HIGH POWER RFQS

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Abstract

This paper main focus is on recent developments in RFQs for high power proton and deuteron beams, for both scientific and diverse purposes (e.g. Radioactive Nuclear Beam facilities, long-term irradiation tests of materials for Thermonuclear Fusion Reactors). The experience of the group at LNL in the field of cw RFQs originates from the realization of the PIAVE RFQ (superconducting, 585 keV/u) and the construction of the TRASCO RFQ (5 MeV, 30 mA protons). More recently, within the collaboration between Europe and Japan for the construction of IFMIF-EVEDA in Rokkasho, the group at LNL is in charge of the design and construction of the RFQ (130 mA deuteron, 5 MeV). The physics design and the first construction test results are presented. In the same talk, the design approaches and experimental results of cw RFQs under development (for lower beam power) by other groups in Europe are reviewed.

INTRODUCTION

The term high power RFQs (HP-RFQ) indicates linear accelerators of Radio Frequency Quadrupole kind able to accelerate (light) ions for a beam power above 100 kW (about 670 kW reached up to now).

The main application of these devices is related to their use as injectors of multi MW superconducting linacs able to accelerate cw proton (or H-) beams above 1GeV. 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 HP-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}) 14 MeV neutron source facility, in order to test materials to be employed in the future fusion reactors. The final facility will be based on two high power CW accelerator drivers, each one delivering a 125 mA deuteron beam at 40 MeV (5 MW power) hitting a liquid lithium target 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. For the second application instead the IFMIF-EVEDA [3] project has recently been funded, with the task to produce the detailed design of the entire IFMIF facility, as well as to build and test a number of prototypes, including a high-intensity CW deuteron accelerator. INFN, mainly through the LNL labs and Padua section, will design, build and test with beam the high intensity deuteron RFQ [4]. The RFQ will be installed 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 (ECR kind), one superconducting linac cryomodule, the RF system, the beam transport lines and the beam dump, are provided by the other two European partners, CEA (France) and CIEMAT (Spain).

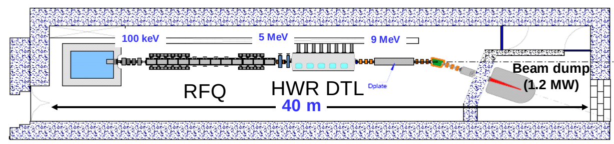

Figure 1: Schematic lay-out of the IFMIF-EVEDA prototype linac (125mA, 9 MeV).

Other applications of cw RFQs, at much lower beam power on target, are related with the development of the injector for new superconducting cw linacs (energy about 40 MeV). 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 at GANIL in France [6]. The two projects are respectively in commissioning phase (up to the first cryomodule) and in construction. For this application the optimization of the beam time structure is dictated by the superconducting linac characteristics (many two-gap independent cavities driven by solid state amplifiers) so that one has a cw beam with rather low peak current.

Finally, the stand alone application of HP-RFQs for relatively small neutron sources should be mentioned. This is the case of the proposed application of TRASCO RFQ (5 MeV 30 mA) at LNL [7], as neutron source for Boron Neutron Capture Therapy, making use of a 150 kW beryllium target, or the case of the project FRANZ (2.5 MeV p onto Li target) at Frankfurt University [8].

STATE OF THE ART

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.

In the following 20 years the RFQs have mainly been used as the first RF accelerating structure of pulsed accelerators, and have proven to be a compact and reliable alternative to High Voltage electrostatic accelerators. This experience, and the development of theory, computer 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. The main parameters of these accelerators are in Table 1 [10-21].

An important high current RFQ, for 200 mA peak current, was developed at CERN by Mario Weiss and co-workers [10]. This structure substituted the 750 kV Cockcroft and Walton as injector of Linac2 DTL in 1992. The beam transmission of this accelerator was above 90%. The main Accelerator Physics challenges solved with this accelerator were first the space charge modeling (especially in the bunching region) for a 200 mA beam and secondly the evaluation of the real acceleration field (the coefficient A) and of the non linear field coefficients for the actual geometry of the vane machined with a fixed radius milling tool. The vane tip modulation in this case does not follow the perfect two terms potential shape (hyperbolic section with variable tip radius) but has constant radius cross section.

The second pulsed RFQ in operation at CERN is the lead ion RFQ built by INFN for Linac3 [12]. In this case, due to the low space charge, the modulation can increase quite rapidly and the correction of the factor A due to non linearities (calculated with PARI [22]) is for some critical cells above 30%. This RFQ is in operation since 1994 and is a good example of nominal transmission (above 90%) reached in routine operation.

The RFQ of LEDA is the most important high power RFQ, with the record of accelerated beam power, total dissipated power, dissipated power density and length in lambda units [2] [23] [24] (indicator of the RF field stability). Most of these figures were more challenging than those to be reached by IFMIF RFQ. Many specific features of HP-RFQ were developed within this project, like the 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. 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. The design is quite different (also respect to LEDA); IPHI [14] 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 [7] [15] 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).

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		Emax	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	30
pulsed	CERN linac 2 (CERN)	p	0.75	178	200	150	440	202	1.8	1.2	2.5	-	-
	SNS (LBNL)	H-	2.5	83	70	175	664	402.5	3.7	5.0	1.85	11.4	10
	CERN linac 3 (LNL)	8.3	0.25	70	0.08	0.04	300	101	2.5	0.8	1.9	-	-
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	54
	→ 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	-	-

Both RFQs are being brazed at CERN, with the same work sequence and few differences due to the details of the mechanical design and realization. TRASCO is now more advanced, with two modules ready and tuned, while 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 and the vertical brazing for the connection of the vacuum flanges are scheduled to be concluded within this summer.

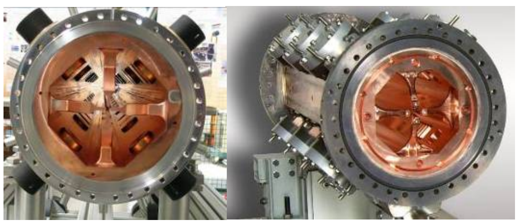

Figure 2: The first two modules of TRASCO and the first module of IPHI RFQ.

Concerning the installation, 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 has been recently designed as part of SPES project and should be funded as a neutron source mainly for BNCT application.

The two RFQs of SPIRAL2 and SARAF projects are both designed to accelerate deuterons, with low beam losses.

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

SPIRAL2 RFQ [19] 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 [25]. The order for the entire structure has been placed, and beam tests in the final tunnel are foreseen in 2011.

The SARAF RFQ [18] 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.

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 [20] is a quite long (8 m like LEDA) low frequency structure, PIAVE at LNL [21] is based on a single cryomodule (about 2.5 m long) with two super-conducting RFQs. Both RFQs have external beam bunching.

The use of a superconducting RFQ at 80 MHz can in principle be considered for a deuteron beam current up to about 5 mA. An SRFQ within a larger superconducting linac, beside reducing the power consumption, allows to decrease substantially the beam losses (due to the large transverse acceptance). The application of SRFQ for HP RFQs is at the moment very difficult to conceive, since one should anyway guarantee losses below 20 W (10^{-5} scale) [21].

CHALLENGES FOR IFMIF-EVEDA

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. The new beam dynamics design 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.

Beam Dynamics

The beam dynamics design [26] should minimize the activation caused by beam losses in the RFQ, and 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:

$$n \propto Nw^2 ,$$

with *N* and *w* number and energy of the lost deuterons.

This means that, beside the high transmission, one has to concentrate the beam losses at low energy.

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 -60^0 to -32^0) is optimized cell by cell, keeping the maximum surface field and increasing the acceptance up to a large value (4.2 mm mrad norm.).

The intervane voltage 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 kilp. along the structure. As a result beam losses and the estimated neutron production along the RFQ follow the curves in Fig. 4; the importance of the acceptance maximization in the second part of the RFQ is really evident.

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 1-2%.

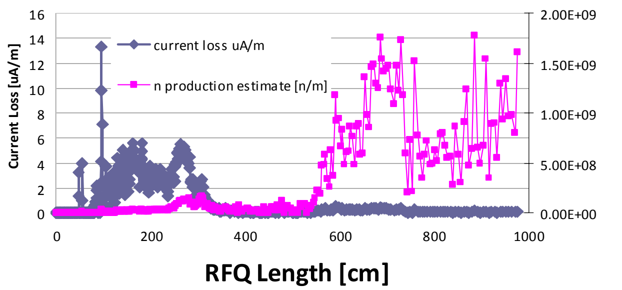

Figure 4: Simulated beam losses along IFMIF RFQ for a 130 mA water-bag distribution, 0.25 mm mrad r.m.s normalized, simulated by PARMTEQM; the integral losses amount to 1.4 mA, corresponding to 550 W beam power and estimated neutron production of 3.8×10^9 n/s.

Cavity Design

The resonator of IFMIF EVEDA RFQ [27] 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.

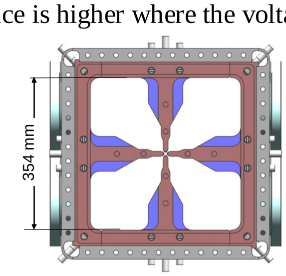

Figure 5: Cross section of IFMIF–EVEDA RFQ. The 20 cooling channels and the shape variation can be seen.

The choice of the "square" cross section has mechanical advantages like well accessible planar surfaces to machine, it allows also accessibility for the apertures (tuners, couplers, vacuum ports..) and it 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, whose frequencies can be very close to the operating mode.
The TE_{110} frequency in a pure four vanes is lower than the operating frequency TE_{210}; this can be corrected increasing the magnetic coupling between quadrants (PILs [28] or a four-rod or ladder kind structure) at price of increasing the peak magnetic field and power dissipation, These approaches are therefore quite unsuited 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 [29].

Concerning TE_{211} mode, the contamination can be estimated (for pure four vanes or for rods) as:

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

with ℓ length of the RFQ, $\delta\omega_0$ and δR_0 are the error amplitudes for the cut off frequency and the vane tip location (for the worst perturbation shape); 1% contamination corresponds to a tolerance as small 7 kHz or 0.6 µm.

The situation can be improved dividing the RFQ in N resonantly coupled segments [30]: for N=2, for example, contamination reduces, but less than a factor two, without advantage of the dipole contamination and evident improvement on beam dynamics. Therefore it has been decided to build 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) with and without resonant coupling cell.

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 identical 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, in development by JAEA.

Mechanics and Layout

The mechanical design is based on vacuum brazing; the approach chosen can cope with the specific IFMIF RFQ geometry [31]. 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, two of such blocks will be brazed 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. The accelerator is composed by 9 of these modules.

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 cooling system is designed in order to minimize the frequency change induced to the cavity due to the RF power. To keep this condition along the module the water channels in the cavity are dimensioned to have similar temperate increase along the structure. Moreover, the lines cooling the vanes and the cavity skin are separated in order to have the possibility of controlling the frequency via the two water temperatures.

A preliminary vacuum system layout has been designed, 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 10^{-7} mbar.

CONCLUSIONS

The field of high power RFQs is very lively, and with the recent approval of IFMIF EVEDA the design and construction of an extremely ambitious high power RFQ 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.

ACKNOWLEDGMENTS

The author wishes to thank R. Ferdinand, B. Pottin, A. Bechtold, R. Jameson and Alessandra Lombardi for their very informative discussions. The IFMIF RFQ team has actively participated to the discussion of this paper, and in particular M. Comunian, A. Palmieri and P. A. Posocco have given an important contribution.

REFERENCES

[1] IFMIF-CDA Team (Ed.) M. Martone, “IFMIF Conceptual Design Activity Final Report”, ENEA Frascati Report, RT/ERG/FUS/96/17 (1996).
[2] L. Young et al., “High power operations of LEDA RFQ”, LINAC 2000 Conference, Monterey (USA).
[3] A. Mosnier, this Conference.
[4] A. Pisent et al., “IFMIF-EVEDA RFQ design”, EPAC 2008, Genoa (Italy).
[5] A. Nagler et al., “The SARAF CW 40 MeV Proton /Deuteron Accelerator”, LINAC 2008, Victoria (Canada).
[6] M. H. Moscatello, “Spiral2 at GANIL”, LINAC 2004, Lübeck, (Germany).
[7] A. Pisent “Advances of LNL BNCT project”, EPS 19th Nuclear Physics Divisional Conference New Trends in Nuclear Physics Applications and Technology, Pavia (Italy) (2005).
[8] C. Zhang, “Development of a High Current Proton Linac for FRANZ”, EPAC 2006, Edinburgh (UK).
[9] W. D. Cornelius, “CW Operation of the FMIT RFQ”, PAC 1985, Vancouver (Canada).
[10] M. Weiss, “The RFQ2 Complex: the Future Injector to CERN Linac 2”, EPAC 1992, Berlin (Germany).
[11] A. Ratti et al., “Conceptual Design of the SNS RFQ”, LINAC 1998, Chicago (USA).
[12] G. Amendola et al., “Beam Dynamics Studies for the CERN Lead-Ion RFQ”, EPAC 1992, Berlin (Germany).
[13] L. Young,“Simulations of the LEDA RFQ 6.7 MeV Accelerator”, PAC 1997, Vancouver (Canada).
[14] P. Y. Beauvais, “Recent Evolutions in the Design of the French High Intensity Proton Injector (IPHI)“, EPAC 2004, Lucerne (Switzerland).
[15] A. Pisent et al., “The TRASCO-SPES RFQ”, LINAC 2004, Lübeck (Germany).
[16] E. Fagotti et al., ”Fabrication and testing of TRASCO RFQ”, LINAC 2008, Victoria(Canada).
[17] S. J. Mathot, “RFQ Vacuum Brazing at CERN”, EPAC 2008, Genoa (Italy).
[18] P. Fischer, A. Schempp, “A CW RFQ Accelerator for Deuterons”, PAC 2005, Knoxville (USA).
[19] R. Ferdinand et al., “SPIRAL 2 RFQ design”, EPAC 2004, Lucerne (Switzerland).
[20] R. L. Poirier et al., “CW Performance of the TRIUMF 8 meter long RFQ for exotic ions, LINAC 2000, Monterey (USA).
[21] A. Pisent et al., “Results on the Beam Commissioning of the Superconducting-RFQ of the New LNL Injector“, LINAC 2006, Knoxville (USA).
[22] K. R. Crandall et.al., “PARMTEQ-A beam dynamics code for the RFQ linear accelerator, LA-UR-88-1546.
[23] L. Young et al., “Tuning the 6.7 MeV LEDA RFQ Accelerator”, PAC 1997, Vancouver (Canada).
[24] L. Young et al., “High power conditioning of the LEDA RFQ”, PAC 1999, New York (USA).
[25] R. Ferdinand et al., “SPIRAL2 RFQ prototype first results”, EPAC 2006 Edinburgh (UK).
[26] M. Comunian et al., “Beam dynamics design of IFMIF-EVEDA RFQ”, EPAC 2008 Genoa (Italy).
[27] F. Grespan et al., “RF design of IFMIF-EVEDA RFQ”, LINAC 2008, Victoria(Canada).
[28] A. Ueno, Y. Yamazaki, NIM-A, Volume 300, Issue 1, 1 January 1991, pp. 15-24
[29] F. Grespan, A. Pisent, A. Palmieri, NIM-A, Volume 582, Issue 2, pp. 303-317.
[30] L.M. Young, Segmented Resonantly Coupled Radio Frequency Quadrupole (RFQ), PAC 1993, Washington D.C. (USA).
[31] A. Pepato et al., this conference.