MULTIPACTOR DISCHARGE IN A RESONATOR AS AN ACTIVE SWITCH FOR RF PULSE COMPRESSION

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Abstract

Pulse compression is a method of increasing the peak power of the microwave pulse at the expense of its length. Over the years a number of pulse compressors had been demonstrated with some being bulky but efficient, like the binary pulse compressor and other being compact but less efficient, like SLED-II. An active pulse compressor had been proposed to increase the efficiency and compression ratio which relies on a high power active switch. Currently there are no practical switches that can work reliably with 100 s of megawatts of power. Most of the switches (ferroelectric, plasma-based, semiconductor) are limited by the breakdown strength of various dielectric inserts. In this paper we report on an active switch development which is based on a pure copper resonator and controlled by a single-side multipactor discharge at a metallic wall in the presence of a resonant DC magnetic field and a normal to metal rf field. The discharge is ignited by external rf power produced by inexpensive 2.45 GHz, 1-5 kW magnetrons.

INTRODUCTION

A high gradient accelerator requires sub-microsecond input pulses at the multi-megawatt level. It is wasteful and dangerous in terms of RF breakdown to feed a much longer RF pulse at such a power level. At the same time running a klystron with reduced pulse length is also inefficient: the peak power does not increase as the pulse shrinks [1]. A better alternative is to operate the klystron at a longer pulse and utilize a pulse compressor, a device that increases the peak power of the microwave radiation at the expense of its pulse length. Passive pulse compressors (types SLED and SLED-II) appeared 40 years ago and demonstrated high compression ratios at high power at a sufficiently high efficiency [2-6]. A power gain ratio of 3 with efficiency greater than 50% was achieved at 2.856 GHz. These compressors are successfully employed today, and recently compression with a gigawatt power level output was demonstrated in X-band. Pulse compression is performed via a fast 180^{o} phase change of an input signal feeding two identical resonators through a -3 dB (50%) directional coupler. In the SLED-II pulse compressor, resonators are replaced by resonant delay lines that produce a flat top output pulse, required for particle acceleration. Power gain and compression efficiency are limited due to transient processes which result in a portion of the power being left in the compressor. For this reason, active pulse compressors, which allow minimizing the Q-factor of the resonator in the “switched state”, potentially have an advantage in terms of the gain achievable with the same efficiency. In this project we are developing a compressor of the SLED-II type with an active switch based on multipactor ignition with a gain of 8 and efficiency over 70%.

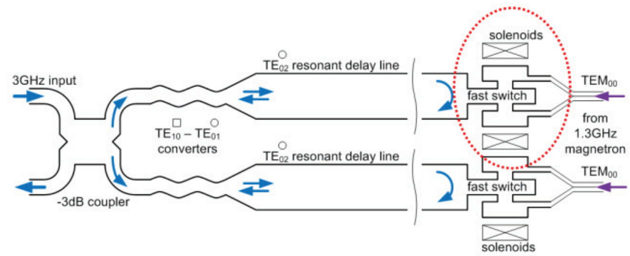

Figure 1: Schematic of a 3 GHz RF pulse compressor based on 1.3 GHz active switch.

Research in active pulse compressors has been going on for decades as well. Fast laser-driven semiconductor-based switches have been developed [7-9]. Ferroelectric switches driven by external static fields were also demonstrated [10]. A large number of studies have been devoted to discharge (plasma) switches in X-band (11.424 GHz) [11-15], with a power output of 100 MW successfully demonstrated. However, in all these switches the electric breakdown strength at high levels of microwave power is weakened by various dielectric inserts. For this reason, much research recently has been focused on hollow all-metal switches with small surface fields. One of the most successful examples of such systems is a switch based on the injection of an electron beam into the cavity [16-18]. In one implementation in X-band, the output pulse power reached approximately 200 MW [18]. However, the use of a relativistic electron beam as a switch is not practical for applications that require high repetition rate and a large total number of pulses. High repetition rate might also be questionable because the used field emission cathode implies production of plasma having long relaxation decay time.

ACTIVE SWITCH

A schematic view of a 3 GHz compressor designed to compress the pulse length of 2 μs with a compression ratio (in time) of 10 and power gain of 8 is shown in Fig. 1. Current calculations are done for the main pulse (to be compressed) at 3 GHz and the frequency of the multipactor ignition pulse at 1.3 GHz. The resonator cavity can be redesigned for any frequency depending on the availability of the multipactor ignition source. The RF pulse compressor consists of two resonant delay lines fed

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through a -3dB coupler so that the outgoing power is not going towards the source.

RF power is injected into the resonant delay line in a form of TE_{01} mode but it is partially converted into the TE_{02} mode when reflecting from the end of the line. The TE_{02} mode is forbidden to exit the resonant delay line. Hence the energy is stored in the resonant delay line in the TE_{02} mode. The active switch is needed to change the RF properties at the back of the line and force a 100% conversion of TE_{02} mode into TE_{01} so that the energy previously stored in the TE_{02} mode leaves the delay line as a TE_{01} mode. With a waveguide diameter of 136.5 mm, TE_{03} and higher order modes are forbidden, the length of the delay line, $L=T_d \cdot v_{gr}/2$, is 17.3 m, where v_{gr} is the group velocity of the TE_{02} mode, and the output pulse length $T_d = 200$ ns.

The active switch transforms the incoming TE_{01} into a proper amount of the TE_{02} mode in a delay line. This consists of a smaller diameter TE_{01} mode waveguide with a TE_{011} mode resonator attached to it with a Q-factor of 130. The engineering design of an active switch is shown in Fig. 2.

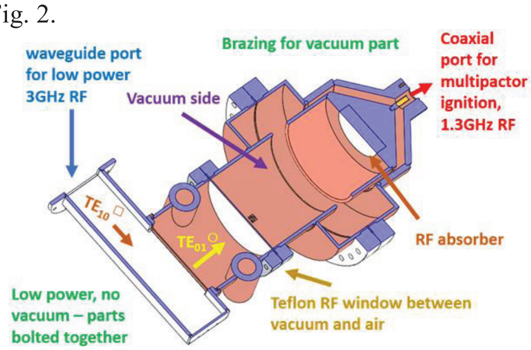

Figure 2: Engineering design of an active switch.

In the charging regime (Fig. 3) the interference of the RF pulse reflected from the diameter step and from a resonator provide a coupling coefficient of 0.23 (power) for the TE_{01} and TE_{02} modes. This provides 80% efficiency with losses taken into account. In the discharge mode the coupling coefficient becomes 100%, i.e. all stored power in the TE_{02} mode is transferred into TE_{01}. Figure 4 shows simulations of the discharge regime, when the resonator is filled with multipactor plasma (inactive) and the reflection from the switch changes by 180 degrees in phase. In simulations the resonator was loaded with a plasma with concentration, $N_e = 10^{11}$ cm^{-3} and collision frequency, $f_i = 1.3$ GHz.

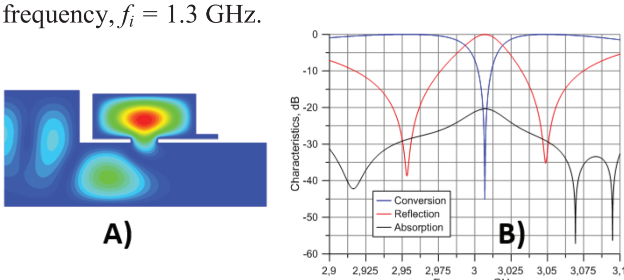

Figure 3: Active switch in the “charging” regime. A (left) – fields, B (right) – S parameters.

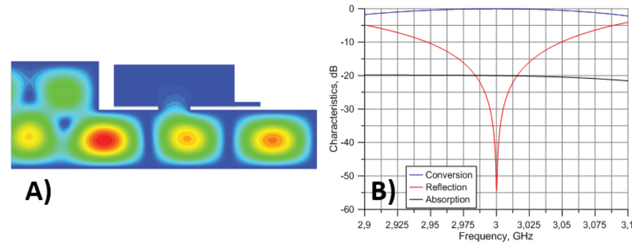

Figure 4: Active switch in the “discharge” regime. A (left) – fields, B (right) – S parameters.

Pulse compressor efficiency is reduced due to the finite active switch operating time, incomplete switching, and losses in the delay lines and in the switch resonator (in the walls and the plasma layer). We simulated the pulse compressor taking into account all of these factors. We define the efficiency of the pulse compressor as the ratio between the energy of the output pulse (high peak power compressed portion) to the total energy in the incident pulse. The compression efficiency is found to be 79% in the case of uniform plasma with $N_e = 10^{11}$ cm^{-3} filling the whole resonator. We also simulated a case with a $N_e = 10^{11}$ cm^{-3} plasma of a finite layer thickness of d = 10 mm. In this case, the efficiency decreases to 73%.

Figure 5: Active RF pulse compressor parts machined ready for brazing.

All parts of the cavity have been machined (Fig. 5) and sent for brazing. The cavity will be tested at ANL/AWA test facility in Phase II of the project.

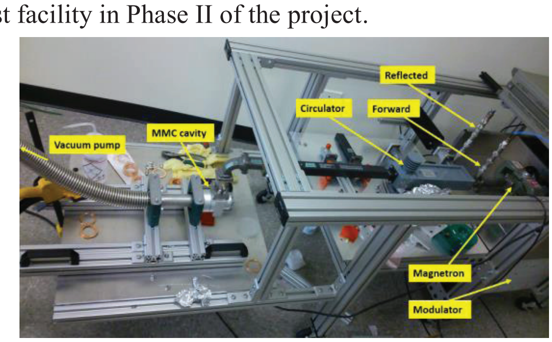

Figure 6: High power X-band multipactor ignition switch experiment layout.

RF SWITCHING BY MULTIPACTOR

Meanwhile, we built a smaller cavity to test multipactor ignition by an X-band source available at Euclid’s R&D facility. We had chosen a mode with one extra longitudinal variation, the TM_{012} mode of a cylindrical resonator. This was done to have a circle with zero

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magnetic field on the cavity wall, where we could split the cavity into two halves to make brazeless engineering design possible. The TM_{012} mode is excited from a coupler on the side of the structure (Fig. 6) by a 0 – 200 kW magnetron at 9.290 GHz. The cavity was manufactured out of aluminum and successfully passed the vacuum testing. After network analyzer measurements confirmed that the required RF properties were achieved, the cavity was installed on the X-band stand (Fig. 6) and high power measurements were performed.

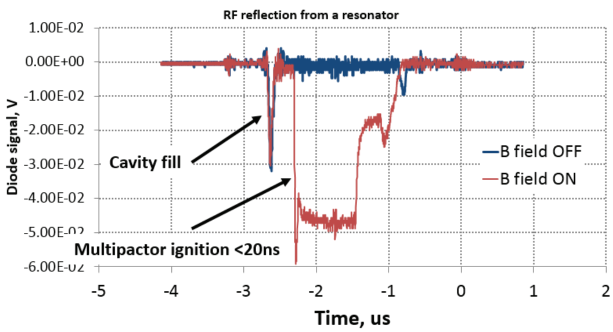

Figure 7: Multipactor switching. Blue line – typical resonator filling curve (reflection). Red curve – magnetic field is turned on: multipactor is ignited and reflection from the resonator appears due to secondary electron avalanche loading. Switching time is 20 ns.

Because of the high coefficient of secondary electron emission of aluminum, multipactor ignition can be driven by a 20 kW drive at 9.3 GHz. The typical measured reflection curve for a resonator driven at its resonant frequency is depicted in Fig. 7 in blue. When the RF pulse begins, most of the power is reflected (hence the dip) then it starts filling the cavity and returns to zero reflection. When the RF pulse ends there is a reflection from the resonator again. There is a solenoid wound on top of the cavity. When the magnetic field is turned on at some field strength (time during the RF fill) the multipactor discharge turns on. When multipactor turns on, beam-loading from secondary electrons detunes the cavity and RF from the source is reflected back because of the impedance mismatch. This sharp (in time) effect is used for active switching. Note that the switching time is short, <20 ns in this case (Fig. 7). The typical jitter in the onset was <2 ns.

ACKNOWLEDGEMENT

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