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ON-LINE OPTIMIZATION OF THE CONTINUOUS TRANSFER EJECTION EFFICIENCY

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ABSTRACT

The continuous transfer ejection efficiency can be optimized by choosing the appropriate septum angle of the electrostatic deflector in the PS straight section 31. At the instant of ejection towards the SPS the minimum number of protons are then lost on the septum itself and around the PS accelerator ring. A fully automatic on-line optimization procedure has been implemented as a part of the continuous transfer computer control system. The optimization can be initiated at any time by the PS operators or be scheduled to run without further operator intervention at regular intervals during PS operation.

Experience up to now shows that on the average 1 to 2% of efficiency can be gained provided this optimization procedure is scheduled regularly. This gain represents a reduction of 20 to 50% of the total continuous transfer ejection losses. In view of the future PS multibatch transfer to the SPS at high beam intensities, the value of this optimization process is obvious for ejecting properly as well as for reducing the general radiation level in the accelerator.

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CONTENTS

1. INTRODUCTION

The primary function of the PS continuous transfer (CT) control system is to steer the CT process in order that the best possible proton beam is made available to the SPS [1]. Another objective is that the radiation level in the accelerator be kept to a minimum thus increasing the lifetime of accelerator equipment.

Early in the CT control system development period, it was realized (see Section 7 of Ref. 1) that the approach of applying on-line optimization procedures seemed to be the most promising method for attaining these objectives. On the other hand, closed loop control processes require high development effort and long practical experience before they can be safely used during routine operation. In the beginning, in such cases it is often an open question whether the benefits will finally justify the investments. Furthermore, during the development period, testing of such procedures may considerably disturb the accelerator operation.

The problem with on-line optimization is not generally the mathematical optimization routine, but to make the whole procedure clever enough to provide convergence towards reasonable end results under all conditions, including abnormal accelerator situations, such as instabilities, failures of equipment, etc.

The optimization process described in this report uses in fact only one single, independent, variable, namely the septum angle of the electrostatic septum deflector ES 31 [2]. By varying the angle within a certain range, the optimum of the ejection efficiency is determined with the least squares fit method. The solution of the mathematical problem is simple (see Appendix) and absorbed only a few per cent of the total effort which had to be invested in the development of the whole procedure.

2. THE EQUIPMENT

The hardware used by the efficiency optimization procedure consists of the ES 31 deflector, several beam diagnostic elements and several elements of the CT control system. Figure 1 shows a schematic of all the relevant components and their inter-relations.

The absolute high-voltage setting value of the ES 31 is not critical for the quality of ejection, only its long-term stability is important. Radial movements of the ES 31 septum and cathode as well as the septum angle movements are actuated via slowly-turning d.c. motors. All commands to the high-voltage power supply and to the ES 31 position control pass through a special purpose interface (SPI) with extensive diagnostic and manual back-up facilities. The same is true for all acquired ES 31 status and setting data. The SPI is linked to the parallel CAMAC branch highway via a single I/O register CAMAC module. The only ES 31 parameters important in the context of the efficiency optimization are the septum angle acquisition value and the stepping-up or -down commands for the angle movement.

Two beam current transformers (TR 68 and TR 103) measure the ejected and internal proton beam intensities, the quotient of which represents the ejection efficiency to be optimized.

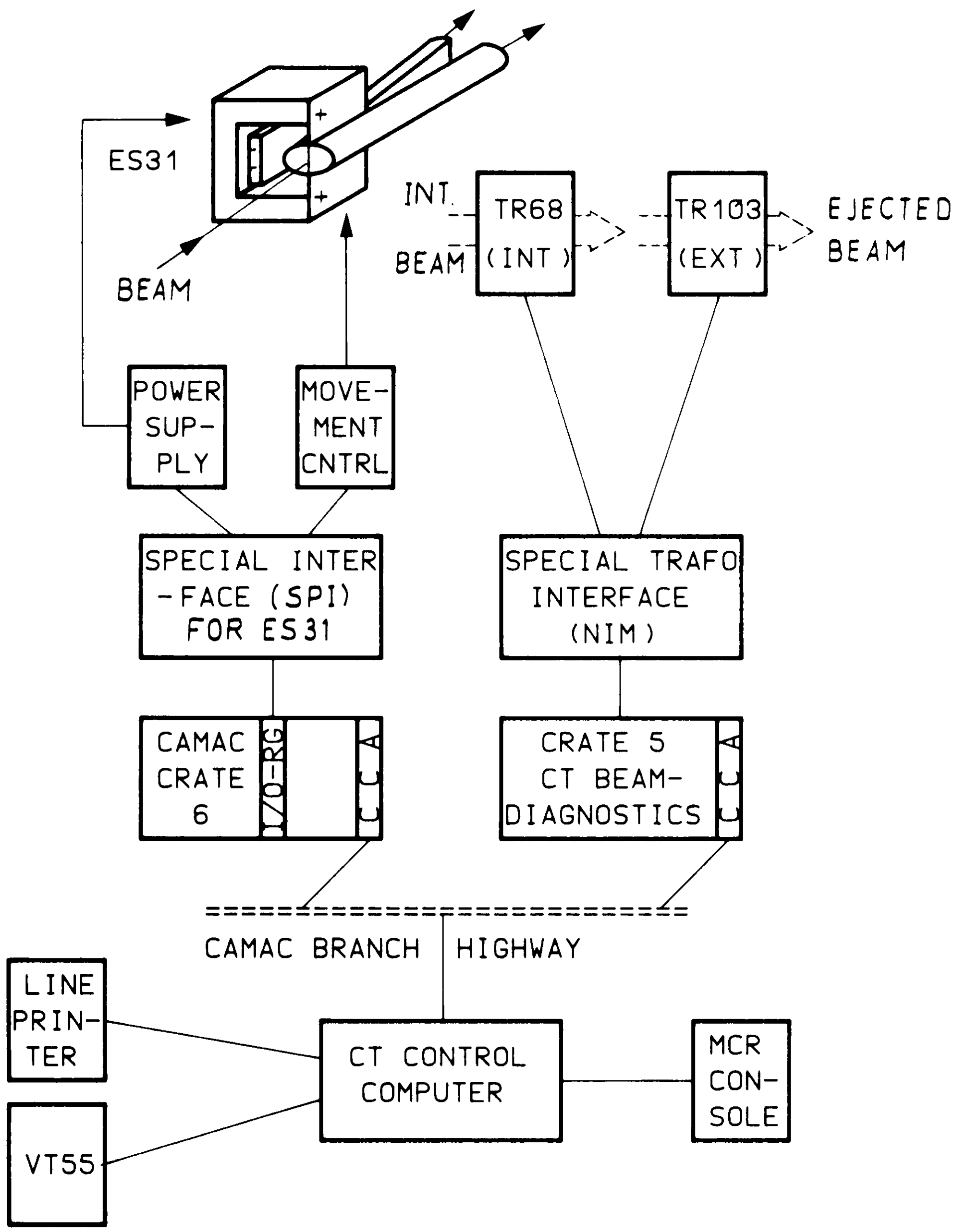


Fig. 1 Schematic diagram of equipment involved in the CT ejection efficiency optimization procedure

The integrated beam intensity signals for the total number of circulating and ejected protons are acquired together with the other beam diagnostic data via fast multiplexed ADC CAMAC modules[3].

PS cycle information data, such as type of cycle, programmed operations and programmed beam intensities, are acquired via a DR11C interface from the PS program line sequencer (PLS). This interface also provides the synchronizing pulses at significant PS cycle events like PS supercycle or subcycle start, end of flat top, CT instant, etc.

The whole CT equipment is linked via a parallel CAMAC branch highway to a PDP 11/40 computer (see Section 4.2 of Ref. 1). The main operator interface is the PS Main Control Room CT console, consisting of a VT05 video terminal, 2 TV monitors and an analog oscilloscope display. In the context of the efficiency optimization procedure, three other peripheral devices fulfil important functions. The LA 36 Dec-writer console produces a log containing all significant events during CT operation and regular reports on the CT ejection performance. A hard copy of the efficiency distribution during one efficiency optimization cycle can be plotted with the Versatek line-printer, normally only used for program development. The same can be done with the hard copier of a VT 55 video terminal in the CT computer room.

3. THE CT EFFICIENCY OPTIMIZATION PROCEDURE

As described in Section 2 of Ref. 1 and in Ref. 4, the ES 31 deflector acts as a peeling device in the CT ejection (Fig. 2a). The CT fast bumper system[5] allows the switching of 11 consecutive beam slices of one PS revolution duration over the electrostatic system. During this shaving process the electrostatic system represents an obstacle for the shaved beam leading to unavoidable beam losses (theoretically of the order of a few per cent depending on beam intensity and emittance). However, these systematic losses at ejection depend strongly on the relative angle between septum and beam direction (Fig. 2b). The apparent width of the septum increases in proportion to this angle. Hence for all PS beam conditions an optimum ES 31 angle exists which minimizes the beam losses on the septum itself and also the losses all around the PS ring provoked by scattering on the septum.

Two methods may be used to achieve the ES angle optimization. One method maximizes the ejection efficiency (= 100 × ejected intensity/circulating intensity) as a function of the septum angle. The other consists in minimizing the losses measured at the ES 31 (with a beam loss monitor or via the measured temperature rise of the septum). However this latter method, which does not take into account the losses occurring elsewhere in the accelerator, is not dealt with here.

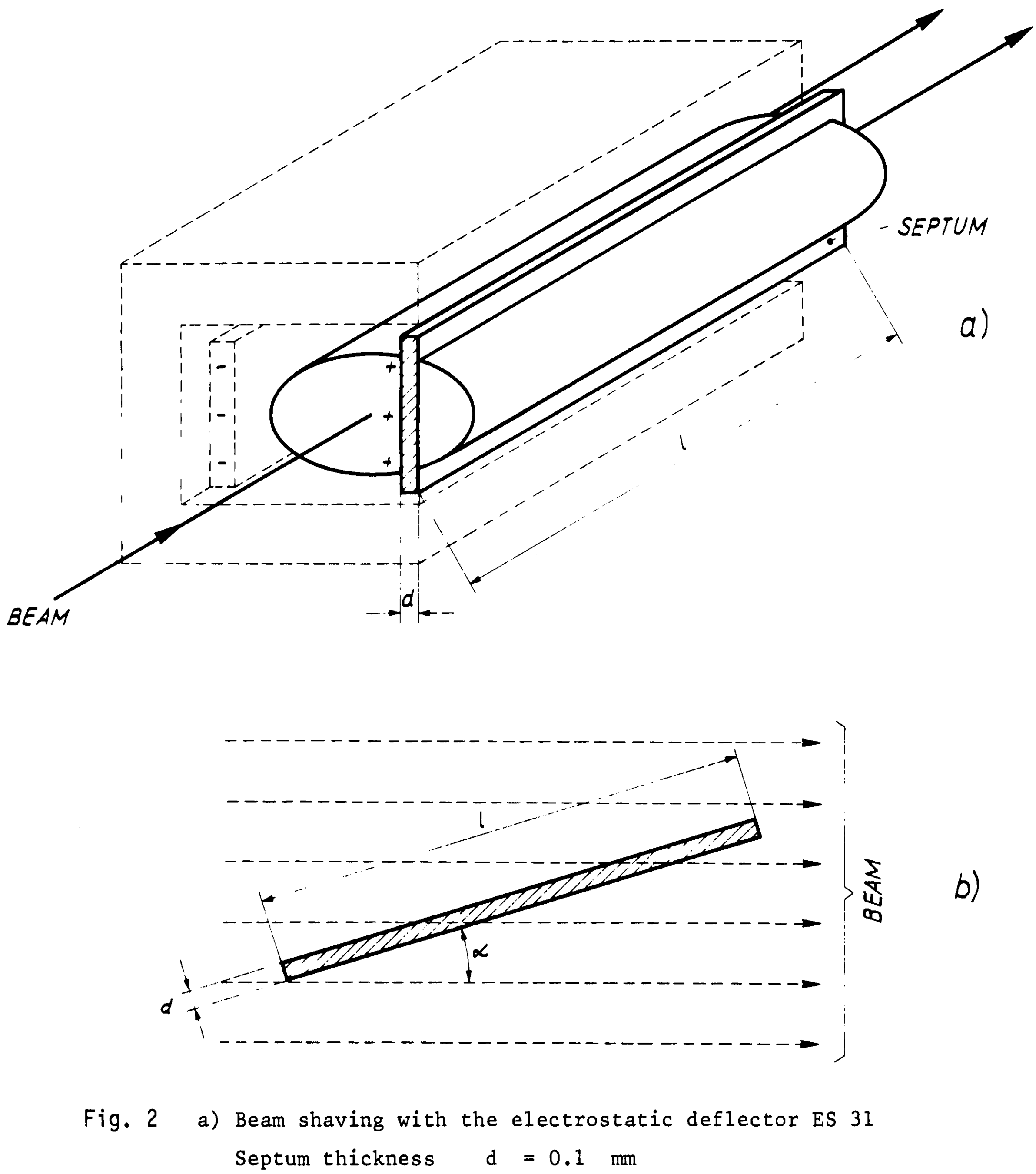


Fig. 2 a) Beam shaving with the electrostatic deflector ES 31

Septum thickness $d = 0.1$ mm
Effective thickness $d_e = 0.18$ mm
Length of septum $\ell = 1800$ mm

b) The septum acts as an obstacle to the beam with an effective cross-section proportional to $d + \ell|\alpha|$ (for small angles α)

The principle of the first optimization procedure consists in slowly varying the septum angle around its initial reference value within a certain angle range once or several times (single or multiple angle scan). During the septum movement, the ejection efficiency and the momentary angle are measured at each CT ejection instant. Typical distributions of efficiencies as functions of angle movement can be seen in the computer optimization plots shown in Figs. 3 and 4. The distribution is approximated by a second-order polynomial and the maximum of the parabola is calculated with the least squares fit method (see Appendix). When the optimum angle is found within the optimization angle range, the septum angle is then automatically set to this value. If it is outside the angle-scan range, it will be positioned to a value inside the range limits but near to the optimum.

Many checks are performed on the optimization data to exclude instabilities, degradations, and wrong results of the optimization procedure. The number of efficiency-angle data pairs must exceed 20 before any optimization is executed. Whenever the standard deviation of the efficiency data is greater than 10%, the PS beam is considered too unstable for the efficiency optimization. Any actions are avoided whenever the efficiency distribution seems to be too flat or even has a minimum within the chosen scan range, or whenever other ejection equipment is down. Protection is provided against faulty operator manipulations. Easy recovery in case of equipment or system failures is guaranteed by a simple control system restart or cold start.

The MCR console allows the operators to initiate or to stop the optimization procedure in different ways. A standard "one-shot" optimization (1 cycle of ±0.2 mrad around the initial reference value) can be initiated at any moment. Another option allows up to 3 angle-scan cycles to be chosen with a variable angle range. In addition, this option permits the plotting of the efficiency distribution on the line printer or with the VT 55 hard copier (see Figs. 3, 4 and 5) A single optimization procedure takes several minutes, depending on the number of chosen scan cycles. During this period the operator can execute any other CT control program, since the optimization process once started runs automatically in the background.

A third option allows the scheduling of fully automatic optimization procedures running regularly at selectable intervals without further operator intervention. Any optimization process may be interrupted at any moment. However, the septum angle will then stay with the value it had at the instant of interruption. Descheduling of scheduled regular optimization can be specified explicitly by the operator or occurs automatically at control system restart.

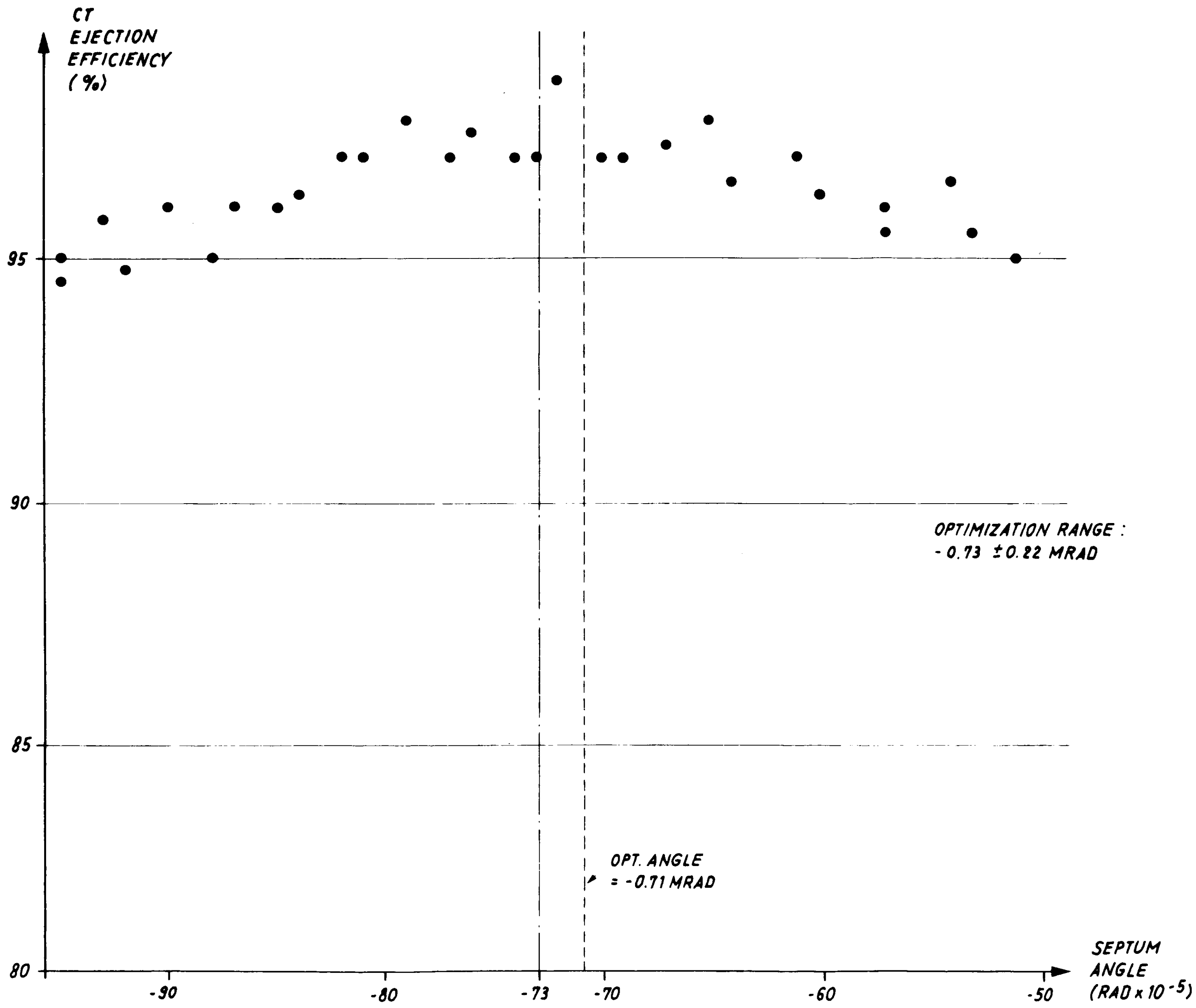


Fig. 3 Plot of efficiency distribution measured during one single angle-scan around a nearly optimum position.
PS beam intensity = 10^{13} ppp.

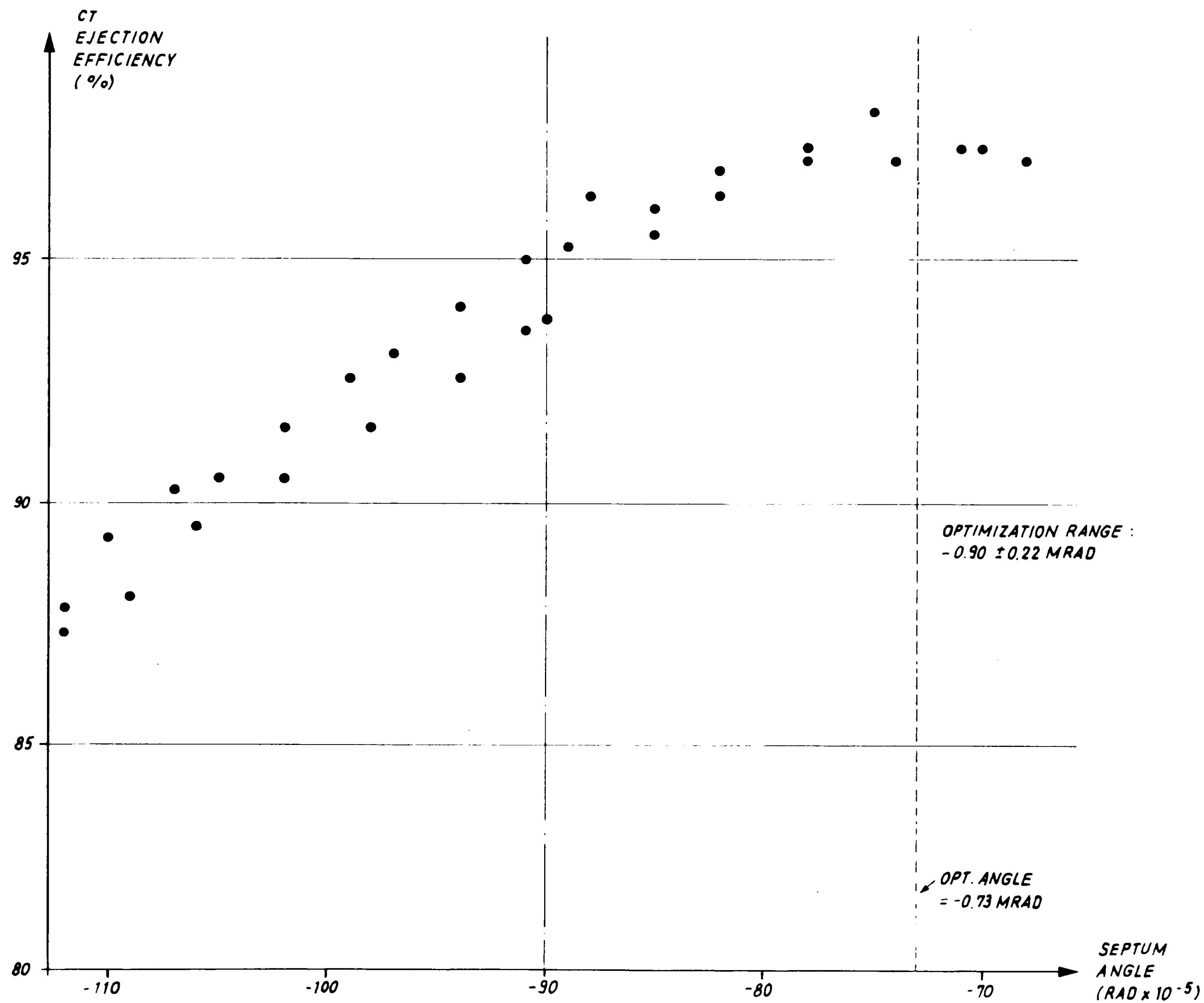


Fig. 4 Plot of efficiency distribution measured during an angle scan starting from a position 0.2 mrad away from the optimum angle. PS beam intensity = 10^{13} ppp.

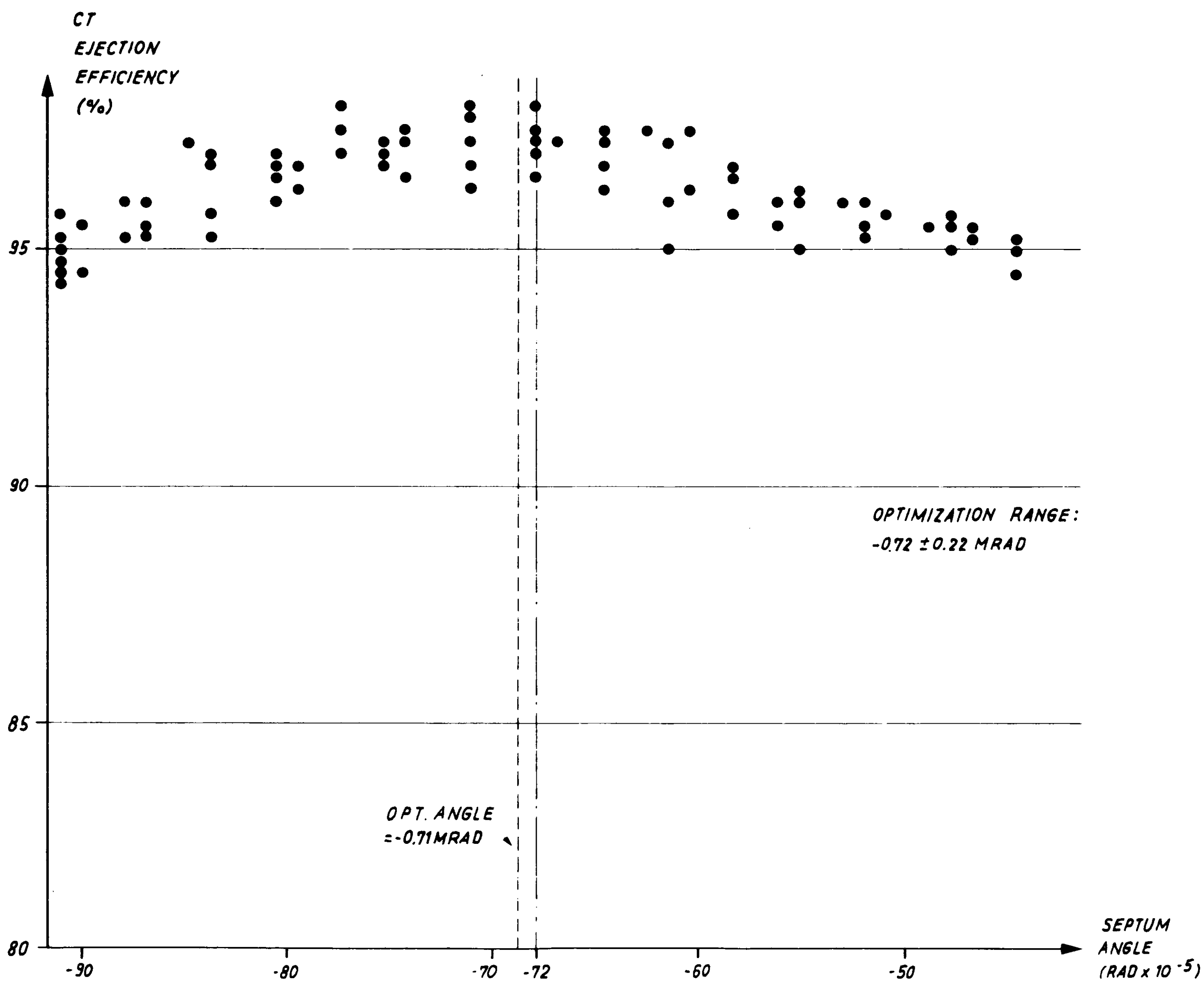


Fig. 5 Plot of efficiency distribution measured during two angle-scan cycles around nearly optimum position. PS beam intensity = 10^{13} ppp.

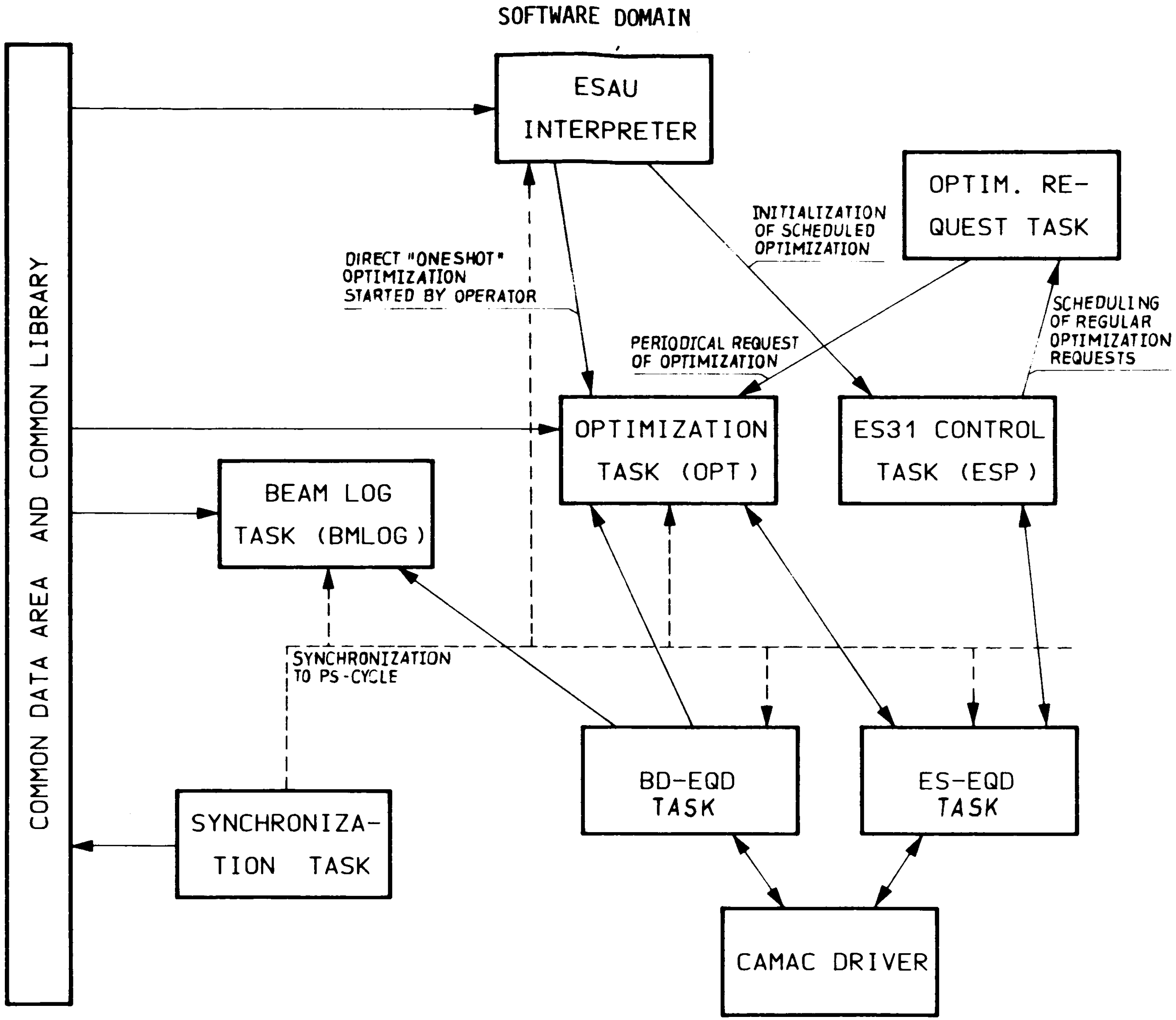
4. SOFTWARE

The software structure of the CT control system has been described in detail in Section 5 of Ref. 1. Figure 6 shows the main software elements which are needed for the realization of the efficiency optimization process. The initialization and interruption of single optimizations, and the scheduling and descheduling of regular optimizations are brought into operation by a special ESAU interpreter control program linked to the main ES 31 ESAU control program as an overlay. On the same level a number of checks are performed, e.g. if the operator commands are correct, within the permitted limits, or if an optimization process is already in progress.

The ES 31 angle movement is controlled by an intermediate control task, called ESP (in assembler language), which, when loaded with the desired angle values, autonomously moves the system in discrete steps until the final position is reached. The ESP task also controls all other ES 31 control functions like power supply start-up or switching off, high-voltage setting, and radial movements of septum and cathode; however only one of these processes can be active at a time. Hence it is not possible to optimize the efficiency and change the high-voltage setting at the same time. The ESP task also serves as an intermediate node for scheduling the intrinsic efficiency optimization control task (OPT) via another assembler task which is needed to provide the correct optimization input parameters at any time the scheduled optimization becomes active. Each single CAMAC command and each acquisition executed by the ESP and ESAU control tasks pass through the ES 31 equipment driver (ES-EQD).

The optimization task OPT is an intermediate control task written in FORTRAN. It steers the optimization process by executing the necessary angle movements via the ESP task and gathering the efficiency and angle data from the ES 31 and the beam diagnostic equipment drivers (ES-EQD and BD-EQD). After the angle scan the acquired data are processed according to the least squares fit method. The optimum angle is calculated and when the checks performed on the data and the general ejection situation do not indicate any abnormality the septum angle is moved to its optimum value. The results of each optimization, whether successful or not, are logged on the CT computer log and optionally the efficiency distribution can be plotted on the line printer or the VT55 hard copier.

Whenever the ES 31 control program or the main console ESAU program are active at the MCR console the OPT task generates appropriate displays on TV screen 2 giving information about the actual status of some vital optimization parameters.



CORRESPONDING FUNCTIONS

Operators interface of ES 31 control, initialization and scheduling of efficiency optimization.

Automatic periodical request of efficiency optimization.

OPT : Efficiency optimization procedure.

ESP : ES 31 power and movement control.

BMLOG: CT ejection performance evaluation with regular printout every 1000 PS supercycles.

Basic data transfer to and from CAMAC, basic data treatments (surveillance, fast displays, etc.)

Synchronization of CT control system to PS cycle events.

Data transfers between computer memory and ICP 11B CAMAC branch highway driver.

Fig. 6 Schematic diagram of the software elements and their inter-relations concerning the efficiency optimization procedure

The statistical evaluation of the optimization procedure is based upon a further intermediate control task (BMLOG) which surveys the main CT ejection beam parameters and performs every 1000 PS supercycles a very simple performance evaluation. The results are regularly printed onto the computer log (e.g. the numbers of missing ejection pulses, of badly ejected pulses, and of cycles without CT ejection request, the average CT ejection efficiency, the change in programmed beam intensities, etc.). The necessary data are acquired from the BD-EQD and from the system COMMON DATA area.

The synchronization of all elements participating in the optimization procedure to the PS cycles and to the CT ejection instants is achieved with the RSX11-M operating system event flags. Together with the PS cycle information data they are created in the PS program line sequencer and loaded into the CT computer via the DR11-C interface with the aid of the system scheduling interrupt routines contained in the CT synchronization task SCHED.

5. PRELIMINARY RESULTS AND EXPERIENCE

Already during the development and testing period the optimization procedure gave some interesting results, which allowed the choice of adequate optimization parameters for future operation. An angle-scan range of ±0.2 mrad delivers 25 to 40 angle-efficiency data pairs for the calculation of the optimum angle in less than 5 minutes. This angle variation deteriorates the ejection efficiency by not more than 2.5% during a few PS cycles, provided it starts near the optimum angle, as can be seen in Figs. 3 and 4 which show two examples of computer plots generated after two optimizations starting at different initial angles. The starting angles and the computed optimum angles are indicated. Figure 4 demonstrates the linear dependence of ejection efficiency (or losses) on angle for larger deviations from the optimum angle (see Appendix). Figure 5 gives the efficiency distribution at high beam intensity around the initial reference value of a double angle scan of ±0.22 mrad. The maximum efficiency spread for a fixed angle is of the order of 1.5%, the mean spread being ±0.8%. For low beam intensities the spread may double.

In several test runs with and without regularly scheduled efficiency optimizations the experience gained up to now demonstrates the benefits the procedure will represent in future CT ejection operation. The maximum range in which the optimum septum angle varied during CT operation and machine developments was -0.85 ± 0.30 mrad. Figures 3, 4 and 5 show that a deviation of 0.2 mrad from the optimum angle position lowers the mean ejection efficiency by more than 2%.

During a particular run with rather stable machine conditions the maximum spread of the optimum angles is generally measured below ±0.1 mrad with a standard deviation better than 0.02 mrad. Figure 7 gives the distribution of optimum angles (-0.73 ± 0.02 mrad) during 6 days of CT ejection operation with the efficiency optimization scheduled every three hours. In the same period an over-all mean efficiency of 97.3% with a standard deviation of 0.2% was measured (Fig. 8).

Afterwards CT ejection was continued without scheduled optimization procedures at a constant septum angle of -0.70 mrad. Despite this value being near to the optimum angle the over-all efficiency deteriorated by about 0.6% and the standard deviation increased to 1.3% compared with the previous operation period.

The situation became more drastic in the following run period after a short PS shut down. The CT ejection was continued without any further optimizations or changes in septum angle setting. However the valid optimum angle had moved from -0.7 to about -0.9 mrad. Consequently the ejection efficiency decreased by more than 2% to 94.7%, corresponding to a 50% increase of the beam losses at CT ejection (Fig. 9)! After 6 days the optimization procedure was rescheduled regularly. The average efficiency was then again raised to about 97% (see Fig. 10) and the angle optimum had shifted to the range -0.87 ± 0.02 mrad.

During many weeks of tests with the efficiency optimum procedure no instabilities or divergences occurred. Negative effects on normal CT control system performance could not be observed. It has to be investigated if the angle for optimum ejection efficiency coincides with the angle for optimum emittance of the ejected beam. Theoretically there should be little difference between both values and optimization for highest efficiency should not lead to an increased emittance value of the ejected beam.

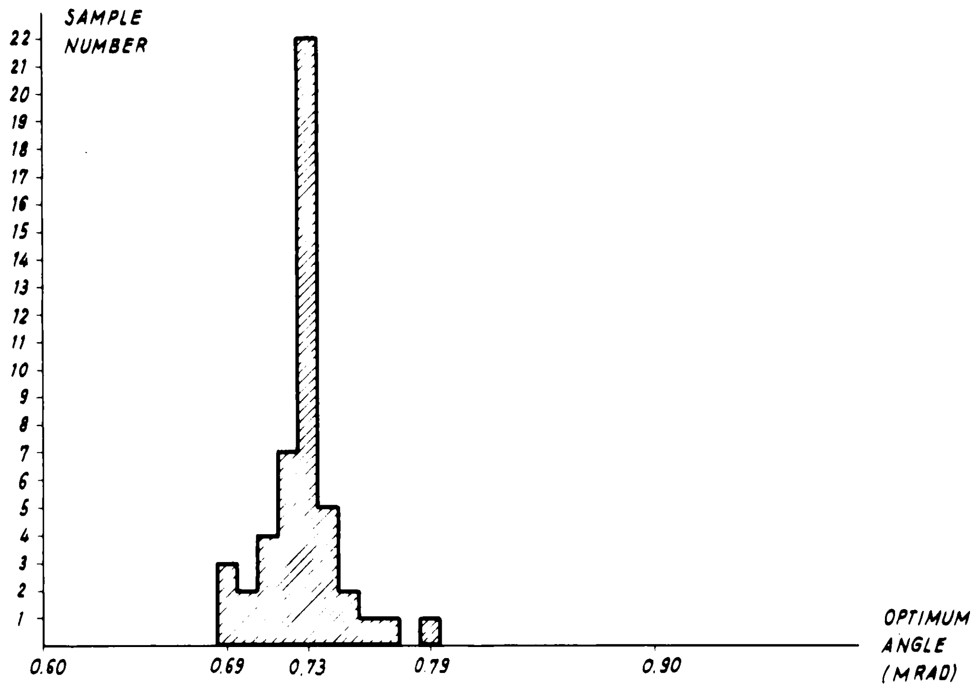


Fig. 7 Distribution of optimum angles during one week of CT operation with scheduled optimization of beam intensities of 10^{13} ppp

Mean value = -0.73 mrad
Standard deviation = 0.02 mrad
Scheduled optimization interval = 3 h
Number of samples = 48

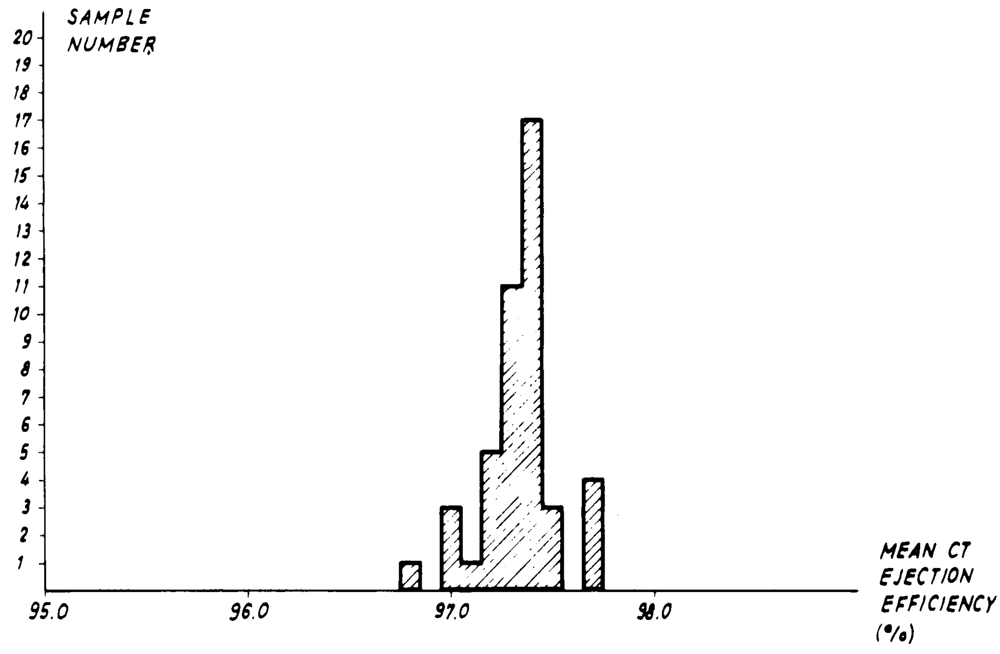


Fig. 8 Distribution of mean ejection efficiencies each averaged over 1000 PS supercycles valid for the same PS operation period as in Figure 7.

Over-all mean ejection efficiency = 97.3%
Standard deviation = 0.2%
Number of samples = 45

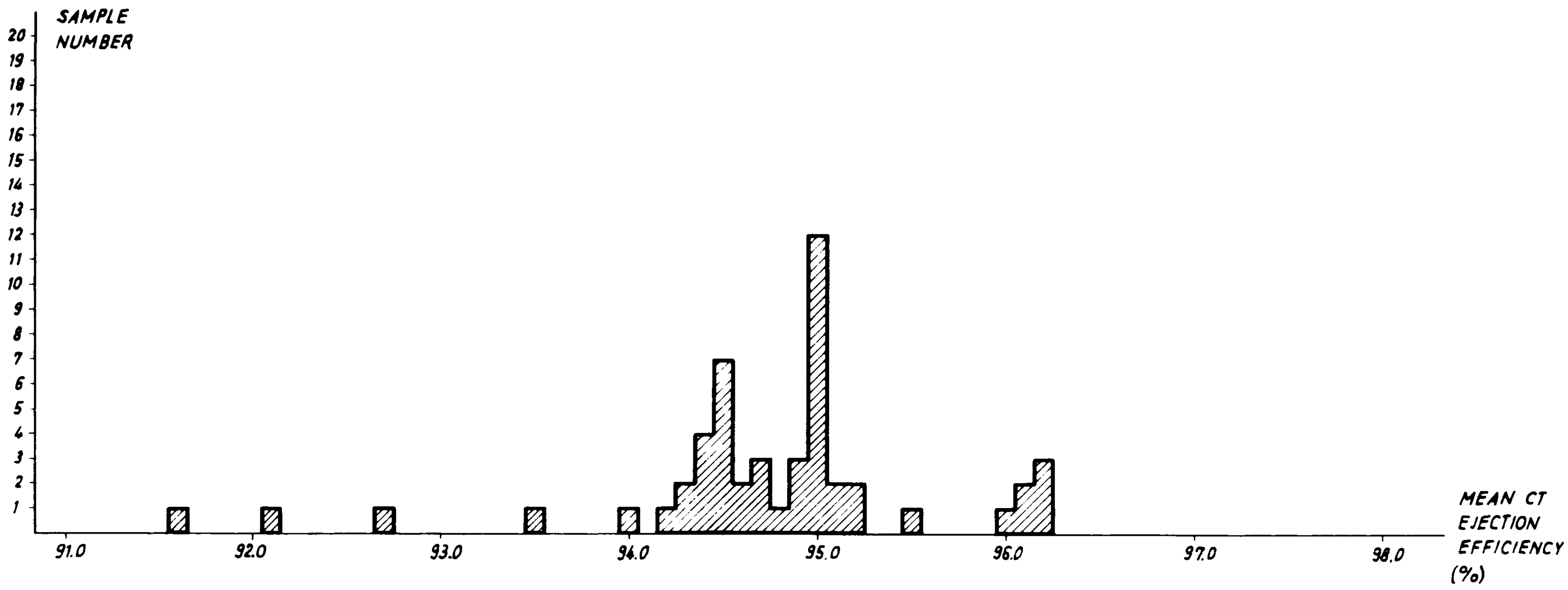


Fig. 9 Distribution of mean ejection efficiencies each averaged over 1000 PS supercycles during 6 days of CT operation without regularly scheduled efficiency optimization.

Constant ES 31 angle : -0.70 mrad
Over-all mean ejection efficiency : 94.7%
Standard deviation : 0.9%

Beam intensity : 10^{13} ppp
Number of samples : 51

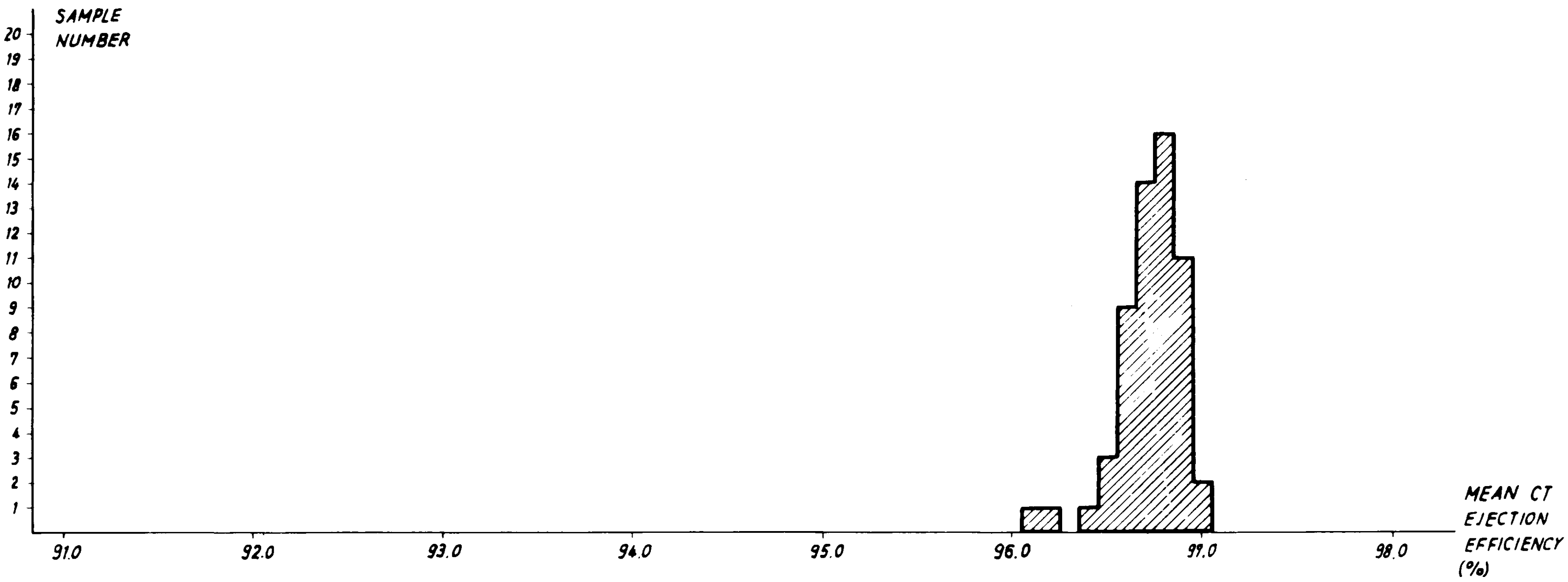


Fig. 10 Distribution of mean ejection efficiencies each averaged over 1000 PS supercycles during CT operation with scheduled optimization following the period covered by Fig. 9.

Mean optimum angle position	: −0.87 mrad	Scheduled optimization interval	: 3 h
Standard deviation of optimum angles	: 0.02 mrad	Beam intensity	: 10^{13} ppp
Over-all mean ejection efficiency	: 96.7%	Number of samples	: 58
Standard deviation	: 0.2%		

6. DISCUSSION

The results of various test runs presented in the previous section clearly demonstrate that the ejection efficiency optimization is an effective tool to limit the beam losses during CT operation to a minimum as far as they are caused by the septum ES 31. For an operator in the PS main control room it is difficult to find the optimum septum angle setting manually. Reasons are the normal spread of the ejection efficiency data and the dependence of the absolute efficiency values on external machine conditions, like the value of the beam intensity, beam fluctuations, the choice of the orbit bumps for CT ejection, etc.

The computer-based optimization procedure, however, determines the optimum angle setting fast and automatically with a minimum disturbance of the ejection performance. A single angle variation of ±0.2 mrad around the reference value generally delivers enough data for an accurate optimum calculation and decreases the efficiency during the optimization cycle by less than 1% (for a period of 5 minutes).

Owing to its isolated effect on CT ejection efficiency, the optimization procedure can be scheduled to run regularly once every 2 to 4 hours without any risk to the CT operation and with a disturbance of the mean efficiency of far less than 1‰. An active angle correction is only performed whenever the PS beam conditions are rather stable and the CT ejection is functioning properly. The possibilities of descheduling or interrupting efficiency optimization cycles at any instant by specific commands or by restarting the control system should give enough security for unforeseen situations or other major failure conditions.

Special optimization cycles can be initiated whenever the beam stability is poor and more angle scans are required to deliver a higher number of data in a selected range, or when plots of the efficiency distribution are required. The optimization procedure can serve as an excellent tool for studying the correlation between beam losses and other beam parameters influenced by the septum angle like the temperature rise of the ES 31 system, the emittance of the ejected beam, etc.

In contrast to the beam intensity optimization procedure (see Section 7.4 of Ref. 1), which runs as an ESAU program and, therefore, when active blocks the CT console for other manipulations, the CT efficiency optimization is fully running in the background without interfering with arbitrary operator actions. Only setting commands to the ES 31 are excluded during the efficiency optimization cycle. The intensity and the efficiency optimization procedures may in principle be run simultaneously.

Hardware and software interfacing constraints, such as the peculiar ES 31 movement control and the fact that ESAU is a single user interpreter and does not, in its present form, allow the scheduling of RSX11-M tasks, all contribute to the cost of providing the efficiency optimization facility and to its relative complexity (Fig. 6).

The tests and implementation of the CT efficiency optimization have been done fully on-line, e.g. during full PS and CT operation. No special machine development time was needed. Disturbances of normal CT operation due to these tests have not been observed. This shows once more the high flexibility and reliability of the CT control system.

7. CONCLUSIONS

In the CT control system an optimization procedure has been implemented, which allows the minimization of the beam losses caused at CT ejection by the electrostatic septum deflector ES 31. The efficiency optimization, once initiated automatically or by an operator command, moves the septum angle autonomously in a range of ±0.2 mrad around its reference value, measuring angle and ejection efficiency at each CT instant, calculating the optimum angle, and finally positioning the septum to this value. The optimization delivers a result of good accuracy in a short time (about 5 minutes) and with negligible disturbance of the beam. It can be performed as a "one-shot" action or scheduled to run automatically in preselected time intervals. Compared with PS run periods, where no optimization was used, the application of the procedure improved the average ejection efficiency by more than 2% corresponding to about 50% reduction of the total ejection losses or 2×10^{11} protons per CT ejection pulse*).

The efficiency optimization procedure will be an effective tool to reduce the radiation level in the PS during CT cycles. With multipulsing operation at high intensities in the future the regular use of the procedure in the scheduled mode is strongly recommended.

The fact that an "operation" parameter (ES 31 angle) is frequently changed without operator interaction should not disturb the performance in this particular case. On the contrary, minimizing the beam losses with the septum angle also improves the quality of the ejected beam (efficiency and emittance). Experience with scheduled optimizations up to now indicates no risk for the performance of the CT system. An optimization interval of 3 hours is recommended. Additional efficiency optimizations can and should be performed at any significant change of the PS beam conditions (intensity, bump strengths, etc.).

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*) This value corresponds to the maximum intensity per pulse the CERN PS could accelerate in 1962.

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APPENDIX

Least Squares Fit Method Applied to Ejection Efficiency Optimization

As a first approximation the losses of a parallel beam caused by an ideal septum of thickness d and of length ℓ are proportional to the effective cross-section area it presents to the beam (Fig. 2). If the system forms a small angle α with the beam direction, the efficiency η follows a linear function with the angle

$$\eta(\alpha) = \text{const.}\ (d + \ell\,|\alpha|) \tag{1}$$

The efficiency should have a sharp peak for $\alpha = 0$; however, experimentally the efficiency function around the peak is found smoothly rounded and can be well approximated by a polynomial of second degree with the coefficients C_0, C_1, C_2

$$\eta(\alpha) = C_0 + C_1\alpha - C_2\alpha^2 \quad . \tag{2}$$

Reasons for the smooth efficiency maximum are the divergence of the particle trajectories, their bending in the electric field of the deflector, and the non-ideal mechanical shape of the septum.

The coefficients C_0, C_1, C_2 in Eq. (2) are determined from N measurements with the least squares fit method such that the expression

$$Q = \sum_{i=1}^{N} \left(\eta_i - C_0 - C_1\alpha_i + C_2\alpha_i^{\,2}\right)^2 \tag{3}$$

becomes a minimum. The necessary conditions are therefore

$$\frac{\partial Q}{\partial C_m} = 0 \qquad (m = 0,\ 1,\ 2) \tag{4}$$

or, using the Gaussian notation,

$$\sum_{i=1}^{N} \equiv [\ ]$$

$$[\eta_i] \quad - C_0 N \quad - C_1[\alpha_i] \ + C_2[\alpha_i^{\,2}] = 0 \tag{5}$$

$$[\eta_i\alpha_i] \ - C_0[\alpha_i] \ - C_1[\alpha_i^{\,2}] + C_2[\alpha_i^{\,3}] = 0 \tag{6}$$

$$[\eta_i\alpha_i^{\,2}] - C_0[\alpha_i^{\,2}] - C_1[\alpha_i^{\,3}] + C_2[\alpha_i^{\,4}] = 0 \tag{7}$$

With these three equations the parameters of the parabola and its angle α_m for maximum efficiency η can be calculated. Using the mean angle $\bar{\alpha} = [\alpha_i]/N$ the optimum angle is found as

$$\alpha_m = \bar{\alpha} + \frac{1}{2}\,\frac{[\alpha_i'^{2}]^2\,[\eta_i\alpha_i'] + N\,[\alpha_i'^{3}][\eta_i\alpha_i'^{2}] - [\alpha_i'^{3}][\alpha_i'^{2}\,[\eta_i] - N\,[\alpha_i'^{4}][\eta_i\alpha_i']}{N\,[\alpha_i'^{2}][\eta_i\alpha_i'^{2}] - N\,[\alpha_i'^{3}][\eta_i\alpha_i'] - [\eta_i][\alpha_i'^{2}]^2} \tag{8}$$

where $\alpha_i' = \alpha_i - \bar{\alpha}$. It corresponds to an efficiency maximum only if $C_2 > 0$.