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Design of an RFQ Accelerator optimised for Linac4 and SPL

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Abstract

In the Linac 4 and the SPL a 3 MeV RFQ is required to accelerate the H^- beam from the ion source to the DTL input energy. The IPHI RFQ, primarily designed for high beam power applications, is presently being built within a collaboration between CEA, IN2P3 and CERN and is intended to become the front end for the new CERN accelerator complex. However, a new shorter RFQ optimised for the CERN lower duty application would present several advantages with respect to the IPHI one. The design of such an RFQ is the subject of this note.

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1 Introduction

In 2001 a collaboration has been set up between CEA, IN2P3 and CERN for the continuation of the IPHI (Injecteur de Protons de Haute Intensité) project [1]. The original goal of this project, which started in 1997, was the construction and testing of a Radio Frequency Quadrupole (RFQ) accelerator designed for CW operation in a transmutation demonstration facility, which would accelerate a 100 mA proton beam to an energy of 5 MeV. Because of reduced funding for IPHI and of difficulties in finding a company accepting to braze the RFQ with the requested tolerances, in 2001 it was decided to limit the RFQ output energy to 3 MeV, in order to make it compatible with the requirements of the CERN Linac4 [2] project and to allow CERN to join the collaboration. The CERN Workshop would then take care of the brazing procedures, and after few months of CW reliability tests at Saclay required by the EUROTRANS initiative, the RFQ was to be moved to CERN to be permanently used as Linac4 and SPL injector. The original planning considered that the RFQ had to operate on a test stand at CERN as from 2007 with the aim of measuring the 3MeV beam characteristics before freezing the design of the Linac4 high-energy part. However, since 2001 problems in the correct setting up of the brazing have considerably delayed the construction of the IPHI RFQ, while Linac4 is coming close to being approved with a tight schedule that foresees the installation of the RFQ in its final location at the beginning of 2010. In case of further delays, the extensive testing required at CERN before the installation of the 3 MeV front end at the Linac4 site could become incompatible with the CW testing required at Saclay prior to shipment at CERN. Moreover, the 6-m long IPHI RFQ requires an amount of RF power at the limit of what can be provided by a single LEP klystron and a considerable investment in terms of infrastructure.

Considering the relatively low duty cycle required at CERN (5% in the case of full-power SPL) and the medium beam current to be accelerated (70 mA) a new design, specifically conceived for the CERN requirements, can be envisaged, resulting in a much shorter RFQ. In this note we report a design optimized for the less demanding CERN operation and give a rough estimate of the cost and schedule for the realization of such RFQ.

2 Main Beam Parameters

The CERN RFQ is aimed to work as the front end injector of Linac4 in a first stage, and of SPL in a second stage. If in the Linac4 scheme the duty cycle is naturally limited at 0.08 % by the PSB operation at 2 Hz, in its SPL operation the RFQ should be able to operate up to 5 % duty cycle. The beam parameters defining the RFQ specification are listed in Table 1:

Parameter	min Value	max Value	Units
Beam energy	3.0	3.0	MeV
Peak beam current (during pulse)	20	70	mA
RF duty cycle	0.08	5	%
Transverse emittance (input)	0.20	0.35	π mm mrad
Longitudinal emittance (output)	0.11	0.20	π deg MeV

Table 1: Specified beam parameters for the RFQ design

3 Beam Dynamics

The Linac4 low energy end (0-3 MeV) has been adapted to the parameters of the 3 MeV version of the IPHI RFQ. The IPHI RFQ accepts a 95 keV proton beam with currents from few mA to 100 mA. It accelerates with excellent transmission over the entire current range and, for the Linac4 design current of 70 mA, delivers a beam with the parameters given in Table 2. These parameters have been taken as the input for the design of the chopper line that, in the Linac4, matches the RFQ beam into the following DTL structure.

Parameter	**Value**	**Units**
Energy	3.0	MeV
Current	70	mA
Transverse alpha twiss parameters x,y	1.0, -1.6	
Longitudinal emittance	0.14	π deg MeV

Table 2: Specified beam parameters for the chopper line design.

From the beam dynamics point of view the IPHI RFQ, being a high performing accelerator designed for CW operation with a high intensity beam, has characteristics somehow over dimensioned with respect to the Linac4 and SPL operation. Releasing some of the IPHI-specific constraints, not applicable to the Linac4/SPL case, could result in a “lighter” design.

The assumptions for the re-design were the following:

- Output beam characteristics equal or compatible with the IPHI parameter (to avoid redesigning the chopper line and/or the following accelerators);
- Transverse acceptance equal or better than IPHI (to avoid inserting a bottleneck);
- Mechanical and RF design compatible with the RFQ projects that are presently under realization with the participation of CERN (IPHI and TRASCO [3]), to avoid starting a new RF and mechanical design;
- Elementary modules of 1 m;
- Maximum RF Power required: 0.8 MW to allow the use of one single LEP klystron;
- Maximum beam current: 70 mA;
- Minimum extraction energy from the H^- ion source: 35kV.

The lower beam current required for CERN operation suggests a reduction of the input energy, which in turn reduces the length of the RFQ cells in the bunching section and therefore the overall RFQ length. A less energetic beam is more efficiently (i.e. in a shorter distance) bunched without compromising on beam quality and transmission if space charge effects can be kept under control. After some optimisation, the injection energy could be lowered from the IPHI energy of 95 keV down to 45 keV, limit below which the space charge effects for a 70 mA beam start to be so important that they balance out the gain in length.

The voltage and the minimum aperture have also been reduced with respect to IPHI without losing in transverse acceptance, profiting from the fact that the phase advance per period is proportional to the voltage and inversely proportional to the square of the minimum aperture. A smaller minimum aperture will nonetheless entail stricter machining tolerances, which in turn might be released if the RFQ is shorter, so it is not clear at present if this point is really a disadvantage.

Two alternative designs, which are 3 and 4 meters long respectively, have been defined and presented in Table 3 where they are compared with the IPHI RFQ parameters.

Parameter	**IPHI**	**Design 1**	**Design 2**	**Units**
Length	6.0	3.0	4.0	m
Vane voltage	87-120	84	70	kV
Minimum aperture a	0.35	0.18	0.16	cm
Average aperture r_0	0.36-0.52	0.33	0.29	cm
ρ/r_0	0.85	0.85	0.85	
Max field on pole tip	31.6	35	32	MV/m
Kilpatrick value	1.7	1.9	1.7	
Focusing parameter	4.7-3.5	6.0	6.2	
Acceptance at zero current	1.7	1.7	1.7	π mm mrad
Transmission(*)	99	93	93	%
Trans. emittance growth(*)	8	0	0	%
Input transverse emittance	0.25	0.25	0.25	π mm mrad
Longitudinal emittance(*)	0.14	0.14	0.14	π deg MeV

(*)= calculated at 70 mA for a matched beam.

Table 3: Comparison of IPHI main parameters with two design options.

The two designs assume $\rho/r_0=0.85$ as it is the case in the IPHI RFQ. While the TRASCO mechanical design assumes $\rho/r_0=1.0$, it could be easily modified for $\rho/r_0=0.85$.

A comparison, to the first-order, shows that the three RFQs are equivalent from the beam dynamics point of view, although the transmission of IPHI is higher. The alternative RFQ designs have not been studied in the same depth as the IPHI RFQ and their transmission should, with some fine optimization, be improved.

The smaller minimum bore is compensated by a stronger focusing, kept constant all along the RFQ, resulting in the same transverse acceptance for the three RFQs.

The main difference between the two alternative solutions lies in the maximum pole tip field. For the shorter case (Design 1), which is also economically more favourable, the maximum surface field is at 1.9 times the Kilpatrick limit. This value is more challenging than what has been chosen by IPHI (1.7 Kilpatrick). The 4-m alternative solution has a maximum field comparable to the IPHI one. The comparison of the surface field along the length of the 3 RFQs is shown in Figure 1. Figures 2 and 3 show the main parameters for the alternative designs.

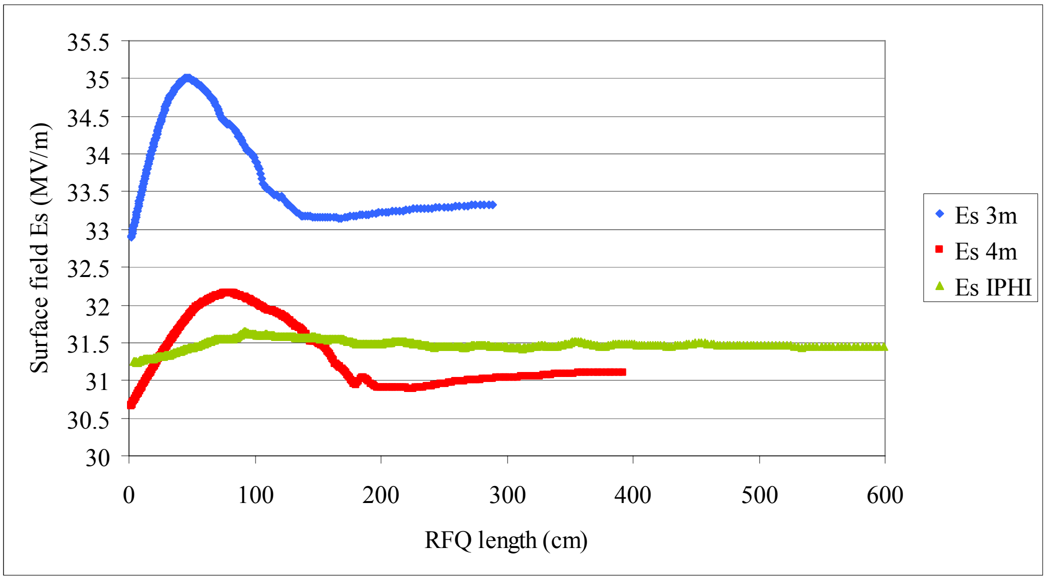


Figure 1: Comparison of the pole-tip field for IPHI and the two alternative solutions.

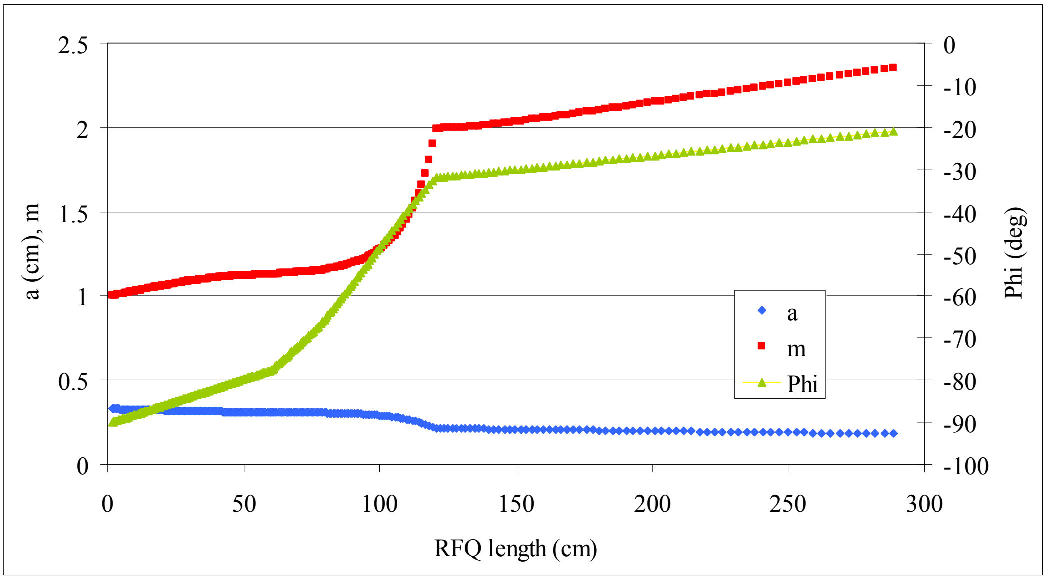


Figure 2: Parameters of Design 1, 3-m long.

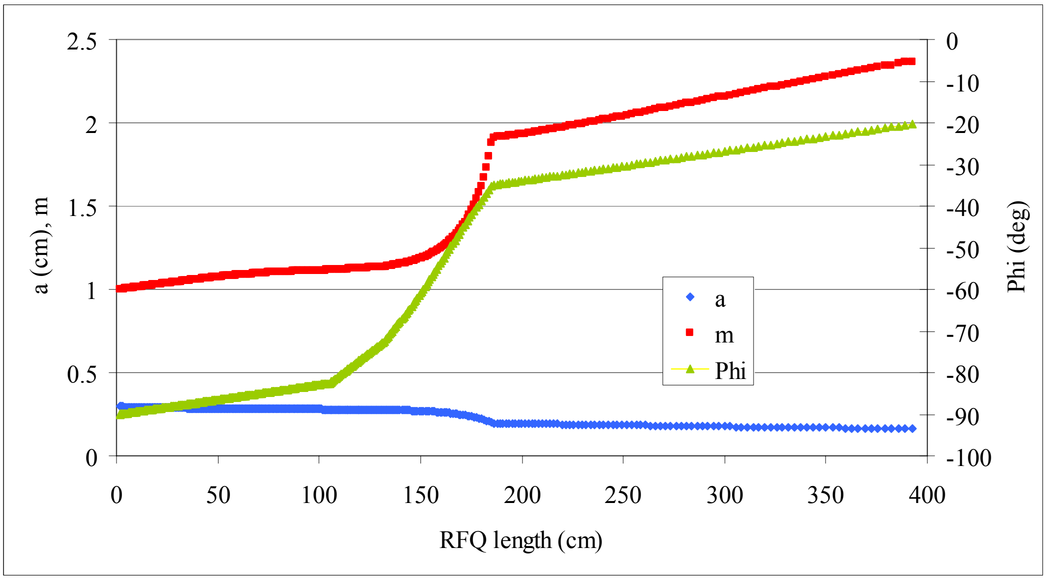


Figure 3: Parameters of Design 2, 4-m long.

4 RF Design

After comparing the different solutions, the 3 m long RFQ looks most attractive in terms of RF structure cost and tuning complexity. From the RF power point of view, Table 4 compares the estimation of RF power required for the three alternative designs, as given by the Superfish simulation code with a 20% safety margin for additional losses.

Parameter	IPHI	Design 1	Design 2	Units
Length	6.0	3.0	4.0	m
Vane voltage	87-120	84	70	kV
ρ/r_0	0.85	0.85	0.85	
Kilpatrick	1.71	1.9	1.7	
Cavity power (Superfish*1.2)	796	331	321	kW
Total power (including beam)	1006	541	531	kW

Table 4 : Comparison of IPHI RF parameters with two design options.

The power required by the IPHI RFQ approaches the limit for a single LEP-type klystron, meaning that a small reduction in the Q-value due to any problem during construction or to any effect not accounted for in the simulations would require two klystrons to feed the RFQ with a considerable increase in the cost and complexity of the RF system. On the contrary, both alternative designs have a significant safety margin with respect to the LEP klystron power. An additional advantage is that power levels around 500 kW can be fed into the RFQ from a single RF coupler, instead of the two foreseen for the IPHI RFQ.

The peak field of 1.9 Kilpatrick for the Design 1 is at the level of what has been already achieved during routine operation in some pulsed RFQs. Table 5 reports some basic RF parameters for three pulsed RFQs: the 200 MHz RFQ2 at CERN commissioned in 1993 and two RFQ's recently commissioned in the same frequency range as the Linac4 RFQ, the JPARC and SNS RFQ's.

	Frequency (MHz)	Length (m)	Repetition freq. (Hz)	Pulse length (μs)	Max. field (Kilpatrick)
RFQ2	202.56	1.8	1	360	2.45
SNS	402.5	3.76	60	1000	1.85
JPARC	324.0	3.1	50	500	1.8

Table 5 : Comparison between different operational RFQs.

CW RFQs need to be more conservative in terms of maximum field, because the probability of a breakdown in the cavity is proportional to the duty cycle and because the persistence time of the electrons in the cavity after a breakdown makes re-establishing the voltage more difficult in a high repetition rate system. RFQs working at low repetition rate can accept a higher field; a typical example is the CERN RFQ, which at 1 Hz can accept a field as high as 2.45 Kilpatrick. Recent projects operating at repetition rates comparable with the SPL have chosen for the RFQ a maximum field in the range 1.8-1.85 Kilpatrick, and have been operated successfully, suggesting that a Kilpatrick level of 1.9 can be envisaged for the new CERN RFQ. An additional advantage of the Linac4/SPL RFQ is that in the first stage (Linac4) it will have to operate only at 2 Hz repetition rate. SPL operation is foreseen only after many years, during which the cleanliness of the electrodes will be improved by the effect of the RF itself.

Moreover, the reduced length of the Design 1 (3.5 λ) gives the opportunity to build an RFQ composed of a single RF structure without coupling cells between sections, simplifying considerably the tuning and further reducing the cost. In conclusion, the short RFQ (Design 1) is the preferred choice from the RF point of view.

Concerning the RF and mechanical design of the RFQ resonator, there are no particular reasons to develop a special design for the Linac4/SPL RFQ. Both the IPHI and the TRASCO RFQ designs, although aimed at CW operation, could be easily adopted for the Linac4/SPL RFQ. Their design and engineering have required a considerable amount of time and effort, the technical solutions adopted have been validated by accurate simulations, and they represent the state of the art in this kind of realization. Segments of both RFQs have already been built, and they are both being brazed at CERN. Adopting one of these designs, although with some simplification in the cooling circuitry aimed at reducing the cost, represents an excellent opportunity for reducing the engineering effort that would be normally required by the design of a new RFQ and for profiting from the experience gained so far on their mechanical fabrication and assembly.

5 Parameters and Tentative Schedule

Table 6 reports the main parameters of the preferred design for the Linac4/SPL RFQ.

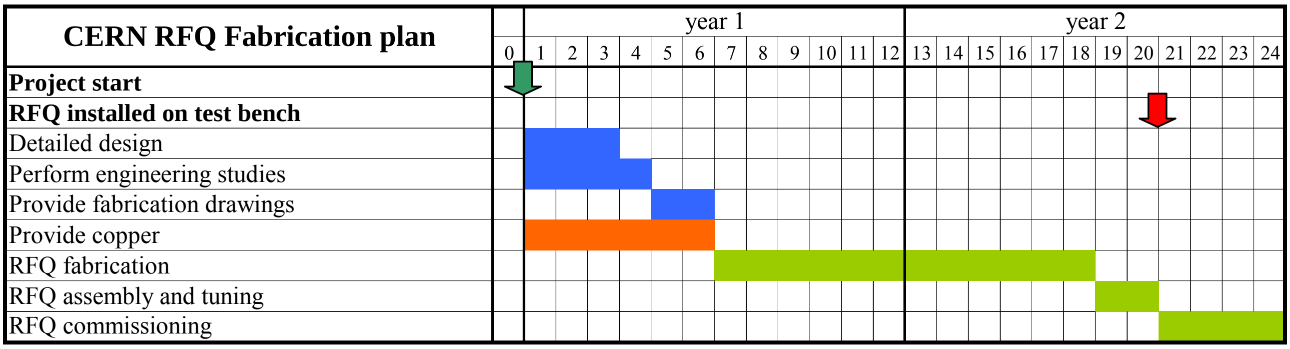
Parameter	CERN RFQ	Units
RFQ frequency	352.2	MHz
Length	3.0	m
Electrical length	3.4	λ
Intervane voltage	84	kV
Average radius r_0	3.2	mm
ρ/r_0 ratio	0.85	
Stored energy	0.433	Joules/m
Capacitance	123	pF/m
Power dissipation (Superfish)	91.8	kW/m
Quality factor	10400	
Shunt impedance (Superfish)	77	kΩ-m
Total power dissipation (1.2*Superfish, only cavity)	331	kW
Energy input	0.045	MeV
Energy output	3.0	MeV
Max RF duty cycle	5	%
Beam peak current during pulse	70	mA
Beam power (70 mA)	210	kW
RF total peak power	541	kW
Minimum aperture a	0.18	cm
Max field on pole tip	35	MV/m
Max surface field	1.9	Kilpatrick
Focusing parameter	6.0	
Acceptance at zero current	1.7	π mm mrad
Transmission(*)	93	%
Input transverse emittance	0.25	π mm mrad
Transverse emittance growth(*)	0	%
Longitudinal emittance(*)	0.14	π deg MeV

(*)= calculated at 70 mA for a matched beam.

Table 6: CERN RFQ relevant parameters.

The time required for the machining of the three sections and their main accessories has been estimated as one year from the delivery of the fabrication drawings, excluding the time required by brazing, which could be performed at CERN and which should be planned in the shadow of the machining time.

A very preliminary planning for the construction of the RFQ is given in Figure 4.



CERN RFQ Fabrication plan		year 1												year 2											
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Project start	⬇																								
RFQ installed on test bench																					⬇				
Detailed design		🟦	🟦	🟦																					
Perform engineering studies		🟦	🟦	🟦	🟦																				
Provide fabrication drawings						🟦	🟦																		
Provide copper		🟧	🟧	🟧	🟧	🟧	🟧																		
RFQ fabrication								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
RFQ assembly and tuning																				🟩	🟩				
RFQ commissioning																						🟩	🟩	🟩	🟩

Figure 4: Preliminary planning for the realization of the CERN RFQ.

Preliminary offers for the machining of the RFQ components have been asked from two companies. Up to now only one company has answered, giving a preliminary cost estimate for the machining of the three segments, complete with end cells and tuners. Adding up the cost of copper to this estimation together with the brazing, to be performed at CERN, the construction of the vacuum pumping manifold and the mechanical support we come to a very preliminary cost estimate of about 1 MCHF. This estimate assumes that CERN can have access to the drawings and to the tuning and assembling tools from either IPHI or TRASCO.

References

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[3] A. Pisent, The TRASCO-SPES RFQ Proc. of the Linear Accelerator Conference 2004, Lubeck, Germany, 2004. [http://cdsweb.cern.ch/record/925443]