SYSTEM FOR GUIDING A RELATIVISTIC HIGH-CURRENT ELECTRON BEAM*

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Summary

For the purpose of guiding a 400-ampere, 4-MeV electron beam through the Astron accelerator, a combination of several kinds of focusing and steering coils are used in conjunction with current-regulated power supplies. The present guiding system – accelerator layout, along with design and control features of the guiding elements, is given in the first section. Following this is a discussion of how system components affect the accelerated electron beam. Finally, conclusions from design and operating experience are drawn.

Beam-Guiding System

The complete beam-guiding system layout is shown in Fig. 1:

1 and 2 are iron-shrouded, large-diameter, vacuum-tight focusing coils; 2A is an iron-free large-diameter focusing coil; 3, 4, 4A, 5, 5A, 6, and 7 are iron-shrouded, small-diameter focusing coils; H1, H2, H3, V1, V2, and V3 are specially wound, iron-free steering coils; and A, B, C, D, E, and F are hand-wound, iron-free coil pairs used for beam deflection, steering, and perhaps some degaussing.

All of these coils operate at a high voltage-to-current ratio. Therefore, placement of coil lead wires is not critical.

Iron-Shrouded Focusing Coils – Small Diameter

A 6-inch i. d. iron-shrouded focusing coil is shown in Fig. 2, and Fig. 3 gives field curves for this type of coil.

Coil Parameters

Operating parameters for this type of coil were found to be:

peak longitudinal field –	~265 G/A
effective field length –	13 cm
refractive power[1] at 2 A (4 MeV) –	3.53×10^{-3} cm^{-1}
beam particle rotation[2] at 2 A (4 MeV) –	2.4×10^{-1} rad
maximum coil current –	4 A dc
maximum coil current density –	1475 A/in.^{2}
maximum power consumption –	480 W
cooling water flow rate –	4 gal/min
cooling water temperature rise –	<20°F

Construction Details

Spool. The spool core is a section of 316 stainless steel pipe. This type was found to be the least magnetizable of all the commercial stainless steels available. Weld joints on type 316 are made with type 310 stainless steel rod. Both types are resistant to ferrite transformation on the weld zone, cryogenic martensite transformation, and cold-work magnetism.[3]

The spool is completed by arc-welding mild steel spool ends to the stainless steel core.

Coil. The spool is used as the coil form after it is coated with 0.0025-inch mylar. The coil itself is random-wound of ~3100 turns of Anaconda No. 16 A. W. G., AI 220C-coated, solid copper wire. During the winding process the coil is potted with Epon 815 (11% agent D) mixed with levigated alumina. Heat conductivity of the potting compound is improved by a factor of four when 150% by weight of levigated alumina is added to the eopxy.[4]

Coil Cover, Mounts, and Cooling Tubes. Dimensions of these components are given in Fig. 2. The coil cover and the mounting pad are welded up from the same mild steel as used for the spool ends.

It is recommended that all mild steel parts – bolts included – be annealed before assembly.

Note that the cooling tubes are used only on the outer periphery of the coil assembly. For use at higher current densities, a design modification is now in process which will allow an annular water passage 1/8-inch thick about the spool core. This should at least double the current-carrying capacity of the magnet, and will also provide more skin depth attenuation of any magnetic field ripple that exists in the coil.

Coupling to Vacuum System and Mechanical Alignment. Vacuum (beam) pipe flanges are constructed with O-ring gaskets and roll-pins, and are bolted to holes which are blind-tapped into the mild steel spool ends. Consequently, the inner

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spool surface becomes part of the Astron accelerator beam path, and is exposed to 2×10^{-6} mm Hg of system pressure.

If adjacent beam pipe and flanges are accurately made, then pinning and bolting them to a focusing coil assembly automatically aligns this coil with the accelerator axis. Transparent cross-hair targets may also be bolted to the coil faces for optical alignment.

Iron-Shrouded Focusing Coils – Large Diameter

The Astron accelerator electron beam has a nominal 7-inch diameter as it emerges from a high-gradient, 600-keV gun. This beam must be reduced in diameter and prepared for injection into the 4-inch-diam aperture of the accelerator. For this purpose, large-diameter focusing coils are disposed inside the gun-accelerator vacuum pipe.

A 14-inch i. d. iron-shrouded focusing coil is shown in Fig. 4.

Coil Parameters

Operating parameters for this type of coil were found to be:

peak longitudinal field –	100 G/A
effective field length –	40 cm
refractive power at 3A (600 keV) –	$\sim 5 \times 10^{-2}$ cm^{-1}
beam particle rotation at 3 A (600 keV) –	~1.5 rad
maximum coil current –	4 A
maximum coil current density –	1312 A/in.^{2}
maximum power consumption –	700 W
cooling water temperature rise –	<20°F

Construction Details

Spool. The spool components and assembly for the large-diameter coils are the same as for the 6-inch coils.

Coil. Again, the spool is used as the coil form after it is coated with 0.002-inch Mylar sheet. The winding and potting processes are the same as for the 6-inch coils. This coil uses 3260 turns of No. 16 A. W. G. wire.

Coil Cover. The coil cover, or outer ring, is a mild steel forging that is machined for vacuum gaskets on the edges.

Mounting and Alignment. Mounting is done by means of brass screw jacks that butt against the inside wall of the vacuum chamber. Transparent cross-hair targets are used for optical alignment.

Cooling. Copper tubing is soft-soldered into machined recesses on the inside diameters of the coil ends.

Electrical Connections. Since this entire focusing coil operates in vacuum, coil leads are brought out on vacuum feed-throughs.

Vacuum. The coil housing is constructed to have a leak rate of less than 1×10^{-10} std. atm cc/sec when checked with a helium mass spectrometer. To further ensure against leakage into the accelerator vacuum system, the housing is independently pumped down to system pressure.

Iron-free Coil – Large Diameter

This coil (No. 2A in Fig. 1) was built as an afterthought when it was found that injected beam current was low compared to the gun output current. No figure is exhibited here because no formal engineering was involved in the coil construction.

Coil Parameters

Since this focusing coil was hand-wound in place, and there are many mechanical obstacles, no field parameters are available.

maximum coil current –	4 A dc
maximum coil current density –	582 A/in.^{2}
maximum power consumption –	580 W

Construction Details

The spool "core" is formed by twelve 3/8-inch-diam brass rods spaced 30° in azimuth on a $19\frac{1}{2}$-inch-diam about the accelerator axis. The brass rods are bolted to band-sawed, 3/4-inch exterior grade plywood spool ends.

The coil was random-wound (in place) of No. 16 A. W. G., stranded, tinned, Teflon insulated circuit wire. The number of turns needed was found empirically by noting the effect of the coil on the accelerator beam, and then adding more turns. The coil now has about 2000 turns, resulting in dimensions of $19\frac{1}{2}$ inches i. d. $\times$ $5\frac{1}{2}$ inches long $\times$ $2\frac{1}{2}$ inches deep.

Coil 2A is disposed entirely in air, and is cooled by air circulated by two strategically located 115 V ac office fans.

Alignment of this coil depends on the alignment of the vacuum chamber to which it is bolted.

Steering Coils – Cosine Type

A cross-sectional sketch of the winding distribution for this coil is shown in Fig. 5. These coils[5] provide a transverse field to correct for beam deflections caused by the ambient earth field and randomly magnetized local structural iron. Two in-line steering coils are used for relocating the beam on or parallel to the accelerator.axis. One coil alone merely deflects the beam.

Coil Parameters

Operating parameters of interest are:

field strength –	5 G/A
field diameter –	2 in.
field length –	6 in.
two-coil beam offset (4 MeV) –	0.04 in./A
one-coil bending angle (4 MeV) –	0.004 rad/A
maximum coil current –	5 A
maximum power consumption –	5 W
cooling –	none

Construction Details

Spool. The spool is machined from thick-wall Micarta tubing. Longitudinal slots are azimuthally spaced on the outside walls to give a cosine current distribution for a constant number of turns of wire per slot.

Coil. The coil is hand-wound of No. 16 A. W. G. Formvar-coated solid copper wire. Turns are held in place with Mylar tape on the sides, and fast-setting epoxy resin on the ends.

Electrical Connections. An eight-terminal Johnson strip is glued on the outside wall. Since this coil has very few turns, the power supply leads must be brought up in twisted pairs, or coaxial cable, so as not to perturb the coil field.

Alignment. The cosine coils are clamped to the outside wall of the beam pipe. Therefore, if the beam pipe is aligned, the cosine coils are aligned.

Steering Coils – Helmholtz Type

These coils operate in pairs, of course, to provide a transverse field. The large pairs, A, B, C, and D, deflect the accelerator beam, and probably also help degauss the neighborhood a bit. The small pairs, E and F, function only as deflecting coils.

All coil pairs were empirically constructed. As for No. 2A, turns were applied when the coils were found wanting.

Coil pairs A, B, C, and D are square in shape, about 4 feet on a side, each coil 100 turns of No. 14 A. W. G. stranded plastic insulated copper wire. Maximum current used is 5 A, while power consumption is about 350 W.

Pairs E and F are 10 inches on a side, 30 turns of No. 14 A. W. G. stranded, plastic-insulated wire. These pairs use 5 A and less than 10 W.

All coil pairs are wired in series electrically such that the magnetic field of one coil adds to the magnetic field of the other coil in that pair.

Power Supplies

All types of coils and coil pairs described above are independently powered by the same type of current-regulated supply. These supplies were specially built for us by Hyperion Industries Corp. Their operating capabilities are 0-5 A and 0-160 V dc. After installation, current ripple was ~0.001 A, and current regulation was <0.2% for 1 hour after a 2-hour warm-up. Short term regulation is <0.1%.

Controls

As mentioned earlier all focusing coils, steering coils, and coil pairs each have their own power supply. This means that the accelerator operator has 22 power supplies to adjust when tuning the beam. Therefore, for the sake of compactness at the operator's console, power supply operation is done remotely.

Remote control modules for each power supply are designed into 3 × 5 × 12 inch rack-mounted packages which are closely stacked for operator convenience. Each module face contains a 0-5 A meter, reversing switch, two current-direction indicator lights, and one 10-turn helipot that controls the power supply current output.

Optimum helipot resistance valves for each control module were arrived at after a trial-and-error process during which the accelerator operator noted the effects on the output beam pulse.

Discussion

Occasionally, with the right man at the controls, the accelerator transmission efficiency is better than 90%. Good transmission is about 75%.

Now, there are five current-monitoring devices (bugs) along the accelerator. First, the operator optimizes the beam pulse at each bug – starting from the upstream end – by adjusting the focusing coil currents and reversing switches in any sequence he finds necessary. Then the operator adjusts all steering coil fields, looking at each bug in turn. Finally, all guiding elements are fine-tuned for maximum output beam.

When the output beam is optimized, one can see that certain elements are energized to much higher values than calculation would indicate necessary, and that (usually) all steering stations are in use. When a focusing coil chronically operates at a high level, it is conjectured that either there is a beam waist near the center of this coil, or that this coil is acting as a deflector for an off-axis beam. When steering coils are used, an off-axis beam is definitely being corrected for. Steering, of course, is necessary to correct for spurious beam deflections which always seem to be present.

Insofar as effects on the output beam are concerned, changing any one element – especially upstream – reduces the output beam, changes the output pulse shape, and allows some beam to splash along the accelerator bore and get lost. For example, focusing coils 1 and 2 can be used to reduce the output beam to as low as 1 A. Also, the output beam may be gently "steered" by slight changes in some of the upstream focusing coils. Recently it was verified that changing pulse shape – even though optimum amplitude is maintained – has a marked effect on the beam energy spectrum. That is, a different energy spectrum results from each mode of guiding element system tuning.

Conclusions

The Astron linear induction accelerator provides an intense beam of electrons which is used for several purposes – some of which require more beam than presently available. Consequently, the accelerator is often subjected to major developmental changes. Therefore, the beam guiding system heretofore described is a pioneering effort, and the success of the system is justification for having built the latest stages of it according to the demands of an operating machine. It is generally felt by those concerned that with a small increase in refractive power of the focusing coils, this type of beam guiding system will be capable of transporting over 1000 A of 4- to 5-MeV electrons through and beyond a linear induction accelerator.

Acknowledgments

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References

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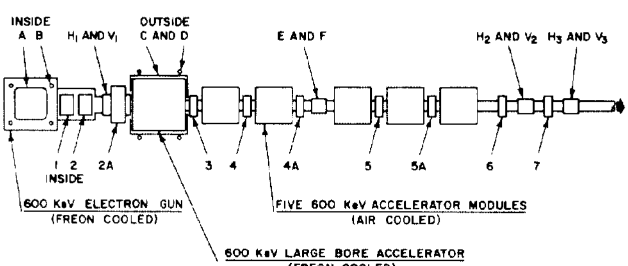

Fig. 1. Schematic of Astron accelerator indicating present locations of guiding system elements.

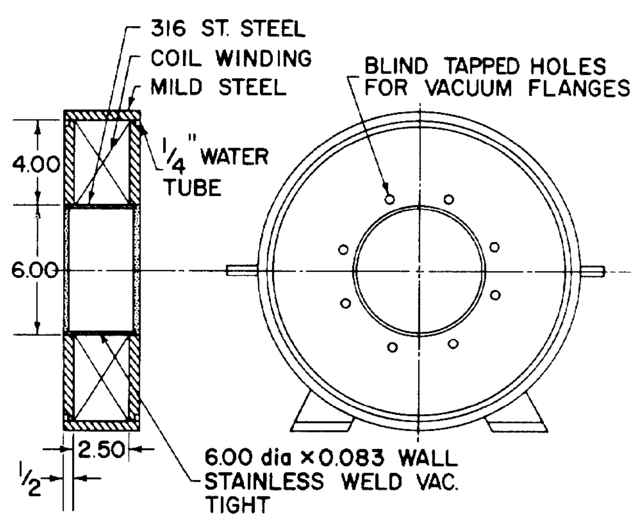

Fig. 2. Sketch of 6-inch i.d. iron-shrouded focusing coil assembly.

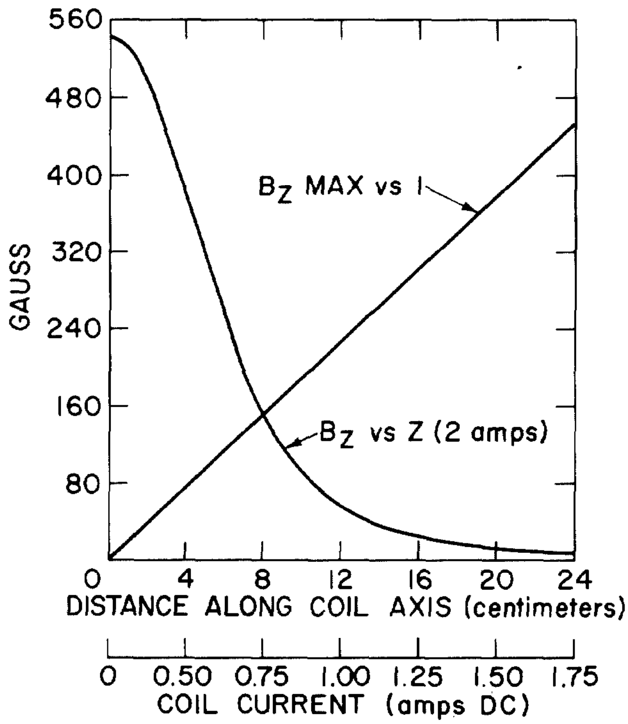

Fig. 3. Axial flux density as a function of axial distance from magnetic center of 6-inch focusing coil and peak flux density vs coil current.

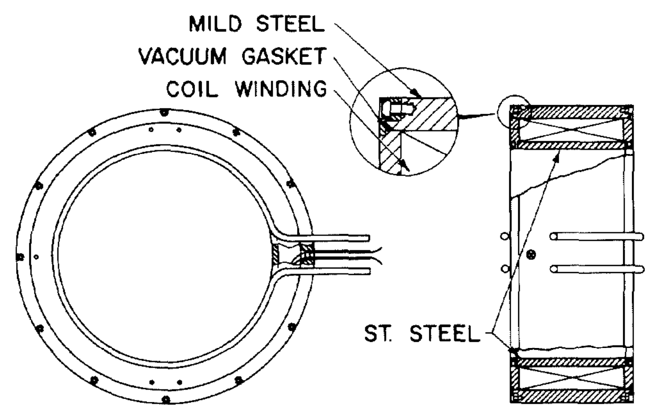

Fig. 4. Sketch of 14-inch focusing coil assembly.

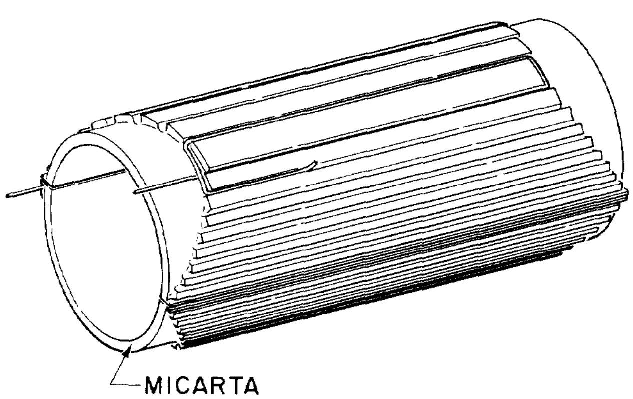

Fig. 5. Cross section of a cosine-type steering coil. Length can be varied to suit conditions.