Accurate electron gun-positioning mechanism for electron beam-mapping of large cross-section magnetic surfaces

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A method of accurately supporting and positioning an electron source inside a large cross-sectional area magnetic field which provides very low electron beam occlusion is reported. The application of electrical discharge machining to the fabrication of a 1-m truss support structure has provided an extremely long, rigid and mechanically strong electron gun support. Reproducible electron gun positioning to within 1 mm has been achieved at any location within a $1 \times 0.6\text{-m}^2$ area. The extremely thin sections of the support truss ($\leqslant 1.5$ mm) have kept the electron beam occlusion to less than 3 mm. The support and drive mechanism have been designed and fabricated at the University of Wisconsin for application to the mapping of the magnetic surface structure of the Advanced Toroidal Facility torsatron[1] at the Oak Ridge National Laboratory.

The Stellarator class of plasma confinement devices is characterized by the complete production of confining magnetic fields (magnetic surfaces) by some combination of external helical and vertical magnetic field coils.[2] The Advanced Toroidal Facility torsatron (ATF), at present in its commissioning phase, will be the largest stellarator device in the world, with a major radius of 2.1 m and an average minor radius of 0.3 m. Because good plasma confinement is predicated upon the existence of well-formed closed nested magnetic surfaces, and because stellarator magnetic surfaces have been shown[3] to be extremely sensitive to deterioration and breakup at very low levels of stray magnetic fields ($B_{\text{stray}}/B_0 - 10^{-4}$),[4] it is necessary to accurately determine the magnetic surface structure in the vacuum field situation. The classical technique involves launching an electron beam on a magnetic surface and monitoring the toroidal transits of the beam using a collection probe.[5] This has recently been supplemented by more rapid detection schemes involving fluorescent screens[6] and diode/triode-electron impedance measurements.[7] However, all of the techniques of electron detection require launching a low energy (< 100 eV) electron beam at various places within the magnetic surface structure under investigation. The present note addresses this problem of supporting and accurately positioning an electron source, particularly within the modern-day large confinement devices.

The inherent difficulty involved in electron beam mapping of magnetic surfaces is the interception of the electron beam during one of its toroidal transits by the electron gun support structure. This leads to the loss of available information about some of the magnetic surfaces. ATF and similar large stellarator devices require an electron beam to be launched over extremely large areas, necessitating long and often bulky support structures for the electron producing filament to minimize vibration and sag. The ATF device has been designed to have approximately elliptical magnetic surfaces with a major axis of nearly 1 m and a minor axis of approximately 0.6 m. The problem was, therefore, how to support the emissive filament while offering the smallest possible cross-sectional area of the support to the electron beam and yet still be able to access any point within the entire cross-section of the magnetic surfaces. Furthermore, this support structure had to be able to be repeatedly and accurately positioned within the magnetic surfaces to within 1 mm, to be constructed of nonmagnetic material, to be electrically grounded so as not to disturb the electron trajectories through electrostatic charge deflection, and to be constructed entirely from high-vacuum compatible materials. The high-positional accuracy was required to enable accurate determination of the maximum size of any magnetic island structure present in the ATF magnetic configuration under investigation.

Straightforward mechanical considerations of a hollow metal tube support, 1 m in length and of an acceptable diameter (less than 1 cm), showed that the tip would have a significant degree of sag under its own weight and could possibly be sensitive to slow-timescale mechanical vibrations. A 0.7-cm-diam stainless-steel tube, with a wall thickness of 2 mm and a length of 1 m, was demonstrated to have a tip sag of approximately 0.5 cm. More seriously, tip vibrations of several millimeters were measured when the support point of the tube was moved vertically a short distance and then stopped; vibrations which took many seconds to decay to an undetectable level. Thus, reproducible positioning of the electron source would be extremely questionable. Using multiple, shorter, support mechanisms could improve the reliability but at an increase in expense, and significant doubt as to the overall positional accuracy would still remain. Accordingly, an extremely thin-section truss support was investigated, designed, and fabricated which satisfies all of the criteria desired for the electron source support structure.

The support truss (Fig. 1) has been made from high yield strength stainless steel (Nitronic 33) which has a low magnetic permeability (1.0013) and is compatible with high vacuum conditions. The truss was fabricated from a solid bar ($2.5\times1.25\times100$ cm^3) using electrical discharge machining techniques. Before the discharge machining of the extremely thin truss sections, a 0.75-mm-wide slot 7 mm deep was cut along the length of the bar 0.38 mm from the bottom edge. This slot was inserted to house the wires used to power the electron producing filament. The bar stock was then discharge machined into the truss structure shown in Fig. 1. Fifty-nine (59) triangular sections were removed leaving wall thicknesses of 0.5 mm except along the bottom strut (where the slot had been cut) which was kept to 1.5 mm in thickness. The availability of the electrical discharge machining process for the truss fabrication was critical since this machining process can fabricate very thin or fragile components with extremely high accuracy in a cost effective manner; the virtual absence of tool force on the piece being machined means that high tolerances can be maintained while avoiding stressing or deforming the piece. The total machining cost of the entire truss was under $1000. Measurements of the unloaded deflection of the truss tip showed deflections of less than 0.1 mm, and a tip deflection of less than 0.5 mm with a weight of 0.5 kg applied to the tip. Since the electron source to be applied to the truss weighs less than 50 g, these deflections were well within the design criterion of a tip deflection of less than 0.5 mm required for accurate magnetic island mapping. Occlusion thickness to the electron beam, allowing for magnetic field curvature in the region of the truss, of less than 3 mm has been calculated. This level of occlusion is far below that anticipated for any more conventional support structure.

Associated with the design and construction of this truss, a small, replaceable cartridge-type tip for housing the electron producing filament has been designed and fabricated. This tip had to be as small as possible to avoid interception of the electron beam, and is shown in Fig. 2. This gun was made to be easily replaced in the event of filament failure. The replacement gun was required to coincide with the location of the original to within 0.5 mm to maintain a reproducible electron launch location. The end of the gun which mates to the support truss, and the associated end of the truss, were discharge machined to have matching alignment and support grooves to permit accurate gun replacement. Connections to the wires for heating the filament are made using gold plated push-on pins which match an associated set of sockets housed in a small mating connector mounted to the truss tip. The small support blocks for these pins are made from machinable ceramic (Macor®) which also provides for pin-to-pin and pin-to-housing electrical insulation. Wires connected to each of the truss mating connector pins were run along the slot in the truss to the truss support point and then connected to an instrumentation vacuum feedthrough. The filament is a thoria-coated iridium filament as used in modern ionization gauges; these filaments are extremely rugged and have a high electron emission at a relative low filament temperature as compared to a tungsten-type filament. The third connection shown in Fig. 2 is for a collection probe on the opposite side of the gun which is used for the collection of electrons coming back to their launch point after one or more toroidal transits of the magnetic field. The entire housing for the gun was fabricated from 304 stainless steel, into which narrow grooves for the copper wires and the insulating alumina jackets were milled. This electron source has been tested under 10 h of continuous electron emission, and was found to perform extremely well with no failure throughout the entire test. Continuous total filament emission of over 1 mA, with extracted beam currents of several hundred microamperes, were obtained.

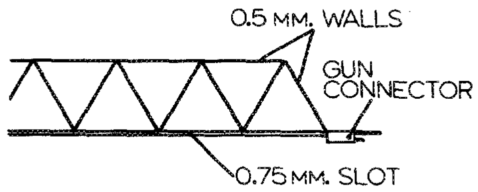

FIG. 1. Side view of the end section of truss used for the electron gun support. Each triangular section was removed by electrical discharge machining to leave a 0.5-mm wall. The lower 0.75-mm slot is for housing electrical wires which connect the gun-connector pins to a vacuum feed-through. Overall truss dimensions are: length = 1.0 m, height = 2.5 cm, width = 1.25 cm.

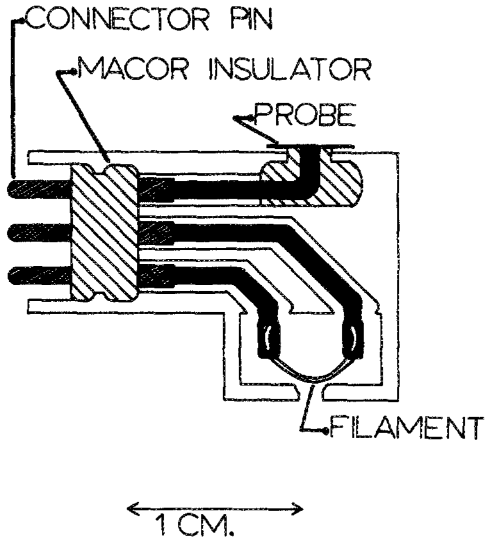

FIG. 2. Top view of the replaceable electron gun. The copper conductors joining the pin connectors to the filament were flattened at the filament junction and drilled with two 0.5 mm holes. The thoria-coated, iridium ribbon filament was then threaded in and out of these holes to make the electrical connection. These copper conductors were insulated by small sections of alumina in the slot regions. A boron-nitride suspension was then painted over all conductors and alumina joints and baked to form an excellent insulating layer.

Positioning of the entire truss and gun assembly is accomplished by a precision R-Z drive (Fig. 3). This drive unit

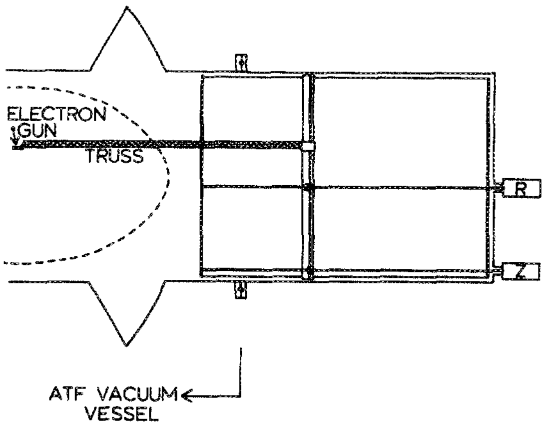

FIG. 3. Schematic representation of the cross-sectional view of the R-Z drive unit attached to the ATF vacuum vessel. The radial (R) drive is a direct drive, 1-mm pitch screw. The vertical (Z) drive is a hexagonal shaft which couples at 90° to a vertical, 1-mm pitch screw. Bearings in the 90° coupler permit radial motion of the entire vertical drive section, thus decoupling the radial and vertical drive actions.

was designed to operate within the vacuum environment required for the experiment, and uses rotary feedthroughs to couple the dc motors with optical encoders to the translation screws which position the gun. The motors, encoders and motor control unit are an off-the-shelf item which permit accuracies of up to 1/1000 of a revolution in the drive motors. Each motor was mounted directly to a rotary feedthrough, the other end of which was coupled to a threaded drive-screw. Using a 1.0 mm pitch threaded rod for the R and Z motion drive screws permits a positional accuracy of well under 0.1 mm for the electron source. Home switches on the drive unit permit absolute gun position referencing to within this accuracy. A computer link-up to a Vax 11/780 is used to control the functions of the motor controller. This permits remote positioning of the probe as well as providing direct access to the computer of the current position of the probe at any desired time. The motor controller was ordered with a RS232 serial line interface, and program control of the controller was a relatively straightforward programming task performed at the Oak Ridge Laboratory. To ensure proper functioning of the drive in the vacuum environment, special attention was given to the design of the drive components. Moving metal-to-metal interfaces are of a rolling type[9] to minimize the possibility of vaccum welding (galling) of vacuum clean components, and the metal-to-metal contacts use stainless-steel/nitronic combinations for the same reason. Precision guide bars parallel to the drive screws maintain the positional accuracy of the carriage, and reproducible positioning of the carriage to under 0.5 mm has been measured.

Thus, we have designed, fabricated, and tested an electron beam launch structure which is able to access all of the 1×0.6 m area of the ATF magnetic surfaces. The electron gun truss structure provides a rigid, low profile support for accurate positioning of the electron source. The cartridge-style gun tip is a small, easily, and accurately replaceable unit which has been demonstrated to be a reliable electron source. Through the use of dc motors and optical encoders coupled to accurate drive screws, the electron source can be accurately and repeatedly positioned to within 0.5 mm. The actual magnetic surface mapping experiments are scheduled to be performed early in the experimental program proposed for the ATF device to verify the quality of the obtained magnetic surfaces.

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Spark gap monitoring circuit

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I describe a circuit which gives reliable data of the firing sequence of a laser chain with the use of cheap plastic fiber-optic cables and counter circuits. This eliminates the need of an oscilloscope. The circuit is able to store data of up to 16 shots, and it can pinpoint a malfunctioning stage of a Marx bank from a large number of such units.

In a TEA CO_2 laser chain, many spark gaps are used. Roughly, the number equals the number of Marx bank stages and some more which are either in delay/trigger generator circuits or in pulse slicing units. For proper and peak performance of the system, the firing of spark gaps should have a fixed correlation in time with each other.[1,2] This becomes more important when the excitation of amplifiers has to be done by short-duration pulses such as in high-pressure