AN OPERATOR ASSISTANCE SYSTEM FOR THE AVF CYCLOTRON

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ABSTRACT

A computer-based operator assistance system installed at the AVF cyclotron in Japan is described. This system provides CRT display of cyclotron beam trajectories, feasible setting regions (FSRs), and search traces designed to enhance beam parameter adjustments. A system evaluation experiment was conducted and the operation time to reach required beam conditions was reduced by approximately 65%. In addition, results of an operator questionnaire survey indicated high system operability.

1. INTRODUCTION

A computer-based operation system which assists inexperienced operators has been implemented at the AVF (Azimuthally Varying Field) cyclotron of the Japan Atomic Energy Research Institute (JAERI)[1,2]. Cyclotron start-up operations require dozens of adjustable parameters to be finely tuned to maximize beam extraction efficiency. Veteran operators use their experience and relatively easily perform a trial-and-error procedure. On the other hand, inexperienced operators have a difficult time because operator consoles displaying measured beam parameters, alarm information, component status, etc. do not provide enough information to guide these new operators.

This operator assistance system provides three visual human interfaces to support beam adjustment of the axial injection and central and extraction regions, i.e.,

(1) Beam trajectory is rapidly calculated and graphically displayed whenever the operators change the cyclotron parameters.
(2) Feasible setting regions (FSR) of the parameters that satisfy the cyclotron's beam acceptance criteria are indicated.
(3) Search traces, being a historical visual map of beam current values represented by various colored blocks, are superimposed on the FSRs.

Since the above visual information is based on ap-

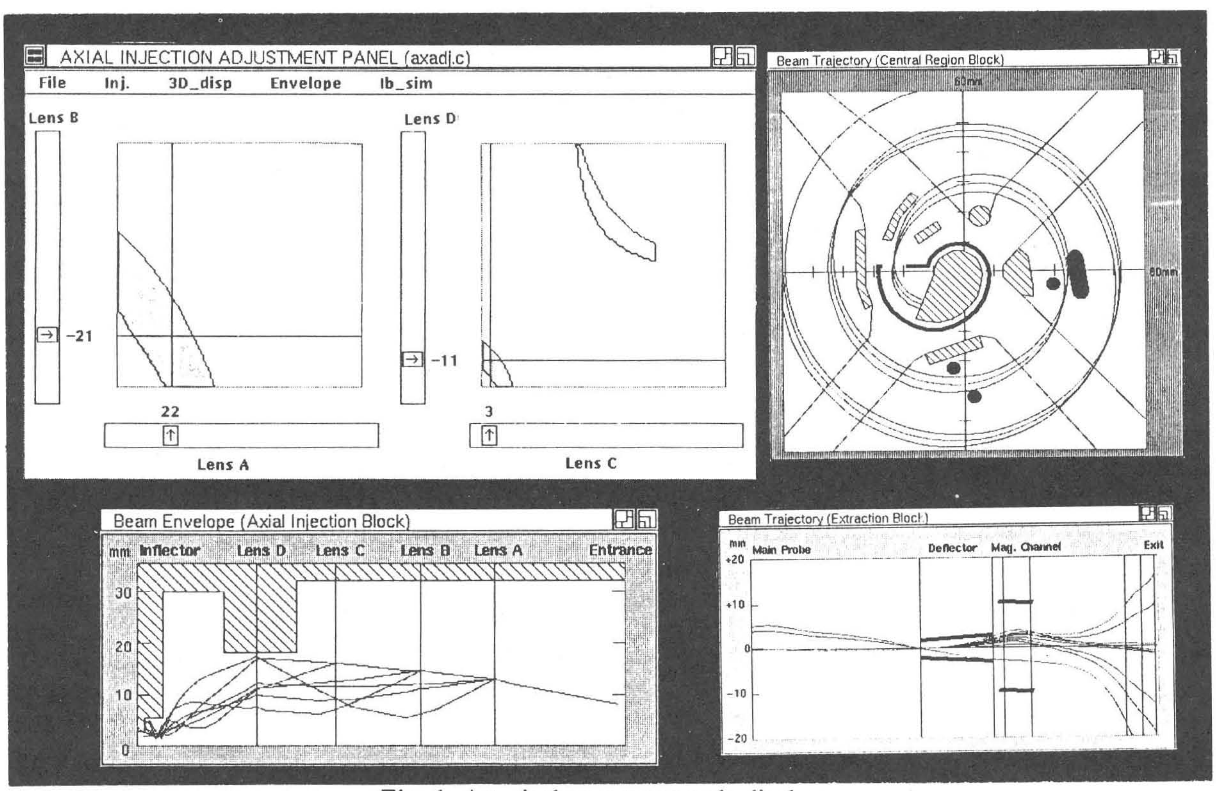
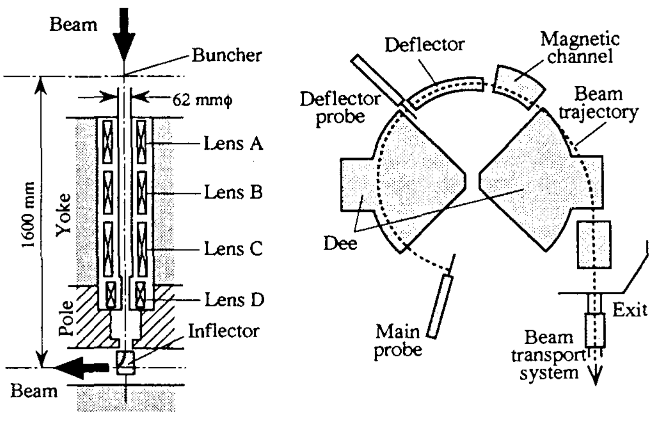


Fig. 1. A typical operator console display.



(a) (b)

Fig. 2. Schematic of the axial injection block (a) and the extraction region (b).

plicable theoretical equations and numerical simulations, operators are able to quickly gain valuable operation experience which ultimately leads to a reduction of the time to reach the planned cyclotron conditions. This systematic combination of the computer computational power and human intuitive ability is the primary advantage of our assistance system.

The present study describes details concerning these three interface displays, and also discusses the results of a system evaluation experiment and an operator questionnaire survey on system operability.

2. VISUAL INTERFACES

2.1. Beam Trajectory Display

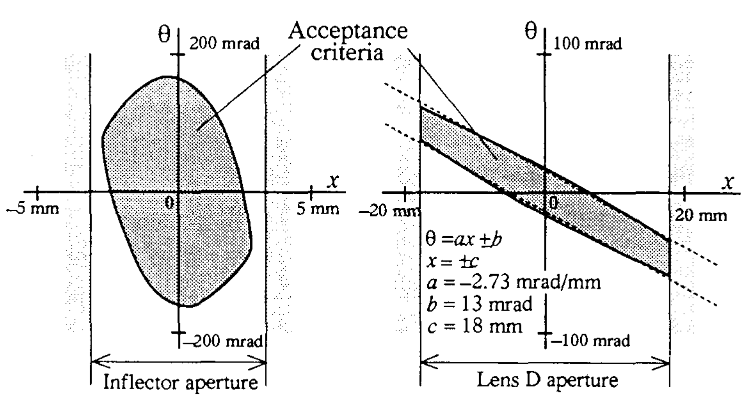
Veteran operators normally infer the beam trajectory parameters using their knowledge of the beam's internal behavior. The beam adjustment interface calculates the beam trajectories/envelopes using actual parameters and displays them on a CRT, thus whenever an operator changes the adjustable parameters, a graphical image is created which is similar to the expert's mental model.

In Fig. 1, showing a typical operator console display, the bottom left CRT display shows a typical beam envelope of the axial injection block,[3] the region between the entrance to the yoke and the inflector (Fig. 2(a)). The resultant envelopes are calculated within several milliseconds from the coil currents of four glazer lenses (A-D) and the magnetic field distribution using the transfer matrix method.[4] The top right display shows the central region beam trajectories which occur between the inflector and the second phase slit, being calculated within 3-4 s by the Runge-Kutta-Gill (RKG) method.[5,6] In addition, the layout of the phase slits is dynamically updated whenever they are changed. The bottom right display shows the extraction region which is between the deflector and the beam exit (Fig. 2(b)), where the x-axis represents the ideal trajectory. Before calculating the extraction region trajectory, the trajectory entering the deflector is infered by measuring the position of the final turn using both the main probe and the deflector probe. Similarly to the phase slits, the layout of the deflector and the magnetic channel have a dynamically updated display.

2.2. FSR Display[7]

Veteran operators generally know the approximate range of parameter values; hence a real-time display of FSRs is provided. The FSR represents the parameter range which allows the beam to pass through its respective region without hitting any components. By taking into account the spatially dependent beam acceptance criteria determined by the internal components, the FSR is derived by solving an inverse problem of the trajectory model.

The procedure to calculate the FSR for the axial injection block is presented as an example. The acceptance of the inflector in the x-θ phase plane is shown in Fig. 3(a), whereas Fig. 3(b) shows that occurring just after lens D, being considered as the adjustment target. The acceptance after lens D is approximated by the interior of a parallelogram defined by the four lines



(a) (b)

Fig. 3. Acceptance criteria of the axial injection block. (a) For inflector (b) following lens D.

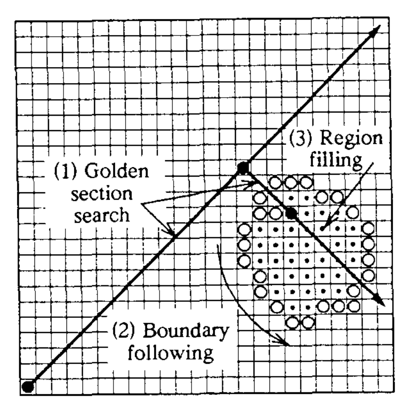


Fig. 4. Process used by the "search method" to obtain an FSR.

$$x = \pm c \qquad (1)$$
$$\theta = ax \pm b \qquad (2)$$

On the other hand, the beam is represented by an ellipse

$$\sigma_{22}x^2 - 2\sigma_{12}x\theta + \sigma_{11}\theta^2 = \sigma_{22}\sigma_{11} - \sigma_{12}^2 \qquad (3)$$

where σ_{ij} are the x-θ elements of the sigma matrix for this beam state, being determined by functions of the adjustable focal lengths of the lenses (F_a, F_b, F_c, and F_d).

For the injected beam to pass through the inflector, the ellipse in Eq. 3 can not intersect the acceptance characteristics in Eqs. 1 and 2. This condition is derived from the discriminant of a quadratic equation, i.e.,

$$w_1 = \sigma_{11} - c^2 < 0 \qquad (4)$$
$$w_2 = \sigma_{22} - 2\sigma_{12}a + \sigma_{11}a^2 - b^2 < 0 \qquad (5)$$

Where w_1 and w_2 represent the degrees of insufficiency which satisfy the conditions of Eqs. 4 and 5.

Determining combinations of the focal length values (F_a, F_b, F_c, and F_d) which satisfy Eqs. 4 and 5 is analytically difficult, although a nonlinear minimization problem can be formulated. An objective function $w(F_a,F_b,F_c,F_d)$ is defined by

$$w(F_a,F_b,F_c,F_d) = \begin{cases} 0 & (w_1 \le 0 \text{ and } w_2 \le 0) \\ \sqrt{\alpha w_1^2 + \beta w_2^2} & (w_1 > 0 \text{ or } w_2 > 0) \end{cases} \qquad (6)$$

where α and β are respectively the weights of w_1 and w_2. The FSR is defined as an area where the objective function is zero.

To visualize an FSR in a two-dimensional plane, we developed a "search method" in which a fast search algorithm is applied to a gridded search plane. This new method combines nonlinear programming and image processing techniques. Figure 4 shows the process used by the search algorithm. A golden section search, a type of line search algorithm, is first carried out to find a point where w=0. Then, starting from this point, the boundary of the region where w=0 is searched for. Next, the boundary is tracked (boundary following) using an image processing boundary following technique. Finally, it is assumed that w=0 at all points inside the boundary (boundary filling). The resultant region and its boundary is an FSR. The top left display in Fig. 1 shows typical FSRs for the axial injection block. Operators change the displayed parameter by pointing/clicking a mouse on the desired search plane.

The FSR also represents the sensitivity of each parameter and their mutual relation. A parameter's sensitivity is determined by the length of the cursor lines inside the FSR, where a shorter length indicates a more sensitive parameter. The mutual relation between parameters is indicated by the gradient of the FSR, e.g., an FSR sloping downward to the right indicates that the lens A and B will give the almost same effect on the beam.

Using a VAX-station 3100, 200 ms is required to search for and display an FSR for a particular plane, thereby providing real-time beam information.

2.3. Search Trace Display[7]

It is believed that operators are able to visualize, i.e., generate a mental map, of the beam current values in the operation space by memorizing action-response-sequences. To complement an operator's short term memory, search traces are superimposed on an FSR (Fig. 5). This display shows a historical summary of measured beam current values after any parameter "setting" adjustment by an operator. The beam current values are converted to a color scale and plotted as colored blocks at a position corresponding to the measured beam values. It should be noted that the search trace display indicates the cyclotron's actual condition, whereas the FSR shows the theoretical one. Operators can refer to either display, correct the differences between them, and search for the optimum set point which provides maximum beam current.

2.4. Operation Flow Using the Interfaces

Figure 6 is a block diagram of the information flow between the operator, assistance system, and cyclotron. The operator initially performs parameter setting adjustment by pointing/clicking the mouse at any position on the displayed search plane. The computer simultaneously calculates the new FSRs and beam trajectory, and

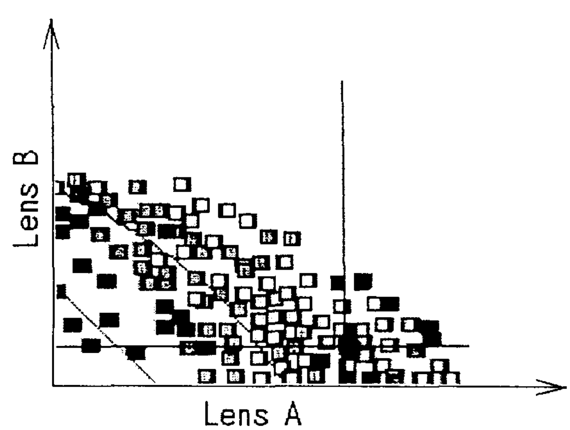


Fig. 5. Search trace display showing colored blocks of the measured beam current values superimposed on the FSR display.

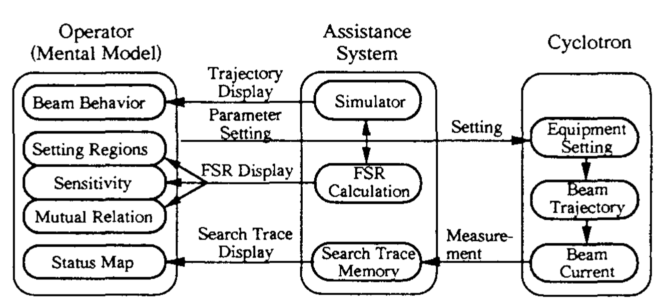


Fig. 6. Block diagram of information flow in the operator assistance system.

the assistance system transmits the setting values to the cyclotron components and measures the new beam current, which is then displayed on the search trace display as a colored block at the corresponding value. The operator can search inside or in the neighborhood of the regions by referring to the colored blocks. The three displays enable operators to feel as if they are actually interfacing with the beam, even though it is not visible.

3. SYSTEM EVALUATION

To evaluate system effectiveness, the search time required to reach maximum beam current conditions was measured. In addition, system operability was evaluated using written questionnaires.

Nine operators (1 expert, 4 trainees, and 4 novices) were asked to obtain maximum beam current by performing adjustments of the axial injection block by tuning the four lenses using three different interface modes:

Mode 1: Using the existing console with four dials and a beam current meter.

Mode 2: Using the assistance system without the FSR display.

Mode 3: Using the full assistance system.

Table 1 summarizes the resultant search times for the three modes and give their medians. All values were normalized by mode 1.

In mode 2, the average search time was reduced by ≈80% of that in mode 1. This improvement in operation is attributed to the search trace display and the ability to make beam settings using a mouse.

Operational improvements were increased an additional 15% using the full assistance system (mode 3), i.e., the search time was reduced by ≈65% in comparison to mode 1. The FSR display decreased the search time because an operator searches a smaller parameter area than without the display; thus more quickly reaching the desired optimal setting even though the theoretical model does not exactly represent the actual cyclotron conditions.

Table 2 summarizes the results of an operator questionnaire survey given to 7 operators (1 expert, 4 trainees, and 2 novices) to evaluate system effectiveness. Five system functions are considered and scored from 1 (not effective) to 5 (very effective). Since scores ranged from 4.0-4.7, the operators highly evaluated the effectiveness of system operability.

4. CONCLUSION

Three human interface, real-time CRT displays used for cyclotron beam adjustment are described, i.e., beam trajectories, FSRs, and search traces. The beam trajectory display enables operators to feel as if they are directly interacting with the beam, while the FSR display provides a visible expression of constraints among the adjustable parameters. The search trace display gives operators a visual feedback of their beam set point adjustment.

Results of a system operation experiment showed that the search time to reach specific beam conditions was significantly reduced using these displays. The written questionnaires survey showed the operators highly evaluate system operability.

Table 1 Summary of search times using three inteface modes.

Operator	Level[a]	Mode 1	Mode 2	Mode 3
1	E	1.0	1.07	0.59
2	T	1.0	0.76	0.86
3	T	1.0	0.68	0.63
4	T	1.0	0.97	0.73
5	T	1.0	0.67	0.46
6	N	1.0	0.92	0.85
7	N	1.0	0.95	0.80
8	N	1.0	0.65	0.42
9	N	1.0	0.47	0.34
Median		**1.0**	**0.76**	**0.63**

[a] Level: E; Expert, T; Trainee, N; Novice.

Table 2 Questionnaire results on the effectiveness of the operator assistance system.

Function	Ave. Score	Histogram 5	4	3	2	1
(1) Trajectory display	4.29	2	5			
(2) FSR display	4.00	2	3	2		
(3) Search trace display	4.14	3	3			
(4) Display layout	4.71	5	2			
(5) Operation by mouse	4.14	2	4	1		

5. REFERENCES

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