TOKAPOLE MONITOR SYSTEM

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Introduction

For many years a Radio Shack Model I, Level II, 16 K TRS-80 with a Connecticut Microcomputer Model AIM16, 8 bit, 16 channel, 100 µsec A-to-D converter has been used to monitor standard machine and discharge parameters on Tokapole II. The system has slowly evolved over the years, but has remained relatively unchanged for the past year. It is appropriate, therefore, to document the system in its present form for those who need to understand how it works. The documentation here applies to the 26 Jan 83 version of the software and is subject to change if improvements are made. A compiled version of the program is also available, dated 28 Jan 83, and differs only in minor details such as timing loops. It runs at about five times the speed of the BASIC version.

Loading Instructions (BASIC version)

1) Make sure the computer and video display are ON. The computer is turned on by a push-button on the rear of the keyboard next to the three plugs that attach to the cassette and video display. The computer is ON when the red LED on the keyboard is illuminated. The computer powers up with the question MEM SIZE?_. You can cause the computer to initialize itself and ask the MEM SIZE question from BASIC by typing:

SYSTEM <ENTER>

/ ø  <ENTER>

(<ENTER> means press the white ENTER key.) The MEM SIZE question allows you to reserve memory for use of machine language programs. Although the TOKAPOLE MONITOR program requires 767 bytes of reserved memory
MEM SIZE = 32000), this is done automatically by the program, and therefore one need only press <ENTER> in response to this question. The computer should respond with

READY

> to indicate that it will now accept BASIC commands.

2) Place the cassette tape labeled TOKAPELE MONITOR in the recorder and rewind. Press the PLAY button on the recorder and type CLOAD <ENTER>. Within about 5 seconds a pair of flashing asterisks will appear in the upper right corner of the screen indicating that the program is loading. If the asterisks fail to appear or do not blink, the volume is probably set wrong on the recorder, or the plugs are not inserted, or the tape is defective. A backup version of the program is located a little further along (counter setting 050) on the same tape. When loading is complete (after about 1-1/2 minutes), the recorder will stop. Rewind the tape and put it away. It is no longer needed. Type RUN <ENTER> to cause the program to run. It will identify itself and request a baseline shot (a machine shot without plasma). Before it runs, it performs a memory check to see if the correct number of bytes was loaded and gives an error message, MEMORY CHECK ERROR ON LOAD, if it detects a problem. If this happens, start over. A BASIC listing of the program is included in Appendix A.

Loading Instructions (Compiled version)

1) Make sure the computer and video display are ON and enter BASIC as described in 1) above.

2) Place the cassette tape labeled TOKMON in the recorder and rewind. Press the PLAY button on the recorder and type
SYSTEM <ENTER>

TOKMON <ENTER>

The asterisks in the upper right corner will flash, but more slowly than with the BASIC version. When the tape stops (after about 3-1/3 minutes), rewind and put it away. Then type

/ <ENTER>

RUN <ENTER>

The program will identify itself and run as before, except at five times the speed.

3) If you interrupt the program by pressing the <BREAK> key, you normally cannot continue by typing CONT <ENTER> as with a BASIC program. You will have to type RUN <ENTER>, and all previous data will be lost. You can LIST the program, but you won't see anything very interesting. You cannot EDIT or add anything to the program. Attempting to do so will likely necessitate reloading the program from scratch.

Running the Program

The program is intended to run unattended. The default option is for the program to display plasma current ($I_p$), ion saturation current density ($J_{SAT}$), toroidal field ($B_T$), poloidal gap voltage ($V_{PG}$), hoop current ($I_H$), and the time derivative of the plasma current ($dI_p/dt$) for the first 10 msec after the poloidal field is fired. It does this immediately after the shot and then rears itself and waits for the next shot as indicated by a single illuminated pixel in the upper right corner of the video display. When it receives a trigger, a second adjacent pixel will illuminate. Other command sequences can be programmed by pressing the P key. Most of these are obvious or can be learned by trial and error. A command sequence is a series of letters and numbers indicating the sequence in which the various
commands are performed. A single digit between 1 and 9 will cause a delay of the corresponding number of seconds. For example, the command sequence 515J5L5A <ENTER> will cause the default data table, the plasma current graph, the ion saturation current graph, the amp-seconds for the previous shots, and the table of additional derived data to be displayed in sequence with a five second delay between each. For longer delays one can use, for example, 999 which will cause a 27 second delay.

Otherwise, the only attention the program requires is to take a new baseline when requested. The program determines this by comparing the measured plasma current at 20 msec (which it assumes should be zero) with the baseline signal. If the difference exceeds 9 kA, all successive shots will request a baseline, and the data should be interpreted with caution until a new baseline is taken. When the measured plasma current at 20 msec is not zero, the computer assumes that the error is due to a change in hoop temperature and adjusts the displayed currents accordingly, so that the current indicated by the computer will always read within 1 kA of zero at 20 msec. The computer recognizes a baseline if the sum of the ion saturation current density at 2.5, 5.0, and 7.5 msec is less than 50 mA/cm². During a run, the plasma current baseline will slowly drift downward as the hoops heat up, changing their resistance, but the computer will correct for this up to a point. The seriousness of this effect will depend on the poloidal field strength and the recycle time. It is also generally impossible to get a good baseline at normal poloidal field strengths without using the core cocking circuit because the iron core saturates before 20 msec at a slightly different time with and without the plasma. When making careful measurements, it is advisable to retake a baseline whenever
any of the capacitor bank voltages is altered even though the computer's criterion for needing a baseline may not be met.

**What the Program Does**

When the program is ready to receive data (pixel in the upper right corner illuminated), the $V_{PG}$ channel is being interrogated every 100 μsec by a machine language software loop (see Appendix B). Whenever the highest order bit becomes a one (>127), the five channels ($I_p$, $J_{SAT}$, $B_T$, $V_{PG}$, and $I_H$) are read in sequence at a rate of 100 μsec each for a total time of 20 msec, thereby generating 200 values which are stored in a two-dimensional array with dimensions $X(5,40)$. The baseline is similarly stored in an array $XB(5,40)$. The value of a quantity $I$ is determined at time step $J$ from

$$S(I,J) = SC(I)*(X(I,J) - XB(I,J))$$

where $SC(I)$ is a scale factor for that particular channel to make the units come out as follows:

<table>
<thead>
<tr>
<th>quantity</th>
<th>scale factor</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p$</td>
<td>$SC(1)=1$</td>
<td>kA</td>
</tr>
<tr>
<td>$J_{SAT}$</td>
<td>$SC(2)=10$</td>
<td>mA/cm²</td>
</tr>
<tr>
<td>$B_T$</td>
<td>$SC(3)=200$</td>
<td>gauss</td>
</tr>
<tr>
<td>$V_{PG}$</td>
<td>$SC(4)=0.5$</td>
<td>volts</td>
</tr>
<tr>
<td>$I_H$</td>
<td>$SC(5)=2$</td>
<td>kA</td>
</tr>
</tbody>
</table>

The scale factor can also be thought of as the smallest measurable increment of the corresponding quantity. Actually, in order to determine the quantities at a given time (such as 4 msec), the values are interpolated from the one just below and just above the desired time. The first measurement of $I_p$ occurs at $t=0.1$ msec, the first measurement of $J_{SAT}$ occurs at $t=0.2$ msec, etc. The second measurement of $I_p$ occurs at $t=0.6$ msec, etc. Note that the trigger scheme introduces a 100 μsec jitter into the timing,
and that there is a threshold trigger level, but neither of these has ever been a serious problem. A sixth channel, neutral pressure, is read from the fast ion gauge just after the 20 msec point and compared with a baseline pressure just before the A-to-D is rearmed. This reading has not proved very reliable or useful because the $I_p$ channel is often saturated at that time, resulting in erroneous pressure readings.

Whenever the absolute value of the measured plasma current at 20 msec exceeds 1 kA, the computer assumes the plasma current baseline has drifted due to a change in hoop resistance and adjusts the measured current by subtracting from it a quantity,

$$\Delta I_p(t) = I_p(20) \int_0^t H dt / \int_0^{20} H dt$$

where $t$ is in milliseconds. The justification for this correction is given by Eq. (12). Although the computer will continue to track a drift in resistance indefinitely, whenever the unadjusted current at 20 msec, $|I_p(20)|$ exceeds 9 kA, a baseline is requested.

The program calculates the amp-seconds (a figure of merit for the discharge) by numerically integrating the plasma current:

$$AS = \int_0^{20} I_p dt$$

where $I_p$ is in kA and $t$ is in milliseconds. If the plasma current is negative, it is set to zero in the above integral to reduce the effect of an erroneous baseline. Whenever a baseline is needed, the amp-seconds is not calculated but rather set to zero to avoid meaningless readings.
From the measured quantities, several additional derived data can be displayed (using the A command). An effective minor radius of the plasma (in cm) is calculated from

$$a = 17.4 \left| \frac{I_p}{I_H} \right|^{1/4}$$

This radius is meant to be the radius of a circle of the same cross-sectional area as that enclosed by the square-shaped plasma inside the separatrix. This quantity is only approximate because of a number of assumptions, the most serious of which is that the entire measured current flows in a circularly symmetric fashion within a circle of radius a centered on the geometric axis of the machine. It also assumes a degenerate octupole field in the absence of plasma, such that in the vicinity of the field nulls the octupole field varies like $r^3$.

The average safety factor $<q>$ is determined by assuming that the plasma current density is uniform over the cross-section of a circle of radius a centered on the axis. The current density is then independent of radius, and $<q>$ is constant out to a radius at which the octupole field starts to compare with the plasma field (near the separatrix). Near the axis the $<q>$ is given by

$$<q> = 10^{-4} \frac{a^2 B_T}{I_p}$$

Calculation of the loop voltage $V_L$ is considerably more difficult. To begin with, we mean by loop voltage only the resistive part of the voltage applied to the plasma, i.e.: the voltage that would be measured by a single turn loop of wire that goes once around the machine toroidally at the magnetic axis. Other tokamaks measure loop voltage by a toroidal loop at
the plasma edge, and hence there is a contribution to the measured signal from the time derivative of the poloidal magnetic flux in the plasma. The loop voltage can be expressed in terms of the measured quantities ($I_p$, $V_{PG}$, and $I_H$) using the circuit model of PLP 777:

$$V_\lambda = \alpha V_{PG} + (1-\alpha)R_H I_H - \alpha(1-\alpha)L_H \frac{dI_p}{dt} - \frac{d}{dt}(I_p I_p)$$  \hspace{1cm} (5)$$

where $\alpha$=private flux/common flux in the absence of a plasma (typically 0.5), $R_H$ is the hoop resistance, $L_H$ is the hoop inductance, and $L_p$ is the plasma inductance. This equation differs from Eq. (7) of PLP 756 in that the sign of the $L_H dI_p/dt$ term is opposite. The reason is that the plasma inductance is here defined so as to include the image currents of the plasma in the hoops, i.e.: the hoops represent a conducting boundary which alters the plasma inductance. In PLP 756, the plasma inductance is calculated as if the hoops were absent. This difference is of little consequence, however, since the plasma inductance $L_p$ cannot be measured directly, but rather the quantity $L_p + \alpha(1-\alpha)L_H$ (as defined above) is measured as described in PLP 756 to have a value of $\sim 0.7 \mu H$. The term $I_p dL_p/dt$ cannot be easily measured and undoubtedly gives rise to some high frequency structure on the loop voltage, but is is thought to be unimportant for the low frequency components of $V_\lambda$. Actually, the method of determining the plasma inductance by experimentally measuring $dV_\lambda/dI_p$ takes into account that portion of the $I_p dL_p/dt$ that results from a simple expansion or contraction of the plasma radius $a$ in response to a change in $I_p$. Current profile changes are not modelled properly, however. The quantities $\alpha$ and $R_H$ can be estimated theoretically, but since they change in time due to soak-in, a better representation was obtained by Sprott and Shepard by measuring the loop voltage directly as
described in PLP 756 in the absence of plasma and then fitting the results to a function of the form

\[ V_p = \frac{1}{2}(1+At)V_{PG} + B(1+ Ct)I_H \]  

(6)

where A, B, and C are constants. Such a method gives a first-order correction to the time dependence of \( \alpha \) and \( R_H \) as well as the initial value of \( R_H \). The data (45 points) were taken at 2 msec intervals up to 20 msec for a crowbarred, damped poloidal field waveform for a variety of poloidal bank and power crowbar settings. Similarly, the effect of \( I_p \) on the loop voltage was determined by measuring the loop voltage difference \( \Delta V_p \) with and without a plasma using a probe on axis as described above. The data (20 points) were taken at 0.5 msec intervals for several 4 msec discharges with peak current of \(~\) 25 kA at 1.5 msec and fitted to a curve of the form

\[ \Delta V_p = -AaB I_p \]  

over the range \( 7 < a < 11 \) cm. The fit was not excellent but gave \( A = 2.3 \) and \( B = -0.5 \). This method undoubtedly hides a multitude of sins, and it should be redone more carefully. Nevertheless, the values obtained give

\[ V_p = \frac{1}{2}(1+t/75)V_{PG} + 0.0045(1-t/37)I_H - 2.3I_p/\sqrt{a} \]  

(7)

where \( t \) is the time in msec after the start of the poloidal voltage pulse, and the currents are measured in kiloamps. Calculation of the time derivative of the plasma current \( I_p \) poses some special problems. The plasma current trace is not perfectly smooth, and the differentiated value of the wiggles can overwhelm the low frequency signal that is thought to be of primary interest. After much experimentation a method was settled upon in which a parabola is fit to the four \( I_p \) points nearest the time of interest
(spanning a 1.5 msec interval), and the derivative at the desired point is determined analytically from the parabola. The round-off error in the A-to-D converter gives an rms error in the loop voltage measurement of ±0.5 volts which is considerable since our standard discharges have \( V_L \) in the range of 2-3 volts. The errors in \( V_L \) are probably the weakest link in the calculation of all subsequent quantities.

The ohmic input power is simply calculated from

\[
P_{OH} = I_P V_L
\]

In addition to the errors in \( V_L \) previously discussed, the ohmic input power is subject to assumptions about the plasma current profile, namely that the underestimate of \( P_{OH} \) for current flowing near the hoops where \( V_L \) is small is just compensated by the overestimate of \( P_{OH} \) for current flowing near the wall where \( V_L \) is large.

The electron temperature (in eV) is calculated from \( I_P \) and \( V_L \) assuming Spitzer resistivity with \( Z_{eff} = 1 \) and assuming the current is distributed uniformly over a circular cross-section of radius \( a \):

\[
T_e = 376(\frac{|I_P/V_L|}{a^2})^{2/3}
\]

The actual peak electron temperature is probably larger by a factor of ~2-3 because \( Z_{eff} \) is greater than 1 and the current is presumably somewhat peaked near the axis.

The average electron density is determined from the ion saturation current density \( J_{SAT} \) and the conductivity electron temperature using the usual Langmuir probe relation \( J_{SAT} \propto n\sqrt{T_e} \) for \( T_e > T_i \). However, the coefficient was adjusted so that the density determined in this fashion
agrees with the line-averaged density (averaged along the entire path between the interferometer horns) using a 72 GHz microwave interferometer for a standard discharge:

\[
\langle n \rangle = \frac{0.05 J_{\text{SAT}}}{\sqrt{T_e (1-e^{-45/T_e})}}
\]

(10)

\(J_{\text{SAT}}\) is in mA/cm\(^2\) and \(\langle n \rangle\) is in \(10^{12}\) cm\(^{-3}\). The factor \(1-e^{-45/T_e}\) is included to account for the fact that only 45 V bias is used on the probe, and thus not all electrons are repelled when the temperature is high. This voltage is provided by a power supply but should be checked occasionally. The actual peak density depends on the profile and is probably \(\sim 2-3\) times the value indicated here. The Langmuir probe is located on the octupole separatrix in the lower outer bridge and uses as a reference a large electrode which extends across the plasma nearly to the hoop in the upper outer bridge at the same (330 degree) toroidal azimuth.

Finally, the electron energy confinement time is calculated from

\[
\tau = \frac{0.144 \langle n \rangle T_e}{P_{\text{OH}}}
\]

(11)

where \(\tau\) is in msec and the other units are as before \((10^{12}\) cm\(^{-3}\), eV, and kW). This confinement time assumes a quasi-steady state, i.e.: \(\tau\) is much less than the time scale for change in either plasma energy or ohmic input power. In the above formula, the total machine volume inside \(\psi_{\text{crit}}\) is used \((5 \times 10^5\) cm\(^3\)), and thus it represents an overall machine confinement time rather than a confinement time for the central current channel. As such, it
is probably an overestimate since the volume-averaged $T_e$ is probably less than that calculated from the conductivity which assumes the current flows only within a radius $a$, unless $Z_{\text{eff}}$ is high enough to compensate for this effect. To get an estimate of the confinement of the central current channel, one should use a smaller volume ($\sim 1 \times 10^5 \text{ cm}^{-3}$). However, since $<n>T_e$ is low by a factor of $\sim 4-9$, the errors offset, and the calculated $\tau$ is probably a reasonable estimate for the confinement of the central current channel to within about a factor of two. It is interesting to note as pointed out by Prager that the method used to calculate $\tau$ involves multiplying the measured density by $I_{\text{eff}}^{1/3} I_P^{-2/3} V_{\perp}^{-5/3}$, and thus the confinement time is most sensitive to the loop voltage and very little else. This is unfortunate since the error in $V_{\perp}$ exceeds that of any other quantity.

**A-to-D Converter**

The A-to-D converter is a Model AIM16, available for about $\$300$ from Connecticut Microcomputer, Inc., 150 Pocono Road, Brookfield, CT 06804. Excerpts from the Data Sheet are included in Appendix C. It has the virtue of being the first such unit made for the TRS-80 with specifications adequate for the present purpose. Better units are now available but at higher cost. The unit has 16 multiplexed inputs with a maximum conversion time of 100 $\mu$sec per channel. Each channel has 8-bit accuracy (0-255) and responds to positive voltages in the range 0-5.12 volts (20 mVolt resolution). The absolute maximum error is 10 mVols + 0.7%. In order to achieve reasonable time resolution (500 $\mu$sec), only channels 1-5 are used for the high speed recording of data. The remaining channels are available for monitoring other slowly varying quantities, but only channel 6 is being used at present (to monitor neutral pressure). The unit has two significant limitations: 1) It does not have a sample-and-hold circuit and thus will
produce erroneous results if the input voltage varies significantly over the
100 μsec conversion interval. 2) Saturation of any channel in either
direction ($V_{\text{in}} < 0$ or $>5.12$ volts) will produce erroneous readings in all the
other channels during the time the channel is saturated.

The A-to-D converter was repackaged in a shielded rack panel with a
filtered internal power supply (+5.12 volts), BNC input connectors, and $1 \text{ MΩ}$
potentiometer gain adjustments on each channel. In addition, input
filtering was provided to protect the AIM16 from noise, damage due to
overvoltage, and rapidly changing input signals. The filtering typically
limits the input response time to $>24$ μsec ($<6.6$ kHz) on most channels. The
input resistance of each channel is $1 \text{ MΩ}$, and a $10 \text{ kΩ}$ input resistor
protects the A-to-D from damage by overvoltage for any reasonable input
signal. Some channels are provided with a dc offset to allow a negative
voltage swing at the input. Although channel 0 is designated as a trigger
channel, the software actually uses channel 4 ($V_{\text{PG}}$). The trigger channel
can be changed by POKEing an integer corresponding to the desired channel
number (0–15) into memory location 32011 after the program is running (BASIC
version only). A schematic of the input circuitry for the A-to-D converter
is included in Appendix D.

Current Monitor Circuit

The A-to-D circuit requires inputs proportional to plasma current and
hoop current to operate properly. Unfortunately, there is no simple,
non-perturbing method for generating such signals. Rather, one has to take
the available signals (poloidal gap voltage $V_{\text{PG}}$ and primary current $I_{\text{PR}}$ in
the iron core) and deduce the plasma and hoop currents based upon some
reasonable model of the plasma current profile. Several PLP's have been
written on this subject (712, 756, 777), and the emphasis here will
therefore be on the circuitry used to generate the signals rather than the justification of the model. Simply stated, the model assumes that the plasma current profile is such that in some appropriate flux space average, the current can be treated as if it were all concentrated at the geometric axis (or octupole null). Then the circuit model of PLP 777 gives

\[ I_p = \frac{N}{\alpha} I_{PR} - \frac{1}{\alpha L_H} \int V_{PG} dt + \frac{1}{\alpha L_H} \int I_H R_H dt \tag{12} \]

and

\[ I_H = NI_{PR} - I_P \tag{13} \]

where \( N \) is the poloidal field turns ratio (typically 40). An analog computer circuit was constructed to calculate \( I_p \) and \( I_H \). The circuit as shown in Appendix E uses 10 type 741 operational amplifiers and generates a number of other useful quantities:

\[ \Phi = \int V_{PG} dt \quad \text{(poloidal flux: 0.1 webers/volt)} \]
\[ AS = \int I_p dt \quad \text{(amp-seconds: 1000/volt)} \]
\[ \dot{I}_p = \frac{dI_p}{dt} \quad \text{(time derivative of } I_p: 10 \, \text{kA/msec/volt)} \]

Actually, for calculating plasma current, the circuit solves the equation:

\[ I_p = A V_{PG} + B I_{PR} - 9.1 \int V_{PG} dt + C \int I_H dt - D \int [\int I_{PR} dt] dt \tag{14} \]

in which \( A, B, C, \) and \( D \) are constants adjustable from the front panel and labeled "EARLY", "MID", "LATE", and "VERY LATE" respectively. The first term \( (A) \) is typically small and corrects for stray capacitance not included
in the circuit model. The last term (D) compensates for magnetic field soak-in \( R_H, \dot{q}, \) and \( L_H \) as well as the magnetizing inductance of the iron core and other effects which become important only after a long time. Note that one of the coefficients (9.1) is fixed by the circuit (corresponding to an initial hoop inductance of \( L_H=0.22 \ \mu\text{H} \) and \( \alpha=0.5 \)), such that the calibration of the plasma current is ensured once the other coefficients are adjusted to give \( I_p=0 \) at all times in the absence of a plasma. In practice, one adjusts the circuit so as to give as nearly a flat baseline as possible when the fields are pulsed in the absence of a plasma. The plasma current is filtered by an active RC low pass filter with a cutoff frequency of 1.6 kHz (100 \( \mu\text{sec} \) response time) to reduce high frequency noise. The circuit has only two inputs, \( V_{PG} \) and \( I_{PR} \). These inputs enter the circuit through LC low-pass filters with a cutoff frequency of 160 kHz. The poloidal gap voltage is measured by a single loop of wire around the iron core. The primary current is determined by measuring the voltage across a \( 10^{-3} \ \Omega \) resistor (1 kA/volt) in series with the primary through a special, low-frequency, 1:2 turns ratio isolation transformer (Jensen Model JE-11S-L) to eliminate ground loops. The transformer is terminated in 150 \( \Omega \) through a 1 MH inductor to compensate for the inductance of the current shunt, to produce a 2:1 voltage reduction, and to increase the volt-second limit of the transformer. All grounds are referenced to the panel of the current monitor circuit, and the computer gets its ground through the signal cables that connect to the A-to-D converter. The computer rack should float if these cables are disconnected.

In order to account for the time-varying hoop resistance, a modification was made to the circuit in Appendix E using the results of a calculation by Kerst of the voltage at the surface of a Tokapole hoop versus
time in the presence of a current step. The actual current waveform can be decomposed into an infinite sum of such current steps. The calculation treats the hoop as a uniform cylinder with a constant poloidal field at its surface. The result is a time varying resistance given by

$$R_H(t) = R(0)[1 + \sum_{i=1}^{\infty} e^{-t/\tau_i}]$$

where in cgs units

$$\tau_i = \frac{4r_0^2}{\pi(i+0.24)^210^9\rho}$$

In Eq. (16), $r_0$ is the radius (2.5 cm) and $\rho$ is the resistivity (2.2 $\mu\Omega$-cm) of the hoops. The first 20 values of $\tau_i$ are tabulated in Appendix F along with a schematic of an RC network whose reciprocal $(I/V)$ approximates this function and replaces the 100 k$\Omega$ resistor between the output of op amp 7 and the input of op amp 5 in Appendix E. Actually, the ratio of voltage to current is not purely resistive in either the hoops or in the circuit model since part of the voltage at the hoop surface is due to the time varying magnetic flux inside the hoops. In other words, the product of voltage and current does not give the instantaneous ohmic power dissipated by the hoops as was the case in Spencer's calculation (PLP 771). Thus the time dependent hoop resistance automatically accounts for that portion of the variation of the hoop inductance, $L_H(t)$, that is due to flux soaking into the hoops. When the current monitor circuit was modified in this way, the result was a considerably flatter baseline and a plasma current trace whose initial peak is suppressed and moved considerably later in time.
APPENDICES

A. BASIC Listing of Tokapole Monitor Program
B. AIM16 Machine Language Routine
C. AIM16 Data Sheet Excerpts
D. Schematic of A-to-D Input Circuit
E. Schematic of Tokapole Current Monitor Circuit
F. Schematic of Circuit to Model Hoop Resistance
APPENDIX A

BASIC Listing of Tokapole Monitor Program

DIMX(5,40),XB(5,40),GR(40),AS(127),S(18,10)
SM=MEM
20 IFM<>6769:PFG:NT"MEM OF Y CHEC") EF<>W ON LOAD": PFG INT"MEM ="M;" (SHOULD BE 6769)"; PRINT"TRY RELOADING CASSETTE II"; ENDELSE:POKE16526,1
POKE16527,125:FORI=82001TO82145:READXIPOKEI,X:NEXT
30 DATA62,1,50,4,56,182,33,16,56,182,33,64,56,182,33,68,125,211,228,62,4,211,228,58,1,56,33,2,5
6,182,33,4,56,182,33,16,56,182,33,64,56,182,33,68,125,211,228,62,4,211,228,58,1,56,33,2,5
19,223,203,217,242,14,206,33,45,126,22,1,122,211,223,20
40 DATA122,254,6,32,2,22,1,6,6,16,254,62,255,211,223,219,223,119
22,211,223,35,13,32,230,62,0,50,44,126,42,42,126,1,45,126,30,4
1,22,5,54,0,35,54,0,35,10,119,35,64,56,182,192,62,255,211,223,20
50 DATA235,221,42,42,126,253,42,40,126,14,246,6,2,175,221,126,0,
253,158,0,221,119,0,221,35,253,35,16,241,13,32,235,201
128:FORI=1TO5:OUTPP,I:OUTPP,192:XB(I,0)=INP(PP):FORJ=1TO40:
XB(I,J)=XB(I,0):NEXTJ,I
60 SC(1)=1ISC(2)=10:SC(8)=200:SC(4)=0.5:SC(5)=2
70 IFBM ::: 0 PRINT" K TA(E A BASELINE SHOT II";
80 SET(125,0):OUTPP,128:OUTPP,6:OUTPP,125:PR=INP(PP):POKE32299,I
NT(VARPTR(X(0,0»/256):POKE32298,VARPTR(X(0,0»)-256*INT(VARPTR(X
(0,0»/256):POKE32297,INT(VARPTR(XB(0,0»)/256):POKE32296,VARPTR(X
B(0,0»)-256*INT(VARPTR(XB(0,0»)/256):X=USR(0)
90 OUTPP,128:OUTPP,6:OUTPP,125:PR=INP(PP):SET(127,0):IFPEEK(3230
0)THEN270ELSEBL.=X(2,5)+X(2,10)+X(2,15):IFBL.>0THENBL.=1:GOTO110ELS
E:BM=1:FORJ=1TO2:FORJ=1TO40:XB(I,J)=XB(I,J)+X(I,J):NEXT:NEXT
100 FORJ=1TO40:XB(I,J)=XB(I,J):NEXT
110 C1=0:IFBL.>THENPRINT("BASELINE";ELSEPRINT"SHOT NUMBER:";NS:IFAB
S(X(1,40»)>9THENBM=0
120 IFABS(X(X(1,40»)>1THENIH=0:FORJ=0TO40:IH=IH+X(5,J):NEXT:IFIHTH
EXT=0:FORJ=0TO40:IT=IT+X(5,J):X(1,J)=X(1,J)-X(1,40»*IT/IH:NEXT:
130 IM=X(1,0»:AS=0:FORJ=0TO40:AS=AS+X(1,J):IFX(1,J)>.IMTHENIM=X(1,
J):JM=J
140 IFX(1,J)<0THENAS=AS-X(1,J)
150 NEXT FORJ=1TO40:IFXI(J)+0THENAS=AS-X(1,J)
160 NEXT
170 AS=AS*EM*EL:TM=5*JM+1:IFJM<>0ANDJM<40THENSO=X(1,JM-1»:S2=X(1,
JM+1»:IF2*IM<>0+S2THENTM=TM-2.5*(S2-S0)/(S2-2*IM+S0):IM=IM-0.10
0*(S2-S0»:(S2-S0»/(S2-2*IM+S0)
180 IFIMPRINT"MAX IP =";SC(1)*IM;"KA AT";TM/10;"MSEC"ELSEPRINT"M
AX IP = 0"
190 PRINT"AMP SECONDS IF";SC(1)*AS/2:PRINT"PRES =";4*(PR-PB);"E-5 TORR"
PRINT"TIME IP" JSAT BT VPG IHoop DIP /DT";FORJ=1TO10:JL=FAS*J/5:S(0,J)=FAS*J/10:PRINTS(0,J);ENDFORJ=1TO5:
XP(I)=(5-I)*X(I,J)+IM+IX(I,J-1)+5
200 X1=BL*X(I,J)+XB(I,J)+X2=BL*X(I,J-1)+XB(I,J-1):IFX1<.00RX
2=C=0PRINTTAB(8*I);"SAT-";GOTO210ELSEIFX1>.2550X2=255PRINTTAB(8*I);"SAT+";GOTO210ELSEFW(8*I):PRINTTAB(8*I);S(I,J);
210 NEXT: J2=J1+1: IF J2=41 THEN J2=40
220 J0=J1-2: IF J0<0 THEN J0=0
230 S(13,J)=SC(1)×S×(1,J2)+2×(1,J1)-8×(1,J1-1)-2×(1,J0)/10
240 IFNS>127 FOR I=1 TO AS(I-1)=AS(I)
250 NEXT: IF BL=0 THEN 260 ELSE SENT=127: IF NS(128 THEN NT
260 IF CS$<>"" THEN GOSUB 170: IF Q$<>"" THEN 280
270 IF Q$<>"": IF W<>1 THEN PRINT "PLASMA CURRENT VS TIME"
280 IF Q$<>"": IF Q<>"" THEN 290 ELSE IF Q$="": GOTO 170: IF Q$="": GOTO 170
290 IFQ$="": GOTO 190: IFQ$="": GOTO 210: IFQ$="": GOTO 230
300 IFQ$="": GOTO 250: IFQ$="": GOTO 270
310 IF Q$="": INPUT "WHAT COMMAND SEQUENCE"; CS$; GOTO 170: IF Q$="": GOTO 170
340 PRINT, "P: PROGRAM COMMAND SEQUENCE": IFQ$="" THEN NC$="" THEN PRINTS$="" THEN CS$="" THEN JS$="" THEN PRINTT$="" THEN PRINT, "WHAT COMMAND SEQUENCE": CS$=GOTO70 ELSE 260
350 IFBL=1 PRINTTAB(52); "SHOT"; NS ELSE PRINTTAB(52); "BASELINE"
360 Y1=0: Y2=0: FOR J=0 TO 40: GR(J)=X(I,G,J): IF GR(J)<0 THEN Y2=Y2+GR(J)
370 IF GR(J)<0 THEN Y1=Y1+GR(J)
380 NEXT: IF Y2>Y1 THEN PRINT; PRINT "****** NO DATA TO GRAPH": GOTO 20 ELSE Y=34/(Y2-Y1): FOR J=0 TO 40: SET(3×J+5, 44.5-SY×(GR(J)-Y1))
390 NEXT: IF Y>44.5 THEN Y=44.5: FOR J=0 TO 40: SET(I,Y)
390 NEXT FOR I=3 TO 125: SET(I,Y): NEXT FOR Y=15553 TO 16257 STEP 61: POKE Y, 170: NEXT
390 PRINT@961, "O 2 4 6 8 MSEC 12 14 16 18 20": PRINT@80, "MAXIMUM VALUE":; SC(I)×Y2; GOTO 260
400 FS=10: INPUT "HOW MANY MSEC FULL SCALE (DEFAULTS TO 10)"; FS: IF FS>20 THEN PRINT "MAXIMUM IS 20 MSEC": GOTO 400 ELSE IFFS<5 PRINT "MINIMUM IS 5 MSEC": GOTO 400 ELSESECLS: RETURN
410 PRINT,"AMP SECONDS FOR LAST";INT;"SHOTS";Y2=0;FORI=0TONT;IFAS(I)>Y2THENY2=AS(I)
420 NEXT:IFY2=0PRINT"PRINT"****NO DATA TO GRAPH";RETURNELSEPRINT INT@960,STRING$(63,CHR$(176));POKE16363,176;FORI=1TONT;SET(I,47-41*AS(I)/Y2);NEXT:FORY=6TO46;SET(0,Y);NEXT:PRINT@80,"MAXIMUM VALUE";Y2=SC(1)/2;RETURN
430 CLS;PRINT,"ANALOG INPUT FOR EACH CHANNEL";PRINT;OUTPP,128;FO RI=0T015;PRINTUSING"###";I;NEXT;PRINT@396,"PRESS ANY KEY TO RESUME TOKAPOLE DATA"
440 PRINT@192,"";FORI=0T015;OUTPP,I;OUTPP,192;PRINTUSING"###"; INF(PP);NEXT;QQ=INKEY$;IFQQ$="""THEN440ELSERETURN
450 PRINT,"ADDITIONAL DERIVED DATA";IFBL=1PRINTTAB(52);"SHOT";N SELSEPRINTTAB(52);"BASELINE"
460 PRINT;PRINT"TIME A <Q> VLOOP POH TE <N> TAU";FORJ=1TO10;IFS(5,J)THENS(6,J)=17.4*(ABS(S(1,J)/S(5, J)));C.25ELSESES(6,J)=0
470 IFS(1,J)THENS(7,J)=1E-4*S(6,J)*S(6,J)*S(3,J)/S(1,J)ELSESE(7,J )=0
480 S(8,J)=5*(1+S(0,J)/75)*S(4,J)+.0045*(1-S(0,J)/37)*S(5,J);IFS S(6,J)THENS(8,J)=S(8,J)-2.3*S(13,J)/SQR(S(6,J))
490 S(9,J)=S(8,J)*S(1,J);IFS(8,J)*S(6,J)THENS(10,J)=376*(ABS(S(1 ,J)/S(6,J)/S(6,J))/SQR(S(10,J)))/(1-EXP(-45/S (10,J))));ELSESE(10,J)=0
500 IFS(10,J)>0THENS(11,J)=.050*S(2,J)/SQR(S(10,J))/(1-EXP(-45/S (10,J))));ELSESE(11,J)=0
510 IFS(9,J)THENS(12,J)=.144*S(11,J)*S(10,J)/S(9,J)ELSESE(12,J)=0
520 PRINTTAB(0);S(0,J);FORI=6TO12;PRINTTAB(8*I-41)INT(100*S(I,J )+.5)/100;NEXT;PRINT;NEXT;PRINT"MSEC CM VOLTS KW EV E12/CC MSEC";RETURN
530 LS=LEN(CS$);QQ=QQ+1;IFQQ<=LSTHENQQ$=MID$(CS$,QQ,1)ELSEQQ$=""
540 FORI=0TO600;VAL(QQ$);NEXT;IFVAL(QQ$)THEN530ELSERETURN
550 CLS;PRINT"MESSAGE";M$;CLS;IFLEN(M$)<192THENM$=STRING$(31," ");M$ELSEM$=M$
560 FORI=1TOLEN(M$);PRINT@448,CHR*(23);MID$(M$,I,31);STRING$(31," ");FORJ=1T050;NEXT;I;QQ$=INKEY$;IFQQ$="""THEN560ELSECLS;RETUR
210 NEXT J2=J1+1:IF J2=41 THEN J2=40
220 J0=J1-2:IF J0<0 THEN J0=0
230 S(13,J)=SC(1)*8*X(1,J2)+Z*X(1,J1)-8*X(1,J1-1)-2*X(1,J0)/10
!PRINTTAB(48)S(13,J):NEXT:IFBL=0 THEN260 ELSE SENT=127:IF NS<128 THEN NT =NS
240 IF NS>127 FOR I=1 TO 127:AS(I-1)=AS(I):NEXT
250 AS(NT)=AS
260 IF CS<>"" THEN GOSUB 530:IF QQ$<>" " THEN280
270 QQ$=INKEY$:IF QQ$="THEN70
280 IF QQ$="0" THEN PRINT "***** COMPUTER ON STANDBY---PRESS 1 TO CONTINUE TAKING DATA"
310 IF CH$="S" THEN PRINT "CURRENT SHOT NUMBER =";NS:INPUT "NEW SHOT NUMBER";NS:GOTO70 ELSE IF QQ$="E" THEN GOSUB430:GOTO280 ELSE IF QQ$="E" THEN GOSUB 450:GOTO260 ELSE IF QQ$="M" THEN GOSUB 550:GOTO280 ELSE CLS:PRINT "COMMANDS":
350 IFBL=1PRINTTAB(52);"SHOT";NS;ELSE PRINTTAB(52);"BASELINE";
360 Y1=0;Y2=0:FOR J=0 TO 40:GR(J)=X(IG,J):IF GR(J)>Y2 THEN Y2=GR(J)
370 IF GR(J)<Y1 THEN Y1=GR(J)
380 NEXT:IF Y2=Y1 PRINT;PRINT;PRINT "***** NO DATA TO GRAPH";GOT0260 ELSE SE=34/(Y2-Y1);FOR J=0 TO 40:SET(3*XJ+5,44.5-SY*(GR(J)-Y1));NEXT:FOR Y=44.5+SY*Y1:FOR I=3 TO 125:SET(I,Y);NEXT:FO4RY=15553 TO 16257 STEP 64:POKEY,170:NEXT
390 PRINT@9,61,"0 2 4 6 8 10 12 14 16 18 20";PRINT@80,"MAXIMUM VALUE:";SC(IG)*Y2;GOTO260
400 FS=10:INPUT "HOW MANY MSEC FULL SCALE (DEFAULTS TO 10)";IF FS>20 PRINT "MAXIMUM IS 20 MSEC";GOTO400 ELSE IF FS<5 PRINT "MINIMUM IS 5 MSEC";GOTO400 ELSE CLS:RETURN
TOKAPKE MONITOR -- AIM16 ROUTINE

APPENDIX B
AIM16 Machine Language Routine

7D01 00100 ORG 32001
7D01 3E01 00110 LD A,1
7D03 322C7E 00120 LD (32300),A;STORE 1 IN 32300
706 3EC0 00130 LD A,192
/08 D3DF 00140 OUT (223),A;INITIALIZE SYSTEM
7D0A 3E00 00150 NOSIG LD A,0
7D0C D3DF 00160 OUT (223),A;SELECT TRIGGER CHANNEL
7D0E 3A0138 00170 LD A,(3801H);STROBE KEYBOARD
7D11 210238 00180 LD HL,3802H
7D14 B6 00190 OR (HL)
7D15 210438 00200 LD HL,3804H
7D18 B6 00210 OR (HL)
7D19 211038 00220 LD HL,3810H
7D1C B6 00230 OR (HL)
7D1D 214038 00240 LD HL,3840H
7D20 B6 00250 OR (HL);SET FLAG IF KEY PRESSED
7D21 C0 00260 RET NZ;RETURN IF KEY PRESSED
7D22 3EFF 00270 LD A,255
7D24 D3DF 00280 OUT (223),A;ENABLE TRIGGER
7D26 DBDF 00290 IN A,(223);READ TRIGGER SIGNAL
7D28 CB7F 00300 BIT 7,A;TEST HIGH ORDER BIT
7D2A 2BDE 00310 JR Z,NOSIG;RETURN IF TRIGGER < 128
7D2C 0ECE 00320 LD C,206;NUMBER OF POINTS
7D2E 212D7E 00330 LD HL,32301;BEGINNING MEMORY ADDRESS
7D31 1601 00340 LD D,1
7D33 7A 00350 LD A,D
7D34 D3DF 00360 OUT (223),A;SELECT CHANNEL 1
7D36 14 00370 CONT INC D;INCREMENT CHANNEL NUMBER
737 7A 00380 LD A,D
33 FE06 00390 CP 6;HIGHEST CHANNEL ! EXCEEDED?
7D3A 2002 00400 JR NZ,MORE;GOTO MORE IF D<>6
7D3C 1601 00410 LD D,1;RESET TO FIRST CHANNEL
7D3E 0606 00420 MORE LD B,6;DELAY BETWEEN POINTS
7D40 10FE 00430 LOOP DJNZ LOOP;LOOP UNTIL B=0
7D42 3EFF 00440 LD A,255
7D44 D3DF 00450 OUT (223),A;ENABLE DATA
7D46 DBDF 00460 IN A,(223);READ DATA
7D48 77 00470 LD (HL),A;STORE DATA
7D49 7A 00480 LD A,D
7D4A D3DF 00490 OUT (223),A;SELECT CHANNEL
7D4C 23 00500 INC HL;INCREMENT MEMORY LOCATION
7D4D 0D 00510 DEC C;DECREASE C BY 1
7D4E 20E6 00520 JR NZ,CONT;CONTINUE IF MORE DATA
7D50 3E00 00530 LD A,0
7D52 322C7E 00540 LD (32300),A;STORE 0 IN 32300
7D55 2A2A7E 00550 LD HL,(32298);X BLOCK ADDRESS
7D58 012D7E 00560 LD BC,32301;DATA BLOCK ADDRESS
7D5B 1E29 00570 LD E,41;# OF TIMES
7D5D 1605 00580 JLOOP LD D,5;# OF CHANNELS
7D5F 3600 00590 LD (HL),0
7D61 23 00600 INC HL
7D62 3600 00610 LD (HL),0
7D64 23 00620 ILOOP INC HL
7D65 0A 00630 LD A,(BC);MOVE DATA
766 77 00640 LD (HL),A
7D67 23 00650 INC HL
7D68 3600 00660 LD (HL),0
7D6A 03 00670 INC BC;NEXT DATA POINT
7D6B 15 00680 DEC D
7D6C 20F6 00690 JR NZ,ILoop;GOTO ILoop IF D>0
7D6E 23 00700 INC HL
7D4F 1D 00710 DEC E
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7D70 20EB</td>
<td>00720</td>
<td>JR</td>
<td>NZ, JLOOP; GOTO JLOOP IF E&gt;0</td>
<td></td>
</tr>
<tr>
<td>7D72 DD2A2A7E</td>
<td>00730</td>
<td>LD</td>
<td>IX, (32298); START X ADDRESS</td>
<td></td>
</tr>
<tr>
<td>7D76 FD2A2B7E</td>
<td>00740</td>
<td>LD</td>
<td>IY, (32296); START XB ADDRESS</td>
<td></td>
</tr>
<tr>
<td>7D7A 0EF6</td>
<td>00750</td>
<td>LD</td>
<td>C, 246 # OF X VALUES</td>
<td></td>
</tr>
<tr>
<td>7D7C 0602</td>
<td>00760</td>
<td>BLINE</td>
<td>LD</td>
<td>B, 2 # OF BYTES/VALUE</td>
</tr>
<tr>
<td>7D7E AF</td>
<td>00770</td>
<td>XOR</td>
<td>A</td>
<td>; RESET CARRY</td>
</tr>
<tr>
<td>7D7F DD7E00</td>
<td>00780</td>
<td>BLOOP</td>
<td>LD</td>
<td>A, (IX) ; GET X</td>
</tr>
<tr>
<td>7D82 FD9E00</td>
<td>00790</td>
<td>SBC</td>
<td>A, (IY) ; SUBTRACT XB</td>
<td></td>
</tr>
<tr>
<td>7D85 DD7700</td>
<td>00800</td>
<td>LD</td>
<td>(IX), A ; STORE RESULT</td>
<td></td>
</tr>
<tr>
<td>7D88 DD23</td>
<td>00810</td>
<td>INC</td>
<td>IX ; PtNT TO NEXT HIGHER X</td>
<td></td>
</tr>
<tr>
<td>7D8A FD23</td>
<td>00820</td>
<td>INC</td>
<td>IY ; PtNT TO NEXT HIGHER XB</td>
<td></td>
</tr>
<tr>
<td>7D8C 10F1</td>
<td>00830</td>
<td>DJNZ</td>
<td>BLOOP ; GOTO BLOOP IF MORE</td>
<td></td>
</tr>
<tr>
<td>7D8E 0D</td>
<td>00840</td>
<td>DEC</td>
<td>C ; NEXT VALUE</td>
<td></td>
</tr>
<tr>
<td>7D8F 20EB</td>
<td>00850</td>
<td>JR</td>
<td>NZ, BLINE; GOTO BLINE IF MORE</td>
<td></td>
</tr>
<tr>
<td>7D91 C9</td>
<td>00860</td>
<td>RET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7D01</td>
<td>00870</td>
<td>END</td>
<td>32001</td>
<td></td>
</tr>
</tbody>
</table>

TOTAL ERRORS:

-22-

BLINE 7D7C
ILOOP 7D64
JLOOP 7D5D
LOOP 7D40
MORE 7D3E
CONT 7D36
NOSIG 7D0A
AIM16 DATA SHEET

ANALOG PORT - 16 Channels - Specifications for each channel:
Vin - analog input voltage conversion range: 0 to 5.12 volts
Vin (max) - absolute maximum input voltage: -.3 to plus 5.4 volts
Ilna (max) - maximum analog input current: 2 microamps
Vref - reference voltage: 5.120 volts plus or minus .01 volts

Conversion data:
Tc - conversion time, per channel: 100 microsec max, 80 typ
counts per channel: 256
output range (each channel): 00-FF (hex)
0-255 (decimal)
000-377 (octal)
0000-1111 1111 (binary)

Absolute maximum error: .7 %
Typical maximum error: .5 %

Physical Dimensions - 51/4 x 61/4 x 21/4.

AIM16 BLOCK DIAGRAM

AIM 16 TIMING

APPLICATIONS

APPENDIX A. AIM16 DATA SHEET
## PORT PIN FUNCTIONS

### Computer Port (Connector L)

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Function</th>
<th>Pin No.</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GND</td>
<td>2</td>
<td>GND</td>
</tr>
<tr>
<td>3</td>
<td>D0 (LSB)</td>
<td>4</td>
<td>D4</td>
</tr>
<tr>
<td>5</td>
<td>D1</td>
<td>6</td>
<td>D5</td>
</tr>
<tr>
<td>7</td>
<td>D2</td>
<td>8</td>
<td>D6</td>
</tr>
<tr>
<td>9</td>
<td>D3</td>
<td>10</td>
<td>D7 (MSB), EOC</td>
</tr>
<tr>
<td>11</td>
<td>plus 12v</td>
<td>12</td>
<td>plus 12v</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>3s enable</td>
<td>16</td>
<td>Start Strobe (SS*)</td>
</tr>
<tr>
<td>17</td>
<td>Add 0</td>
<td>18</td>
<td>Add 2</td>
</tr>
<tr>
<td>19</td>
<td>Add 1</td>
<td>20</td>
<td>Add 3</td>
</tr>
</tbody>
</table>

### Analog Port (Connector R)

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Function</th>
<th>Pin No.</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GND</td>
<td>2</td>
<td>5.120 VREF</td>
</tr>
<tr>
<td>3</td>
<td>IN0</td>
<td>4</td>
<td>IN8</td>
</tr>
<tr>
<td>5</td>
<td>IN1</td>
<td>6</td>
<td>IN9</td>
</tr>
<tr>
<td>7</td>
<td>IN2</td>
<td>8</td>
<td>IN10</td>
</tr>
<tr>
<td>9</td>
<td>IN3</td>
<td>10</td>
<td>IN11</td>
</tr>
<tr>
<td>11</td>
<td>IN4</td>
<td>12</td>
<td>IN12</td>
</tr>
<tr>
<td>13</td>
<td>IN5</td>
<td>14</td>
<td>IN13</td>
</tr>
<tr>
<td>15</td>
<td>IN6</td>
<td>16</td>
<td>IN14</td>
</tr>
<tr>
<td>17</td>
<td>IN7</td>
<td>18</td>
<td>IN15</td>
</tr>
<tr>
<td>19</td>
<td>5.120 VREF</td>
<td>20</td>
<td>GND</td>
</tr>
</tbody>
</table>

### Computer Port Pin Functions

<table>
<thead>
<tr>
<th>Pin Name to the AIM16</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cmd</td>
</tr>
<tr>
<td>2</td>
<td>GND</td>
</tr>
<tr>
<td>3 D0 (LSB)</td>
<td>Digital output for analog inputs.</td>
</tr>
<tr>
<td>4 D1</td>
<td>Digital output for analog inputs.</td>
</tr>
<tr>
<td>5 D2</td>
<td>Digital output for analog inputs.</td>
</tr>
<tr>
<td>6 D3</td>
<td>Digital output for analog inputs.</td>
</tr>
<tr>
<td>7 D4</td>
<td>Digital output for analog inputs.</td>
</tr>
<tr>
<td>8 D5</td>
<td>Digital output for analog inputs.</td>
</tr>
<tr>
<td>9 D6</td>
<td>Digital output for analog inputs.</td>
</tr>
<tr>
<td>10 D7 (MSB)</td>
<td>Digital output for analog inputs.</td>
</tr>
</tbody>
</table>

### Direction with Respect to Pin Name to the AIM16

- **GND**: Signal ground - tied to analog ground
- **30 Volts DC power from a DAM SYSTEMS power pack or other source.** If a DAM SYSTEMS power pack is used at the POWER PORT then this voltage is available to supply other DAM SYSTEMS modules. If a DAM SYSTEMS power pack is not used at the POWER PORT then a positive 12 volts (well-filtered DC) must be supplied at these pins.

### Notes

- **DO** is the least significant bit. **D1** is the most significant bit. A hi voltage is a logical 1. A lo voltage is a logical 0.
- **EOC**: End of conversion signal. **EOC** is hi when the AIM16 is busy. When **EOC** is lo, the AIM16 has finished a conversion and the converted value may be read.
- **O1 (when SS' pin is 10)** is the end of conversion EOC. When EOC is 10, the AIM16 is busy. When EOC is hi, the AIM16 has finished a conversion and the converted value may be read.
- **11 ADD1** through **12 ADD3** are address lines - select the analog input to be converted according to the following table:

### Load in or Drive

- **TTL Load**
- **LSTTL Load**

### Warning

DO NOT USE A DAM SYSTEMS POWER PACK AT THE POWER PORT while power is applied to the AIM16. If a DAM SYSTEMS power pack is used at the POWER PORT then this voltage is available to supply other DAM SYSTEMS modules. If a DAM SYSTEMS power pack is not used at the POWER PORT then a positive 12 volts (well-filtered DC) must be supplied at these pins.

---

**Note:**

- **Three state enable**: A lo voltage disables the outputs. A hi voltage enables **00-07**.
- **Start Strobe (SS)**: A hi to lo transition resets the AIM16 and starts the conversion of the analog input selected by the digital inputs on pins **17 to 20**. While **35** remains lo, and the **35 ENABLE** is hi, the **EOC** (End of Conversion) signal appears on pin **16**. When **35** is hi, and the **35 ENABLE** is hi, **01** is on pin **10** and **DO** are on pins **3 to 9** respectively.

---

**Address input: A00, A01, A02, A0 D0 D1 D2 D3 D4 D5 D6 D7**

<table>
<thead>
<tr>
<th>Analog input</th>
<th>A00</th>
<th>A01</th>
<th>A02</th>
<th>A03</th>
<th>A0 D0</th>
<th>D1 D2 D3 D4 D5 D6 D7</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN0</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo lo lo lo lo lo lo</td>
</tr>
<tr>
<td>IN2</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>hi</td>
<td>lo lo lo lo lo lo lo</td>
</tr>
<tr>
<td>IN4</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>hi</td>
<td>lo lo lo lo lo lo lo</td>
</tr>
<tr>
<td>IN6</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>hi</td>
<td>lo lo lo lo lo lo lo</td>
</tr>
<tr>
<td>IN8</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>hi</td>
<td>lo lo lo lo lo lo lo</td>
</tr>
<tr>
<td>IN10</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>hi</td>
<td>lo lo lo lo lo lo lo</td>
</tr>
<tr>
<td>IN12</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>hi</td>
<td>lo lo lo lo lo lo lo</td>
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<tr>
<td>IN14</td>
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<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>hi</td>
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</tr>
<tr>
<td>IN16</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>hi</td>
<td>lo lo lo lo lo lo lo</td>
</tr>
<tr>
<td>IN18</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>lo</td>
<td>hi</td>
<td>lo lo lo lo lo lo lo</td>
</tr>
</tbody>
</table>

**Vin(lo) = 3.5 volts min**

**Vin(lo) = 1.5 volts max**
Send START STROBE high

Send channel address

Send START STROBE low

Send ENABLE high

Read D7 (EOC) and wait until it goes high

Send START STROBE high

Read data

Leave

SS*=1.

SS*=0
This starts the conversion and puts EOC on D7.

DO-D7 are enabled.
Only D7 (now EOC) is meaningful.

EOC (End Of Conversion) takes 70 to 100 microseconds.

Puts converted data on all eight bits.

DO (least significant bit) to D7 (most significant bit)

Flowchart for reading one channel of data from the AIM16.
APPENDIX D

Schematic of A-to-D Input Circuit
APPENDIX E

Schematic of Tokapole Current Monitor Circuit
APPENDIX F

Schematic of Circuit to Model Hoop Resistance

\[ Z = Z_{DC}[1 + \sum_{i=1}^{\infty} e^{-t/\tau_i}] \]

\[ R_1 = 100 \, \text{k}\Omega \]

<table>
<thead>
<tr>
<th>( i )</th>
<th>( \tau_i ) (msec)</th>
<th>( C_i ) (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.43</td>
<td>24300</td>
</tr>
<tr>
<td>2</td>
<td>.73</td>
<td>7300</td>
</tr>
<tr>
<td>3</td>
<td>.35</td>
<td>3500</td>
</tr>
<tr>
<td>4</td>
<td>.2</td>
<td>2000</td>
</tr>
<tr>
<td>5</td>
<td>.132</td>
<td>1320</td>
</tr>
<tr>
<td>6</td>
<td>.0979</td>
<td>929</td>
</tr>
<tr>
<td>7</td>
<td>.0690</td>
<td>690</td>
</tr>
<tr>
<td>8</td>
<td>.0533</td>
<td>533</td>
</tr>
<tr>
<td>9</td>
<td>.0424</td>
<td>424</td>
</tr>
<tr>
<td>10</td>
<td>.0345</td>
<td>345</td>
</tr>
<tr>
<td>11</td>
<td>.0287</td>
<td>287</td>
</tr>
<tr>
<td>12</td>
<td>.0242</td>
<td>242</td>
</tr>
<tr>
<td>13</td>
<td>.0207</td>
<td>207</td>
</tr>
<tr>
<td>14</td>
<td>.0189</td>
<td>189</td>
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<td>15</td>
<td>.0156</td>
<td>156</td>
</tr>
<tr>
<td>16</td>
<td>.0137</td>
<td>137</td>
</tr>
<tr>
<td>17</td>
<td>.0122</td>
<td>122</td>
</tr>
<tr>
<td>18</td>
<td>.0109</td>
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<tr>
<td>19</td>
<td>.0098</td>
<td>98</td>
</tr>
<tr>
<td>10</td>
<td>.0088</td>
<td>88</td>
</tr>
</tbody>
</table>

\[ \sum_{i=1}^{\infty} \tau_i = 4.27 \]

\[ \sum_{i=1}^{\infty} \tau_i = 4.27 \, \text{msec} \]

\[ \sum_{i=1}^{\infty} C_i = 42700 \, \text{pF} \]
AIM16 DATA SHEET

ANALOG PORT - 16 Channels - Specifications for each channel -
Vina - analog input voltage conversion range: 0 to 5.12 volts
Vin (max) - absolute maximum input voltage: -.3 to plus 5.4 volts
Vina (max) - maximum analog input current: 2 microamps
Vref -- reference voltage: 5.120 volts plus or minus .01 volts

Conversion data -
Tc - conversion time, per channel: 100 microsec max, 80 typ
counts per channel: 256
output range (each channel): 00-FF (hex)
0-255 (decimal)
000-377 (octal)
0000 0000-1111 1111 (binary)

Absolute maximum error: .7%
Typical maximum error: .5%

Physical Dimensions - 51/4 x 61/4 x 21/4.

AIM16 BLOCK DIAGRAM

AIM 16 TIMING

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>CHARACTERISTIC</th>
<th>MIN</th>
<th>MAX</th>
<th>UNIT</th>
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</thead>
<tbody>
<tr>
<td>T1</td>
<td>ADDX must become stable</td>
<td>1 microsec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>ADDX must remain stable</td>
<td>3 microsec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>EOC becomes stable on 07</td>
<td>60 nanosec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>EOC in reset</td>
<td>100 nanosec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>EOC goes high indicating conversion complete</td>
<td>100 microsec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>DO-D7 becomes stable after 35 goes high</td>
<td>250 nanosec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T7</td>
<td>DO-D7 or EOC becomes stable after 35 enable goes high</td>
<td>290 nanosec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T8</td>
<td>DO-D7 or EOC enter tri-state after 35 enable goes low</td>
<td>290 nanosec</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

APPLICATIONS

6.12V Reference

AIM16

APPENDIX A. AIM16 DATA SHEET