COMPACT SOLID STATE DIRECT DRIVE RF LINAC

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Abstract

An RF accelerator driver concept is introduced, which integrates a distributed solid-state RF power source with the RF resonator. The resulting structure plays a double role as RF combiner and particle accelerating structure.

The key enabling technologies are Silicon Carbide RF transistors and a power combiner concept which includes insulating parallel cavities to ensure consistent RF current injection.

The main advantages compared to current vacuum tube driven accelerators are unprecedented RF peak power levels in the VHF to GHz frequency range, high power efficiency, cost effectiveness and conceptual simplicity. Individual drive of each accelerating gap gives new opportunities in accelerator design and operation, e.g. variable energy and extremely high power LINACs.

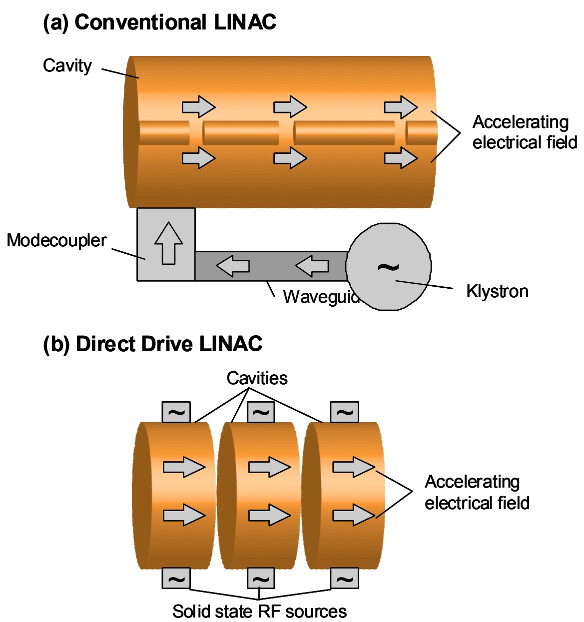

Figure 1: Conventional and direct RF cavity drive.

DIRECT RF DRIVE CONCEPT

Traditional RF LINACs consist of an electromagnetically coupled set of resonating cavities connected to a single external RF power source via waveguide and mode coupler (see fig. 1).

The available RF power sources are tetrodes at VHF and klystrons and magnetrons at microwave frequencies. Their peak output power is limited to about 1MW for tetrodes and 50MW for klystrons. Additionally, these RF sources require output impedance matching, with significant cost and complexity penalties.

In the past the overall complexity and cost of these RF sources was a strong motivation to develop accelerator structures with a single RF feed point and internal resonant redistribution of the RF power before coupling it into the beam. Such structures are difficult to build, expensive, and inflexible to operate.

Our approach provides an RF source which is inherently distributed. In essence an array of RF power modules are connected parallel across a slit in the cavity wall so that the RF wall surface current flows through

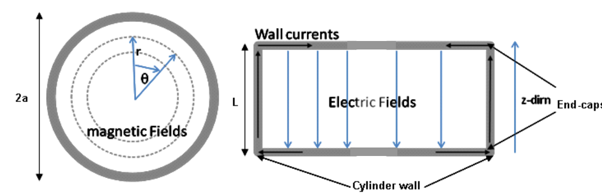

Figure 2: RF fields and currents in a pillbox cavity.

these modules. This slit injection concept replaces the usual mode couplers.

As an example, a TM010 pillbox resonator (Fig. 2) contains an accelerating axial E field accompanied by an azimuthal H field [1]. The associated surface RF currents flow radially on the end cap surface and axially on the inside of the cylinder wall.

In the vicinity of the resonant current antinode a circumferential slit cuts through the cylinder wall (the slit is usually bridged by a non-conducting vacuum seal). RF current injection into the slit effectively drives the cavity in series resonance. Equi-distribution of parallel RF power modules and the absence of other resonance modes in the vicinity of the operation frequency guarantee a homogeneous current injection around the circumference and sufficient load sharing between the modules. In essence the circumferential slit acts as RF power combiner. A practical implementation is shown in Figures 3a-b.

Direct RF cavity drive has several implications:

1. The distributed RF feed avoids any power density hot spots and thus power limitations in cables, waveguides and mode couplers. The only component under full, combined RF power load is the RF cavity itself. This allows to reaching unprecedented RF peak power levels.
2. It is now advantageous to decompose the overall accelerator structure in small, independently directly driven RF cavities or sections.
3. Multi-feed accelerators achieve independent phase and amplitude control over each accelerator gap, and thus much more design and operational flexibility than e.g. the usual standing or travelling wave resonant LINAC structures.

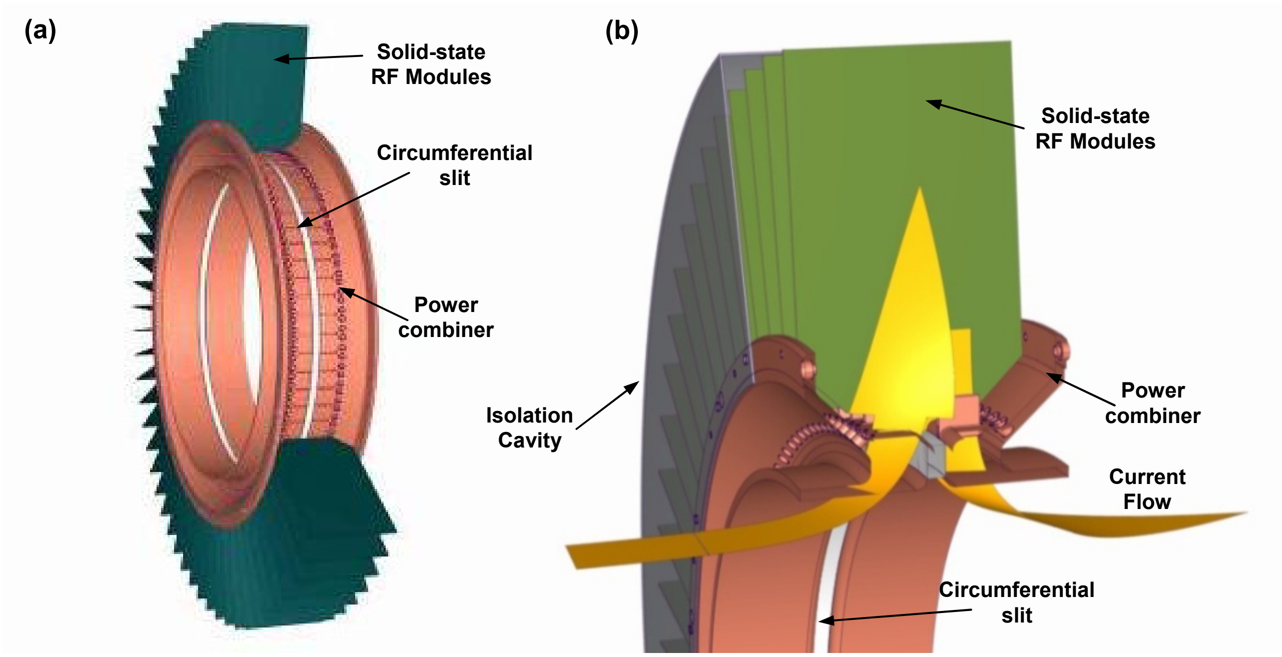

Figure 3a-b: Arrangement of RF modules across a current injection slit.

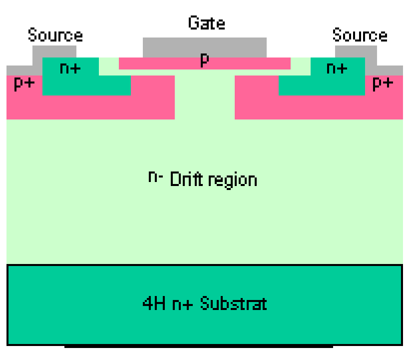

Figure 4a: SiC vJFET cell structure

RF TRANSISTORS AND MODULES

Our RF drive modules utilize Silicon Carbide vertical Junction FETs (SiC vJFET). The advantages of these new semiconductor devices over silicon RF transistors are

1. SiC is intrinsically 10x faster, with power unit gain frequencies in the 10 GHz range
2. SiC allows significantly higher power levels for a given device size
3. SiC is significantly more radiation hard.
4. The intrinsic body diode has reverse recovery times below 1ns.
5. A large positive Rdson temperature coefficient tends to thermally stabilize parallelized devices.

The SiC RF vJFETs developed for us by SICED [2] currently provide a peak current of Idss=25A at a maximum blocking voltage of Udsmax=3.4kV. The chip area is about 6mm^2. The next design iteration will exceed Idss=100A per device at Uds=1.7kV. The input and output capacitances are a fraction of the values of silicon LDMOS devices.

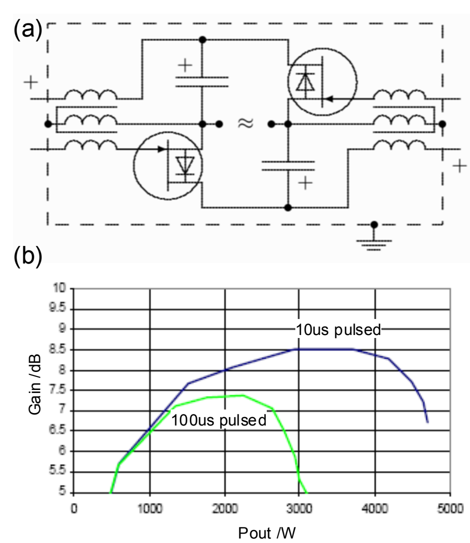

Figure 5a-b: In (a) a schematic of the circlotron topology used is shown. The results are shown in (b)

The decisive property of SiC vJFETs is the ability of the body diode to rectify any reflected RF power instead of destroying the device. In sharp difference to Si transistors these devices can be operated unmatched and under highly varying loads, as represented by high Q resonators e.g. during RF fill. Another favourable consequence is that the output RF power can be scaled by straightforward parallelizing of devices.

In order to provide a load-oblivious low impedance RF source we employ a fully symmetric parallel push pull circuit (Fig. 5a). Originally introduced for audio applications (as "Circlotron" [3]) this topology offers several key advantages for the projected application

1. Fully symmetric output
2. Fully symmetric input
3. Push-pull operation, enables load independency
4. Inherent highly efficiency Class-F operation (in conjunction with a high Q series driven resonator): push-pull circuit shorts even harmonics, odd harmonics do not excite resonator series resonance.
5. Bidirectional (4 quadrant) operation: energy recovery during cavity ring down, flashover protection
6. No DC pulse generator, hard pulse tube etc. required

Our first RF module generation incorporates two parallel JFETs per side (4 transistors in total). Due to limitations of the RF load used the results of figure 5b were gained at only 160V instead of 1500V DC supply voltage. The output power was 4kW over 50us, dropping to 3kW after 100us due to thermal Rdson runaway.

It is foreseeable that a next generation 2x10x16cm^3 sized module delivers more than 500kW over 50us burst duration at an efficiency exceeding 85%. RF Transmitters in excess of 2GW peak power at VHF should be feasible.

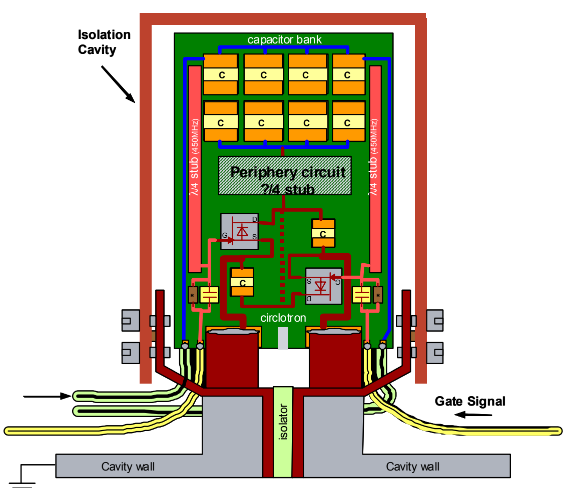

Figure 6: RF module including shield box

ISOLATION CAVITY

Direct drive RF cavities have probably never been proposed so far because of the – perceived – impossibility to avoid RF voltages (and their negative side effects like EMC problems and safety hazards) on the outside of the accelerator structure. Ideally the accelerator should have ground potential over its whole outer surface.

Our solution is to cover the ring of RF drive modules with a toroidal shield enclosure. The inner volume of this RF screen effectively represents a parallel connected second cavity with a resonance frequency very different to the main resonator (~390MHz vs. 150MHz in our case). Its shunt impedance at the operating frequency is thus significantly larger (~7i Ohm) than the series resonance impedance of the resonator (~1mOhm), which effectively guarantees that the overwhelming majority of the RF power flows through the resonator as desired, and the current across the shield is low. As side effect the volume enclosed by the shield can also play the role of the Gerth ("Guanella") baluns in Fig. 5a.

The shield represents a continuous conducting surface separating the fields within from the surroundings. The whole outer accelerator surface is thus a single closed metal surface free of RF voltages.

EXPERIMENTAL PROGRAM

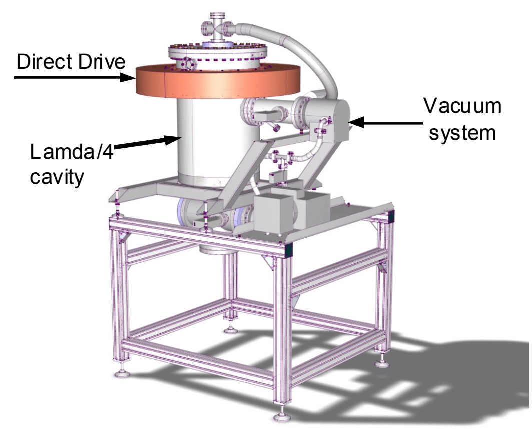

Figure 6. The direct drive experimental cavity.

A development program has been initiated to demonstrate direct drive RF cavities. The modules perform as intended on a coaxial λ/2 resonator, and survived multiple hard flashovers without any output protection.

The upcoming first direct drive RF accelerator cavity is a 150MHz λ/4 resonator powered by 64 RF modules equally spaced on the circumference (Fig. 6). 500kW peak RF power over 50us should result in up to 120MV/m E field over a 1cm accelerating gap, intended for low energy proton acceleration.

REFERENCES

[1] S. Ramo et al, Fields and Waves in Communication Electronics, Wiley, p497ff (1993).
[2] C. T. Hall U.S. Patent 2,705,265
[3] M. Hergt et al, 2010 International Power Modulator and High Voltage Conference.