible improvement on field configuration and beam dynamics with the adoption of resonant coupled segments[23] was not evident for IFMIF parameters.

It has been therefore decided to keep the pure for vanes configuration and to built a full scale model of the RFQ (see Fig. 6) to gain practical experience with the tuning procedure (based on 3D simulation and waveguide circuits models developed for TRASCO RFQ) and bead pulling on such long structure with and without resonant coupling cell. The results obtained [24] show that it is possible to tune such long structure without segmentation. Moreover with a proper design of the end region it was possible few iterations to obtain a symmetric dipole free

region around the operating frequency without stabilizing rods, the possibility of implementing the dipole stabilizers is kept in the mechanical design.

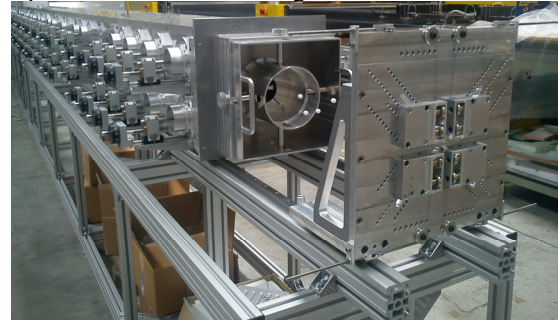


Figure 6: Full scale low power model of IFMIF RFQ.

RF System and Couplers

The approach chosen for the RF system is to use eight 220 kW RF chains; such chains, based on tube amplifiers, are equal to those used for the superconducting linac cavities, so that this modular system has the advantage of standardization, availability and reliability. Each RF chain feeds an independent power coupler based on a water cooled coupling loop, developed by JAEA.

Mechanics and Layout

The mechanical design is based on vacuum brazing; the approach chosen can cope with the specific IFMIF RFQ geometry [25]. 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 (so that for an assumed transversal shape the longitudinal one is fixed). Starting from these constraints, the choice of the basic construction units of the RFQ was to use copper blocks of length 550 mm. Such blocks will undergo two brazing cycles: in the first, the four electrodes of each block will be joined in a horizontal oven, then, in the second, Stainless Steel details like head flanges, lateral flanges and cooling tube connectors are brazed. The accelerator is composed by 18 of these modules.

The subdivision in many tanks has various advantages: each tank can be machined with very precise (and diffused) milling machines; vacuum ovens of these dimensions are also more diffused. The cavity wall interruption has almost no consequence on power consumption, while the vane interruption with a gap of about 100 μm can be made without increasing the local surface field.

To minimize the use of Ultra-pure CUC2 and to limit the induced stresses on the raw material, and the deformation during thermal cycles, a rough-cut of the shape of the sub-module components from a starting block of about 500x280x570 mm is performed, by using a EDM (wire electroerosion).

A complete prototype (full scale transversally, 30% shorter) has been machined in INFN and brazed at CERN, proving the production method (Fig. 5 left).

The RFQ is subdivided in three “super-modules”, with independent support (Fig. 7). The cooling system follows this architecture, with two cooling circuits (vanes and tank skin) for each third of the structure. The resonant frequency is controlled acting on the difference between vane and tank temperature. The thermal deformation of the cavity has been extensively simulated with 3D FEM to take into account the actual channel distribution, the stiffening determined by the head flange of each module, the lateral flanges for tuning, pumping and power coupling [26]. The most severe hot spots are foreseen in the vane undercut at high energy[27].

The vacuum system layout is based on cryogenic pumps mounted on pumping manifolds able to use two vacuum ports each. The nominal pressure with full power beam is lower than $5 \cdot 10^{-7}$ mbar.

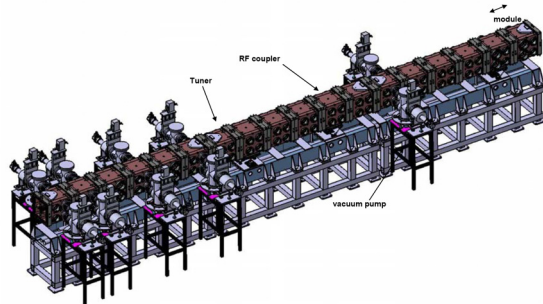


Figure 7: Schematic lay-out of IFMIF RFQ (9.8 m long).

CONCLUSIONS

The field of cw RFQs is very lively, and with the approval of IFMIF accelerator prototype construction the realization of an extremely ambitious high power RFQ has been launched; design and prototyping of this accelerator have now been concluded and the production of modules has started. The experience of RFQ construction is diffused between different laboratories and the recent achievements for cw RFQs are a solid basis for the success of this project.

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