34 GHZ, 45 MW MAGNICON: FIRST EXPERIMENTAL RESULTS*

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Abstract

A high efficiency, high power magnicon at 34.272 GHz has been designed and built as a microwave source to develop RF technology for a future multi-TeV electron-positron linear collider. To develop this technology, this new RF source is being perfected for necessary tests of accelerating structures, RF pulse compressors, RF components, and to determine limits of breakdown and metal fatigue. After preliminary RF conditioning of only about 2×10^5 pulses, the magnicon produced an output power of 10.5 MW in 0.25 μs pulses, with a gain of 54 dB. Slotted line measurements confirmed that the output was monochromatic to within a margin of at least 30 dB.

INTRODUCTION

In order to develop RF technology in the millimeter wavelength domain for a future multi-TeV electron-positron linear collider, it is necessary to test in realistic regimes accelerating structures, RF pulse compressors, RF components, and to determine limits of breakdown and metal fatigue. A key element of a test facility required for these kind of experiments is a high-power (tens of MW), 0.5-1 μsec pulse microwave amplifier. The most attractive candidate for this role is the magnicon, a microwave amplifier employing circular deflection of an electron beam [1]. Magnicons have shown great potential with both high efficiency and high power. A first magnicon to have demonstrated these qualities was built and tested in the 80's in Novosibirsk. A power of 2.6 MW was obtained at 915 MHz with a pulse width of 30 μsec and an electronic efficiency of 85% [2]. In experimental tests also at Budker INP [3], a second harmonic magnicon amplifier operating at 7.0 GHz achieved an output power of 55 MW in a 1.1 μsec pulse, with a gain of 72 dB and efficiency of 56%. Another frequency-doubling magnicon amplifier at the NLC frequency of 11.424 GHz has been designed and built in a collaboration between Omega-P, Inc and Naval Research Laboratory (NRL). The tube is designed to produce ~60 MW at 60% efficiency and 59 dB gain, using a 470 kV, 220 A, 2 mm-diameter beam. At present, the tube is conditioned up to power level of 25 MW for a 0.2 μsec pulse width [4].

In scaling magnicon amplifiers from cm to mm wavelengths (consequently, to smaller physical dimensions), a few design problems arise at high power due to the limitations imposed by cathode loading, breakdown field, and pulsed heating of the cavity walls. A third harmonic magnicon amplifier described in this paper is introduced to overcome these limitations [5,6,7].

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THIRD HARMONIC MAGNICON AMPLIFIER

In general, a magnicon (as a klystron) consists of four major components, namely an electron gun, magnet, RF system and beam collector. The electron gun injects a 500 kV, 215 A beam with a diameter of about 1 mm into a chain of cavities forming the RF system. The deflection system consists of a drive cavity, three gain cavities and two "penultimate" cavities (working in "angle summing" mode [8]). The external magnetic field provides both beam focusing and coupling between the electrons and the RF fields in the cavities. The electron beam is radially deflected by the RF magnetic fields of rotating TM_{110} modes in the deflection system cavities. The scanning beam rotates at the frequency of the drive signal (11.424 GHz), then enters the output cavity and emits radiation at three times the drive frequency (34.272 GHz) by interacting with the TM_{310} mode. Fig. 1 shows the required magnetic field profile (top) and the superconducting coil configuration and iron yoke geometry to achieve this profile (bottom).

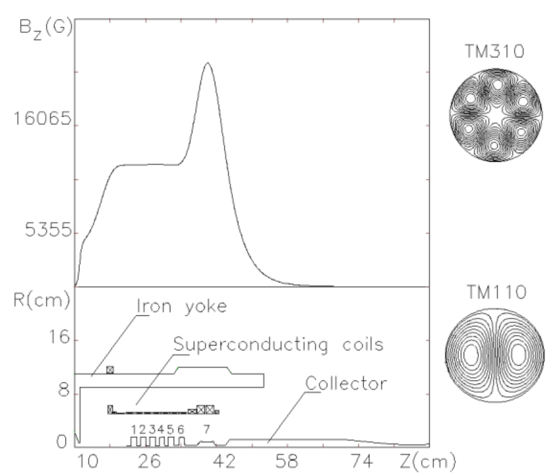

Fig. 1: Required axial magnetic field profile (top), and superconducting coil and iron yoke layout (bottom). Cavity chain and collector are also shown. Inserts at the right show RF field patterns for cavities #1-6 of deflecting system (TM_{110} mode at 11.424 GHz), and for the output cavity (TM_{310} mode at 34.272 GHz).

For effective deflection, the magnetic field in the deflection system should be such that $\Omega/\omega \sim 1.5$, where Ω is the cyclotron frequency and ω is the drive frequency.

In the output cavity, however, for efficient extraction of energy, the magnetic field should be chosen such that $\Omega/3\omega \sim 0.9$ [6].

The design parameters of this amplifier are given in Table 1.

Table 1: Magnicon design parameters.

Operating frequency, GHz	34.272
Power, MW	44-48
Pulse duration, µs	1.5
Repetition rate, Hz	10
Efficiency, %	41-45
Drive frequency, GHz	11.424
Drive power, W	150
Gain, dB	54
Beam voltage, kV	500
Beam current, A	215
Beam diameter, mm	0.8-1.0
Magnetic field, deflecting cavities, kG	13.0
Magnetic field, output cavity, kG	22.5

The complete engineering design of 34.272 GHz magnicon is presented in Fig. 2.

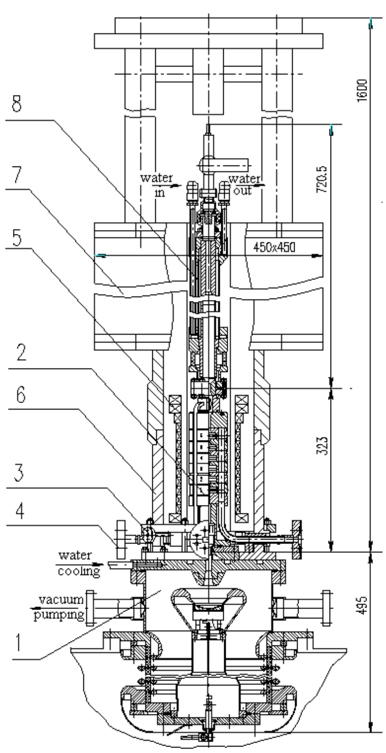

Fig. 2: 34.272 GHz magnicon amplifier tube: *1*-electron gun, *2*-RF system, *3*-output waveguide (WR28), *4*-WR90 waveguide, *5*-superconducting coils, *6*-iron yoke, *7*-cryostat, *8*-beam collector.

The diode gun design calls for a cathode current density of 12 A/cm^2, and a maximum surface electric field strength of 238 kV/cm on the focus electrode. It is found in this design that 95% of the current is within a diameter of 0.8 mm [9].

The RF system consists of seven cavities: one drive (#1) three gain (#2-4), two "penultimate" (#5-6), and one output cavity (#7). The shapes and dimensions of the cavities are chosen to avoid monotron self-excitation of axisymmetric modes, and harmonic frequency modes [6]. All cavities of the deflection system are about 1.25 cm long and their diameters are about 3.0 cm. There are four WR90 waveguides built in the body of deflecting system. One of them is for the drive cavity, and the rest are for diagnostic measurements in cavities #3, 5 and 6. These waveguides are also used for pumping. The length of the output cavity (3.15 cm) and its shape were optimized to achieve maximum efficiency, absence of parasitic oscillations, and acceptable surface electric fields [5,6]. The diameter of the output cavity is about 1.75 cm. Power is extracted by a set of four WR28 waveguides with an azimuthal separation $\Delta\theta = \pi/2$ that couple to both field polarizations [5]. One of them is shown in Fig. 2. The RF system is made as a brazed monoblock that allows baking up to 400° C.

EXPERIMENT

Before assembling the magnicon, the gun and beam collector were assembled and tested up to the design power of 100 MW in µsec pulses [9]. Initial conditioning up to ~515 kV was carried out without beam current. To achieve this, a matched load was connected to the primary of the pulse transformer. After cold conditioning, the gun was conditioned and tested hot up to ~480 kV and ~200 A. The measured beam current is in excellent agreement with the design value, with differences within the measurment error of less than ±2%.

The magnicon was then assembled, cold tested and baked out in 2002. The general view of the fully assembled tube is shown in Fig.3.

Fig. 3: The general view of the fully assembled tube.

Preliminary tests of the tube were started in May, 2003. The beam voltage in the first set of experiments was 435 kV, and the beam current was 185 A. The modulator pulse was shortened, as shown in Fig. 4, in order to reduce the risk of the gun arcing during conditioning. Oscillograms of the signals from cavities #3, #5 and #6 are shown in Fig. 5.

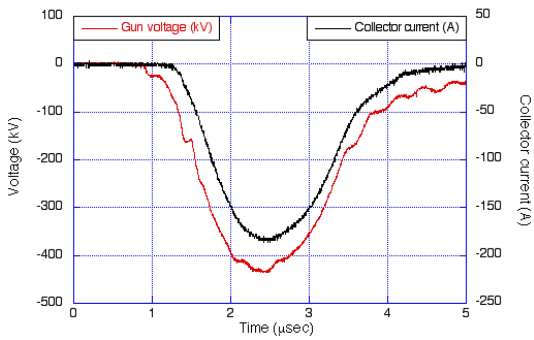

Fig. 4: Beam voltage (lower curve) and beam current (upper curve).

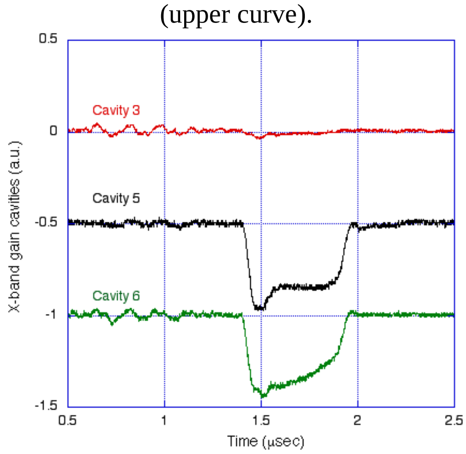

Fig. 5: The signals from deflection cavities #3, #5 and #6.

The four magnicon outputs are terminated with vacuum waveguide loads *via* bi-directional couplers [10]. Examples of measured output signals from these four directional couplers are shown in Fig. 6.

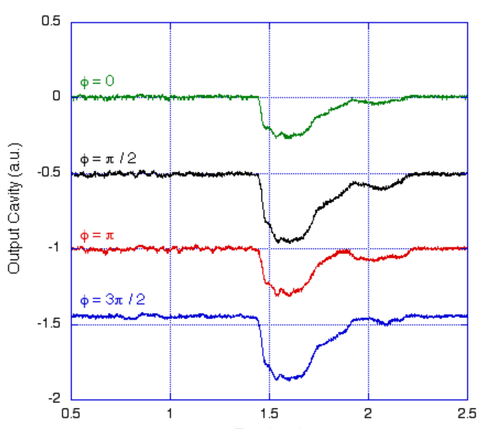

Fig. 6. Output signals from the four WR-28 output waveguides.

The maximum value of total measured power in these experiments was about 10 MW, based on applying calibration data to measurements such as in Fig. 6. After about 2×10^5 pulses at a repetition rate of about 1 Hz the process of conditioning has progressed, the shapes of output signals and signals from deflection cavities are not yet stable, and pressure rises are observed. At the same time, the tube demonstrates single frequency operation as a third harmonic amplifier with high gain of about 54 dB. Shorted slotted line measurements confirmed that the output signals are monochromatic to within a margin of at least 30 dB.

The results of the first tests are summarized in Table 2.

Table 2: The first tests results.

Power, MW	10.5
Pulse duration, μsec	0.25
Repetition rate, Hz	~1
Gain, dB	54
Beam voltage, kV	435
Beam current, A	185

CONCLUSION

The 34.272 GHz magnicon amplifier is assembled and the first tests have been conducted. To date the measured output power is 10.5 MW in 0.25 μs pulses.

The program of future experimental work on the 34.272 GHz magnicon test facility includes experimentation on metal fatigue caused by pulse heating and development high-power components, e.g. output windows, mode converters, etc.

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