H-1 DESIGN AND CONSTRUCTION

SYDNEY M. HAMBERGER, BOYD D. BLACKWELL, LESLIE E. SHARP, and D. B. SHENTON
Australian National University, Plasma Research Laboratory
Research School of Physical Sciences, Canberra, 2601 Australia

Received April 10, 1989
Accepted for Publication June 29, 1989

H-1 is a three-field period medium-sized heliac \((R_0 = 1 \text{ m}, r = 0.22 \text{ m}, \text{ and } B_0 = 1 \text{ T})\) nearing completion at the Australian National University, Canberra, and is intended for basic plasma physics studies, including finite beta effects, in toroidal confinement systems. Its design allows a wide range of “current-free” magnetic configurations to be explored for their properties of equilibrium and stability.

INTRODUCTION

The H-1 heliac is intended as a general research facility for basic studies of the behavior of plasma confined in current-free toroidal systems at high rotational transforms \((\epsilon > 1)\), with particular emphasis on effects related to changes in field structure resulting from finite plasma pressure. A wide range of configurations\(^1\) can be produced to introduce both favorable and unfavorable features as required. Operation with both pulsed \((\leq 1 \text{ T})\) and continuous fields \((\leq 0.25 \text{ T})\) is available and good diagnostic access is maintained. The project follows the group’s successful experience with the much smaller\(^2\) \((\text{approximately one-sixth})\) prototype heliac SHEILA (see Table I for comparison) and differs from the medium-sized heliac TJ-II (Ref. 5) planned by CIEMAT in several significant respects, e.g., plasma aspect ratio and number of field periods.

The “coil-in-tank” arrangement adopted offers great configurational flexibility and suits local facilities and resources. The magnetic design was predicated on the desire to maximize plasma cross-section size (mean circularized radius \(\geq 0.2 \text{ m}\)), to minimize \(|B|\) ripple, and to keep the desired high-field operation within the allowable pulsed utility line power \((10 \text{ MV} \cdot \text{A})\). The choice of \(N = 3\), as in SHEILA, allows a wide range of configurations\(^4\) including those with few low-order resonances. In the small-aspect-ratio configurations of most interest, the toroidal curvature remains dominant.

<table>
<thead>
<tr>
<th>Table I</th>
<th>Parameters of Canberra Helia cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHEILA</td>
<td>H-1</td>
</tr>
<tr>
<td>Number of field periods</td>
<td>3</td>
</tr>
<tr>
<td>Number of toroidal coils</td>
<td>24</td>
</tr>
<tr>
<td>Mean radius of toroidal coils (m)</td>
<td>0.065</td>
</tr>
<tr>
<td>Swing radius of toroidal coils (m)</td>
<td>0.025</td>
</tr>
<tr>
<td>Major radius (m)</td>
<td>0.19</td>
</tr>
<tr>
<td>Typical mean minor plasma radius (m)</td>
<td>0.03</td>
</tr>
<tr>
<td>Plasma volume (m(^3))</td>
<td>0.004</td>
</tr>
<tr>
<td>Maximum field (T)</td>
<td>0.4</td>
</tr>
<tr>
<td>Duration (s)</td>
<td>0.04</td>
</tr>
<tr>
<td>Maximum ring current (kA)</td>
<td>28</td>
</tr>
<tr>
<td>Mean radius of control helix (mm)</td>
<td>1.4</td>
</tr>
<tr>
<td>Diameter of vacuum enclosure (m)</td>
<td>0.6</td>
</tr>
<tr>
<td>rf heating power (kW)</td>
<td>0.4</td>
</tr>
</tbody>
</table>

GENERAL DESCRIPTION

The construction and coil arrangement is shown in Fig. 1. The 36 toroidal field (TF) coils have their centers located on the helix

\[
R = R_0 + \rho_s \cos 3\phi, \quad z = \rho_s \sin 3\phi, \quad (\rho_s = 0.22 \text{ m}, R_0 = 1 \text{ m})
\]
Fig. 1. Coils and vacuum vessel (support structure not shown).
and their midplanes vertical, spaced according to the law

$$\phi = \phi' - 0.0097 \sin 3\phi' ,$$

where

$$\phi' = \frac{2\pi}{36} \left( j - \frac{1}{2} \right) , \quad j = 1 \text{ to } 36 .$$

This modulation in azimuthal spacing reduces the $|B|$ ripple significantly and also allows better coil packing (and thus reduced electrical power requirements). 6,7

Each TF coil consists of two five-turn spiral pancakes wound from 29.2-mm square-section copper, with a 6-mm-diam cooling hole, the individual lengths of conductor being radio-frequency (rf) butt-brazed together. Each pair is sealed inside a 1.2-mm-thick welded stainless steel jacket, which provides both vacuum-quality and ground-potential surfaces, and is vacuum encapsulated with Sylgard 170. Individual coil assemblies are held in place by four clamps connected to a structural space frame (Fig. 2). The mounting arrangement allows for small adjustments to accommodate variations in magnetic axes and centers as previously measured for each coil.

The poloidal field (PF) coil is wound in situ, linking the TF coils, and consists of 36 turns (three double pancakes with 12 turns each) of 17.5-mm square conductor with a 9-mm square cooling hole, encapsulated inside a stainless steel jacket in a manner similar to the TF coils. The ring is supported by the space frame in 12 places, with three separate current feeds (one in each helical period).

The helical control (HC) winding consists of four turns of the same conductor as the PF coil, with centers poloidally spaced 12.5 deg apart, and encircles the ring three times in phase with the TF coils. The mean helical pitch angle is 16 deg and the mean helix radius $r_0 = 95.5$ mm. Finite element stress analysis (using both SAP-V and STRAND codes) predicts that conductor movements should not exceed 1.8 mm at maximum field.

Two sets of vertical field (VF) coils are used, both wound from the larger section (TF coil) conductor. The main vertical field is produced by two large-diameter coils, each of 8 turns, located outside the vacuum tank, which approximate a Helmholtz pair. The second, smaller pair with 16 turns each (in two double pancakes) is encapsulated in a manner similar to the TF coils and mounted on the coil support structure. These are required mainly to control the variation of the vertical field $B_v$ with major radius $R$, i.e., the index $\gamma$, where $B_v \propto R^{-\gamma}$. For example, $B_v$ can be made constant (within $\pm1\%$) over the whole plasma volume ($\gamma = 0$) or made to follow the law $\gamma = 1$ to further reduce the $|B|$ ripple.

Special care is taken throughout to minimize field perturbations caused by current feeds, interconnections, etc., for example, by using coaxial arrangements where practicable. Furthermore, effort is made to retain the threefold symmetry wherever possible to minimize the introduction of symmetry-breaking field components.

After assembly and mechanical alignment of all coils on the support frame, the whole coil set will be installed inside the vacuum tank, with its 11-tonne weight transmitted via three tubular pillars through the bottom tank section to the floor.

**POWER SUPPLIES**

Some typical coil power requirements are shown in Table II. The 13.5 kA required for 1-T operation (1-s flattop) is supplied to the series-connected coils by four
six-phase grid-controlled mercury arc rectifiers operating at 865-V dc transformed from the 11-kV, 50-Hz supply. Steady-state operation is limited to 0.25 T by thermal stress in the PF coils. An alternative, extra-low-ripple motor generator supply is also available for steady, lower field operation (≤0.15 T). Invariance of magnetic geometry with field strength is ensured by using series connections as far as possible, with tap changes and shunts used for adjustment of current ratios.

**CONTROL**

The machine control system (which is independent of the plasma diagnostics control and data system) is based on IBM-AT computers with touch-screen monitors. The computers are interfaced through CAMAC by an optoisolated parallel ring system that delivers the latched instruction set between machine sequences to up to 16 remote data handling stations. Each station can handle up to 32 function modules with differing tasks, e.g., analog-to-digital converters, digital-to-analog converters, and input/output optoisolated relays. In addition to controlling the machine parameters (such as magnetic field, timing sequences, and gas injection), the control system monitors all parameters that affect the safety of the machine and personnel (cooling water flows, coolant and equipment temperatures, vacuum integrity, power supply voltage and current, safety interlocks, etc.), and will initiate shutdown procedures in the case of faults or emergencies. A limited function manual override system also exists to allow the machine to work over a restricted operational range independent of the computer.

**TABLE II**

H-1 Heliac Power Supplies

<table>
<thead>
<tr>
<th>Coil Set</th>
<th>Rectifier</th>
<th>Motor Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-T Pulse Mode (MW)</td>
<td>0.25-T Continuous Mode (kW)</td>
</tr>
<tr>
<td>TF coils</td>
<td>3.68</td>
<td>230</td>
</tr>
<tr>
<td>PF coil</td>
<td>3.84</td>
<td>240</td>
</tr>
<tr>
<td>Helical coil</td>
<td>0.43</td>
<td>27</td>
</tr>
<tr>
<td>VF coils</td>
<td>1.41</td>
<td>88</td>
</tr>
<tr>
<td>Total</td>
<td>9.36</td>
<td>585</td>
</tr>
</tbody>
</table>

---

Fig. 3. Fast-wave ICRH antenna showing outer flux surface at φ = 135 deg.
PLASMA HEATING

In the first instance, plasma will be produced and heated by rf power in the ion cyclotron frequency range: Six commercial transmitters, each rated at 30-kW continuous wave in class AB operation in the range from 4 to 26 MHz, will be coupled via a tuning box to antennas located inside the bore of the TF coils. A fast-wave antenna, consisting of two shielded loops shaped to conform to an outer flux surface in a plane of constant $\phi$, is shown in Fig. 3. Antenna designs for launching ion Bernstein and whistler waves are being prepared. The capability exists for applying electron cyclotron resonance heating (ECRH) (at $\omega_{ce}$ or $2\omega_{ce}$) if and when suitable gyrotrons are obtained.

VACUUM SYSTEM

The 32.5-m$^3$ vacuum vessel, ~3.9 m in diameter x 3.4 m high, is fabricated from Type 304 stainless steel. The two large-diameter joints (between the central cylinder and the spherically dished ends) will initially use Viton O-rings but have been prepared to allow for eventual sacrificial welding after machine commissioning is completed. All other vacuum connections apart from the two 0.85-m-diam access ports use standard knife-edge metal seals. The interior surface is polished to a 0.6-µm finish, with care taken to remove all surface inclusions (by hand grinding). Water channels in good thermal contact with the outside walls provide for 150°C bakeout by circulating pressurized hot water. The internal coil jackets can be outgassed in a similar way by passing hot water through the coolant circuit.

The main evacuation is by two Balzers 2200 l/s turbomolecular pumps with smaller turbomolecular pumps for auxiliary purposes. There are 56 ports of various sizes for diagnostic access and for supply feedthroughs. Space exists within the tank to allow the installation of a liquid-helium cryopanel should additional pumping be necessary. All internal components are also polished to a 0.6-µm finish, and any exposed organic material needed for electrical insulation is limited to small quantities of vacuum-grade epoxy.

The actual plasma boundary, nominally determined by the outermost flux surface that is physically unobstructed, can, if required, be defined by a carbon limiter. To provide an effectively continuous toroidal first wall, and to aid differential pumping during plasma formation, the option exists of either closing the spaces between the inner surfaces of the TF coils by thin-wall stainless steel segments or supporting carbon tiles from the coils. (Note that the inner TF coil surfaces themselves subtend almost half the area presented to the plasma column.)

Preliminary tests, with the tank empty, cleaned but unbaked, and with Viton O-rings in place, resulted in a base pressure of $1.2 \times 10^{-8}$ Torr, corresponding to a surface outgassing rate of $\sim 5 \times 10^{-11}$ Torr l s$^{-1}$ cm$^{-2}$.

MAGNETIC CONFIGURATIONS

A wide variety of closed toroidal flux surface configurations can be achieved by varying the proportions of current in the TF, PF, inner and outer VF, and helical field coils. Figures 4 and 5 illustrate some typical flux surfaces, chosen in this case to make the most effective use of the available volume and to avoid most low-order resonances. Figures 6a and 6b show examples of two other configurations, and Figs. 7a and 7b show several rotational transform and magnetic well profiles resulting from varying the ratio $I_h/I_e$, where $I_h$ is the current in the control helix and $I_e$ is the current in the circular ring. The shape of the vertical field affects both the $|B|$ harmonic content and the magnetic well properties; e.g., changing from uniform $B_0(\gamma = 0)$ to one with $\gamma = 1$ reduces the $|B|$ ripple on axis from 10 to 4%, at the same time reversing the sign of the magnetic well.

FIELD ERRORS

An extreme example of the effect of a symmetry-breaking field error on the flux surfaces for a configuration very similar to the one shown in Fig. 5 is illustrated in Fig. 8. The effect of various kinds of error is indicated in Fig. 9, which compares the largest widths of the biggest island produced (in this case $n/m = 7/6$) by various types of error. Such calculations show that, for example, to limit islands in the central 75% of the plasma volume to <5 mm requires that the

Fig. 4. Typical flux surface surrounding ring conductors (coil-to-coil ripple of magnetic field lines smoothed out for clarity). The magnetic field lines are shown in white, and the cross section is at $\phi = 220$ deg.
PHYSICS PROGRAM

The apparatus is expected to be fully assembled early in 1990. Initial studies will concentrate on the integrity and geometry of the flux surfaces (a) by the use of recently developed low-energy electron-beam techniques that have been shown capable of tracing field line trajectories with a resolution of ~0.3 mm, and (b) by Langmuir probe measurements on low-energy and density plasma under steady magnetic field conditions, as performed in SHEILA (Ref. 4) on a much smaller scale.

An experimental program to study the effects of finite beta on both flux surface geometry and topology and on plasma stability will be formulated once sufficient operational experience concerning the heating and confinement performance of H-1 is acquired. However, given that the energy confinement time $\tau_E$ is likely to lie in the range $1 < \tau_E < 10$ ms, and that the maximum available heating power is 200 kW, we would expect to reach values of volume-average beta $\langle \beta \rangle$ between 0.04 and 0.4% at full-field operation (1 T). This would be appropriately higher provided reasonable heating and confinement can be sustained at lower fields, but realistically is unlikely to exceed ~1% with the available heating power. It is felt that further increases in beta would best be achieved with the use of ECRH (at 28 or 56 GHz) if and when suitable sources become available.

---

Fig. 5. Typical set of flux surfaces, $\phi = 0$, showing actual conductors but excluding field errors.

central ring conductor is located to within 0.5 mm of its nominal position, whereas to produce the same consequence, random errors up to 4 mm in the toroidal coil position can be tolerated.

Fig. 6. Examples of other possible magnetic configurations: (a) low-shear case, $I_h/I_e = 0.09$ and (b) high-transform case, $I_h/I_e = 0.3$.  
Fig. 7. (a) Rotational transform and (b) magnetic well profiles, for various current ratios $I_B/I_e$. For $I_B/I_e = 0$, the vertical field is also given in parenthesis.

In contrast, magnetohydrodynamic (MHD) calculations suggest that in well-chosen configurations, flux-surface deformation, axis shift, and pressure-induced island formation are unlikely to become serious until

Fig. 8. Effect of field error due to external dipole field on flux surfaces for a configuration close to that shown in Fig. 5. For clarity, an error field magnitude 100× larger than expected is chosen (54 G on axis).

Fig. 9. Comparison of the effect of various symmetry-breaking field errors.

$\beta(0) > 7\%$. Hence, in order to make experimentally accessible at least some of the important phenomena, such as island formation, normally undesirable features like low-order rational surfaces or magnetic hills will be deliberately introduced. In the same spirit, computations are in progress to identify suitable cases of marginal Mercier stability that can be experimentally studied in the range $0 < \beta < 1\%$.

ACKNOWLEDGMENTS

Significant contributions to the design and construction of H-1 have been made by G. D. Conway, G. C. J. Davies, E. A. Fox, R. Gresham, R. J. Kimlin, Y. F. Li, G. McCluskey, N. Trama, J. Wach, E. K. Wedhorn, C. F. Vance, and
D. F. Zhou. The help of T. K. Chu and A. B. Erhardt of Princeton Plasma Physics Laboratory is gratefully acknowledged. Some of the MHD computations referred to above were performed by R. L. Dewar, B. A. Carreras and colleagues at Oak Ridge National Laboratory, and N. Takeuchi of Tohoku University.

REFERENCES


