

# COMPACT SOLID STATE DIRECT DRIVE RF LINAC EXPERIMENTAL PROGRAM

O. Heid, T Hughes, Siemens AG

## Abstract

We introduce a **solid state direct drive<sup>TM</sup>** linear induction particle accelerator concept, which integrates a modular solid state RF power source and a resonant RF accelerator cavity [1]. Individual RF drive of each cell in multi-cavity accelerators obviates RF power distribution issues between cavities as in conventional LINACs and allows arbitrary RF phases and amplitudes in each cell.

Key enabling technologies are novel Silicon Carbide (SiC) JFET RF transistors and a power combining RF wall current injection scheme including EMV suppressor cavity.

An experimental direct drive  $\lambda/4$  cavity with a power rating of 1MW at 150MHz has been constructed. The integrated RF power source consists of one to 64 RF modules with eight SiC JFETs each, which are connected to a radial power combiner and surrounded by a toroidal EMV suppressor cavity. Initial trials with four power modules succeeded in delivering 200  $\mu$ s bursts with 10kW RF power, which corresponds to 16MV/m electrical field strength at the accelerating gap (Fig. 3).

## INTRODUCTION

In its current implementation the solid state direct drive<sup>TM</sup> concept [1] includes a  $\lambda/4$  cavity and up to 64 RF modules (Fig. 1).

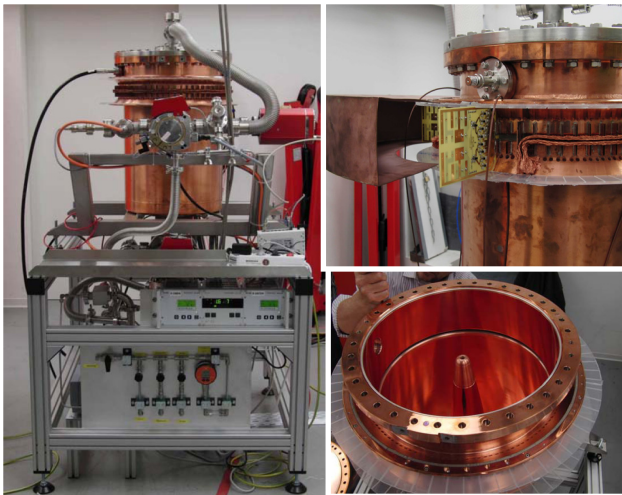


Figure 1: The experimental cavity and support equipment (left). Module mounted on current injection slot (right top). Interior cavity electrode (right bottom).

Each RF module contains eight SiC JFETs in class F push pull parallel (PPP, circulator) arrangement [2], and currently provides 80A peak output current and 500V peak output voltage (20kW RMS) at negligible internal source impedance and with high efficiency. Fig. 2 shows the module PCB layout.

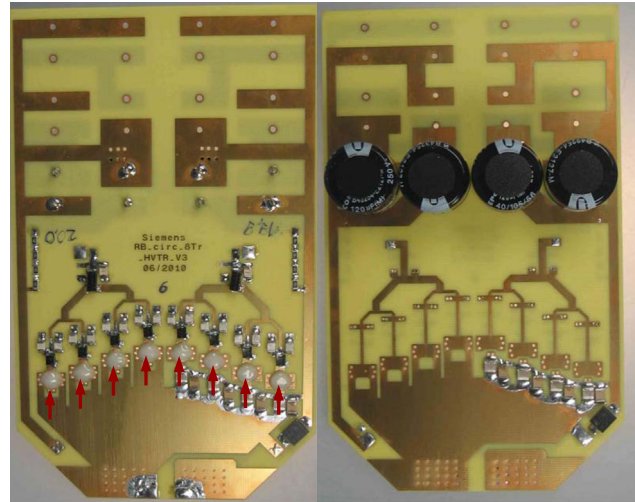
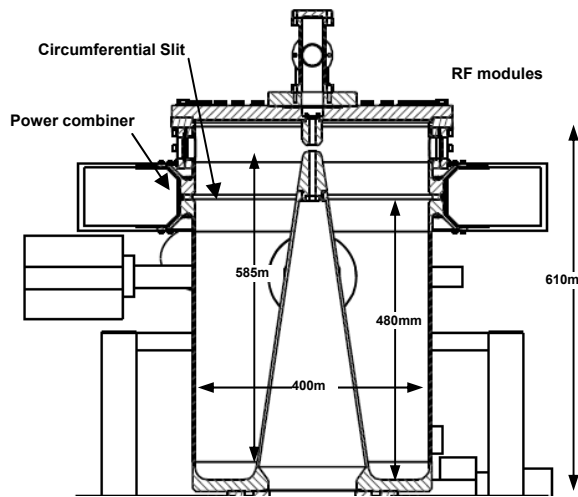


Figure 2: 20kW RF module with SiC devices (red arrows).

## EXPERIMENTAL

The first implementation of a solid state direct drive<sup>TM</sup> accelerator is based on a  $\lambda/4$  cavity (Fig. 3). The tank material is copper plated stainless steel conditioned by Argon RF processing. Two ports accommodating calibrated RF pickup antennae serve as Argon processing power feeds and RF pickups. The cavity was characterised with shorted RF injection slit using standard RF techniques: Resonance frequency 150.043 MHz, unloaded Q 13200, loaded Q with Ar processing antenna 7666. The effective load impedance for each module was  $(90/N^2) \Omega$  with N active modules.

Figure 3: Cross-section through the  $\lambda/4$  test cavity

The resonator cavity has been designed to operate at up to 1 MW RF power and  $>100\text{MV/m}$  E field over  $200\text{ }\mu\text{s}$  RF burst duration when driven by 64 RF modules. So far the tests used a maximum of four modules. Shorting the unused slots enabled the majority of the wall current to flow unimpeded across the slit to preserve the fundamental resonance mode.

The RF chain and energy flow is shown Figure 4. Not shown is the measurement probe for free electrons within the cavity as indicator for breakdown and electron multipacting.

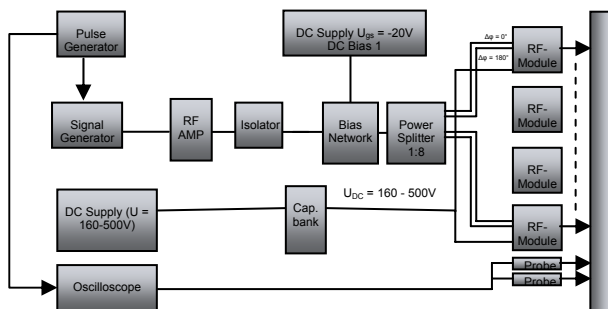


Figure 4: RF circuit schematic

## RESULTS

The first experiment investigated low RF power cavity operation. The observed fill time was about  $25\text{ }\mu\text{s}$ . Electron multipacting could be observed at around 4-7 MV/m (Fig. 5), and vanished with increased RF power. Four modules delivered up to 10kW into the load when the 60 remaining slot were shorted (see below).

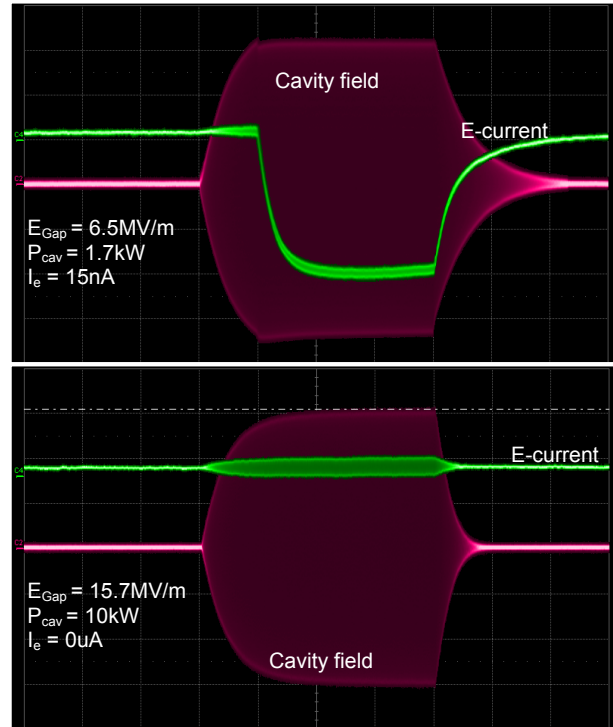
Figure 5a-b: Cavity E field (red trace) and electron probe signal (green trace) with and without multipacting.  $200\text{ }\mu\text{s}$  RF burst duration.

Fig. 6 shows the cavity RF power under DC supply voltage variation. 500V supply resulted in 10kW RF power and 16 MV/m across the cavity gap. The effect of the electron loading at certain power levels can also be recognized as anomalies in the electric field amplitudes.

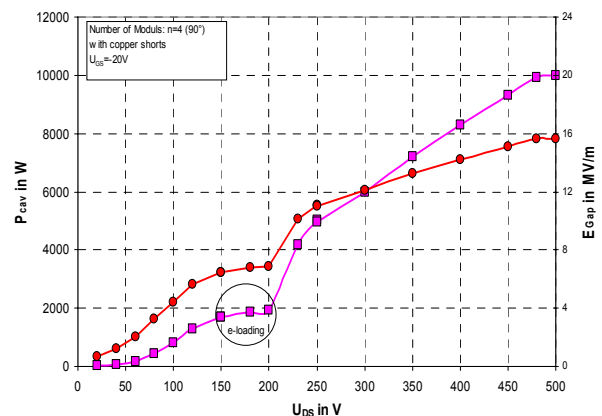


Figure 6: The power in the cavity (purple, square) and electric field at the nose cone (red, circle) are plotted as a function of the RF module output voltage. Four modules are used.

We also investigated the RF power scaling with the number of modules. The expected quadratic power scaling with the number of modules was observed, obviously overshadowed by electron loading effects at certain DC supply voltages (Fig. 7).

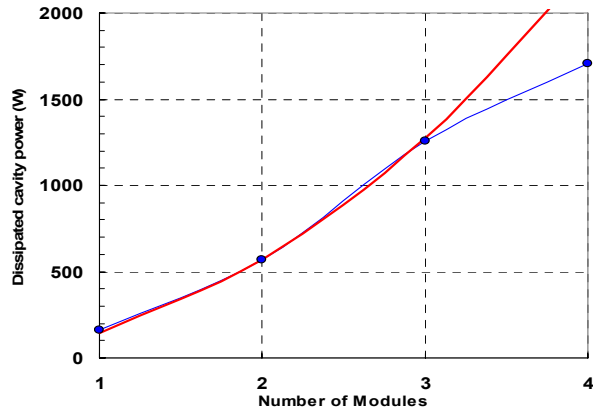


Figure 7: Combined RF power output (blue) over the number of active modules at 150V DC supply. Expected parabolic dependence (red).

## DISCUSSION

Depending on being active or passive the RF modules represent approximate bidirectional voltage sources and sinks. Their intentionally mismatched operation into the cavity impedance has several ramifications:

1. The Q with transmitter is essentially the unloaded Q.
2. The RF modules are oblivious to reactive loads, i.e. cavity detuning.
3. Load sharing between modules is enforced by the resonance mode wall current distribution
4. The gap feed power combiner represents inductive voltage adding [3]: The effective RF drive voltage therefore is the sum of the module voltages, and the module load current is proportional to the number of

modules. The combined RF power thus scales quadratic with the number of modules.

5. The wall current distribution is maintained even with deactivated modules.
6. Unused feed slots can be shorted to raise the effective load impedance of the remaining modules and maintain the cavity wall current distribution.
7. Redundancy: Individual module failures are not catastrophic. The dominant effect is RF power reduction.
8. Remaining RF energy during cavity ring down is partially recovered into the DC power supply by rectification via the extremely fast SiC vJFET body diodes.

## SUMMARY

A solid state direct drive<sup>TM</sup> RF accelerator cavity has been built. So far four out of 64 RF modules have been integrated and tested. These low power tests demonstrate for the first time that the proposed concept is feasible and practicable. This approach may well lead to a dramatic reduction of the costs of RF power. The implications on the design of particle accelerators are far-reaching.

## REFERENCES

- [1] Heid O., Hughes T. THPD002, IPAC10, Kyoto, Japan (2010)
- [2] Hergt M et al, 2010 IEEE International Power Modulator and High Voltage Conference, Atlanta GA, USA (2010)
- [3] Bouwers, A: Elektrische Höchstspannungen, p. 83, Springer (1939)