A NEW LIFE FOR HIGH VOLTAGE ELECTROSTATIC ACCELERATORS

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Abstract

Air insulated Cockcroft-Walton (or Greinacher) cascades have historically been used to generate high voltages for particle acceleration. This paper explores how this technology can be redeployed using a different design approach and modern materials to develop more compact accelerator configurations with much higher voltage gradients. Compact accelerators may enable a greater range of potential opportunities in new business areas.

One such concept is presented for a 10MV tandem proton accelerator that can realise a beam current of exceeding 100μA, within a <2m^2 footprint including all accessories like vacuum pumps etc.

INTRODUCTION

A method to multiply AC voltages was first discovered by Greinacher [1] in 1920, using a network of capacitors and diodes. Cockcroft and Walton [2] adapted the circuit and applied it to achieve high voltage potentials, <1MV for nuclear physics experiments. The basic configuration of the voltage multiplier is shown in figure 1.

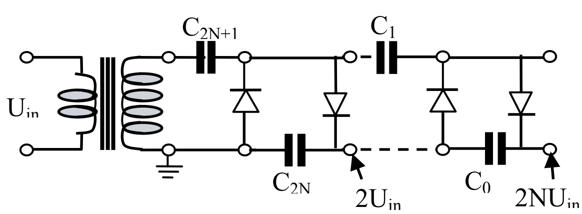

Figure 1: Greinacher Cascade

A Greinacher cascade rectifier [2, 3] consists of two stacks of capacitors interconnected by a string of diodes (figure 1), so that an AC voltage applied to one end of the cascade charges both strings of capacitors. Without load all even capacitors C_{2k} (figure 1) will ultimately become charged to twice the peak AC drive voltage U_{in}, so the resulting unloaded output voltage is

$$U_{out} = 2NU_{in} \tag{1}$$

The main advantage of the cascade accelerator has been its capability as a source of high output currents, up to several hundred mA. Practical application has revealed limits like excessive shunt capacitances, lead inductances [4] and about 2MV output voltage [1,3] even when employing huge physical structure to counteract the low breakdown strength of air or pressurized gas based insulators.

The development of a significantly more compact high voltage particle accelerator with high current capability would open new business opportunities for a wide range of potential applications outside the laboratory in security, healthcare and industry etc.

DESIGN FOR THE NEW CONCEPT

The cited limitations are all not inherently connected to the operating principle of multiplying rectifiers.

The key innovation for the proposed concept is to integrate the DC voltage generator with the insulator and accelerator structure. The discrete capacitor components in figure 1 are replaced by a stack of concentric shells shaped to contain all the high potential electrodes within the smallest possible volume while maintaining nearly constant electric field amplitudes throughout the whole system. Vacuum insulation and a large number of small electrode gaps allow high electric fields even in the presence of radiation, which in turn, minimises insulator surfaces and associated flashover problems.

A cross-section of such a structure is shown in figure 2. The two capacitor stacks result from cutting the grading electrode shells on the equatorial plane. It is merely necessary to connect the string of diodes to opposing electrodes across the cut plane to arrive at a self contained high voltage source. The diode action automatically stabilizes the grading electrode potential differences to about twice the input voltage, which suggests roughly equal electrode spacings. The drive voltage can then applied between the outer two hemispheres.

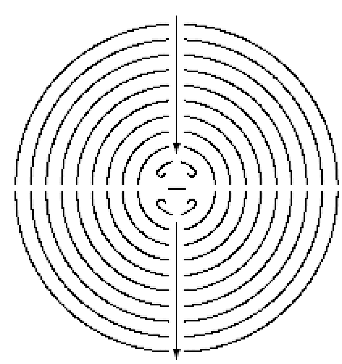

Figure 2: Schematic of a concept spherical tandem accelerator

The proposed particle accelerator achieves its unique performance from:

- A novel concept of concentric shells around the centre high voltage electrode combines the two capacitor stacks of a Greinacher voltage multiplier circuit with an electric field potential grading structure.

- Use of high vacuum instead of pressurised gas insulation avoids any beam tube or other insulator surface in the vicinity of the beam and is self healing after breakdown. The accelerating electric field can thus exceed the usual, low beam tube breakdown limits.
- Concentric grading shell electrodes with distances on the order of 1 cm raise the permissible electrical field strength beyond 10 MVm^{-1}, about a 10-fold increase compared to the usual large free electrode spacing.
- Modern soft avalanche semiconductor diodes have very low parasitic reactance and reverse recovery times, so series connection does not require voltage equilibrating measures. The rectifier can be operated at a high enough AC drive frequency to arrive at workable effective generator impedance by use of the relatively small vacuum inter-electrode capacitances of the potential grading structure as capacitor columns.
- A radial series of holes through the capacitor electrodes serves as beam tube. The stack of concentric electrodes keeps the voltage distribution along the beam approximately linear. The absence of any physical beam tube wall should avoid the common E field flashover limitations of conventional beam tubes.

Accelerating structures utilising the compact concentric shell systems have been developed previously [5, 6] however, they have not incorporated the combined functionality of also being part of the voltage supply. As a result these systems have required a large direct high voltage feed for every shell. Something not required for the current concept.

Capacitors

The system geometry approximates a hypothetical spherical capacitor with a homogeneous electrical field

$$E = \frac{U}{R - r} \tag{2}$$

which would have a capacitance

$$C = 4\pi\varepsilon_0 \frac{R^2 + rR + r^2}{R - r} \tag{3}$$

Hemispherical shells and equal electrode spacing's d = {(R – r)/N} for N stages results in r_k = (r + kd) and electrode capacitances. For the two hemispherical shells, $C_{2k} = C_{2k+1}$,

$$C_{2k} = 2\pi\varepsilon_0 \frac{r^2 + rd + (2rd + d^2)k + d^2k^2}{d} \tag{4}$$

Output Voltage

If the circuit only contains the capacitances of figure 1 steady state operation at drive frequency f delivers a charge

$$Q = \frac{I_{out}}{f} \tag{5}$$

per full wave into the load through the capacitor C_0 (Figure 1) and each of the capacitor pair C_{2k} and C_{2k+1} transfers a charge (k + 1) Q. Overall the charge pump represents a generator source impedance R_G;

$$R_G = \frac{1}{2f} \sum_{k=0}^{N-1} \left(\frac{2k^2 + 3k + 1}{C_{2k}} + \frac{2k^2 + 4k + 2}{C_{2k+1}} \right) \tag{6}$$

at the DC output, so a load current I_{out} reduces the output voltage according to

$$U_{out} = 2NU_{in} - R_G I_{out} \tag{7}$$

Note that the often decried apparent cubic dependence of the generator impedance R_G on the number of stages N is deceiving. A fair comparison e.g. Dynamitrons [7] has to include the effect of N on the capacitances values: At given overall volume R_G scales essentially quadratically with N.

The load current causes an AC ripple voltage at the DC output terminal with a peak to peak value

$$\delta U = \frac{I_{out}}{f} \sum_{k=0}^{N-1} \left(\frac{k+1}{C_{2k}} \right) \tag{8}$$

PROPOSAL FOR A TANDEM ACCELERATOR

Our prototype vacuum insulated tandem accelerator serves to produce a continuous 10MeV proton beam with a current in excess of 100µA. In figure 3, a beam of low energy H^- ions from the source is injected into the electrostatic tandem generator and accelerated towards the +5MV centre electrode potential. After charge-exchange in the centre of this electrode, via a carbon stripper foil the resulting H^+ ions gain a further 5MV energy on their way to the outside of the structure.

The outermost electrode is the vacuum vessel. A 5MV DC power source may consist of N = 30 stages, i.e. a total of 60 diodes and capacitors driven by a 100kV_{eff}, 100kHz AC inverter. Given an inner radius of r = 0.1m and vacuum insulation stressed to 11MVm^{-1} field strength the outer radius is R = 0.55m.

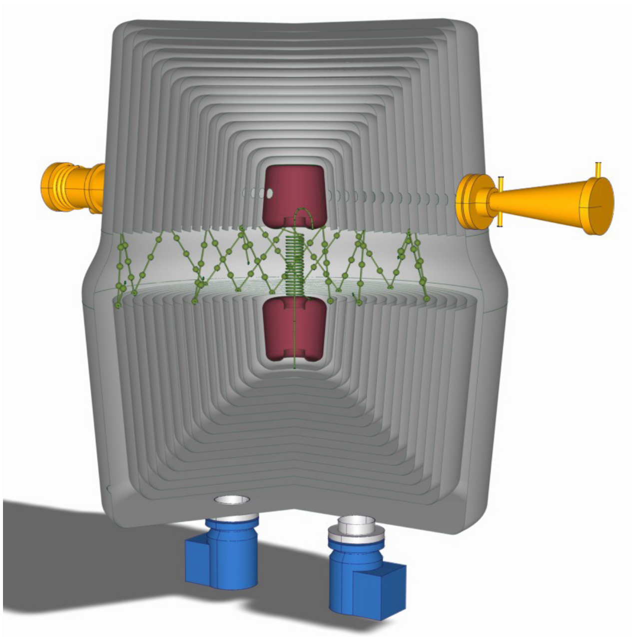

Figure 3: Cross-section through the proposed vacuum insulated tandem accelerator

Each hemisphere consists of 30 gaps with 15 mm spacing between adjacent shell electrodes. A lower number of stages reduces the number of charging cycles and the effective internal source impedance, but increases the AC pump voltage requirements. The equatorial cut plane allows to attach the diodes to both capacitor stacks, e.g. in a spiral pattern. The total capacitance of 90pF and total energy stored is 1.1kJ. Note that a flashover between adjacent shells liberates only a small fraction of this energy.

CONCLUSION

This exciting new system concept for high voltage electrostatic accelerators offers the advantages of simplicity, low cost, modularity and size compared with the previous application of the technology. It is envisaged that as a consequence, it will increase the potential breathe of potential applications and enable accelerators to be seen in a new light. A brief study into some of these potential application areas has already identified the following; radioisotope production, oncology, neutron sources, materials processing etc.

A demonstration system is currently under construction at Siemens Corporate Technology to evaluate the technology and potential commercialisation

REFERENCES

[1] H. Greinacher, "Erzeugung einer Gleichspannung von dem Vielfachbetrage einer, Wechselspannung ohne Transformator", Bull. Schweiz. Elektrotechn., Ver. 11 195 (1920)

[2] J.D. Cockcroft and E.T.S. Walton. "Experiments with high velocity ions", Proc. Royal Soc., Series A 136 (1932), 619-30

[3] H. Greinacher. "Über eine Methode, Weschselstrom mittels elektischer Ventile und Kondensatatoren in hochgespannten Gleichstrom umzuwandeln". Z. Physik 4 (1921) 195

[4] G. Reinhold. "Ultra-high voltage DC power supplies for large currents", Technical, Report E1-72, Emil Haefeli & Co Ltd, Basel, Switzerland, (1987).

[5] Yu. Belchenko et al. "Initial high voltage tests and beam injection experiments on BINP proton tandem-accelerator". Proc. RuPAC (2006) 135

[6] R. Adler et al. "Advances in the development of the nested high voltage generator". Proc. SPIE 2374 (1995)

[7] M. Cleland et al. "Dynamitrons of the Future". IEEE Trans. NS-12 (1965), 227.