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NEW INITIATIVES FOR PRODUCING HIGH CURRENT ELECTRON ACCELERATORS

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NEW INITIATIVES FOR PRODUCING HIGH CURRENT ELECTRON ACCELERATORS

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New classes of compact electron accelerators able to deliver multi-kiloamperes of pulsed 10-50 MeV electron beams are being studied. One class is based upon rf linac technology with dielectric-filled cavities. For materials with $\varepsilon / \varepsilon_0 >> 1$, the greatly increased energy storage permits high current operation. The second type is a high energy injected betatron. Circulating current limits scale as $\beta^2\gamma^3$.

INTRODUCTION

Advancements in high power technology have brought intense, high current electron accelerators to the threshold of feasibility. Such accelerators may be inappropriate for applications requiring high duty factor operation. However, for the radiography of fast processes, for medical and material processing applications needing large dose rate as well as dose, and for the excitation of phenomena with large damping rates, these accelerators hold enormous potential. Two new types of high current electron accelerator which are being studied at Los Alamos National Laboratory will be the focus of this paper. The first concept is basically a standing wave radiofrequency linear accelerator (rf linac) with the substitution of dielectric material for vacuum in the cavities. This concept, due to Humphries and Hwang[1] in 1983, allows for much greater energy storage in the cavities. The enhanced energy storage then allows greater current acceleration before cavity depletion. The second concept is an ironless betatron, where the high currents are facilitated by energetic electron injections. This effort is both inspired and stimulated by the landmark research of A. I. Pavlovskii and his colleagues [2-4]. There are other interesting efforts involving high current electron accelerations such as the Inductive Voltage Adders, pioneered at Sandia National Laboratory, and numerous linear induction accelerators, but these efforts are not discussed in this paper.

DIELECTRIC-FILLED RF LINACS

Radiofrequency linear accelerators are a very reliable source of energetic electron beams for medical, material processing, and research applications. Because high accelerating gradients (10-100 MV/m) and modularity are easily obtainable, these machines can be relatively compact for a given use. High currents have never been a strong characteristic for this type of machine, however. The reason is intrinsic: efficient, narrow bandwidth storage of electromagnetic energy in cavities, plus the desire to minimize wall heating has promoted the design of high Q cavities. Such cavities have correspondingly long fill times. To accelerate high currents in such a configuration, the beam extracts much more power than an external power source can supply. The stored energy for any cavity is $\mathrm{E}_c = \int_V dV\left(\varepsilon_o E^2 + \frac{1}{\mu_o}B^2\right)$ where V is the cavity volume, and the energy extracted by a beam with total charge $Ne = \int I dt$ is $\Delta \mathrm{E} = \mathrm{N}_e\, \delta \mathrm{E}$, where $\delta E = \oint \overline{E \bullet dl}$. If we approximate $N_e \cong \langle I \rangle \tau$, then the depletion time is roughly $\tau < \mathrm{E}_c / \langle I \rangle \delta \mathrm{E}$. PHERMEX [5] is a three cavity 50 Mhz accelerator at Los Alamos that is designed to push cavity depletion to the limits. The experience on PHERMEX is that a factor of 50% depletion is close to the limit.

The substitution of a high dielectric constant material, $\varepsilon = \varepsilon_r + i\varepsilon_i, \varepsilon_r >> \varepsilon_o$, for vacuum in the cavities can increase stored energy by a factor of $\varepsilon_r / \varepsilon_o$. For a good dielectric like deionized water $\varepsilon_r / \varepsilon_o$ can approach 80. A small beamline section on axis must still be vacuum, but the overall stored energy is $E_d = (\varepsilon_r / \varepsilon_o) E_c$. Adding this dielectric will also depress the resonant cavity frequencies, by a factor of $(\varepsilon_o / \varepsilon_r)^{1/2}$. In addition, the longitudinal energy dispersion within the pulse is decreased, leading to more monoenergetic output beams.

Water has a significant value for ε_i. By adding a new and large source of dissipation due to bulk dielectric losses, the overall Q can be enormously depressed over its vacuum value. This dissipation of energy can heat the water at a high rate for high gradient fields. This effect limits water-filled cavities to pulsed applications. The duration of operation will depend on how much power is fed into the cavity. Quantitative estimates of time-dependent operation must account for the temperature scaling of ε in water [6].

We have performed small signal experiments in a pillbox aluminum cavity with an outer radius $R_o = 14$ cm and a length $L_o = 14$ cm. Power is supplied by a variable frequency 10 W source, driving a simple loop antenna. Cavity fields were measured along the axis as a function frequency. The entire structure could be heated and the temperature of the water was monitored. Analysis of this structure show that the resonant TM_{mnp} modes occur at

$$\omega_{mnp} = \frac{k}{\sqrt{\varepsilon_r \mu_o}} \left(\frac{1}{1 + (\varepsilon_i / \varepsilon_r)^2} \right)^{1/2} \tag{1}$$

where $K = \left(\frac{X_{mn}^2}{R_o^2} + \frac{\pi^2 p^2}{L_o^2} \right)^{1/2}$, $p = 0,1,2,\ldots$ and χ_{mn} is the zero of the Bessel function, $J_m(\chi_{mn} R_o)$. The cavity Q can be decomposed into component contributions, Q_j, such that $Q^{-1} = \sum_j Q_j^{-1}$. That portion of the total Q which arises from losses in the dielectric is given by

$$Q_d = \frac{\varepsilon_i}{\varepsilon_r}. \tag{2}$$

We also conducted numerical studies of this structure with the rf cavity code, CFISH. A comparison of the measured data with both analytic and numerical results as a function of temperature is shown in Fig. 1. The quantitative agreement is quite good at these low powers. We also measured the line width of TM resonances to infer the total Q. The numerical and analytic predictions are shown in Fig. 2. The qualitative estimates obtained from the data confirm the trend, but quantitative values are subject to significant uncertainty due to loading effects from the antenna and the axial field probe. We are measuring those effects more carefully.

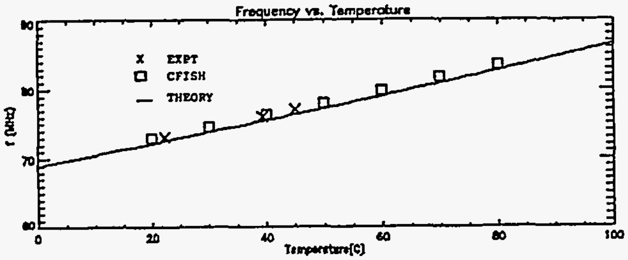

Figure 1. TM_{010} frequency as a function of temperature.

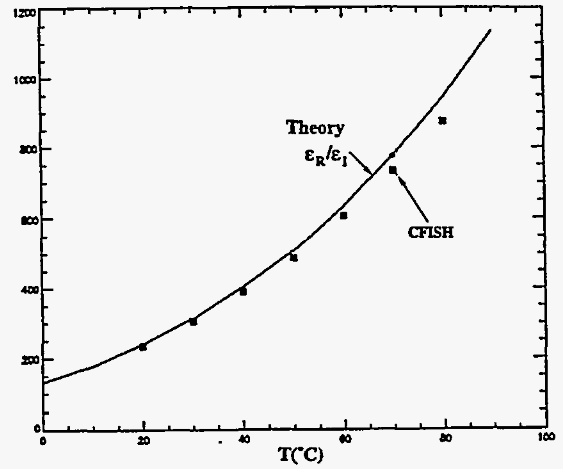

Figure 2. Comparison of cavity Q evaluated with CFISH and simple theory (solid line).

The next phase of this effort is to conduct high power tests of this cavity, including a window to allow a vacuum beamline on axis. Electromagnetic PIC calculations are being performed to estimate the magnitude of field stress on the interfaces and of dynamic loading when electron pulses are injected into the beamline.

HIGH ENERGY INJECTED BETATRON

The betatron is a compact, efficient accelerator for producing low emittance electron beams of 10-100 MeV energy. By the 1950's, peak energies of 340 MeV had been generated, but the weight had also grown to 300 tons. Moreover, low energy electron injection severely limited the total current which could be accelerated. An alternative to iron core betatrons was advanced by A. I. Pavlovskii at about the same time[4]. He proposed using electromagnet coils to produce the time-varying fields, a so-called "ironless betatron".[2]

By 1965, using energetic electron injection, Pavlovskii's effort had succeeded in accelerating 90 A of electrons to 100 MeV.[2] These machines are exceedingly compact, with an orbital radius $r_o = 23.4$ cm and a total mass on the order of 2 tons. The outer machine dimensions were roughly 1 meter in diameter and 10-15 cm high. A unique design employing helical field coils yielded an exceptionally large region of orbital stability, $\Delta r = 0.7\ r_o$ and $\Delta z = 0.6\ r_o$.

The exact mechanism for particle trapping in betatrons has never been satisfactorily explained. There is not space here to discuss the various hypothesis which have been advanced over the last 55 years. Suffice it to say that electron capture does occur, and it is very reliable. Pavlovskii, et. al. [3] conducted exhaustive experimental studies to determine the scaling for the trapping in their ironless betatrons. One important result was that, for any given size of the accelerator, the peak confined current scales as $(\gamma^2 - 1)\gamma$, where γ is the relativistic factor, $\gamma = 1 + \varepsilon / mc^2$, ε being the injected electron energy. They verified this scaling between 0.01 and 2.0 MeV. The peak circulating current in their initial betatron design was 90A. Recent results with double helix coils has extended this confinement up to 10^{13} electrons and currents of 300 *A*[4]. We are exploring the possibility of designing betatrons with multi-kiloampere currents through higher energy electron injection. There are many potential candidates for use as a high energy injector. The microtron is a simple device that accelerates very low emittance electron streams, but at low currents. A 25 MeV microtron injector is feasible; the betatron filling time would be hundreds of microseconds. Induction accelerators generate much more intense electron beams of 5-10 MeV without an enormous capital investment. As an example, a 50 ns pulselength induction accelerator which delivers 5 kA could inject 250 µC into a betatron. Another potential type of injector is a modern rf linac. Using technology developed for the FEL program, one could consider a 10 MeV, 10 A accelerator for betatron injection. Operating such an rf linac for 10 µs yields a total charge of 100 µC. The choice of injector type must satisfy conditions of high energy, low emittance electrons, total charge, and time-scale for delivery. This last requirement is the least understood because of lack of detailed understanding about collective trapping dynamics.

An example of an ambitious betatron design can illustrate these issues. Consider a design goal of $N = 10^{14}$ electrons and $r_0 = 25.0$ cm. This corresponds to a circulating current $I = 3.06$ kA. Extrapolation from the early performance of ironless betatrons and assuming that the $(\gamma^2 - 1)\gamma$ scaling holds, an injector must provide at least 6.8 MeV electrons. With this minimum energy the B_z field at r_o will be 1000 gauss. Fields inside the radius must be substantially larger to allow betatron acceleration. Recent results[4] indicate that no more than 5% of the injected current is trapped. This figure may be modified if the trapping mechanisms are better understood, but for present purposes, we should use this number. The injector must provide at least 2 x 10^{15} electrons, or 320 µC . Finally injection times seem to effect confinement efficiency. Times short compared a circulation period do not seem to yield good trapping. Since the circulation time in this hypothetical design is only 5.2 ns, this is probably not a practical issue. Longer time injection also tends to decrease efficiency, however. A conservative time is 204 circulation periods, roughly 10-20 ns. This suggests that the injector current must be between 16-32 kA. These considerations tend to confirm that multi-kiloampere betatrons, though requiring sophisticated injection systems, are within current technology.

CONCLUSIONS

The pursuit of high current electron accelerators promises to be an exciting and challenging enterprise. The two types of accelerators discussed in this paper will require detailed analyses and experimental study before final evaluations can be made. At this time, though, there do not appear to fundamental obstacles standing in the way of demonstrations with state-of-the-art technology.

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