3 GHz SUPERCONDUCTING ACCELERATOR CAVITY FOR USE IN AN ELECTRON SYNCHROTRON*

R. Sundelin, E. von Borstel, J. Kirchgessner, D. Rice, and M. Tigner

Laboratory of Nuclear Studies
Cornell University
Ithaca, New York 14850

Summary

Experience has shown that superconducting accelerator cavity performance improves as the operating frequency rises. To use this effect to advantage in an electron synchrotron one must develop cavities of aperture large enough to provide the necessary phase space admittance and of such a configuration as to avoid problems with lost particles and synchrotron radiation in the orbit plane. The development of such a cavity, open in the mid-plane, is described and test results given.

Introduction

The investigation of superconducting accelerator structures at Cornell has been motivated by the desire to attain higher electron energies while maintaining a good duty cycle. Higher energy electron beams having good duty cycles would permit exploration of very interesting areas of electron physics which are presently inaccessible.

In an electron synchrotron, the energy which must be supplied per revolution to each electron due to synchrotron radiation losses begins to exceed the required energy for acceleration in the neighborhood of 10 GeV, and increases as the fourth power of the energy. In an electron synchrotron having conventional copper accelerating cavities, the RF power required becomes proportional to the eighth power of the energy because cavity wall losses are large compared to beam loading. With superconducting cavities, however, beam loadin is the dominant power requirement, so that the RF power requirement is proportional to the fourth power of the energy, for a given length of cavities. The change from the eighth to the fourth power makes the attainment of much higher electron energies practical.

Superconducting cavity research at a number of laboratories[1] has led to a state of the art value of 1 MeV per foot as the energy per unit length which one can impart to a relativistic electron passing through a superconducting cavity. Because the electrons in an electron synchrotron pass through each cavity thousands of times, this gradient is ideally suited for use in a high energy electron synchrotron. The limitation imposed by synchrotron radiation losses does not become prohibitive at energies up to at least 40 GeV.

There are several ways in which superconducting cavities could be used at Cornell. The most modest of these would be the replacement of the present copper cavities with superconducting cavities. This would, in conjunction with modifications of the magnet power supply, permit the synchrotron energy to be increased from its present 12 GeV to at least 15 GeV. This could also be accomplished with conventional cavities, but would require a significant increase in RF power. Another possibility is the replacement of the present magnets and accelerating cavities. This has the advantage of utilizing the present tunnel, but would require an extended interruption of the experimental program. By optimizing the ratio of magnets to accelerating cavities in the present tunnel, an energy of 25 GeV could be achieved. A third possibility is the construction of a new tunnel, tangent to the present tunnel and using the present synchrotron as a 5 GeV booster. Beams from this new ring could be brought into the present experimental halls. A magnetic radius of 140 meters and sufficient straight section length for 493 meters of superconducting cavities would permit achieving the energies indicated in Table I as the required lengths of cavities were installed. An accelerating field of 1 MeV per foot is assumed.

Table I

Installed Cavity Length, Meters	Maximum Electron Energy, GeV
9.8	15
31	20
75	25
156	30
289	35
493	40

The required fractional overvoltage for phase stability in the presence of quantum fluctuations in the synchrotron radiation has been calculated and found to be small, particularly at the higher energies.

Cavity Structure

The use of superconducting cavities in electron synchrotrons presents some unique problems. The most serious of these is the necessity of preventing synchrotron light from striking the cavity surfaces. The synchrotron light would represent an intolerable heat load if it were permitted to strike a surface at liquid helium temperatures, and in any event would presumably cause severe loading due to photoelectron emission. Another problem is the presence of inwardly spiralling electrons which are dropped from stable orbits at injection or extraction time. The use of a large aperture between cells of the structure would permit passage of synchrotron light and spiralling electrons through the structure without their striking any cavity surfaces. With a conventional cylindrical structure, the use of large apertures implies the use of low frequencies. However, results obtained at other laboratories indicate that operation at S-band or above is advisable to minimize multipactoring problems.[2]

A structure which operates at S-band, but which is completely open in the horizontal mid-plane to permit passage of synchrotron light and spiralling electrons, has been devised at Cornell. A single cell of this structure is shown in Figure 1, and a series of such cells, as they would be used in a synchrotron, is shown in Figure 2. The structure may be visualized as being formed by intersecting two parallel conducting planes with an enclosed rectangular cavity operated

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in the TM_{110} mode (Cartesian notation), with the planes parallel to the electric field lines in the cavity. The portion of the planes within the cavity is removed, and the portion of the cavity between the planes is removed. The spacing of the planes is such that the modes excited between them are below cutoff, and no energy can escape. Synchrotron light and spiralling electrons, after passing through the structure, are stopped in a room temperature absorber.

RF Properties

Various RF properties of the structure described above have been measured using aluminum models. In a single cell model, of length appropriate to π-mode operation, the resonant frequency is found to be within 1% of that of an enclosed cavity of the same dimensions, and the Q is found to be equal, within the measurement error, to that of an enclosed cavity. The geometry factor, $G = R_sQ_o$, is 233 ohms. The shunt impedance for the single cell structure, considering only the accelerating effect of the fields within the cavity volume, is given by ZT^2/Q = 3140 ohms/meter. The accelerating field is thus 93% of the value for an enclosed cavity. The cell coupling coefficient was found, based on dispersion measurements on an 11 cell model, to be k = 0.0459. The relationship of the peak magnetic intensity (amps/meter) to the effective accelerating field (volts/meter) is given by $|H|_{peak} = |E|_{eff} \cdot 1.4/\eta$, where η = 377 ohms.

Materials Studies

The effects of several surface preparation techniques have been studied, and typical results (not to scale) are shown in Figure 3. The three cases shown each started with a mechanically flat niobium surface. The fired sample is the most nearly planar, and the electropolished sample exhibits the smallest curvatures.

Surfaces of reactor grade niobium have been examined using a scanning electron microscope. The presence of carbon-bearing inclusions, occurring primarily at grain boundaries,[3] has been established using a bent crystal X-ray spectrometer in conjunction with the SEM. In an unfired chemically polished sample, 350 carbonaceous inclusions per square inch were observed, with an average diameter of 11 microns. The other constituents of these inclusions were not measured, but none of the inclusions was pure carbon. The volumetric carbon concentration in the material is approximately 16 parts per million. Another sample, which was fired for 7 hours at 2100°C at $1 \cdot 10^{-8}$ torr, was similarly examined. The number of carbonaceous inclusions was lower by a factor of 4 than in the chemically polished case, and the total carbon observed was lower by a factor of 6.

Surface Preparation

The surface preparation technique which we have been using consists of electropolishing and anodizing.[4] The cavity geometry is ideally suited for electropolishing, as the two halves can be electropolished separately. As discussed above, electropolishing yields the smallest curvatures at grain boundaries, which is advantageous for reducing field emission. The anodizing technique has been found to provide some degree of protection of the surface against atmospheric exposure,[4, 5] which protection would greatly facilitate assembly of a complex structure. The susceptibility of the anodized surface to radiation damage[5] may not be a problem because of the relatively low neutron fluxes associated with an electron synchrotron. Preliminary estimates predict a useful life before reprocessing in excess of a year, but further life studies will be required.

Cryogenic Testing

Tests have been performed on a single cell niobium structure of the geometry discussed above to measure values of breakdown fields and of Q_o. We consider an average accelerating field of 1 MeV per foot and a Q_o of 10^9 to be adequate for large scale use in an accelerator.

Power is coupled into the cavity through a movable coaxial electric probe, which is usually adjusted for critical coupling. The phase of the reflected power is used to lock a voltage controlled oscillator to the resonant frequency of the cavity.

The cavity surfaces are electropolished and anodized, and the cavity is assembled using a spacer ring to which the half cells are attached. Silver loaded indium joints between the ring and the half cells are used to make the structure vacuum tight. The spacing of the half cells is such that the TM cut-off mode provides 50 dB of isolation between the cavity and the indium joints.

The values of Q_o which have been measured have ranged from $1 \cdot 10^8$ to $5 \cdot 10^8$, and the values of the effective accelerating fields at which breakdown occurs have ranged from 1.2 to 4.0 MV/foot. The breakdown mechanism has been identified as thermal breakdown due to the relatively low values of Q_o^8; this mechanism is identified by a breakdown rise time of the order of 1 msec. Variations in the basic test procedure have included stress annealing (which produced no improvement in Q), freezing in external magnetic fields (which degraded the BCS component of the Q by the predicted amount[7]), mechanically tuning the half-cells separately while cold (which did not affect Q), varying the power and varying the coupling coefficient from 0.3 to 3.0 (which yielded a constant Q_o), and reducing the half-cell spacing from 1 in to 11/16 in (which produced no improvement in Q). Efforts are now in progress to determine whether the low values of Q are due to surface losses or due to losses in the joints or probe. The cavity is being fired at 2000°C in the BNL UHV furnace, and its properties will be studied with an unanodized surface.

Multiple Cell Cavity

An 11 cell niobium structure, 23 inches long, is presently being designed. After initial laboratory testing, it will be inserted in a straight section of the Cornell 12 GeV synchrotron. A succession of ion pumps and high pumping impedance beam pipes will be used to reduce the pressure in the vicinity of the cavity from its normal 10^{-6} torr to a value of 10^{-9} torr. This cavity will be used to verify the feasibility of using a structure of the type described in an electron synchrotron. If the structure performs satisfactorily, it will be capable of accelerating electrons to an energy exceeding 4 GeV.

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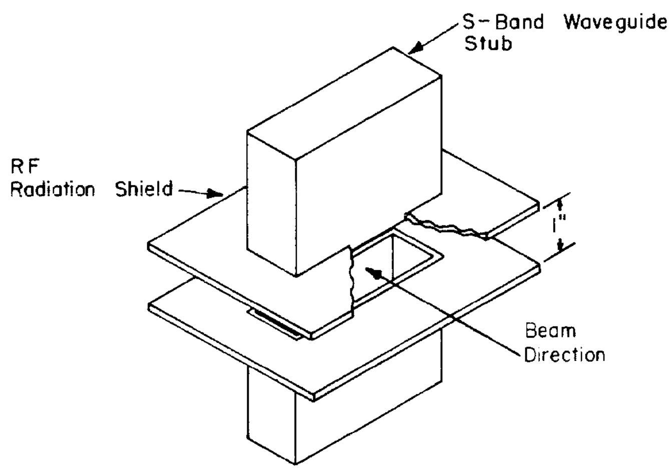

Fig.1. Single cell open accelerating cavity.

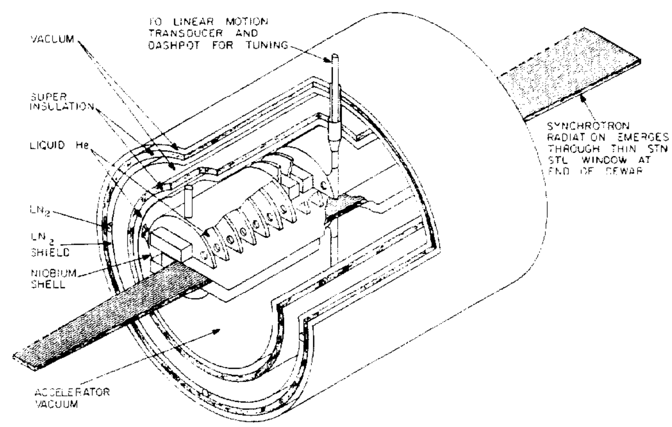

Fig.2. Multiple cell open cavity structure, including dewar.

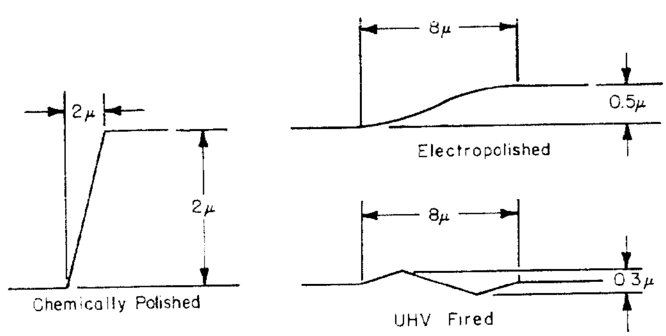

Fig.3. Typical grain boundary regions resulting from chemical polishing, electropolishing, and firing.