EXPERIMENTAL AND NUMERICAL STUDIES OF PARTICLE ACCELERATION BY AN ACTIVE MICROWAVE MEDIUM

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Abstract

There has been considerable theoretical work on the so-called PASER concept, in which a particle beam is accelerated directly by absorbing energy from an active medium, analogous to the amplification of an optical signal in a laser. Use of an active microwave (maser) medium would have the advantage of requiring relaxed beam quality (mm vs. nm characteristic beam dimensions) compared to techniques based in optical frequencies. Recent work using electron paramagnetic resonance (EPR) techniques has demonstrated activity in the microwave regime (i.e. negative imaginary part of the magnetic susceptibility) for a class of organic compounds. A solution of fullerene (C60) in a liquid crystal solvent has been reported in the literature to possess a maser transition in the X-band region. An external DC magnetic field is required to obtain the effect; the frequency of the maser transition is adjustable by varying the magnetic field strength. We will report on the status of numerical and laboratory tools to evaluate the use of this material for accelerator applications, and eventually the feasibility of an accelerating structure based on an active microwave medium.

INTRODUCTION

Recent theoretical work [1] has shown that a charged particle (or particle bunch) traversing an active medium (i.e. one in which population inversion has been generated) can absorb energy from the medium and be accelerated. This technique has the potential to be the basis of a new method of acceleration providing high gradients. The effect is similar to the action of a maser or laser with the stimulated emission of radiation being produced by the virtual photons in the electromagnetic field of the beam. While this effect has been explored theoretically there has of yet been no experimental work in this area and little in the way of numerical simulations. We have initiated a research program that would lead to both an improved conceptual understanding of this technique through the development of sophisticated and physically realistic numerical models of the effect, tools for production and bench measurements of the material and eventually to a demonstration of particle acceleration by an active medium.

Until recently, existing solid state maser materials were usable only at cryogenic temperatures [5], limiting them to a few specialized applications like ultralow noise amplifiers for radio astronomy. Recently published work [2] reports the observation of maser amplification at near room temperature in an optically pumped Fullerene-based material at 9.4 GHz. While the physics of the masing transition in fullerene compounds is outside the scope of the paper, the basic effect is that an intense optical pulse creates a population inversion in the magnetic Zeeman levels of the molecules.

The material we plan to use must be cooled to -20 C, which is easily achieved with a Peltier device or with dry ice as a coolant. The material is a liquid but can be isolated from the beam channel by a thin walled quartz capillary.

There are a number of possible implementations of active media devices for particle acceleration. The first involves acceleration of a single bunch by the active medium (the basic PASER concept) without the use of a resonant structure. A second related technique would load the active medium in a resonant structure, similar to the dielectric wakefield accelerator, with the fundamental resonant frequency of the structure adjusted to correspond to the frequency of the masing transition. The device could then be used to amplify the wakefield of a drive beam for acceleration of a trailing witness beam. Yet another approach is to use the active medium, loaded into a resonant cavity of the appropriate frequency and with appropriate optical pumping as an rf power source to drive a conventional iris-loaded or dielectric structure directly. We are developing numerical simulation tools to investigate all these configurations.

Published work on these new active materials [4] is oriented towards the physical chemistry of the media. Activity is diagnosed in small samples using EPR techniques. Reference [2] examines potential microwave applications of the material and presents a design for a microwave amplifier using the active medium. This group has also built a benchtop device to diagnose the properties of the medium by measuring S11 for a rectangular waveguide loaded with the material [3].

NUMERICAL SIMULATIONS

Initial simulations of active microwave structures have been performed using the Arrakis code [8]. Arrakis is particularly useful in problems where material properties more complicated than constant permittivity/permeability are important.

An active gain medium can be treated as one in which the imaginary parts of the permittivity or permeability are negative rather than positive, so that an electromagnetic wave propagating in the medium gains energy rather than attenuates. From a numerical standpoint the situation is complicated by the frequency dependence of ε and μ,

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whereas we want to solve the problem of an accelerated beam in the time domain.

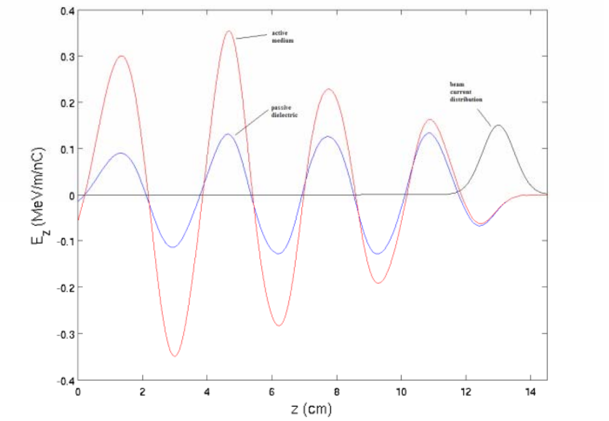

Figure 1: Arrakis simulation of the longitudinal wakefields in 9.4 GHz structures loaded with an active medium and a conventional dielectric of the same permittivity.

Consider a wakefield structure consisting of a dielectric tube, outer radius 1.5 cm, inner radius 0.75 cm. We assume that the medium has a permittivity $\varepsilon = 2$ and an imaginary part of the permeability $\mu_i = -0.01$ [2]. This structure then has its fundamental TM01 mode at 9.4 GHz. We model the gain with a magnetic current term in Faraday's law:

$$\mathrm{curl}\ \mathbf{E} = -\mu_r/c\ \partial\mathbf{H}/\partial t + 4\pi\ \sigma_M /c\ \mathbf{H}.$$

Here σ_M is the magnetic conductivity, and $\mu_i = 4\pi\ \sigma_M /\omega$. We compute the wakefield in this structure taking a rms bunch length $\sigma_Z = 0.5$ cm, sufficiently long that the TM01 mode predominates, so we can ignore any frequency dependence of σ_M. We also neglect saturation effects and dielectric losses. The longitudinal electric field in the vacuum gap is shown in Figure 1.

We note in this case that the wakefield of the bunch is indeed amplified due to the activity of the medium. The accelerating gradient is enhanced by an easily detectable factor ~3 over the structure with no media activity.

A more realistic algorithm has recently been developed by Taflove and Hagness [6] to incorporate the effect of an active medium into a time-domain finite-difference code and to include dispersive effects. In this approach the imaginary part of the frequency domain permittivity function for the medium is converted using the inverse Fourier transform to a time-dependent auxiliary differential equation for an effective current. At each time step, the effective current is advanced using this equation. The frequency domain conductivity is a quotient of polynomials in the frequency. The order of the auxiliary differential equation is the same as the highest power of ω present in either the numerator of denominator.

Another possibility is to use a running FFT of the fields and to invert the constitutive relation directly at the cost of additional memory since some portion of the time history for each finite difference mesh cell must be retained throughout the calculation. A similar technique [7] has been used to model dispersion in ferrites but to our knowledge has not been applied to active media.

EPR MEASUREMENTS

This work will rely heavily on development and EPR measurements of fullerene materials. We will develop a design for a prototype accelerating structure using this material with attention to details of pumping and maximizing energy gain. Preparation of the active material described in [2] a solution of C60 in a nematic liquid crystal, is not problematic. We plan to also study a number of related materials to optimize the stored energy density of the accelerating device.

The basic EPR resonance condition in a paramagnetic spin system is $\omega = g\beta H$, where ω is the Larmor frequency, β is the Bohr magneton. The g-factor can vary between 1 and 2 depending on spin-orbit interactions in the material. A free electron has g =2. Thus EPR frequencies are in the microwave regime (λ~3 cm for H ~3000 Oe.) The conventional way to detect EPR is to measure the change in the quality factor of a microwave cavity under the resonance condition. The sensitivity of EPR spectrometers is about 10^{10} spin/Oe. The ratio to magnetic units means that the sensitivity depends on line width and the narrower the line, the easier it is to detect it. The conventional continuous wave EPR spectrometer uses a modulation of the magnetic field (usually 100 kHz) to observe the spectrum.

Transient signals excited for example by laser pump pulses can be time resolved by applying a pulse sequence and sampling at an increasing time offset with respect to the start of each pulse to obtain a time-resolved spectrum. In the case of exciting transient EPR spectra of C60 it is necessary to apply a laser pulse sequence directly into the microwave cavity. This technique is especially relevant to the diagnosis of activity in our samples since the generation of a population inversion in the fullerene-liquid crystal solution requires an optical pulse excitation. Both steady state and transient measurements can be performed with the same spectrometer shown schematically in Figure 2.

Experiments carried out earlier showed that the EPR spectra and activity of C60 are strongly dependent on the solvent used. It is important for our purposes that C60 in different organic solvents or liquid crystals is light sensitive and undergoes reversible changes in the optical or EPR absorption spectra. Such light sensitive media demonstrate transient magnetization for about 1 s in duration after laser or xenon lamp pulse excitation. Thus the experiments can be carried out by either steady-state or time-resolved EPR in the presence of repetitive light pulses.

An absolute quantity of C60 in the 5×10^{-4} - 2.5×10^{-3} M range supplies no less than 3×10^{14} spins per probe; thus one can easily establish the requirements for EPR instrumentation sensitivity. These spins contribute to the C60 EPR signal that can be excited by 20-25 mJ/pulse irradiation with wavelengths of 200-350 nm. The EPR signal of the triplet state of C60 can be generated by pulses either from an excimer laser with a wavelength of 308 nm or from Nd:YAG laser at a second harmonic of 532 nm [2,9]. The pulse length was 10-12 ns with a repetition rate of 10-80 Hz, easily synchronizable with the EPR magnetic field sweep.

TEST CELL

In order to evaluate the usefulness of the active media for particle acceleration, we propose to design a test system that would permit the electromagnetic properties of active media loaded structures to be measured using standard microwave techniques. A conceptual design of the test cavity is shown in Figure [3]. The medium fills the cavity. Two ports are provided so that S11 (reflection) and S21 (transmission) measurements can be performed with a vector network analyzer. Use of an electric dipole stub antenna on axis couples to the accelerating TM modes of the structure; alternatively magnetic loops at the outer radius of the structure can be used to couple to the azimuthal magnetic field.

The pumping radiation is input to the medium through transparent longitudinal slit windows on the cavity wall. This technique preserves the symmetry of the TM modes, analogous to the dielectric wakefield parasitic mode suppressor [10]. Different pumping geometries could also be used; for example, light could be injected through windows in the endcaps of the structure.

Using this test system, the gain of the material should be easily measurable. Spontaneous emission from the active medium (which can compete with stimulated emission) will be diagnosed using a spectrum analyzer with no rf power input to the cell. Furthermore, by sweeping the bias magnetic field we will also be able to determine the level of amplified spontaneous emission present by measuring the rf power emitted when the masing frequency of the medium corresponds to the resonant frequency of the test cavity.

SUMMARY

We are investigating a new microwave active material for accelerator applications. Initial work in this area will emphasize numerical modeling and sample preparation and characterization. If successful this effort will lead to beam tests of an active media based accelerator.

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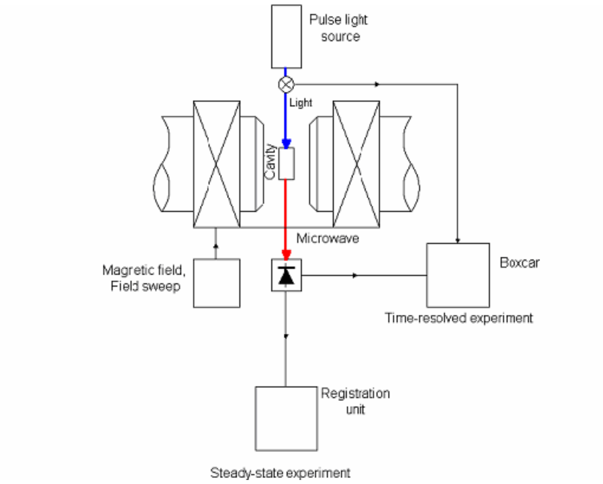

Figure 2: EPR spectrometer schematic. The material sample is placed in a high Q resonant cavity in a magnetic field. Both steady state and transient measurements (of particular interest for active media measurements) can be made with this apparatus.

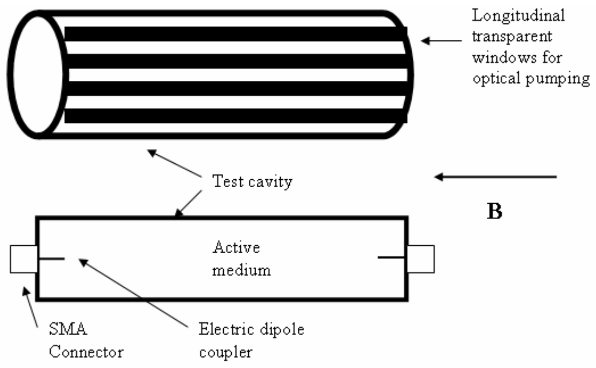

Figure 3: Conceptual design of the active media test cavity. Longitudinal transparent windows on the structure admit the optical pump signal while leaving the TM01 mode of the structure unaffected.