Nuclear Instruments and Methods in Physics Research A 754 (2014) 28–35

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Electron cloud density measurements in accelerator beam-pipe using resonant microwave excitation

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ARTICLE INFO

Article history:
Received 25 November 2013
Received in revised form
8 March 2014
Accepted 29 March 2014
Available online 5 April 2014

Keywords:
Accelerator
Storage ring
Electron cloud
Plasma
Microwave
Resonance

ABSTRACT

An accelerator beam can generate low energy electrons in the beam-pipe, generally called electron cloud, that can produce instabilities in a positively charged beam. One method of measuring the electron cloud density is by coupling microwaves into and out of the beam-pipe and observing the response of the microwaves to the presence of the electron cloud. In the original technique, microwaves are transmitted through a section of beam-pipe and a change in EC density produces a change in the phase of the transmitted signal. This paper describes a variation on this technique in which the beam-pipe is resonantly excited with microwaves and the electron cloud density calculated from the change that it produces in the resonant frequency of the beam-pipe. The resonant technique has the advantage that measurements can be localized to sections of beam-pipe that are a meter or less in length with a greatly improved signal to noise ratio.

1. Introduction

An accelerator beam can generate low energy electrons by ionization of the residual gas in the beam-pipe, lost beam particles or from the photo-electrons produced by synchrotron radiation. These electrons can then produce secondary electrons, generating an electron cloud (EC) that may result in instabilities and emittance growth in a positively charged accelerator beam [1,2]. Several techniques have been developed to measure the EC density in order to test mitigation techniques and for comparison with the results of numerical simulations of cloud development [3,4].

One of these techniques couples microwaves into the beam-pipe and uses the interaction of electrons with the microwaves to measure the EC density. When this technique was first introduced, the microwaves were propagated for some distance through a section of beam-pipe. A change in EC density within this section produces a change in the phase of the transmitted signal that is proportional to the electron cloud density and the transmission length [5–8]. For a periodic EC density, such as that produced by a short train of bunches in a storage ring, this results in a received signal with phase modulation sidebands above and below the drive frequency that can be observed with a spectrum analyzer. These measurements are referred to as microwave transmission measurements or – since they generally use the fundamental TE mode propagating in the beam-pipe – the TE wave technique of electron cloud measurement.

In practice, transitions in the cross-section of the beam-pipe for accelerator hardware such as wigglers, gate valves and the longitudinal slots for vacuum pumps produce reflections of the microwaves. In general, such reflections dominate the beam pipe transmission spectrum just above the cutoff frequency. This results in a series of resonances rather than the usual waveguide transmission function, except for cases with long portions of uniform beam-pipe. The calibration of the transmission measurement is a phase shift per unit length, but reflections make the length of propagation difficult to determine.

An alternative to the microwave transmission method is to make use of the resonant response of the beam-pipe when microwaves are coupled into it. The simplest case would be a region of beam-pipe that contains two perfect reflectors. This is equivalent to a length of waveguide with its ends shorted, where the lowest resonant frequencies are given by Eq. (1), with n an

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http://dx.doi.org/10.1016/j.nima.2014.03.063
0168-9002/

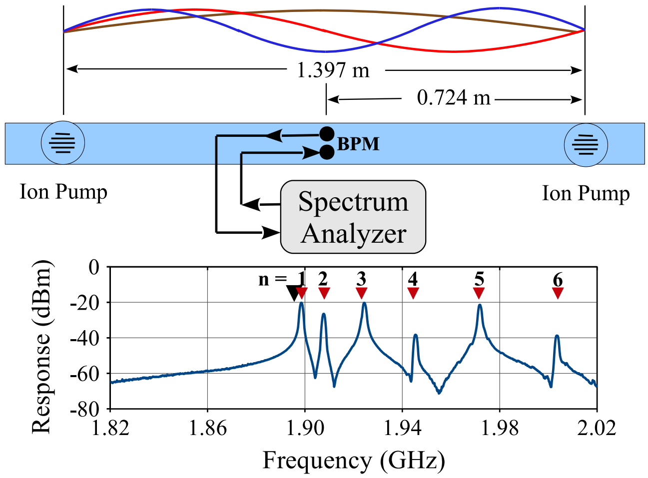

Fig. 1. At the location 43E in the CesrTA storage ring, a response measurement shows resonances produced by reflections at two ion pumps. The numbered triangles show the resonant frequencies expected for a shorted section of waveguide of length $L = 1.385$ m. The leftmost dark triangle is the beam-pipe cutoff frequency f_c of 1.8956 GHz.

integer greater than zero, f_c the cutoff frequency of the beam-pipe, c the speed of light and L the length of the resonant section.

$$f^2 = f_c^2 + (nc/2L)^2. \tag{1}$$

Fig. 1 shows an example from the Cornell Electron Storage Ring Test Accelerator (CesrTA) [9] where a response measurement from a section of beam-pipe is consistent with the model of a shorted section of waveguide. At this location, the beam-pipe is of uniform cross-section in the region between two vacuum pumps. Above the cutoff frequency of the beam-pipe, longitudinal slots at the vacuum pumps generate reflections and a resonant response. The measured resonances are plotted in Fig. 1 along with the frequencies calculated with Eq. (1), where L is roughly the distance between the ion pumps. For this measurement, the microwaves are coupled in and out of the beam-pipe at the same longitudinal position using electrodes within this section that are normally connected to the beam position monitor (BPM) system.

When the beam-pipe has a resonant response, the analysis to determine the EC density within it needs to be based on the response of these resonances to changes in EC density [10–12]. This paper describes a variation on the microwave transmission method that is based on techniques for plasma density measurement using resonant cavities. This method is referred to as a resonant microwave or resonant TE wave measurement of EC density.

2. Resonant frequency shift due to a plasma

The natural frequency ω_0 of a resonator will be shifted by an amount $\Delta\omega$ by the presence of a plasma within it. In the absence of a magnetic field, the frequency shift is given by Eq. (2), where the integrals are taken over the volume of the resonator, ν is the collision frequency of the plasma and ω_p its plasma frequency [14]. This approximation is valid for $\Delta\omega/\omega_0$ small, where the electric field in the presence of a plasma is approximately equal to the electric field E_0 of the empty cavity.

$$\frac{\Delta\omega}{\omega_0} \approx \left(\frac{1}{1+(\nu/\omega_0)^2}\right)\left(\frac{1}{2}\right)\frac{\int_V (\omega_p^2/\omega_0^2) E_0^2\, dV}{\int_V E_0^2\, dV}. \tag{2}$$

In accelerators, relatively low EC densities n_e are expected. Based on experimental evidence as well as analytical models and simulations, n_e of only about 10^{12} e$^-$/m^3 are sufficient to produce beam instabilities [2–4]. The approximate collision frequency ν of electrons in a plasma is given in Eq. (3) with temperature T in Kelvin [13].

$$\nu \approx \frac{3.75\times 10^{-6} n_e}{T^{3/2}}. \tag{3}$$

If the electrons have an average energy of 1.5 eV, their equivalent temperature is on the order of 10^4 K. An EC density of 10^{12} e$^-$/m^3 would have a collision frequency of under 40 Hz. So under these conditions $\nu \ll \omega_0$ and $\nu/\omega_0 \to 0$. There is also a change in the resonator Q at higher plasma densities, but this change is roughly proportional to ν/ω_0, so changes in Q will not be treated here.

The plasma frequency ω_p is related to the plasma (electron cloud) density n_e by $n_e = \omega_p^2 \varepsilon_0 m_e / e^2$ [15], where ε_0 is the vacuum permittivity, m_e is the mass and e the charge of an electron. Combining this with Eq. (2) for a low density plasma ($\nu/\omega_0 \to 0$) in the absence of an external magnetic field, the change in resonant frequency for a given EC density n_e is given by Eq. (4), where the local EC density n_e can be a function of time and of the position within the resonator. This expression and simulations of electron cloud in resonant beam-pipe are in good agreement as described in Ref. [16], this issue.

$$\frac{\Delta\omega}{\omega_0} \approx \frac{e^2}{2\varepsilon_0 m_e \omega_0^2}\frac{\int_V n_e E_0^2\, dV}{\int_V E_0^2\, dV}. \tag{4}$$

3. Calculation of electron cloud density

Equation (4) is the basis for the resonant microwave technique for measurement of EC density. The frequency shift $\Delta\omega$ is related to the EC density n_e through a ratio of integrals where the numerator generally requires knowledge of the product of n_e and E_0^2 everywhere within the resonant volume at any given time.

A detailed evaluation of Eq. (4) includes determining the distribution of microwaves E_0^2 within the resonant section of beam-pipe. With rectangular or elliptical beam-pipe, the transverse distribution of the electric field at the lowest resonant frequencies will be a half wavelength cosine with a maximum in the horizontal center of the beam-pipe. Longitudinally, unless the series of resonant frequencies is very simple as in the example of Fig. 1, the length of the resonant section and the electric field distribution may not be obvious. Some estimates need to be made for the length of the resonant volume in order to determine the possible variation of n_e within that volume. For example, if the resonant section were known to be short, it might be easier to make an approximation that n_e is uniform within that section. Comments on the determination of E_0^2 are deferred to Section 5.

The EC density n_e is generally not uniform over the volume. For example, where synchrotron radiation is present, the production rate of initial photo-electrons will vary with the distance from the radiation source. This will result in a corresponding change in the overall EC density as a function of longitudinal position. The EC density can also vary over the transverse dimensions of the beam-pipe. Calculation or simulation of EC density as a function of position in the beam-pipe is beyond the scope of this paper. In order to more easily connect n_e with a measured frequency shift, the approximation is made that at any instant in time, n_e is uniform over the resonant volume. With this approximation, the ratio of integrals simplifies to the spatially uniform EC density n_e that can be a function of time.

The EC density obtained in this way can also be interpreted as the spatially averaged value, weighted by E_0^2. If the fundamental mode is excited, this will have maximum E_0^2 at the horizontal