# THE RADIOFREQUENCY QUADRUPOLE ACCELERATOR FOR THE LINAC4

C. Rossi, P. Bourquin, J.-B. Lallement, A. M. Lombardi, S. Mathot, M. Timmins, G. Vandoni, M. Vretenar ,CERN, Geneva, Switzerland.
S. Cazaux, O. Delferriere, M. Desmons, R. Duperrier, A. France, D. Leboeuf, O. Piquet, CEA, Saclay, France.

*Abstract*

The first stage of acceleration in Linac4, the new 160 MeV CERN $H^-$ injector, is a 352 MHz, 3-m long Radiofrequency Quadrupole (RFQ) Accelerator. The RFQ will capture a 70 mA, 45 keV beam from the RF source and accelerate it to 3 MeV, an energy suitable for chopping and injecting the beam in a conventional Drift Tube Linac. Although the RFQ will be initially operated at low duty cycle (0.1%), its design is compatible with higher duty cycle (10%) as the front-end for a possible high-intensity upgrade of the CERN linac facility.

The RFQ will be of brazed-copper construction and will be built and assembled at CERN. Beam dynamics design allows for a compact structure made of a single resonant unit. Field symmetry is ensured by fixed tuners placed along the structure. In this paper we present the RF and mechanical design, the beam dynamics and the sensitivity to fabrication and to RF errors.

## INTRODUCTION

In Linac4 an RFQ is required to capture the beam extracted from the $H^-$ ion source and accelerate it to an energy suitable for injection in the following DTL [1]. This energy must also be compatible with the operation of a chopper line, used to create a microstructure in the beam pulse. The initial Linac4 plans considered using the RFQ developed and built by CEA and IN2P3, for their IPHI project [2].

The possibility to adopt a lighter design, by reducing the injection energy and adopting a different acceleration profile, made CERN decide in 2007 to build a dedicated RFQ, which could profit from the tools and experience developed at CEA within the IPHI and SPIRAL2 projects, thus reducing the R&D cost and time. Besides, CERN has recently brazed the RFQ for the TRASCO project and therefore has contributed to the related mechanical design and gained access to this manufacturing experience [3].

## BEAM DYNAMICS CONSIDERATIONS

The RFQ must initially be able to operate in Linac4 to fill the PS Booster, delivering beam pulses of 400 µs at 1.1 Hz, and, at a later stage, to fill a Superconducting Proton Linac (SPL) operated as LHC injector (1.2 ms, 2 Hz). In case a high intensity beam programme would be approved, the option is left open to operate with 400 µs, 50 Hz pulses. These different requirements represent an additional complication to the design. The specification parameters are listed in Table 1.

Table 1: Main Design Specification for the Linac4 RFQ, with rms Values of Emittance in the Two Planes

| Linac4 RFQ Parameter | Min | Max | Units |
|---|---|---|---|
| Beam energy | 3.0 | 3.0 | MeV |
| Operating frequency | 352.2 | | MHz |
| Peak beam current (pulse) | 10 | 80 | mA |
| RF duty cycle | 0.08 | 7.5 | % |
| Transverse emittance (in) | 0.20 | 0.35 | π mm mrad |
| Longitudinal emittance (out) | 0.11 | 0.20 | π deg MeV |

The decision to designing a dedicated RFQ came after the chopper line elements had already been procured and assembly plans made. The output beam parameters of the new RFQ have to be similar to the IPHI ones or at least compatible with the existing chopper line. Other constraints on the design are the requirement to limit the RF power to 0.8 MW peak, corresponding to a single LEP klystron with a sufficient safety margin, and to keep the RFQ length around 3 m. This allows dividing the RFQ into 3 segments of 1 meter while keeping the overall length at 3.5 λ, thus allowing the direct coupling of the three RFQ sections without using coupling cells between sections.

The results of the redesign is a compact RFQ (3 m vs 6 m of IPHI) with an intra-vane voltage of 78 kV and a peak surface field of 34 MV/m (1.84 times the Kilpatrick limit). The main design parameters are shown in Figure 1.

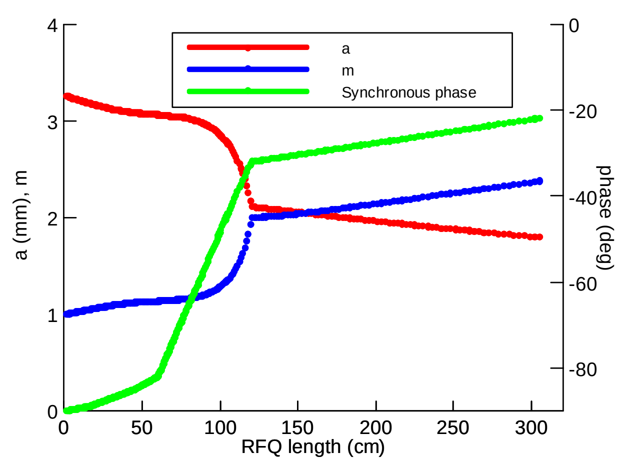


Figure 1: Graph of the synchronous phase, with the RFQ aperture a and modulation parameter m.

The considerable reduction in length was made possible by the lower injection energy, a higher focusing factor and a compromise on the current limit (80 mA vs. 100 mA). The beam quality for the nominal current is equivalent to that of the 6 m long IPHI RFQ. The value for the peak surface field appears acceptable as it is reached over a short section and the RFQ is not meant to work in CW mode.

The minimum value for the aperture a is 0.18 cm and the maximum modulation factor m is 2.38.The main beam parameters, evaluated for 70 mA of beam current, are summarized in Table 2.

Table 2: Summary of the Main Beam Dynamics Parameters for the Linac4 RFQ (rms Values of Emittance)

| RFQ Beam Parameter | Value | Units |
|---|---|---|
| Beam input energy | 0.045 | MeV |
| Beam output energy | 3.0 | MeV |
| Nominal beam current | 70 | mA |
| Average aperture $r_0$ | 0.33 | cm |
| Ratio $\rho/r_0$ | 0.85 | |
| Focusing parameter | 5.77 | |
| Input emittance (norm) | 0.25 | π mm mrad |
| Acceptance at zero current | 1.7 | π mm mrad |
| Longitudinal emittance (out) | 0.13 | π deg MeV |
| Transmission | 95 | % |
| Transverse emittance growth | 0 | % |

## RF DESIGN

The RFQ cavity design has been driven by the aim of keeping the design as simple as the project requirements could allow.

The 2D section of the RFQ cavity has been kept constant over the full RFQ length, in order to simplify the mechanical fabrication. The intra-vane voltage is also constant at 78 kV and the tuning of the accelerating field profile is left to 12 tuners per quadrant distributed over the accelerator length. Table 3 shows the 2-dimensional electrical parameters for the quadrupole cut-off frequency mode, i.e. without tuner and end-cell contributions.

Table 3: RFQ Electrical Parameters (2D Simulation)

| RFQ Electrical Parameter | Value | Units |
|---|---|---|
| Vane voltage | 78.27 | kV |
| Quality factor (unloaded) | 10269 | - |
| Stored energy | 0.372 | J/m |
| Dissipated power | 78.738 | kW/m |
| Magnetic field (max) | 5444 | A/m |

The design of a short RFQ has helped in minimizing the RF power requirements from the klystron and one klystron should be sufficient to drive the RFQ in all conditions. This also allows the use of a single input RF coupling port: an iris coupled ridged waveguide connecting the WR2300 reduced height RF window to the RFQ cavity.

The impact of the vane modulation on the cut-off frequency of the transmission line modes has been studied by means of 3D simulations, showing a frequency reduction of 0.208 MHz for the quadrupole mode and of 3.871 MHz for the fundamental dipole mode when the modulation is taken into account.

The frequency separation between the accelerating quadrupole mode and the adjacent dipole modes is about 5 MHz, which should guarantee sufficient stability during operation in all conditions. The study for the tuning of the end cells has shown that dipole rods are not required to displace the dipole modes which are closer to the accelerating mode due to the favourable length of this design. The proper tuning of the end-cells should guarantee a voltage error in the RFQ not exceeding ±1 %.

First simulations have shown that eight cooling channels should be sufficient to allow temperature stabilization of the RFQ cavity, because of the limited dissipated power in pulsed mode. The dynamic tuning strategy is based on two cooling circuits, one using four channels drilled inside the vane pole tips and the other using four channels in the RFQ body. The dynamic tuning of the RFQ cavity is obtained by regulating the water temperature difference between the two circuits.

Thirty-two fixed tuners (80 mm diameter) plus the RF and the dummy RF ports will allow achieving a flat electrical field for the quadrupole accelerating mode. The nominal tuner position has been set at 15 mm inside the cavity to allow linear frequency variations as a function of the tuner penetration. The total peak power dissipated in the tuners will be less than 100 kW.

## MECHANICAL DESIGN

The RFQ cavity is made of three sections, each one-meter long, directly coupled. Each of the three sections results from the assembly of two major vanes and two minor vanes. A CAD picture of the RFQ is shown in Figure 2.

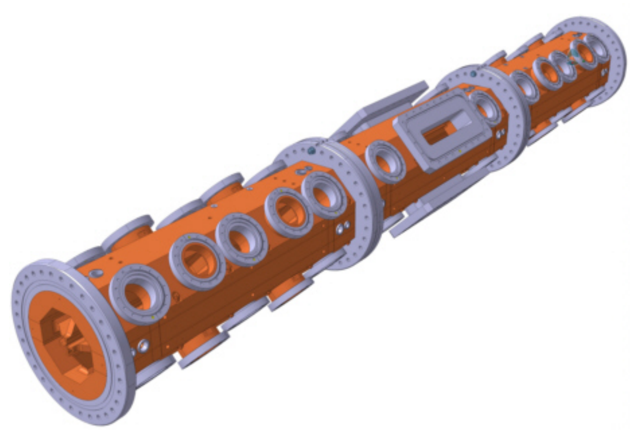

Figure 2: Linac4 RFQ.

The structure is equipped with a total of thirty-two circular apertures, 82 mm diameter, to host the fixed tuners; four rectangular apertures have been designed in the central section for the RF input(s). The first and last section holds eight circular apertures that have been designed to host the vacuum pumping ports. The design of the vacuum system takes into account that the main gas load is coming from the LEBT gas injection used for neutralization and is estimated at $1.1\ 10^{-3}$ mbar l/s, whereas the gas load from outgassing is only $1.5\ 10^{-5}$ mbar l/s. By using eight diode ion pumps and four turbo molecular pumps the effective pumping speed of 2700 l/s is obtained, which allows to keep the dynamic vacuum level of the RFQ in the range of $10^{-7}$ mbar.

The vane modulation is achieved by a milling machine using a wheel shaped cutting tool. The assembly of the RFQ cavity will be performed by means of a two-step brazing procedure that has been developed at CERN during the fabrication of the IPHI and TRASCO RFQs [4].

The first assembly step of the four poles is made by brazing in the horizontal position, at 825 °C, which allows a uniform diffusion of the brazing material, by capillary action. The second assembly step, performed in a vertical oven at 790 °C, brings the stainless steel flanges and end-flanges onto the RFQ cavity.

The OFE copper used for fabrication has been submitted to a severe 3D forging, in order to obtain the maximum of homogeneity in the raw material. A detailed procedure, alternating machining phases to thermal annealing cycles has been established in order to stabilize the material and avoid deformations and possible displacements of the vanes, especially on the occasion of the first brazing step.

The machining and assembly tolerances have been defined following an error study simulation campaign, which showed that the beam dynamics design adopted is relatively insensitive to errors. The most important contributions come from section tilts and electromagnetic field errors. The set of errors considered is summarized in Table 4, while Table 5 shows how such errors affect the beam dynamics.

Table 4: RFQ Mechanical and Field Tolerances

| **Linac4 RFQ Tolerances** | **Value** | **Units** |
|---|---|---|
| Machining error | ± 20 | µm |
| Vane modulation error | ± 20 | µm |
| Vane tilt over 1 m | ± 100 | µm |
| Vane positioning error (displacement h+V) | ± 30 | µm |
| Vane thickness error | ± 10 | µm |
| Contiguous section gap | 100 ± 15 | µm |
| Section tilt over 1 m | ± 30 | µm |
| Klystron error | ± 1 | % |

Table 5: Beam Degradation Due to Mechanical and Field Errors

| | Losses % | EmitX % | EmitY % | EmitZ % |
|---|---|---|---|---|
| Average | 1.674 | 2.034 | 2.146 | 3.497 |
| Min | -0.940 | -1.839 | -1.573 | -3.442 |
| Max | 5.098 | 6.813 | 6.508 | 17.107 |
| StDev | 0.940 | 1.337 | 1.239 | 3.093 |

## ORGANISATION, STATUS AND PLANNING OF THE PROJECT

The RFQ project has been organized in two work packages: the first is responsible for establishing the general design (beam dynamics, RF design, thermal loads) and performing the RF measurements, tuning and final commissioning, while the second is in charge of the mechanical design and of the fabrication (raw material procurement, machining, assembly). The first work package relies on the contribution from CEA for the RF design, the thermo-mechanical calculations, the RF measurements and the final tuning.

The general design is now complete and execution drawings are being prepared. The 3D forged copper has been purchased and delivered; first machining tests have started at the CERN workshop. The start of the machining of the first section is expected before the end of 2008.

The Linac4 RFQ is expected to become available earlier than needed for Linac4 installation. It will be installed in a dedicated 3 MeV Test Stand to test the beam dynamics of the Linac4 low energy end [5]. Since all emittance increase and beam degradation occurs before 3 MeV, three aspects of beam dynamics must be carefully studied: the space charge control at low energy, the beam chopping and re-matching to the DTL and the beam matching to the RFQ in the presence of neutralization. Studies cannot be performed any more once the front end has taken its place in the Linac4 tunnel. The 3 MeV Test Stand is already in an advanced stage of preparation, the klystron and the prototype modulator that will be used for feeding RFQ have already been tested. The ion source is presently being assembled and the LEBT and chopper lines are in the installation phase. The RFQ schedule is shown in Figure 3.

The Linac4 RFQ will accelerate beam at the Test Stand during 2010 and the first half of 2011. In order to achieve this goal, the RFQ construction has to be completed in the first months of 2010.

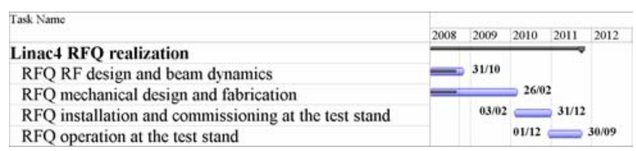


Figure 3: Linac4 RFQ project schedule.

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