Design and Test of a Prototype Cavity for the ELFA Injector

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Abstract

We investigated the RF properties of some possible designs for the injector cavities of the ELFA project. By using a combination of computer simulations and lumped parameter models, a design procedure has been found. The method has been checked by measuring the field distribution on an aluminum 1:5 prototype. A very good agreement between the computer simulations and the experimental results was found.

1 INTRODUCTION

The ELFA (*Electron Laser Facility for Acceleration*) Project [1] has the aim to construct a single pass free electron laser to test different regimes of radiation emission at different wavelengths (λ = 3-8 mm), with high gain and high output power, in the range of GW, also testing the existing of three different regimes: *Steady State, Weak* and *Strong Superradiance* [2].

In order to obtain the maximum energy transfer between the electron beam and the electromagnetic field, to limit the energy spread of the radiated electromagnetic field and to investigate the Superradiant regimes, very tight requirements on beam parameters are imposed (see Table 1).

Table 1: Required Beam Parameters

Peak Current	400 A
Micropulse Length	200 psec
Charge per Micropulse	80 nC
N. of micropulses	4
Energy	10 MeV
Energy Spread	1 %
Normalized Emittance	5 10^2 mm mrad

The fulfilment of the aforementioned requirements is obtained only by reducing the space charge effects, at the first approximation proportional to $1/\gamma^2$.

A possibility to overcome the space charge effects is to use as an injector for the accelerating structure a Photocathode housed in a suitable RF cavity (RF Gun).

The conditions reported in Table 1 can be obtained by using very high accelerating fields in the first cavity of the RF Gun and with an appropriate ratio of peak accelerating fields in the different cavities of the structure.

We present an investigation on an RF structure both theoretical, by means of lumped parameters models and computer codes simulations, as well as experimental, by means of an aluminum prototype of the injector cavity.

The result was a structure very simple to realize and multipactoring free at low field levels.

2 GENERAL CHARACTERISTICS OF THE INJECTOR

Though several designs of the injector were possible, from beam dynamics calculations it was concluded that some general features had to be satisfied to optimize the structure performance [3].

The RF Gun is composed of two 352 MHs, normal conducting, accelerating cavities. The first one, $\lambda/4$ long, presents a flat wall where the photocathode is housed. The shape of this cavity was designed to minimize the emittance growth. The second one is a standard $\lambda/2$ accelerating structure designed to maximize the shunt impedance [3].

The overall energy gain in the injector is 3 MeV, which added to the 7 MeV gained in the accelerator (LEP II four-cell superconducting-cavity) gives a total beam energy of 10 MeV at the wiggler. This energy gain can be reached, consistently with required emittance values, with an average field of 9.4 MV/m in the first cell and 5.6 MV/m in the second cell.

A magnetic focusing system should be provided at first cell stage to reduce emittance growth. This implies that no separate RF feed is possible for the two cavities. A single RF feed should be used in the $\lambda/2$ cell and so an high coupling is necessary in the structure due to the repetition rate required for FEL performance. In practice coupling coefficients between the two accelerating cells ranging from 2 % to 4 % have been obtained.

3 INVESTIGATION METHODS

Lumped parameters models and computer codes calculations were used during the injector design. Their results were tested by means of a prototype cavity (scale 1:5) suitable to investigate different designs.

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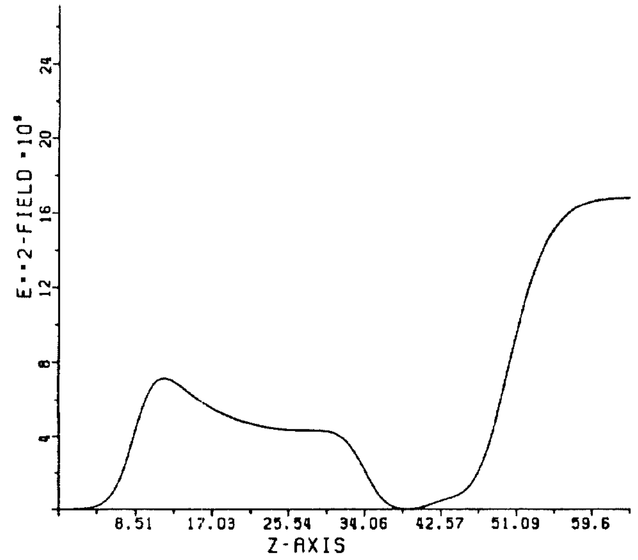

Figure 1: OSCAR 2D Calculated Axial Field for the Three-Cell Structure.

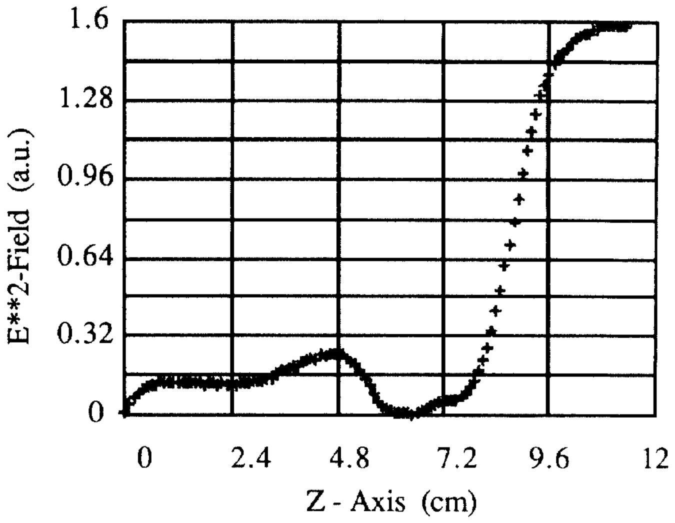

Figure 2: Measured Axial Field Distribution for the Three-Cell Structure (coupling coefficient=2.5 %).

3.1 Computer Simulations

Two different structures were studied: a three-cell cavity (two accelerating cells and a central coupling cell) operating in the $\pi/2$ mode; and a two-cell structure (without coupling cell) operating in the π mode.

For the initial approach to the problem 2D codes (SUPERFISH and OSCAR2D [4]) were used and their results were found in very good agreement. However the 2D calculations were limited to the possibility of investigating only structures in electrical coupling.

The principal result of the simulations was that the fields distribution in the coupled structure is different from that calculated for the single-cell case. In particular for coupling coefficients of 3-5 %, the electric axial field in the $\lambda/2$ cavity shows a strong asymmetry between the two peaks near the noses. This effect grows with the coupling coefficient and in the electric coupling case we have the peak near to the coupling slots lower than the other (see Fig.1). We can anticipate that during the experimental tests on the magnetic coupling case, we still find the asymmetry but with the peak near to the coupling slots greater than the other.

3.2 Lumped Elements Equivalent Circuit

A different theoretical approach was used, based on a lumped elements equivalent circuit of the injector cavity.

We found that for the three-cell structure the condition of null field in the coupling cell is in contrast with a fixed choice of fields ratio in the accelerating cells because the ratio is determined by the coupling coefficients between the accelerating and coupling cells, and at the same time by the equations for the two-cell structure.

With this method, for this last structure, both the electrical and the magnetic coupling problems were solved, finding the ratio of the frequencies of the accelerating cavities which follows from the request of a suitable coupling coefficient and a fixed ratio of the accelerating fields.

3.3 Experimental Results

In order to verify the results obtained with computer simulations and lumped elements model, two prototypes in reduced scale at 1.8 GHz were built to study both the three-cell as well as the two-cell structure.

The measurements were performed introducing a small dielectric probe inside the cavities and monitoring the resonant frequency shift due to the perturbation. Slater's perturbation theory [5] allowed us to deduce the axial fields distribution and coupling coefficient values with different coupling-slots area.

The agreement between calculations and experimental results was in general very good, showing that when the ratio of the mean accelerating fields is different from one there is always some stored energy in the coupling cavity, while it is expected to be empty when operating in the $\pi/2$ mode. The relationship between fields ratio and single cell frequency was also confirmed.

The presence of asymmetry in the accelerating field of the $\lambda/2$ cavity predicted by computer simulations was experimentally verified, though its features are different from those calculated, as stated before (see Fig. 2).

This disagreement is explainable with the difference in the coupling mechanism between the real structure, magnetically coupled via the coupling slots, and the 2D simulated structure, electrically coupled.

Furthermore, the different field shape with respect to the uncoupled system, experimentally confirmed, should be borne in mind for further computer beam dynamics simulations.

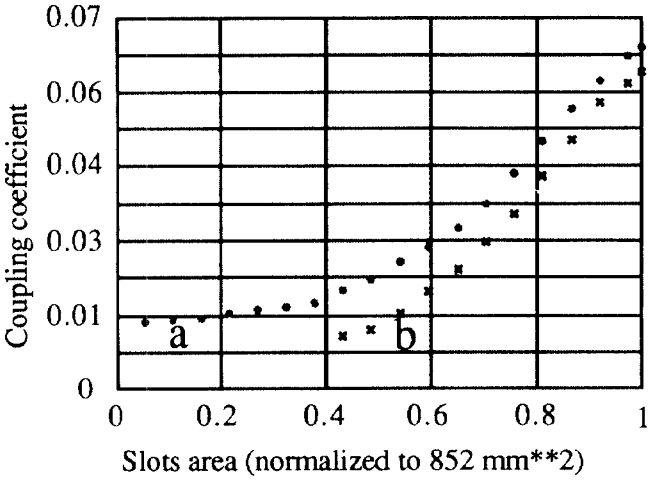

Figure 3: Measured relationship between the Coupling Coefficient and Slots Area for the Two-Cell Structure.

The variation of the coupling coefficient with slots area was measured: in Fig. 3, curve (a) shows the measurement result when the resonant frequencies of the two cells are different; curve (b) shows the same quantity when the frequencies are equal.

4 MULTIPACTORING

As previously stated, the tilt in the mean accelerating fields of the $\lambda/4$ and $\lambda/2$ cells has the consequence that some electromagnetic energy is present in the coupling cell. This field, which during the measurements is found to be approximatively the 20 % of the field in the $\lambda/2$ cell, is responsible for the build up of two-point multipactoring levels previously found in this cell in structures of the same kind already operating at different frequencies [3]. This behaviour can be easily predicted by a simple model of the dynamics of one electron in an RF field [6]. It is found that resonant discharges build up at voltages across the gap of

$$V_n = 4\pi m_0 c^2 \left(\frac{L}{\lambda}\right)^2 \frac{1}{2n-1} \tag{1}$$

In our case the gap lenght is L=2.2 cm. It follows that:

$$V_n = \frac{15}{2n-1} kV \tag{2}$$

This condition is easy to be reached. The shortness of the gap makes the impact energy not high enough to have secondary emission coefficient greater than one. Eliminating the coupling cell, like in the structure operating in π mode, the remaining cavities are too wide to allow the build up of two-point multipactoring.

5 CONCLUSIONS

We compared, computationally and experimentally, two coupled structures for the injector cavity, composed by two and three cells respectively.

Due to their shortness, at first-order perturbative-theory level the two structures are not distinguishable.

Experimentally we found a similar general behaviour for the two systems as far as accelerating field shapes are concerned.

The two cell cavity presents the advantages of being mechanically simpler and easier to tune according to the lumped elements model. It is multipactoring free in the concerned field range and avoids the problems on beam dynamics tied to the presence of field in the coupling cell.

6 REFERENCES

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