J. Plasma Fusion Res. SERIES, Vol.1 (1998) 422–425

Design and Construction of HSX: a Helically Symmetric Stellarator

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(Received: 30 September 1997/Accepted: 16 January 1998)

Abstract

An advanced stellarator configuration is under construction at the Torsatron/Stellarator laboratory. The magnetic geometry of this stellarator is a quasi-helically symmetric. This unique magnetic structure is generated by a set of 48 (8 coils of 6 different coil types) modular coils designed using NESCOIL code developed by IPP Garching. This device called the helically symmetric experiment (HSX) is in the final stage of construction. The magnet coils are fabricated using standard magnetic technology. The vacuum vessel is made using explosive forming techniques.

Keywords:

helically symmetric experiment, quasi-helical symmetry, coil mold, vessel mold, explosive forming

1. Introduction

The Helically Symmetric Experiment (HSX)[1,2] is an advanced stellarator configuration, in which magnetic geometry is quasi-helically symmetric (QHS)[3]. The magnetic spectrum is dominated by a single helical component. This configuration has significant advantages as a confinement device in that it avoids direct orbit losses, as well as the large low-collisionality neoclassical transport that dominates conventional stellarators, while retaining the stellarator advantages of no plasma current, no disruptions, and steady state operation. The goals of HSX are to experimentally measure the improved confinement associated with the QHS configuration and to determine the degree of symmetry required to realize these benefits. HSX is characterized by four field periods with a major radius of 1.2 m, average plasma radius of 0.15 m, and a nominal magnetic field of 1.0 Tesla. The major components of the HSX device are the vacuum vessel, Ring/Main-coil/Auxiliary-coil modules, and support structure.

2. Magnet Coils

The magnetic field structure of HSX is produced by a set of 48 modular coils designed using the NESCOIL code developed by IPP Garching[4]. The main coil set consists of 6 different coil types with 8 identical coils of each type reflecting the four field period nature of HSX. The coils are formed without tension on a precision CNC machined mold using a copper-fiberglass-kevlar-epoxy matrix. Fabrication tolerances are set at a maximum 2 mm deviation from the design coil

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envelope. These constraints are set by the requirement of well-formed magnetic surfaces; quasi-helical symmetry does not require a tighter envelope. These 14 turn coils are wound in a 7×2 arrangement where each turn is made up of 6 separate copper conductors arranged in a 3×2 bundle. The two middle conductors are hollow to provide coil cooling channels. The other two pairs of conductors are solid copper. This arrangement of conductors facilitates coil forming while maintaining a high copper to cross-section packing factor. Each of the six conductors is cleaned, abraded, and primed with Dexter Hysol (EA9210H), to improve epoxy bonding, prior to being wrapped with 0.005 inch thick fiberglass. The bundle of 6 conductors is then wrapped with a 0.040 inch layer of kevlar tape, formed, and clamped into the mold in 2 to 3 foot segments to allow for conductors to slip past each other as they are formed around the mold. The whole coil is then wrapped with a 0.040 inch layer of fiberglass tape as a ground wrap.

To maintain the shape and accuracy requirement of the coils, the winding mold is also used to vacuum impregnate the coil with a conventional liquid epoxy resin (Bisphenol A-type) Dow Chemical DER 332. Aliphatic Diepoxide, Dow Chemical DER 732, is blended with the Bisphenol A-Base resin to impart some flexibility, and improve impact and crack propagation resistance. For alignment purposes, the winding mold has 12 witness points that are accurately known. These reference features, transferred into the coil during the potting process, are used to position and align the coils to their final location. Each coil is supported within a planar stainless steel ring, which picks up the main radial loads. The planar rings are 0.75 inch thick and 4 inch wide and follow the shape of the coils.

An additional set of 48 planar non-circular coils (Auxiliary coils) will be used to break the helical symmetry generated by the main coils and to generate different magnetic configurations in the same physical device. The shape of these coils conforms to the shape of the planar rings. The coils are fabricated using the same epoxy impregnation process as the main coils and mounted to the rings, thus forming a Ring/Main-Coil/Auxiliary-Coil (RMCAC) module. The module is then supported at 3 locations from a common superstructure, which will be described in section 5.

3. Ring/Main-Coil/Auxiliary-Coil Module

The assembly of the modules, shown in Figure 1, is a critical first step in the alignment of the main coil set that generates the HSX magnetic field. First the main coil is aligned with respect to the ring using the 12 witness points of the coil. Then the coil is then rigidly fixed in the plane of the ring with a set of pressure pads and a set of support castings. The pressure pads are 2 inch sections of stainless steel channel, which also provide out-of-plane support. Six to eight pads are typically used on each coil at the locations where the coil crosses the plane of the ring. The pads are held against the coil with two bolts with locating spherical heads that socket into detents in the pressure pads. These bolts unthread out of the ring to push against the pads and center the coil inside the ring. The pads/bolts transfer the coil radial load out to the ring. The support castings are used to provide stiffening of the inner bore of the coil in the high torsional regions to reduce the coil stresses down to acceptable levels of 30 MPa and provide the main support to the out-of-plane loads. The castings are bolted to the ring with a set of splice plates. Both the pressure pads and the support castings are permanently attached to the coil with Lord 410/#19 Acrylic adhesive. The auxiliary coil is attached to the ring with a simple set of brackets and bolts. For the final assembly the ring with the auxiliary coil will be installed in the support structure and properly aligned using the witness point features of the ring. Then the main coil

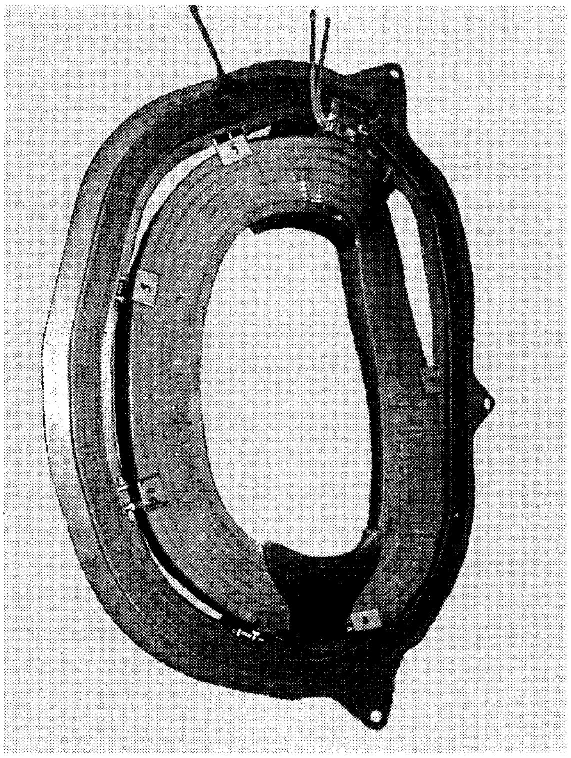

Fig. 1 The ring/main-coil/auxiliary-coil module.

with the pressure pads and the support castings is installed into the ring. Final measurements of the coil features will be made to ensure that the main coil is in the proper place in the global device coordinate system.

4. Vacuum Vessel

Located inside the main magnet coils is the vacuum vessel, made from 8 identical sections. The vessel, supported independently from the superstructure, is separable into four field-period units. Each field period will have two sections welded to the two sides of a box-port and a vacuum flange welded to the free end of each section. The vacuum vessel is made using explosive forming techniques. A mold that has a CNC machined cavity in the shape of the outer wall of the vessel section can be assembled around a pre-form. The mold pieces are assembled inside a 6 inch wall thick cylindrical housing for containment during the explosion. A stainless steel pre-form, 0.25 inch stainless steel 304 sheet bent into a U shape, is inserted into the cavity of the mold and explosive charges are detonated a number of times inside the pre-form until it conforms to the shape of the cavity. Water is used as the medium to transfer the shock wave to the stainless steel. For ease of production, each vessel section is made of four pre-forms that were trimmed and welded together after they were explosively formed. The whole vessel section is then solution annealed, to reduce the mechanical stresses, and inserted into the mold cavity for final forming and resizing of the vessel section. This is followed by another annealing process to remove the permeability induced by the explosion working of the material. A grid of lines oriented in the poloidal and toroidal directions is machined into the mold. The grid is coined onto the vacuum section outer surface during the explosion to form reference features that are used in surveying the formed sections and for locating the diagnostic ports.

5. Support Structure

The main support structure for the HSX device is a set of box-beam weldments that are assembled into four field-period units. The Ring/Main-coil/Auxiliary-coil module and the vacuum vessel are mounted to the box-beam structure using a set of three adjusters per ring and eight adjusters for the vacuum vessel. The adjusters permit fine-tuning of the position and alignment of the coils and vessel. Central to the device assembly and alignment, is the utilization of an accurate, portable, coordinate measurement machine (CMM). The CMM references a the witness points of each component to the witness points of the connecting components to insure precision sub-assembly of each field period. Ultimately the four field periods are connected to form HSX with all components now referenced to single global machine coordinate system (MCS).

6. ECRH and Power Absorption

To test the neoclassical properties of HSX, hot electron plasma will be generated and heated with a 200 kW gyrotron at 28 GHz with maximum pulse length of 100 ms. A ray tracing code [6] is used to estimate the absorption efficiency and power deposition profile. The optimum location of the ECH antenna was found to be at the box-port because of the minimal refraction of the beam and large access to the plasma. The wave incident on the plasma is assumed to have a Gaussian power distribution where the width and the divergence of the beam are chosen for an open-end-waveguide or a focusing mirror. The Gaussian beam is represented by a set of 61 rays distributed over 5 concentric circles whose centers coincide with the beam axis. The weight of the rays in each circle is proportional to the Gaussian power distribution. The plasma density and temperature profiles are fixed and given by

$$n_e(\rho) = n_{eo}(1 - \rho^4) \text{ and } T_e(r) = T_{eo}\exp(-2\rho^2)$$

where $\rho = r/\langle a \rangle$ and $\langle a \rangle$ is the plasma average radius, and T_{eo} is held constant at 500 eV. Twenty-five flux surfaces are used to evaluate the power deposition profiles. Two possibilities are explored; one uses the extraordinary mode at the second harmonic at 0.5 Tesla, the other uses the ordinary mode at the first harmonic at 1 Tesla.

For the extraordinary wave, it was found that the refraction of the beam is relatively weak up to plasma densities of 4×10^{12} cm^{-3}. A single pass absorption efficiency of 53% and narrow absorbed power profile were obtained without any focusing of the beam. However, with a focusing mirror, the power density into the plasma increases and the deposition profile becomes more peaked, as seen in Figure 2. For the ordinary wave, the refraction of the rays is much stronger and the power absorption profile is broader than in the case of the extraordinary wave. An absorption efficiency of 38% at 6×10^{12} cm^{-3} was obtained without any focusing which increases to about 42% with the focusing mirror. At higher plasma density, refraction is so strong that only a few rays reach the resonance layer even with the focusing mirror. At plasma density of 8×10^{12} cm^{-3}, the absorption efficiency drops to 7%.

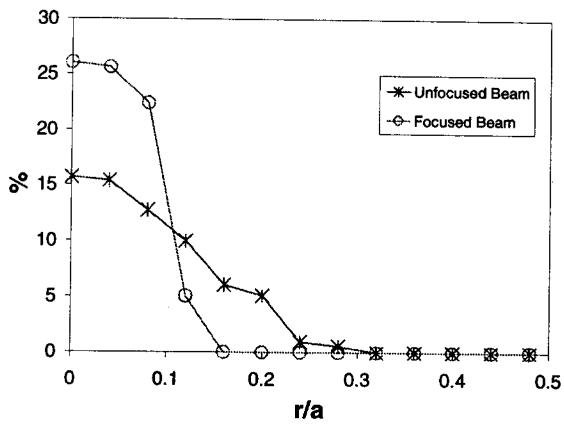

Fig. 2 Absorption power profiles at 0.5 Tesla.

The gyrotron output, which is in the TE_{02} mode, is a circular waveguide 2.5 inch in diameter. For efficient plasma heating, a symmetric, narrow Gaussian beam, is formed using the following mode conversion sequence: TE_{02} to TE_{01} to TE_{11} to HE_{11}. The TE_{02}-to-TE_{01} mode converter is a three cycle quasi-periodic component with a total length of 43 cm and mode purity above 99%. The TE_{01}-to-TE_{11} mode converter is also a three cycle quasi-periodic component with 120 cm in length 97.7% mode purity. The last mode converter follows a 4th order polynomial with 22.3 cm for total length.

7. Summary

HSX is a unique toroidal experiment that combines the positive features of the tokamak and the stellarator concepts. The experimental program[5] is designed to study QHS properties of HSX, such as reduced neoclassical transport. Quasi-helical symmetry can be attained without any tighter fabrication tolerances than what is required for a conventional stellarator. The design and the fabrication of the main components of HSX such as the main coils, auxiliary coils, vacuum vessel, and the support structure are complete. The construction and alignment of the Ring/Main-coil/Auxiliary-Coils modules is in progress. The porting of the vacuum vessel is also in progress.

Acknowledgment

The Torsatron/Stellarator Laboratory would like to thank Stoughton Trailers Inc. of Stoughton, Wisconsin for the generous loan of a welding table on which the main and auxiliary coils were fabricated.

Work Supported by United States DOE under Grant #DE-FG02-93ER54222

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