DESIGN COCEPTS FOR RF-DC CONVERSION IN PARTICLE ACCELERATOR SYSTEMS

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Abstract

In many particle accelerators considerable amounts of RF power reaching the megawatt level are converted into heat in dummy loads. After an overview of RF power in the range 200 MHz to 1 GHz dissipated at CERN we discuss several developments that have come up in the past using vacuum tube technology for RF-DC conversion. Amongst those the developments of the cyclotron wave converter CWC appears most suitable. With the availability of powerful Schottky diodes the solid state converter aspect has to be addressed as well. One of the biggest problems of Schottky diode based structures is the junction capacity. GaAs and GaN Schottky diodes show a significant reduction of this junction capacity as compared to silicon. Small rectenna type converter units which have been already developed for microwave powered helicopters can be used in waveguides or with coaxial power dividers.

MOTIVATION

The necessity to recover power in RF-driven particle accelerators can be shown with the example of the SPS. It utilizes a travelling wave (tw.) cavity, in which the charged particles travel with the phase velocity on the crest of an electromagnetic wave. To ensure the tw. operation, it has to be terminated by a matched load resistor (RL), resulting in an RF architecture shown in Fig. 1. A small part of the power from the RF amplifier is transfered to the beam or dissipated in the cavity walls, while the biggest part is converted to heat in RL. The SPS is composed of 4 tw. cavities, each operated at an average RF-Power of 379 kw. Thus altogether 1500 kw of RF-Power is converted to heat continuously and has to be dissipated in the underground tunnel.

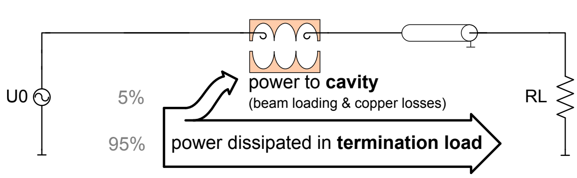

Fig. 1: Overview of a typical accelerator RF plant.

The most direct way to recover that RF-Power is to feed it back – with the right phase angle – to the input of the tw. cavity. Experiments showed that, due to different load situations caused by the beam, instability may occur. Hence a solution, which converts the power to an intermediate DC voltage, is pursued.

The general architecture can be seen in Fig. 2. The coaxial transmission line to RL is fitted with a large number of power couplers. Each output feeds one RF/DC converter module with a nominal design power of ≤ 1 kW. The DC output of the modules gets combined and will be fed back to the DC link of the tetrode RF amplifiers or supplied to the mains distribution grid.

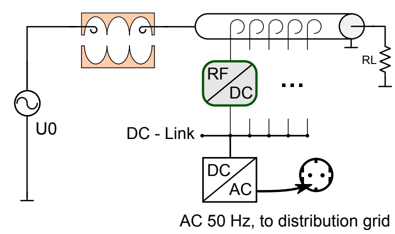

Fig. 2: Architecture of the RF - Recovery device.

RF DESIGN OF THE POWER DIVIDER

The coaxial line has a characteristic impedance of 50Ω and an air dielectricum. Its inner conductor diameter is 100 mm. The peak input power of 500 kW must be split in several hundreds of channels, each with a constant power level of 1 kW. Therefore a coupling of -27 dB is required at the input of the power divider. Allowing 10% of the input power to be absorbed in RL (90% power divider efficiency) results in a coupling of -17 dB for the last coupling antenna. The feasibility of coupling at this level has been studied. Different solutions have been analyzed:

A) Electrical coupling with a pin.
B) Electrical coupling using a pin with a capacitive plate at the end to increase the coupling.
C) Magnetic coupling using a loop.

A is too weak for our application. *B* and *C* give similar levels of coupling for the same dimensions. However it is much easier to materialize *B* than *C*, since no electrical contact is required inside the coaxial line. So the solution *B* has been chosen. The geometry of the coupling antenna and the electric field distribution around the pin and the capacitive plate are shown in Fig. 3. Varying the height of the pin and the length of the plate changes the coupling in the range from -27 dB to -17 dB. These parameters are chosen, so that the coupling is increasing from one stage to the next. While the power flowing along the divider is decreasing linearly from 500 kW to 50 kW, the power coupled out to the rectifier circuits maintains a 1 kW level. In this case 450 kW is coupled out to the rectifier circuits in 45 stages. Each stage has 10 coupling antennas distributed around the circumference of the outer conductor of the coaxial line. The overall length is about 5 m. Further investigations are ongoing to reduce the length of the system.

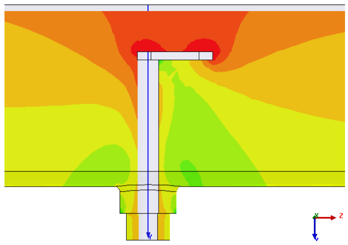

Fig. 3: Geometry of the coupling antenna and its electric field distribution.

RF TO DC CONVERTERS

The demands on the RF/DC modules are quite high, as the RF - Amplifier and the cavity are sensitive to reflected power. A proper 50Ω resistive match over a wide range of power levels has to be maintained. The radiation of harmonics on the device input must be inhibited. Aspects concerning the reliability, size and cooling have to be taken into account. Therefore different RF to DC converters are examined and their feasibility for this application is evaluated.

Cyclotron Wave Converter (CWC)

The CWC device is a new kind of RF to DC converter, patented by V.A. Vanke in 2003 [1].

The input RF-Power is used to accelerate electrons on a spiral path by a classic cyclotron structure. The rotational movement is then converted to an increase in longitudinal velocity by a specifically shaped external magnetic field. A "depressed collector" catches the electrons and converts their kinetic energy to a large DC voltage at the load resistance.

The feasibility as an energy recovery device for the SPS is summarized in Tab. 1. A positive aspect is the large input power per unit as well as the ability of the device to stand large peak powers. The wasted power of the SPS could be recovered with one single device, keeping the system complexity low and preventing losses through excessive deployment of RF power splitters. The main disadvantage of the device – for this application – is its need for a resonant cyclotron RF-Cavity. At the operating frequency of the SPS, which is 200 MHz, this would yield an exceptionally large device. The other disadvantages are the need for an ultra high vacuum, the maintenance requirements and the warm-up time.

Table 1: Positive and negative aspects of the CWC

Property	Value	Suitability
Power range [kW]	0.5 ... 50	✓
Achieved efficiency [%]	83	✓
Output voltage [kV]	1 ... 50	⚠
Operating frequency [GHz]	1 ... 50	⚠
Usable Bandwidth [%]	0.5 ... 5	✓

In [2] the CWC device has been implemented and tested for the recovery of RF Energy in a particle accelerator. In a simulation the authors were able to predict an overall RF to DC efficiency of 73% in the S-Band at an input power of 1 MW. This could not be confirmed in measurements because the electron collector broke down as the output voltage reached 125 kV. At these voltages, considerable engineering effort is needed to prevent losses through corona discharge, breakdown or even danger by the generation of X-Rays.

This shows that the CWC device is not easily scaled to higher power levels, as the high electron energy and the consequent high output voltage poses a limitation.

Rectenna circuits

The idea of using semiconductors to convert RF-Power to DC has been around since 1964 when W. C. Brown invented the rectenna. He was able – with this combination of antenna and diode-rectifier – to transmit a substantial amount of power wirelessly. The system operated at 2.5 GHz and used an array of 4480 small signal point contact diodes. The DC output power was 270 W, enough to build a demonstration helicopter which held itself in the air by RF-Power only [3]. At present times RF-Rectifiers are in the focus of research again. Three substantial reasons for this can be named:

- Wireless powered technologies as *Radio Frequency Identification* are getting more and more popular.
- Switch mode power converters are constantly miniaturized. The passive components can only be made smaller by choosing a higher operating frequency – which nowadays reaches the RF area.
- Significant advantages in semiconductor materials (band structure engineering) revealed a new generation of schottky power diodes which can be used up to the RF region.

Taking advantage of these points, it is possible to build an RF/DC converter, utilizing semiconductors, which can handle power levels in the 200 W range and does not suffer the drawbacks of ultra high vacuum devices. This provides the basis for the energy recovery concept, which is presented in the following sections.

CONCEPTUAL RF/DC MODULE

A general overview of the proposed RF/DC module is shown in Fig. 4. The RF signal from the power divider comes in through a 50Ω coaxial cable.

A "backup" termination resistor is connected to the input through a circulator. It ensures that the modules do not reflect RF power – under any circumstances – back to the cavity. This approach guarantees a failsafe system, which degrades gracefully in case of component failures. When a rectifier defect occurs (open or short), the overall recovery efficiency of the RF/DC array will be degraded but the operation of the particle accelerator will not be restricted in any way.

The matching network guarantees an optimum power transfer while not exceeding the maximum voltage or current ratings of the diode. The small bandwidth (¡2%) of the input signal allows the use of standard resonant matching techniques. Care must be taken with the design and simulation procedure, as the rectifier is a nonlinear device and its input impedance is likely to change with different input power levels [4].

The last block is the DC lowpass filter and the actual load. For simulation purposes it is modelled as a simple resistance. In the actual system, multiple module outputs will be combined to reach usable power levels [6].

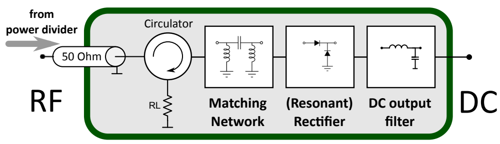

Fig. 4: Basic scheme of an RF/DC module.

DC-AC-Converter

To make use of the recovered power, it might be directly fed back to the DC - link of the tetrode RF-amplifiers or alternatively converted to standard utility AC power and supplied to the distribution grid. For this purpose, it seems to be most convenient to take power converters as they are used in solar power systems. These are rugged devices, which are available off the shelf. Only power converters equipped with an output transformer are feasible for this application as the circulator in the RF/DC modules forces a connection of one input node to earth. These solar power converters are using a maximum power point tracking system. That means, the input voltage of the converter is left constant, while the available current at that voltage defines the converted power. This kind of control system can easily be adopted in our application, as the rectifier has a well defined generator resistance.

Resonant Diode Rectifiers

The rectifier block converts 200W of RF-Power to DC in the most efficient way. Modern diodes like the *GS150TC25110* from IXYS can handle these voltage and current levels easily. The critical point for RF operation is its large chip area and thereby high junction capacity (for this diode $C_j = 120pF$ at zero reverse voltage). This equates to a parallel reactance of 6.6Ω at 200 MHz and does not allow the design of a traditional half wave rectifier. Anyway, by adding additional passive elements to the circuit, the energy stored in C_j can be recovered. These kinds of resonant rectifiers radiate less harmonics on the input, exploit the parasitic elements of the diode as an integral part of the circuit and allow the diode to turn on or off with a controlled dU/dt [4] [5] [6]. The disadvantages of these architectures are the relatively high voltage and current stress on the diode and the need to tune the circuit to a single input power and frequency.

A voltage output series resonant rectifier with a single *GS150TC25110* diode was simulated in PSpice. A realistic model was obtained from its datasheet. Parasitics of all components were included. The simulation showed an RF to DC efficiency of up to 88.8% at an output power of 196 W while staying in the safe area of operation of the diode. The efficiency got worse with a change of power level, frequency or load resistance. In a practical implementation this number is expected to drop to 70%.

Alternatively, schottky drain transistors might be considered. They can be operated in a diode like fashion by appropriately connecting the gate electrode. These devices are used in high power RF amplifiers at up to 2 GHz and promise a good performance for this application [7].

OUTLOOK

The basic building blocks of the energy recovery system have been shown and their tasks outlined. The next step is to obtain these blocks and build a working laboratory prototype. Alternative architectures for the resonant rectifier need some investigation in the form of simulations and real life measurements. Also, state of the art semiconductors, which are not yet commercially available, are going to be examined for this application.

ACKNOWLEDGEMENTS

The authors would like to thank Edmond Ciapala and Roland Garoby for supporting this project. We are grateful for the practical hints and assistance from: Johannes Broere, Reinier Louwerse, Eric Montesinos, Hans-Joachim Würfl and Veli Ylidiz.

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