HYBRID CONFIGURATION, SOLID STATE–TUBE, REVAMPS AN OBSOLETE TUBE AMPLIFIER FOR THE INFN K-800 SUPERCONDUCTING CYCLOTRON*

A. Caruso†, F. G. Caruso, A. Longhitano, A. Spartà, INFN-LNS, Catania, Italy
J. Sura[1], Warsaw University, Warsaw, Poland
G. Primadei, CERN, Geneva, Switzerland

Abstract

An insertion of a solid state amplifier is substituting the obsolete first stage of a full tube RF power amplifier. The amplifier is based on two tube stages. The first, equipped by a tetrode, the RS1054, was being manufactured by Thales until some years ago. Some spare parts have been ordered but not enough to guarantee smooth cyclotron operation for the next few years. It was necessary to come up with a new solution. We were basically at a crossroad: replace the first stage with another tube still in production or change the technology from tube to solid state. A study, from market research to the technology point of view was carried out and the final decision was to use a solid state stage as an innovative solution for this kind of power vs frequency range of operation. The prototype of this hybrid amplifier has been in operation with our cyclotron since January 2015. The details of these decisions, the description of the modified amplifier (solid state – tube) and the successful results of this hybrid configuration will be shown in this presentation.

RF AMPLIFIERS STORICAL OVERVIEW

The RF power amplifiers are made by two tetrode stages driven by solid state commercial amplifiers. The drivers are class A, wideband, 50 dB gain and a maximum out power of 200 W. The RF power amplifier can deliver a maximum power of 75 kW, the total gain between 1st and 2nd stage is about 30 dB. The first stage is wideband, based on the tetrode RS1054L by Thales, in ground-cathode configuration, air-forced cooling. The second stage is a narrow band stage, common grid configured, based on 4CW100000E by CPI, water cooled.

Figure 1: RF amplifiers and the 1st – 2nd stages view.

The three RF power amplifier cabinets with the internal view of the final stage are shown in Fig. 1. The tuning system for all the frequency range (15-50 MHz) is automatic. This amplification system was made, under technical specification by our Institute, at the end of 1980s. Since the commissioning of the Superconducting Cyclotron, 1994, the amplifiers have been operating, related to the RF power stages, without significant changes or upgrade. The robust and classical electrical design of the amplifiers has ensured, more or less, an uninterruptable operation, for the last 30 years. Figure 2 shows a simple block diagram of the RF system, with drivers and final amplifiers [1].

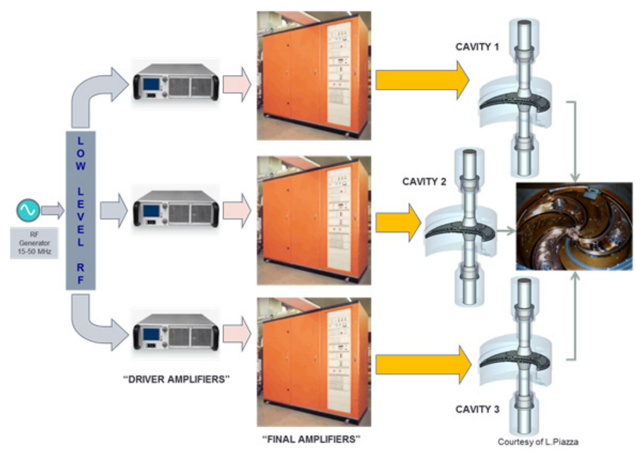

Figure 2: Block diagram of the RF system.

The total gain between drivers and final amplifiers is approximately around 80 dB. The distribution is about 50 dB for the driver and 30 dB for the final amplifier. The final is divided between 14 and 16 dB respectively for the 1st and 2nd stages. Despite the cost of the two tetrodes, in terms of spare parts, has greatly increased in the last decade, we decided to continue operating with this configuration. But some expedients was adopted. For example, we optimized the main parameters of the amplifiers, to reduce the maximum output power from 75 kW to 30 kW, enough for our cyclotron performance and as result, the average life span of the tetrodes was increased. We decided to refurbish the exhausted tetrodes, instead of buying new ones, reducing the cost by a third, and the reconstructed tetrode, can be considered like new. Unfortunately, this refurbished technique can be done only for the second stage, the 4CW100000E by CPI, while for the first stage, the RS1054L by Thales, it was not available. Apparently, the type, hardware and geometry of the tetrode itself made the rebuilding of the Thales tetrode almost impossible [2, 3].

* INFN-LNS
† caruso@lns.infn.it

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TETRODE VS SOLID STATE

In any case, the main reason for modifying the amplifiers and consequently changing the first stage, was the end of production of the tetrode, RS1054E, in a few months. The strong decrease in demand on the worldwide market for this specific tetrode, was the reason Thales stopped production altogether. We were only given the opportunity to buy the last three tetrodes at the very unreasonable price of about 60 k€! In the meanwhile the cyclotron was in operation, the total RS1054L spare parts were not many, no specific planning was scheduled, in terms of funding/timing, because Thales sent us notification a very short time before ending production. Figure 3 shows the schematic of the RF amplifier and, in the dotted line, the obsolete 1st stage to be removed and replaced.

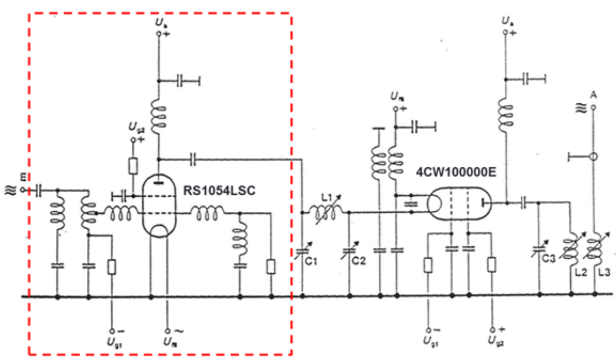

Figure 3: RF schematic, part to be removed in dotted line.

Obliged to change this tetrode, we had two options: use another tetrode or a new solid state technology. The first approach was more conservative, we considered more than one possible tetrode. Commercial partners such as Eimac and Thales offered very few valid alternatives and, it is not a plug and play job, some hardware modifications have to be made, like new sockets, some changes in the polarization network, redesign of the matching board between the 1st and 2nd stages, and recalibration of the RF response. As a possible alternative to the originally used RS1054L the CPI tube 4CX3500A was selected. This tube is less powerful than the original one but was selected because we thought that the final power of 30kW was enough for normal cyclotron activity. The obsolete and new tetrodes are shown in Fig. 4.

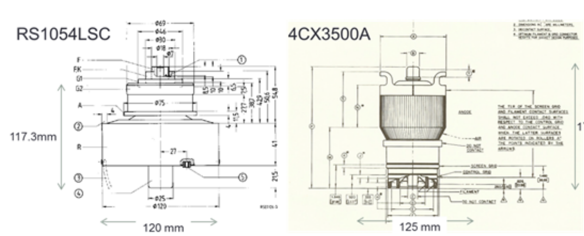

Figure 4: Mechanical difference between the two tetrodes.

The most critical parameter is the input capacitance of the 4CX3500A as it influences the input circuit negatively. The existing input wide band circuit has to be redesigned in order to cope with the higher tube capacitance. An insertion of new crowbar circuit in the anode power supply plus retuning of anode matching circuit.

The positive points of this “conservative” choice are:

- 4CX3500 cost is relatively low, high efficiency, high reliability, robustness;
- apparently no end of production in the near future, according to the manufacture;
- CPI, ensured total assistance to rebuild the tube in case of failure (not necessary to buy a bright new tube every the time).

The risk and negative points of this operation are:

- The tetrode manufacturer can notify the end of the production of this new tetrode at any moment. With a very short margin in terms of time, according to our experience;
- It is not possible to store a lot of spare parts, economic and vacuum tube technology;
- Cost/timing of the total operation is quite high.

But, the most important point, to investigate other solutions, for example the new emerging solid state technology, was the increased number of dismissed tetrodes and absence of new products in our frequency/power range.

Figure 5 shows the trend of the power tube market. The area of our interest inside the dotted line is empty.

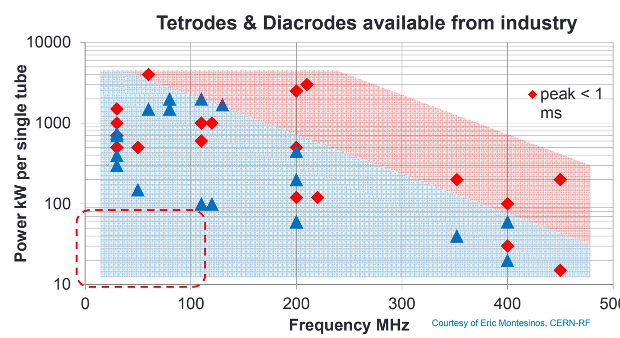

Figure 5: Frequency and power range of tetrodes.

The interest of the market in our frequency/power range is moving from vacuum tube to solid state devices. The miniaturization of the RF power components and the maximization of power per single device is only one reason for this new trend. The new solid state technology is going to cover the slice of market under a power of 100 kW and up to few hundred MHz of bandwidth [4].

SOLID STATE AMPLIFIER FIRST STAGE

Removing the first stage based on the tetrode and installing a solid state amplifier means to adapting and matching this new device mainly in terms of impedance and amplification factor. In the original configuration of the amplification section, according to Fig. 2, the driver, a commercial amplifier, was connected to the main amplifier, through a 50Ω wide band input circuit of the first stage, based on the tetrode RS1054. The output of this stage, through a further matching section, a variable π-filter tuning system, is connected with the input of the second stage, cathode of the 4CW100000E tetrode. For

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each frequency, the variable components of the matching networks, tune the amplifier parameters and maximize the transmission. Our goal, once the first tetrode is removed, is to minimize the hardware modification of the remaining amplifier, adapt the new solid state first stage, reproduce the previous performance and contain the cost. The block diagram of the new amplification sections, in Fig. 6, includes a solid state amplifier, as the new first stage, a matching box, the second stage of the main amplifier.

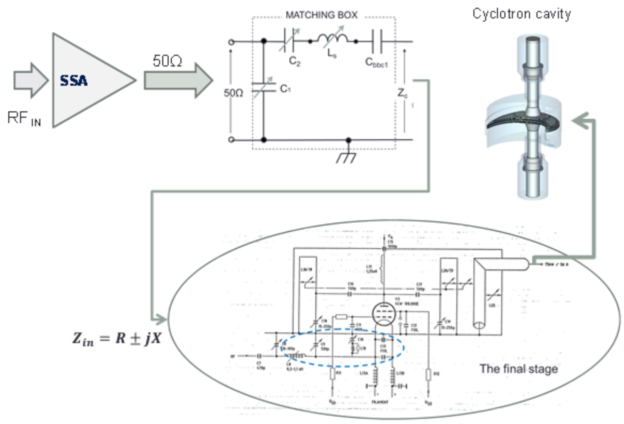

Figure 6: Block diagram of the new amplification section.

The core of the system is the matching box. This wide band tuneable circuit adapts, in terms of impedance, the standard 50 Ω first stage solid state amplifier output, with the input section of the second stage, tetrode based. The matching is between the real part of the tetrode 4CW100000E cathode impedance, Z_c and Z_0 (50Ω). We may use the simple Γ-matching network, because $Z_c << Z_0$. The SSA plus the matching box includes the driver and the first stage, based on the obsolete RS1054L. Figure 7 shows the matching box in details, with the matching formulas, in terms of impedance transformer, to adapt the cathode equivalent load with the standard SSA 50Ω [5].

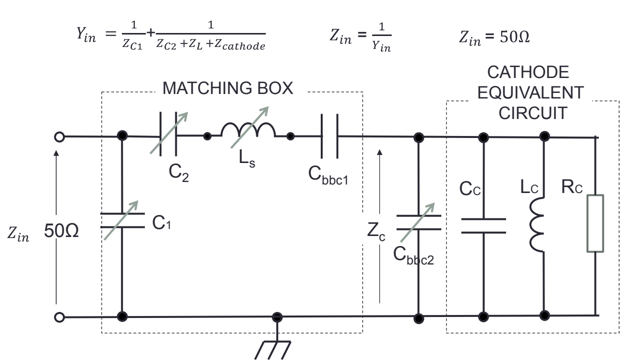

Figure 7: Matching box connected with the cathode load.

Through the matching box we can easily connect all the commercial or custom solid state amplifiers. The second stage of the main amplifier, with this impedance transformer, shows always 50Ω, after the tuning of the variable vacuum capacitors, C_1 and C_2, basically the 2 new elements of this circuit. The remaining components of the matching box were parts of the original amplifier. Figure 8 shows the main steps of the amplifier revamps of the first stage, from tetrode into solid state based. We have removed the tetrode RS1054L, the space available is occupied by two new elements of the matching network, C_1 and C_2, variable vacuum capacitors 10-1000pF, the amplifier cabinet is closed and the manual tuning has been done.

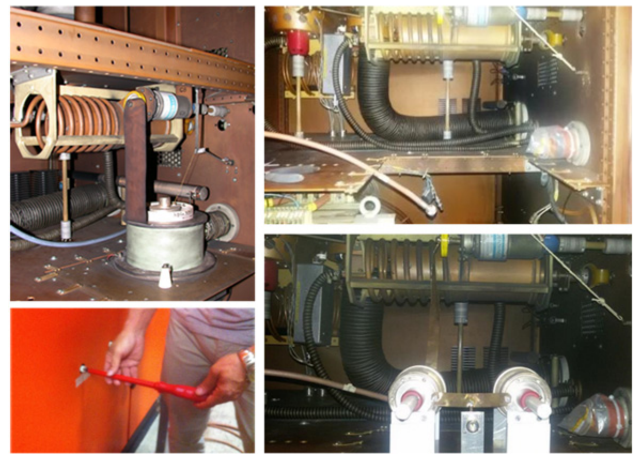

Figure 8: Step by step, from tetrode to SSA as first stage.

All the frequency range is perfect matched at 50Ω, an example of this result, at 43,61 MHz is shown in Fig. 9.

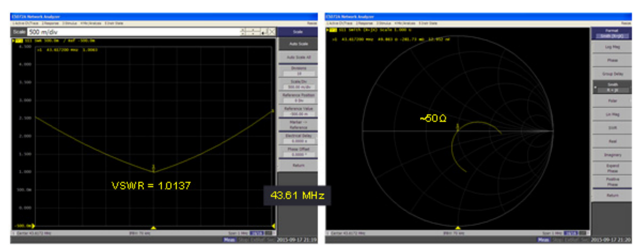

Figure 9: Matching between SSA and 2^{nd} final stage.

CONCLUSION

In conclusion, we obtained very successful results:

- The frequency range 15-50 MHz was achieved;
- Mismatch up to 2.0:1 was tested too (30%);
- The system works very well with a lot of final 1^{st} stage configuration (tetrode, mosfet, bjt, new LDMOS etc) of the SSA drivers, we used amplifier research, Kalmus, ENI, dB, in-house custom amplifier based on BLF188XR;
- Enough power, 20-30 kW, at the output of the final tetrode, was achieved in the cyclotron cavity;
- Automatic tuning of the matching network, in the near future.

In the end, the solid state solution greatly reduces the cost of the revamp and the maintenance operations. Only one amplifier is equipped with this new solution, the other 2 are still working with the tetrode 1^{st} stage, until the last spare parts, related to the RS1054L, are used up.

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