p Note 374

TARGET STATION INSTRUMENTATION

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TARGET STATION INSTRUMENTATION

The antiproton production target station includes the following devices:

1. beam stop
2. three beam profile monitor stations
3. target
4. lithium lens
5. pulsed magnet
6. beam dump
7. cooling water systems for lens, magnet, dump
8. pulsed power supplies for lens, magnet
9. target vault air system

For each device a number of analog quantities and status bits are monitored. Most analog quantities, such as thermocouple outputs, DC voltages and water flow, pressure and conductivity can be read out with MADC's. Some of these signals require voltage amplification, status bits, and status bit generating modules. Some of the status bits are used to generate interlock chains. Modules for amplification, status bits, and interlock chains are being built by R. Oberholtzer and R. Barner. Status bits will be read out with a multiplexed C-180 module which can handle up to 256 bits in. The multiplexer is a rack mounted module. Table I includes details of analog quantities and status bits.

Some time dependent quantities such as lens current and voltage are of particular interest at a specific time with respect to beam passage. These will be read out with a sample and hold module which was originally designed for the linac. The rack mounted module has 16 sample and hold channels multiplexed to a single ADC. The sample and hold module is controlled by a C-057 module.

Lens and magnet current, voltage and magnetic field waveforms will be digitized with C-191 transient recorders. Standard C-191 modules are not fast enough for this application, but modified C-191's with supporting software are now available from the controls group. Delivery is currently about 16 weeks. One module can operate as a single channel digitizer at a 600 kHz sampling rate. Data will be transferred to the main computer system via the 10 MHz serial link. The computer can display data, and it can store data from a number of beam pulses. The stored data will be especially useful in analyzing device failures. The target and lens can be moved independently under computer control. The target, which is composed of a vertical stack of constantly rotating discs, can be moved horizontally and vertically across the beam. The horizontal movement allows adjustment of target length; vertical movement allows selection of new target material when a layer has been damaged by radiation. The lens can be

moved in a horizontal plane to any point within .250 inch radius of a nominal center by a pair of eccentrics. The coordinate transformation between x, z and the eccentric angles is derived in Appendix 1. The lens can also be moved vertically, and it can be rotated about a vertical axis. Lens rotation and all linear displacements except target elevation are measured with LVDT's. Target elevation is measured with an RVDT, due to space limitations. Lens eccentricity and target rotation are measured with 10 bit rotary encoders.

The position control system has the following components:

1. C-057 module

2. Interface module containing motor drive latches and position data multiplexer for LVDT's and rotary encoders

3. Motor driver cards and crate

4. 16-channel sample and hold with multiplexed 12-bit ADC for LVDT's, RVDT

5. 11 LVDT's, 1 RVDT, 3 rotary encoders

6. 13 DC gearmotors

The C-057 module contains a microprocessor, 8 address lines, and 16 bi-directional data lines for communication with position transducers and motors. The main computer communicates with the C-057 thru the CAMAC serial link to obtain position data and the status of limit switches. The computer also transmits a destination as a 12-bit word, when an operator wishes to move a device. The C-057 module will be built and programmed by the Controls Group. To execute a move, the operator types in a destination at a terminal. The destination is loaded into the C-057. Locally, the C-057 reads the current position of the device (LVDT's RVDT, or encoders) through an interface module designed by John Funk, compares this value to the destination and decides which way the motor should rotate. The 057 then sets the appropriate motor direction and power on latches located in the multiplexer module. Outputs of these latches are connected to the motor driver cards. The 057 then waits in a loop, reading out the current position and comparing it to the destination every 10 milliseconds. When the comparison is equal the C-057 resets the motor power on latches to stop motion.

DC gearmotors were chosen instead of stepping motors in order to minimize start-stop vibration. Output speeds were chosen to allow the full range of travel in approximately 1 minute. Limit switches are incorporated at the endpoints of each motion. The limit switch outputs through the interface module, where they can inhibit motion; they are sent through the C-057 to the main computer as status bits. If a switch fails to inhibit motion, the motor will stall when it reaches a rigid mechanical stop. Current to the motor increases as torque increases; a current overload sensor will then turn off power.

There will be beam profile measuring stations at 3 locations along the 3.7 m between the last quadrupole in the proton beam and the $\bar{p}$ production target. Each

station will contain 2 SEM grids to measure the x and y profiles. Each grid will consist of 24 parallel 100 μm diameter beryllium wires in a plane transverse to the beam. The central 12 wires will have center to center separations of 250 μm; the outer 6 wires on each side will have 500 μm separation. Wires will be stretched with sufficient tension (6 grams minimum) to overcome tension loss causd by thermal expansion from beam energy deposited in the wire. Signals from the wires will be read out by SWIC scanners. The scanners calculate the centroid and sigma of each profile using a Gaussian fit. Profile, centroid, and sigma information can be sent from the scanner to a video monitor or through the CAMAC system to the main computer.

A sketch of controls and instrumentation cabling is shown in Figure 1. Communications with the main computer are via a 10 MHz serial link to two CAMAC crates located in the control racks near the target vault. In addition to CAMAC modules, the control racks contain thermocouple amplifiers, miscellaneous other amplifiers, power supplies, SWIC scanners, oscilloscopes, timers, and interlock logic. All direct communications between the control racks and devices in the target vault pass through the target vault master panel. The control racks are also connected to the pulsed power supplies and cooling water systems, which are located outside of the target vault, but which service devices inside the vault. Table II contains a detailed list of all analog and digital signals between the control racks and the target vault master panel. Table III is a count of all cables required between the control racks and the vault master panel, between the vault master panel and individual devices, and between the control rack and pulsed power supplies and cooling water systems. In general, twinax is used for transmission of analog signals, and unshielded twisted pairs are used for digital signals. Both types of cable are available in bundles containing many individual pairs. Appropriate twinax or multipin connectors remain to be chosen. End rack style connector panels will be used at the controls racks and as the target vault master panel.

A summary of controls module requirements is shown in Table IV. CAMAC crate and rack space requirements are shown in Table V. A proposal layout for end rack connector panels (vault master panel and control rack panel) is shown in Figure 2.

Table VI lists programming to be done.

Figure 1

Cable connections to target vault devices

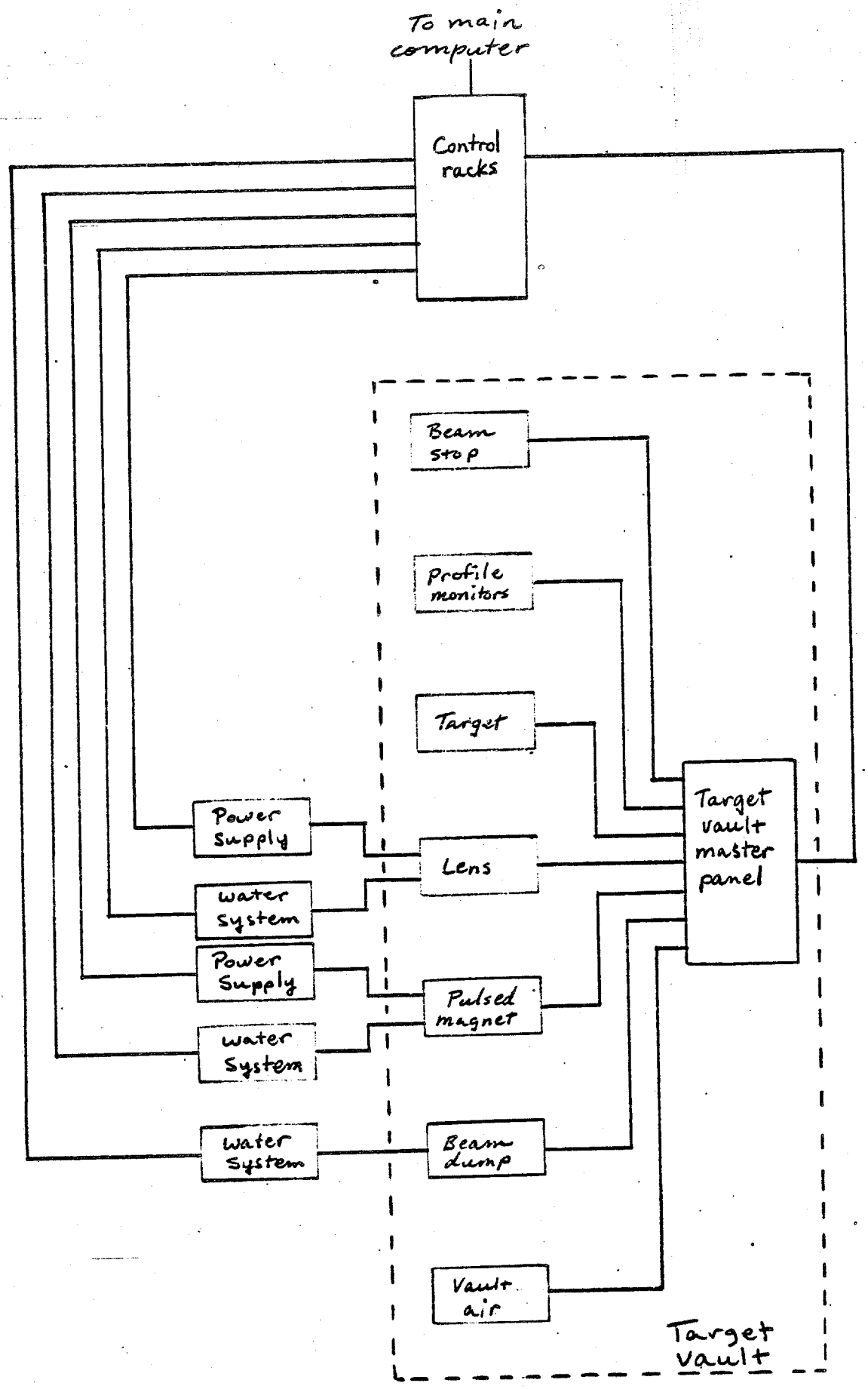
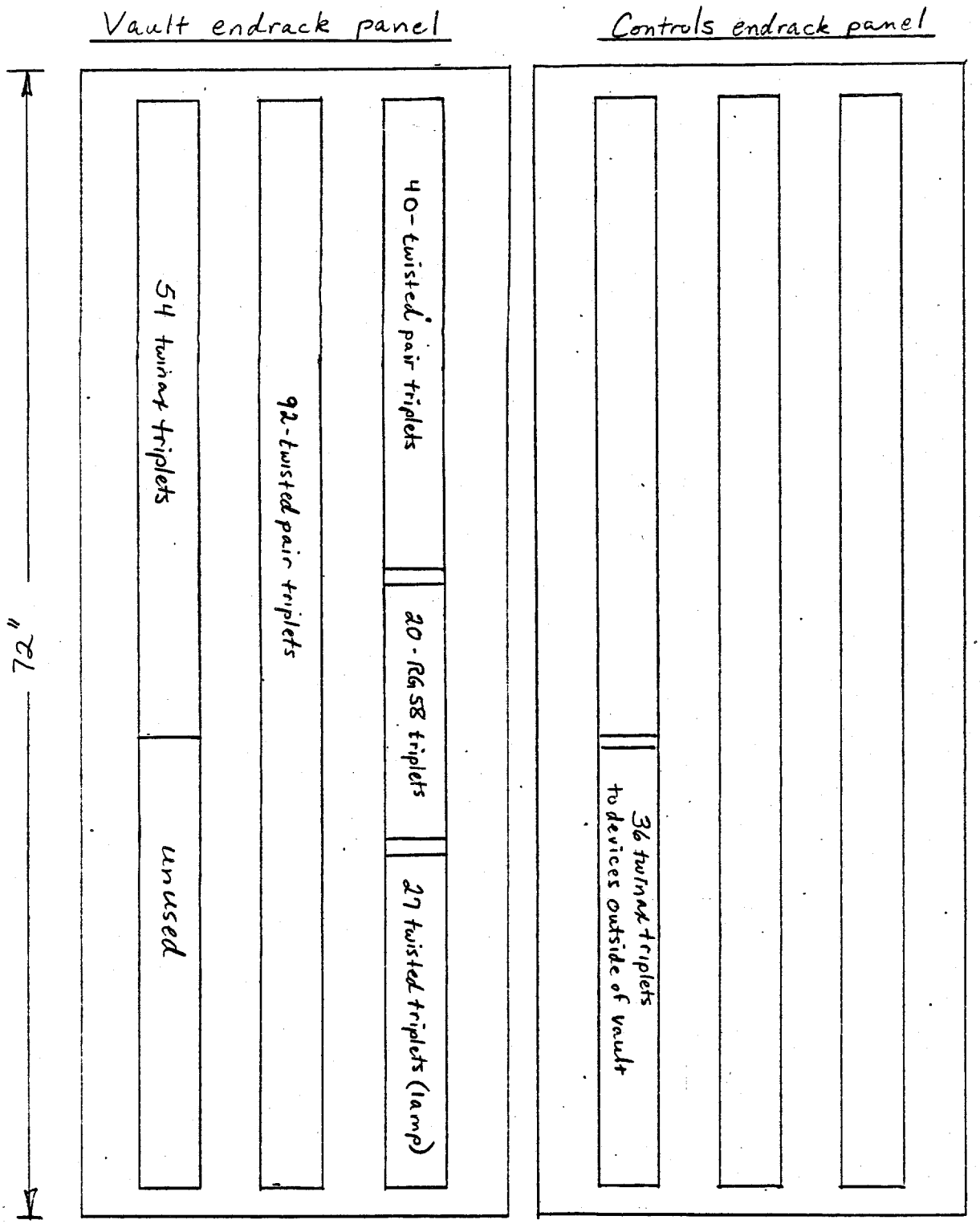


Figure 2

Endrack connector panel layouts



The vault endrack panel connects wire for wire to the controls endrack panel. The controls endrack panel has connections for an additional twinax triplets which will connect to devices outside of the vault. There are approx. 50% extra cables to vault as spares.

Twinax is used for low frequency analog signals. Twisted pairs are for digital levels. RG58 is for high frequency signals. Twisted triplets rated at 1 amp are for power to gearmotors. Thermocouple wires, high voltage, and multiconductor flat coax do not use panels – they will be direct runs from controls to modules.

Do we need some H.V. cables spare? How many spares do you put? C.

Table 1

Target vault instrumentation

Device	Quantity to be measured	transducer	transducer range	range to be measured	required accuracy	amplifier/ status buffers	readout module
TARGET	x. position	Schaevitz LVDT GCD-121-250	±.250"/ ±10 V	±.250"	±.005" = ±1% target	—	MADC
	y. position	Schaevitz RVDT R30D	±60° ±7.5 V	±20°	±.015" (12 bits)	—	MADC
	rotation	10 bit rotary encoder	360°	360°	±1°	—	C057
	4 limit switches	—	—	—	—	—	C057
	4 cooling air temperature	Thermocouple		0-100°C	±1°C	yes	4-MADC 4-C180
	2 air flow		—	0-20 cfm	±.5 cfm	yes	2-MADC 2-C180
	2 air pressure					yes	2 MADC 2-C180
	1 humidity		—	0-100%	±2%	yes	1-MADC 1-C180
LENS	x-position	Schaevitz LVDT GCD-121-250	±.250" ±10V	±.250"	±.002"	—	Sample and h
	z-position	Schaevitz LVDT GCD-121-250	±.250" ±10V	±.250"	±.002"	—	Sample an
	outer eccentric angle	10 bit rotary encoder	360°	360°	±1/785 rev	—	C057
	inner eccentric angle	10 bit rotary encoder	360°	360°	±1/785 rev	—	C057
	y-position	Schaevitz LVDT GCD-121-1000	±1.00" ±10V	±1.00"	±.002"	—	Sample and ho
	y-position (Invar rod)	Schaevitz LVDT GCD-121-1000	±1.00" ±10V	±1.00"	±.002"	—	Sample and ho
	rotation	Schaevitz LVDT GCD-121-250	±.250" ±10V	±.061" (±1°)	±.0012" (±.02°)	—	Sample and h
	6 limit switches	—	—	—	—	—	C057
	command to reset interlocks	40ma@3V	—	—	—	—	C180
	command to initiate purge	40ma@3V	—	—	—	—	C180
	command to turn water on/off	40ma@3V	—	—	—	—	C180
	command to set bias current	unipolar DAC	—	—	±5%	—	C052
	power supply peak current	Sample and hold	±10V	±10V	±1%	—	MADC
	power supply high voltage	Sample and hold	±10V	±10V	±1%	—	MADC
	power supply current during beam	analog P.S. output	±10V	±10V	±1%	—	Sample and hold

Device							Table 1 cont.
	lens current and transformer primary current	Rogowski coil	—	0-2.7V	±1%	—	2-C191 @600KHz
	lens voltage	1000:1 divider	—	-1.5 to +2.5V	±1%	—	C191 @600KHz
	bias current	shunt	—	0-10 amps (0-1V)	±5%	yes	MADC C180
	power supply controller	—	—	—	—	—	C119
	pulse timing	—	—	—	1μsec	—	XMR 2C177
	9 temperatures	thermocouple		0-100°C	±1C°	yes	9 MADC 9 C180
	1 T.C. reference	OM101		0-100°C	±.1C°	yes	MADC
	~~primary and secondary~~ 2 cooling water flow			10 gal/min (2.5V)	±1%	yes	4-MADC 4-C180
	2 cooling water conductivity	resistivity meter K5660-70	0-25MΩ/cm (0-9V)		±1%	yes	2-MADC 2-C180
	~~primary and secondary~~ 2 cooling water pressure		—	—	—	yes	4-C180
	Strain gage and pressure transducer	Ailtech SG125-01F (1.5)-10-6S				—	2-MADC
	water on/off		—	—	—	yes	C180
	water purge	conductivity meter	—	—	—	yes	C180
Pulsed magnet	current	Rogowski coil	—		±1%	—	C191
	voltage	divider	—		±1%	—	C191
	magnetic field	B-dot	—		±1%	—	C191
	power supply peak current	Sample and hold	±10V	±10V	±1%	—	MADC
	Power supply peak voltage	Sample and hold	±10V	±10V	±1%	—	MADC
	power supply current during beam	analog P.S. output	±10V	±10V	±1%	—	Sample and hold
	3 temperatures	thermocouple			±1C°	yes	3-MADC 3-C180
	~~primary and secondary~~ 2 cooling water flow				±1%	yes	4-MADC 4-C180
	2 cooling water conductivity	resistivity meter K5660-70	0-25MΩ/cm (0-9V)	10 gal/min (2.5V)	±1%	yes	2-MADC 2-C180
	~~primary and secondary~~ 2 cooling water pressure		—	—	—	yes	4-C180
	Power supply controller	—	—	—	—	—	C119

Table 1 continued

Beam dump	10 temperature	thermocouple		0-100°c	±1c°	yes	10-MADC 10-C180
	primary and secondary 2 cooling water flow				±1%	yes	4-MADC 4-C180
	primary and secondary 2 cooling water pressure		—	—	—	—	4-C180
Vault air system	2 temperature	thermocouple		0-100°c	±1c°	yes	2-MADC 2-C180
	2 pressure	differential gage			±5%	yes	2-MADC 2-C180
	2 air flow			0-1000 cfm	±10%	yes	2-MADC 2-C180
	1 humidity	relative humidity gage		0-100%	±2%	yes	MADC C180
Beam Stop	1 position	Schaevitz LVDT				—	MADC
	4 limit switches		—	—	—	—	4-C180
	command - motor forward		—	—	—	—	C180 (out
	command - motor reverse		—	—	—	—	C180 (out
Misc	Beam loss monitors						5 MADC
	Beam current torode						5 MADC

In addition we probably needs some measurement on the water cooling for the heat exchanges like Temp. in and Temp out & pressures. ✓ J.K. added to list

C.

Table 2

Analog signals from vault master panel to control racks

	Device	Signal	Quantity		Initial Destination	Final Destination
1.	Beam stop	in-out position	1			MADC
2.	Profile Monitors (3 x-y stations)	x, y position	6		Sample + Hold	C-057
		~~high, low voltages~~	6			MADC
		vacuum	3		amp.	MADC
		analog data	6x24 lines		Swic scanner	C-032
3.	Target	x, y position	2		Sample + Hold	C-057
		air temp. TC	4		TC amp.	MADC
		air flow	2		amp.	MADC
		air pressure	2		amp.	MADC
4.	~~Lens~~	~~PS current at beam time~~	1	X	~~Sample + Hold~~	C-057
		x, y, z, rotation	4		Sample + Hold	C-057
		temp. TC	9+1		TC amp., ref	MADC
		bias current	1		amp.	MADC
		argon primary pres	1	X	amp.	MADC
		water pressure	2	X	amp.	MADC
		water flow	2	X	amp.	MADC
		water conductivity	2	X	amp.	MADC
		strain gage	2		amp.	MADC
		Current waveforms	2			C-191
		Voltage waveform	1			C-191
		PS peak I, V	2	X		MADC
5.	Pulsed Magnet	Temp. TC	3		TC amp.	MADC
		current waveform	1			C-191
		mag. field waveform	1			C-191
		other waveform	1			C-191
		water pressure	2	X	amp.	MADC
		water flow	2	X	amp.	MADC
		water conductivity	2	X	amp.	MADC
	PS current at beam	current, field at beam	2		Sample + Hold	C-057
		PS peak I, V	2	X	Sample + Hold	MADC
6.	Beam dump	temp TC	10		TC amp.	MADC
		water pressure	2	X	amp.	MADC
		water flow	2	X	amp.	MADC
7.	Vault air	air temp TC	2		TC amp.	MADC
		pressure	2		amp.	MADC
		flow	2		amp.	MADC
		humidity	2		amp.	MADC

	chan	modules
MADC	73	2
Sample + Hold	15	1 or 2
C-057		1 or 2
C-191	5	5
TC	39	

X = not from vault

Table 2 continued

Digital signals from vault master panel to control racks (status bits, limit switches, encoder outputs)

	Device	Signal	Quantity	Initial Destination	Final Destination
1.	Beam Stop	in-out limits	4		C-180
		moving	1		C-180
2.	Profile monitors	x, y limits	12		C-180
		moving	6		C-180
		high, low voltage	6		C-180
		vacuum	3	X	C-180
3.	Target	x, y limits	4		C-180
		rotation reference	1		C-180
		moving	3		C-180
		air temp	4	X	C-180
		air flow	2	X	C-180
		air pressure	2	X	C-180
		rotary encoder	10 bits	multiplexer	C-057
4.	Lens	x, y, z, rotation limits	8		C-180
		rotation reference	2		C-180
		moving	4		C-180
		bias on	1		C-180
		temp	10	X	C-180
		water pressure	2	X	C-180
		water flow	2	X	C-180
		water conductivity	2	X	C-180
		purge	1	X	C-180
		argon primary pres.	1	X	C-180
		rotary encoder	20 bits	multiplexer	C-057
5.	Pulsed Magnet	temp	3	X	C-180
		water pressure	2	X	C-180
		water flow	2	X	C-180
		water conductivity	2	X	C-180
6.	Beam dump	temp	10	X	C-180
		water pressure	2	X	C-180
		water flow	2	X	C-180
7.	Vault air	temp	2	X	C-180
		pressure	2	X	C-180
		flow	2	X	C-180
		humidity	2	X	C-180
8.	Interlocks	interlock chain broken	5	X	C-180

X = generated at control racks

Table 2 continued

Analog signals from control rack to vault master panel

Device	Signal	Quantity	Source	
1. Beam stop				
2. Profile monitors	high, low voltage	6	power supply	
3. Target				
4. Lens	bias supply	1	power supply	
5 Pulsed magnet				
6 Beam dump				
7. Vault air				

Digital signals from control rack to vault master panel

1. Beam stop	motor power	1	motor driver card	180 (3 bits out)
2. Profile monitors	motor power	6	motor driver card	
3. Target	motor power	3	motor driver card	
4. Lens	motor power	4	motor driver card	
5. Pulsed magnet	reset interlocks, purge, H_2O on X	3	180 (3 bits out)	
6. Beam dump				
7. Vault air				
	X does not go to vault			

Table 3

Cable count – control racks to vault master panel

Signal	quantity	conductor
analog		
TC to amplifier	28	TC wire
misc. to amp.	15	twinax
misc to MADC	7	twinax
position to Sample+Hold	14	twinax
waveform to 191	6	twinax
data to SWIC scanner	6	24 conductor ribbon coax AMP P/N 2-220464-5
high voltage to monitors	3	RG59
low voltage to monitors	3	3 conductor (1 amp)
bias supply to lens	1	2 conductor (10 amps)
digital		
limit switch	31	twisted pairs
motor power on	14	twisted pairs
voltage on	7	twisted pairs
encoder	3	12 conductor cable
power to motor	14	3 conductor (1 amp)

Cable count – misc. sources to control racks

analog		
pulsed supply to MADC	4	twinax
water systems to amp.	28	twinax
lens purge to amp.	1	twinax
pulsed supplies to S+H	2	twinax
c119 to pulsed supply	2	twinax
digital		
c180 to lens H_2O purge	3	twisted pairs
c119 to pulsed supply	2	36 conductor

Cable count – within control racks

analog		
TC amp to MADC	29	twinax
misc amp to MADC	32	twinax
052 (DAC) to lens bias	1	twinax
digital		
amp to 180 multiplexer	60	60 conductors + ground
180 to beam stop motor	3	3 conductors + ground
Interlocks 180 multiplexer	5	5 conductors + ground

Table 3 Continued

Cable count - modules to vault master panel

Device/signal	quantity	conductor
1. Beam Stop		
analog		
position to sample + Hold	1	twinax
digital		
limits, motors on	5	twisted pairs
motor power	1	3 conductor (1 amp)
2. Profile monitors		
analog		
misc. to amp.	3	twinax
misc to MADC	6	twinax
position to S+H	6	twinax
data	6	24 conductor ribbon coax
High voltage to mon.	3	RG 59
low voltage to mon.	3	3 conductor (1 amp)
digital		
limits, motors on	18	twisted pairs
voltages on	6	twisted pairs
motor power	6	3 conductor (1 amp)
3. Target		
analog		
TC to amp	4	TC wire
misc. to amp	4	twinax
position to S+H	2	twinax
digital		
limits, motors on, ref. pt.	8	twisted pairs
encoder (10 bit)	1	12 conductor cable
motor power	3	3 conductor (1 amp)
4. Lens		
analog		
TC to amp.	9	TC wire
misc to amp.	2	twinax
position to S+H	4	twinax
waveforms	2	RG 58
lens bias current	1	twinax
digital		
limits, motors on, ref. pts.	14	twisted pairs
bias on	1	twisted pair
encoders (10 bit)	2	12 conductor cable
motor power	4	3 conductor (1 amp)
5. Pulsed magnet		
analog		
TC to amp	3	TC wire
Sample + Hold at beam time	2	twinax
wave forms	3	RG 58

Table 3
continued

cable count - modules to vault master panel, continued

6. Beam dump		
analog		
TC to amp.	10	TC wire
7. Vault air system		
analog		
TC to amp.	2	TC wire
~~misc to amp.~~	6	twinax

Table 4

Module requirements for target vault instrumentation

Module	channels required	number of modules required*	required delivery date	supplier	Connector
MADC differential in	89	2	1-June1 1-Oct1	controls group	twinax into interface box
C-190 (MADC control) or S+H control		3	1-June1 2-Oct1	"	
Sample + Hold differential in.	12+4	2	1-June1 1-Oct1	"	
C-057 (S+H control) for LVDT's		1	June1	"	
C-177 (delay)	5	2	Sept1	"	
C-180 (bits in-out)	129 in 6 out	1	Sept1	"	
C-180 multiplexer in Eurocrate		1	Sept1	"	Burndy
C-191 digitizer	6	6	1-May1 5-Oct1	"	Viking edge : back of modu
C-052 (DAC)	1	1	Sept1	"	
C-119 (P.S. controller)	2	2	Sept1	"	
XMR	1	1			
motor drive card	14	14	2-June1 12-Oct1	John Funk	
motor drive interface		1	June1	John Funk	
High Voltage Supply	5	5	Nov 1	Droege	
TC amps.	35	35	all-Oct1	1/4 built by Obie, Bob	
TC amp. crate		4			
Misc amps.	39	39			
Misc amp. crates		4			
interlock systems interlock crates	5	3			
SWIC Scanners		3	Sept1		
Scanner Controller (032)		3	1-June1 2-Sept1	controls group	
CAMAC crates with power		2	1-June1 1-Oct1	"	
CAMAC crate controller		2	1-June1 1-Oct1	"	

* totals do not include spares

Rack space required

item	quantity	height(each)	total height
MADC	2	7.00"	14.00"
Sample + Hold	2	3.50	7.00
Motor drive crate	1	7.00	7.00
180-multiplexer	1	7.00	7.00
TC amp crate	3	5.25	15.75
misc. amp crate	4	5.25	21.00
interlock crate	3	5.25	15.75
SWIC scanner	3	1.75	5.25
link driver	1	3.50	3.50
CAMAC crate	2	8.75	17.50
5223 oscilloscope	2	7.00	14.00
NIM crate	2	8.75	17.50
Motion System power	1	5.25	5.25
Lens bias supply		5.25	5.25
Total inches of rack space			155.75

CAMAC crates required

module	quantity	width(each)	total width
032	3	2 slots	6 slots
052	1	1	1
057	1	1	1
119	2	1	2
177	1	1	1
180	1	1	1
190	3	1	3
191	6	2	12
motor control	1	2	2
crate controller	2	4	8
total CAMAC space required			37 slots

Programming to be done:

I. Parameter page display
1. Read out status bits via multiplexed C-180
2. Read out MADCs via C-190
3. Read out LVDT positions – Sample and Hold via C-057
4. Read out rotary encoders via C-057
5. Read out limit switch status via C-057
6. Read out sample and Hold of waveforms at beam time

II. Miscellaneous control operations from keyboard
1. control beam stop via C-180 bits out
2. control water systems, lens purge via C-180 bits out
3. control lens bias current supply via C-052
4. control pulsed power supplies via C-119
5. control all module positions via C-057
(requires routine to transform from Cartesian to cylindrical coordinates)
6. control waveform digitization via C-191
(requires C-191 control plus processing and display and storage of data)
7. control SWIC scanners via C-032 – process data? display?

III. C-057 microprocesser programming (Al Franck will do this)

IV. Application programs.

1. Lens translation with excentrics.

2.- Calculation of Beam Spot Size at target

3.- Special scanning programs to measure $\bar{p}$ yield vs. parameters in the target station.

Appendix 1

$(X,Z) \rightarrow (\theta_1, \theta_2)$ coordinate transformation for lens eccentrics

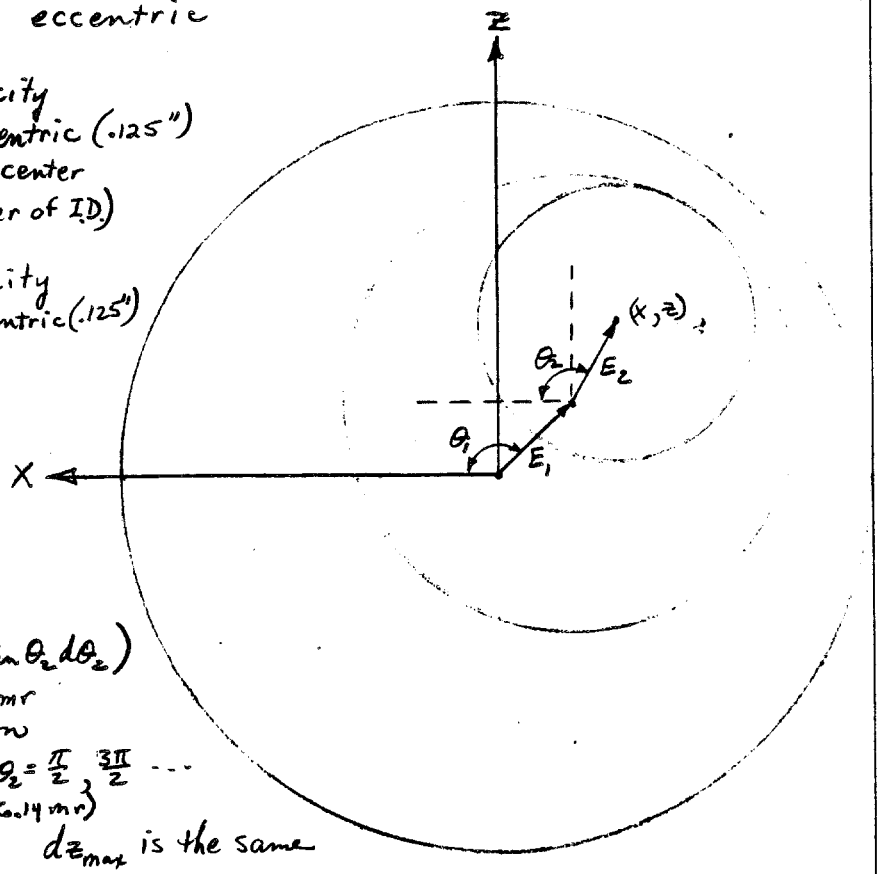
1. (x,z) are the Cartesian coordinates of the center of the bore in the inner eccentric

θ_1 is the angle between the x-axis and the radius of eccentricity of the outer eccentric

θ_2 is the angle between the x-axis and the radius of eccentricity of the inner eccentric

E_1 is the eccentricity of the outer eccentric (.125") (distance between center of O.D. and center of I.D.)

E_2 is the eccentricity of the inner eccentric (.125")



The equations relating (θ_1, θ_2) to (x,z) are,

$$\boxed{\begin{aligned} x &= 0.125(\cos\theta_1 + \cos\theta_2) \\ z &= 0.125(\sin\theta_1 + \sin\theta_2) \end{aligned}}$$

2. Resolution in x is:

$dx = -0.125(\sin\theta_1\, d\theta_1 + \sin\theta_2\, d\theta_2)$

$d\theta_1 = d\theta_2 = \frac{1}{1024}\text{ rev} = 6.14\text{ mr}$

= angular resolution

dx is maximum at $\theta_1 = \theta_2 = \frac{\pi}{2}, \frac{3\pi}{2} \ldots$

$dx_{max} = -0.125(6.14\text{ mr} + 6.14\text{ mr})$

$\boxed{dx_{max} = 0.00154 \text{ inch}}$ $\quad dz_{max}$ is the same

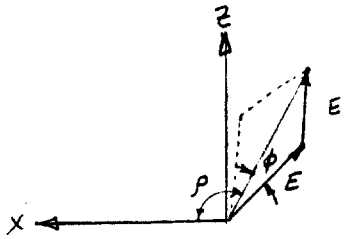
3. To solve for the inverse equations:

- There are two (θ_1, θ_2) solutions for each (x,z) except (1) the origin which has an infinite number of solutions, and (2) any point on the circle of radius $E_1 + E_2$ which has one solution $\theta_1 = \theta_2$

- Define the variables $\rho = \tan^{-1}\frac{z}{x}$, $\phi = \cos^{-1}\left(\frac{\sqrt{x^2+z^2}}{2E}\right)$, where

ρ = the angle between the x axis and the line segment from the origin to (x,z)

ϕ = the angle between E_1 and the line segment from the origin to (x,z)

$$\left\{\begin{aligned} \theta_1 &= \rho - \phi \\ \theta_2 &= \rho + \phi \end{aligned}\right\} \text{ or } \left\{\begin{aligned} \theta_1 &= \rho + \phi \\ \theta_2 &= \rho - \phi \end{aligned}\right\}$$

$$\boxed{\begin{aligned} \theta_1 &= \tan^{-1}\frac{z}{x} \mp \cos^{-1}\left(\frac{\sqrt{x^2+z^2}}{2E}\right) \\ \theta_2 &= \tan^{-1}\frac{z}{x} \pm \cos^{-1}\left(\frac{\sqrt{x^2+z^2}}{2E}\right) \end{aligned}}$$