NEW DEVELOPMENT IN HIGH DUTY CYCLE, HIGH CURRENT RFQ'S*

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Abstract

RFQs are the standard solution for new ion injectors. Injectors for light and heavy ions, low and high currents, low and high duty factors, fixed or variable energy require very different solutions for beam dynamics, rf- and mechanical design of the RFQ.

An survey on work on high duty factor high current RFQs will be given to illustrated the various solutions and the special problems in that field, which covers e.g. RFQs as spallation source injectors, neutron generators and implanters as well as industrial applications.

1 INTRODUCTION

Accelerators have been developed as tools for nuclear and particle physics. The vast amount of applied research did grow from these technologies. The "production" of secondary particles as purpose of a facility was another big step in accelerator technology, because there production rates can be increased by optimizing the beam energy and target arrangement and naturally by increasing the beam current to the target

In case of heavy ion beams the duty factor of the machines had to be large because of the limits of sources for (multiple charged) heavy ions. For protons and deuterons the beam currents from ion sources could be pushed up to the 100 mA region, so the duty factors of the accelerators could be modest.

Examples are the spallation sources LAMPF, ISIS with beam powers of up to 200kW and the synchrotron injectors specially modified or operated as drivers for neutron production or sources of radioactive beams with beams of some kW.

To reach MWs of beam power the duty factor has again to be increased up to cw operation. This requires new technologies and different optimisation but also another magnitude of technical and financial effort.

There are three kinds of projects, which can be distinguished by their beam requirements:

1.: Spallation sources with H^- beams and "modest" duty factors between 2% and 10%, beam powers up to 5 MW.

2.: ADS systems which need cw beams of up to 100MW.

3.: Material test accelerators, which deliver low energy beams p.e. 35-40 MeV of D^+ for IFMIF, 2-4 MeV D^+ for neutron sources.

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2 RFQ DESIGN

RFQ design is sometimes treated as being completed when the beam dynamics design is finished. Especially for high power beams it is crucial to have a balanced design which takes into account the special rf-problems as well as the engineering to ensure tolerances, to handle the rf-losses, the beam with losses, the diagnostics and also maintenance possibilities and control.

Beam dynamics is defined by the choice of frequency f, electrode voltage U, beam current, input and output energy and emittances ε and the cell parameters along the RFQ: cell length Li, aperture a_i, modulation m_i. The result is an RFQ with certain total length L and power consumption N which adiabatically bunches and focuses the dc beam from the ion source with small emittance growth $\Delta\varepsilon/\varepsilon$.

While for smaller neutron sources RFQ aspects can dominate the choice e.g. of the frequency and length and rf-power consumption to simplify alignment and tuning,

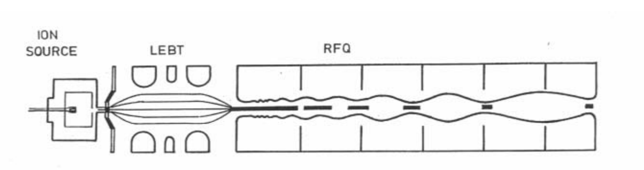


Fig. 1 Scheme of a RFQ injector

Table 1: RFQ parameter scaling

Parameter		
input energy	T_{in}	~ f
output energy	T_{out}	~ f, U
acceptance	a	~1/f, U
beam current	I	~U, 1/f
frequency	f	
electrode voltage	U	I, N^2
focusing strength	B	~ U/a^2
charge per bunch	q_b	~1/f
emittance growth	Δε	~ 1/L
output energy spread	ΔT	~1/L, 1/U
beam losses		~1/L
mechanical tolerances	Δa/a	~1/f
rf-power	N	~U^2
power density	P	~ f
tuning sensitivity	ΔUi/U	~ $(L/f)^2$
Kilpatrick	U_K	~1/f
costs	$,Eu,Y,,	~P_{beam}^2 ~$1/\varepsilon^2$

for bigger project like a spallation source, the optimization of the total linac, the availability of power sources and naturally costs will set some design input parameters and e.g. will increase the frequency to lower the charge per bunch, to avoid funneling and ease emittance growth and matching problems.

A major concern are beam losses in the RFQ but also losses along the following linac which can be influenced by proper shaping and preparing the beam in the RFQ. So even 99+x% theoretical transmission seem to be academic thinking, the work being done there is essential for understanding and avoiding losses and halo formation in the RFQ and in the following linacs.

The choice if a rather high frequency shifts the mechanical and rf-parameters to a region where tolerance and tuning problems and power density question require even new solutions and prototype developments.

The 4-vane RFQ structure employed in most cases can be treated as four weakly azimutally coupled resonators in longitudinal 0-mode a system which is very sensitive against unbalance of the four quadrants. in addition the longitudinal field tilt sensitivity is proportional to $(L/\lambda)^2$. Mechanical tolerances, coupler loops, tuners, vacuum ports, changes of electrode modulation all contribute to field tilts.

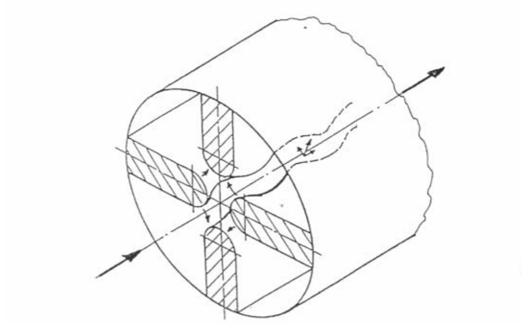


Figure 2: Scheme of a 4-Vane RFQ structure

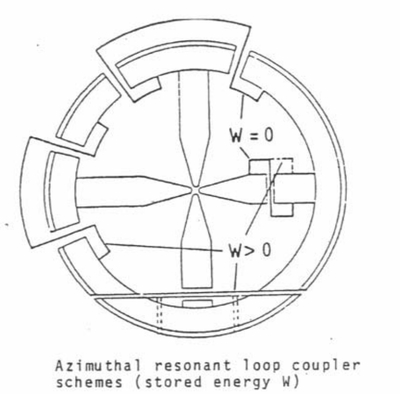
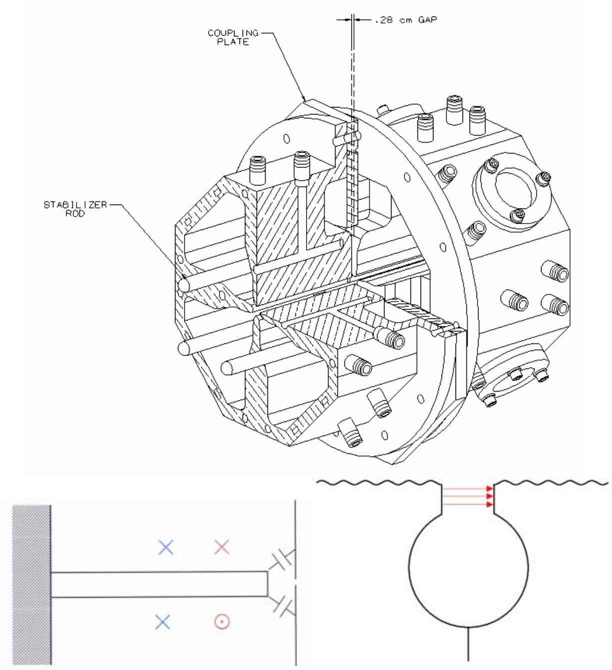


Figure 3: Stabilizing a 4-Vane resonator

Since the early development of the RFQ structure a number of resonant and nonresonant stabilizing schemes have been proposed and tested (Linac84/86). Examples for nonresonant stabilizers are VCR rings and their magnetic equivalent the PISLs. Resonant devices are resonant rings and posts connecting the quadrants. Typically there is no field in these stabilizers and no additional losses, if the structure is balanced.

The RFQ should be short to reduce possible field tilts. One can break the RFQs into several individually driven structures, which creates complexity and matching problems. A unique system has been developed at LANL, where like in a CCL the structure is subdivided into e.g. four parts but the connection is via resonant cells. The electrode structure is nearly unchanged but now the tilt sensitivity is reduced and depending linear on the cavity length L/λ only. Azimutal posts (like post couplers in the Alvarez) have been incorporated into these cells as indicated in fig. 4, so that the RFQ is still difficult to tune but very stable.



a.) b.)

Figure 4: Scheme of a RFQ coupling cell with azimutal (a) and longitudinal (b) resonant stabilisation

Another good solution for operational stability is the compensation of thermal drift by different cooling water temperature in electrodes and tank which eases problems during conditioning and avoids large numbers of moving tuners. These solutions have been adopted by a number of other projects and allow 4Vane-RFQs with a length of up to 8 meters at frequencies of 350 MHz, which is a ratio of $L/\lambda > \tilde{9}$.

These 4-Vane structures are used for high beam current applications especially if the frequency has to be in the range above 300 MHz. If the boundary conditions allow for lower frequencies one can also use another RFQ structure, the 4-rod RFQ, which is widely used at lower frequencies up to 200 MHz, especially for heavy ion applications

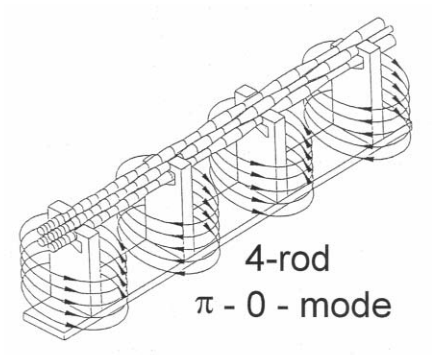


Figure 5: Scheme of a 4-Rod-RFQ resonator insert

It can be described as a chain of interlaced λ/2-resonators in π0-mode. The electrodes can have the typical rod shape, for cooling a cooling tube can be added radially converting it into a small vane like electrodes. with unchanged rf-properties. The radial dimensions of the 4-rod RFQ are appr. half as for a 4-Vane structure at the same frequency. Beam dynamics and experimental results for emittances and transmission are the same as for 4-Vane RFQs.

While the power consumption is also roughly the same, there are some advantages because the 4-rod structure cannot show dipoles and longitudinal coupling is stronger. So a single rf-coupler and 1-2 tuners are necessary.

The rf-fields are confined in the resonant insert. A change of tank dimensions results in very little change of the frequency, so ports in the tank and e.g. the top lid along the tank do not change fields and coupling in the structure. So long RFQs can be aligned, tuned and inspected through such a top lid and tank contacts are not critical because less than 10% of the rf-power is dissipated in the tank , most of it close to the insert.

The rf-power density is appr. 2-4 times higher than for 4-Vane structures which might be a problem for cw operation especially if one would try to go for the 350 MHz region. The simple way of direct cooling of the stems and rods compensates for that and operation with a temperature rising by $\Delta T=50^o$ have shown little change of beam properties

Numerous 4-Rod RFQs with low duty factors have been built but also a number of structures with duty factors up to 25% –100% are in routine operation with heavy ions.

3 ADS RFQS

High energy proton beams can be used to produce neutron via the spallation process. The energy should be around 1 GeV, the beam power between 100kW and 100MW depending on the application.

For ADS application the beam power should be as high as possible to get reasonable throughput of material resp. production rates. CW operation and RFQ injectors accelerating 100mA protons from 100 keV to 5-8 MeV are typical values.

The LEDA project at LANL was the first of a generation of high (average) power RFQs. This prototype RFQ was based on the work on GTA, CWDD and the Crits RFQ at CRNL, where also the new generation of ECR high current proton source was developed.

The successful operation of LEDA, the characterisation of the 100 mA cw beam and all the rf-and mechanical engineering can well compete with the beam dynamics developments, which also gave new insights on losses and stability.

Table 2: Parameters of the LEDA-RFQ

Operating Frequency	350 MHz
Proton Input Beam	75keV, 105mA, 0.2 mm* mrad, rms, normalized
Proton Output Beam	6.7 MeV, 100mA, 0.22 rms,n
Duty Factor	100% (cw)
Peak Surface Field	1.8 Kilpatrick, 330kV/cm
Structure Power Loss	1.2 MW, 85 l/s
Total RF power	1.9 MW, fed by 12 WG irises
Surface Heat Flux	11 W/cm^2, 65 W/cm^2 peak
Configuration (OFE copper)	4 resonant segments, 8 brazed sections, each 1m long
Structure Tuning	static: 128 tuners, dynamic: water temperature

Figure 6: View of the LEDA RFQ structure

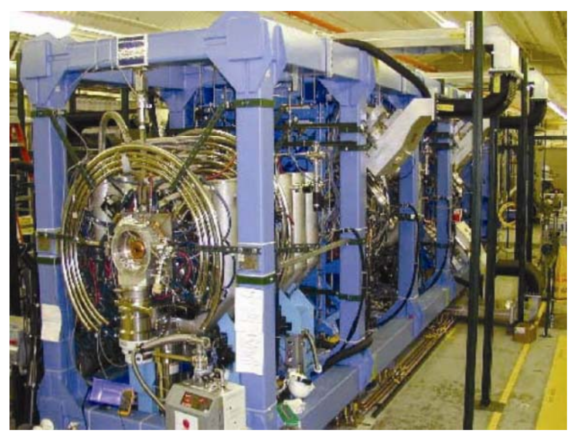


Figure 7: View of the LEDA RFQ after installation

The IPHI-project at CEA was also aimed at a demonstration of the possibility to generate and accelerate high current proton beams for various applications. The project has generated a large number of remarkable developments in beam dynamics and structure development. Based on the experience at LANL a RFQ has been designed and prototyped which will outbeat its predecessor. A number of problems were studied in time consuming modeling and simulations, so improved solutions for optimized RFQ have been found, like for transmission and emittance growth.

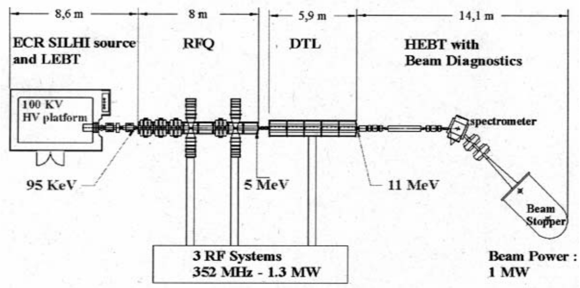


Figure8: Layout of the IPHI project

The IPHI study has a big impact on the other studies in Europe: the ESS spallation source, the energy breeder project and the IFMIF fusion material study where the CEA group has proposed a CONCERT project which incorporates the various efforts for a combined project.

Compared to these projects the TRASCO study at INFN in Legnaro aims at a "modest" average current of 30mA for a prototype for waste transmutation. The linac consists of a 80kV ECR source, a 5MeV RFQ, an independently phased low energy linac and a multi cell HE-linac, both superconducting. The RFQ is also derived from the LEDA, but aims at a less complex solution.

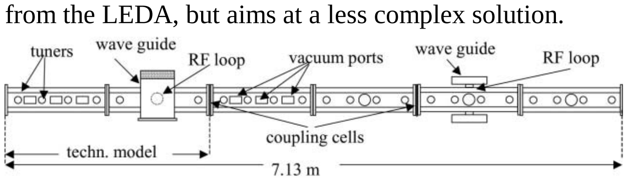


Figure 9: The TRASCO-RFQ layout

The KOMAC project at KAERI in Korea is also looking for waste transmutation and energy breeding application of a GEV high current proton linac. Design studies and prototyping have led e.g. to the successful acceleration of a 30mA beam in an first RFQ prototype.

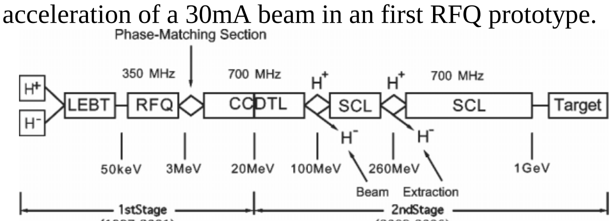


Figure 10: The Komac linac layout

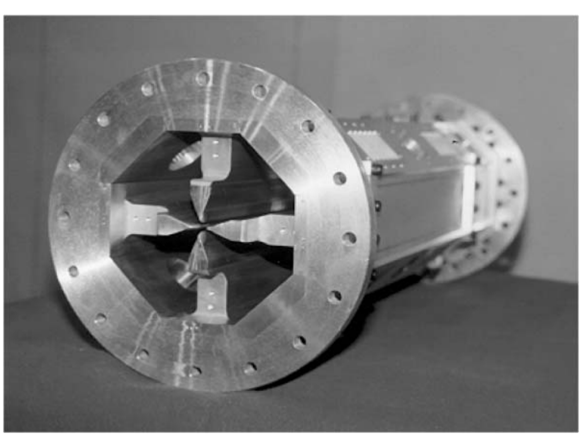


Figure 11: The KOMAC RFQ resonator

The RFQ-group in Bejing and at CAT in Indore have also started work on an ADS type RFQs for high current linacs. also as projects on ADS to help solving the predictable future energy problem in these countries. At first both project plan for a low energy demonstrator linac, to study this high current technology.

4 SPALLATION SOURCE RFQS

Designs for spallation sources aim at beam powers of "only" 1-10MW. This and the special pulse shape on the target require H$^-$ acceleration and a storage ring for pulse lengths compression. The 10 MW beam comes in 1□sec pulses with 50 Hz as a typical value.

The RFQ injector for such a system is plane d for 50mA at output energies of 2-5 MeV

While projects like ESS, EHF, JHF and others have been discussed and modified for years and years the SNS project went ahead and the collaboration of six US Labs resulted in the building of SNS in Oak Ridge. LBNL was building the injector, which has been successfully operated with full specifications. The 4-Vane RFQ (2.5 MeV, 402 MHz) is stabilized with PISLs, longitudinal stabilization is not used. Fig shows the module of the brazed Cu-Glidcop structure module.


Figure 12: View of the first SNS-RFQ module

In Japan a common project of KEK and JAERI is going ahead with the building of a new multipurpose facility JKJ, which finally will reach 50 GeV protons.

One planned operation mode corresponds to a spallation source. Specifications and technology of the RFQ injector is similar to the one from LBNL, tests of short parts have been successful

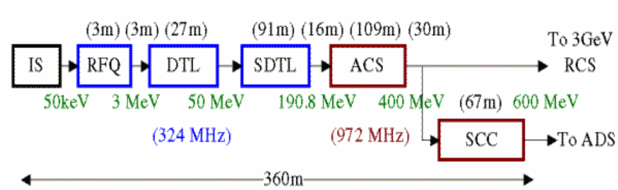


Figure 13: Block diagram of the JKJ high current linac

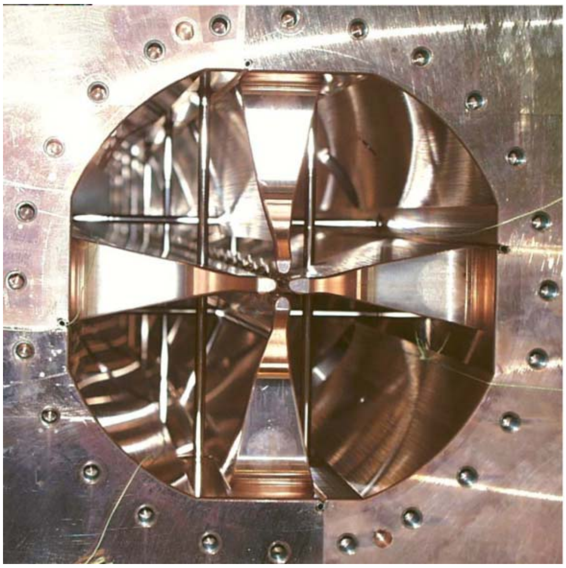


Figure 14: View of the JKJ-RFQ prototype

For the spallation source ISIS at RAL a new RFQ injector has been built to replace the CW-Injector. There the choice of final energy and frequency was determined by the "ancient" linac to 665keV and 202.5 MHz, which is favorable for using an short 4-Rod type RFQ-structure. The duty factor can be as high as 10%, a beam of up to 35mA has been accelerated and characterized in the first experiments. Until SNS will become operational, ISIS will still be the most powerful n-source with its 200kW beams.

Another application which aims at even higher currents is done for low energy material testing n-sources.. Fig. 17 shows the 4 MeV RFQ (L=4m), designed for 50mA, 20% duty factor operation, showing a typical 4rod RFQ design with a top lid along the tank for easy access, for alignment, tuning and inspection of the structure

The average beam current which is appr. 1μA in a typical HE-machine can be as high as 1-2mA for a spallation source injector and up to 100mA in ADS applications. This illustrates the steps in development and the advances in beam physics, structure development and technology.

5 ACKNOWLEDGEMENTS

I want to thank D.Schrage, A.Pisent, J.Staples for supplying information and A.Bechtold and H. Zimmer-mann as well as K.Kühnel and C.Welsch for help.

6 REFERENCES

Numerous papers on the different projects have been presented at this conference and at the recent EPAC 02 in Paris and the PAC 01 in Chicago. Therefore I will restrict to the two basic papers which ignited the RFQ development:

[1] I.M. Kapchinskij, V. Tepliakov, Prib. Tekh. Eksp. 119, No.219 (1970)

[2] K. Crandall, R.H. Stokes, T.P. Wangler, LINAC79, BNL51134 (1979) 205

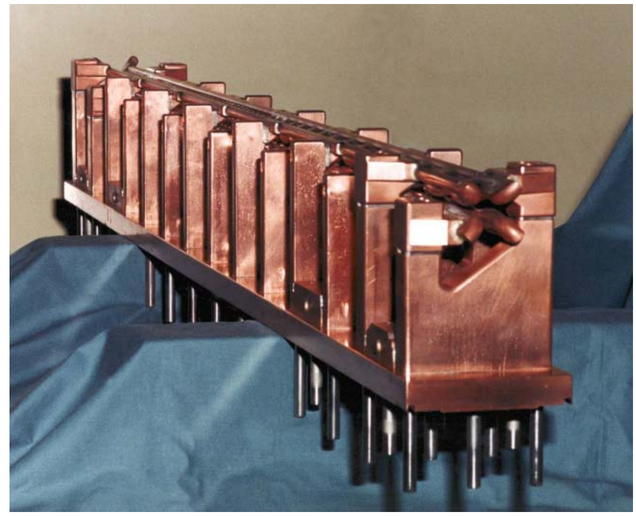


Figure 15: The 4-Rod RFQ insert for ISIS

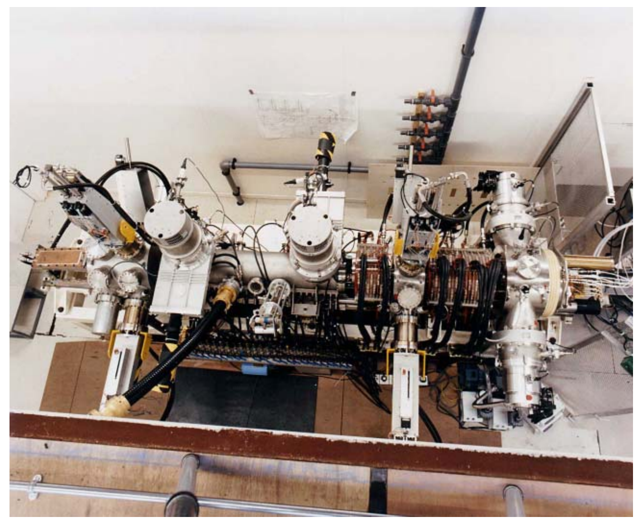


Figure 16: Ion source - RFQ test bench at RAL


Figure 17: View of the 4 MeV 4 Rod-RFQ