34-GHz PULSED MAGNICON FOR LINEAR COLLIDER APPLICATION

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Abstract

The feasibility of a third harmonic magnicon amplifier at 34.272 GHz as a RF source for future multi-TeV e^+-e^- linear collider is examined. A third harmonic operation of the magnicon is necessary to stay within the constraints imposed by cathode loading, breakdown field and pulse heating of the conductive walls. A low emittance 500 keV, 200A pencil electron beam interacts with the cylindrical TM_{110} mode in the deflection system and the cylindrical TM_{310} mode in the output cavity. The drive signal is at 11.424 GHz. Preliminary calculations show an efficiency of about 42% with output power in excess of 42 MW. The surface RF field in the cavities is in the range of 700 - 900 kV/cm which is below the breakdown level at 34 GHz for 1 µs pulse length. The maximal cathode loading does not exceed 15 A/cm^2.

1 INTRODUCTION

Recently there is a great deal of interest in developing electron-positron multi-TeV colliders. The next linear colliders (NLC) have been designed in the 0.5 Tev - 1.0 TeV center of mass energy (c.m.) range[1]. The RF operating frequencies for these accelerators range from 1.3 GHz to 30 GHz and the beam-loaded accelerating gradients range from 25 MV/m to 90 MV/m. Considerations are being given to future linear colliders in the 5 - 15 TeV c.m. energy range[2]. High accelerating gradients will be required to keep a reasonable over-all length for these high energy colliders. As a result, the accelerating structure will require high peak power per unit length and a high peak power per RF source. The accelerating gradient is strongly correlated to the operating frequency. At a constant stored energy per unit length in the accelerating structures, the gradient increases linearly with frequency. Hence, it is possible to design high energy colliders keeping the active length and ac power within reasonable limits (L_A ~ 30 km and P_{ac} ~ 200 - 300 MW) by operating at higher frequencies. The scaling relations for the variation of RF power with frequency and gradient has been investigated by Wilson[2] and design parameters are provided in the 1 - 15 TeV c.m. energy range. The parameters for 5 TeV linear colliders are: f = 34.272 GHz (12 times SLC frequency of 2.856 GHZ and 3 times NLC frequency of 11.424 GHz), L_A = 30 km, P_{ac} = 300 MW, peakpower per meter, P_m = 825 MW/m, unloaded accelerating gradient, E_0 = 250 MV/m and pulse length at the structure, T_p = 50 ns. A repetition rate of 120 Hz is assumed in the designs. The accelerating gradient is limited by the breakdown threshold, dark current capture threshold and the rise in temperature due to pulse heating of the walls. The high peak power at the accelerating structure may be obtained by pulse compression techniques. New pulse compressors, e.g. [3], are being developed to have a compression ratio of 32 with an efficiency of 78% and a power gain of about 25. Thus, for an output pulse length of 50 ns, the RF source pulse length is 1.6µs. If two 0.6m structures[2] are fed from each compression unit, the required RF power is (825 MW/m x 1.2)/25 = 39.6 MW/source. A magnicon amplifier[4] will be a suitable RF source to meet these requirements.

In scaling magnicon amplifiers to higher frequencies (consequently, smaller physical dimensions), a few design problems will arise at high power due to the limitations imposed by cathode loading, breakdown field and pulse heating of the cavity walls. The concept of a third harmonic magnicon amplifier is introduced to overcome these problems. It is possible to design electron gun and microwave circuits satisfying the restrictions on current density, electric field and cooling. Fundamental or second harmonic operation of the output cavity is not possible at the frequency and power of interest. At the fundamental frequency, the Larmor diameter will be large and the beam tunnel will not be cut-off to the operating mode of the output cavity. For the second harmonic, the RF fields will exceed the breakdown limit in the penultimate cavity. Of course, it is possible to use harmonics higher than third, but the efficiency will be lower at higher harmonics.

2 THIRD HARMONIC MAGNICON

The magnicon amplifier at 34.272 GHz will operate with a 500 kV, 200 A electron beam to produce about 40 MW output power with 1.5 µs pulse duration. The drive frequency is 11.424 GHz in the TM_{110} mode and the output cavity will operate in the TM_{310} mode at the third harmonic of the drive frequency. A schematic of the magnetic and RF systems are shown in Fig. 1. For efficient interaction in the output cavity, the beam diameter should be less than 1 mm, i.e., one-eight of the radiation wavelength. Hence, the electron gun is to be designed to produce a 200A beam with a diameter of 0.8 mm at the entrance to the drive cavity. Since the

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maximum cathode loading is 15 A/cm^2, a cathode diameter of 4.4 cm is chosen. Therefore, a beam area compression ratio of 3000:1 will be required. The total compression will be achieved through a 630:1 electrostatic compression and a 4.8:1 magnetic compression. An electrostatic compression of 630 is necessary to obtain a maximum dc electric field on the electrostatic focusing electrode of about 265 kV/cm which is acceptable[5] at 1.5 μs pulse duration. The gun layout is shown in Fig. 2. The shape of the electrodes are optimized to produce the required perveance, beam compression and the electric field strength. This design is based on an electron gun [6] already in operation at INP with an area compression ratio of 2400:1.

Careful design of the output and penultimate cavities are necessary to minimize the RF field without sacrificing the efficiency. Due to perturbations of the beam opening, the oscillations in the output cavity are

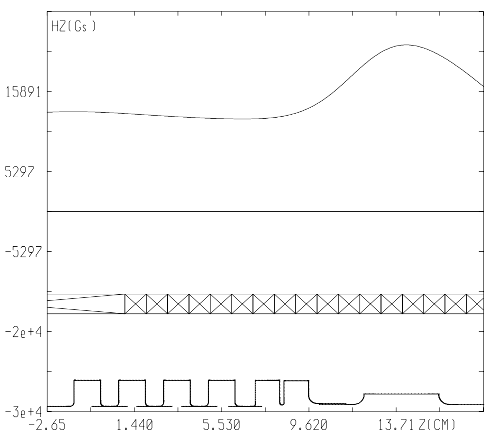

Fig.1 Magnetic field profile in Gauss vs coordinate in cm (top); and layout of coils, cavities (bottom) for 34.272 GHz magnicon.

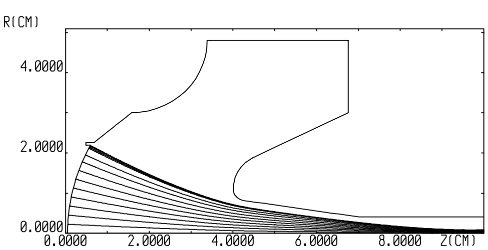

Fig. 2. The electron gun layout and the electron trajectories

not pure TM_{310} mode but has some admixture of the TE_{312} mode which depend on the length of the cavity and the shape of the beam tunnel opening. The maximum value of E at the cavity surface as a function of the cavity length is shown in Fig. 3 for different beam openings. The surface electric field is an oscillatory function of the cavity length. The output cavity length and the radius of the beam opening are chosen to produce a maximum electric field of about 860 kV/cm in the output cavity. The penultimate cavity is formed as a double-gap structure where the maximum electric field is 730 kV/cm.

The deflection system consisting of a drive cavity, three passive cavities and a penultimate cavity is placed

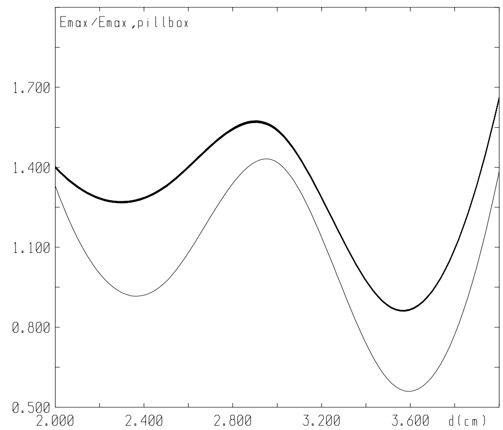

Fig.3. Dependence of surface electric field on cavity length. Beam opening radius of curvature r = 5.0 mm (upper curve) and r =3.0 mm (lower curve).

inside a superconducting solenoid providing a magnetic field of 13 kG (i.e.,$\Omega/\omega\approx1.45$). The relativistic cyclotron frequency is denoted by W. All cavities of the deflection system are 1.3 cm long with a diameter of 3.2 cm. The penultimate cavity is made up of two such cavities. The diameter of all deflection cavity apertures is 0.5 cm except the output aperture of the penultimate cavity which has a diameter of 0.7 cm to match the aperture of the output cavity. The electrons exiting the penultimate cavity have a deflection angle of about 39 degrees. The deflection angle is further increased to about 50 degrees as the electrons pass through an uptapered magnetic field in the drift region between the penultimate and the output cavities. The output cavity (length = 3.5 cm, diameter = 1.75 cm) is placed inside the second part of the superconducting solenoid giving a magnetic field of 22 kG (i.e.,$\Omega_2/3\omega\approx0.9$). Efficient interaction occurs when the cyclotron frequency is close the operating frequency. The applied magnetic fields in the deflection system and the output cavity are different, but there is no field reversal. The axial magnetic field profile is also shown in Fig. 1

The simulation results for the beam propagation during deflection and deceleration shown in Fig. 4 are based on the numerical code developed at INP, Novosibirisk. The physical and numerical models in the code are described in ref. [7]. The physical model considers finite transverse beam size, spatial distribution of dc magnetic fields, and actual rf fields of the cavities. The numerical model is based on macro particle method. The space charge effects and the finite beam emittance are neglected in the numerical code. The evolution of the electron trajectories and the rf fields are done self-consistently. Both steady state and time dependent simulations were done. Steady state calculations are used

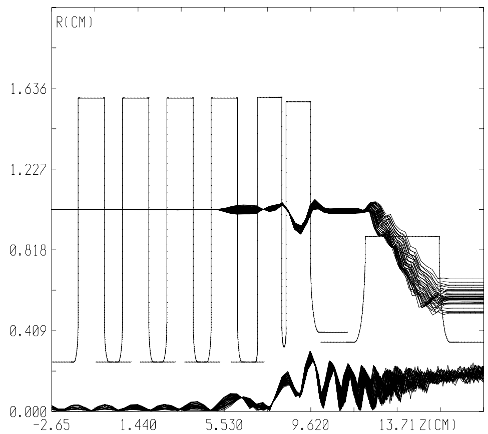

Fig. 4. Simulation results for 34.272 GHz magnicon. Shown is an outline of the RF cavities, energy and radial coordinates of beam electrons as functions of coordinate along the axis.

for magnicon optimization and stability analysis. The time dependent code is applied for investigation of transient processes. The results of the preliminary optimization are given in table I. The results in the table are obtained with an electron beam 0.8 mm in diameter and a cathode loading of 15 A/cm^2. The efficiency of a magnicon amplifier decreases with increase in the beam diameter. The calculated efficiency of the 3rd harmonic amplifier drops to 34% as the beam diameter is increased to 1.2 mm. The cathode loading for this beam is 6.7 A/cm^2 assuming the same beam area compression of 3000:1. The magnicon amplifier can be operated with a cathode loading lower than 10 A/cm^2 with only a moderate decrease in efficiency.

III CONCLUSIONS

Design parameters have been obtained for a 34.272 GHz third harmonic magnicon amplifier for powering a 5 TeV c.m. energy electron-positron linear collider. The calculated efficiency is 42% with a peak power of 42 MW in a pulse of 1.5 μs duration. The drive frequency is 11.424 GHz and the gain is 51 dB. The design takes into consideration the limitations imposed by cathode loading, breakdown field and pulse heating of the conductive walls. The cavities have been carefully designed to avoid self excitation and spurious harmonics generation.

Table I

Operating frequency	34.272	Ghz
Output power	42.0	MW
Pulse duration	1.5	μs
Repetition rate	10.0	Hz
RF energy	60.0	J/pulse
Efficiency	42.0	%
Drive frequency	11.424	Ghz
Drive power	300.0	W
Gain	51	dB
Output cavity E_{max}	860	kV/cm
Output cavity E_{max}/H_{max}	240	Ohm
Temperature rise (Output cavity)	120^0	C
Penultimate cavity E_{max}	730	kV/cm
Penultimate cavity E_{max}/H_{max}	250	Ohm
Temperature rise (Penultimate cavity)	45^0	C
Beam voltage	500.0	kV
Beam current	200.0	A
Microperveance	0.56	
Beam diameter	0.8	mm
Cathode diameter	4.4	cm
Total Area compression	3000	
Electrostatic compression	630	
Maximum cathode loading	15	A/sq.cm
E_{max} (focusing electrode)	265	kV/cm
Beam emittance (thermal)	π	mrad-cm
Beam emittance (geometric)	0.15π	mrad-cm

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