DEVELOPMENT OF A DIELECTRIC-LOADED ACCELERATING STRUCTURE WITH BUILT-IN TUNABLE ABSORPTION MECHANISM FOR HIGH ORDER MODES

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Abstract

As the dimensions of accelerating structures become smaller and beam intensities higher, the transverse wakefields driven by the beam become quite large with even a slight misalignment of the beam. These deflection modes can cause inter-bunch beam breakup and intra-bunch head-tail instabilities along the beam path. We propose a built-in tunable absorption mechanism for damping the parasitic transverse modes without affecting the operational modes in dielectric loaded accelerating (DLA) structures and wakefield power extractors. The new principle for HOM absorption is based on electron paramagnetic resonance. The dielectric tube of the DLA has to be doped with a material exhibiting high EPR, for example ruby, Al_2O_3 heavily doped ~1% with Cr^{3+}. The absorption frequency can be tuned by an external DC magnetic field to match the frequency of the transverse mode. At the resonance the imaginary part of permeability becomes significant and the dielectric tube acts as an absorber for the transverse modes. The external DC magnetic field is solenoidal and has to have a magnitude of about 3 kG. This configuration in fact is desirable to focus the beam and provide additional control of beam break up.

INTRODUCTION

When an off-axis particle travels through a DLA structure, parasitic HEM modes will be excited that can impart transverse deflection forces to trailing particles and degrade the beam quality if they are not sufficiently suppressed [1, 2]. All new metal based accelerating structures, like the accelerating structures developed at SLAC for the ILC or power extractors at CLIC, have designs in which the transverse modes are heavily damped [3-7]. Similarly, minimizing the transverse wakefield modes (here the HEM_{mn} hybrid modes in DLA structures) is also very critical for developing dielectric based high energy accelerators. Some progress has been made in the last decade [8, 9], but a sufficiently damped transverse mode DLA structure has not been developed.

The conventional DLA structure has a very simple geometry: a cylindrical, dielectric tube with an axial vacuum channel is inserted into a conductive sleeve [10, 11]. The new principle for HOM absorption is based on electron paramagnetic resonance of the dielectric tube. The resonance frequency can be tuned by an external DC magnetic field to match the frequency of the transverse mode. At the resonance the imaginary part of permeability μ'' becomes significant. This means that magnetic loss tangent is large at the resonant frequency. If the resonant frequency is matched to the transverse mode excitation spectrum the dielectric tube acts as an absorber for the deflecting mode. The absorption process is resonant and localized at the frequency of the resonance. Hence the fundamental mode is not affected by.

The accelerating mode used in the DLA structure is typically the TM_{01} mode. The most harmful transverse modes in dielectric-lined circular waveguides are the hybrid modes (HEM_{mn}, where m and n refer to the azimuthal and radial harmonics respectively). The lowest frequency mode is the HEM_{11} [12, 13]. Figure 1 shows a typical electric field distribution (E_z component) of the accelerating mode and one of the major transverse modes, HEM_{11}.

TRANSVERSE MODE DAMPING IN DLAS USING PARAMAGNETIC RESONANCE

In the case of an iris-loaded metal accelerating structure, manifolds can be used to damp the parasitic (dipole) modes [4, 7]. For a DLA structure segmented conductors can be placed around the outside of the dielectric layer [8, 9]. This segmentation interrupts the azimuthal surface currents needed to support the HEM modes so that the quality factor of the HEM modes is dramatically reduced.

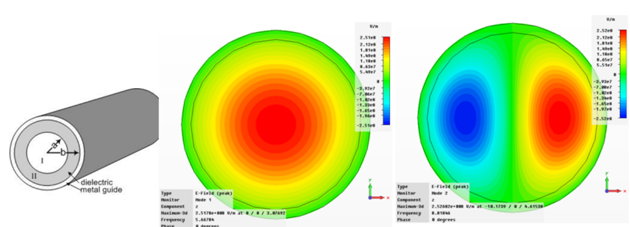

Figure 1: Partially Dielectric-Loaded Circular Waveguide for particle acceleration. The dielectric tube has inner radius a and outer radius b. Region I is vacuum; region II is dielectric; and the outermost layer is metal. Longitudinal (E_z) electric field distribution of the fundamental (5.67 GHz) and dipole (8.82 GHz) modes.

In this paper, we propose a different idea that does not require altering the outer copper jacket geometry. With the proper choice of the dielectric tube for the DLA and external magnetic field the absorption of the dipole mode will happen in the dielectric material itself.

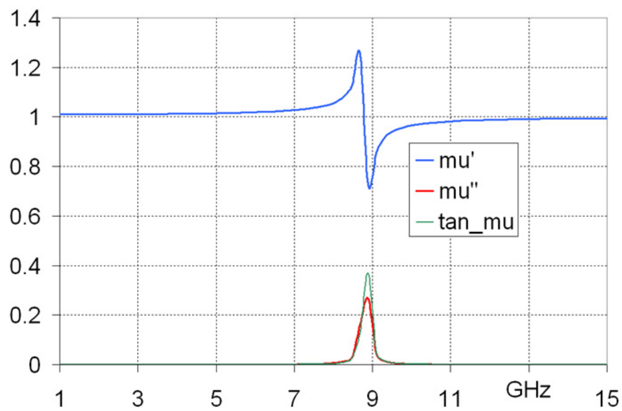

Figure 2: Paramagnetic material magnetic properties. Resonant absorption at around 9 GHz.

Assume that besides the dielectric properties the ceramic (or any other material of choice for DLA) tube exhibits paramagnetic resonance, as depicted in Figure 2. The magnetic properties are pronounced only in the vicinity of a resonant frequency. In the following paragraphs we will describe how such properties can be achieved with so-called electron paramagnetic resonance. Besides the real and imaginary parts of the permeability μ we plot magnetic loss tangent (tan $\delta_m = \mu'' / \mu'$). The material is very lossy at resonance.

As an example we consider ruby doped with Cr3+, popular in MASER technology [15, 16]. If an external magnetic field of 2.5 kGauss is applied perpendicular to the c-axis of ruby (doped with 0.05% of $CR3^+$), three absorption lines appear: at 2.398 GHz, 12.887 GHz and 24.444 GHz with line-width on the level of 50-100 MHz [17]. (Line widths can always be broadened if needed by introducing spatial inhomogeneities into the DC manetic field.)

If we design our structure in such a way that the dipole mode frequency overlaps with absorption line then the dipole mode will be effectively suppressed.

To demonstrate the idea we simulated wakefield generation in a DLA resonator with the following dimensions: inner diameter 36 mm, outer diameter 40 mm and length 10 mm. Dielectric constant is 6.64 and the value of the imaginary part of magnetic susceptibility at the resonance is $\chi'' = 0.3$. We have shown that such numbers are practical.

In this simulation a $\sigma_z = 3$ mm, 15 MeV electron bunch passes through the structure and excites a wakefield. We monitor the frequency content of the wake. When there are no losses a dipole mode is excited at around 9 GHz. If a resonant magnetic loss is present (Figure 2), the dipole mode is significantly attenuated (Figure 3).

Different EPR-active materials would have different number of absorption lines, resonance frequencies and linewidths. Optimizations of the chemistry can be done for a particular application and properties of the accelerating structure. In principle it may be possible to line up several higher order modes with absorption lines of the material.

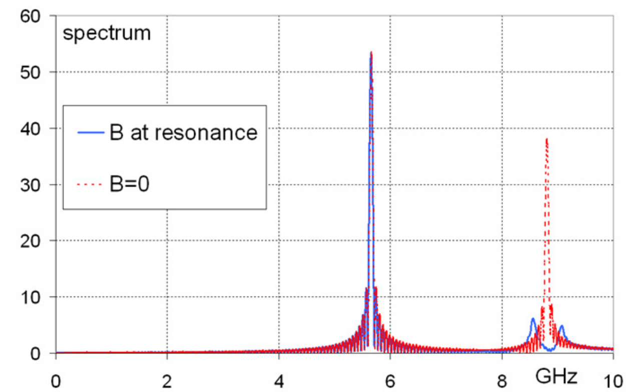

Figure 3: Wake spectrum for the case when media has resonant paramagnetic losses compared to the case when there are no magnetic properties. The dipole mode is significantly suppressed.

One important condition for the resonance absorption to take place is for the mode to have a component of the magnetic field perpendicular to the external magnetic field. The experimental realization that is planned will have a solenoidal external field, parallel to the DLA axis – optimal for beam-generated wakefields. A strong solenoidal field focuses the beam through the DLA and helps avoid beam break up (BBU) [17].

PROPERTIES OF PARAMAGNETIC MATERIALS

The tunable absorption idea is based on the Zeeman effect – the splitting of energy levels in the presence of external static magnetic field. The experimental work relies heavily on EPR (electron paramagnetic resonance, also known as ESR, electron spin resonance) measurements [18]. The resonance is achieved when frequency of microwave irradiation matches the energy difference between the Zeeman - split energy levels (Figure 4). In this case absorption is observed.

The basic EPR resonance condition in a paramagnetic spin system is:

$$\hbar\omega = g\beta H_0 \qquad (1)$$

where ω is the Larmor frequency, and β is the Bohr magneton. H_0 is the magnetic field strength. The g-factor can vary between 1 and 2 depending on spin-orbit interactions in the material. A free electron has g =2. Typically EPR measurements are made with a constant frequency X-band microwave source, and the spectrum is actually obtained by sweeping the applied magnetic field (H~3000 Oe for λ ~3 cm). The EPR measurement result can be quantified in terms of imaginary part of susceptibility, which describes losses [19, 20].

A realistic order of magnitude for the inverted (emissive) magnetic susceptibility of MASER ruby, χ''_{max} is 10^{-2} [21]. The doping of ruby with Cr^{3+} is optimized for emission. We are not limited by such an optimization and can increase the doping by at least two orders of magnitude [22] to achieve a loss tangent ~ 0.5, including the effects of band widening for heavily doped ruby that reduces the peak value of χ''.

Another important issue with resonant paramagnetic absorption is the effect of saturation. The material can absorb microwave photons only to the point when the spin population of the Zeeman split levels is equalized.

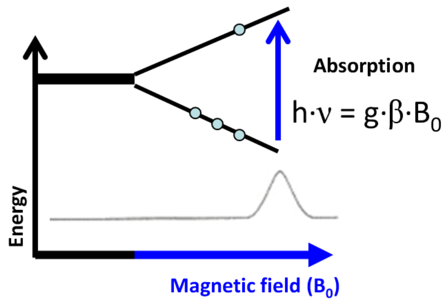

Figure 4: Energy level diagram. When magnetic field is zero the state is spin-degenerate. Once the field is non-zero the energy level splits (Zeeman splitting). As magnetic field increases the energy difference increases.

Recently the Argonne Wakefield Accelerator facility demonstrated 7.8 GHz power extraction from a bunch train of high charge electron bunches [23]. At this frequency 40 MW of RF power was extracted in a form of short 5 ns pulse. Based on this result we can assume (to have some realistic numbers), that the dipole mode could have absorbed 1 MW from the bunch train in 5 ns. Also assume that the dipole mode frequency is around 10 GHz, which is also reasonable. The total energy in the dipole mode then would be $5 \cdot 10^{-3}$ Joule. Hence the RF pulse carries $7.5 \cdot 10^{20}$ photons to be absorbed.

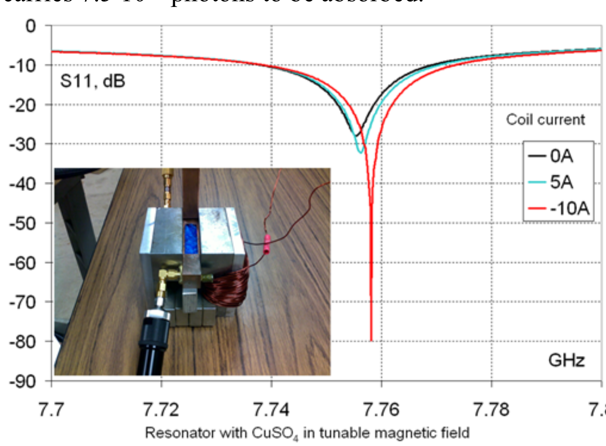

Figure 5: Room temperature bench test. S_{11} (reflection) is measured for different values of the tuning coil current. Resonant absorption affects the Q-factor and coupling.

If we assume a heavily doped ruby as discussed above we would have on the order $2 \cdot 10^{19}$ spins per cc ready to absorb in a dipole mode bandwidths, that is typically ~ 100 MHz (at 4.2 K temperature). That means that we should have on the order of 40 cm^3 of absorbing material. The DLA structure that was used as a decelerator had the following dimensions: length was 26.6 cm, inner dielectric diameter– 12.04 mm and outer diameter – 22.34 mm. The volume of dielectric was ~ 70 cm^3. This means that heavily doped ruby would be capable of absorbing 1 MW per 5 ns in 100 MHz bandwidth of the dipole mode at 10 GHz. To ensure that the material used in DLA will exhibit high EPR absorption rates we propose to dope the ceramics, quartz, ruby or any other DLA material with paramagnetic species, like Cr^{3+}, fullerene C_{60}, TEMPO (2,2,6,6-Tetramethylpiperidine-1-oxyl) and others.

BENCH TEST

We performed a bench test using a constant magnet-based dipole with a tuning coil. A resonator was filled with $CuSO_4$. The resonant frequency of the cavity was around 7.76 GHz. As the magnetic field was swept we observed the effect of resonant absorption changes on resonator tuning (Fig. 5).

SUMMARY

We discussed the possibility of utilizing electron paramagnetic resonance to absorb deflecting modes that are generated by a misaligned beam. Preliminary simulations show the effectiveness of dipole mode suppression. We estimated that ruby doped at ~ 1 % with Cr^{3+} can absorb about 1 MW of power per 5 ns at 10 GHz. Such high number does require cryogenic cooling of the ruby; room temperature absorption for this material drops by two orders of magnitude, but can be increased through the use of other dielectrics and dopants.

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