RF DESIGN OF A SINGLE CELL SUPERCONDUCTING ELLIPTICAL CAVITY WITH INPUT COUPLER

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Abstract

A prototype single cell elliptical cavity for accelerating 100 MeV high intensity proton beam has been designed [1]. The cavity shape is optimized for cavity $\beta_g = 0.42$ at a frequency of 700 MHz. using SUPERFISH [3] code. Calculated Q value of the cavity is 0.61×10^9 at 4.2 K. A rigorous analysis of trapped modes via eigenmode and time domain simulation [8] has been done in the frequency range 2 – 5 GHz using CST MICROWAVE STUDIO [9]. The result shows Q value of the order of 10^3 for trapped modes. This analysis also removes the ambiguity of some candidates which are treated as trapped modes in closed cavity model. An input power coupler is also designed on the basis of operating frequency and source power. It has been designed taking into account the advantages of both the waveguide type and coaxial type coupler. The optimized coupler parameters are calculated that provide perfect matching ($Q_0 \approx Q_{ext}$) under different operating conditions. For superconducting coupler with 20 mA beam load the optimized coupler position w.r.t. cavity centre is 13 cm, penetration depth is 0.2 cm and the evaluated Q_{ext} = 1.39 E +6. The calculated resonance frequency under beam loading condition due to the presence of coupler is 699.807 MHz

INTRODUCTION

A high current proton linac (1 GeV, 30 mA) has been considered for many applications [2]. In the high energy part of this accelerator RF superconducting elliptical cavities are used to accelerate protons up to 1 GeV [4]. In this report we will discuss the RF design of a prototype single cell elliptical cavity with input power coupler. Cavity shape optimization has been done by means of 2D simulation code SUPERFISH. Since trapped higher order modes are one of the dominating factors from the point of view of beam instabilities we studied the trapped modes with the conventional eigenmode analysis as well as with the time domain analysis using CST MWS.

OPTIMISATION OF CAVITY SHAPE VARIABLES

An elliptical cavity design is a compromise between various geometric parameters [5]. The main advantage of any SC cavity is a possibility of high accelerating electric field gradient E_{acc}. The peak surface electric field E_{pk} and the peak surface magnetic field H_{pk}, limit an achievable value of E_{acc}. To maximize the accelerating field it is necessary to minimize E_{pk}/E_{acc} and H_{pk}/E_{acc}. There are some more figures of merit to compare different designs such as power dissipation, quality factor Q and effective shunt impedance ZT^2. But these parameters are not so crucial to the SC cavity design [5].

To achieve a most optimal cavity shape we have investigated the influences of cavity shape variables on E_{pk}/E_{acc} and H_{pk}/E_{acc}, then on cavity's other characteristics as well [6]. Cavity cell length L is determined by β_g value and the design frequency as $L = \beta_g \lambda/2$. We have used cavity diameter for frequency tuning [4] because it is most sensitive to frequency. From mechanical point of view circular dome is preferable [6]. So instead of an ellipse we chose a circular dome. The Wall Angle influences the mechanical behavior of the cavity. We have observed that up to wall angle 5^o the ratio E_{pk}/E_{acc} is more or less constant but after that it is strongly increasing.

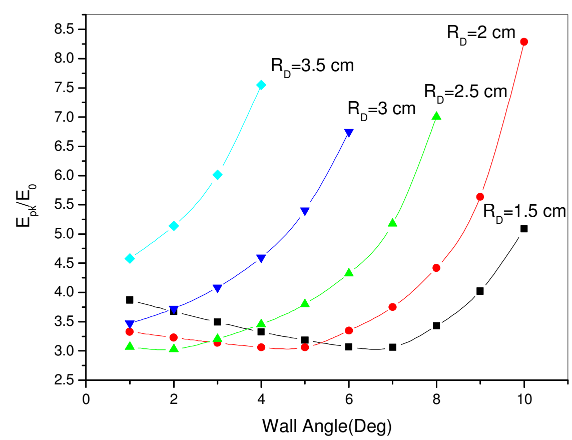

Figure 1. Variation of peak electric field with wall angle and dome radius.

So to minimize E_{pk}/E_{acc} it is desirable to keep wall angle below 5^o. Peak field and power dissipation increases with bore radius. So a smaller bore radius is preferable. Bore radius has to be considered in conjunction with beam dynamics calculations because a larger bore radius may decrease beam loss and avoid higher order mode trap. For any cavity geometry and parameters, there is an optimal value for the iris aspect ratio that minimizes the peak electric field with marginal influence on the other electromagnetic parameters [7]. It has been observed that for wall angle 4^o, E_{pk}/E_{acc} is minimum at $a_I/b_I = 0.65$. Design parameters of the single cell cavity are listed in the table below.

Table 1:

Accelerating Gradient	5 *MV/m*
Bore Radius	5 *cm*
Cell Length L	8.994 *cm*
Cavity Diameter	37.384
Wall Angle	4^o
Iris a_I/b_I	0.65
Dome Ellipse a_D/b_D	1
Dome Radius r_D	2.5 *cm*
E_{pk}/E_{acc}	3.6
H_{pk}/E_{acc}	8.3 *mT/MV/m*
Q	$0.61\text{X}10^9$ @4.2*K*
r/Q	8.069 Ω

BASICS OF TRAPPED MODES

We have simulated one quadrant of the cavity cross-section with proper boundary conditions at the symmetry planes using the program CST Microwave Studio. With these boundary conditions only odd azimuthal numbered modes (i.e. dipole, sextupole ….etc) are excited. Total Q value is determined as follows [10],

$$1/Q_{TOT} = 1/Q_{RAD} + 1/Q_{MAT}$$

Q_{MAT} considers the wall current loss where as Q_{RAD} takes into account the loss of the travelling modes through the beam tube ports. Cavity modes with high Q_{RAD} factors are identified as trapped modes. In superconducting cavities material loss is small and we have neglected Q_{MAT}.

EIGEN MODE ANALYSIS

The conventional eigenmode analysis of the cavity structure includes two different kinds of terminations, in one case the beam tube is terminated with ideal electric wall (PEC) and in other it is terminated with ideal magnetic wall (PMC). With this the corresponding frequencies are calculated and the influence due to the change in boundary condition (B.C) is used to infer the presence of the possible trapped modes. In this respect the coupling factor K is defined as follows [10],

$$K = 2\frac{|f_M - f_E|}{f_M + f_E}$$

Where f_M and f_E are resonance frequencies of the cavity terminated with PMC and PEC walls respectively. Table 2 shows the result of the calculated dipole modes with the indication of possible trapped modes in the frequency band 2.5-5 GHz.

Table 2: Influence of B. C on the eigenmodes.

No	f_E	No	f_M	f_{mid}	K=Δf/f
5	2.84271	5	2.84271	2.84271	0
6	2.94567	7	2.94705	2.94636	0.00047
8	2.21259	8	3.21259	2.71259	0.36865
9	3.30792	10	3.30792	3.30792	0
11	3.36781	11	3.36777	3.36779	1.19E-05
12	3.37565	12	3.37565	3.37565	0
14	3.6781	14	3.67808	3.67809	5.44E-06
15	3.70969	15	3.70951	3.7096	4.85E-05
16	3.7414	17	3.74141	3.74141	2.67E-06
19	3.85274	19	3.85264	3.85269	2.6E-05
		20	3.89901	3.89901	
20	3.90357	21	3.90506	3.90432	0.00038
24	4.12039	24	4.12039	4.12039	0
25	4.19012			4.19012	

TIME DOMAIN ANALYSIS

In the time domain analysis of the open structure we have introduced few virtual probes in the inner volume. In the simulation process we have chosen a modulated Gaussian pulse in the frequency range 2.5-5.0 GHz with centre frequency at 3.75 GHz. A typical Discrete Fourier Transform (DFT) of the amplitude signal of one of the virtual probes is shown in Figure 2.

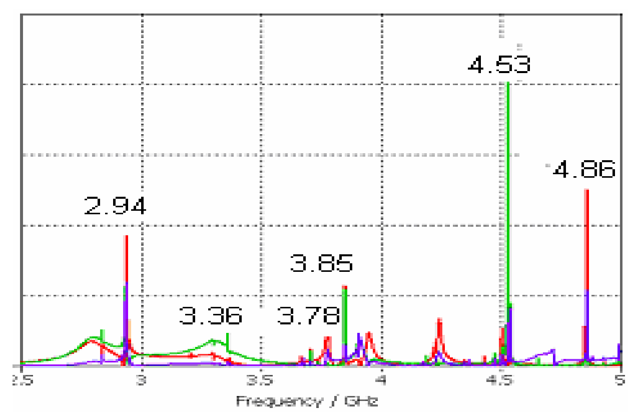

Figure 2. Spectra of some e-field probes as a result of DFT

It is found that some modes of the eigen mode analysis do not show up at all in the time domain open structure analysis.

Table 3. Comparison of conventional eigen mode analysis and time domain analysis.

Eigen mode with magnetic BC		Time domain analysis	
No.	f_{res}	f_{peak}	Q value
7	2.95	2.94	1062
11	3.3678	3.3625	919
17	3.741	3.776	491
19	3.85	3.85	2092
×	×	4.528	2551
×	×	4.86	2283

In conclusion we may say that this approach produces the true trapped eigen modes within the elliptic cavity. The last two resonances exited in TDA are sextupole modes.

DESIGN OF POWER COUPLER

Two types of couplers can be used viz., waveguide type and co-axial type. Both have some advantages and disadvantages in terms of design, power handling capacity and multipacting.

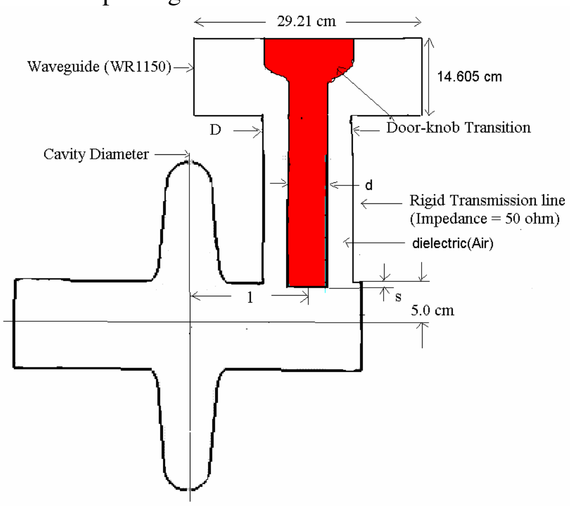

Figure 3. Schematic of cavity with Coupler

In SC cavity field levels are much higher hence to avoid the electric field breakdown and the multipacting, position of the coupler is chosen to be on the beam axis of the cavity where the field levels are much lower as compared to the actual cavity. The power flow to the accelerator is maximum when source is matched or critically coupled (β~1 or Q_0~Q_{ext}) to the load i.e. accelerator. Considering the above factors, coupler was designed to obtain Q_{ext}~1.39 x 10^6 at a beam current of 20 mA [11].

Power generated by power source is carried by waveguide up to the cryostat. Inside the cryostat a co-axial antenna having characteristic impedance~50 Ω and air as dielectric, is used to feed power to the cavity. The coupler port is situated on the beam pipe of the cavity. The junction between waveguide and co-axial coupler is designed to ensure loss-free transition (Door-knob transition).

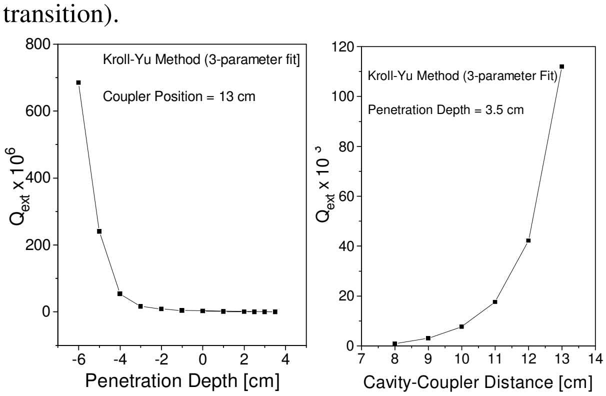

Figure 4. Effect of Penetration Depth and coupler position

The optimization of coupler parameters like penetration depth, position etc., to obtain required Qext was carried out using Kroll-Yu method [12] with the help of CST Microwave Studio. Coupler placed at a distance of 13cm from cavity center and at inner conductor penetration of 0.2 cm could provide required Qext. The calculated resonant frequency was about 699.804MHz.

DESIGN OF DOOR-KNOB TRANSITION

Transition between rectangular waveguide and co-axial line can be designed in numerous ways. Of which door-knob transition is widely used as it provides broadband matching and is more reliable at high power [13]. The position and the size of the door-knob was optimized to achieve return loss~ -32.55 dB and transmission loss ~ 0dB at a frequency of 700 MHz which indicates matched transition.

CONCLUSIONS

Cavity shape optimization of a prototype single cell superconducting elliptical cavity has been done using SUPERFISH code. Trapped higher order modes inside the cavity are analyzed using CST MSW code. An input power coupler has been designed taking advantages of both waveguide and coaxial coupler.

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REFERENCE

[1] A. Roy et al., “Preliminary Design of a RF Superconducting single cell elliptical cavity for proton linac.” INPAC 2005.
[2] N. Ito et al. Proc. of the 18th Int. Linear Accelerator Conf., Geneva, Switzerland, p671 (1996)
[3] J. H. Billen and L. M. Young, Proceedings of the 1993 Particle Accelerator Conf., Vol. 2, p. 790.
[4] H. Padamsee et al Cornell University Ithaca, New York “RF Superconductivity for Accelerators” Wiley-Interscience Publication (1998)
[5] E. Zaplatine et al Germany, Proceedings of the 1999 Particle Accelerator Conference, New York, 1999
[6] C. Pagani et al, Italy SRF 2001.
[7] D. Barni et al, INFN Milano- LASA EPAC 2000
[8] J. Mondal et al, “Analysis of Trapped Modes in 700 MHz Single Cell RF Superconducting Elliptic Cavity” INPAC 2005
[9] CST Microwave Studio 5.0, (www.cst.de)
[10] R.Schuhmann et al., “Rigorous Analysis of Trapped Modes in Accelerating Cavities”, TESLA-report 2000-08, DESY.
[11] A.S.Dhavale et al., “Design of Power Coupler for SC cavity for ADSS Project”, BARC Internal report
[12] N.M.Kroll et al., “Computer determination of the External Q and Resonant Frequency of Waveguide loaded cavities”, SLAC-PUB-5171, Jan 1990 (A)
[13] “Microwave Transmission circuits”, edited by G.L.Ragan, Radiation laboratory Series, McGRAW HILL Book Company Inc., 1948, p 349