DESIGN OF AN ELECTRON CLOUD DETECTOR IN A QUADRUPOLE MAGNET AT CesrTA*

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Abstract

We have designed a detector that measures the electron cloud density in a quadrupole magnet using two independent techniques. Stripline electrodes collect electrons which pass through holes in the beam-pipe wall. The array of small holes shields the striplines from the beam-induced electromagnetic pulse. Three striplines cover a roughly 0.45 radian azimuth near one of the pole tips. The beam-pipe chamber has also been designed so that microwave measurements of the electron cloud density can be performed. Beam-position-monitor-style buttons have been included for excitation and reception of microwaves and the chamber has been designed so that the resonant microwaves are confined to be within the 56 cm length of the quadrupole. This paper provides some details of the design including CST Microwave Studio® time domain simulation of the stripline detectors and eigenmode simulation of the TE_{11} modes in the resonant chamber. The detector is installed in the Cornell Electron Storage Ring and is part of the test accelerator program for the study of electron cloud build-up using electron and positron beams from 2 to 5 GeV.

INTRODUCTION

At the Cornell Electron Storage Ring (CESR) we have been comparing electron cloud (EC) measurements with the results of simulations both with and without external magnetic fields for several years as part of the test accelerator (CESRTA) program [1, 2]. One measurement technique uses an electrode to sample the electron current that impacts the beam-pipe wall [3]. The simulation of EC buildup in a quadrupole shows that for a 20-bunch train of 5.3 GeV positrons, there is a non-linear increase in EC density with bunch populations greater than 1.0×10^{11} [4]. At low bunch populations, the impact of the electrons on the beam-pipe wall is centered on the poles of the quadrupole since the low energy cloud electrons generally follow the magnetic field lines. At bunch populations above 1.0×10^{11}, there is a splitting of the area of electron impact about the pole face. This splitting is large enough that our previous detector, centered on the pole face and 6 mm wide, was not wide enough to include the peak electron currents [4]. As a result, while the data shows a non-linear increase in electron current, it is not as large as predicted by the simulation.

In order to confirm the simulation results we designed and constructed a new detector (Fig. 1) with three 6-mm-wide segments, so that it would cover a wider azimuth about the pole face. Since a new vacuum chamber was to be constructed for the detector, the chamber was also designed to support measurements of EC density made using resonant microwaves [5], an independent measurement technique.

The detector is positioned inside a new quadrupole magnet (Fig. 2) that is placed near an existing quadrupole of the same polarity. Since they are powered independently, the field of the detector quadrupole can varied from zero to about 3.6 T/m with beam in the storage ring by applying a compensating reduction in the strength of the nearby quadrupole. The new quadrupole has an aperture of 150 mm dia., leaving a radial space of about 25 mm for the new detector, between the outer diameter of the beam-pipe and the pole face.

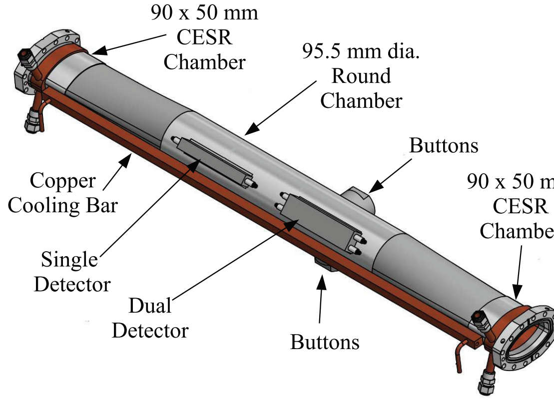

Figure 1: The detector chamber with electron detectors and the button electrodes used for microwave measurements.

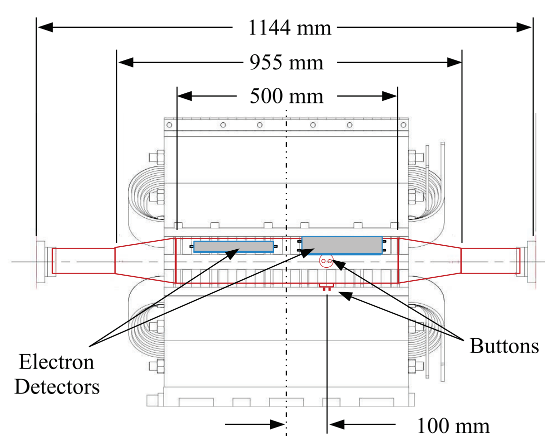

Figure 2: Detector chamber within the quadrupole magnet.

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STRIPLINE DETECTOR

The overall design of the stripline detector includes an array of 0.79-mm-diameter holes in the beam-pipe wall that attenuate the beam-induced signal and allow cloud electrons to pass through. The electrons are collected by a 10 mm wide electrode biased at +50 V. The signal from the electrode is routed to amplifiers and an oscilloscope for data collection.

Comments on an Earlier Detector

Our earlier design for a stripline detector in a quadrupole was based on a flex circuit of 0.125-mm-thick Kapton with a copper collector on one side and a ground plane on the other. This detector was used in our initial observations of trapping of electrons in a quadrupole [6]. The design choice came from the limited radial space for the insertion of the detector between the beam-pipe wall and the pole face of the quadrupole as well as a history of using flex circuits of this type for detectors that measure DC currents from the electron cloud [7]. With 10 mm wide copper on Kapton, the 100-mm-long stripline collector has an impedance of a little more than 2 ohms. This requires a tapered matching section for connection to the 50-ohm vacuum feedthrough, cable, etc. Limited longitudinal space for this taper results in a poor impedance match at lower frequencies. So while we obtained a usable signal from this detector, post-process filtering was required and there was room for improvement.

Design of the Present Detector

For the present detector, we took advantage of the 25 mm radial detector space provided by the larger aperture quadrupole and designed a stripline collector with a 50 ohm impedance. CST Microwave Studio® was used to determine that the dimensions shown in Fig. 3 result in 50 ohms. All conductive parts are made of 304 stainless steel with no dielectric except for ceramic supports at the connections to the vacuum feedthroughs. The feedthroughs are manufactured by Solid Sealing Technology, Inc., part number FA25858.

There are three striplines in the design, a single stripline centered on the pole face and a pair of striplines azimuthally positioned to either side of center. The pair of striplines are in the same vacuum enclosure, separated by a conductive wall. The single and double striplines are in different longitudinal positions along the same pole. Simulations indicate that the longitudinal variation in the EC density within the quadrupole field should be small, so the three detectors are in a similar electron cloud buildup environment.

Arrays of 300 holes, 0.79 mm in diameter, are fabricated in 2.7 mm thick stainless plates using Die-sink electrical discharge machining (EDM) as shown in Fig. 4. These plates are then tack-welded into slots made in the beam-pipe so that the plate surfaces are flush with the wall. The holes for the central detector are normal to the plate surface since the magnetic field (and low energy electron trajectories) will be normal to the pole face. For the two outer detectors, the holes are angled at 0.158 radian so that they will be roughly aligned with the magnetic field at their position off the center of the pole face.

During detector assembly, stainless tees are tack-welded to the feedthrough inner conductors and the stripline plate is attached with screws shown in Fig. 5. The screws are tack-welded in place once the stripline has been tested, before the final welding of the detector assembly onto the beam-pipe.

The detectors were tested during the assembly, using a time delay reflectometer, which showed that the stripline impedance was close to 50 ohms and the feedthroughs were closer to 60 ohms. Unfortunately, after the final weld of the detector boxes onto the beam-pipe, one of the dual detector striplines was found to be shorted at one end. So we will have the central detector and only one of the offset detectors for the upcoming measurements.

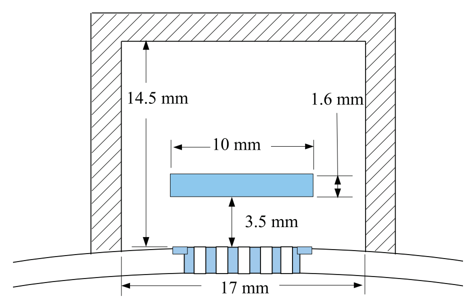

Figure 3: An array of small holes allows electrons to enter the detector vacuum space and be collected on the stripline.

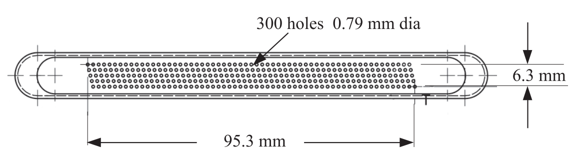

Figure 4: Holes are made in stainless steel plates which are then spot welded into slots in the beam-pipe wall.

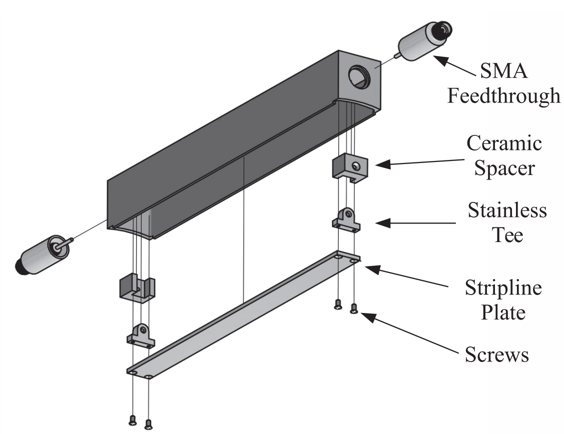

Figure 5: Exploded view of the single stripline detector.

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MICROWAVE DETECTOR

Beam-pipe with changes in cross-section will have a resonant response to microwaves. For rectangular beam-pipe, the lowest frequency waveguide mode is TE_{01}; for round beam-pipe, it is the TE_{11} mode. If the changes in cross-section produce significant reflections, resonances similar to those of a waveguide shorted at both ends will be seen. The resonances will be characterized by the number of half wavelengths m in the resonant field along the length of the waveguide.

The presence of an electron cloud will shift the resonant frequency of the beam-pipe by an amount that is proportional to the EC density. This effect is used for density measurement [5]. Generally, beam-pipe resonances are not intentional, but the new chamber presented the opportunity to make design choices with microwave measurements in mind. In the overall design, the length of the round section of beam-pipe needs to be long enough to accommodate the stripline detectors, but short enough to confine the resonant fields to be within the quadrupole's magnetic field.

The standard cross section of CESR beam-pipe is roughly elliptical with vertical side-walls. The horizontal dimension is 90.5 mm and the vertical dimension about 50 mm. The measured cutoff frequency of the TE_{01} mode of this beam-pipe is 1.8956 GHz [8]. The beam-pipe for the stripline detectors is round and tapers both horizontally and vertically down to the standard CESR cross-section – a geometry that provides resonant modes in the beam-pipe.

CST Microwave Studio® was used to find the eigenmodes of the chamber when the inner diameter of the round beam-pipe was 95.5 mm – larger than either the horizontal or vertical dimension of the standard CESR beam-pipe. With this geometry, the fields of the first four TE_{11} modes – two horizontal, two vertical – are primarily within the quadrupole field region as shown in Fig. 6, with resonant frequencies below the cutoff frequency of the CESR beam-pipe.

When the diameter was made 88.9 mm, slightly smaller than the horizontal dimension of the CESR beam-pipe, the simulation shows that the modes with vertical E-field are not confined, but propagated out into the CESR pipe. This is because the frequencies of these vertical modes are above the 1.8956 GHz cutoff frequency of the CESR beam-pipe. The lowest modes with horizontal E-field are confined, but their frequencies are higher than the lowest vertical modes. There is the potential for some of the vertical and horizontal mode frequencies to overlap, depending on the details of the CESR beam-pipe beyond the chamber. So in the design, the larger 95.5 mm inner diameter is used.

In order to excite the beam-pipe with microwaves, beam-position-monitor-style buttons are used in pairs– one button to couple microwaves in and the other to couple microwaves out of the beam-pipe. Two pairs of buttons are included – one pair on the bottom of the beam-pipe, the other on the side. This allows the excitation and detection of both horizontal and vertical TE_{11} modes in the round beam-pipe. The buttons are offset longitudinally by 100 mm to allow coupling to both the $m = 1$ and $m = 2$ resonances.

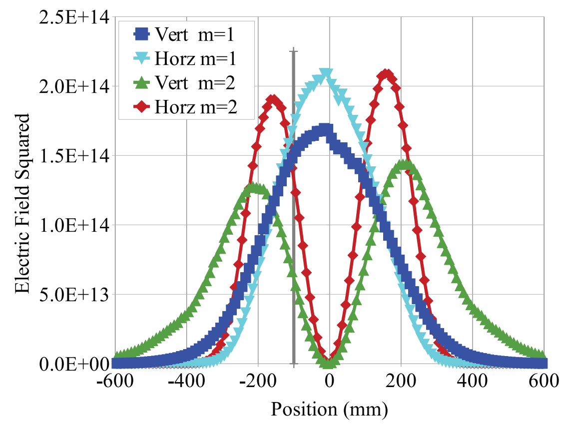

Figure 6: The results of a Microwave Studio® simulation show that the resonant microwave fields of the lowest four modes are contained within the 560-mm-long quadrupole magnet. Zero is the longitudinal center of the quadrupole.

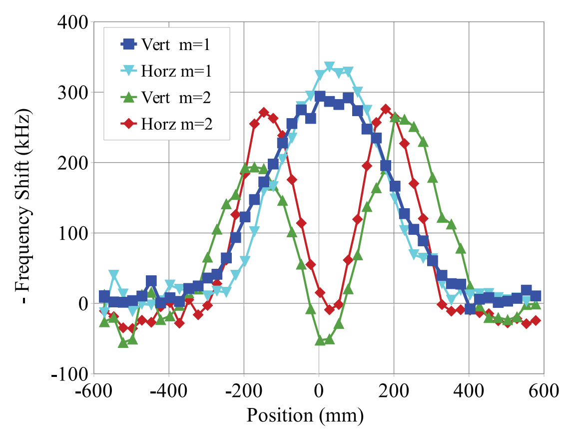

Figure 7: Beadpull measurements of the first two horizontal and first two vertical modes of the completed chamber.

After the chamber was fabricated, we wanted to confirm the nature of the resonances that had been predicted by simulation. We recorded the shift in resonant frequency produced by a 0.3 cm^3 dielectric bead as it was pulled through the assembled chamber. The frequency shift is proportional to the square of the resonant electric field at the location of the bead [9, 10]. Our measurement is somewhat crude in that it uses the peak response of a spectrum analyzer instead of a phase locked loop circuit. But the beadpull results in Fig. 7 are sufficient to confirm the simulation results of Fig. 6, i.e. that the first four modes are mostly confined to be within the 560 mm length of the magnet.

MAGNET CONSTRUCTION

The quadrupole that surrounds the detector is a duplicate of a magnet made in 2004, which required the machining of existing laminations and adding spacers to produce a larger

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aperture [11]. The machining was performed on the laminations of four quadrants which had been previously stacked. The coils are formed using 1/4 inch square copper tubing with a round 1/8 inch diameter water channel. There are 72 turns on each pole comprised of an assembly of 6 coils of 12 turns each. For cooling, the six coils are grouped as 3 pairs, with a water flow of about 0.12 gallons/minute through each coil pair at 60 psi. Several of these coils had been built in 2004 and were taken out of storage and tested. To obtain a gradient of 3.6 T/m, a current of about 110 amps will be provided by a remotely variable standard CESR magnet power supply.

SUMMARY

We have designed and built an electron cloud detector intended for use in a quadrupole magnet. Two independent measurement techniques will be used in the same chamber – sampling the flux of electrons onto the wall of the beam-pipe and measuring the cloud-induced shift in the resonant frequency of the chamber. The chamber and magnet are to be installed in CESR in September 2016.

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