METAMATERIAL-BASED ACCELERATING, BENDING AND FOCUSING STRUCTURES

I. McGregor, K. M. Hock, University of Liverpool, Liverpool, UK and
Cockcroft Institute, Warrington, UK

Abstract

We report on the progress of our research into metamaterial-based accelerating, bending and focusing structures at the Cockcroft Institute. The effort during the last year has been directed towards designing and investigating practical RF structures that are suitable for industrial and medical applications. We have shown that, by introducing structures based on metamaterial resonators, RF accelerating structures can be made more compact and higher gradient. This year, we will concentrate on focusing and bending structures.

INTRODUCTION

Metamaterials are artificially engineered electromagnetic media which exhibit simultaneous, effective, negative permittivity and permeability over some finite frequency range. They exhibit unusual characteristics which are not found in naturally occurring electromagnetic media, including reverse-orientated Cerenkov radiation, inverse Doppler shift and negative refraction [1]. Owing to these unusual properties, metamaterials have received much attention in fields as diverse as electromagnetic cloaking [2], travelling wave amplification at microwave and mm-wave frequencies [3,4] and particle accelerator technology [5].

The negative permeability is usually obtained from Split-Ring Resonators (SRRs) [6] and the negative permittivity from wires or Complementary Spit-Ring Resonators (CSRRs) [7]. Both SRRs and CSRRs have the property of 'concentrating' EM energy at their resonant frequencies. This feature is used as the basis of our designs. Accelerating structures can be formed from structures which use CSRRs to concentrate electric fields. Deflecting and focusing structures can be formed by proper use of either CSRRs or SRRs. In the former case, electric dipole and quadrupole fields are used and, in the latter case, magnetic dipole and quadrupole fields. All of our structures are made from copper.

ACCELERATING STRUCTURES

Standing Wave Structure

Figure 1 shows a perspective and an internal view of the structure. The feeding rectangular waveguide has two CSRRs cut into the upper and lower walls. In order to maintain the vacuum, the spaces above and below the C-SRRs are enclosed by 'pillbox'- shaped metallic cavities. Beam pipes connecting to the outer walls of these pillbox cavities project through the centre of the CSRRs. These narrow beam pipes shield the particles from the decelerating portions of the fields of the CSRRs. The field in the space between CSRRs is, however, uni-directional.

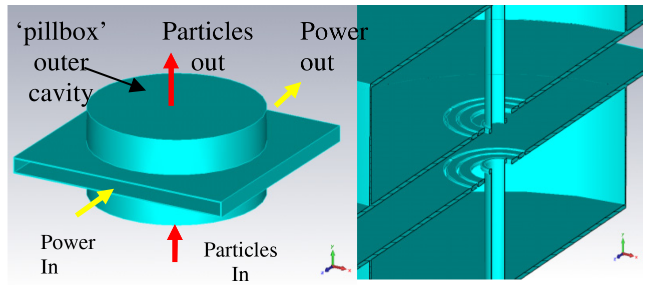

Figure 1: Perspective (left) and cut-plane (right) perspective view of the structure.

This particular design operates at 1 GHz and is 67 mm long from the bottom of one the 'pillbox' cavities to the top of the other. Due to high surface electric fields, the maximum safe RF power which can be applied is around 10 kW. At this power level, the gradient referred to the actual accelerating gap (feeding waveguide height) is 8.76 V/m. This relatively high gradient for a small input RF power and the compact size makes the structure well suited to low energy applications such as are found in proton therapy.

Figure 2 shows a phase space plot of the energy of a particle bunch as it traverses the structure. The path of the bunch as it passes through the beam pipe, is accelerated between the CSRRs and then drifts without acceleration again can clearly be seen.

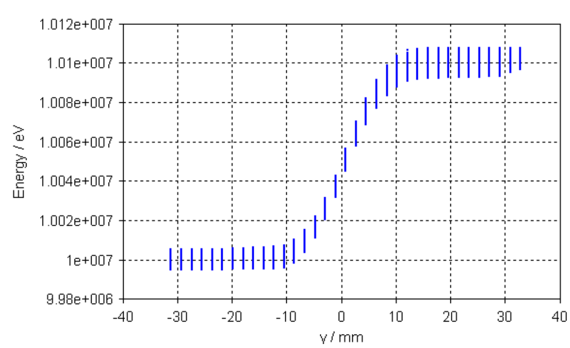

Figure 2: Phase space plot of particle bunch travelling through the standing wave structure.

Travelling Wave Structure

Figure 3 shows a perspective and internal view of the travelling wave accelerating structure. The structure can be seen to consist of a circular waveguide with, in this particular case, four cells coupled together by CSRRs. Two cells at either extremity of the structure allow power to be injected and removed from the structure via rectangular waveguides. The particle bunch is injected into the middle of the circular wall closest to the source of RF power, traverses the structure via holes in the C-SRR inner 'ground plane' and exits the structure through the middle of the outer circular wall closest to the rectangular waveguide which removes the RF power.

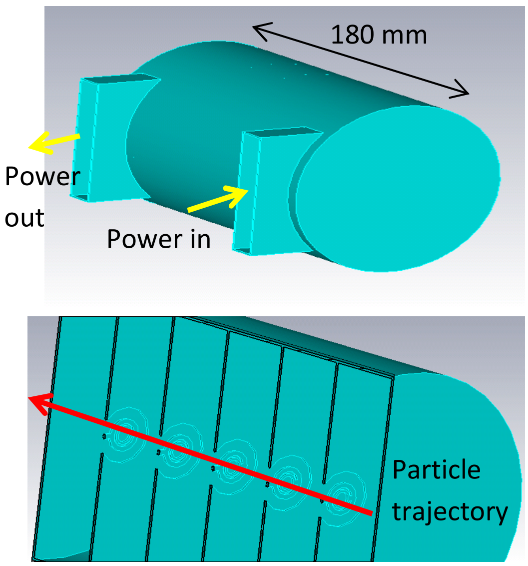

Figure 3: Perspective (top) and cut-plane perspective view (bottom) of the travelling wave accelerating structure.

This particular structure operates around 1.9 GHz. Key figures of merit for operation in the π/3 mode are given in table 1.

Table 1: Figures of Merit for Travelling Wave Structure

Frequency	RF Power	R_{shunt}	Q	Gradient
1.9 GHz	3.7 MW	1089 MΩ	2.61×10^6	17.77 MV/m

BENDING STRUCTURES

Electric Bending Structure

Figure 4 shows two views of the proposed deflecting structure. Two CSRRs are etched into the upper and lower walls of a rectangular waveguide and produce a strong uniform field in the gap between. Two inductive irises placed immediately before and after the C-SRRs shield the incoming and outgoing particle bunches from fields of opposite polarity to that desired to deflect the beam. As can be seen from figure 4, cylindrical cavities encapsulate the space above the C-SRRs. To give an indication of the scale of the structure, the width of the feeding waveguide is 100 mm.

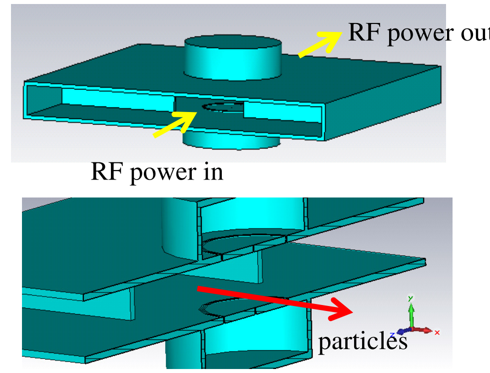

Figure 4: Perspective (top) and cut-plane perspective view (bottom) of the travelling wave accelerating structure.

Figure 5 gives some results from particle simulations. A 10 MeV electron bunch is shown to be deflected whilst passing through the structure from left to right. The applied RF power is 10 kW. The operational frequency is 2.55 GHz.

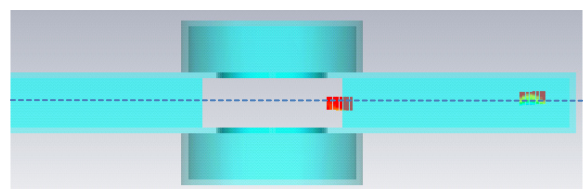

Figure 5: Plot showing path of particle bunch being deflected through the structure.

Magnetic Bending Structure

Particle accelerators traditionally make use of magnetostatic fields to bend the trajectory of particle bunches. However, there is, in some low energy applications, the need for simple, compact and inexpensive bending structures. In this section, we present a Broadside Coupled Split Ring Resonator (BSRR) – loaded waveguide structure operating at 1.3 GHz. In our structure, instantaneous field strengths of $8.10^{-5}\sqrt{P}$ Tesla –where P is the applied power - are achievable without recourse to special magnetic and/or superconducting materials.

Figure 6 shows a diagram of the structure. A modified BSRR is housed in a rectangular waveguide. The modified BSRR consists of thick metal 'immersed' in ceramic. The two rings of the BSRR are separated by vacuum to allow a particle bunch to pass through the space between. Figure 7 shows the trajectory of a 10 MeV electron bunch as it traverses the structure. It can be seen that the path the bunch follows is bent.

ISBN 978-3-95450-122-9

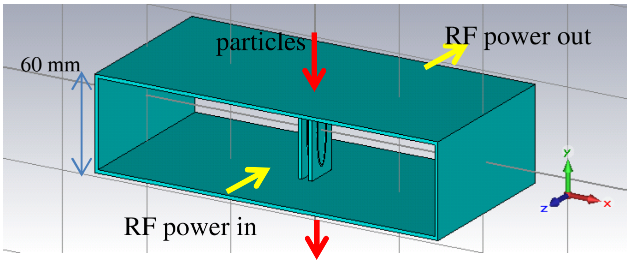

Figure 6: Perspective (top) and cut-plane perspective view (bottom) of the travelling wave accelerating structure.

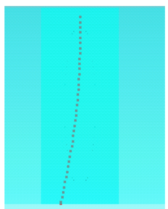

Figure 7: Plot showing trajectory of electron bunch through the structure.

FOCUSING STRUCTURES

Electric Focusing Structure

A modification to the structure shown in figure 4 can make it suitable for transverse focusing. In particular, the inductive irises are removed and one of the CSRRs is rotated by 90 degrees. Figure 8 shows a 2D cut of a 10 MeV electron bunch before and after processing by the structure. Each point represents an electron. The bunch is shown to have been focussed in the y-direction and defocused in the x direction.

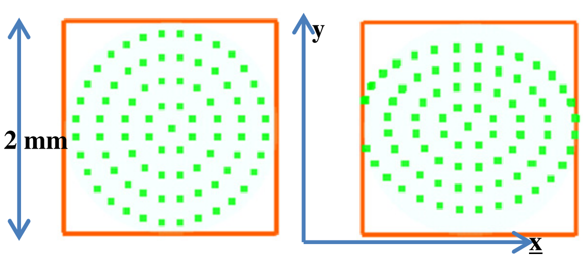

Figure 8: 2D cut of electron bunch at input (left) and output (right) of electric focusing structure (same scale).

Magnetic Focusing Structure

An SRR exhibits multiple resonances. The second resonance of the structure shown in Figure 6 has a magnetic quadrupole-like field associated with it which can be used to focus particle bunches. Figure 9 shows a 2D cut of a 10 MeV particle bunch before and after processing by the structure. The bunch is rotated and focussed in one transverse plane.

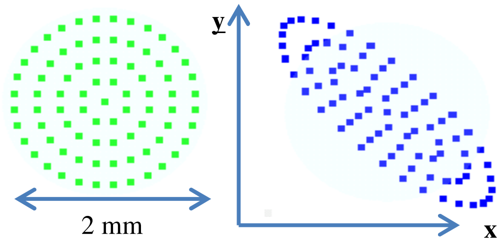

Figure 9: 2D cut of electron bunch at input (left) and output (right) of magnetic focussing structure (same scale).

CONCLUSIONS

Novel accelerating, bending and focusing structures which make use of metamaterial resonators to magnify either electric or magnetic fields have been described. We plan to make field emission studies to better determine the maximum RF powers which can be applied to the structures.

ACKNOWLEDGMENT

We thank the Science and Technology Facilities Council (UK) for financial support.

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