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COMPARISON OF LONGITUDINAL EMITTANCE OF VARIOUS RFQs

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Abstract

In various projects a large variety of RFQs has been developed, for different application, with different average current, frequency, and energy range. On this article a comparison, in a scaled way, will be done, using the build RFQs of IFMIF, ESS, SPES, ANTHEM, PIAVE. On particular the beam dynamics characteristics will be analysed, like transmission, output longitudinal emittance and real performance versus simulation.

INTRODUCTION

Longitudinal emittance at the RFQ output is a very important parameter that define the beam quality in the subsequent accelerator. A low value of longitudinal emittance permits higher real state energy gain, so a more compact Linac. Achieving a small longitudinal output emittance is difficult because the initial bunching of the injected dc beam, initially emittance dominated for low current beam and space charge dominated for high current beam, tends to fill the evolving bucket separatrix in both cases. On the other hand, an external multi harmonic buncher do not guarantee high particles capture efficiency, especially for a high current beam.

A standard strategy is the use of slow of quasi-adiabatic bunching process that is highly nonlinear, this process requires tens of RFQ cells. The result from this slow adiabatic bunching process would require an unrealistically long RFQ to accommodate the several longitudinal phase space rotations needed.

An example of limits on longitudinal emittance optimization is reported in Fig. 1, where it is shown for each point a full multiparticle simulation obtained by the LANL chain of programs and a swarm optimization algorithm [1,2]. In this example the TRASCO RFQ [3] has been re-designed with the IFMIF voltage shape law, to check the possible improvements. The lower left part of the figure shows the lower peak RF power and longitudinal emittance, with respect to the TRASCO RFQ with a shorter RFQ if the dot colour is near to blue. The dashed lines are the actual characteristics of TRASCO RFQ. In this example to get a factor 2 lower longitudinal emittance is necessary to increase of about 1-meter the RFQ length, with a factor 2 increase on peak RF power.

Another way to look at the trade-off on the longitudinal emittance is the shaper length. Figure 2 shows the length of the shaper for the same TRASCO RFQ cases.

To get a factor 2 less longitudinal emittance, it is necessary to increase the shaper length of a factor 3, obtaining an increment of the total RFQ length of more than 1 meter.

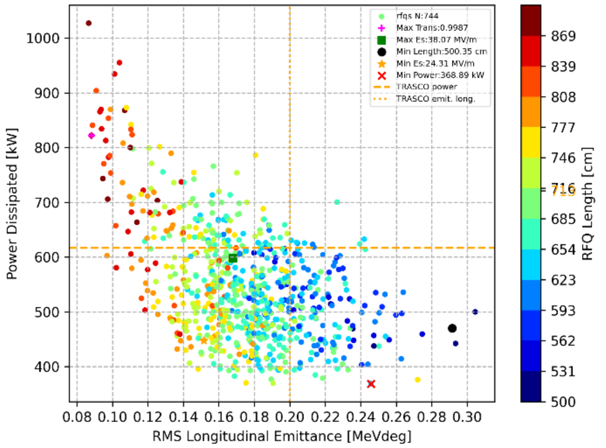

Figure 1: Longitudinal emittance as function of RF power and total RFQ Length.

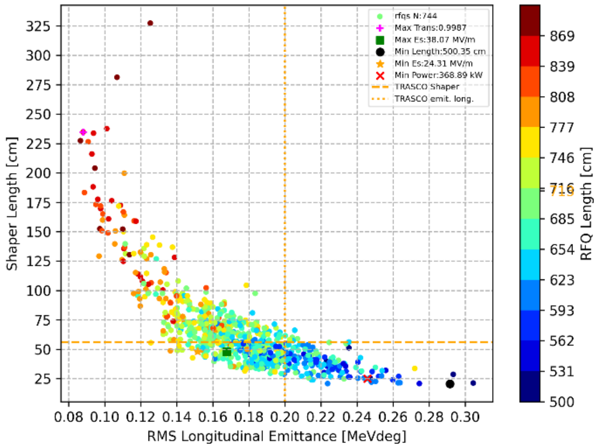

Figure 2: Longitudinal emittance as function of shaper length and total RFQ length.

RFQ SELECTIONS

In this context the analysed 4-vane type RFQs are already built; each of them is the result of several optimization processes which involve practical consideration such as realistic length, RF power, and manufacturing process. The selected RFQs for the comparison are: the TRASCO RFQ that now is used for the ANTHEM BNCT project; the IFMIF/EVEDA RFQ is high current CW RFQ now under commissioning in Rokkasho (Japan) [4]; the RFQ for the LNL RIBs beams project SPES also CW but for low current and able to handle a range of 3<A/q<7 [5]; the SPIRAL2 RFQ is CW for ions [6]. The ESS proton RFQ is a pulsed machine with 14 Hz as d.c [7].

In Table 1 is reported in summary the main parameters of the RFQs. Each RFQs has been designed with a specific

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goal in terms of performance and reliability and cost optimization.

Table 1: RFQ Main Specifications

	Freq MHz	L m	Ion	Wout MeV/u	Cur. mA
TRASCO	352.21	7.13	p	5	30
IFMIF	175.0	9.8	d	2.5	130
SPES	80.0	6.95	A/q≤7	0.727	0.1
SPIRAL2	88.05	5.077	A/q≤3	0.73	1
ESS	352.21	4.54	p	3.6	62.5

DESIGN CONSIDERATION

The RFQs have been designed to match the specification in terms of energy and current; the design method has been similar for the TRASCO/IFMIF RFQ, with the LANL code chain (CURLI-RFQUICK-PARI-PARTEQM) for high current. The SPES RFQ has been designed with a home-made personalization based on the program used for the design of CERN linac3 RFQ. The SPIRAL2 and ESS RFQs have been designed with the help of CEA RFQ Designer code [8].

There are no general rules about the design, and this produces different laws for the voltage shape, transverse, and longitudinal phase advance, focusing force and modulation. In a general way, in each RFQs it is possible to define a shaper section where the parameters like phase and modulation are changed smoothly, a Gentle Buncher where the almost adiabatic process is done to capture as mush as possible particles and the Acceleration section, where the focusing force is typically reduced and the acceleration rate increases as much as possible.

In Fig. 3 is reported the various voltage laws used in the mentioned RFQs.

In the TRASCO case, the voltage is constant along the structure, due to the classic design choice done in 2000. The voltage is linearly increasing with respect to the beam axis (SPES) and slowly increases along the RFQ (IFMIF, SPIRAL2, ESS), but in the latter cases with a different and non-linear voltage law.

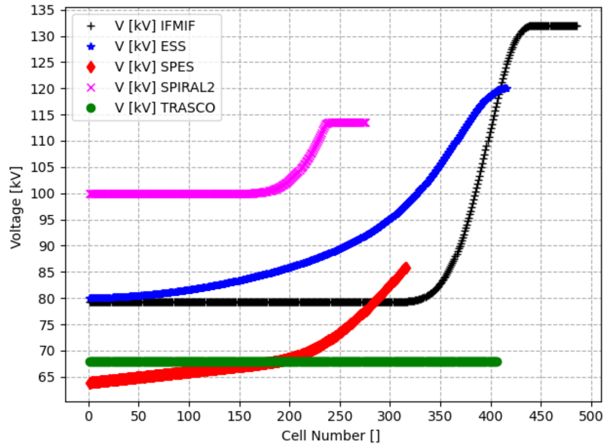

Figure 3: Voltage along the RFQs as function of cell number.

In the case of SPES RFQ, a large modulation has been used (m>3.2); this is almost at the limit of what has been typically done on RFQs. Such modulation value is used to get a value of A10, the acceleration coefficient, of about 0.81 (i.e., almost all the voltage is used for the acceleration).

In Fig. 4 is reported the modulation used on the RFQs. Before the gentle buncher the modulation is changed smoothly to get a lower longitudinal emittance and avoid losses. In the accelerator region the change of m is very fast, obtaining the maximum value of m at the RFQs end.

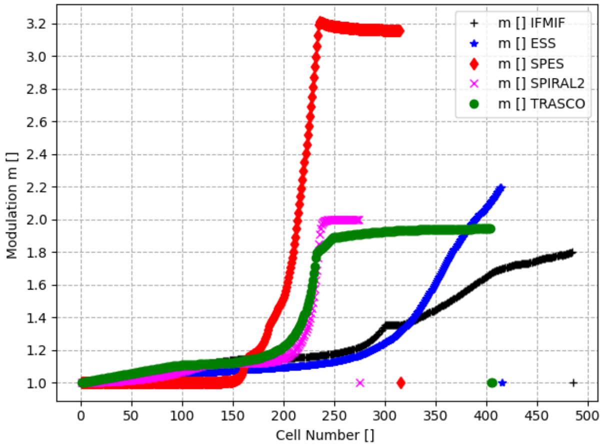

Figure 4: Modulation "m" in the RFQs as function of cell number.

The focusing force B in the RFQs is typically increased from the beginning to the end of Gentle Buncher (where a maximum is reached). After that point, B is reduced to get more voltage for acceleration on the accelerator section. The various focusing force B is reported on Fig. 5.

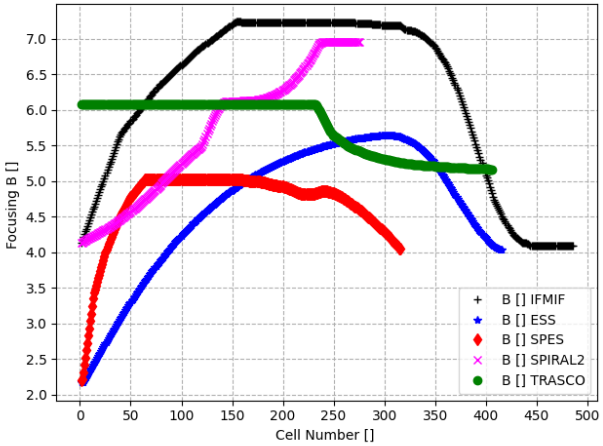

Figure 5: Focusing force B as function of cell number.

The larger value of B is on the IFMIF RFQ; this is due to the high value of design current that must consider the effect of the large space charge effects. At the RFQs start, the focusing force is typically reduced to permit an easy way to do the RFQ injection from the LEBT. For a smooth injection into the MEBT the focusing force is also reduced at the RFQ end. The variation of B along the RFQ can also be done in a fast way without compromising the beam quality.

COMPARISON METHOD

The program used for the comparison is TraceWin/Toutatis [8], for all the RFQs a multiparticles run has been done with 100k macroparticles on the nominal design input file. In this way a full control is possible on all the simulation parameters used, input conditions and program option like steps and longitudinal cutting.

A perfectly matched input beam Twiss parameters has been chosen for each RFQs, this has permitted to avoid differences linked to the source and LEBT injection line. The selected beam input distribution is a 3 sigma Gaussian with 20 steps per cell period on Toutatis, without energy spread. To consider only the accelerated particles, the longitudinal limit for the rejection has been put at +/- 0.2 MeV/u respect to the synchronous energy. The input values used in the simulation are reported on Table 2.

Table 2: Values Used on Simulations

	Tr. rms Emit. mm·rad	**A/q**	**Curr.** mA
TRASCO	0.2	1	30
IFMIF	0.25	2	130
SPES	0.1	7	0.1
SPIRAL2	0.4	3	1
ESS	0.25	1	62.5

COMPARISON

The calculated longitudinal and transverse emittances at full nominal current are reported on Fig. 6, as function of cell number. The cell number allows toto do the comparison for various frequencies. After the emittance formation process, typically in 50 cells, there is an increase of the emittance due to the not accelerated particles, that are cut off by the longitudinal energy limit. After the cut off, the longitudinal emittance is almost preserved up to the end of the RFQs. The RFQs designed for high current i.e., >20 mA shows larger emittances, with the TRASCO RFQ that has a longitudinal emittance of 0.2 MeVdeg/u. On the other side, the RFQs designed for low current and for ions, show a lower longitudinal emittance, with a minimum on the SPES RFQ of 0.045 MeVdeg/u. This is due to a long shaper region in the SPES RFQ, about 1.2 meters, and a small separatrix area.

The obtained output longitudinal emittances are also reported on Table 3: it is reported also the emittance inside the 95% of the particles and the relative rms emittance. From the ratio of total particles and rms, it is possible to calculate the longitudinal halo; TRASCO resulted to have the larger halo with respect to the RFQs here analysed.

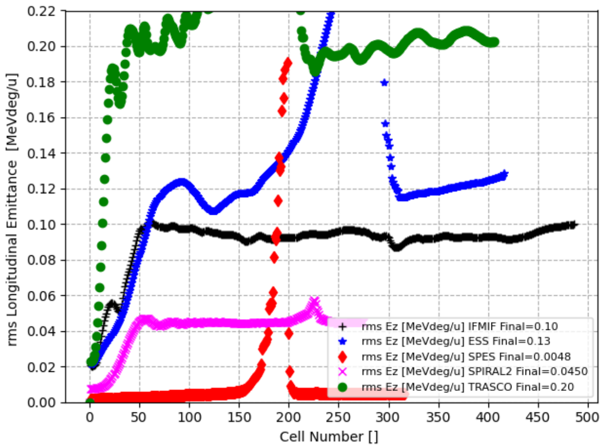

Figure 6: rms longitudinal Emittance as function of cell number.

Table 3: Output Longitudinal Emittance

	rms MeVdeg/u	**95%** MeVdeg/u	**rms (95%)** MeVdeg/u
TRASCO	0.2	1.4	0.16
IFMIF	0.1	0.6	0.08
SPES	0.0048	0.031	0.0037
SPIRAL2	0.045	0.28	0.038
ESS	0.13	0.87	0.1

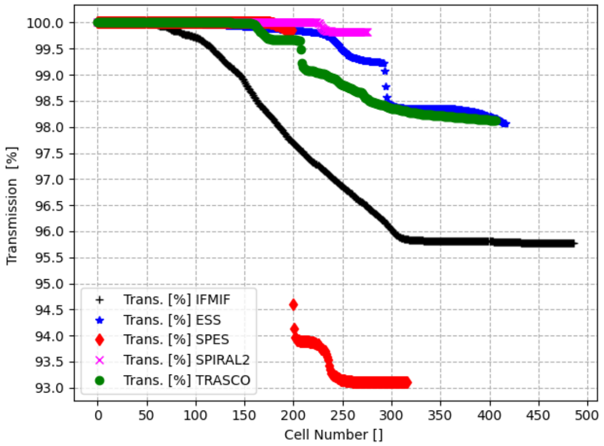

Figure 7: RFQs transmission as function of cell number.

The measured longitudinal emittance is for the SPIRAL2 RFQ of 0.74 MeVdeg (=0.046 MeVdeg/u) for $^{18}O^{6+}$, in agreement with the relative TraceWin simulations [9]; the SPES RFQ presents the lowest longitudinal emittance, at the cost of a reduced transmission (93% of the accelerated particles).

In Fig. 7 is reported the transmission of the accelerated particles; the best transmission is obtained by the SPIRAL2 RFQ, with almost all the particles accelerated, for A/q=3. This result has also been confirmed experimentally [10]. The RFQs of IFMIF and ESS shows a nominal transmissions that agree with the measurements.

The IFMIF RFQ obtained a transmission of more than 90%, in a pulsed d.c. of 0.1%, with a total of 125 mA of deuteron on output at the beam dump [11].

CONCLUSION

A direct comparison of the nominal RFQs have shown the following points:

- The simulations codes can well define the beam dynamics inside any RFQs.
- The design can be optimized to reduce the longitudinal emittance.
- There are no general common rules about how to do an RFQ design.

The simulation code has been compared with success with the experimental results. In general way, the voltage can be ramped along the RFQ, like the modulation. The RFQ parameters must be carefully defined at the end of Gentle Buncher to get a good degree of longitudinal capture. A low longitudinal emittance can be obtained with a longer shaper; however, this will cost in increase the RFQ length and decreases the transmission.

Typically, a longitudinal emittance formation is done on about 50 RFQ cells. For getting a very low longitudinal emittance in SPES RFQ the number of cells used is about 100.

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REFERENCES

[1] K. R.Crandall *et al.*, “PARMTEQ-A beam dynamics code for the RFQ linear accelerator”, *AIP Conf. Proc.*, vol. 177, no. 1, pp. 22-28, 1988.

[2] L. Bellan *et al.*,“Updates on VeRDe, beam dynamics optimization toolkit for RFQ design” Annual report, INFN-LNL-266(2022), ISSN1828-8561.

[3] M. Comunian *et al.*, “TRASCO RFQ Design”, in *Proc. EPAC'00*, Vienna, Austria, Jun. 2000, paper THP6B13, pp. 927-929.

[4] M. Comunian *et al.*, “Beam Dynamics Redesign of IFMIF-EVEDA RFQ for a Larger Input Beam Acceptance”, in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper MOPS031, pp. 670-672.

[5] M. Comunian *et al.*, “The New RFQ as RIB Injector of the ALPI Linac”, in *Proc. IPAC'13*, Shanghai, China, May 2013, paper THPWO023, pp. 3812-3814.

[6] R. Ferdinand *et al.*, “SPIRAL 2 RFQ Design”, in *Proc. EPAC'04*, Lucerne, Switzerland, Jul. 2004, paper WEPLT076, pp. 2026-2028.

[7] A. Ponton, “The ESS RFQ Beam Dynamics Design”, in *Proc. LINAC'12*, Tel Aviv, Israel, Sep. 2012, paper THPB029, pp. 915-917.

[8] TraceWin/Toutatis: `https://www.dacm-logiciels.fr/`.

[9] G. Normand *et al.*, “SPIRAL2 RFQ bunch lengths and longitudinal emittance measurements”, *J. Phys.: Conf. Ser.*, vol. 1350, p. 012098, 2019. `doi:10.1088/1742-6596/1350/1/012098`

[10] A. K. Orduz *et al.,* “SPIRAL2 Final Commissioning Results”, in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 314-318. `doi:10.18429/JACoW-LINAC2022-TU2AA02`.

[11] F. Grespan *et al.*, “IFMIF/EVEDA RFQ Beam Commissioning at Nominal 125 mA Deuteron Beam in Pulsed Mode”, in *Proc. IPAC'20*, Caen, France, May 2020, p. 21. `doi:10.18429/JACoW-IPAC2020-TUVIR11`.