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72 MHz SOLID-STATE AMPLIFIER POWER TEST

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Abstract

In this paper, we present the performance of 72 MHz 18 kW RF power source developed for cyclotrons. The machine is equipped with 9 class-AB power amplifier modules (each with up to 2 kW output) based on highly reliable LDMOS transistors. The whole system is arranged inside a single 19” cabinet and has 50 Ohm coaxial output. The test environment and high power measurement results are described.

INTRODUCTION

The current RF power source is designed for upgrade of cyclotrons that are being used for PET isotopes production (^{18}F, ^{11}C, ^{13}N and ^{15}O) with H- ions at 11 MeV [1]. The upgrade of the system is required to provide higher RF beam energies for new isotopes and hence more powerful RF source. On the other hand, facilities hosting the PET centers are limited in AC means. In this situation the way out would be to rise both: the output power and efficiency of the RF source.

Compared to conventional vacuum tubes generators, the solid-state generator benefits in significantly higher efficiency, smaller footprint, perspective of lower cost, and better reliability.

GENERATOR SYSTEM OVERVIEW

The assembled 72 MHz generator (1st prototype) is presented in Fig. 1. 190 cm high 19” cabinet consists of 9 RF power amplifier modules (RFPA) 1, 9-to-1 power combiner 2, control system 3 and of the power distribution system 4.

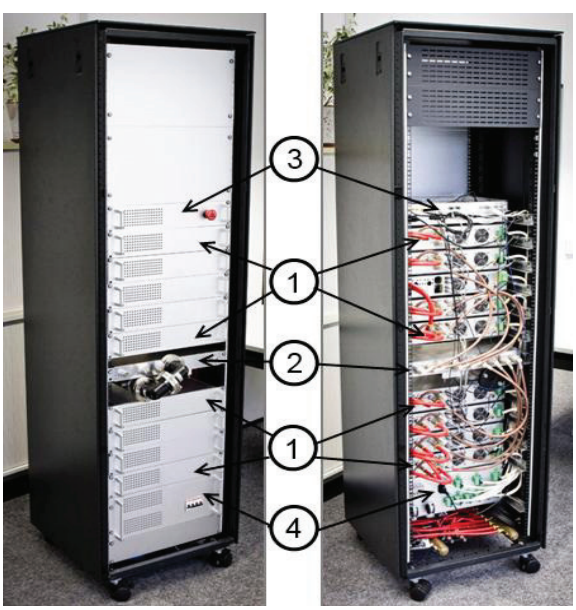

Figure 1: Assembled 72 MHz RF generator.

Each RFPA has logic scheme that collects the measured parameters (supply voltage and current; input LLRF power level; forward/reflected power at the amplifier output) and communicates with the control system 3.

The control system has function of resonance frequency tracking of the cyclotron during operation and adjusts simultaneously the operation frequency of the generator.

The cooling system is placed in the bottom of the generator assembly and performs the water flow through the RFPAs and the control system.

RFPA MODULE TEST

The manufactured RFPA module is presented on Fig. 2. Currently, there are three main components in it: DC power supply block, the PCB-based solid-state amplifier and the circulator connected downstream to the amplifier.

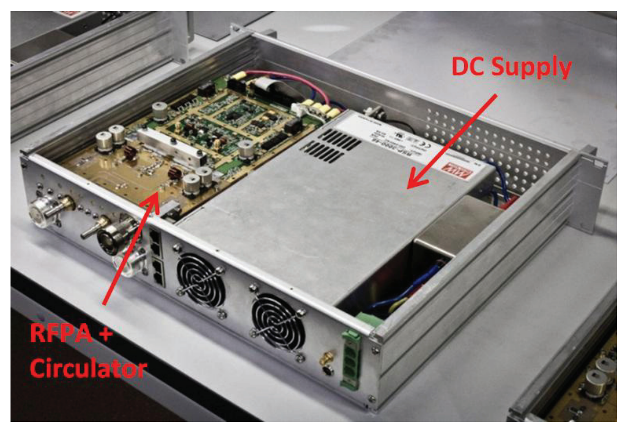

Figure 2: RFPA module.

A single RFPA module has been tested in two regimes – with a matched 50 Ohm load and with resonant cavity which represents the operation with cyclotron.

During the first test type, the RFPA showed the following performance (see Table 1).

Table 1: RFPA Specifications

Parameter	Value
Bandwidth	72..73 MHz
Output RF power	max. 2500 W
RF efficiency	~75%
Gain	51 dB
Input RF power	max. 20 mW
Supply voltage	48 V
Input/Output impedance	50 Ohm
Input/Output VSWR	max 1.3

The frequency range from 72 MHz to 73 MHz is defined due to the accelerating cavity resonant frequency

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drift during the cyclotron operation. The power added efficiency of 75% was measured without using the circulator.

As for now, the maximum output power of 2500 W can be handled during short pulses. The CW regime is limited because of the following reasons. The output impedance of the transistor amplifier is ~1 Ohm, which has to be matched to a 50 Ohm output. Currently, we use a single-stage planar transformer which results in too high current that leads to the local overheating (115°C) as shown in Fig. 3.

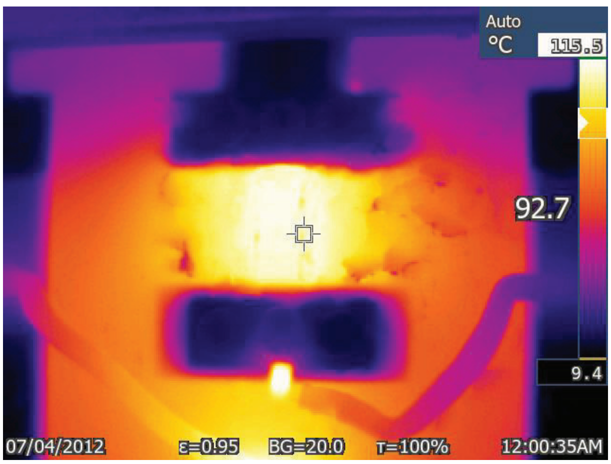

Figure 3: IR capture of the impedance transformer at maximum output RF power.

This problem will be solved in the next version of RFPA by using prematching circuit between transistor output and planar transformer. In order to reduce the risk of RFPA damage, for further tests the output RF power has been limited to 1800 W at 5 ms pulses with 20% duty cycle.

We have created the quarter-wave coaxial resonator to simulate how each of the RFPAs can drive the cyclotron cavities and operate without use of circulator. This resonator features the Q-factor of 2600 and its resonance frequency f_0 is adjustable between 72 MHz and 73 MHz. Two trombone phase shifters were connected between the RFPA and the cavity to represent different transmission line lengths to the cavity and to adjust the phase difference between forward and reflected waves.

The test bench scheme is shown in Fig. 4. During these tests, forward and reflected RF powers as well as the cavity field probe signal were measured at different phase shifts with and without the circulator. 50 us pulses used at these measurements. Use of longer pulses makes no sense because the fill time of the cavity is nearly 10 us. The measured time curves of these signals are plotted in Figs. 5 and 6.

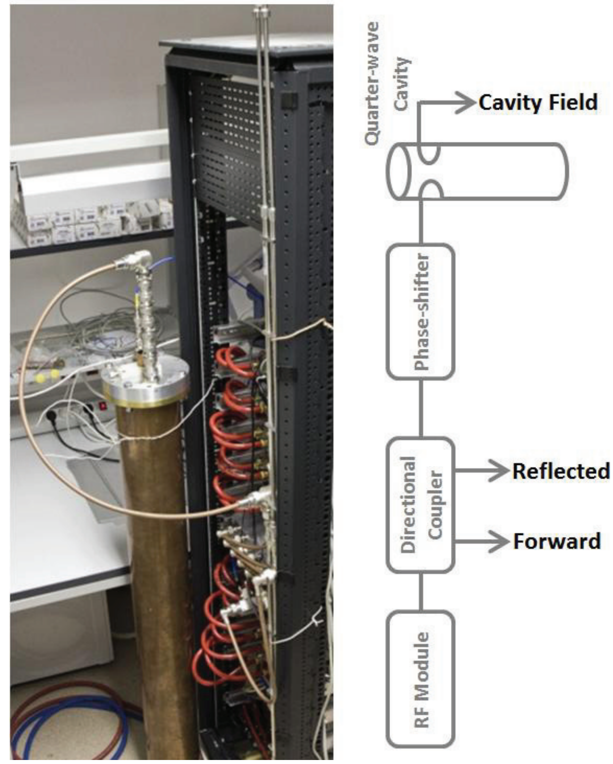

Figure 4: Resonant test scheme.

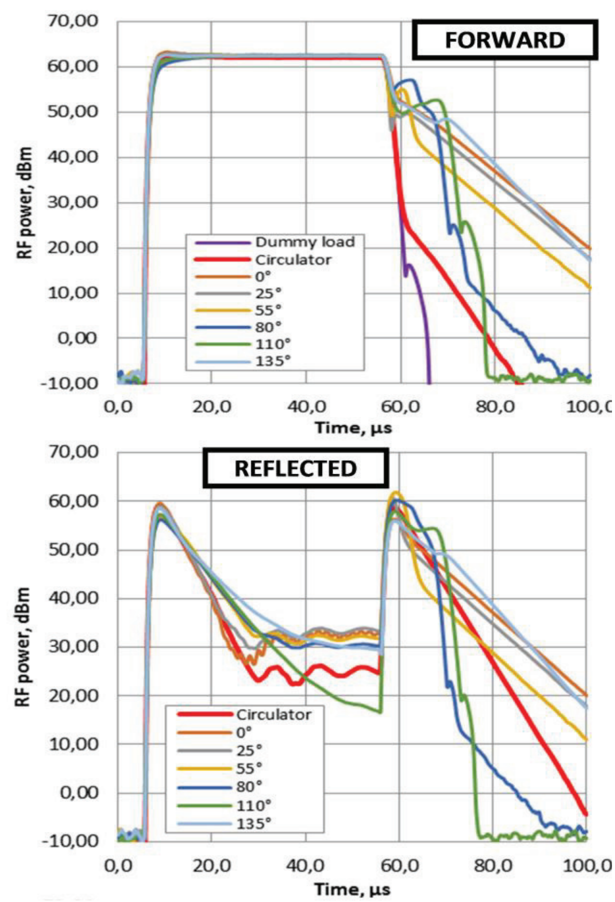

Figure 5: Forward (top) and reflected (bottom) powers oscillograms at different phase shifts.

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These measurements showed that the RFPA experiences no problems when feeding the resonator (can handle full reflection), even if at certain phaselengths filling and decay times raised and the reflected power level increased. Nevertheless, these issues will not negatively affect the generator during CW cyclotron operation, taking into account matched conditions with cavity beam loading.

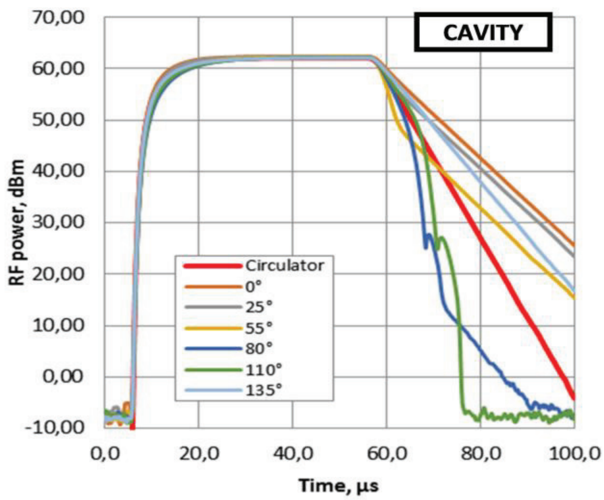

Figure 6: Cavity field probe oscillograms at different phase shifts.

POWER COMBINER

The power combiner [2] (see Fig. 7) was manufactured, assembled into the system and successfully tested at the full power. RF measurement results are listed in Table 2.

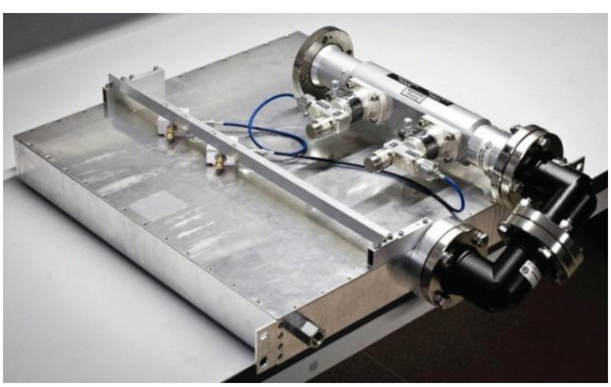

Figure 7: 9-to-1 power combiner with external directional coupler.

Table 2: Power Combiner Features

Parameter	Value
Frequency	72..73 MHz
Return loss (within BW)	27..34 dB
Dissipated RF power	0.5 %
Power splitting equality	<1 %
Isolation	14..16 dB

It shows good power splitting equality, low insertion loss (no cooling is needed) but also insufficient and unequal isolations between inputs which is subject for further improvement. The overall height of the combiner including external directional coupler is ~16 cm.

CURRENT GENERATOR OPERATION

The overall system performance shows the following features:

- operation frequency range – 72..73 MHz
- output RF power of 13.5 kW at 5 ms pulses with 20% duty cycle
- wall-plug efficiency 50%.

Unfortunately, we had to use circulators upstream to the power combiner that dissipate tremendous amount of RF power. Therefore the output power and overall efficiency decreased by 15%.

The necessity of using the circulators is due to low and unequal isolations (from 14 dB to 16 dB) between power combiner inputs that lead to 'cross-talking' effect between the RFPAs thus causing parasitic oscillations in the total output spectrum. This problem will be solved by replacing the power combiner with a new version having appropriate level of isolation.

SUMMARY

We have presented the current performance of the 72 MHz 18kW power generator. The solid-state class-AB RF amplifiers show commendable efficiency of 75% at the operation output RF power level of ~2 kW.

CW regime has not been reached yet but will be possible soon after several modifications of RFPA. In the next iteration, the following changes will be made referring to output power and efficiency improvements:

- the RFPA's output impedance transformer will be redesigned;
- using only 8 RFPAs out of 9;
- excluding the circulators;
- using the 8-to-1 power combiner with improved isolation.

Also every element will be more compact. The power combiner height will be reduced in half down to 8 cm. The control system is planned to be redesigned into 15 cm high rack and will be VME-based.

REFERENCES

[1] Siemens Medical Solutions website: http://www.medical.siemens.com/siemens/en_GB/gg_nm_FBAs/files/dash/ds_09_eclipse.pdf

[2] A.Yu. Smirnov et al., "The Layout of 72 MHz 16 kW RF Power Generator," WEPHO04, p. 940, Proc. of NA-PAC2013, Pasadena, USA (2013); http://jacow.org