Laser Power Stabilization in the TRIUMF Optically Pumped Polarized H⁻ Ion Source

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Abstract

Power stabilization of the lasers, used in the TRIUMF optically pumped polarized ion source prior to 1991, was crucial to maintaining the laser wavelength and hence nuclear polarization. Output power of the dye lasers was dependent on a number of variables, including the relative drift between the transmission peaks of the birefringent filter and the etalon used to tune each dye laser. The power control system used a program running in a CAMAC crate based PC/AT to control the birefringent filter. Heuristic algorithms implemented to control power and their performance in the steady state and the wavelength shifting modes are described.

I. INTRODUCTION

The current system used at TRIUMF for optically pumping the polarized H- ion source is different. However the stabilization of laser power in the previous system represented a challenging class of problems with parallels in many other areas and is of general interest. This paper describes the implementation of heuristic algorithms for control of processes which are badly characterized, for which there are many unknowns and which fall in to the category that cannot be easily formulated as a classical controls problem. This implementation shows that heuristic methods can provide solutions to such problems even in the presence of extremes of noise.

Three tuneable CW dye lasers pumped by Argon lasers were used (until early 1991) to optically pump sodium vapor cells in the TRIUMF Optically pumped polarized H⁻ ion source and has been described in reference[1,2]. A fourth CW dye laser was used as a probe to measure the sodium polarization. The laser system was used in two modes. For final ion source polarization in either the spin up or the spin down state the lasers were all operated at a single frequency. When the ion source was operated in a spin flipping mode the lasers were operated in a wavelength shifting mode with the operating frequency of the lasers tuned to the absorption bands of the sodium vapor in the hot cells. To maintain stable polarization the frequency and the power of the laser system must be maintained within required tolerances[3]. The lasing frequency is determined by factors such as the combined transmission characteristics of the solid etalon and the bi-refringent filter, the laser system gain and the pump laser power. Although the bi-refringent filter is used to control power, it is loosely coupled to the output frequency, until it is tuned to adjacent etalon transmission peaks - and causes the laser to mode hop.

The goal of the laser power stabilization program is to maximize and maintain dye laser power for the single frequency laser operation, to maintain constant power ratio for two frequencies in the wavelength shifting mode of operation, and to prevent mode hopping in both the single frequency and wavelength shifting modes of operation.

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II. SYSTEM CHARACTERISTICS

The task of stabilizing the power of the dye lasers was made difficult for a number of reasons. The laser output power changes randomly due to thermal drifts caused by convection currents within the laser housing, by bubbles in the dye jet, by jet pressure and shape fluctuations and by Argon pump laser power and incident angle changes. The dye laser output is noisy. Dye breakdown with operation adds to the laser noise which at times is greater than 50% of peak amplitude.

The problem was further complicated by implementation details of the bi-refringent filter controls. There was no optical encoder to provide position readback on the bi-refringent filter motor drives due to space limitations within the laser housing, there was backlash on the spring loaded motor drive which also had different loading for travel in the forward and the reverse direction.

To further complicate matters change in the controlled variable (output power) depended on the relative position of the bi-refringent filter and the etalon. Neither of these positions were measurable even relatively in this system. The output power versus frequency envelope shape changed with time and between the edges of adjustment favoring particular modes the system simultaneously lased at two frequency bands - (Although the output power was not changed markedly).

Initially an attempt was made by others to implement degenerate power stabilization in an analog circuit along with closed loop frequency control implemented using feedback from a spectrometer which gave the laser frequency reading accurate to 1 Ghz. This was abandoned when it was found difficult to cope with drive backlash and to keep track of laser power changes. An attempt was made to cast the process as a classical controls problem with the intention of implementing it on the I4 laser control Micro-VAX processor - since maximization of laser power was thought to be a slow and simple process. This was abandoned as some of the system complications mentioned above became apparent.

III. ALGORITHMS

The laser power stabilization processes used modified versions of the hill climbing algorithm to cope with laser noise and drift and for the two modes of operation.

A. Hill Climbing Algorithm

In a simple hill climbing algorithm (figure 1) the operating point is stepped in a given direction and the power change δp determines direction of motion in the succeeding step: if $\delta p < 0$ the direction is reversed, else direction of motion is unchanged. The system is stepped continuously and oscillates

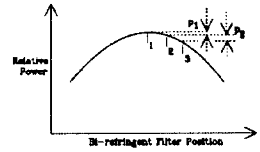

Figure 1: Ideal Power versus frequency characteristics.

about the maximum with oscillation amplitude dependent on step size and measurement threshold. The first refinement to this algorithm is to remember the maximum value and deactivate when the maximum has been reached and to activate only when the power drops below the maximum power by a predetermined minimum amount. This works for the ideal amplitude versus position relationship shown in figure 1.

In reality the power v/s frequency envelope shape is quite different. Figure 2 shows the power v/s frequency characteristics for one of the dye lasers as measured by keeping the

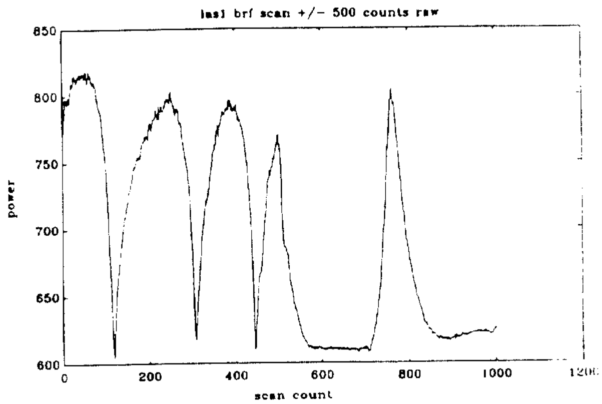

Figure 2:Real Power versus Frequency envelope

etalon constant and stepping the bi-refringent filter 500 steps in one direction and then back 500 steps. This characteristics varied from laser to laser and for the same laser with time and as the operating point changed.

B. Single Frequency mode

The modification required to the hill climbing algorithm for the single frequency mode of operation was to account for the apparent 'hill shape changes' caused by laser drifts and by laser noise. Noise affects the peak finding process. After a direction reversal and retraverse of the peak a simple algorithm is confused by either falsely reaching the peak value too quickly or in not reaching the peak at all. The solution in this case was to traverse the peak more than two times, if the maximum value for the last traverse was off by more than a given percentage, from the previous traverse. If after three traverses power was different from last activation and if after this peak power matched on two successive traverses, then the peak power was updated to the new value, as also the activation threshold which is a percentage of the peak power.

C. Wavelength Shifting Mode

There were two categories of operation for the wavelength shifting mode - slow for shifts at a maximum of once per minute and fast at a 100 hz. The slow mode of operation was implemented first since it was easier to implement etalon controls for slow frequency shifting. However, this was the most difficult task for power stabilization process since it was not possible to distinguish between bi-refringent filter drift and laser power changes while sitting at one of the two operating frequencies. This is addressed by using partial correction at each state.

Operation in the wavelength shifting mode is different from the single frequency mode, since the algorithm is required to maintain the bi-refringent filter transmission slope (not peak) on the operating frequencies. Power is expected to increase or decrease as a function of direction. Taking a step in the wrong direction increases error and the time to recover from this condition. Since operation time at each frequency is limited one has to maximize the time at the optimum power level or maintain correct power ratio between the two operating states as setup. Two modes of operation in the wavelength shifting mode was allowed. Based on initial selection the program either equalizes the power in the two states, or tries to maintain the power ratio from start of run.

Ideally the laser output power is expected to increase or decreases monotonically as a function of birefringent filter position due to its transmission characteristics. Had this been the case, at any operating point the direction of bi-refringent filter motion for increasing or decreasing power would be fixed. The 'direction-map' for the bi-refringent filter movement for increasing power was not expected to be constant over the range of operation due to the large number of variables determining the output power at any given setting and the drift in these parameters. An algorithm was used to dynamically build and alter the 'direction-map' at any given operating point. It had built in hysteresis against noise in that a change in direction would be recognized only after a selectable number of consecutive direction errors.

IV. IMPLEMENTATION

The I4 laser control system has been described in reference [4]. The laser power is sensed using photo diodes and is digitized using a 32 channel auto-ranging ADC with rudimentary signal filtering. The software was implemented for the three pump plus one probe laser as a single tasking program run on an IBM PC/AT. The laser power read task was implemented as an independent DOS terminate and stay resident task triggered off the system clock to allow timed sampling. Raw power data was filtered to remove high frequency noise initially using a straight averaging filter and later with a finite impulse response filter. Low frequency noise along with short term laser power drift could not be filtered.

The program was implemented over a period of about 1 year and was approximately 6600 lines of 'C' code. This could have been reduced by about 30% but would have required additional effort and made the maintainability of the program more difficult.

V. RESULTS

The program performed better than initial requirements for the single frequency mode of operation. The program first maximized the power - with sizeable increases in power frequently seen over that achieved by manual tuning - and then maintained power at the maximum possible for a given pump laser power. The program was able to keep the output power at maximum with pump power variations of greater than 25% seen for periods exceeding two to three days (figure 3) as against a requirement for stable operation of eight hours.

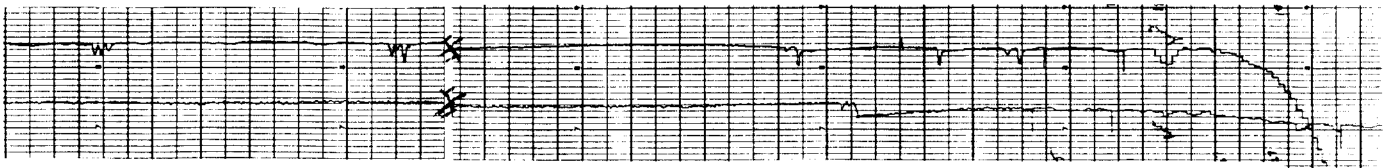

Figure 3: Power Stabilization in Single Frequency Mode of Operation

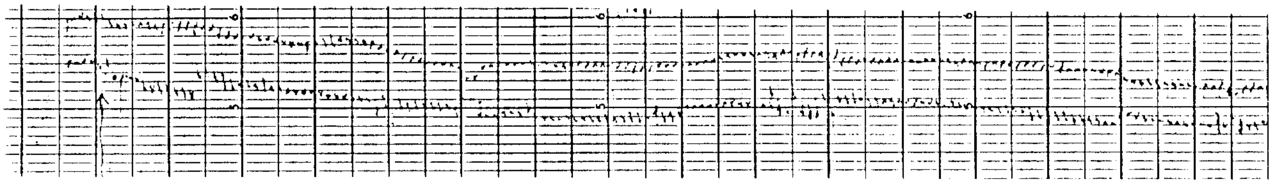

Figure 4: Power Stabilization in the Wavelength Shifting Mode - Laser with Average Noise

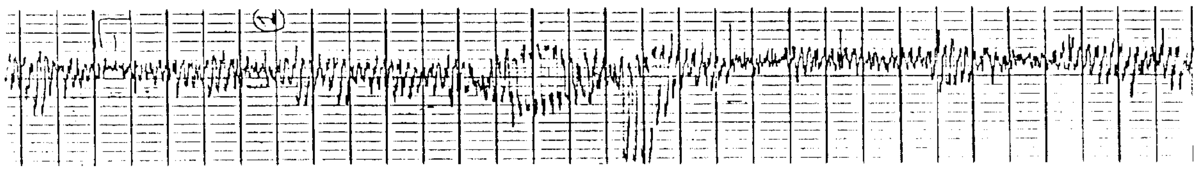

Figure 5: Power Stabilization in Wavelength Shifting Mode - Laser with extreem noise.

In the wavelength shifting mode the performance is close to that required. The laser power was held within required limits without mode hop for the required eight hours (figure 4) except for the most noisy laser where periods of six to seven hours were achieved (figure 5). Hysteresis dead band was increased to reduce system activation but this caused operation with power divergent to the dead-band limits. With the expected changeover to Titanium sapphire lasers, noise is expected to be lower and these programs or simpler versions should be able to meet or exceed requirements for operation in the wavelength shifting mode.

VI. DISCUSSION

The choice of slow spin flip operation to simplify the frequency stabilization process was not optimum from the system point of view. The power stabilization process was made difficult since laser power variations and bi-refringent filter drifts could not be distinguished before a long elapsed time. The solution generated was to carry out a partial correction at each stage and then verify against perceived drifts for the bi-refringent filter and laser power variations in the other frequency state - power variations cause similar changes in the laser power whereas bi-refringent filter causes complementary changes. For the quick spin-flip operation this is not a problem, however the correction algorithm must optimize straddling many frequency state changes.

This type of control problem is ideally suited to software implementation the control cycle is slow but the algorithm is sufficiently complex and undeterminable and has enough variables such that a hardware implementation becomes difficult. The results point out a class of problems that are hard to analyze using classical controls theory but can be solved heuristically.

The lasers are not too difficult to tune manually - the question is where is the pitfall in translation to an automated system? First the perception that manual tuning is easy needs to be verified. Performance of manual tuning needs to be logged over a period of time to allow comparison against the performance of an algorithm. One part of the comparison exists and that is for single frequency mode of operation the algorithm was able to better adjust for peak power as evidenced by the consistent increases in power after a manual maximum had been achieved : conclusion is that in the case of simple well directed tasks involving magnitudes or maintaining a parameter within tolerance limits an algorithm based on digital measurements performs better than the human analog. However where more qualitative information is involved such as evaluating when a mode hop is likely to occur or what is the past history of the laser system settings or factors such as the hill shape for a particular laser and the expected range of tuning - the simple algorithms fail against manual tuning because they do not include the complexity, the adaptiveness, and learning or the capability to switch to new algorithms of the human. However the human approach suffers (usually) from a lack of trace of the procedures done. In translating human operations to algorithms the hidden processes need to be first observed, then the important ones need to be selected, followed by translation and implementation as wrappers for the simple (kernel) control programs. Examples being the implementation of the three traverse peak finding wrapper for noise compensation for the hill climbing algorithm and the implementation of partial optimization to prevent against over compensation in the slow spin-flip mode of operation.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

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