Achieving Next Generation Performance of Ion Implanters with the Varian Control System (VCS)

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Abstract-**This paper addresses the practical realization of a complex hierarchical control system, which is able to maintain controllability and observability conditions in a fault tolerant manner for a variety of ion implanters as well as other related systems.**

I. INTRODUCTION

The primary goal of any control system is to make the system observable and controllable [1]. A primary problem, in this regard, is to adequately determine state and appropriately operate under an operational space that constitutes a full range of typical scenarios. I.e., the control system must be able to maintain controllability and observability in the event of exceptions as well as in a variety of operational modes. Many control systems are designed to excel in one mode and not another. For example, an auto-pilot works for straight and level flight and manual intervention is required under other conditions. Similarly, typical control systems for implanters require manual intervention or else lose observability and controllability as a rule rather than an exception. The Varian Control System (VCS) is designed to maximize the conditions under which controllability and observability of the system are maintained.

Moreover, given the importance of the process integrity considerations associated with the main function of an ion implanter, integrity is something that can be measured and, in the case of VCS, the state of the system can be replayed at a future time.

The concept of a hierarchy has been around for a while, but it remains difficult to precisely quantify mathematically. It is a necessary aspect of modern control system implementations; therefore, its origins are of interest. Mesarovic provided some foundations [2], but formalized realizations for large-scale systems are not easy to identify.

The idealized set of functional characteristics is as follows:

1. The control system must be partitioned as the sheer complexity and magnitude of the system requires this for practical considerations from an implementation as well as a comprehension perspective.
2. The controllability and observability must be determined within each partition in a periodic and deterministic manner. In much the same way that an integrated circuit is synchronized by a periodic clock, the control of the system in question must be synchronized in order to maintain controllability and observability.
3. To formally confirm the above principles as well as for audit and analysis purposes, observability and controllability must be demonstrable via an ability to replay whatever happens in the system, past or present. Such a capability is a prerequisite for predictive capabilities [3], which are presently under development.
4. The means for implementation of the above must be 'reusable' in the sense that once applied to a particular system, the next system should be at least as fast or faster (assuming a high degree of reuse) to implement.

   NOTE: Simultaneous realization of all of the above constitutes necessary conditions in order to estimate, control and predict the state of the system [3].

The manner in which these are realized is the focus of this paper.

II. REALIZATION

Condition 1 – Hierarchy of Subsystems: Organizations and control are often partitioned and organized into a hierarchy. While it is difficult to prove necessity of such an organizing structure, it is also difficult to imagine sufficiency without one. Within VCS there exist the following principle components, all or part of which may comprise a subsystem (which may be nested):

a. state machines, comprised of states and transitions
b. resource objects, which are computational components
c. signals, which are data elements that are used in data flow diagrams with the resource objects

Examples are shown in Figures 1 and 2.

Condition 2 - Periodicity of Subsystem Execution: There is a strict sequence of execution combined with an overall time constraint of (nominally) 50 msec, or else an integer multiple of 50 msec of time, during which each subsystem must execute in order to ensure that the control is deterministic under all conditions. In order to ensure that this is the case, we have developed a scheduling function that ensures that this occurs and also ensures that execution duration of each subsystem is rigidly controlled to tight tolerances. Should an exception occur, sophisticated cycle skipping measures are implemented in order to ensure uninterrupted control and observability of the system. The hierarchy is illustrated in Figure 3.

Condition 3 – Replay of the State of the Entire system: Given that the system is comprised of a hierarchy of subsystems, which constitutes the state of the system, and given that these subsystems are comprised of states and signal values, replay constitutes the ability to record and reconstruct the causal nature

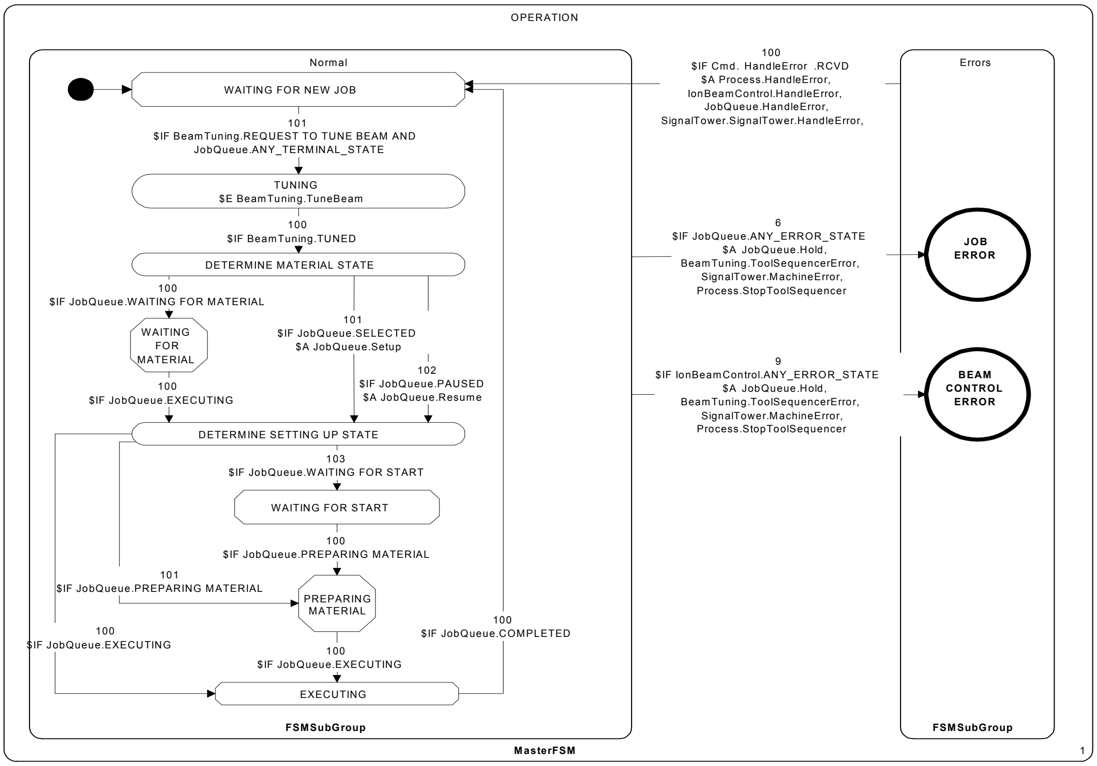


Fig. 1 Finite State Machine (FSM)

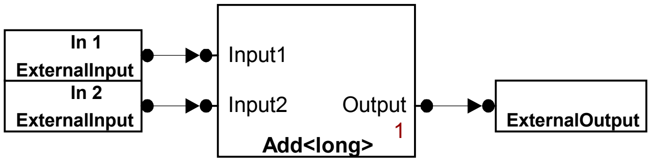


Fig. 2 Data Flow Diagram

of the physical system (implanter) under control. This condition is an assertion of the sufficiency of Condition 1 and 2 for maintaining controllability and observability and requires limited additional effort. The interfaces to the data are shown in Figures 4, 5, and 6.

Condition 4 – Conditions 1 – 3 are met with a compiler that we call "Vizard" and by defining drawings and interfaces with levels of abstraction that are convenient for reuse. The user interface functionality is achieved by "interpreting" what is contained within the hierarchy of subsystems through links that are called connectors. The set of connectors provides the interface to the set of states and signals that are not necessarily hierarchy dependent. This is done in a manner that allows the user interface to "react" in a manner that is consistent with the device under control, which in this case is an implanter. The input to the Vizard is a set of control drawings as well as data that describe the particular configuration of the implanter to be controlled.

III. FAULT TOLERANCE

Perhaps the most important aspect of a complex control system, assuming it works at all, is how it works in the event of an exception or an abnormal condition. In this regard, the combined set of capabilities for VCS are the distinguishing characteristics that provide for reliable control under any circumstances. To see this, we can compare it to other approaches to control.

Event Driven Systems (virtually all other systems in the semiconductor industry) – Often control systems are designed to operate in response to pre-given events, which constitute the state of the system. The problem for digital computer based control, typically, is the fact that as the permutations and combinations of all possible events become intertwined with all possible physical occurrences for the system under control, the response of the is not deterministic. An undesirable side effect of this is the fact that the state of the system is no longer controllable and observable, at least to the same criterion that existed before the occurrence of the exception. This is the key problem with event driven systems. The key advantage is that they are simpler to implement, especially as compared to implementing a large-scale deterministic control system.

In a manner of speaking Conditions 1 – 4 give rise to the possibility of implementing a maintainable and reliable control system that functions under the full range of operational scenarios that we encounter in production environments.

IV. ADVANTAGES OF CONDITIONS 1 -4

Advantage of Condition 1 – Fault isolation is rapid and simple. The hierarchy of subsystems creates a linked list that "points" directly to the problem subsystem by virtue of a path name that identifies the subsystem in error as well as the parents of the errant subsystem from the level of the

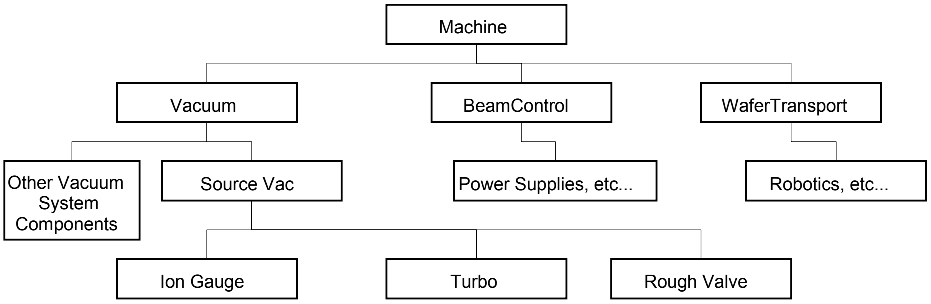


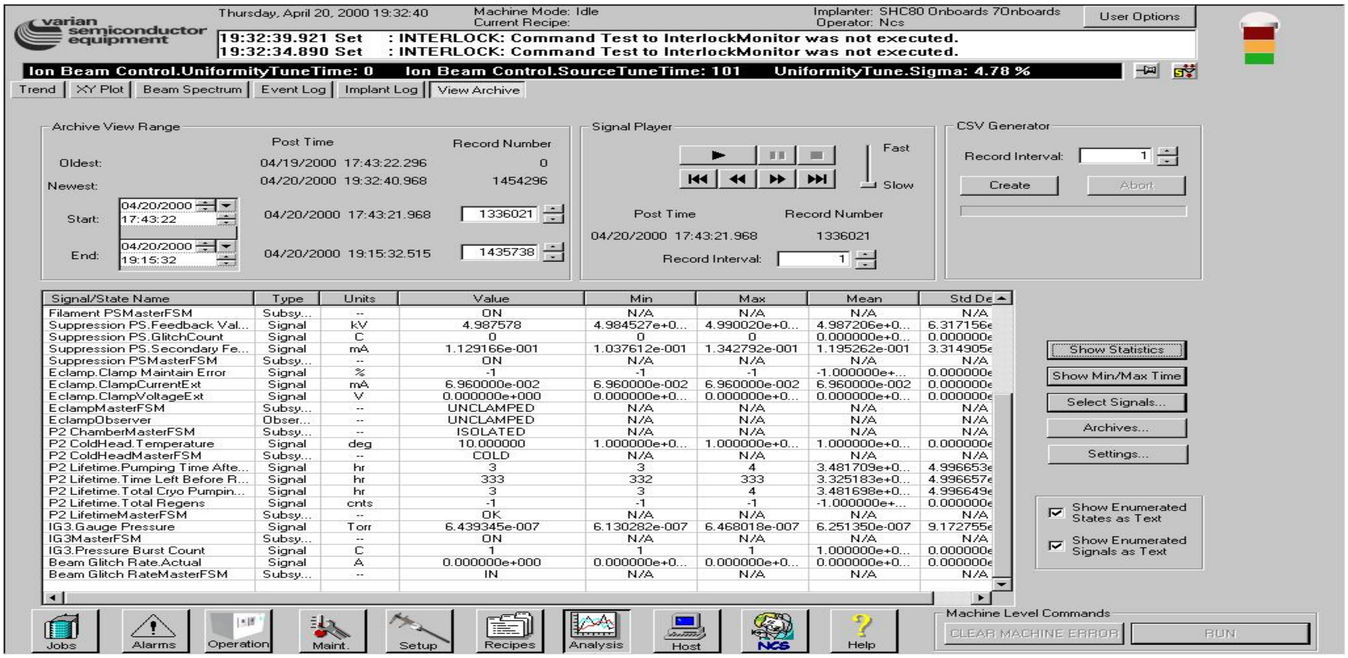
Fig. 3 Hierarchy of Ion Implanter

error to the highest level in the system. You can imagine a tree diagram with a branch that turns red under error conditions. This highlights error conditions for the operator.

Advantage of Condition 2 – Observability and controllability are maintained even under fault conditions. In addition, determinacy makes it easy to optimize performance of the state machines which correspond to physical system performance such as wafer motions and beam tuning. Once a state machine resource object combination is implemented and the associated physical events to be controlled are piecewise approximately deterministic, then the entire sequence of operations can be optimized in order to avoid any dead time, which translates into higher throughput. Our VCS based control of exact same hardware components, compared with conventional control system design, is about 30% faster due to the ability to reliably optimize performance of the associated sequence of events to be controlled.

Advantage of Condition 3 – Observability of the system is transferable electronically, independent of the actual time of recording. Analysis of intermittent conditions associated with the hardware/software interface of the implanter are no longer a problem. If there is an intermittent event (or problem) it is recorded and can be reviewed on site or sent back to the factory for explanation. Therefore, unusual interaction between the hardware and software can usually be identified and explained within 10 minutes of receipt of the associated archive file. Historically such characterizations, especially for intermittent problems, could take weeks or months.

Advantage of Condition 4 – Development of new systems and products is rapid. With the compiler and the built in levels of abstraction, we can re-use existing control drawings, assuming they are applicable to new hardware components, or else we can generate new ones. Time to market is significantly improved, which allows taking advantage of new algorithms and other market driven needs as rapidly as possible. Currently, implanter hardware development is typically gating software development due to the reusability of software components within the VCS architecture.



Thursday, April 20, 2000 19:32:40
Machine Mode: Idle
Current Recipe:
Implanter: SHC80 Onboards 7Onboards
Operator: Ncs

```
19:32:39.921 Set    : INTERLOCK: Command Test to InterlockMonitor was not executed.
19:32:34.890 Set    : INTERLOCK: Command Test to InterlockMonitor was not executed.
```

Ion Beam Control.UniformityTuneTime: 0   Ion Beam Control.SourceTuneTime: 101   UniformityTune.Sigma: 4.78 %

	Post Time	Record Number
Oldest:	04/19/2000 17:43:22.296	0
Newest:	04/20/2000 19:32:40.968	1454296
Start: 04/20/2000 17:43:22	04/20/2000 17:43:21.968	1336021
End: 04/20/2000 19:15:32	04/20/2000 19:15:32.515	1435738

Post Time	Record Number
04/20/2000 17:43:21.968	1336021

Record Interval: 1

Record Interval: 1

Signal/State Name	Type	Units	Value	Min	Max	Mean	Std De
Filament PSMasterFSM	Subsy...	--	ON	N/A	N/A	N/A	N/A
Suppression PS.Feedback Val...	Signal	kV	4.987578	4.984527e+0...	4.990020e+0...	4.987206e+0...	6.317156e
Suppression PS.GlitchCount	Signal	C	0	0	0	0.000000e+0...	0.000000e
Suppression PS.Secondary Fe...	Signal	mA	1.129166e-001	1.037612e-001	1.342792e-001	1.195262e-001	3.314905e
Suppression PSMasterFSM	Subsy...	--	ON	N/A	N/A	N/A	N/A
Eclamp.Clamp Maintain Error	Signal	%	-1	-1	-1	-1.000000e+...	0.000000e
Eclamp.ClampCurrentExt	Signal	mA	6.960000e-002	6.960000e-002	6.960000e-002	6.960000e-002	0.000000e
Eclamp.ClampVoltageExt	Signal	V	0.000000e+000	0.000000e+0...	0.000000e+0...	0.000000e+0...	0.000000e
EclampMasterFSM	Subsy...	--	UNCLAMPED	N/A	N/A	N/A	N/A
EclampObserver	Obser...	--	UNCLAMPED	N/A	N/A	N/A	N/A
P2 ChamberMasterFSM	Subsy...	--	ISOLATED	N/A	N/A	N/A	N/A
P2 ColdHead.Temperature	Signal	deg	10.000000	1.000000e+0...	1.000000e+0...	1.000000e+0...	0.000000e
P2 ColdHeadMasterFSM	Subsy...	--	COLD	N/A	N/A	N/A	N/A
P2 Lifetime.Pumping Time Afte...	Signal	hr	3	3	4	3.481709e+0...	4.996653e
P2 Lifetime.Time Left Before R...	Signal	hr	333	332	333	3.325183e+0...	4.996657e
P2 Lifetime.Total Cryo Pumpin...	Signal	hr	3	3	4	3.481698e+0...	4.996649e
P2 Lifetime.Total Regens	Signal	cnts	-1	-1	-1	-1.000000e+...	0.000000e
P2 LifetimeMasterFSM	Subsy...	--	OK	N/A	N/A	N/A	N/A
IG3.Gauge Pressure	Signal	Torr	6.439345e-007	6.130282e-007	6.468018e-007	6.251350e-007	9.172755e
IG3MasterFSM	Subsy...	--	ON	N/A	N/A	N/A	N/A
IG3.Pressure Burst Count	Signal	C	1	1	1	1.000000e+0...	0.000000e
Beam Glitch Rate.Actual	Signal	A	0.000000e+000	0.000000e+0...	0.000000e+0...	0.000000e+0...	0.000000e
Beam Glitch RateMasterFSM	Subsy...	--	IN	N/A	N/A	N/A	N/A

☑ Show Enumerated States as Text
☑ Show Enumerated Signals as Text

Fig. 4 Archive Viewer

V. CONCLUSIONS

The characteristics of VCS give rise to at least 4 specific advantages, which are particularly useful for implementing complex control of ion implanters in a highly reliable and efficient manner.

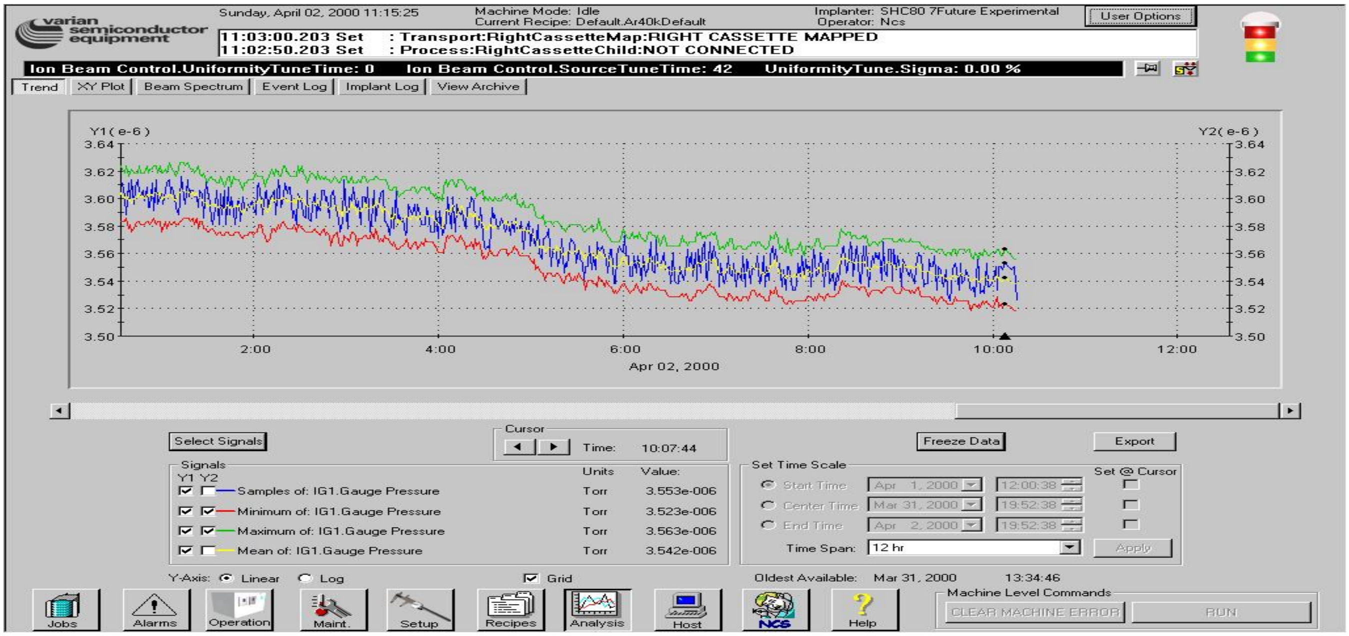
In summary, we conclude by noting that we have demonstrated Mean Time Between Assists (MTBA) that are an order of magnitude better than previous generation implanters that have been in production for more than 10 years. This, combined with much faster throughput, is the verification of the basis of the design for VCS.

REFERENCES

[1] W.L. Brogan, "Modern Control Theory," Third Edition New Jersey: Prentice Hall, 1991.

[2] M.D. Mesarovic, "Theory of hierarchical, multilevel, systems," in Mathematics in Science and Engineering, vol. 68. New York: Academic, 1970.

[3] A. Gelb, "Applied Optimal Estimation," MIT Press, 1974.



Sunday, April 02, 2000 11:15:25

Machine Mode: Idle
Current Recipe: Default.Ar40kDefault

Implanter: SHC80 7Future Experimental
Operator: Ncs

```
11:03:00.203 Set    : Transport:RightCassetteMap:RIGHT CASSETTE MAPPED
11:02:50.203 Set    : Process:RightCassetteChild:NOT CONNECTED
```

Ion Beam Control.UniformityTuneTime: 0 Ion Beam Control.SourceTuneTime: 42 UniformityTune.Sigma: 0.00 %

Cursor Time: 10:07:44

Signals

Y1	Y2	Signal	Units	Value:
☑	☐	Samples of: IG1.Gauge Pressure	Torr	3.553e-006
☑	☑	Minimum of: IG1.Gauge Pressure	Torr	3.523e-006
☑	☑	Maximum of: IG1.Gauge Pressure	Torr	3.563e-006
☑	☐	Mean of: IG1.Gauge Pressure	Torr	3.542e-006

Set Time Scale

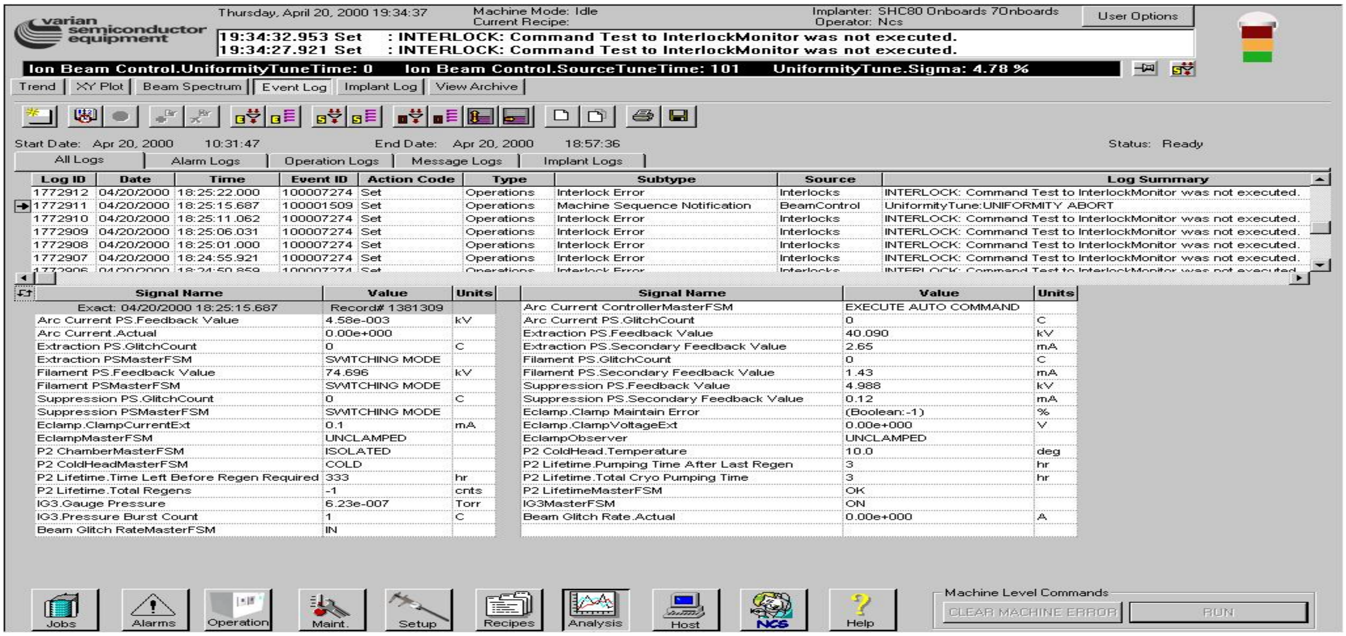
			Set @ Cursor
● Start Time	Apr 1, 2000	12:00:38	☐
○ Center Time	Mar 31, 2000	19:52:38	☐
○ End Time	Apr 2, 2000	19:52:38	☐

Time Span: 12 hr

Y-Axis: ● Linear ○ Log ☑ Grid

Oldest Available: Mar 31, 2000 13:34:46

Fig. 5 Trends



Thursday, April 20, 2000 19:34:37

Machine Mode: Idle
Current Recipe:

Implanter: SHC80 Onboards 7Onboards
Operator: Ncs

```
19:34:32.953 Set    : INTERLOCK: Command Test to InterlockMonitor was not executed.
19:34:27.921 Set    : INTERLOCK: Command Test to InterlockMonitor was not executed.
```

Ion Beam Control.UniformityTuneTime: 0 Ion Beam Control.SourceTuneTime: 101 UniformityTune.Sigma: 4.78 %

Start Date: Apr 20, 2000 10:31:47 End Date: Apr 20, 2000 18:57:36 Status: Ready

Log ID	Date	Time	Event ID	Action Code	Type	Subtype	Source	Log Summary
1772912	04/20/2000	18:25:22.000	100007274	Set	Operations	Interlock Error	Interlocks	INTERLOCK: Command Test to InterlockMonitor was not executed.
1772911	04/20/2000	18:25:15.687	100001509	Set	Operations	Machine Sequence Notification	BeamControl	UniformityTune:UNIFORMITY ABORT
1772910	04/20/2000	18:25:11.062	100007274	Set	Operations	Interlock Error	Interlocks	INTERLOCK: Command Test to InterlockMonitor was not executed.
1772909	04/20/2000	18:25:06.031	100007274	Set	Operations	Interlock Error	Interlocks	INTERLOCK: Command Test to InterlockMonitor was not executed.
1772908	04/20/2000	18:25:01.000	100007274	Set	Operations	Interlock Error	Interlocks	INTERLOCK: Command Test to InterlockMonitor was not executed.
1772907	04/20/2000	18:24:55.921	100007274	Set	Operations	Interlock Error	Interlocks	INTERLOCK: Command Test to InterlockMonitor was not executed.

Signal Name	Value	Units
Exact: 04/20/2000 18:25:15.687	Record# 1381309	
Arc Current PS.Feedback Value	4.58e-003	kV
Arc Current.Actual	0.00e+000	
Extraction PS.GlitchCount	0	C
Extraction PSMasterFSM	SWITCHING MODE	
Filament PS.Feedback Value	74.696	kV
Filament PSMasterFSM	SWITCHING MODE	
Suppression PS.GlitchCount	0	C
Suppression PSMasterFSM	SWITCHING MODE	
Eclamp.ClampCurrentExt	0.1	mA
EclampMasterFSM	UNCLAMPED	
P2 ChamberMasterFSM	ISOLATED	
P2 ColdHeadMasterFSM	COLD	
P2 Lifetime.Time Left Before Regen Required	333	hr
P2 Lifetime.Total Regens	-1	cnts
IG3.Gauge Pressure	6.23e-007	Torr
IG3.Pressure Burst Count	1	C
Beam Glitch RateMasterFSM	IN	

Signal Name	Value	Units
Arc Current ControllerMasterFSM	EXECUTE AUTO COMMAND	
Arc Current PS.GlitchCount	0	C
Extraction PS.Feedback Value	40.090	kV
Extraction PS.Secondary Feedback Value	2.65	mA
Filament PS.GlitchCount	0	C
Filament PS.Secondary Feedback Value	1.43	mA
Suppression PS.Feedback Value	4.988	kV
Suppression PS.Secondary Feedback Value	0.12	mA
Eclamp.Clamp Maintain Error	(Boolean:-1)	%
Eclamp.ClampVoltageExt	0.00e+000	V
EclampObserver	UNCLAMPED	
P2 ColdHead.Temperature	10.0	deg
P2 Lifetime.Pumping Time After Last Regen	3	hr
P2 Lifetime.Total Cryo Pumping Time	3	hr
P2 LifetimeMasterFSM	OK	
IG3MasterFSM	ON	
Beam Glitch Rate.Actual	0.00e+000	A

Fig. 6 Event Log Viewer with Signals