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A VERY-HIGH-LEVEL NEUTRAL-BEAM CONTROL SYSTEM

Victor Elischer, Van Jacobson, and Edward il

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Victor Elischer
Van Jacobson
Edward Theil

Real Time Systems Group
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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A Very High Level Neutral Beam Control System

Victor Elischer
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Edward Theil

Real Time Systems Group
Lawrence Berkeley Laboratory
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As increasing numbers of neutral beams are added to fusion machines, their operation can consume a significant fraction of a facility's total resources. LBL has developed a very high level control system that allows a neutral beam injector to be treated as a "black box" with just 2 controls: one to set the beam power and one to set the pulse duration. This "2 knob" view allows simple operation and provides a natural base for implementing even higher level controls such as automatic source conditioning.

1. Introduction

In this paper we restrict ourselves to a general discussion of neutral beam control and to principles we believe contribute to a successful system. In particular, we believe the system is based on a control hierarchy with two essential features:

(1) Its levels reflect actual stages of beamline construction and operation. This tends to encourage appropriate software done at an appropriate time.

(2) There is an explicit recognition that data produced at any level must be saved and available for use at higher levels. This tends to make a system which grows by building on previous work, rather than by

redoing it.

In the following sections of this paper we first discuss the control hierarchy in general, followed by a description of its levels. Often the control structure leads to a particular software methodology and we enlist these cases as examples of the usefulness of the hierarchy.

All our statements are based on experience in designing and implementing such a system, which is currently in operation at NBSTF. (Other papers by our group have dealt with the original ideas for neutral beam control [1], the operator interface [2], basic design principles [3] and a general overview [4]).

2. The Control Hierarchy

A neutral beam system (including equipment, operators, physicists, etc.) is developed in a number of consecutive stages. In general there is

- A checkout and commissioning phase for individual sensors. For example, thermocouples are checked with a heat gun to see if they respond, then examined during operation to see if they respond uniformly and if their readings are physically reasonable.

- A subsystem investigation phase that examines the behavior of related sensors. For example, once one believes the thermocouple temperatures, it is possible

to compare the temperature distribution given by all the thermocouples on a calorimeter to the predictions of various mathematical models. Once a model with fair agreement is found, the entire distribution can be characterised by the parameters of the model.

- A manual operation phase that examines the shot-to-shot variations of various models and uses them to develop operating strategies for the system. For example, one learns that an optimum perveance is only valid for about a 10KV range of accel voltage. These empirical observations then give rise to operational rules: e.g., when conditioning a source by moving up in accel voltage, "tune" the source by doing a perveance sweep every 10KV.

- An automated operation phase in which a computer implements the mechanical aspects of the operating strategies by using the models to make predictions. For example, one can directly control the accelerator voltage, but not the current; the latter is determined by the arc power. That, in turn, is a function of the arc and possibly filament voltages and currents. Thus a small change in accel voltage requires adjusting the accel, arc and filament power supplies. Given models for accel, arc and filament impedances and the arc power-accel transfer function, an operator request for a new accel voltage can be translated into the

setpoints for the three power supplies.

Although these levels show roughly chronological development, the lower levels remain essential to the operation. I.e., debugging a beamline requires essentially a trace back through the levels. As an example, the divergence angle of the beam may be abnormally large; the cause may be a bad thermocouple or a melted accelerator. Inspection of the low level thermocouple and waveform data allows one to distinguish between the two possibilities.

These stages of implementation translate directly into four levels for neutral beam programs and, indirectly, to a corresponding system structure. The levels we identify are:

(1) Data Acquisiton and Display

(2) Static Subsystem Modeling

(3) Dynamic Systems Modeling

(4) Prediction and Control

Each of these levels will now be discussed individually.

3. Level 1: Data Acquisition and Display

This level is of course the most obvious and fundamental one. At NBSTF, the data acquired by the computer includes a wide variety of thermocouple data, waveforms and many scalar beamline values (see Fig. 1). While it is obvious that

nothing can be done unless and until data is acquired, it is equally obvious that useful information derived from the data must be displayed, at least in some rudimentary form. For that reason, we include display at this level as well.

At NBSTF, an effort has been made to have all displays as graphical as is reasonably practical. For example, temperature information for any device instrumented with thermocouples is displayed on a screen (color or black and white) by a scale drawing of the actual object with temperatures at each thermocouple position. Almost precisely the same information may be used to implement control "buttons" that turn individual thermocouples "on" or "off" in software, indirectly causing more analytic models to recalculate their derived values.

The example we have chosen to follow from the lowest to the higher levels starts with the temperature display of Fig. 2. Since the target dump is a rather unexciting rectangular slab, the display is simply an array of values with auxiliary information appended.

We had many such displays to do, and their commonality led us to think about some general methods for doing them. The displays became data-driven in a quite literal sense. That is, not only is the temperature data an input to the display program, but the location of the sensors, the geometry of the physical device, the location of display labels and the colors to be used are input data as well. Thus a single task

serves to display the thermocouple temperatures for every instrumented collimator and beam dump in any of several beamlines. Figures 2 and 3 are two examples of outputs from this task.

In turn, this imposes a requirement on the storage of the data itself. For example, the display task is clearly going to need thermcouple data (e.g., temperatures, sensor locations) for any of a number of devices. Given a database that allows a request of that type ("give me all temperature data for device X"), in a completely uniform way across all such devices, the display task can avoid the need for special "wired-in" information about any particular device.

If the database contains an explicit description of the beamline for the computer to use, then it can contain descriptions of more than one beamline. The name of any device, and the data set associated with it, can be extended to include a beam-source identifier in order to permit multi-beamline operation. In this way, the control hierarchy leads to a requirement for the software architecture, as we suggested earlier.

4. Level 2: Static Subsystem Modeling

At this level we have in mind the use of models, simple or complex, that help to describe and control the current state of a subsystem when it depends only on the latest shot. For example, a particularly important static model is the neutral

beam timing system. The actual timing sequences are modeled by a collection of software pulses, with each pulse having its leading and trailing edges referenced to edges of other pulses. An advantage of this scheme is that pulses can be slaved to others automatically in software. This guarantees that certain events cannot precede others if they are not supposed to and that all events in a timing chain will be set correctly by merely setting the primary event. A fairly elaborate graphical display on the touch panel allows the operator to easily vary timing parameters. For example, varying beam request time not only changes that parameter, but will also change the timing pulses for filament, arc and accel automatically (Fig. 4).

Our example from level 2 is continued in Fig. 5. Here the temperature data from level 1 is input to a two-dimensional error function model of the beam profile and a data fitting routine derives quantitative information. Again, we note the usefulness of data-driven tasks: When the target dump was introduced into the NBSTF beamline, the same programs that had performed the calorimetry analysis on the earlier beam dump ran successfully with no change in code. As in the case of temperature displays, the geometry of the dump and the location of the sensors form part of the data input to the task, which does not contain assumptions about the device it is to model. In itself, this form of calorimetry is very valuable (the model is not original with us [5]). However, it also produces information that serves as inp to the next

higher level of the control system.

5. Level 3: Dynamic System Modeling

The word dynamic implies that now we are concerned with states that are time dependent. In order to model such states, one must have available information that incorporates historical data either explicitly , as from an archive, or implicitly, as with recursive filters. We give an example of each.

Fig. 6 continues our example. Basically, the beam divergences from a certain number of previous shots are plotted against their respective perveances (or accel currents) and fitted to a parabola. The idea is to determine the optimum beam perveance (and thus accel current) for a given accel voltage. The primary inputs to this scheme are the waveform averages from level 1 and the beam divergences from level 2 (see figures 5 and 6).

A more ambitious task is illustrated in Fig. 7. Source models are mathematical descriptions of the various components of the ion source: filament, arc, accel/arc and accel/perveance. The describing equations are coupled. The models estimate the current state of various source parameters: arc impedance, arc "efficiency" (in producing accel current), etc. Because these values depend on many different variables that change in time (e.g., rate of flow of source gas, cryo temperatures), we have used Kalman

filters for the estimation process. (The details of this task are the subject of a separate LBL Report, to appear). Again, these models depend on waveform data generated at level 1 and beam divergences from level 2.

6. Level 4: Prediction and Control

In figure 8 the source modeling idea is carried to its logical conclusion. Given estimates of all the source parameters derived from lower level data and a "knob" with which a beam operator (or some computer program) can choose V-accel, all other voltages and currents can be computed and set via the source models. That is, given V-accel, the accel current is a function of the perveance. Given accel current, the arc power is determined by the accel-arc transfer function. Given arc power, and estimates of the arc and filament impedances, the filament and arc voltages and currents may be computed. Then another set of lower level static models of the NBSTF power supplies translates each (I,V) pair into the appropriate units of the local power supply hardware.

Finally, we observe that automatic source conditioning requires essentially one additional step: a decision making process by which the computer can decide when V-accel should be stepped up or down and by how much. We have recently implemented such a process (its display is shown in Fig. 9). Space does not permit a detailed explanation of it here but,

briefly, a filtered "conditioning index" and its derivative are updated and examined on every shot. When both pass certain (operator setable) thresholds, the decision to raise or lower V-accel is made.

Thus, we have the "2 knob view". The operator (or computer) chooses the accel voltage and the computer uses its internal models to set all other source requirements. The operator chooses a pulse duration and the computer uses other internal models to set all other timers.

7. Summary and Conclusions

We have discussed a neutral beam control system whose underlying hierarchical structure plays a critical role in achieving three goals:

(1) The system permits high level operation. That is, a single knob control sets the duration of the pulse and another knob sets the voltage for the accelerator. All other values are calculated internally and set by the computer.

(2) It contains a variety of diagnostic and lower level controls for monitoring and debugging the beam and its subsystems.

(3) It permits multi-source, multi-beamline operation.

The characteristics of the hierarchy enter into the design of the system. First, they help keep separate those functions which must be used independently. For example, originally, the error function fit of calorimeter temperatures was to be combined with the thermocouple data acquisition. This would have deprived the engineer testing the thermocouples of the raw temperature display, making the check-out more difficult. It also would have generated endless speculation during testing of the fit about whether the model, the data or the program was in error.

Equally important, the hierarchy indicates the necessary temporal and logical precursors of programs and prevents programming from being done prematurely and on the basis of incomplete information. It is not only that the structure decouples programs; many possible architectures will help to achieve that desirable result (cf(1)). The point to be emphasized here is that the hierarchy, paralleling as it does the development of the beamline operation, ties the computer system to the real world.

For example, one of our early mistakes was to start work on high level source modeling and autoconditioning before reliable data on source behavior was available. This is neither uncommon nor surprising; the problem was appealing and challenging. Nevertheless, the premature work was necessarily based on assumptions which did not jibe with the reality of the data we eventually obtained. Inevitably, these

assumptions had to be discarded and programs substantially rewritten, with considerable effort wasted. The control structure makes clear that the type of data and its characteristics will shape high level algorithms, rather than vice versa.

By the same token, the hierarchy also makes it clear that the results of one level must be available to the next. For example, when the calorimeter fit program was first written, the only use forseen for the divergence angle was as operator information on a display. On general principles, however, it and all other fit results were put in the database. Then, when the need for automatic source tuning was realized six months later, the tuning program was relatively simple, since it could pick up the divergence and average waveform values from the database.

Finally, the hierarchy tends to group similar functions on the same level, where the commonality of tasks can lead to efficient design and implementation. (Examples of this were given in the sections on Data Acquisiton and Modeling). The existence of these common functions allows the system to be constructed of small, data-driven tasks, much as in an earlier day closed subroutines were first used for their ability to perform identical computations, with only the input arguments varying.

Our belief is that the principles discussed in this paper can be carried over to other control problems. Our hope is that

we have elucidated these ideas sufficiently well to interest others engaged in similar activities.

8. References

1. V. Elischer, S. Fehr, V. Jacobson, K. Wiley, Proceedings of the Sixth Symposium on Engineering Problems of Fusion Research, San Diego, Calif., 1975

2. V. Elischer, J. Fiddler, Graphical Human Interface to a Neutral Beam System, Lawrence Berkeley Laboratory Report LBL-9146 Also, Proceedings of SIGGRAPH Conference, 1979.

3. V. Elischer, V. Jacobson, et al., (Chapter 4 of) A Conceptual Design for the ZEPHYR Neutral Beam Injection System, Lawrence Berkeley Laboratory Report LBL-12383

4. E. Theil, V. Elischer, et al., Progress in Computer-Assisted Diagnosis and Control of Neutral Beam Lines, Proceedings of the Eleventh Symposium on Fusion Technology, Oxford,1980 and Lawrence Berkeley Laboratory report LBL-11839.

5. J. Kim, J.H. Whealton, Nucl. Instruments and Methods,141, 187 (1977)

Acknowledgment

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COMPUTER FUNCTIONS PRESENTLY AVAILABLE AT NBSTF

CONTROL LEVEL	NUMBER OF DISPLAYS per ION SOURCE
DATA ACQUISITON AND DISPLAY	
Cryo Sensors	1
Vacuum Ion Gauges	1
Camac Status	1
Waveform Data	13
Photodiode Waveforms	4
Thermocouples	11
Sensor On/Off Controls	11
Waterflow Calorimetry	11
Misc. Beamline Scalars	Various
Shot Summary	1
STATIC SUBSYSTEM MODELING	
Photodiode Beam Profile	1
Temperature Distribution Profile	2
Isothermal Contours	3
Three-dimensional Temperature Profile	3
Doppler Shift Species Model	1
Plasma Probe Profile	1
Timing Control	8
Power Supply Models	5
DYNAMIC SYSTEM MODELING	
Source Modeling	1
Perveance History	1
Source Tuning	1
PREDICTION AND CONTROL	
Power Supply Control	1
Automatic Source Conditioning	1

Figure 1

SHOT 66214 TARGET DUMP 10/05/81 11:56

0.0 0.4	0.0 5.4	0.0 4.6	0.0 3.7	0.0 7.0	0.0 72*9	0.0 4.2	0.4 7.9	0.0 6.2	0.4 40*7	0.0 5.8	0.0 6.6
0.0 6.6	0.0 7.0	0.0 5.0	0.0 4.6	0.0 6.2	0.0 4.6	0.0 5.0	0.0 2.9	0.0 6.2	0.4 75*1	0.0 7.0	0.0 6.6
0.0 4.6	0.0 0*0	0.0 5.4	0.0 4.2	0.0 2.9	0.0 5.4	0.0 0*0	0.0 3.7	0.0 6.6	0.0 6.2	0.0 6.6	0.0 5.8
0.0 7.0	0.0 5.0	0.0 3.7	0.0 5.0	0.0 5.0	0.0 0.3	0.0 5.0	0.0 3.7	0.0 9.5	0.0 6.2	0.0 6.6	0.0 5.8
0.0 7.0	0.0 2.5	0.0 5.0	0.0 3.7	0.0 6.5	0.0 7.0	0.4 4.2	0.0 2.5	0.0 6.6	0.0 6.2	0.0 34.8	0.0 8.3
0.0 5.0	0.0 6.6	0.0 5.0	0.0 5.0	0.0 5.0	0.0 3.7	0.0 5.4	0.0 3.7	0.0 6.6	0.0 7.4	0.0 7.0	0.0 7.0
0.0 6.2	0.0 -6.3	0.0 5.0	0.0 5.4	0.0 7.9	0.0 5.0	0.0 4.2	0.0 4.2	0.0 6.6	0.0 5.4	0.0 7.0	0.0 6.2
0.0 7.4	0.0 -5.9	0.0 5.0	0.0 5.0	0.0 6.6	0.0 5.4	0.0 4.6	0.0 3.3	0.0 6.6	-0.4 6.6	0.0 7.9	0.0 5.0

		AVG	PEAK
DELTA T	DEL	0.0	0.4
REF TEMP	REF	5.7	34.8
	FIN	5.7	34.8

All temps in degrees C
viewed from source

* 5 BAD SENSORS

Figure 2.

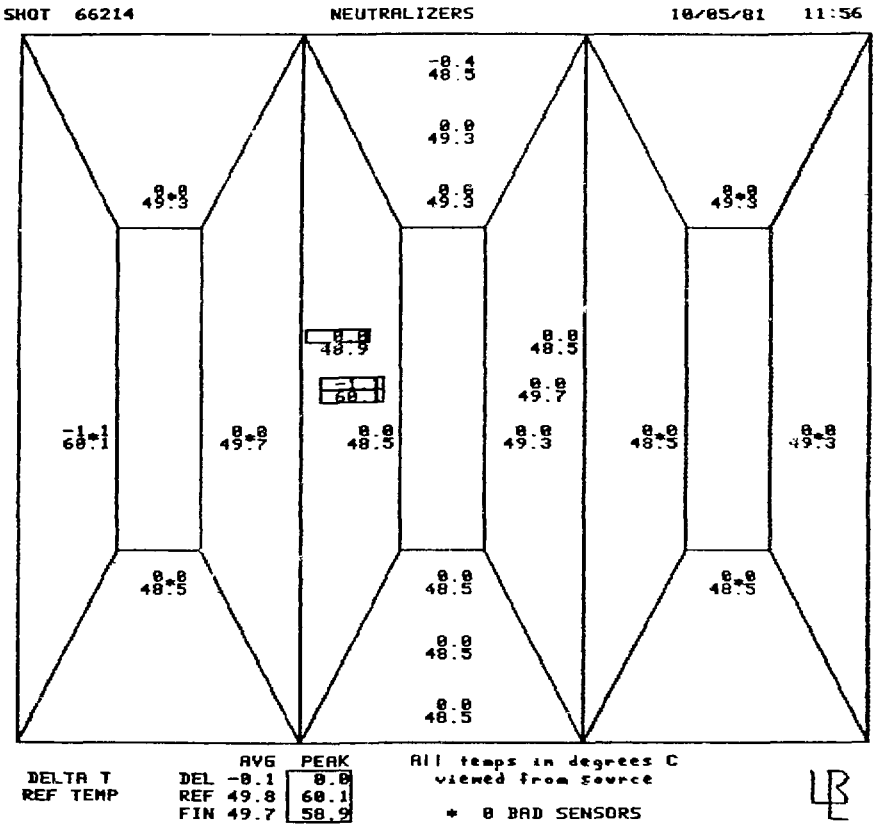

SHOT 66214
NEUTRALIZERS
10/05/81 11:56
-0.4
48.5
0.0
49.3
0.0
49.3
0.0*
49.3
0.0*
49.3
0.0
48.9
-1.1
60.1
0.0
48.5
0.0
49.7
-1.1*
60.1
0.0*
49.7
0.0
48.5
0.0
49.3
0.0*
48.5
0.0*
49.3
0.0*
48.5
0.0
48.5
0.0*
48.5
0.0
48.5
0.0
48.5
AVG PEAK
DELTA T
REF TEMP
DEL -0.1 0.0
REF 49.8 60.1
FIN 49.7 58.9
All temps in degrees C
viewed from source
* 0 BAD SENSORS

Figure 3.

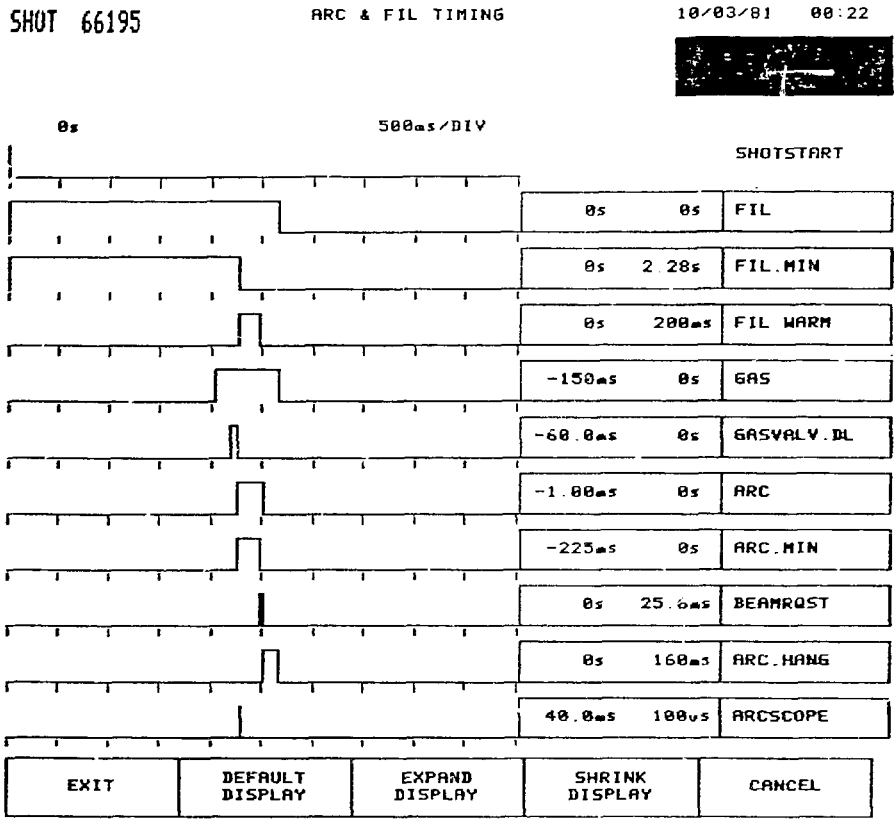

SHOT 66195
ARC & FIL TIMING
10/03/81 00:22
0s
500ms/DIV
SHOTSTART
0s 0s FIL
0s 2.28s FIL.MIN
0s 200ms FIL WARM
-150ms 0s GAS
-60.0ms 0s GASVALV.DL
-1.00ms 0s ARC
-225ms 0s ARC.MIN
0s 25.6ms BEAMRQST
0s 160ms ARC.HANG
40.0ms 100us ARCSCOPE
EXIT
DEFAULT DISPLAY
EXPAND DISPLAY
SHRINK DISPLAY
CANCEL

Figure 4.

TARGET DUMP

SHOT 66708 I-accel 39.3 A. V-accel 89.9 KV. 10/08/81 13:25

Beam on 81.2mS

DIV (+) 1.31 degs(22.9 mrads) 53.5 cm FWHM
DIV (||) 0.41 degs(7.2 mrads) 15.7 cm FWHM

Y-cmt -0.1 cm (-0.1 mrads)
X-cmt 1.3 cm (1.1 mrads)

ROTATION -0.5 degs
CHI-SQUARE 0.5

dT max = 8.2 C
dT max = 8.7 C (from fit)
dT avg = 1.6 C

dP/dA max = 2.14 KW/sq.cm 24.2% Accel pwr
P (t.dump) = 1.81 MW 51.2% Accel pwr
P (t.dump) = 1.8 MW (from fit)

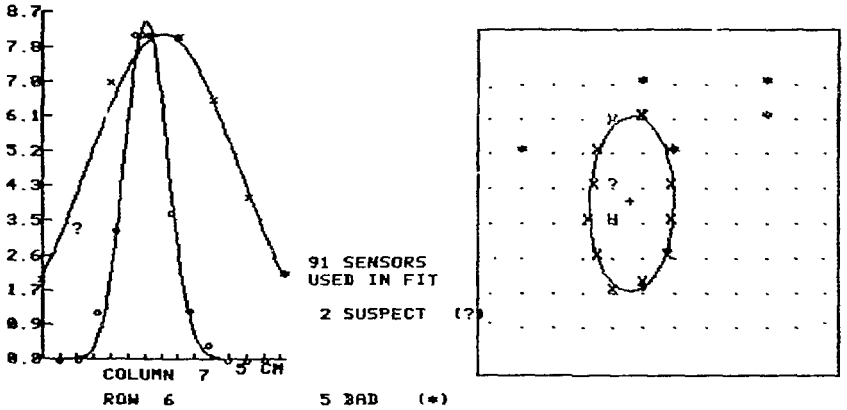


Figure 5.

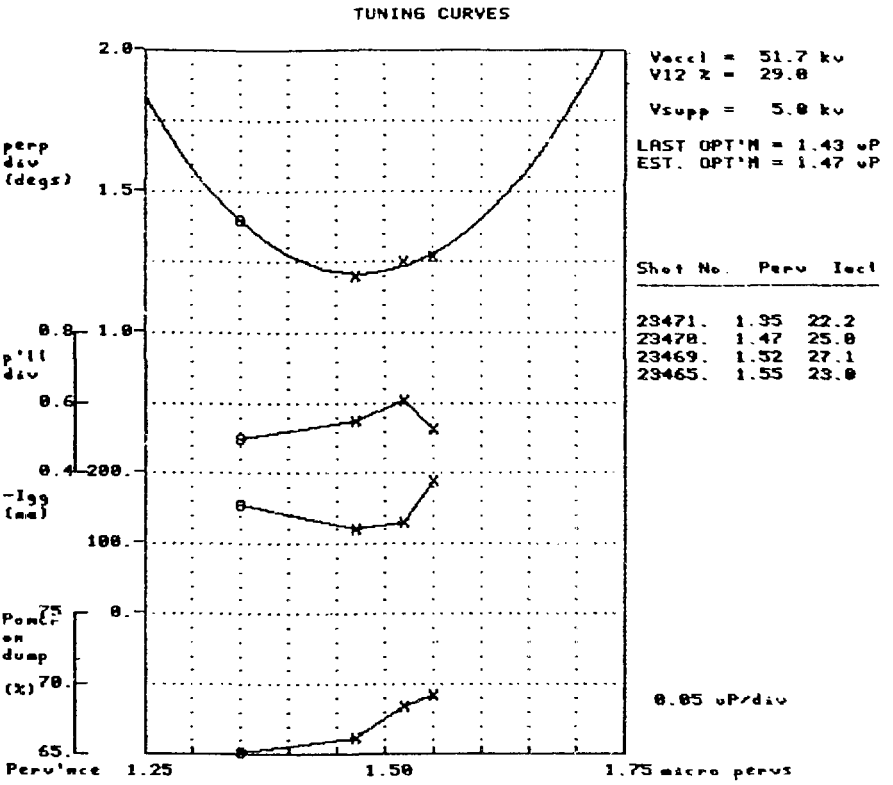
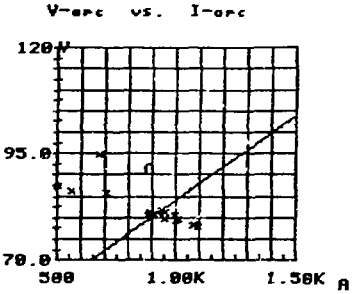

TUNING CURVES
Vaccl = 51.7 kv
V12 % = 29.0
Vsupp = 5.0 kv
LAST OPT'M = 1.43 uP
EST. OPT'M = 1.47 uP
Shot No. Perv Iacl
23471. 1.35 22.2
23470. 1.47 25.0
23469. 1.52 27.1
23465. 1.55 23.0
perp div (degs)
p'll div
-Igg (ma)
Power on dump (%)
0.05 uP/div
Perv'nce
micro pervs
2.0
1.5
1.0
0.8
0.6
0.4
200.
100.
0.
75
70.
65.
1.25
1.50
1.75

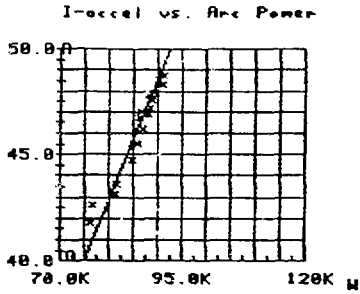
Figure 6.

SOURCE MODELS

SHOT 66214 10/05/81 12:21



V-arc = 0.0396Iarc + 44.36



Iaccel = 0.566E-03Parc + -2.434

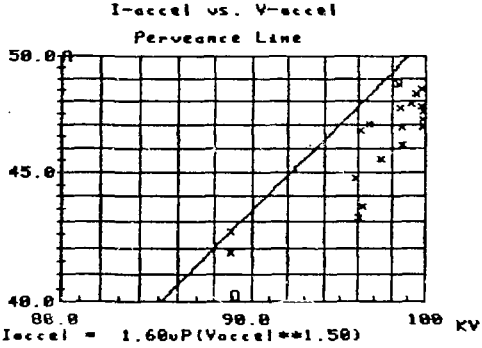
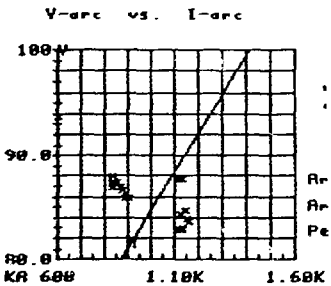


Figure 7.

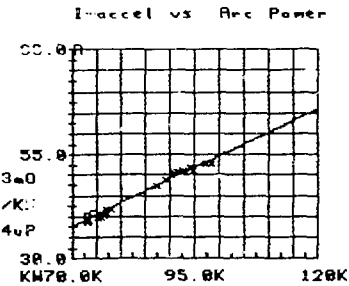
POWER SUPPLY CONTROLS

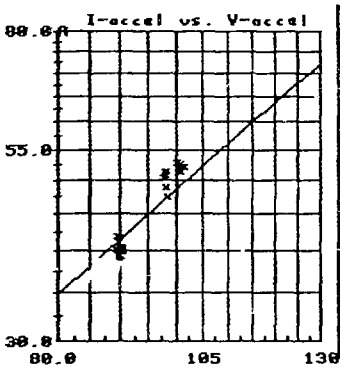
SHOT 66709 10/08/81 13:31



'R' -- REC'D
'A' -- ASKED

Arc Imped 36.83mΩ
Arc eff'y .57mA/K
Perveance 1.54uP



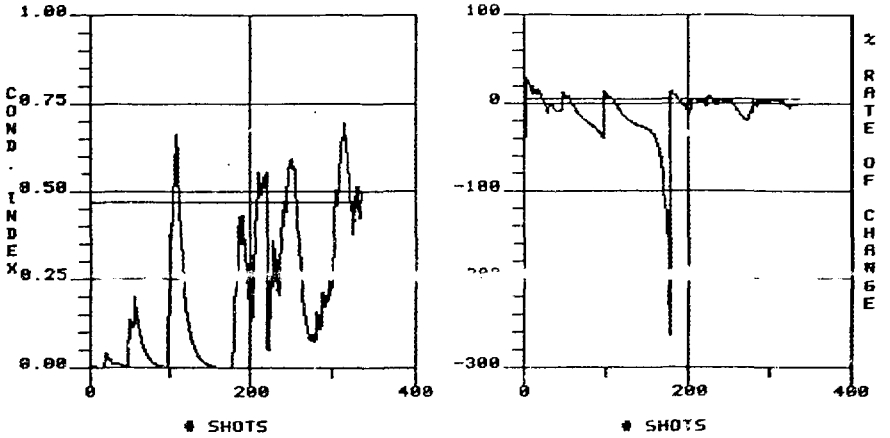


	Current Setpts	Deviations R-A	%	Corrections Abs	%
Perv	1.48uP	-9.13nP	-1		
Vacl	90.3KV	-277V	-0.	8V	0
Iacl	48.2A	[illegible]32mA	-1.	450mA	1
Parc	74.4KW	-972W	-1.	886W	1
Ifil	3.30KA	73.1A	2.		
V12	0%	15.2%	*00.		

Figure 8.

10/08/81 14:25

CONDITIONING HISTORY



V-accel = 90.0KV I-accel = 41.7A

SOURCE SEEMS TO BE CONDITIONED AT THIS LEVEL

V-ACCEL INCREASE REQUESTED

Figure 9.