High Power Accelerator R&D at the NRL 11.424-GHz Magnicon Facility

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Abstract. An 11.424-GHz magnicon amplifier has been jointly developed by the Naval Research Laboratory and Omega-P, Inc. as an alternative technology to klystrons for powering a future X-band linear collider. This paper will discuss its background, operating principles, and results to date, as well its present status as part of a facility for collaborative research on accelerator-related technologies that require high-power 11.424-GHz radiation. Two collaborative research programs are currently under way using the magnicon output. The first, a collaboration with Omega-P, Inc. and the Institute of Applied Physics, is investigating active microwave pulse compressors using plasma switch tubes. The second, a collaboration with Argonne National Laboratory and SLAC, is investigating dielectric-loaded accelerating (DLA) structures, with the ultimate goal of developing a compact DLA accelerator.

INTRODUCTION

The goal of the magnicon development program at the Naval Research Laboratory (NRL) has been to develop a new type of X-band accelerator-class microwave amplifier tube as a competitor to klystrons for use in powering future colliders or other high-gradient linear accelerators [1-3]. The magnicon, originally invented at the Budker Institute for Nuclear Physics (INP) in Novosibirsk, Russia [4], is a "scanning-beam,,, or deflection-modulated amplifier tube that offers the potential for high power and very high efficiency at frequencies ranging from below 1 GHz to 35 GHz [5]. The 11.424-GHz magnicon development program has been carried out as a collaborative effort between NRL and Omega-P, Inc. In this device, an initially linear beam is "spun up,, in a series of deflection cavities containing synchronously rotating TM_{110} modes. The deflection cavities include a drive cavity, three gain cavities, and finally two penultimate cavities, that contain rf high fields and do the bulk of the spin-up. These cavities operate at 5.712 GHz. The output cavity contains a synchronously rotating 11.424-GHz TM_{210} mode that extracts principally the transverse beam momentum. The use of synchronously rotating modes in all of the cavities means that

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conventional bunching, such as the ballistic bunching employed in a klystron or the phase bunching required in a gyroklystron, is not required. In principal, all of the electrons entering the drive cavity at a single point in time experience identical forces during their transit through the entire device. Once steady-state operation is achieved, the operation of the device is time-invariant when viewed in a frame co-rotating at the rf-drive frequency of 5.712 GHz. This synchronism makes possible extremely high efficiencies, since all the electrons will ideally experience identical rf fields. For this reason, the experimental parameter that most directly impacts magnicon efficiency is the size of the electron beam, since the larger the beam, the more that radial gradients in the deflection cavity rf fields create a spread in the electron momentum and phase at the entry to the output cavity. In fact, a near-Brillouin beam is needed to maximize the magnicon efficiency [6,7]. One of the key technical accomplishments of the program was to develop an electron gun producing a 500-keV, 200-A electron beam with a beam radius of ~1 mm [8].

The rf conditioning of the magnicon is still not completed. The goal of the present program is to complete the conditioning, while simultaneously pursuing collaborative research programs that make use of the magnicon output to develop and test other technologies of interest for future collider applications. Two research programs are under way. The first, a collaboration with the Institute of Applied Physics of the Russian Academy of Science, in Nizhny Novgorod, Russia and Omega-P, Inc., is pursuing the development of high-power active microwave pulse compressors based on plasma switch tubes [9]. The second, a collaboration with the Argonne National Laboratory that will involve SLAC in its later stages, is an investigation of high-gradient dielectric-loaded accelerating (DLA) structures, with the ultimate goal of developing a compact dielectric-loaded test accelerator at NRL [10].

STATUS OF THE MAGNICON FACILITY

The magnicon was developed to be an accelerator-class microwave amplifier tube. As such, it operates with a frequency-stable drive signal derived from a low-power tunable oscillator, monitored with a frequency counter, and pulse amplified by a 1-kW TWT amplifier. Its key design parameters, as well as its present level of performance, are shown in Table 1. The basic performance of the magnicon follows its design, but the present power and efficiency are still short of the design parameters due to pulse-shortening effects (e.g., multipactor, breakdown) in the high-field penultimate deflection cavities and in the output cavity. The performance is expected to improve as the rf conditioning process proceeds. In addition to the measurements shown in Table 1, we have measured the magnicon drive curve (power out versus power in), which is well-behaved over a considerable range of drive powers, and the frequency response, which shows an instantaneous bandwidth of ~.05%. We have also demonstrated the magnicon stability, even in the presence of resonant loads, as well as its phase stability.

The magnicon output is extracted in two SLAC-style WR-90 waveguide lines, each with a high-power TE_{01} output window, and then enters SLAC-type directional couplers and loads. Experiments making use of the magnicon output can be connected

Table 1. Magnicon Parameters

	Design	Operation
Frequency	11.424 GHz	11.424 GHz
Power	61 MW	15 MW / 25 MW
Pulse width	~1 μs	1.2 μs / 200 ns
Repetition rate	10 Hz	10 Hz
Efficiency	59 %	~16-28 %
Drive frequency	5.712 GHz	5.712 GHz
Gain	59 dB	~59 dB
Status: Operational; conditioning in progress		

in place of either load. A power combiner for the two magnicon output arms is under development, but at present, only a single output waveguide can be connected to the experimental test component, and thus only half of the total magnicon power can be used to test pulse compressors, accelerator structures, or other test loads. Thus, approximately 8 MW is available in a 1-μs output pulse suitable, for instance, for filling the storage cavity of an active pulse compressor, while ~13 MW is available in 200-ns pulses suitable for driving an X-band accelerating structure. The NRL magnicon facility is illustrated in Fig. 1. Two test stands are located adjacent to the magnicon output. The first, a 5'x25' raised platform for pulse compressor experiments, is 8' high, and passes over the concrete shielding wall. The second, a 10' high concrete deck area, is currently used for testing DLA structures. A concrete bunker will be installed behind the shielding wall for the future DLA accelerator experiment, once an electron beam injector is added to that experiment.

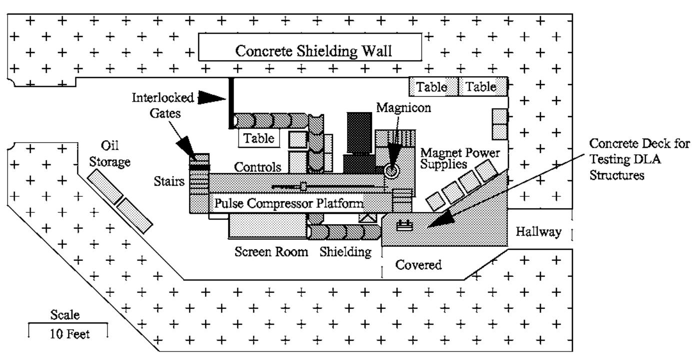

Figure 1. Schematic of NRL magnicon facility.

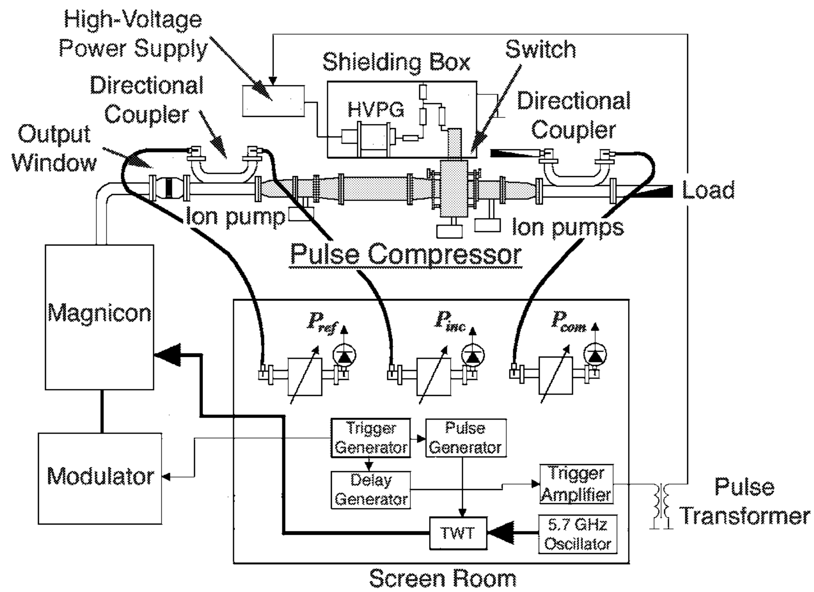

FIGURE 2. Schematic of the active microwave pulse compressor experiment.

ACTIVE PULSE COMPRESSOR EXPERIMENT

Active microwave pulse compressors are of interest to future colliders because they offer the possibility of higher efficiency, higher compression ratios, and/or a more compact configuration (and lower cost) than other approaches that are currently under consideration. A schematic of the active pulse compressor experiment is shown in Fig. 2. The pulse compressor is connected to the magnicon by means of a waveguide line equipped with an output window to separate the vacuum chambers of the magnicon and the compressor. It consists of a section of over-sized cylindrical TE_{01} waveguide connected to the magnicon through a mode converter and a Bragg reflector, which forms the input end of the storage resonator, and to the output waveguide through an iris and a special switch cavity, which constitutes the output reflector of the storage resonator. The output pulse of the compressor enters a high-power matched waveguide load. Signals proportional to the power incident on the compressor (P_{inc}), the power reflected from the compressor (P_{ref}), and the output power (P_{com}) are measured by 55.5-dB directional couplers, with the signals attenuated and measured by crystal detectors located in a screen room. A trigger generator and a set of digital delay generators trigger the magnicon modulator, then trigger the TWT amplifier to provide the magnicon input pulse, and finally trigger a high voltage pulse generator that creates an electrical discharge in a pair of gas-filled quartz tubes in the switch cavity of the pulse compressor near the end of the magnicon output pulse. This

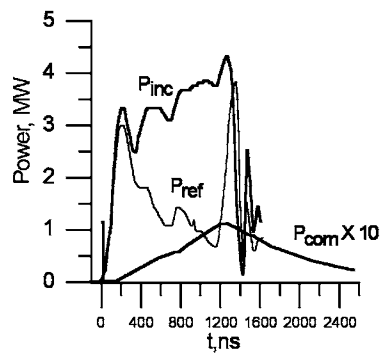

FIGURE 3. Pulse compressor waveforms, showing energy storage and decay without discharge.

shifts the center frequency of the switch cavity, reducing the reflection coefficient at the end of the cavity, and permits the stored energy to discharge rapidly to produce the compressed output pulse. Three ion pumps are used to maintain a pressure of 10^{-6}–10^{-7} Torr in the switch.

The pulse compressor is tuned to the magnicon output frequency by changing the resonator length. The output reflector is then tuned relative to the minimum of the power transmitted through the compressor, P_{com}, under the condition that the difference between the incident and the reflected power, P_{inc}–P_{ref}, is maximized. This setting corresponds to the maximum Q-factor of the resonator (maximum coefficient of reflection from the output reflector). In a previous experiment, the maximum stored energy was limited by multipactor discharge on the exterior of the gas-filled quartz switch tubes. In this experiment, the use of larger diameters discharge tubes and heating the tubes prior to rf conditioning made it possible to increase the incident power up to the level of 5–6 MW with no sign of multipactor discharge. A typical set of oscilloscope traces of the incident, reflected and transmitted signals is shown in Fig. 3, for a case in which the output switch was not discharged. After the magnicon pulse is over, P_{com} decreased exponentially, permitting one to calculate the Q-factor: $P_{com} \propto \exp(-2t/\tau)$, where $\tau = 2Q/\omega$. The Q-factor of the storage resonator was in the range Q=(4-7)·10^4 and depended on tuning of the output reflector to the maximum of the reflection coefficient.

The pressure in the quartz switch tubes was externally regulated. At high levels of incident power, when the value of the electric field in the tubes exceeded the breakdown threshold level for this pressure, a microwave discharge occurred that caused non-triggered switching of the pulse compressor. In this self-breakdown mode of operation, experiments investigated the production of compressed pulses at various pressures of nitrogen, SF_6, and their mixtures in the gas discharge tubes. Oscilloscope traces corresponding to the generation of compressed pulses at 100 Torr and 1 Torr of N_2, respectively, are shown in Fig. 4. The peak power in the compressed output pulses was 14 MW and 24 MW, in these two cases, with pulse durations of 55 ns and 45 ns. The compression factor in the latter case was ~6×. These experiments showed that at higher gas pressures in the tubes, self-breakdown occurs at a higher incident power

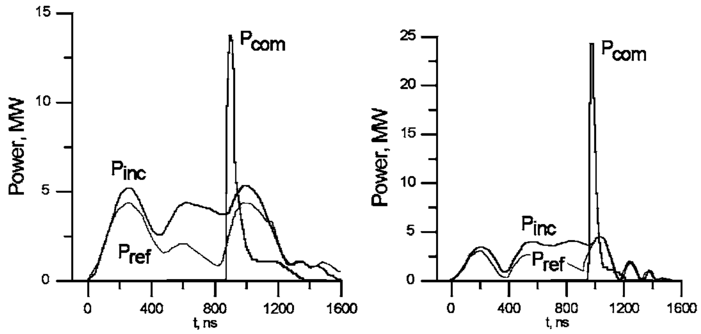

FIGURE 4. Pulse compressor waveforms, showing the compressed pulse in the self-breakdown regime.

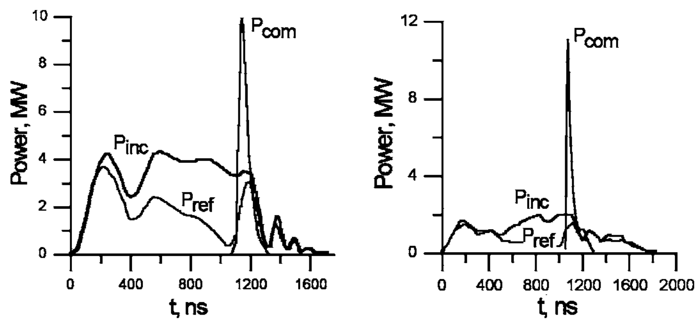

FIGURE 5. Pulse compressor waveforms, showing the compressed pulse in the triggered regime.

level, which makes it possible to store higher energy in the resonator. At the same time, when the pressure is lower, and the switch is operated substantially above its self-breakdown threshold, the efficiency of energy output from the resonator and the power in the compressed pulse both increase.

Next, we studied operation of the compressor with the discharge initiated by a high voltage pulse generator (HVPG). A high-voltage pulse (80 kV, 100 ns) was fed to the tube electrodes via a limiting resistor (300 Ohm) and an inductance-free divider. In these experiments, the incident microwave power was decreased below the level at which self- breakdown occurred at a particular pressure in the switch tubes. High power compressed pulses, with efficient energy output, could be obtained at low gas pressures with an N_2:SF_6 mixture in the tubes. Figure 5 shows experimental traces obtained in the case of triggered discharges. In the left-hand case, 100 Torr N_2+5 Torr SF_6 was used. For a stored energy of 1.85 J, a 90-ns compressed pulse was produced with a peak power of 10 MW. In the right-hand case, using 10 Torr N_2+1 Torr SF_6, for a stored energy of 0.72 J, a compressed pulse with a peak power of 11 MW was produced. The compression factor in the latter case was ~8×. These traces demonstrate that, at lower pressures, when the HVPG generated plasma quickly fills the entire volume of the switch tube, the efficiency (as well as the stability) of energy output from the storage resonator improves significantly.

DIELECTRIC-LOADED ACCELERATOR EXPERIMENT

A hollow dielectric-loaded metal waveguide can be used as a slow-wave electron accelerator by choosing a liner material with an appropriate dielectric constant and choosing inner and outer dimensions to match the phase velocity to *c* [11]. Compared to conventional iris-loaded copper slow-wave structures, the dielectric-loaded accelerator (DLA) configuration is simpler, potentially easier to fabricate, can have comparable shunt impedance, and permits simpler suppression of higher-order modes. In addition, the accelerating field is the largest field in the dielectric-loaded structure, and there are no conduction band electrons, which should assist in suppressing dark current and field emission. The material of choice for the liner is a low-loss ceramic. Argonne National Laboratory has developed test accelerating structures, and subjected them to low-power cold tests. The purpose of the experiments at NRL is to carry out high-power tests in order to determine the performance of these structures at high accelerating gradients.

In a recent experimental run, tests were carried out of both traveling-wave and standing-wave DLA structures. In the traveling-wave configuration (see Fig. 6), we succeeded in coupling ~600 kW into the structure. Traces corresponding to this limit are shown in Fig. 7 (left set of traces), which shows a forward power of ~600 kW, a minimum reflected power of ~40 kW, and a transmitted power of ~170 kW. This corresponds to an accelerating gradient in the structure of ~3-5 MV/m. Slightly above this power level, signs began to appear of arcing in the input coupler (see Fig. 7, right traces), but no sign of breakdown in the main accelerating structure. The location of the arcing could be determined by the lack of visible light in the accelerating tube and by the appearance of a vacuum pressure increase only in IP4, the ion pump directly adjacent to the input coupler. Continued operation at high power levels gradually degraded the performance of the coupler, indicating that this was an issue of coupler

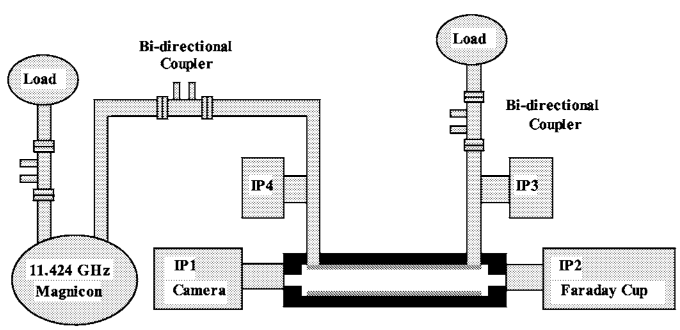

FIGURE 6. Diagram of experimental setup for testing traveling-wave DLA

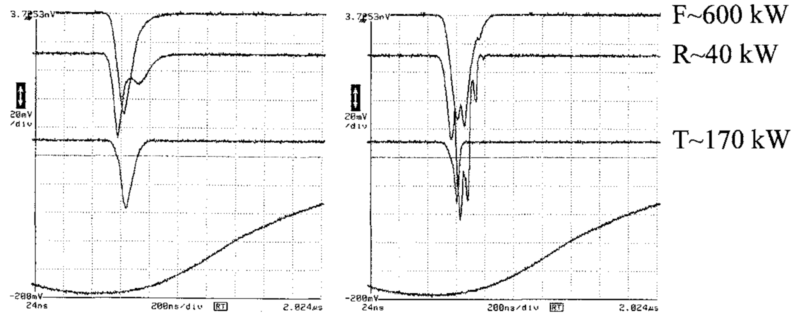

FIGURE 7. Traces from traveling-wave DLA experiment. Left traces: no breakdown; Right traces: breakdown of input coupler.

damage rather than conditioning. Upon disassembly, the input coupler was found to be visibly damaged, with discoloration extending across the center of the coupling aperture at the location of the maximum electric field. Tests were also carried out of a standing-wave DLA structure. However, these tests suffered from a low-power failure of the coupling aperture, apparently due to the presence of a copper residue on the ceramic of the coupling iris (that was observed following disassembly), and did not succeed in coupling sufficient energy into the cavity to produce high accelerating gradients. This work is described in more detail in an accompanying paper [12].

SUMMARY

The conditioning of the magnicon that is at the heart of the NRL 11.424-GHz high-power accelerator test facility is not yet complete. Nevertheless, at its present level of operation, the magnicon is being used to carry out two separate collaborative experimental programs that employ the high-power 11.424-GHz radiation to study high-power active microwave pulse compressors and high-gradient dielectric-loaded accelerating structures. The first sets of experiments in each of these areas have made significant progress, but have also pointed to areas needing redesign. In the case of the active pulse compressors, the next experiment will employ a two-channel compressor with improved plasma switches, coupled to the magnicon by a quasioptical 3-dB hybrid so as to constitute a matched load to the magnicon. This will permit the magnicon to produce a flat, rather than time-dependent, output pulse, and should permit demonstration of significantly higher peak powers in the compressed pulse. In the case of the DLA, a completely new input coupler is being designed that will separate the side-coupling aperture into the accelerator tube from the transition into the dielectric-loaded region. This should eliminate the problem of coupler breakdown, and permit tests of substantially higher accelerating gradients. The next series of tests in both of the collaborative experimental programs should take place later in Fall, 2002. In the periods between these tests, conditioning of the magnicon is to continue, with the goal of demonstrating at least 50 MW of peak power in flat output pulses of 1-μs duration.

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