SOLID STATE DIRECT DRIVE RF LINAC : HIGH POWER EXPERIMENTAL PROGRAM

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Abstract

We report on a 150MHz λ/4 coaxial resonator driven by 32 integrated class F RF power modules according to our direct drive concept [1,2]. Electric fields of 60MV/m at the resonator gap have been reached, which correspond to 80kW RF power. This power level has been achieved at 160V DC supply voltage, significantly less than the component limits. The observed power and Q values can be explained by a simple equivalent circuit. The model predicts that 64 modules at 160V DC supply voltage may provide 170kW RF power, and that 250V DC supply voltage should yield 400kW. The corresponding 134MV/m gap E field may not be reachable due to vacuum flashover.

INTRODUCTION

Initial low power experiments on our Solid State Direct Drive RF LINAC have been reported previously [1,2,3]. A circumferential slot in our λ/4 resonator (HVTR) tuned to 150MHz serves to feed RF power by RF power modules connected across the slot (Fig. 1, [1-4]). We currently use 32 modules on 32 of the 64 RF injection ports. Each module contains a class F push-pull RF power stage incorporating newly developed 8 silicon carbide power transistors.

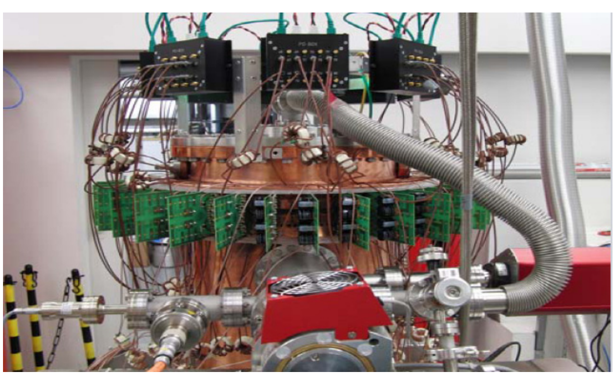

Figure 1: The λ/4 resonator with 32 of 64 modules integrated.

EXPERIMENTAL

Figure 2 shows a schematic of the experimental setup. The RF modules are driven by a conventional multi stage RF amplifier-splitter chain. Two DC power supplies charge the on-board capacitor of the RF modules and provide the DC bias for the depletion type RF SiC vJFET transistors. The readout system includes a calibrated RF antennae connected to a digitising oscilloscope.

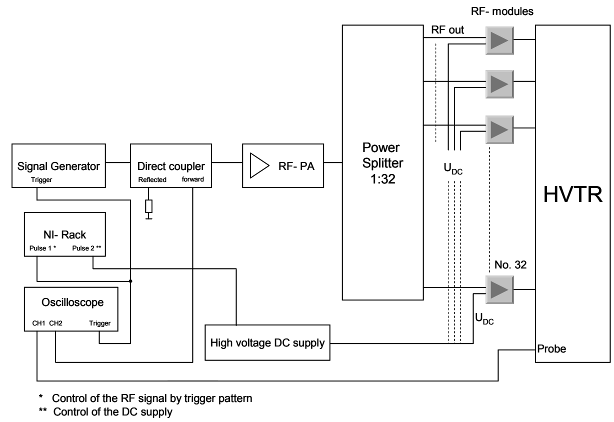

Figure 2: Schematic of the experimental measurement set-up.

The resonator gap E field and effective RF power is measured using a calibrated antenna: 3MV/m gap E field was equivalent to 200W of RF power in the cavity.

We systematically explored the RF power dependence on the number of active modules (1 to 32) and the termination (shorted, open circuited) of the remaining ports.

The total burst duration was approximately 200us to exceed the cavity fill time of approximately 20us.

RESULTS

The measured E-field over the number of active modules is shown in Figure 3, with the inset depicting a typical peak E field time evolution over a 200us RF burst.

Note that our setup does not incorporate any RF circulators or other protection circuits between the RF modules and the RF resonator. In consequence the cavity ringdown drives the full resonant current through the inactive modules. The fact that the silicon carbide transistors survive this is testimony to the robustness and speed performance of their intrinsic body diode [4].

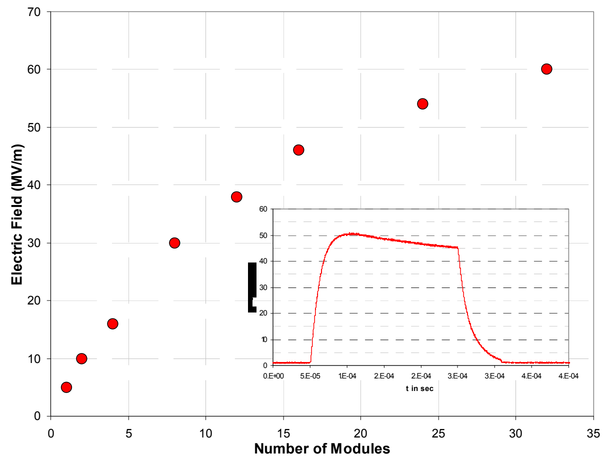

Figure 3. The electric field at the gap is shown as a function the numbers of active modules. The inset shows a time trace for a particular experiment.

Frequency sweeps allowed to assess the resonance Q factors, as shown in Figure 4a-b.

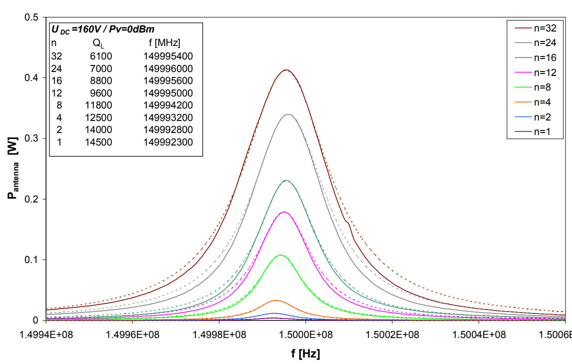

Figure 4: The cavity power is plotted as a function of the drive frequency.

ANALYSIS AND DISCUSSION

The resonator combines the power from up to s = 32 active modules through 32 feed ports. The common RF magnetic field inside the cavity effectively connect the ports similar to a magnetic transformer. For the limiting case where all s ports are driven simultaneously the load impedance seen by each port Z_{load} is given by

$$Z_{load} = Z_{cavity} \cdot s \tag{1}$$

Z_{cavity} is the effective impedance of the cavity, i.e. peak power divided by total peak resonance wall current squared at the injection slot. In case of module failure any port can become inactive, i.e. shorted or open circuited. In such a situation the impedance is not given by (1) but by

$$Z_{load} = Z_{cavity} \cdot \frac{(s+t)^2}{s} \tag{2}$$

with s is the number of actively fed ports and t the number of short circuited ports. If a module fails and becomes open circuit then s → (s-1) and $Z_{load} \rightarrow Z_{cav}(s-1)$. For large s then, in good approximation the number of open ports is irrelevant to the module load impedance transform.

The analysis of power combination also needs to take the internal generator impedance (i.e. the RF modules) into account. The equivalent circuit seen by one module is shown in Figure 5. The module supplies a total voltage of V_{RF}, of which some part drops the internal impedance, and only the remainder is fed to the load - this is the voltage which can be observed at the circumferential slot gap where the modules are mounted.

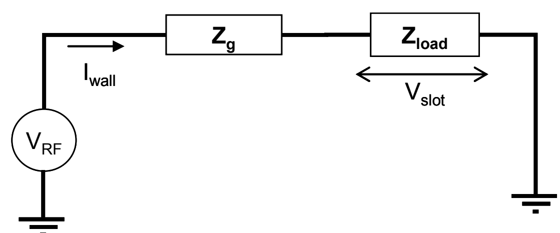

Figure 5: Equivalent circuit as seen from one module.

The RF power delivered to the resonator is given by

$$P_{load} = \frac{V_{RF}^2}{2} \cdot \frac{Z_{load}}{(Z_{load} + Z_g)^2} \cdot s \tag{3}$$

An excellent agreement between this theory and experiment (see Fig. 6) could be achieved by the parameters shown in table 1.

Table 1. Fitted Parameters for the Equivalent Circuit

Z_{cavity}	25mΩ
Z_g	1.4 Ω
V_{RF}	176 Volts

The unloaded RF amplitude exceeds the DC supply voltage, which can be attributed to class F operation of the power stage, i.e. a square-wave like voltage waveform. Its higher harmonics result in over-unity relative amplitude of the fundamental.

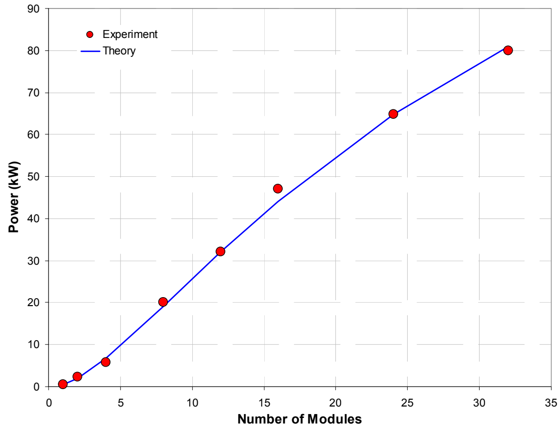

Figure 6: Measured (circles) and theoretical (line) power as derived from Eqn.(3).

Accompanying electromagnetic simulations using CST Microwave Studio predict an effective resistance of 24mΩ for the cavity assuming 1.7 x 10^{-8}Ω.m copper resistivity, which fits well to the experimental data.

The loaded Q needs to take into account the power loss within the modules

$$P_{loss} = \frac{V_{RF}^2}{2} \cdot \frac{Z_g}{\left(Z_{load} + Z_g\right)^2} \cdot s \qquad (4)$$

The corresponding Q_L values show a very good correspondence with the calculated values (see Fig. 7).

The observed internal generator (module) resistance of 1.4Ω was significantly larger than 0.7Ω expected based on DC $R_{ds,on}$ data. The difference may be attributable to incomplete switching of the vJFET cell array due to signal attenuation along the gate contact network. Alternatively the difference could be attributed to self-heating effects. A next generation of transistors promises to rectify this.

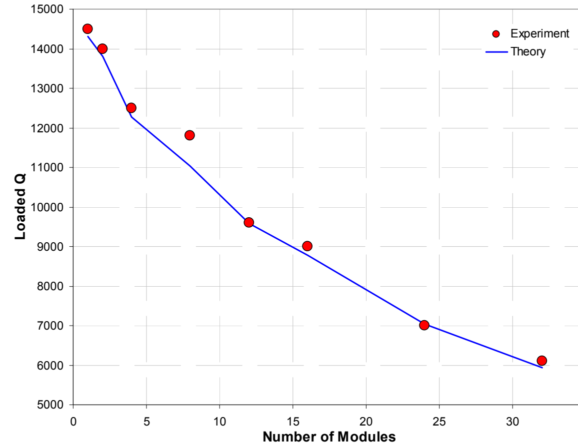

Figure 7: Measured (circles) and theoretical (line) loaded Q as derived from Eqns.(3) and (4).

CONCLUSION

It is possible to combine the output power of 256 Silicon Carbide RF transistors operated in class F mode for at least 80kW delivered RF power and with sufficient robustness to drive vastly mismatched loads and not requiring circulators or other protection circuitry to suppress reflected RF power. We developed a simple but accurate equivalent circuit model. This model indicates that a power level of ~400kW would be achievable with the full planned complement of 64 modules and a modest DC supply voltage increase to 250V, which is well within all component ratings.

REFERENCES

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