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Title: RIGID-BEAM MODEL OF A HIGH-EFFICIENCY MAGNICON

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Rigid-Beam Model of a High-Efficiency Magnicon

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Abstract

The magnicon is a new type of high-efficiency deflection-modulated amplifier developed at the Institute of Nuclear Physics in Novosibirsk, Russia. The prototype pulsed magnicon achieved an output power of 2.4 MW and an efficiency of 73% at 915 MHz. This paper presents the results of a rigid-beam model for a 700-MHz, 2.5-MW 82%-efficient magnicon. The rigid-beam model allows for characterization of the beam dynamics by tracking only a single electron. The magnicon design presented consists of a drive cavity; passive cavities; a pi-mode, coupled-deflection cavity; and an output cavity. It represents an optimized design. The model is fully self-consistent, and this paper will present the details of the model and calculated performance of a 2.5-MW magnicon.

I. INTRODUCTION

The magnicon is a descendant of the gyrocon [1], a deflection-modulated amplifier. Like the gyrocon, the magnicon consists of an electron gun, a deflection cavity, possible passive intermediate cavities, and an output cavity. In both devices, the deflection cavities are TM_{110} mode. The magnicon improves on the gyrocon in two ways: it uses a confining magnetic field to improve gain and improve the electron dynamics, and it substitutes a cusp field for a deflection field in the beam transport to the output cavity. The use of the magnetized beam in the magnicon makes the beam's deflection more circular and even reduces the beam loading in the cavities, as predicted by Nezhevenko [2]. With a low-emittance input beam, and using high voltages to minimize beam spread, the magnicon appears to operate at frequencies as high as 11 GHz, but the device is certainly easier to build for operation at frequencies under 1 GHz. Magnicons operating at high voltages and at many GHz are being developed both in the U.S. [3] and in Russia, primarily as the RF source for the Next Linear Collider. However, the experimental evidence to date [4] indicates that the electron dynamics in the magnicon are complicated, and it has been difficult to verify the predictions of magnicon computer models.

For the past two years, we have been developing a computer model [5] of the magnicon. This model is fully three dimensional, relativistic, and self-consistent, although space charge forces are neglected. The goal of the model is to show that high-efficiency magnicons operating at frequencies below 1 GHz are better than competing RF amplifiers for high-power, CW accelerator applications. A second goal of the model is to confirm that a multi-megawatt magnicon may operate at a reasonable voltage (below 180 kV) and still maintain its operating advantages over competing generators. The computer model is much smaller than the fully three-dimensional codes that account for space charge, such as ISIS [6], but the intent is to include all the essential physics and develop a design code for the magnicon that can run on smaller computers. A novel

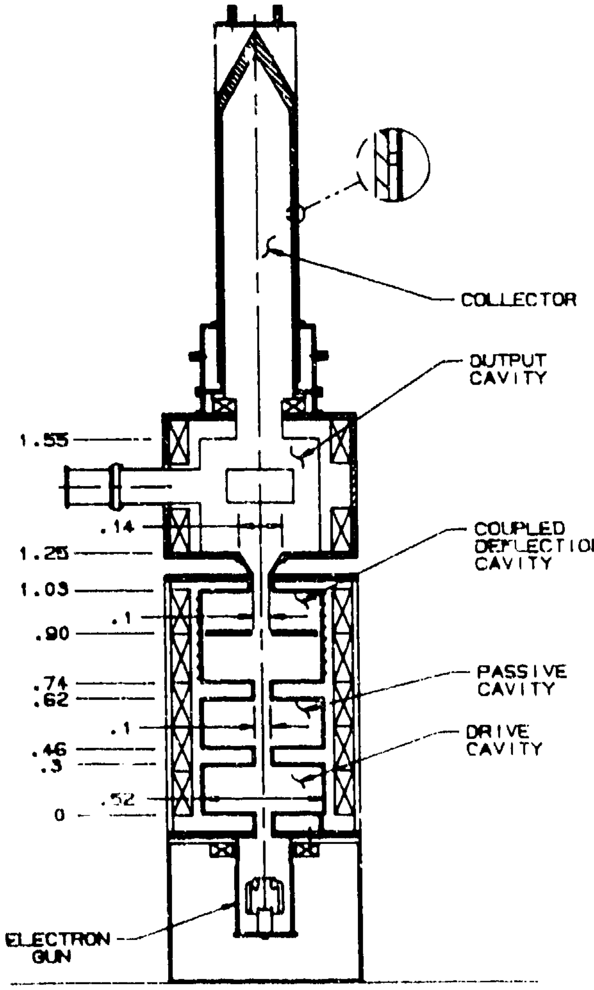

Figure 1. Magnicon architecture.

method of assuring self consistency and energy balance is also presented.

II. ENERGY-BALANCE APPROACH TO SELF-CONSISTENT SOLUTIONS

The energy-balance approach to calculating the self-consistent solution for cavity amplitude and phase follows thesesteps:

1. Select an initial value for cavity field amplitude.

2. Determine the phase that extracts the most power from the beam. This phase is the self-consistent cavity phase.

3. Calculate the power dissipated in the cavity walls for the current value of cavity field amplitude.

4. If the power dissipated in the cavity walls is equal to the power provided by the beam, then the cavity field amplitude is the self-consistent solution for the cavity amplitude. With the self-consistent phase from Step 2, the self-consistent cavity field has been determined.

5. If the conditions of energy balance are not satisfied, then the cavity field amplitude estimate is updated and the process repeats, starting at Step 2.

A unique aspect of the nature of the beam/field interaction in the magnicon is used to simplify implementation of the energy balance approach to self-consistent cavity field determination. In the beam-driven magnicon cavities, under the rigid beam assumption of zero radius in the steady state, each electron sees exactly the same RF fields. This results from the fact that both the entrance vector of the beam and the cavity fields are rotating at the RF frequency. Thus, each subsequent particle that enters the cavity has an entrance vector that has shifted. But the RF fields have shifted by the same amount. Therefore, the energy given up by each electron in the beam during the transit of the cavity is constant. Because each electron sees exactly the same RF fields while in the cavity, a single electron trajectory can be used to calculate the self-consistent fields rather than an entire electron beam, whose longitudinal length exceeds the cavity length. In addition, because the energy extracted from each electron as it passes through the cavity is a constant in time and is proportional to the energy given up by the beam in the cavity at any moment in time, the time-averaged value of power provided by the beam is also a constant and proportional to the energy provided by a single electron as it crosses the cavity. Thus, simply equating the energy lost by a single electron as it crosses the cavity to the time averaged power dissipated in the walls provides the basis for the self consistent solution.

The initial estimate of cavity field amplitude should be as close as possible to the self consistent amplitude in order to minimize the time required for the algorithm to converge on the self-consistent solution.

The phase that extracts the most energy from the beam is determined from a component of the conservation of energy equation. From [7], the real power supplied by the beam is given by

$$P_s = -\iiint_{Volume} \mathcal{E} \bullet J dV \ , \tag{1}$$

where ε is the instantaneous electric field and J is the instantaneous current density. For the rigid-beam model, J is represented, according to [8], by

$$J = I_o \delta(x - x_o)\delta(y - y_o) \tag{2}$$

Substituting Eq. (2) into Eq. (1) results in

$$P_s = -\frac{1}{2}\int_z \mathcal{E}(x, y, z, t) I_o \delta(x - x_o)\delta(y - y_o) dx dy dz \tag{3}$$

This equation is evaluated numerically as particles are advanced through the beam-driven cavity. As an example, for any given cavity-field amplitude and phase, the electron is advanced through the cavity by a constant time step. The instantaneous electric field value at the center of a time step is multiplied by the change in z, Δz, and the beam current. The variation in Δz for the constant time step weights the numerical integral. For example, as longitudinal velocity is transferred into the transverse direction, Δz decreases, lessening the contribution to the numerical integral. This is equivalent to a numerical integration with a constant step in Δz, with the beam current weighted by the ratio of present longitudinal velocity to initial longitudinal velocity. The numerical integration can be represented by

$$P_s \quad \frac{1}{2}\sum_k I_o \mathcal{E}_k \Delta z_k \ , \tag{4}$$

where k represents the cavity transit time divided by the constant time step.

The supplied power calculated in Eq. (4) is compared to the power dissipated in the cavity walls given by [9] as

$$P_d \quad R_s \left(\frac{E_z}{\eta}\right)^2 \pi J_o^2(\chi_{11})\left[a^2 + ah\right] \tag{5}$$

III. RIGID BEAM MODEL RESULTS

The magnicon architecture modeled is shown in Figure 1, which also includes the dimensions of the magnicon geometry. For our modeling, we used a beam voltage of 170 kV, a beam current of 18 A, a frequency of 700 MHz, and a deflection system focusing field resulting in a deflection system cyclotron frequency 1.4 times the RF frequency. The parameters for the model were derived from [10]. With the rigid beam assumption, this model results in a magnicon that produces over 2.8 MW of RF power at an efficiency in excess of 90%. (Of course, the efficiency with a finite beam size would be lower and will be the focus of future work.)

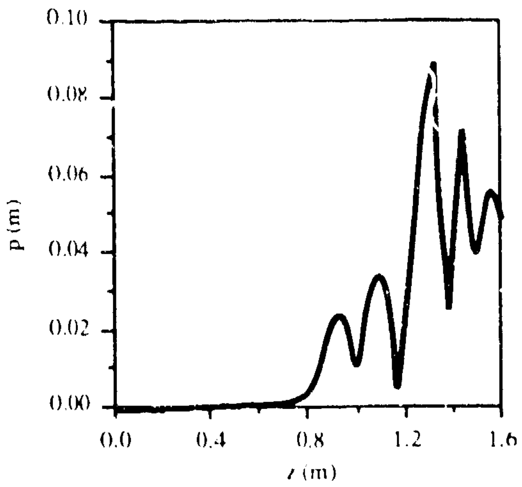

Figure 2. Radial displacement of single particle.

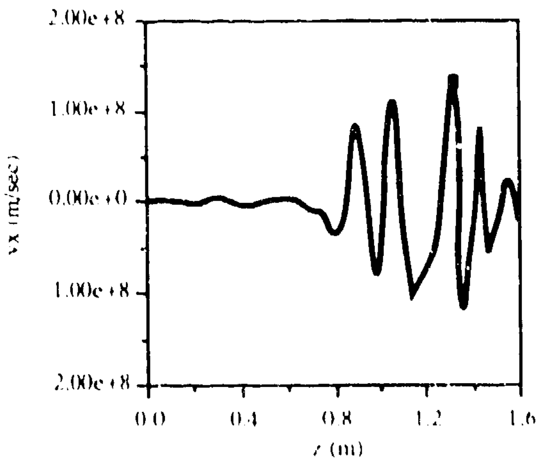

Figure 3. X directed component of radial velocity

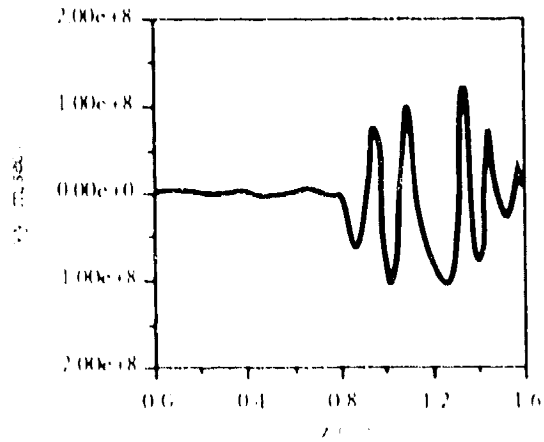

Figure 4. Y directed component of radial velocity

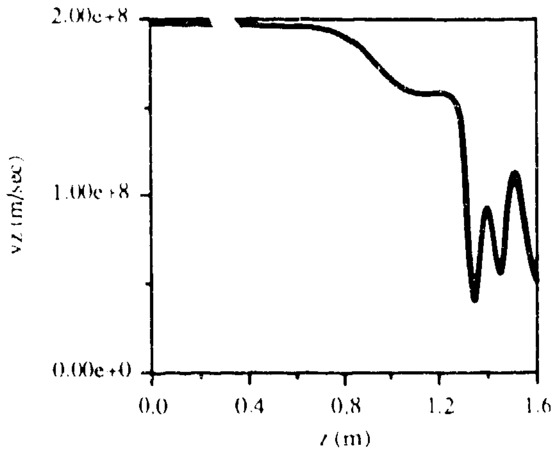

Figure 5. Variation of v_z.

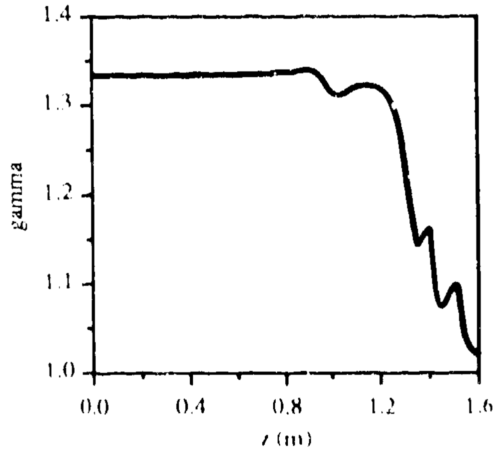

Figure 6. Variation of gamma.

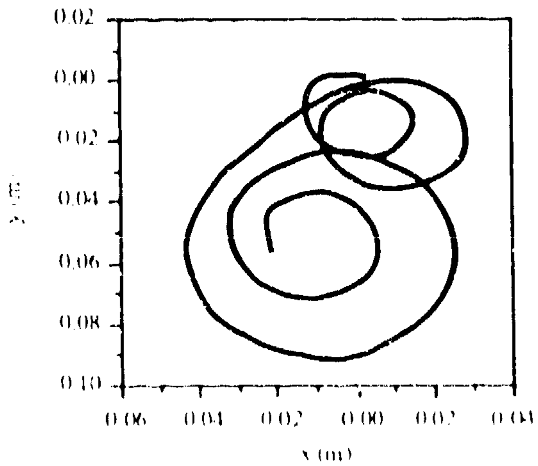

Figure 7. Top view of particle trajectories.

Figures 2, 3, 4, 5, 6, and 7 illustrate the results of the magnicon modeling. Figure 2 shows the radial displacement as a function of longitudinal distance along the magnicon. Figure 3 and 4 show the radial velocity as a function of longitudinal distance. Figure 7 is a view looking at the particle trajectories along the axis of the magnicon, and Figures 5 and 6 show the variation in gamma and v_z as a function of longitudinal position.

IV. CONCLUSION

We have developed a self-consistent approach to calculating magnicon passive- and output-cavity fields. This approach has been used to determine high-efficiency magnicon geometries using a rigid-beam approximation. Geometries that provide a conversion efficiency in excess of 80% have been obtained. The next step in the analysis is to extend the approach to a model with finite beam size and evaluate the performance sensitivity of these geometries to finite beam width.

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