

SIMULATION OF RF COMPONENTS FOR THE ICONE PILOT: RFQ, REBUNCHER, DTL CAVITIES AND AMPLIFIERS

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Abstract

CEA is committed to delivering a study for a warm linac in the frame of the ICONE project. It aims at accelerating an 80-mA beam of protons up to 25 MeV, with a 6% duty cycle. The LINAC consists of: a proton source with low-energy beam transport line, an RFQ, a medium-energy beam transport line, and a warm DTL. All these components must be tuned at 352.2 MHz, to reach the required output energy. This document presents the RF studies made by CEA and INFN on the main RF components, including the RFQ, the rebunchers, IH- and Alva-rez DTL cavities and the RF amplifiers.

INTRODUCTION

CEA is designing a new accelerator facility in the frame of the ICONE project [1]. This accelerator would be a LINAC, able to produce an 80-mA beam of protons up to 25 MeV. The required duty cycle for the beam would be 6%.

The different parts of this LINAC are being studied, from the proton source, to the high-energy beam transport line. Three of these components require RF studies, the RFQ, from 60 kV to 3.6 MeV, the rebuncher cavities of the medium-energy beam transport line, and the warm DTL, from 3.6 MeV to 25 MeV.

For these purpose, different studies were launched from the beginning of 2024, that should end in the end of 2025 in order to achieve a final technical report for a future manufacturing and installation of this machine.

The first component, the RFQ, shows requirements very close to the ones of the ESS RFQ. The frequency is the same, as well as the input and output energies. CEA proposed to use the same design for ICONE. The main difference between ICONE and ESS are the beam current (80 mA instead of 62.5 mA), and the duty cycle (6% instead of 5%).

The second components, the rebunchers, required a new RF design. As the required accelerating field is very low (around 1 MV/m), these parts should not be critical.

Finally, the DTL part is a very critical component, as it must transfer 1,7 MW of RF power into the proton beam. Two solutions are studied, for ICONE. The first solution is based on the ESS first Alvarez DTL. In the frame of a collaboration between CEA and INFN, RF studies of this solution were provided by INFN to ICONE.

On its side, CEA studied an IH-DTL solution. This includes a series of 12 different IH cavities.

RFQ SIMULATIONS

The design of the ESS RFQ was made for a 90 mA beam. The RFQ pole tip design is a four vane-type structure, divided into five approximately 1 m segments (see Figure 1).

The beam physics design was shaped by a desire to profit from the experience and expertise of CEA-Saclay [2] and a commitment to designing in adequate safety margins.

The RFQ design calls for a non-constant voltage. This ensures high values for both the longitudinal and transverse current limits all along the RFQ structure; a constant inter-vane voltage cannot preserve the latter limits without dramatically decreasing the aperture. The evolution has been chosen so that the first derivative of the voltage with respect to the longitudinal axis, z , vanishes at both ends of the RFQ. As a consequence, no circulating currents will occur at the RFQ extremities and no additional losses will be experienced at these locations.

An original feature of the design is the long pure bunching section ($\phi_s = -90$ degrees). This feature, associated with a slow rate of acceleration in the first half of the structure and a large longitudinal acceptance, results in excellent beam transmission, low longitudinal emittances and low transverse emittance growth as indicated in Table 1. The main geometric parameters are summarized in Table 2. The maximum peak power for the RFQ is estimated at 1.548 MW. This power will be delivered via 4 couplers.

Table 1: Main Parameters of the RFQ

| | |
|-------------------------|------------------|
| Transmission | > 97% |
| Trans. emittance growth | < 1% |
| RMS long. emittance | 0.1436 p.deg.MeV |
| Final energy | 3.62 MeV |
| Inter-vane voltage | 80 to 120 kV |
| Sync. phase | -90° to -31° |
| Kilpatrick limit | 1.8 kilp |

Table 2: Main Geometry Parameters of the RFQ

| | |
|--------------------------------|---------------|
| Vane tip to axis mean distance | 3.5 to 5.3 mm |
| Vane tip radius of curvature | 3.0 mm |
| RFQ length | 4.55 m |

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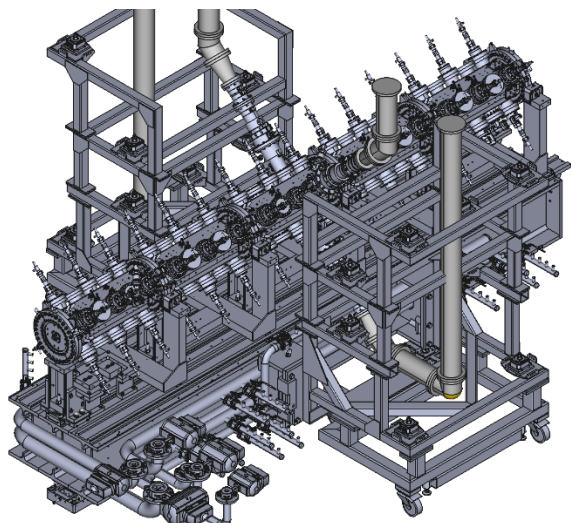


Figure 1: Representation of the ICONE RFQ.

REBUNCHER CAVITIES SIMULATIONS

The rebuncher cavities are IH cavities (Interdigital H-mode cavities, see [3]). In order to reduce the length of these cavities, it was decided to limit the number of gaps to 4. Figure 2 presents a schematic of the cavities. Both rebuncher cavities are identical.

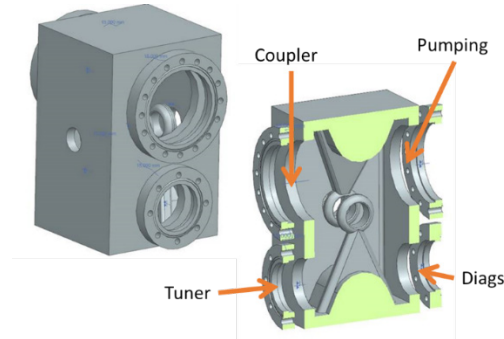


Figure 2: Schematic of one 4-gaps rebuncher.

The diagnostics are installed under the pumping flange. In this way, the length of the rebuncher is reduced, leaving more space for the other MEBT components.

The required accelerating voltage is 143 kV for the first rebuncher, and 113 kV for the second one. The accelerating gradient is close to 1 MV/m for the 143 kV voltage. The required power is around 16 kW peak for the first cavity, and 10 kW peak for the second one.

The maximal electric field, for the first rebuncher is 8,8 MV/m. This corresponds to about 0.5 kilp. These cavities are fully compliant with the requirements of the MEBT.

IH-DTL CAVITIES SIMULATIONS

The 12 cavities were simulated with Ansys HFSS. Table 43 sums up the results of the simulations.

The total RF power dissipated in the walls (copper) of the cavities is estimated to 1,333 kW. For comparison, the total RF power transmitted to the beam is 1,716 kW, to reach 25 MeV @ 80 mA. Finally, the total required power to feed the cavities and accelerate the beam is estimated to

3,049 kW, with no margin. The total efficiency of the IH-DTL system is 56 %.

The accelerating gradient was defined to optimize both the beam dynamics and the efficiency of the system (see Table 3). It is low for the first cavities, in order to optimize the longitudinal emittance. It is high for the middle cavity, in order to quickly increase the speed, and thus, the rigidity of the beam. It decreases a bit for the last cavities, in order to improve the efficiency of the LINAC. The electric peak field is limited to 24.3 MV/m (1.4 kilp).

Table 3: RF Parameters of the 12 IH-DTL Cavities

| # | Beta | Acc. (MV/ m) | RF loss. (kW) | Peak E (MV/ m) | RF beam (kW) |
|--------|--------|--------------------|---------------------|----------------------|--------------------|
| 1 | 0.0900 | 1.4 | 11.2 | 10.2 | 28.1 |
| 2 | 0.0963 | 2.95 | 50.1 | 21.1 | 63.5 |
| 3 | 0.1058 | 3.5 | 74.0 | 24.3 | 82.7 |
| 4 | 0.1167 | 3.12 | 74.8 | 21.8 | 104.1 |
| 5 | 0.1289 | 3.4 | 96.8 | 24.3 | 128.1 |
| 6 | 0.1418 | 3.4 | 106.6 | 23.5 | 142.3 |
| 7 | 0.1548 | 3.4 | 117.2 | 23.7 | 156.9 |
| 8 | 0.1679 | 3.4 | 130.0 | 24.1 | 170.2 |
| 9 | 0.1810 | 3.4 | 143.6 | 23.5 | 185.2 |
| 10 | 0.1941 | 3.4 | 158.8 | 23.7 | 202.2 |
| 11 | 0.2073 | 3.4 | 175.5 | 22.6 | 219.5 |
| 12 | 0.2204 | 3.4 | 194.5 | 22.5 | 233.4 |
| Total: | | | 1333 | | 1716 |

The last IH-DTL cavity is represented in Figure 3. Its length is a bit more than 1 m. The distance between two stems is constant. Figure 4 shows the E-fields in this same cavity, with an RF coupler. The electric field is higher in the center of the cavity, leading to higher accelerating fields in the central gaps. The first and last gaps are twice smaller, to improve the global flatness.

The coupler will be identical to the Spiral 2 RFQ couplers. They have already been qualified in the frame of the Spiral 2 project [4] and will be used as well for the Newgain project. A prototype cavity, with a coupler, will be tested in the end of 2025.

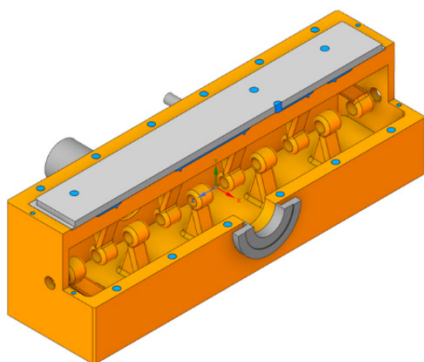


Figure 3: Figure of the last IH-DTL cavity, with 10 stems.

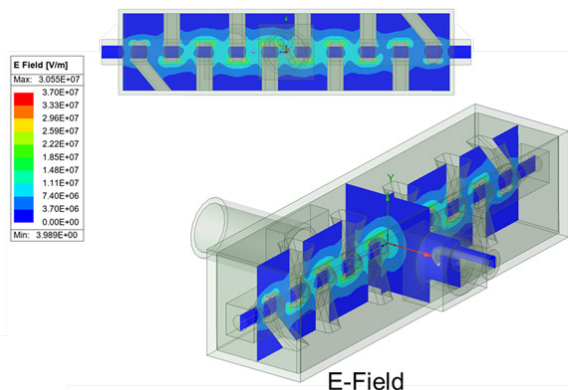


Figure 4: E- field in the last cavity, with a Spiral-2 RF coupler.

THE ALVAREZ DTL ALTERNATIVE

A possible alternative to the IH-DTL is an Alvarez DTL, like the first tank of ESS DTL [5]. Using the ESS DTL as a baseline, a new DTL design has been done to fulfil the ICONE project specifications. The main characteristics, different from ESS DTL are the length of 8.76 m, the lattice scheme FFDD, the final energy of 25.45 MeV, with 66 gaps and a peak copper power of 1.246 MW, which already includes a 25% margin demonstrated with the high-power operation of the ESS DTL tanks [6]. While the peak power values are the same as the ESS DTL, the enhanced duty cycle has been evaluated with RF and thermal simulations on the critical components like the drift tubes, tanks, RF windows, confirming the sustainability of the thermal load. The RF power at full beam current and full duty cycle can be filled by two RF couplers, each one driving 1.5 MW peak power. The error study has been performed starting from the RFQ output beam distribution, including the MEBT source of errors. The result is that losses are below 1 W/m in the 99% of the cases. The distribution of post couplers for stabilization has been defined and a 3D RF design demonstrates the capability to obtain a Tilt Sensitivity of about 10%/MHz and a field uniformity below 2 % with the use of 27 post-couplers (see Figure 5).

RF AMPLIFIERS REQUIREMENTS

This section presents the required infrastructure to provide the RF power for the ICONE accelerator, in particular for the following RF cavities:

- The Radio Frequency Quadrupole (RFQ)
- The rebunchers (MEBT)
- The Alvarez or IH-DTL.

The ICONE accelerator will benefit from CEA experience on SOLEIL and TITAN accelerators, operating at the same frequency, based on similar technology of amplifiers and using a command regulated via demonstrated LLRF systems.

Adding some margin to compensate for several effects such as beam loading, raise time, etc., the minimal required RF duty cycle is set to 10%. The amplifiers will be Solid State Amplifiers (SSA), providing modularity regarding the available power, operating at 352 MHz, with a 1 MHz bandwidth.

To compensate for the manufacturing error, for the worst case, slug tuners should be inserted. For the RFQ it could increase the dissipated power by 33%. An additional margin (10% for RFQ, 5% for the other cavities) is added to compensate for uncertainties regarding the simulations (power dissipation added by wall roughness, unexpected loss through RF gasket...). Finally, a margin (20% for RFQ, 15% for other cavities) is added to compensate reflected power due to a possible detuning of the cavity.

We considered the modularity of the SSA as an opportunity to specify twice the required power as the required maximal power, and then avoid buying SSA which would not be required after measurement of the real performances of the cavities, once the cavity is delivered and almost conditioned.

As a preliminary design, we assumed that the amplifiers would be gathered on one side of the LINAC on an area of about 150 m² (including corridors between the cabinets).

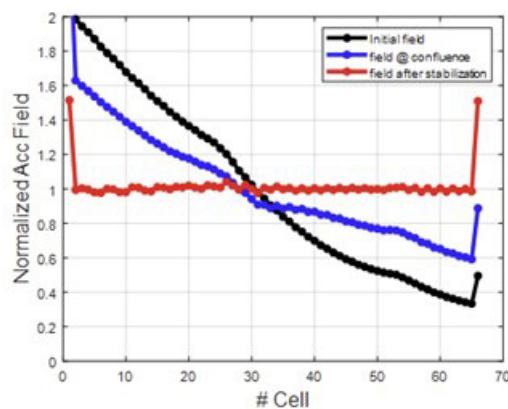


Figure 5: Field of the Alvarez ICON E DTL before and after the process of stabilization.

CONCLUSION

A first version of the technical report for manufacturing of the cavities has been prepared for evaluation by the ICON E project. A decision should be taken in the beginning of 2026 about its realization.

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