CURRENT STRIP FOR EXTRACTION OF THE CEA EXTERNAL ELECTRON BEAM

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Summary

The method presently being employed for extraction of 6 GeV electrons at the Cambridge Electron Accelerator is briefly described. The major element is a current strip, situated close to the orbit inner radius, which acts both as a non-linear focusing element and a magnetic deflector. Major characteristics of the current strip are: long pulse, 60 cycle, 6 GeV operation with an rms current density of 56,000 amperes per square inch at a maximum temperature of 135°F; minimum susceptibility to radiation damage, mechanical distortion and gas evolution; and reproducible remote positioning. As a result of experiments carried out with this current strip, modifications are under consideration which would make the extraction of other beams practicable, and would eliminate the need for a supportive downstream extraction magnet. A brief discussion of the modifications is included.

General

The CEA extraction system has been described in detail elsewhere.[1,2] Briefly, the system employs a current strip and an extraction magnet. The strip is situated close to the inner radius of the circulating beam. Current flowing along the strip produces a magnetic field having a non-linear focusing effect in the horizontal plane. Circulating particles are brought into the field by a "beam bump" system[3] and are deflected away from the strip, causing an increase in the amplitude of their normal betatron oscillations. The oscillations continue to grow until most of the particles jump to the opposite side of the strip, where they are deflected radially inward, away from the principal orbit. Downstream, these particles pass through the gap of an extraction magnet and are deflected radially outward into the desired extraction path.

Boundary Conditions

If the extraction efficiency is to be high, the strip must be thin. Because of the finite thickness of the strip, a fraction of the particles strike its leading edge, exposing the entire assembly and the downstream synchrotron vacuum chamber to intense radiation. Similarly, the strip must be held in rigid alignment to minimize the projected cross section. The current required to effect extraction results in a high current density and considerable generation of heat; the heat must be efficiently removed to prevent distortion and mechanical stresses. The strip assembly is mounted in a straight-section tank, which forms a portion of the synchrotron vacuum chamber "donut". At a normal operating pressure of 10^{-7} torr, the pumping system is sensitive to excessive gas loads; thus, the assembly must also be designed for minimum gas evolution.

Prototype

A prototype current strip[1] was constructed from a thin sheet of copper slitted along its top and bottom edges, the slitted portions being bonded to two stainless steel cooling tubes. Epoxy resin served as the bonding medium and as electrical insulation. This current strip demonstrated the feasibility of the extraction technique quite nicely, but it proved inadequate for long current pulses at 6 GeV due to long term radiation damage to the resin and excessive temperature differentials across the insulating boundary. The assembly became overheated, causing excessive outgassing, mechanical distortion and, finally, rupture of the strip itself. Further development resulted in the strip assembly described below.

Construction

The design of the new current strip is shown in Figure 1. It was cut from a solid copper bar; large masses of copper were left above and below the current-carrying section. Current is restricted to the section by transverse slots machined along the top and bottom edges, defining 44 individual segments which comprise the strip. Two coiled tubes of inconel "x" were soldered into troughs in the upper and lower copper masses such that 120° of each coil bend forms the heat transfer surface for each half-segment. The coils form electrical circuits in parallel with the strip. However, as these circuits are solenoidal, the resultant magnetic fields from the shunted currents are negligible. Inconel "x" has a resistivity approximately 70 times that of copper. Due to the high resistivity, greater length and small cross section of the tubes, the total shunted current is less than 1% of the total input current. The amount of copper immediately adjacent to the strip was held to a minimum to reduce field distortion due to eddy currents. Deionized water is used as the coolant.

The structure is rigidly mounted on a non-magnetic, stainless steel frame and is held in alignment by compression plates, as shown in Figure 2. Mica sheets insulate the copper from the frame. Fasteners are slotted for vacuum service, seated in helicoil inserts and insulated with shouldered ceramic bushings. Bellows assemblies permit remote positioning and provide access for coolant headers, terminals and mounting shafts.

Design Criteria

The magnetic field distribution of the current strip -- in the horizontal plane -- is illustrated in Figure 3. Fall-off along the x-axis is expressed by

$$B_{y(x)} = \frac{\mu_0 I}{\pi H} \tan^{-1} \frac{H}{2x} \qquad (1)$$

where H is the height of the current-carrying section of the strip. The dotted curves show the effect of increasing strip height or current or both. Current is applied in the form of a square wave of two milliseconds duration at 60 cps. For a design field of 1450 gauss at the surface of a strip with dimensions H = 0.594 inches, length L = 23.5 inches and thickness t = 0.036 inches the following conditions exist:

Peak current	= 3500 amperes
Rms current	= 1210 amperes
Rms current density	= 56,700 amp/sq in
Resistance	= 8.44×10^{-4} ohms
Total heat dissipated	= 4140 Btu/hr

The cooling coils were fabricated from 5/16 inch o.d., No. 20 Stubb's Gage inconel tubing, wound into 45 turns of 3/4 inch mean diameter and 1/2 inch pitch. The number of equivalent lengths for flow resistance, L/D, was calculated from experimental data[4]. Flow parameters were determined from the Darcy equation

$$\Delta p = \frac{2 f \rho v^2}{g} \left(\frac{L}{D}\right) \qquad (2)$$

where v is the velocity, ρ the density, g the gravitational acceleration and f the friction factor. For a pressure drop of 20 lb/sq inch the flow is turbulent, the velocity is 8.56 ft/sec and the mass rate of flow is 20.5 lb/min. The maximum temperature profile -- from the center of the turbulent stream to the center of the strip -- was calculated from the thermodynamic model for one half-segment, shown in Figure 4. A considerable fraction of the total temperature differential occurs across the laminar flow boundary, close to the tubing wall. For the above flow conditions, the coefficient of heat transfer for the laminar boundary is given by

$$h = 0.023 \left(\frac{k}{D}\right) \left(\frac{\rho v D}{\mu}\right)^{0.8} \left(\frac{c_p \mu}{k}\right)^{0.4} \qquad (3)$$

where k is the thermal conductivity, μ the viscosity and D the inner diameter of the tube. The temperature profile is shown in Figure 4. An added advantage of the design is that thermal expansion of the strip along its centerline is permittd by the spring constant of the coils.

Performance

The current strip has been subjected to normal operation in the synchrotron for more than six months. The strip thickness of 0.036 inch gives an extraction efficiency of about 70%. Temperature and flow parameters have been confirmed. At full power, the assembly presents no apparent gas load either due to heating or radiation. During a recent shut-down the current strip was thoroughly inspected, with no indication of distortion or discoloration due to local heating.

Proposed Modifications

To facilitate extraction of other electron beams, where extraction angles must be larger and less space is available, other approaches are being studied. One proposed modification would relocate the strip along the outside of the orbit, increase the current and strip height (to reduce the magnetic gradient) and extract the beam directly; the downstream extraction magnet would be eliminated. Another proposed modification would combine the current strip and extraction magnet in a single assembly, with the current strip and magnet excitation coil forming a continuous current loop.

Acknowledgment

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References

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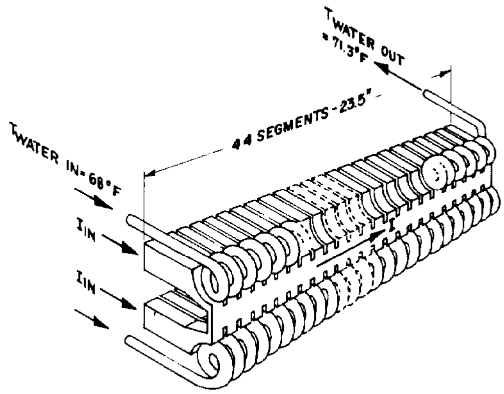

Fig. 1. Current strip.

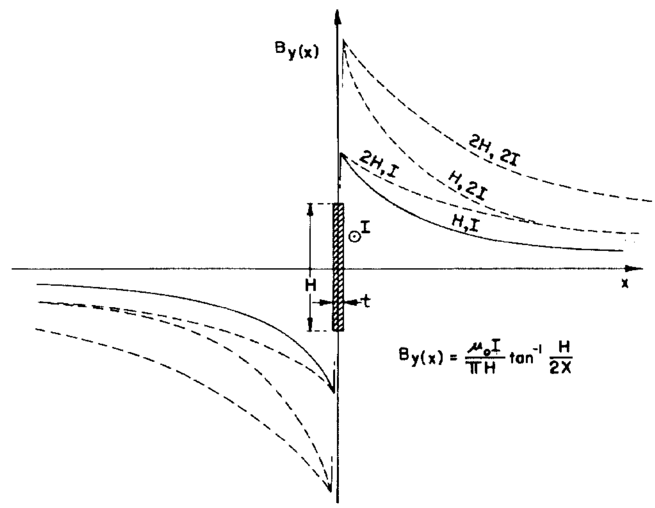

Fig. 3. Field distribution.

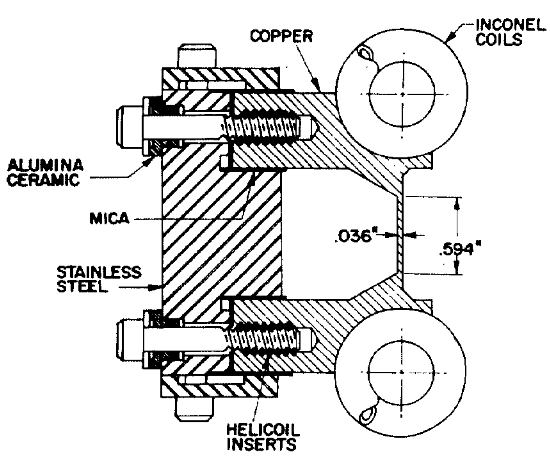

Fig. 2. Current strip cross section.

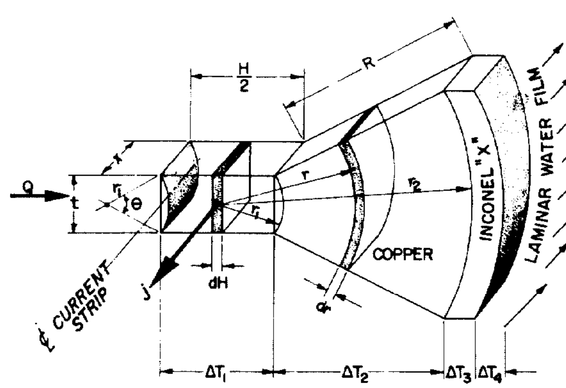

Fig. 4. Thermodynamic model.

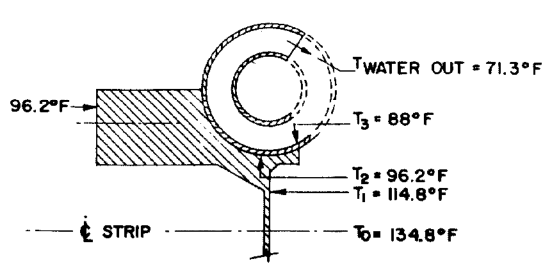

Fig. 5. Temperature distribution.