COMPUTERIZED PRECISION CONTROL OF A SYNCHRONOUS HIGH VOLTAGE DISCHARGE SWITCH FOR THE BEAM SEPARATION SYSTEM OF THE LEP e+/e- COLLIDER

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Abstract: Electrostatic separators are used to separate the beams in LEP. The counter-rotating beams are eventually brought into collision in the four low beta insertions, using switches to discharge simultaneously four high voltage (HV) circuits. Each switch consists of four spark gaps mounted in a pressure vessel. A reduction of the gap widths below the self ignition distance by electric motors results in the initiation of the discharges. Synchronization is ensured by the electrical coupling of the electrodes connected to ground. The design and performance of the computerized precision control of the discharge switch are described. The dynamic characteristics of the prototype switch are also presented.

Introduction

The LEP e+/e- collider has four collision points for experiments. Electrostatic beam separation systems [1], installed symmetrically in relation to each collision point, separate the counter-rotating beams during injection and acceleration.

A separation system consists of two pairs of separator tanks. The electrodes of each pair are powered via coaxial cables, by two HV supplies of opposite polarity but with equal voltage. The voltages on the electrodes of the pairs of separator tanks are typically $U_1 = \pm 110$ kV and $U_2 = \pm 40$ kV.

When the desired energy has been reached the beams are simultaneously brought into collision in the four points equipped with experiments by suppression of the electrostatic fields in the separator tanks.

This suppression is carried out in each individual separation system by a synchronous discharge switch [2] which connects the four HV circuits to ground by means of external resistors.

Such a switch consists of four spark gaps mounted in a pressure vessel. The discharges are initiated by reducing the gap widths below the self ignition distances by electric motors. An internal resistor network ensures that after the ignition of one spark gap the other three ignite within 100 ns [3], thus featuring a perfect synchronization between the four circuits. Complete discharge is obtained by further closure of the gaps until galvanic contact exists.

The simultaneous start of this process in the four points equipped with experiments is triggered by a timing pulse. The fixed delay between this timing pulse and the actual moment that the spark gaps ignite in the four switch assemblies is controlled by a computerized precision control of the motion of the electrodes of the spark gaps. A tolerance on this fixed delay of only ± 2.5 ms is allowed.

Construction of the switch

The four spark gaps are mounted in two pairs inside a pressure vessel. Fig. 1 shows a side view of the mechanical construction of the switch with the bottom part of the vessel removed.

The four upper electrodes are fixed and are connected to the HV circuits via feedthroughs whilst the four lower electrodes are carried in pairs by two moving shafts that pass through gas sealed holes in the top and bottom cover of the vessel. Electric motors mounted on top of the vessel move the shafts independently by means of screw type transmission systems. The lower electrodes are connected by flexible wires to the internal resistor triggering network which is also connected to ground.

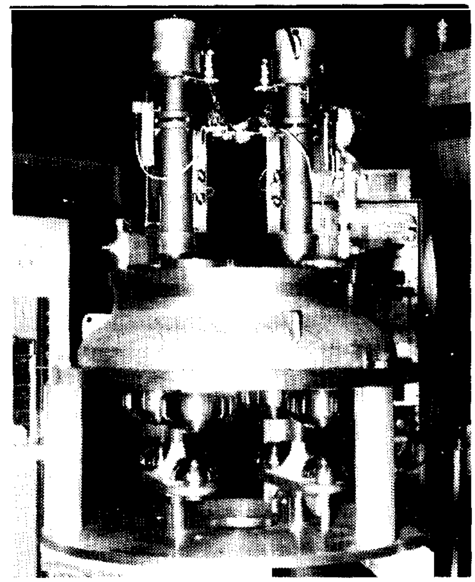

Fig. 1 - Mechanical construction of the switch

Specification of the motion of the electrodes

The self ignition of a spark gap depends on the distance between the electrodes, their shape and the gas pressure in between them. In nitrogen self ignition occurs between spherical electrodes when:

$$d_s \text{ (mm)} \le [\ U \text{ (kV)} - 7\ ] \ / \ [\ 2.1\ p \text{ (bar)}\ ]$$

Once ignited, a separation circuit is discharged exponentially. After a certain time the current through the spark gap becomes so small that the discharge cannot be maintained and the arc extinguishes. The duration of a maintained discharge is for our HV circuits typically:

$$t_s \text{ (ms)} = 13 \ \ln [\ [\ U \text{ (kV)} - 5\ ] \ / \ 5\ ]$$

If, after this time interval the electrodes of the spark gaps make no galvanic contact, a residual voltage would remain on the separator circuits. The gap widths must thus be reduced to zero within this time interval, hence imposing a minimum velocity:

$$d_t \text{ (mm)} = t_s \text{ (s)}\ V_{min} \text{ (mm/s)} \quad \text{with} \quad d_t \ge d_s$$

For a given gas pressure and a constant velocity slightly higher then the minimum velocity, the hatched area of fig. 2 shows the region where the two pairs of electrodes must dwell for meeting these criteria.

From this figure one can see that the greatest tolerance in this region is obtained for the lower voltage electrodes. On the other hand, the mutual ignition of the spark gaps is strongest when one of the higher voltage gaps ignites first, and it is thus obvious that the discharge process should start when the electrodes of these gaps pass through point A, whilst the lower voltage electrodes should be in between B and C.

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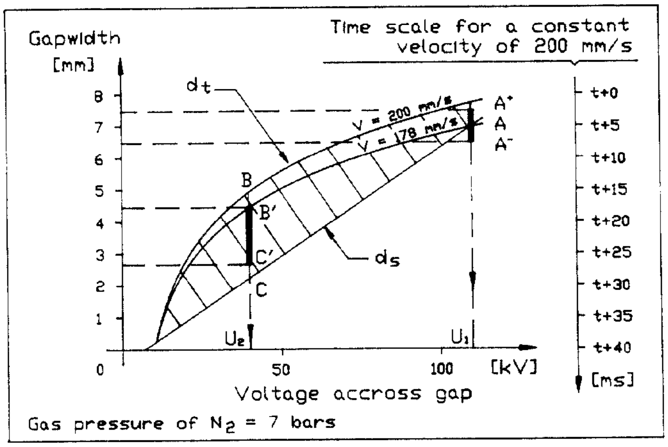

Fig. 2 - Synchronous and continuous discharge region

The need to start the discharge process within an absolute time interval of ± 2.5 ms after a fixed delay confines an equivalent position tolerance around point A on the higher voltage electrodes. In fig. 2 this has been indicated with the bar A+A- and is valid for electrode velocities slightly higher than the minimum demanded. However, this tolerance reduces the position freedom BC of the other electrodes by the same amount, leaving only the distance B'C'.

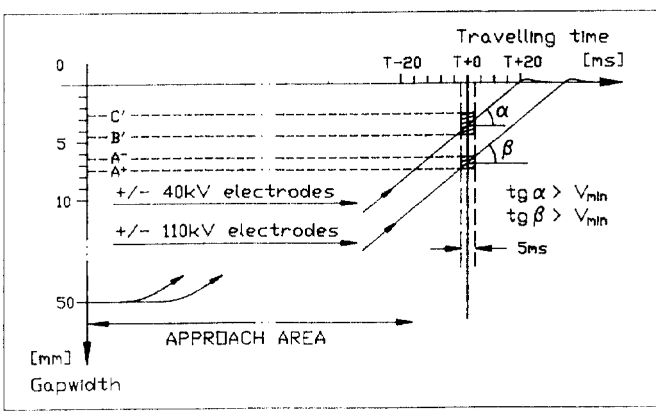

Fig. 3 - The required motion of the electrodes

The arguments described above define the trajectories of the two pairs of contacts. They are shown in fig. 3. Rectangular boxes indicate the target areas through which the electrodes must be steered at velocities > V_{min}. The trajectories followed by the electrodes when passing through the approach area can be chosen freely.

The motor, transmission and electrode assemblies

The transmissions, which move the shafts carrying the electrodes, are driven by low inertia permanent magnet DC motors. The motors are powered from low impedance amplifiers. Friction and inertia have been kept as low as possible without sacrificing mechanical rigidity. The transfer function of these assemblies in the Laplace domain is:

$$d(p) = G_0 \, [\, E(p) - \alpha \, F(p) \,] \, / \, [\, p \, [\, \tau p + 1 \,] \,]$$

With $G_0 \simeq 10$ (mm/V s) conversion constant
$\alpha \simeq 0.0125$ (V/N) conversion constant
$\tau \simeq 22$ (ms) system time constant
$d(p)$ (mm) electrode displacement
$E(p)$ (V) motor voltage
and $F(p)$ (N) static friction and gravitational force on assembly

G_0, α, τ, and F, which are related to parameters such as static and viscous mechanical friction, electrical resistance and temperature, vary because of aging and are furthermore different for each assembly.

Basic principles of the control of the motion

Applying just a DC voltage on the motors would cause arbitrary trajectories for the electrodes due to the variations in the mechanical parameters. The influence of these variations can be reduced by controlling the motors with servo feedback loops which track reference trajectories. However, due to loop gain limitations together with the given time constant of the system, insufficient time precision can be obtained with such tracking servo loops. Therefore the remaining position errors, being timing errors relative to the reference trajectories, need additional correction.

A considerable reduction of the timing errors is obtained by regular corrections of the reference trajectories during the motion of the shafts. The amplitudes of the corrections are derived from the position errors anticipated on the traversal of the target areas at the instant of correction.

The control electronics

A simplified block diagram of the control electronics is given in fig. 4. Two identical servo feedback loops control the individual electric motors. The heart of each loop is a General Purpose Motion IC, HCTL-1000 [4] which is programmable by the microprocessor. Within the loops, eight bit DACs convert the outputs of the HCTL-1000s into input voltages for pulse width modulated amplifiers.

Position and velocity feedback is obtained from incremental encoders [5] mounted directly on the shafts of the motors. Incremental encoders only give relative information on the position. Therefore linear transducers mounted on the moving shafts determine the absolute position of the electrodes.

Electric brakes, which are controlled by the microprocessor, ensure that the switches remain in one of the two end positions after a transition.

A multi-channel ADC allows the measurement of the position transducers, the pressure in the vessel of the synchronous switch, the voltages on and the current through the electric motors.

The voltages on the HV circuits and the currents drawn from the HV supplies are obtained through the LAN that interconnects the different elements of the separation system.

An external trigger starts the simultaneous discharging process. The timebase is obtained from a quartz controlled timer circuit in the microprocessor system.

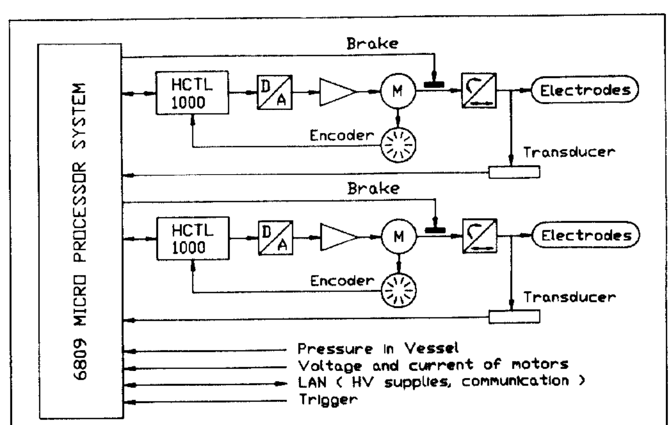

Fig. 4 - Block diagram of control electronics

The General Purpose Motion Controller HCTL-1000

This device, together with an optical four quadrant encoder, forms a servo feedback loop. Sampling time (bandwidth), gain, and phase compensation are programmable. Its operation mode used for the closure of the switches, the integral velocity profiling mode, moves along a trajectory calculated from velocity and acceleration vectors that are loaded in real time into its registers. The time lag between the actual and the reference trajectory, caused by the time constant of such a servo loop, remains. However, momentary friction and stalling are corrected.

Software in the microprocessor

Calibration of transducers and encoders

The zero gap distance must be determined after each power up and after a significant pressure change in the vessel, because of vessel deformation. This is done by moving the electrodes until currents are drawn from the HV supplies.

Preparation of the trajectories

Some time before closing the switches the key parameters determining the electrode trajectories are calculated. This concerns the centres of the target areas mentioned in fig. 3, the gap difference between the centres of the target areas and the minimum velocity. Furthermore the travelling time required by the lower voltage electrodes for moving at minimum velocity from the open switch position to the centre of its target area is calculated.

Procedure for closure of the switches

Immediately after the reception of the LEP timing trigger pulse, the electrodes are cycled several times with a stroke of about 10 mm, starting always from a fully open gap. This operation reduces the sticking or static friction of the gas seals of the moving shafts, which gradually builds up when the switch remains stationary for some time.

Then, after a short waiting time, the lower voltage electrodes start moving at minimum velocity. The starting time is determined by the fixed delay between trigger and desired ignition moment and the previously calculated travelling time towards the target area for these electrodes.

Once the relative gap difference between the two switches equals the required difference, previously calculated from the distance between the centres of the target areas, the higher voltage gaps begin to close at minimum velocity.

From now on at regular intervals this gap difference is measured and compared with the required gap difference. Any difference is corrected by a small modification of the velocity of one of the motors. At the same time the trajectory of the higher voltage electrodes is calculated from its actual position and its actual velocity. A weighted correction is applied to the velocities of both motors if the extrapolation of this trajectory does not go through its target area. The weighting factor is dependent on the actual gap distances, the smaller they are the larger the correction must be.

These corrections result in an increase in velocities, because the real trajectories are delayed by one to two mechanical time constants which are caused by the behavior of the servo loops.

With the correct choice of weighting factor and rate of corrections, this method will steer both contacts through the anticipated target areas at the required instant. Consequently the errors accompanying classical servo feed back systems are eliminated.

Dynamic characteristics of the prototype switch

Tests on the prototype switch have shown that with a gas pressure of 7 bars in the vessel an optimum has been obtained between the minimum required velocity and the misalignment tolerance of the electrodes. A difference of ± 0.3 mm can be tolerated in the gap widths of one pair of electrodes. The minimum required velocity is then 200 mm/s and with a maximum possible velocity of 300 mm/s it leaves enough range for velocity corrections.

Discharging the switch once per minute with a constant electrode velocity of 200 mm/s results in a reproducibility of the ignition moment of ± 1 ms over several days, thus showing a satisfactory stability of the entire system.

Fig. 5 shows the motion of the two mechanisms during the closure of the switch together with the HV recordings. During the motion velocity corrections were continually made at a rate of ≃ 100 Hz in order to keep the difference between the two mechanisms equal to the calculated value. The overshoots in this example are due to a too high correction rate, however, the convergence of the trajectories to the target positions is clearly demonstrated. Tests with several combinations of HV values always gave the required result. At present the final and complete version of the software is in progress.

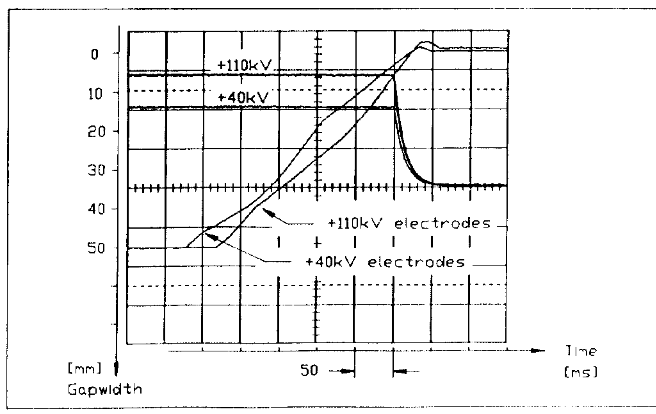

Fig. 5 - Motion of electrodes and HV recordings

Conclusions

With computerized precision control of the electrode motions of an HV discharge switch it is possible to obtain better time accuracy then would have been the case with conventional analogue servo feedback systems. In fact the accuracy can be a fraction of the system time constant and allow large tolerances on the system parameters.

References

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