Theoretical Investigation of Magnicon Efficiency[1]

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Abstract – In the output cavity of a frequency-doubling magnicon amplifier the electrons interact with a rotating TM_{210} mode via a gyro-resonant mechanism. The efficiency of a magnicon may be extremely high since the electrons enter the output cavity almost completely phase-bunched and rotate in synchronism with the rf wave. Results from time-dependent simulation of the electron beam-circuit interaction of a magnicon operating at X-band are presented. Efficient (> 50%), accessible and stable operation of an amplifier employing an electron beam with $\alpha \equiv v_\perp/v_{z0} = 1$, where $v_\perp$ and v_{z0} are the velocity components transverse to and along the z axis, is demonstrated.

I. Introduction

The magnicon[1–5] is an advanced version of the gyrocon[6] and employs a scanning beam that is obtained by the passage of a magnetized pencil beam from the electron gun through a deflection system. The deflection system consists of an input cavity and one or more passive cavities, separated by drift tubes, with the entire system immersed in an axial magnetic field, B_0. The cavities support a rotating TM_{110} mode with a frequency that is $\sim$ 1/2 the gyrofrequency, $\omega_{c0} \equiv |e|B_0/\gamma_0 mc$. Here, e is the charge and m is the mass of an electron, γ_0 is the relativistic factor, and c is the vacuum speed of light. The purpose of the deflection system is to spin the beam to high transverse momentum; i.e., $\alpha \equiv v_\perp/v_{z0} > 1$. Here, $v_\perp$ and v_{z0} are the velocity components transverse to and along the z axis. After passing through the deflection system, the beam transverse momentum is used to drive a gyrotron-like interaction in the output cavity. The entry point of the electrons in the output cavity rotates in space about the cavity axis at the drive frequency. In the frequency-doubling version, the output cavity supports a rotating TM_{210} mode with frequency $\omega \approx \omega_{c0}$, which is twice the drive frequency. Since the electrons entering the output cavity are almost completely phase-bunched and rotate in synchronism with the TM_{210} wave, the transverse efficiency may be extremely high.

II. Time-Dependent Simulation

The time-dependent simulation results presented here are obtained from the full set of Maxwell-Lorentz equations, following the motion of a single electron through the cavity and studying the build-up of the rf field over a much longer time scale. In Ref. 7 we present a detailed analytical and numerical study of the output cavity. Based on single-electron, steady-state simulation of the reduced and scaled Maxwell-Lorentz system of equations we have identified the regions of parameter space wherein high-efficiency operation may be possible. The time-dependent simulation results herein are intended to demonstrate the accessibility and stability of one such high-efficiency operating mode employing a beam with $\alpha = 1$.

Table 1 lists the parameters for the simulation with initial beam $\alpha = 1$, the cold cavity frequency being 11.424 GHz. Figures 1(a), (b), and (c) show plots of the electric field amplitude, $|E_0|$, the rf phase, β, and the efficiency of energy transfer to the external circuit, η, as functions of time. Observe that the system settles into a steady state after a transient that lasts $\approx$ 60 ns. Figure 1(a) shows that the electric field builds up to about 305 kV/cm, Fig. 1(b) shows that the rf phase settles to an asymptotic value of 1.1 rad, and Fig. 1(c) shows the final efficiency in this field is about 52 %.

Figures 2 (a), (b), and (c) show plots of the axial momentum normalized to its initial value, p_z/p_{z0}, efficiency, and α for an electron traversing the output cavity in the final steady-state field. The modulation of the electron momentum is seen to be correlated with the modulation on the efficiency curve. The

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scale-length for the modulation is $\approx 2\pi v_{z0}/\omega$. The length, L, of the cavity has been chosen to be 4.75 cm so that, on exiting the cavity, the axial momentum is a minimum, and therefore the efficiency is a maximum. In this sense, the optimal length for the output cavity is $\approx 2\pi n v_{z0}/\omega$, where n is an integer. Figure 2(c) shows that the value of α declines as the electron spins down on traversing the cavity.

Table 1

Frequency $\omega/2\pi$	11.43	GHz
Voltage	500	kV
Current	180.1	A
Cavity Radius	2.145	cm
Cavity Length L	4.75	cm
Cavity Quality Factor	200	
Beam α	1	
Magnetic Field B_0	6.455	kG
Detuning $(\omega - \omega_{c0})L/v_{z0}$	3.776	
Frequency Shift $\Delta\omega/2\pi$	6	MHz

Table 1: Parameters for time-dependent simulation of an X-band magnicon amplifier output cavity. Initial beam $\alpha = 1$.

III. Conclusions

In conclusion, we may summarize the single-electron simulation results as follows. First, as indicated in Figs. 2, for an ideal beam, it is possible to choose the cavity length so as to convert not only the transverse momentum but also part of the axial momentum into rf field energy. Second, based on the run made with the time-dependent code, we have found a final state that is accessible and stable to an amplifier in which the signal in the output cavity builds up from noise. Third, an efficient (> 50%) final state with $\alpha = 1$ is achievable.

Multi-electron steady-state simulation using the parameters in Table 1 indicate that the efficiency is sensitive to a spread in the beam parameters, declining by $\approx 10\%$ as the beam α spread increases from 0-40%, or the beam radius spread increases from 0-60%, or the energy spread increases from 0-3%.[7]

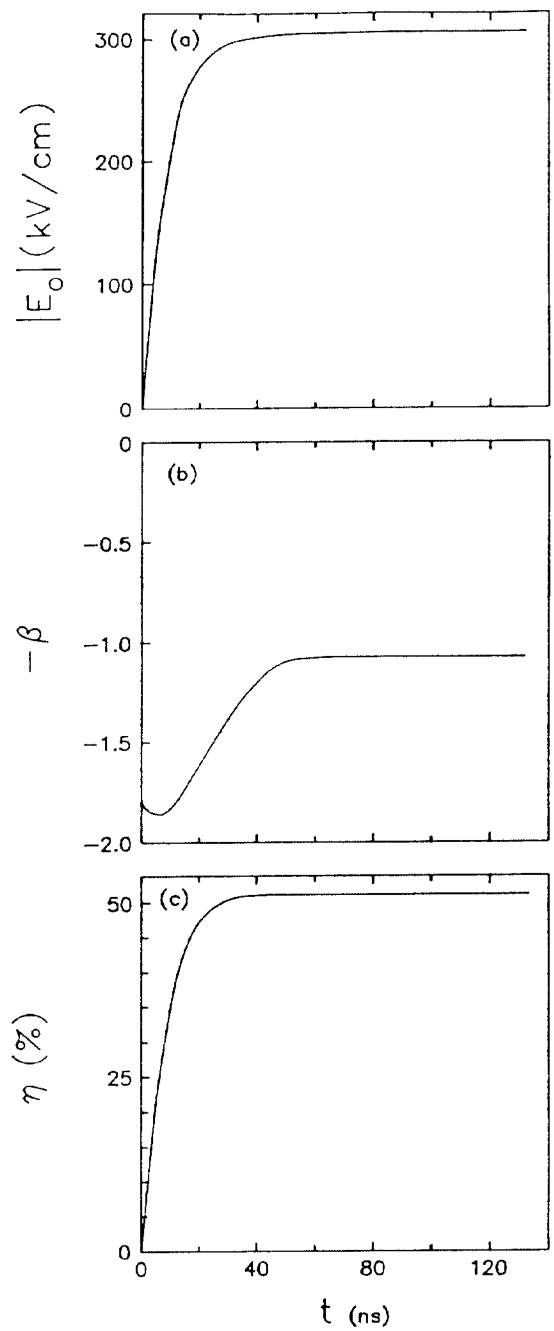

Figure 1: Results from single-electron, time-dependent simulation of X-band magnicon with initial beam $\alpha = 1$ and detuning $\Delta = 3.776$. (a) Electric field amplitude, $|E_0|$; (b) RF phase, β; (c) Efficiency, η. Abscissa is time.

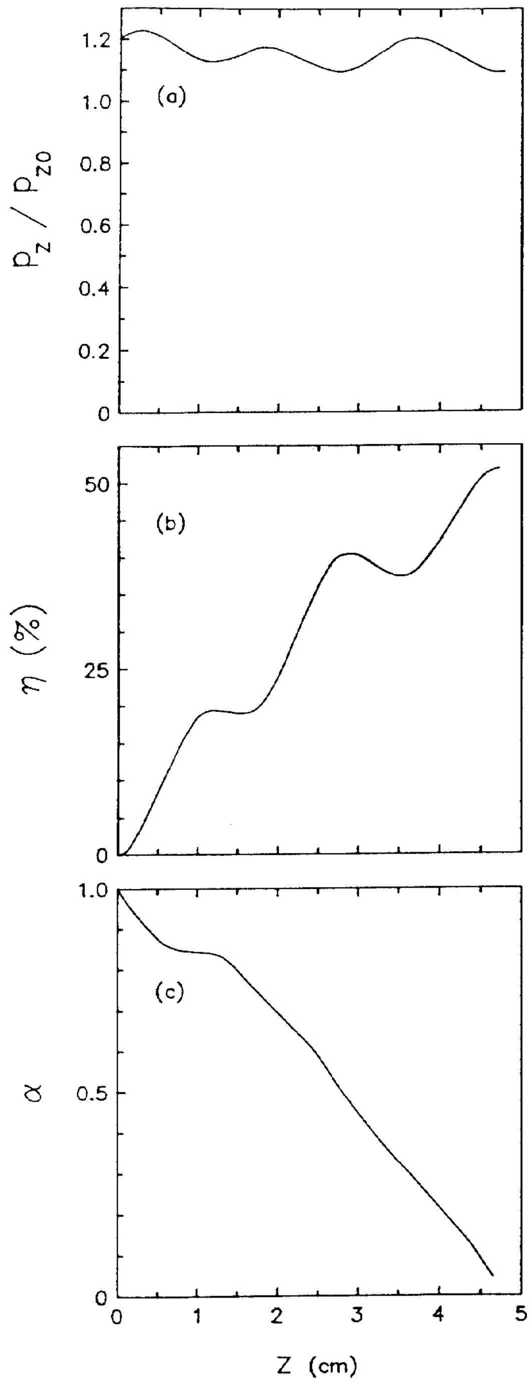

Figure 2: Results from single-electron, time-dependent simulation of X-band magnicon with initial beam $\alpha = 1$ and detuning $\Delta = 3.776$. (a) Axial kinetic momentum normalized to initial value, p_z/p_{z0}; (b) Efficiency, η; (c) α. Abscissa is distance along cavity. These plots correspond to motion of an electron through cavity in final steady state.

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