ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB027

ELECTROMAGNETIC DESIGN AND CHARACTERIZATION OF AN S-BAND 3-CELL RF ACCELERATION CAVITY

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Abstract

An S-Band (2998 MHz) Radio Frequency (RF) cavity to accelerate electrons was developed taking into account the beam space charge, the relativistic change in velocity of the low energy beam particle distribution through the cavity, and the emittance growth. The electromagnetic design and geometry optimization were done using the codes Poisson Superfish (PSF) and CST Studio (CST). In addition, beam dynamics simulations were done using the program Travel to optimize the emittance and take into account the space charge effect.

INTRODUCTION

In recent years, Mexico has promoted the development of particle accelerators [1] for industrial applications and the development of fundamental research [2]. The 3-cell RF cavity has been studied for several applications in electron accelerators [3,4]. This work presents the design of 3-cell RF cavity which takes into account the beam dynamics evolution along the cavity, to improve the acceleration efficiency and keep the emittance growth controlled.

A low emittance beam is essential to enhance the capabilities of the machine in the next acceleration stages, where the beam acceptance can be limited, especially when the goal of this 3-cell RF cavity is to fit a broad range of accelerator applications as synchrotron radiation e-linac, industrial accelerators, and free electron lasers.

The selected RF cavity design is a 3-cell cavity that accelerates the electron beam using the S-Band frequency (2998 MHz) in the $\pi/2$ mode to accelerate in a stable condition.

In order to improve the acceleration efficiency, the design takes into account the electron beam average velocity within the system to set the cavity length, instead of the classical half cell approach [5]. This work reports the electromagnetic design, mechanical design, manufacturing, resonance frequencies measurements, and beam dynamics simulations of the 3-cell RF cavity.

METHODOLOGY

The first step in the construction of this 3-cell RF cavity was the electromagnetic design. This study allowed us to know the behavior of electromagnetic fields within the cavity and thereby modify the geometry to optimize the RF electric field of acceleration.

The simulation codes used were Poisson Superfish (PSF) [6] and CST Studio (CST) [7] for 2D and 3D electromagnetic models, respectively.

The dimension of each cell was calculated considering the increase in the energy of the electrons [8]. From the results of the simulations, the electric fields and resonance frequencies were compared for modes zero, $\pi/2$ and π. The main parameters of the designed cavity are shown in Table 1.

Table 1: Main Parameters of the 3-cell RF Cavity

Parameter	Values
Input Beam Energy	100 keV
Design Frequency	2998 MHz
Acceleration Gradient	6.048 MV/m
Quality Factor	20582
Transit Time Factor	0.485
Shunt Impedance	6.1153 MΩ
R/Q	297 Ω
Beam Pipe Radius	1 cm
1^{st} Cell β	0.55
2^{nd} and 3^{rd} Cell β	0.70
Distance Between Cells	0.41 cm

Once the electromagnetic study and the optimization of the cavity geometry had finished, the mechanical design was continued in the Inventor Autodesk program [9]. For machining reasons, the cavity was built in four pieces which were later joined, and for reduction of costs, the cavity models were made of aluminum. The fabrication was done in a Computer Numerical Control machining center. Figure 1 shows the simulated and machined parts.

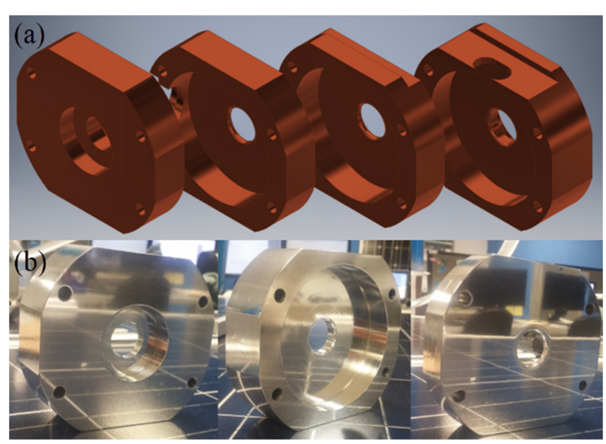

Figure 1: Mechanical design (a) and machining (b).

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The next step was to assemble the parts to form the cavity and make measurements of the resonance frequencies using a spectrum analyzer, the measurements were compared with the simulations performed earlier.

Beam studies were done to select the optimal phase of the resonant RF electric field, because the energy gain depends on the phase between the RF electric field and the particles, but the point of maximum energy gain is not necessary the one where the emittance is lower.

Additionally, studies of the emittance growth as a function of beam size were done. To evaluate the emittance growth produced by the cavity beam tracking, simulations were done using the Travel CERN program [10]. The beam distribution has a Gaussian profile with an initial energy of 100 keV, Table 2 provides a summary of the initial beam parameters used in the beam tracking.

Table 2: Input Beam Simulation Parameters

Parameter	Value
Particles	30,000
Frequency	3001 MHz
$\varepsilon_{\text{norm, trans}}$	0.65 mm mrad
$\alpha_{xx'} = - \alpha_{yy'}$	-4.5
$\Delta\Phi$ (1 σ)	0.3 degrees
$\Delta E/E$ (1 σ)	3 %

RESULTS

Using the simulation codes mentioned above the geometry of a 3-cell RF cavity was optimized, which was built, assembled and characterized. Additionally, beam dynamics simulations were done, the results are presented below.

Frequencies Comparisons

The RF electric fields inside the cavity and the resonance frequency for the 2D model and 3D are in Fig. 2. Also, Table 3 presents the values of the resonance frequencies for the studied modes that exhibit a good agreement between simulations and measurements.

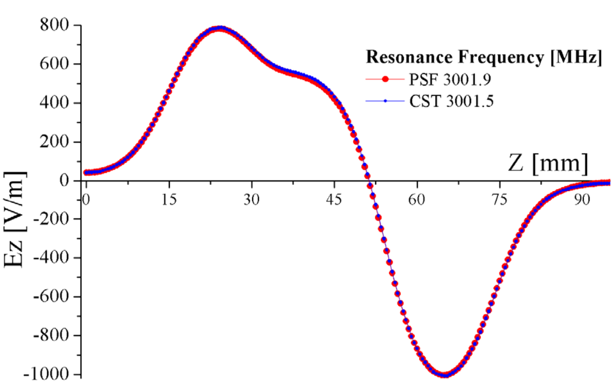

Figure 2: Longitudinal EF at r = 0 for π/2 mode.

The difference between simulations and measurements can be improved using a tuner within one cell. A 3D model had been made to add RF tuners to the design in order to control the resonance frequencies in ±13 MHz if the constructed design needs to be corrected.

Another source for the difference arises from the cavity supports system that is under redesign for better matching. However, the resonant modes are far apart which indicates that there can be a stable acceleration using π/2 mode.

Table 3: Comparison of Measured and Simulated Resonance Frequencies

Case	Mode 0 (MHz)	Mode π/2 (MHz)	Mode π (MHz)
Measurements	2975±3	3007.1±3	3040.4±3
PSF	2977.4	3001.9	3022.9
CST	2977.3	3001.6	3022.7

Beam Study

Figure 3 shows how the average energy and RMS emittance of a beam change when exiting the RF cavity as a function of the RF electric field phase. It can be observed that for the phase from -55 to -90 degrees the emittance remains practically constant while the energy increases considerably. In the region from 0 to -40 degrees the energy gain remains constants while the emittance growths considerable, this location was considered the worst region to inject the beam.

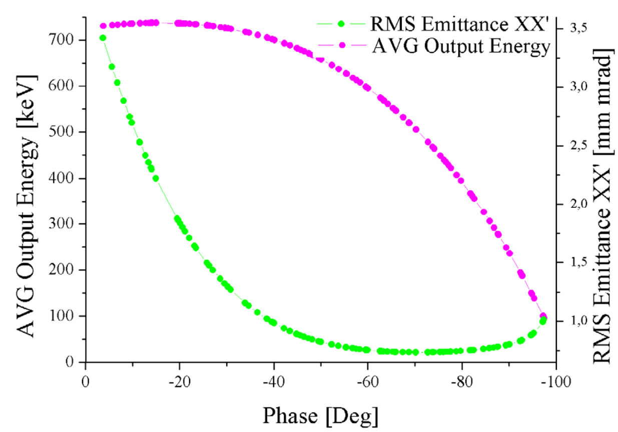

Figure 3: Variation of output energy and beam emittance when changing resonant RF electric field phase. A σ = 1 mm beam size was used.

In Fig. 3 can be seen that to achieve lower emittance growth and higher energy gain the optimal phase is -65 degrees. These results suggest that if the emittance is the most important parameter the cavity can be used to accelerate electrons from 100 to 550 keV as its maximum energy.

Figure 4 shows the particles distribution before and after being accelerated by the cavity for an input beam of σ = 1 mm RMS size and entering to the cavity at -65 degrees RF electric field phase.

Figure 4-(c) shows that the particles are accelerated with a low energy dispersion, the difference between the most energetic particles with the least energetic is only 35 keV.

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For the optimal selected phase of -65 degrees studies were conducted to evaluate the dependence of growth on emittance with the radial input beam size.

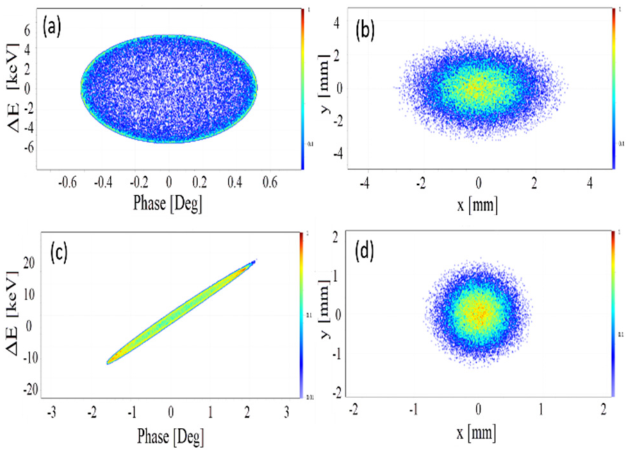

Figure 4: The particle distribution. For the input beam: (a) in phase space centered at 100 keV and (b) transversal cut in real space. For the output beam: (c) in the phase space centered on 555 keV and (d) transversal cut in real space.

Figure 5 showed that for a $\sigma \geq 1.5$ mm the growth in emittance increase considerably, the reason is that in regions far from the center of the cavity the radial component of the RF electric field is large enough to blur the particles, but for $\sigma < 1.5$ mm the emittance practically remains constant.

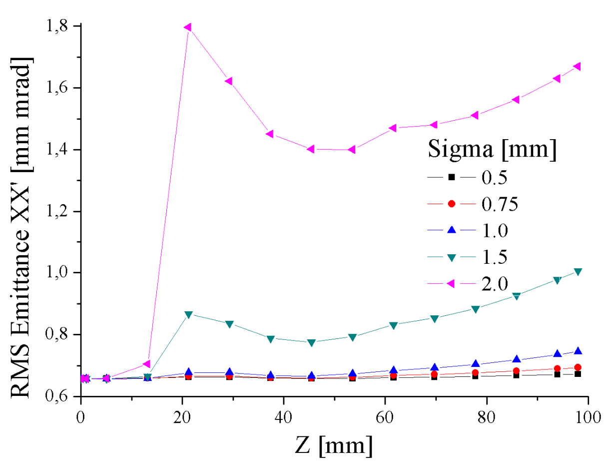

Figure 5: Emittance growth through the cavity.

CONCLUSION

An electromagnetic design of a 3-cell RF cavity was developed for an electron linac using the simulation program PSF (2D model) and benchmarked with CST (3D model). The comparison of the PSF and CST designs present a good agreement in the frequency operation and the longitudinal electric field (See Fig. 2).

In addition, the measurements of resonances frequencies were made to compare with the simulation modes. Table 3 shows a good match between them.

Finally, the beam dynamic studies help to select the initial parameters to reduce the emittance growth. Figure 3 indicates that there is a window of 35 degrees where the cavity provides an adequate tradeoff between lower emittance growth and higher energy gain.

Additionally, the evolution of the different beam sizes shows a good control of the emittance growth for beam size lower than 1.5 mm (1 σ).

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