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RADIO-FREQUENCY ACCELERATORS FOR MULTI-KILOAMPERE ELECTRON BEAMS

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I. INTRODUCTION

Most present work on intense pulsed electron beam accelerators is directed toward linear induction accelerators[1]. In this paper, we will consider the application of resonant accelerators to the generation of pulsed, multi-kiloampere electron beams. The main relative advantages are: 1) low cost and high voltage gradient can be achieved by eliminating ferromagnetic isolation cores, 2) cavity designs are simpler (with optimum utilization of vacuum insulators), and 3) there are no high voltage shorting switches. The later feature implies that RF (radio-frequency) accelerators may operate at higher repetition rate and duty cycle. The only existing high current RF electron accelerator is Phermex[2]. This machine uses large vacuum cavities to store electromagnetic energy which is extracted by a pulsed beam in a few RF oscillations. Phermex generates less than 1 kA. In this paper, we will discuss RF cavities filled with water. The high dielectric constant raises the stored energy density by a factor >60 for enhanced pulsed operation. Furthermore, the lower impedance of the cavity allows CW operation in the 10-50 A level.

In the following section, we will discuss the functions a water-filled cavity can perform and the configuration of a high current RF accelerator. Section III deals with power losses in the cavity walls and dielectric medium. Effects of water heating and cavity distortions on the resonant frequency are treated in Section IV. Baseline parameters for a 750 kV cavity are presented in Section V. The problem of beam loading in CW operation is treated in Section VI.

II. RF CAVITY CONFIGURATIONS

It is useful to review the operation of induction Linacs compared to RF Linacs. An induction cavity is shown in FIGURE 1(a). Pulsed power is transferred directly to a beam which constitutes a resistive load on axis. Electrostatic voltage is applied to the acceleration gap. The gap is surrounded by a cavity containing a high frequency, ferromagnetic isolator. The inductor supplies an EMF around the outside of the cavity which balances the electrostatic voltage, preventing leakage current. Many cavities can be stacked in sequence to accelerate a beam to high voltage without the generation of high voltage. The inductive isolation is non-resonant, so that a square voltage pulse can be applied to the load. The isolation cores have a limited volt-second product and must be reset after each pulse.

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An RF accelerator can be configured in a similar geometry (FIGURE 1(b)). A harmonic voltage is applied from a power source to a load on the axis. At the resonant frequency of the cavity, the leakage circuit impedance is infinite. Thus, if the load is an ideal resistance, power transfer is limited only by the properties of the modulator, not the cavity. Limitations arise from the fact that the load in an RF accelerator is not a resisitor but a series of monopolar current pulses. The pulsed beam current must be small compared to the cavity displacement current to preserve a sinusoidal voltage waveform. A water dielectric increases the displacment current by a factor of $(\epsilon/\epsilon_o)^{1/2}$, so that higher currents can be driven.

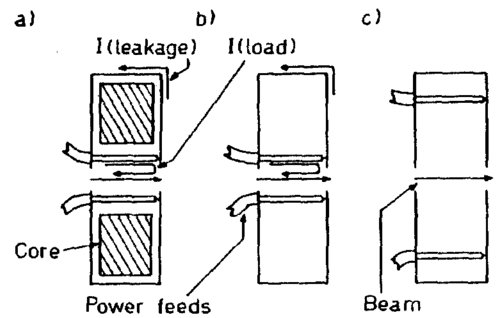

Figure 1

Water-filled RF cavities can perform other functions besides inductive isolation. Materials with high ϵ can store high densities of electromagnetic energy compared to high μ materials. Water cavities can act as energy reservoirs for high power transfer to a pulsed beam This is the operational mode of Phermex. RF cavities can also act as voltage transformers by relocating the entrance of the power feeds (FIGURE 1(c)). The cavity acts as a variable impedance radial transmission line. The average beam impedance must be larger than the maximum impedance of the cavity. Again, the advantages of a water dielectric for hgh current operation are apparent. A final function of water cavities is to regulate voltage, as shown in Section VI.

FIGURE 2 shows a possible cavity geometry. Dimensions correspond to the 750 kV baseline cavity discussed in Section V. Oscillation frequency of the TM^{010} mode is 21 MHz. The frequency is maintained by active modification of cavity volume by a microprocessor-controlled transducer. Thus, the cavity walls do not have to be extremely rigid or resistant to thermal expansion. The skin depth is 15 microns, so a fine surface finish is not necessary. Power losses in the cavity walls are not a major concern, so that anodized aluminum is adequate. Stored energy in the TM_{010} mode is

$$U = (\epsilon E_o^2/2)(\pi R^2 D)\ J_1^2(2.405) \qquad (1)$$

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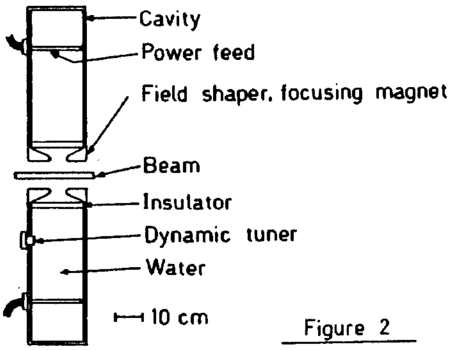

Figure 2

Power is transported from pulsed RF sources through standard 250 kV polyethylene insulated coaxial cable. The feeds are located at a 45 cm radius to produce a 3:1 voltage step-up. The beam is transported through a vacuum region. The absence of water in this volume results in small shifts of cavity parameters. In this paper we will use the approximation of a homogeneous cylindrical cavity. The main drawback of a water-filled cavity is that the vacuum insulator must be located at the position of maximum field stress. Average longitudinal gradients are limited to less than 5 MV/m. The problem of insulator breakdown in less severe in RF accelerators compared to induction accelerators for two reasons. First, the configuration in FIGURE 2 is relatively simple compared to the complex reentrant designs of an induction cavity. Insulator length is maximized in the RF design. Second, water grades the voltage along the insulator. For these reasons, we feel that the field stress value of 40 kV/cm chosen for the baseline cavity is feasible.

III. POWER LOSSES

Power can be dissipated in water-filled RF cavities by three processes. The first is resistive wall loss. This is characterized by the quantity Q, the stored energy in the cavity multiplied by $2\pi f_o$ (f_o is resonant frequency) and divided by the average loss power. The Q value for wall losses in the TM_{010} mode is[3]

$$Q_c = 2D/\delta\ (1 + D/R) \qquad (2)$$

where δ is the skin depth, R is the cavity radius and D the length. For aluminum at 21 MHz, the skin depth is 1.5×10^{-3} cm. The Q for this process scales as $(\epsilon/\epsilon_o)^{-1/4}$, so that the Q is reduced a factor of 3 compared to an identical vacuum cavity. There are also volumetric resisitive losses within the water. These are represented by

$$Q_\rho = 2\pi f_0 \epsilon \rho \qquad (3)$$

where ρ is the water resisitivity in ohm-m.

The dominant power loss is caused by imperfect dielectric behavior of the water. The Q for this process is

$$Q_\epsilon = \epsilon' / \epsilon'', \qquad (4)$$

where ϵ' is the real part of the dielectric constant and ϵ'' is the imaginary part. A plot of the Debye Equations in the frequency range of interest is given in FIGURE 3(a) for high and low water temperature. Dielectric losses are proportional to the frequency, so that large, low frequency cavities are preferred. At elevated temperatures, there is a moderate decrease in ϵ' and a large decrease in ϵ''. This leads to the unusual result that dielectric power loss is lower at high water temperature[4]. Q values are plotted versus temperature for frequencies in 60 cm and 90 cm cavities.

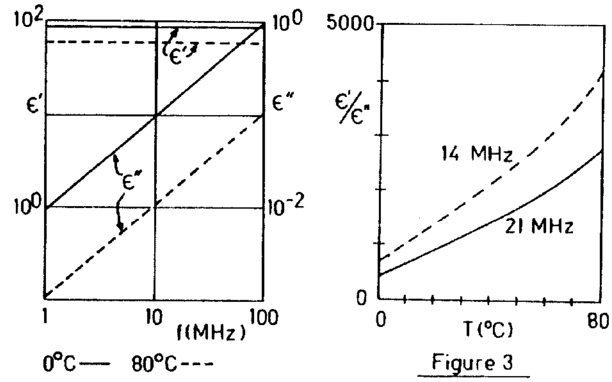

Figure 3

IV. CAVITY DYNAMICS

The resonant frequency may drift because of changes in the cavity volume from thermal expansion or temperature induced changes in ϵ'. The operating frequency is determined by the oscillator that drives the RF power source. This frequency must be contained within the cavity resonance. The resonance width is about f_o/Q. For the baseline cavity (with Q = 2500) properties must be maintained constant to within 0.05%. At a frequency of 21 MHz, oscillations can be counted directly by digital circuits and compared to a standard. This information can control a transducer to bring about small changes in cavity volume.

The change in ϵ' with temperature is

$$\Delta\epsilon'/\epsilon' = 0.4\ \Delta T/T_o. \qquad (5)$$

At 80°, this implies that the temperature should be controlled to within 0.003°C. This is impossible in a large system. A feasible approach is coarse regulation of the water temperature to about +-0.1°, with fine control through variation of the cavity volume.

A major concern is whether power dissipation during a macropulse will shift the resonant frequency. Maximum pulselengths are on the order of 100 microseconds. Mechanical compensation is not possible on this time scale. Using the parameters of the baseline cavity, we can estimate the magnitude of this effect. Average dissipation in the water at 4 MV/m is 6.4 MW. The water mass is 710 kg. The rate of temperature change is 21°C per second. In a 100 microsecond pulse, the net change is 2.1×10^{-3} °C. The corresponding variation of ϵ' is 1.4×10^{-5}, causing a fractional frequency shift of 7×10^{-6}. This is only 1/70 of the resonance width. In general, thermal effects do not constitute a major problem.

V. BASELINE CAVITY DESIGN

To illustrate feasibility of high current cavity operation, we will consider the cavity with parameters listed in TABLE 1 operating in the Phermex mode. The cavity is charged with RF energy over many oscillation periods. Subsequently, a fraction of the stored energy is extracted by a pulsed electron beam in one or more periods.

At a field stress of 4 MV/m, the cavity has a peak acceleration field of 750 kV and stores 125 J. We will consider an electron micropulse with the shape shown in FIGURE 4(a). The electrons are ultra-relativistic (>>0.5 MeV) and the accelerator length is moderate (125 m for a 500 MeV beam). These conditions imply that longitudinal phase stability is not a concern, so that the beam pulse can be centered at the peak accelerating field, as shown. The average accelerating gradient is 705 kV, and the beam emerges with a 6% energy spread.

The cavity operates at 21 MHz, so the FWHM of the micropulse is 8 ns. Each cavity has a seperate supply ad oscillator. In an independently phased configuration, there is no penalty in average gradient associated with low frequency. With heated water, the net Q is 2000. At peak charge the power loss is 8.2 MW.

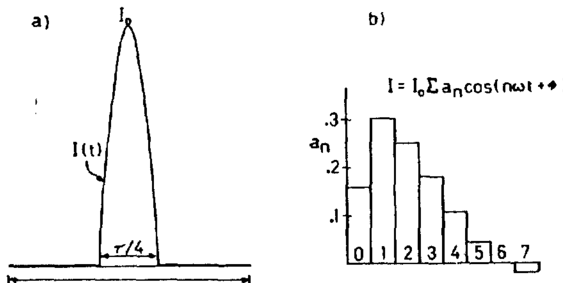

Figure 4

For pulsed operation, we assume a 12 MW RF power supply. Multi-megawatt triodes are available at low frequency. A 250 kV, grid controlled device for low duty cycle operation in the 10 MW range is practical. This corresponds to a net electron current in excess of 40 A, only .3 micropervs. Calculations[5] by Faehl, Lemons, and Thode indicate that single beam pulses in the range of 10 kA peak can be extracted from large vacuum cavities without significant excitation of higher order modes. The situation is improved considerably in the water cavities because of the higher stored energy and strong damping of high frequency oscillations. We assume that a single 8 ns beam pulse extracts 20 per cent of the cavity energy. For the pulse shape of FIGURE 4(a), this corresponds to a peak current of 4.4 kA. (Higher peak currents can be achieved with larger cavities or higher field stress) The power source must replace the extracted energy for the next pulse. The average power excess is about 4 MW, so that the cavity is recharged in 7 microseconds. In summary, 4.4 kA, 8 ns electron pulses are produced in a 100 microsecond burst at a frequency of 160 kHz with 33% efficiency. Net macropulse energy from a 500 MeV accelerator is 270 kJ at a power level of 2.7 GW.

VI. CONTINUOUS OPERATION

Operation in the CW mode for 100 microsecond macropulses may have application to radiation processing and the acceleration of ions for Accelerator Inertial Fusion[6]. In this situation, the beam power matches the source power minus the losses. We will analyze a case that demonstrates the advantage of a parallel water cavity for voltage regulation. We assume direct drive on axis (FIGURE 2(b)). The Fourier components of the beam pulse are shown in FIGURE 4(b). FIGURE 5(a) shows the voltage waveform with no cavity for a generator matched to the fundamental mode of the current. In contrast, FIGURE 5(b) shows the voltage with a water cavity in parallel with the generator. There is a marked improvement, even for this heavily loaded case in which the beam extracts an energy equal to 10% of the stored cavity energy.

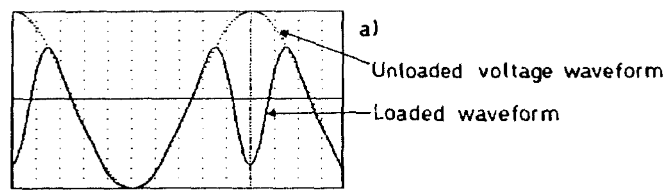

Figure 5

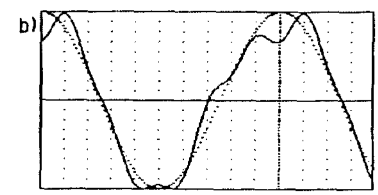

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TABLE 1. 60 CM CAVITY PARAMETERS

Radius	60 cm	Length	18.8 cm
Field stress	4 MV/m	Voltage	750 kV
Volume	.21 m^3	Water mass	210 kG
Temperature	80 °C	Frequency	21 MHz
Cavity wall	Alum.	Energy	125 J
Skin depth	15 μm	Q_t	2800
Q_ρ	9400	Q_c	19000
Power less	8.2 MW	Power in	12.2 MW
Peak current	4.4 kA	Pulse rate	160 kHz