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**"Formation and Sustainment of a Very
Low Aspect Ratio Tokamak Using
Coaxial Helicity Injection
(the Helicity Injected [HIT] Experiment)**

ANNUAL PROGRESS REPORT #5

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December 1, 1993 - December 31, 1994

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DOE GRANT #DE-FG06-90ER54095

Formation and Sustainment of a very
Low Aspect Ratio Tokamak using
Coaxial Helicity Injection
(the Helicity Injected Tokamak [HIT]
Experiment)

Progress Report No. 5

UW AERP #45

December 1, 1993 – December 31, 1994

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University of Washington
Seattle, Washington

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1 Introduction and Summary

This is the fifth Progress Report on the Helicity Injected Tokamak (HIT) at the University of Washington, Seattle, DOE Grant #DE-FG06-90ER54095. This report covers the period of December 1, 1993 through December 31, 1994.

1.1 HIT Results

The past year of the HIT project has been very successful: we have sustained toroidal currents reaching 250 kA (highest value yet attained by helicity injection current drive), and sustained at an average of 225 kA for 2 ms at $T_e \simeq 70 - 80$ eV. A schematic layout of HIT is given in Fig. 1, where the 'injector', 'confinement', and 'absorber' regions are defined.

Thomson scattering electron temperature measurements and VUV spectroscopic measurements of the O VI / O V impurity line ratios show we have achieved burnthrough to helium-like oxygen states.

1.2 Theoretical Work

The EFIT equilibrium fitting code has been further modified for the unique HIT geometry. EFIT solves the Grad-Shafranov equation while fitting to measurements. In the last Report, we described that separate parameterizations of the flux surface quantity FF' (where $F = RB_\phi$) are used in each region: the injector region below the poloidal field X-point, and the confinement region above it. In this Report, we describe fitting to $\Sigma B_p \Delta\ell$ rather than I_p , as this is how we actually measure the plasma current. We also present preliminary discussion of utilizing a third parameterization region for FF' (the open flux in the confinement region).

Time evolution MHD simulation studies of HIT using the 2-D MACH2 code are winding down, as poloidal flux amplification requires 3-D relaxation. Work is progressing on a 3-D time evolution code, to properly model relaxation current drive.

1.3 Diagnostics

The Thomson scattering system is operating, and shows electron thermal energies up to 80 eV.

Initial data for a few channels was obtained with the 16-channel radial - single-channel global bolometer system.

An initial design for a quartz-UV ion Doppler broadening T_i diagnostic has been made. All parts have been acquired, and final assembly will be made in summer 1995.

The Transient Internal Probe (TIP) magnetic field diagnostic is undergoing final modifications and tests to allow it to probe HIT in March 1995.

1.4 Machine improvements

1.4.1 Formation Bank Improvements

The formation bank circuit was further improved from the pulse-forming-network, by addition of a series resistor, preventing charging of the formation bank by the sustainment bank. The cable leads from the formation bank to the injector were increased in number and installed in an axisymmetric fashion.

1.4.2 Sustainment Bank Improvements

The capacitance of the sustainment bank has been doubled by bringing an additional "2XII-B Flat Top Module" online. This gives us 20 independently switchable 36 mF units at 950 V. The number of cable leads from the sustainment bank to the injector has been increased allowing an additional 30-50 V to appear at the injector, previously lost in cable resistance.

1.5 Ohmic Heating Coil

We are presently designing modifications to HIT for the addition of an ohmic heating coil. The design target is to maintain the present plasma shape while replacing the thick copper flux conserver with a thin stainless-steel shell and a set of feedback-controlled coils, (acting like a 'power-crowbarred flux conserver'). The ohmic heating coil will provide additional ohmic heating, and allow us to compare transformer current drive confinement with CHI

current drive confinement. Studies of current profile control may also be possible.

1.6 HIT Program Collaborations

The HIT program is fortunate to participate in a collaborative effort with General Atomics (GA) of San Diego, CA, the Himeji Institute of Technology in Japan, the University of Texas–Austin, and the University of Manchester Institute of Science and Technology (UMIST).

1.6.1 General Atomics

Prof. Jarboe has continued his participation with the Advanced Divertor Group at GA. A mini-proposal is presently being written to obtain run time on DIII-D sometime in 1995.

1.6.2 Himeji Institute of Technology

HIT participates in a US DOE–Japan NIFS collaboration with the Himeji Institute of Technology, Hyogo Prefecture, Japan, with Profs. Uyama and Nagata. Prof. Nelson will spend three weeks at the Himeji Institute of Technology in March 1995, working with Prof. Nagata on the Helicity Injected Spherical Tokamak experiment. Prof. Nagata is submitting a proposal for the next “Fusion Year” period, to come to the University of Washington during the summer of 1995, collaborating on fluctuation studies on HIT.

1.6.3 University of Texas–Austin

Prof. Nelson visited UTA in October 1994, giving a seminar on Coaxial Helicity Injection current drive, and participating in discussions of applications to mega-ampere tokamaks. The HIT group is participating in design and proposal writing of current drive/startup scenarios for the ETG low aspect ratio tokamak, proposed by the UTA group, headed by Prof. Wootton and Dr. McCool.

1.6.4 UMIST

Prof. Jarboe continued collaboration with Prof. Rusbridge and Dr. Browning of UMIST on the SPHEX spheromak project, visiting there for two weeks in June 1994.

1.7 Personnel

The HIT experimental group is lead by Prof. Thomas R. Jarboe (Aeronautics and Astronautics—A & A). Prof. Brian A. Nelson (Electrical Engineering) supervises machine operation and administration. Dr. Cheng Zhang (Visiting Scientist from the Institute of Plasma Physics, Academia Sinica, P.O. Box 1126, Hefei 230031, People's Republic of China) who adapted the EFIT code for use on HIT, left our group the end of December 1993. Prof. Uri Shumlak—A & A, (and Research Scientist at Phillips Laboratory) joined our group in September 1994, and is developing the MACH3 code for use on HIT, (partially supported by an Air Force grant).

Research Engineer Daniel E. Lotz is responsible for much of the mechanical design of the HIT ohmic heating feedback circuitry, the toroidal field coil power supply, and is the building experimental safety coordinator. Engineering Technician John A. Rogers oversees operation, the sustainment bank power supply, and the vacuum and interlock systems. Patrick Miller, Associate Director of the UW Nuclear Reactor (90 % time on HIT) is redesigning the toroidal field coil for addition of the ohmic heating transformer, and oversees radiation monitoring on HIT. Instrument Maker Dennis Peterson oversees design and machining of the experimental components.

Adam K. Martin (Physics) uses internal magnetic field probes to determine the internal field and injector region structure of the Proto-HIT and HIT configurations, and is developing extensions to EFIT. David J. Orvis (Nuc. Engr., DOE Fusion Fellowship) has constructed and installed surface magnetic field probes in the copper flux conservers of HIT, and is performing stability studies using GA and PPPL codes. LiYong Zhou (Nuc. Engr.) operates the Thomson scattering diagnostic and is performing confinement time studies. JianPing Xie (Nuc. Engr.) operates the FIR polarimeter/interferometer and is performing particle inventory studies. Leslie McCullough (A & A) designed and operated the dual VUV spectrometer system on HIT, leaving the group in spring 1994 with a master's degree.

Ogden Jones and Bogdan Udrea (A & A) are running and developing the resistive MHD time-dependent HIT simulation codes (supported by an Air Force Grant).

Several undergraduate students also participated in the HIT experiment. Noah Bettin and Jeff Friesen (Physics) designed and built the bolometry diagnostic, extending previous work by G. Allen Miller (now a graduate student at the University of California-San Diego). Valérie Coquelin of École Polytechnique Féminine, Seaux, France, worked as an exchange student for six weeks, developing neural network analysis software for the bolometry array. Thomas Clymer, (Mech. Engr. Michigan State University) worked on assembling the quartz UV ion Doppler broadening diagnostic.

1.8 Conferences and Publications

HIT results have been presented at the IEEE ICOPS, the IAEA RUST, and the APS DPP meetings.

- Conferences:

- IEEE International Conference on Plasma Science, Santa Fe NM (BAN 6-10 Jun 1994)
- IAEA conference, Seville Spain (TRJ Sep 1994)
- APS-DPP meeting, Minneapolis MN (AKM, BAN, DJO, JX, and LZ 7-11 Nov 1994)
- TOKI conference, Toki City Japan (BAN 29 Nov-2 Dec 1994)

- Seminars:

- University of Manchester Institute of Science and Technology (TRJ Jun 1994)
- Culham Laboratory (TRJ Jun 1994)
- General Atomics (TRJ)

- Lawrence Livermore National Laboratory
(TRJ)
- University of California–Berkeley
(TRJ)
- Massachusetts Institute of Technology
(BAN 29 Sep 1994)
- University of Wisconsin–Madison
(BAN 3 Oct 1994)
- University of Texas–Austin
(BAN 4 Oct 1994)
- Invited Talks:
 - IAEA conference, Seville Spain (TRJ)
 - APS-DPP meeting, Minneapolis MN (BAN)
- Workshops:
 - Spherical Tokamak Workshop, Oak Ridge TN
(TRJ and BAN 18–21 July 1994)

1.8.1 Publications

- Published:

Thomas R. Jarboe. Review of Spheromak Research. Review Article, *Plasma Physics and Controlled Fusion*, 36:945–990, 1994.

B. A. Nelson, T. R. Jarboe, D. J. Orvis, L. A. McCullough, J. Xie, C. Zhang, and L. Zhou. Formation and sustainment of a 150 kA tokamak by coaxial helicity injection. *Physical Review Letters*, 72(23):3666–3669, June 1994.

B. A. Nelson, T. R. Jarboe, A. K. Martin, and C. L. Painter. Tokamak formation and sustainment by coaxial helicity injection current drive. *Nuclear Fusion*, 34(8):1111–1119.

- Accepted:

B. A. Nelson, T. R. Jarboe, D. J. Orvis, A. K. Martin, J. Xie, C. Zhang, and L. Zhou. Low Aspect Ratio Tokamak Formation and Sustainment by Coaxial Helicity Injection Current Drive. (Accepted by *Fusion Technology*, Special 6th International TOKI Conference Issue, April 1995.)

- Submitted:

B. A. Nelson, T. R. Jarboe, A. K. Martin, and C. L. Painter. Coaxial helicity injection formation and sustainment of a tokamak. (Submitted to *Physics of Plasmas*, Special APS-DPP Invited Talks Issue, May 1995)

D. J. Orvis and T. R. Jarboe. Calibration of magnetic probes mounted in a copper wall. (Submitted to *Review of Scientific Instruments*)

- In preparation:

C. Zhang, A. K. Martin, T. R. Jarboe, and B. A. Nelson. Equilibrium Studies on the Helicity Injected Tokamak.

Figure 1: A schematic layout (top view) of HIT is given, where the 'injector', 'confinement', and 'absorber' regions are defined. The tokamak is formed and sustained between the inner and outer conductor. The outer conductor is made from two half shells bolted together at the midplane but hold apart 5 cm by copper bushings called bridges. The openings between the bridges allow diagnostic access. Bridge rogowskis measure the (poloidal) current through the bridges.

Figures 4-(b) & (c) show the VUV impurity line measurements of O V and O VI, and each is normalized to the square of the average electron density in Figs. 4-(d) & (e). The ratio of O VI to O V is shown in Fig. 4-(f).

An $n = 1$, rotating distortion is still seen on these discharges, similar to those previously mentioned[1] for $I_p > 140$ kA, but now is seen at plasma currents down to 110 kA. The frequency of these distortions varies from 30 - 70 kHz, and can either increase, decrease, or remain fixed during the discharge. These $n = 1$ distortions are seen on the outer conductor surface probes in the bad curvature region, and not on those on the central column. Peak-to-peak fluctuations in the poloidal field are up to $\tilde{B}_{pp} \simeq 20$ mT out of $B_p \simeq 0.2$ T, and are largest near the midplane. Analysis of the cross-power phase spectra shows the distortion approximately follows the fieldline pitch.

2.2 Equilibrium Reconstruction

The equilibrium fitting code EFIT[2] is used to reconstruct the equilibria for discharge 6737 (similar to that shown in Fig. 3, but with $T_e = 77$ eV and $\langle I_p \rangle = 210$ kA for 1.75 ms).

Equilibria are calculated with $P' = 0$ and with separate parameterizations of FF' in the confinement ($FF' = \gamma_0 + \gamma_1 y + \gamma_2 y^2$) and injector ($FF' = \beta_0$) regions, where $F = RB_\theta$, $y = (\psi - \psi_m) / (\psi_{up} - \psi_m)$, ψ_m is the value at the magnetic axis, ψ_{up} is the value at the absorber insulator, and γ_0 , γ_1 , and β_0 are constants.[3] Equilibria iterations are interleaved with linear fitting to I_p , $I_{inj} - I_w$, $\Delta\Phi_T$, 15 poloidal surface probes, and 21 poloidal flux loops. The measured and fit values have average errors 1.53 %, 5.86 %, 3.57 %, 6.52 %, and 1.13 %, respectively. (EFIT in its present form does not properly calculate the wall current I_w , which only adds a slight toroidal field to the vacuum value, $\delta B_T / B_T \sim 1$ %. To improve the fit, EFIT is presently being modified to account for this.)

2.3 Preliminary Energy Confinement Time Studies

No radial Thomson scattering scans have been performed yet, and only limited time scans have been performed. However, we can deduce some preliminary estimates of energy confinement time, valid in the context of the assumptions required for the limited data set.

The energy confinement time of up to 0.572 ms is estimated assuming flat current profiles using the formula

$$\tau_E^{\text{global}} = \frac{3 \langle n_e \rangle k_B T_e(0)}{\eta (I_p / \text{Area})^2} \quad (1)$$

where η is the Spitzer resistivity at the center using the measured T_e from Thomson scattering. This method estimates power to the closed flux region to be approximately 5.3 % of the total input power (see the table below). The density is from the interferometry measured line-averaged density. Because the interferometry could not give correct density data at the time when the temperature is measured, only the high-temperature discharge of Fig. 3 can be analyzed thoroughly and is tabulated in Table 2. Also in the table τ_E^{Alcator} , $\tau_E^{\text{Neo-Alcator}}$, and $\tau_E^{\text{AUX Kaye-Goldston}}$ (scaling using P_{inj} as auxiliary heating) is calculated for comparison.

2.4 Discussion

2.4.1 Burn-through of Oxygen

The VUV spectroscopy data and $T_e \sim 70$ eV, Fig. 4, suggest HIT is burning through oxygen. Figures 4-(b) & (c) show O V radiation (normalized to $\langle n_e \rangle^2$) dropping to a very low value then O VI dropping to a flat level. When the plasma current drops at $t = 6.5$ ms, O VI increases, followed by O V, suggesting a cascade through ionization states. (Bolometric measurements are incomplete as the time of this writing.)

2.4.2 Initial Confinement Time Results

Without detailed profile data, only preliminary estimates of energy confinement time can be given. We're using ohmic power as the only input heat source, and we're not subtracting radiative losses from the input power in the confinement time estimate. We're just entering the non-radiation dominated regime, and subtracting radiation could make a large increase in the confinement time. Relaxation power goes mainly to ions, and CHI driven spheromaks can see higher ion than electron temperatures.[4] However, with a close fitting solid flux conserver the temperatures were seen to be nearly equal. We need the ion Doppler broadening measurement for T_i .

EFIT suggests that half the injector flux (ψ_{inj}) and 20 % of the injector current (I_{inj}) forms the open flux region around the tokamak. This leaves the majority of the power dissipation (80 %) and half the helicity dissipation in the injector. This is to be compared with the estimate of 5.3 % of the total power being ohmically dissipated in the closed flux region.

These assumptions make τ_E^{global} an order of magnitude estimate until we measure the electron temperature profile and the ion temperature; estimate the relaxation power; measure the radiated power distribution; and determine the flow of the injector power into the injector, open flux, and closed flux regions.

Parameter	Value		
<u>Device</u>			
Major radius	R	0.3	m
Minor radius	a	0.2	m
Aspect ratio	A	1.5	
Magnetic field	B_0	0.5	T
Toroidal flux	Φ_T	110	mWb
Injector flux	ψ_{inj}	4.9	mWb
<u>Measured Parameters</u>			
Toroidal current	I_p	222	kA
Injector current	I_{inj}	19.1	kA
Injector voltage	V_{inj}	700	V
Average density	$\langle n_e \rangle$	6×10^{19}	m^{-3}
Paramagnetism	$\Delta\Phi_T$	3.32	mWb
Electron temperature	T_e	77	eV
<u>Calculated Parameters</u>			
Energy confinement time (Assuming $Z_{eff} = 2$)	τ_E	0.572	ms
<u>EFIT Reconstruction</u>			
Closed field current		171	kA
Open poloidal flux		3.19	mWb
Open field I_{pol}		5.4	kA
Closed poloidal flux		15.7	mWb
Helicity	K	0.0027	Wb ²
Axis safety factor	q_0	6.76	
Edge safety factor	q_{95}	9.37	
Cylindrical q	q_{cyl}	3.6	
Elongation	κ	1.85	
Major radius	R	0.32	m
Minor radius	a	0.19	m
Aspect ratio	A	1.68	
Upper triangularity	δ_{up}	0.62	
Lower triangularity	δ_{low}	0.91	
Internal inductance	ℓ_i	0.284	
Plasma volume	V	0.38	m ³

Table 1: HIT operating parameters and equilibrium reconstruction.

Parameter		Value
I_p	kA	243
I_{inj}	kA	26.9
V_{inj}	V	766
P_{inj}	MW	20.6
n_e	(10^{19} m^{-3})	5.18
$k_B T_e(0)$	eV	62.6
W	kJ	0.623
V_{eff}	V	34.2
V_{loop}	V	5.63
P_{Ohmic}/P_{inj}	%	5.3
τ_E^{global}	ms	0.572
$\tau_E^{AUX \text{ Kaye-Goldston}}$	ms	0.679
$\tau_E^{Neo-Alcator}$	ms	1.65
$\tau_E^{Alcator}$	ms	8.39

Table 2: Preliminary estimates of energy confinement time for discharge 6812, assuming $Z_{eff} = 2.0$, $q_{cyl} = 3.6$, and $\ln \Lambda = 13.7$.

Figure 2: Time waveforms for a longer-time lower-current discharge: (a) plasma current I_p , (b) injector current I_{inj} , (c) injector voltage V_{inj} , (d) average electron density along the chord $R = 0.37 \text{ m}$ $\langle n_e \rangle$, and (e) ratio of O VI to O V line radiation.

Figure 3: Time waveforms for a shorter-time higher-current discharge: (a) plasma current I_p , (b) injector current I_{inj} , (c) injector voltage V_{inj} , (d) average electron density along the chord $R = 0.37 \text{ m}$ $\langle n_e \rangle$, and (e) current drive power efficiency ϵ .

Figure 4: Time waveforms for discharge in Fig. 3: (a) plasma current I_p , (b) O V line radiation (137.2 nm), (c) O VI line radiation (103.4 nm), (d) O V line radiation normalized to $\langle n_e \rangle^2$, (e) O VI line radiation normalized to $\langle n_e \rangle^2$, and (f) ratio of O VI to O V line radiation.

Figure 5: EFIT reconstruction results for a higher-current ($I_p = 221.8$ kA) higher-temperature ($T_e = 77$ eV) discharge at $t = 4.2$ ms: (a) flux surface contours (dotted lines are $\psi < 0$), (b) q vs. major radius R , (c) J_T vs. major radius R , and (d) $\lambda = \mu_0 J_T / B_T$ vs. major radius R .

3 Theory

Theory support of HIT has focused on three areas: equilibrium reconstruction of experimental data, stability analysis of CHI driven equilibria, and time evolution simulations using non-ideal MHD.

3.1 Further Modifications to EFIT

EFIT is an equilibrium solver developed at GA Technologies.[2] EFIT interleaves Grad-Shafranov iterations with a Singular Value Decomposition fitting procedure, to find the equilibrium solution which best fits the data. FF' and P' are modeled as polynomials in ψ . EFIT has calculated equilibria for recent shots with plasma currents of up to 225 kA, and closed fluxes of approximately 15 mWb, for an injector flux of 3 mWb and injector current of 25 kA.

Crucial to capturing the behavior of the HIT experiment is the correct treatment of the helicity injector, which has a different λ than that of the tokamak. This has been accomplished (described in a previous progress report) by separating the grid into two regions - the injector and the confinement region - and using a different function for FF' in each one. The version of EFIT used on the HIT experiment fits to 16 surface magnetic field probes, 20 flux loops, as well as plasma current, I_p , injector current, I_{inj} , and excluded flux, $\Delta\Phi_T$.

For recent discharges with plasma currents in excess of 200 kA, EFIT has had difficulty in fitting to I_p , and I_{inj} . Calculated I_p has been about 4% too low; calculated I_{inj} about 40% too low. This may be due to one or a combination of three causes: the method used by EFIT to fit to I_p , the inability of only one poloidal current function, FF' , to describe both the plasma edge and interior, and the need to model the poloidal current to the wall.

Plasma current: The measurement of I_p on HIT is made with a discrete rogowski loop composed of the surface magnetic field probes. The fitting routine in EFIT has been modified to compare this measured I_p with an analogous quantity calculated from the equilibrium magnetic fields. This has resulted in a 2% improvement in the fitted I_p .

Poloidal Current Function, FF' : There is no reason to expect that FF' , the poloidal current function, should be the same for the open field-line region as for the closed field-line region, given their different magnetic topologies. While a different function was used for the injector region than for the closed-flux region, this was not the case for the open field-lines outside of the injector, defined by $\psi < \psi_{\text{sep}}$. EFIT is now being modified to allow FF' to be defined differently in these three regions: Closed flux region, injector, and the edge region.

Wall Current: On recent shots, as much as 7 kA of poloidal current flows to the wall; this is a significant fraction of the 25 kA injector current. EFIT will be modified to fit to this wall current.

3.2 Stability Studies

To study the $n = 1$ mode observed in discharges, ideal MHD stability calculations are performed on equilibria similar to the HIT plasma. The principal stability code, PEST 2, is executed on the National Energy Research Supercomputer Center (NERSC) at Lawrence-Livermore National Laboratories.[5] Charles Kessel from Princeton Plasma Physics Laboratories provides assistance in running the code.

For input, the PEST 2 stability code uses the output of the J-Solver fixed boundary equilibrium code.[6] To better simulate the HIT plasma, J-solver was modified to use a more D-shaped outer boundary (see Fig. 6). For typical J-Solver runs, the pressure is set low enough to be considered zero and the total current and the current profile are varied.

Initial PEST 2 results have indicated the presence of unstable $n = 1$ modes in plasmas without conducting boundaries. In Fig. 7, the perpendicular component of the eigenmode is plotted against flux for each poloidal mode number. PEST 2 predicts the magnitude of the unstable mode is largest near the plasma edge. The unstable mode also has a strong $m = 11$ mode structure, which approximates the edge q of 10.4 measured from surface magnetic probes. For this particular run, the equilibrium had $\mathbf{J} \cdot \mathbf{B} / B_\phi$ constant across the flux surfaces and a total toroidal plasma current of 200 kA.

In the future, PEST 2 will be used to map out regions of stability for different currents and current profiles. Also, other stability codes will be used to examine the growth rate of the $n = 1$ mode. A collaboration has

been established with Alan Turnbull at General Atomics to use the GATO stability code.[7] The PEST 1 stability code may also be used.

3.3 Computational Support for HIT

Computational support for the HIT project has been progressing on several fronts in time-dependent two- and three-dimensional modeling. Two-dimensional calculations using the MACH2 code have been performed.[8] We have improved the flexibility in the grid generator in MACH2 to better fit the HIT geometry. Due to the large grids required, three-dimensional simulations of HIT using MACH3 have met with limited success. However, there are efforts to alleviate this problem. MACH3 is currently being modified to run on massively parallel architectures. Another effort is underway to write an implicit algorithm for MACH3 that will allow computational time steps of arbitrary size.

3.3.1 MACH2 Simulations

The MACH2 code uses a block-structured grid which allows for the modeling of complex geometries. However, the grid is restricted to those composed of simply-connected blocks. Simply-connected means that all internal block intersections must contain four vertices. This restriction results in poorly constructed grids when fitting to a toroidal geometry such as HIT. Figure 8 is a plot of the simply-connected blocks that were used to model the HIT geometry. Note that the outer block has two vertices which have an angle of 180 degrees. (These vertices are located by the arrows in the figure.) The grid is greatly distorted around these points which leads to numerical inaccuracies.

We have modified the MACH2 code to allow for block-structured grids that are not simply-connected. This modification has allowed us to better model the HIT experiment. Figure 9 shows the new non-simply-connected grid for the HIT geometry. The new grid is also able to handle the inside corners where the gun and absorber are attached. This can be seen by comparing Figs. 8 and 9.

With these improvements, we have been able to closely match the experimentally measured values of gun voltage and current during the initial

phase of the experiment. Since the relaxation process is inherently three-dimensional, MACH2 does not accurately model it.

3.3.2 Parallelization of MACH3

The supercomputer community has come to the realization that building bigger and faster computers is quickly reaching its limit. The new supercomputers are composed of many processors that individually are much smaller than a supercomputer, but together can perform computational operations in parallel with a much faster net speed. However, this parallel processing requires rethinking how serial codes are written so that naturally occurring parallelisms in the data can be taken exploited and parceled out to the different processors.

MACH3 uses a block-structured grid that is similar to the one used by MACH2. This grid suggests an approach for parallelizing. Since the grid is already divided into blocks, the individual blocks can be parceled to the individual processors. The processors perform the computations just on their small piece of the domain and then sends pertinent information to the processors that contain the neighboring domains. This effort is well underway.

3.3.3 Implicit MHD Computations

We have been developing an implicit algorithm to solve the MHD equations. This advanced algorithm was described in depth in the previous progress report.[9]

To date we have a working version of the algorithm for two-dimensional ideal MHD. Current efforts include the addition of resistivity. Next will be the extension to three-dimensions and the installation into MACH3.

Standard Geometry

HIT Geometry

Figure 6: The outer boundary used by J-Solver (left) was modified for the HIT geometry (right).

Figure 7: The perpendicular component of the eigenmode is plotted against flux for each poloidal mode number. PEST 2 predicts the magnitude of the unstable mode is largest near the plasma edge.

Figure 8: Blocks that compose the HIT geometry using the previous version of MACH2. The arrows point to the vertices of the outer block.

Figure 9: Blocks that compose the HIT geometry using the modified version of MACH2.

4 Diagnostic Systems

All main diagnostics are operating; magnetic diagnostics, VUV spectroscopy, FIR interferometry, and Thomson scattering. Multi-chord bolometry is being re-designed.

4.1 Thomson Scattering

A single-pulse single-point Thomson scattering system has been implemented to measure plasma temperature and density. Through a relatively small entrance port, the system scans seven radial positions in the midplane of the HIT tokamak to obtain temperature and density radial profiles on shot-by-shot basis. The system uses a ruby laser, a triple-grating spectrometer, seven photomultiplier tube detectors, and charge sensitive 10-bit A/D converters to record data, later stored in the HIT main database. Some outputs of the seven photomultiplier tubes are monitored by oscilloscopes to ensure data integrity.

4.2 Density Study using FIR Interferometry and Polarimetry

A heterodyne rotating grating FIR interferometry system, capable of multi-chord shot-to-shot scanning, is successfully operating on HIT. The polarizing beam splitters, which are 500 lpi gold coated mylar, do have membrane-like vibrations. This problem has been eliminated by putting the beam splitter over a plastic flat. However, the time resolution of this FIR system is limited by its 100 kHz heterodyne frequency and the narrow bandwidth (10 kHz) of the tuned amplifier. The maximum time resolution of the system is about $2 \times 10^{17} \text{ m}^{-3} / \mu\text{s}$. Besides, the refractive-bending effects can also cause problems when the plasma density is higher than 10^{20} m^{-3} . To measure high density plasmas, a higher heterodyne frequency system with a shorter wavelength laser is desired.

In HIT, since the laser beam is tangent to the known magnetic field direction (*i.e.*, toroidal direction), the magnetic field weighted line-averaged density can be obtained by using polarimetry to measure the Faraday rotation angle. Due to imperfections of the heterodyne rotating grating, there is a periodic phase and amplitude distortion on the heterodyne signal, known as

ghost effects. This periodic distortions can be corrected by subtracting the reference signals, which are recorded precisely one wheel revolution before the plasma discharge. However, because of the non-reproducibility of the rotating grating's behavior from one wheel revolution to another, there is some random noise which can not be eliminated in this FIR system. In order to make density polarimetry work, the present rotating grating should be replaced.

4.3 Bolometry Diagnostic

The bolometry diagnostic described in the previous Report has been re-designed to relieve serious constraints in access space. The midplane optical access gap is 5 cm wide, and the 16 channel arrays are about 4 cm long, making an axial array difficult to install.

4.3.1 The Photodiode Array

The arrays are Absolute XUV Silicon Photodiodes (Model# AXUV-16EL, Ceramic Package), made by International Radiation Detectors. An array consists of 16 photodiodes, each with an effective surface area of 2 mm by 5 mm. The AXUV-16EL was chosen to be used on the HIT experiment because of its small size (2 cm×5 cm), its rise time of 5 ns (with 50 V biasing), and also its insensitivity to magnetic disturbances and surface contaminations.

The 16 photodiode array will measure the HIT radial radiation intensity. Efforts are being made to have impact parameters of this array ranging from 11 to 50 cm, Fig. 10. This range will allow for a complete radial scan of the confinement region.

A single channel XUV diode will be used to measure the total radiated power. It is positioned to view approximately 30 % of the plasma volume.

4.3.2 The Component Housing and Connection to HIT

The housing for the photodiode array and filter palette is a welded stainless steel box. The face of the box exposed to the plasma is tungsten coated. The base of the box is electrically isolated from the outer-shell of the HIT to prevent any ground-loops. Two holes are machined in the box bottom to allow for electrical feed-through and for the rotatable shaft of the palette.

The housing unit is held in the HIT machine by a hollow stainless steel shaft connected to a bellows assembly, Fig. 11.

4.3.3 Electrical Connection and Data Retrieval

To avoid any ground-loops the photodiode arrays are isolated by Macor blocks. Each block has holes for the photodiode leads. These leads then pass through a hollow alumina shaft to isolate them from the bellows. The leads connect to a high-vacuum electrical feed through, which then connects to a preamp current-to-voltage converter array. Each preamp lead will feed an analog-to-digital converter, a total of 17 channels.

4.3.4 Data Analysis

Assuming axisymmetry, the spatial dependence of the radial array can be transformed to a radial profile by Abel inversion.

We've also developed neural network analysis of the data. Training sets have been generated and passed through a multi-layer perceptron, using a back-propagation error minimization. Software is in place to take the raw data from the 16-channel radial array and unfold radiated power as a function of major radius.

4.4 Ion Doppler Broadening

Preliminary design work has been performed on an ion doppler broadening diagnostic. This diagnostic consists of a 0.5 m visible monochromator with a dual cylindrical lens dispersion section that images onto a multi-channel analyzer. This system should be capable of resolving down to 90 eV using quartz-UV oxygen and carbon lines.

All components have been assembled through surplus equipment from other UW experiments. Finally assembly, installation, and measurements should be completed by summer of 1995.

4.5 Transient Internal Probe

Internal magnetic field measurements using the Transient Internal Probe (TIP) are scheduled to begin in March 1995. This diagnostic will shoot

a magneto-optic probe through the plasma at speeds in excess of 2 km/s minimizing probe exposure to the plasma to less than 500 μ s, well below the time required for significant ablation to begin. Measurement of the local field is achieved by illuminating the probe with an argon laser and measuring the amount of Faraday rotation in the light reflected back from the probe.

Development of the diagnostic is essentially complete. The gun is built, consistently accelerating a 2.3 g projectile to 2.1 km/s. A gas interface system between the gun and plasma chamber is in place and tested, limiting introduction of helium muzzle gas into the plasma chamber to less than 0.5 Torr- ℓ . The optical detection system is also complete. It was evaluated to have 0.3 degree resolution in the polarization angle and a 10 MHz frequency response.

The concept has been tested by firing the probe through a static magnetic field inside a vacuum chamber. The field resolution was 40 gauss with a spatial resolution of 1 cm. Improvements in the probe material should allow measurements of 20 gauss resolution in the future. Currently final testing of the diagnostic is in progress in order to develop procedures and timing sequences for operation on HIT.

Figure 10: Viewing chords of bolometry system.

Figure 11: Close-up view of bolometer housing.

5 Machine Improvements

5.1 Improved Formation Bank

The formation bank was further modified from the pulse-forming-network described in the previous progress report. A $0.0625\ \Omega$ resistor was installed in series with the formation bank, making it an overdamped circuit. Though it requires a higher charging voltage, this prevents the sustainment bank from discharging into the formation bank, preventing the dip in plasma current which was reported in the previous progress report.

The cables leading from the formation bank to the injector collector plate used to be eight in number, all along a 120° arc. A junction header is installed and the eight cables now lead to the injector collector plate, connected in an azimuthally symmetric fashion. This also allows a Rogowski loop to measure the formation bank current at the header.

5.2 Improved Sustainment Bank

An additional 2XIIB flat top module has been made operational. This brings the total number of capacitor bank 'rows' to $20 \times 0.036\ \text{F}$ at 950 V. This is the maximum number of sustainment bank rows we plan to use on HIT for the near future.

The four RG-17/U cables that led from the sustainment bank to the injector collector plate, bunched along a 60° arc, have been replaced with eight low-resistance cables, now attached in an azimuthally symmetric fashion. The two flat-top modules are then connected by a copper buss bar. This reduction in resistance allows up to an additional 50 V to be applied to the collector plate. Every additional increment in applied voltage above the arc drop voltage has been seen to improve HIT performance.

References

- [1] B. A. Nelson, T. R. Jarboe, D. J. Orvis, L. McCullough, J. Xie, C. Zhang, and L. Zhou. Formation and sustainment of a 150 kA tokamak by coaxial helicity injection. *Physical Review Letters*, 72(23):3666-3669, June 1994.
- [2] L. L. Lao, H. St. John, R. D. Stambaugh, A. G. Kellman, and W. Pfeiffer. Reconstruction of current profile parameters and plasma shapes in tokamaks. *Nuclear Fusion*, 25(11):1611-1622, November 1985.
- [3] C. Zhang, T. R. Jarboe, and B. A. Nelson. Equilibrium studies on the helicity injected tokamak. *Bulletin of the American Physical Society*, 38(10):2010, November 1993.
- [4] J. C. Fernandez, Cris W. Barnes, T. R. Jarboe, I. Henins, H. W. Hoida, P. Klingner, S. O. Knox, G. J. Marklin, and B. L. Wright. Energy confinement studies in spheromaks with mesh flux conservers. *Nuclear Fusion*, 28(9):1555, August 1988.
- [5] C Grimm, R. L. Dewar, and J. Manickam. Ideal MHD stability calculations in axisymmetric toroidal coordinate systems. *Journal of Computational Physics*, 49:94-117, 1983.
- [6] J. DeLucia, S. C. Jardin, and A. M. M. Todd. An iterative metric method for solving the inverse tokamak equilibrium problem. *Journal of Computational Physics*, 37:183-204, 1980.
- [7] L. C. Bernard, F. J. Helton, and R. W. Moore. Gato: An MHD stability code for axisymmetric plasmas with internal separatrices. *Computer Physics Communications*, 24:377-380, 1981.
- [8] M. H. Frese. Mission Research Corporation Report AMRC-R-874, 1987. National Technical Information Service Document No. ADA 192285.
- [9] T. R. Jarboe, B. A. Nelson, and the HIT Group. Formation and sustainment of a very low aspect ratio tokamak using coaxial helicity injection (the helicity injected tokamak experiment). University of Washington Aerospace & Energetics Research Program Report UWAERP/41, University of Washington, Seattle, WA 98195, January 1994. Progress Report

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