RF POWER AMPLIFIERS FOR THE SPIRAL 2 DRIVER: REQUIREMENTS AND STATUS

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Abstract

The Spiral 2 project [1] uses a RFQ, normal conducting rebunchers and a superconducting linac to accelerate high intensity beams of protons, deuterons and heavier ions. All cavities work at 88 MHz, are independently phased and powered by amplifiers whose power ranges from few kilowatts to 250kW. The paper describes the amplifier requirements, the proposed solutions and their status.

INTRODUCTION

The search of cost effective solutions has been one of the major aims of the project and studies about the RF power systems have begun since the very beginning phases. Concerning the linac frequency, the possibility of taking advantage of all developments from the FM market in the low level and power electronics, and the amount of RF power required by RFQ cavities at higher frequencies were among the major issues that lead to the choice of 88.0525 MHz.

Once the driver frequency was defined, two ranges of amplifiers were required: above 150 kW for the RFQ cavity and up to 20 kW for the linac cavities and the rebunchers of the medium energy line.

The solid state technology was investigated and definitely chosen for the second range. Security issues, modularity, quick trouble shooting, life time, have been privileged as already done in other accelerator projects and commercial fields.

Industrially available power at competitive cost being increasing quickly, the hope to have the same technology for the RFQ amplifiers too was kept for a while, but recently abandoned due to the amount of power finally required by the cavity.

RFQ AMPLIFIER

Cavity Requirements

Power loss in the RFQ cavity has been continuously upgraded as the contribution of different elements was calculated. Design study simulations, based on a 3D model of a 1-meter section including extremities, and 2D simulations of the other sections with changing beam aperture, had given some 130 kW. Power test on the prototype cavity (corresponding to the 3D model) revealed a Q factor 10% lower than expected which implies a correspondent increase of power loss. More recently, in the framework of the study for tuning procedure, manufacturing and positioning tolerances of the poles have been simulated and losses due to extreme tuner positions have been calculated. According to latest estimation, total loss in the cavity could reach some 180 kW [2].

Another important request from the RFQ team was to respect the quadrupolar symmetry of the RF structure. It was then decided to drive the cavity through four coupling loops, placed in the four quadrants of the same section as shown in Figure 1b.

Choice of the Amplifier Architecture

Manufacturing considerations, as the cost of the power tube and the number of potential manufacturers, influenced the decision of using four different amplifiers too.

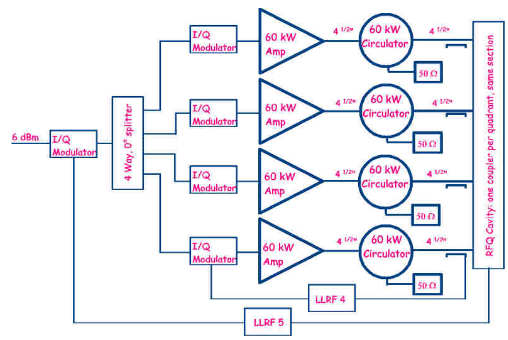
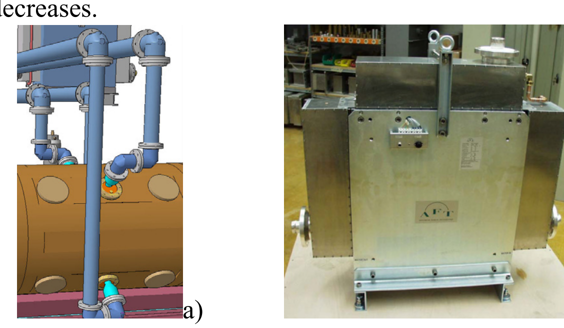


Figure 1a: Four amps and circulators scheme. The scheme shows the fast I/Q RFQ feedback loop (LLRF5) and one of the four local slower loops (LLRF4) to control the combining efficiency.

Up to several tens of kW, commercial, robust and non expensive power triodes working in the FM bandwidth are available and several broadcast companies are equipped with the ancillary systems for power tests. Behind the 30-40 kW threshold, the number of either power devices and potential manufacturers quickly decreases.



a) b

Figure 2: The four lines combined into the cavity and a 60 kW circulator.

Driving a cavity with more than one amplifier can easily be source of oscillation problems, unless they are isolated by circulators. Circulators present some percent of RF loss but match the amplifier load and handle the reflected power. The total balance is then highly positive as one doesn't need to oversize the amplifier power stage (tube and power supply) to work in mismatched conditions, like usual in accelerator applications.

These considerations, associated to the parallel request to drive the cavity keeping the 4-quadrant symmetry, lead to the scheme of Figure 1.

Four slow I/Q loops could be inserted to control the phase and amplitude of the signals at the entrance of the cavity, the amplitude being much more sensitive as shown in Figure 3.

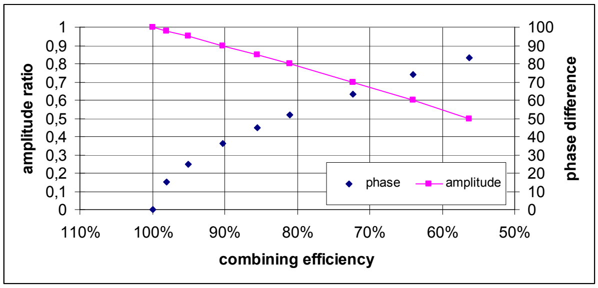


Figure 3: Effect of amplitude and phase difference in a 2-way combiner.

Taking into account circulator losses (.25 dB), combination efficiency and some margin for feedback and reliable operation, four 60 kW amplifiers were finally ordered.

The 60 kW Amplifier

The amplifiers is built by the Italian broadcast company DB Elettronica. As shown in Figure 4, it is based on two stages: a compact, solid state 3 kW driver and a tube and cavity power stage, able to deliver up to 100 kW. The tube is the Thales tetrode TH535 and the cavity is the TH 18546.

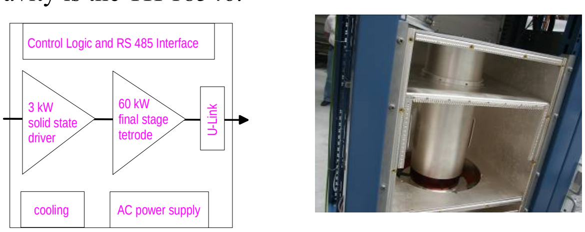


Figure 4: Scheme of the 60 kW amplifier and tube cavity.

Anode and grid supplies are designed for 65 to 70 kW. The driver, the tube anode and the anode voltage controller are water cooled while the tube filament, the cavity, the HV rectifiers and the grid and screen supplies are air cooled by dedicated fans. Filament and anode supply voltages are controlled by thirystor cards and can be set continuously in order to ramp the filament voltage during heating and the anode one at start up. Grid and screen voltages can be adjusted by 5% steps around nominal values.

The driver amplifier is the same 2.8 kW module used in the 10 and 20 kW solid state amplifiers and is described in [3].

A panel with U link integrated on the front face let switch the output on the circulator on to a dummy load. Everything is assembled in a very compact standing on a 2x1.2 meter area.

First Amplifier Test Results

The first prototype was tested in July. It delivers up to 65 kW and performs very well in CW and pulsed modes. Pulsed mode is quite important for the SP2 RFQ as, due to the space charge compensation in the low energy line, it could be required to pulse the cavity to change the beam intensity. The amplifier was then tested from 1Hz to 1 kHz and no oscillation of the power supply filter appeared.

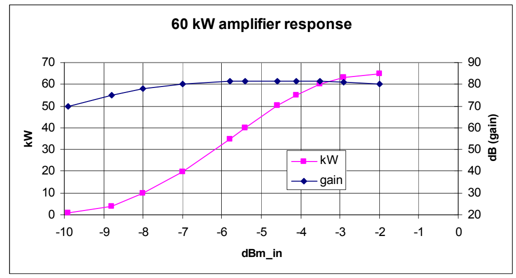


Figure 5: Amplifier response.

Electrical parameters of the final stage at maximum power are summarised in Table 1.

Table 1: Power Stage Electrical Parameters

Input power	2.3 kW	
Filament V and I	8.9 V	192 A
Grid V and I	-140 V	0.5 A
Screen V and I	900 V	0.5 A
Anode V and I	10k V	9.6 A
Efficiency	65 %	
Gain	14.5	

SOLID STATE POWER AMPLIFIERS

Cavity Requirements

Three normal conducting rebuchers [4] are used in the medium energy transport line. Two of them require 5 kW to work at 120 kV while the third one requires much less as it works up to 60 kV only.

Two families of superconducting cavities [1] are used in the SC linac: 0.07 and 0.12. Maximum accelerating field is 6.5 MV/m corresponding respectively to 1.5 MV and 2.6 MV effective voltages. First cavities ask for less power as they are not used at maximum voltage or accelerating phase, while the beam loading is mainly affected by the beta law for the following resonators

Maximum RF power requirements for the 29 cavities of the linac range from few to 13 kW, as shown by the blue curve of Figure 6.

LLRF requires some margin but microphonics could significantly increase this power levels. A 30% margin has then been taken, as represented by the green plot. Superconducting cavities require operation with total reflected power when the beam intensity is reduced, and during conditioning. This situation is the most demanding, as the coupler has to be conditioned above the maximum power it has to deliver.

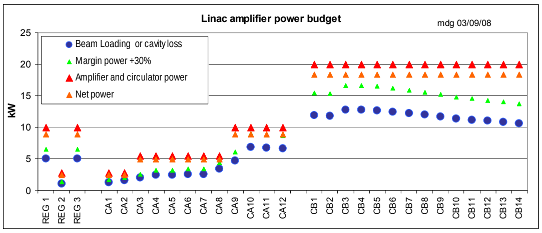


Figure 6: Requirements and choice of the linac amplifiers.

Finally, as some cavities will be operated over a very large range of voltages (factor 100), the amplifier have to be operated at very low power too.

Solid State Amplifiers

To solve the different requirements, solid state amplifiers equipped with external circulators and dummy loads have been chosen, the circulator being placed as close as possible to the linac tunnel.

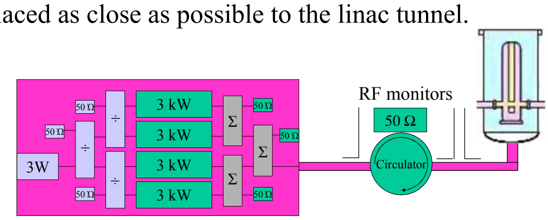


Figure 7 : Amplifier architecture. Circulators and dummy load are out of the amplifier cabinet, at the high power level. Green elements are water cooled.

This configuration was considered more reliable than distributed circulators at the output of the transistors as stands higher SWVR and protects the combiners and the transmission lines too. Measurements on the first prototypes performed on a 20 kW, variable VSWR, test bench[4], have shown that the way the reflected power is split back by the combiners, strongly depends on the phase of the RF, confirming our initial considerations.

b)

Figure 8 : Two 10 kW amplifiers installed at Orsay. Can be combined to obtain 20 kW. B) 10 and 20 kW circulators.

The architecture shown in Figure 7, based on 3 kW racks (2.8kW nominal value), seems the best compromise to fit our power level requirements, to optimise costs, and to let easy handling for maintenance. Roughly, 3, 5.5, 10 and 20 kW figures are available as shown on the red plot of Figure 6. This division covers quite well the requirements, even once loss in transmission line and circulators are considered (the orange curve).

The 10 kW prototype has already been successfully used for the power tests of the first high beta cryomodule at IPN-Orsay. The cavity was completely mismatched, no beam being present. As shown in Figure 9, it was detuned to condition the coupler at maximum power and then several measurements were performed at power levels of several kW, some 3 kW being required for nominal (6.5MV/m) gradient with no beam.[5]

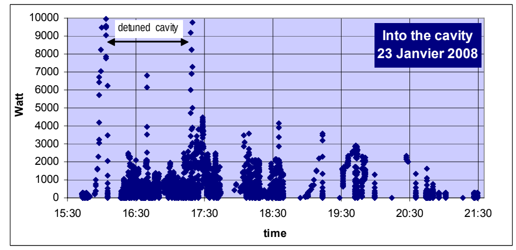


Figure 9: Power tests with the cryomodule.

Class C amplifier have been used by the moment as the digital LLRF should be able to compensate de gain variations. Tests with feedback loop still have to confirm this point.

CONCLUSION

RF power requirements for the SP2 driver are well defined now. Four 60 kW, tube amplifiers are under construction for the RFQ, the first one of which has already been successfully tested. Solid state amplifiers are foreseen for the MEBT rebuncher and the SC linac. A 10 kW, class C prototype equipped with an external circulator has been successfully tested on the first cryomodule. Linearity issues still have to be tested, to confirm the transistor working class.

ACKNOWLEDGMENTS

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