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► To cite this version:

A. Bieńkowski, M. Jaskóla, L. Zemlo. On the analysis of the beam energy stabilization in the Van de Graaff accelerator “ Lech ”. *Revue de Physique Appliquée*, 1977, 12 (10), pp.1323-1325. 10.1051/rphysap:0197700120100132300 . jpa-00244316

HAL Id: jpa-00244316

<https://hal.science/jpa-00244316>

Submitted on 1 Jan 1977

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ON THE ANALYSIS OF THE BEAM ENERGY STABILIZATION IN THE VAN DE GRAAFF ACCELERATOR « LECH »

A. BIENKOWSKI (*), M. JASKÓŁA (**) and L. ZEMŁO (**)

Résumé. — La fluctuation d'énergie du faisceau de l'accélérateur Van de Graaff *LECH* est détectée par un système d'analyse standard consistant en un aimant de 90° suivi d'une paire de fentes. Le signal d'erreur venant des fentes est utilisé pour corriger la haute tension au terminal. La correction des composantes rapides est faite par l'intermédiaire de la triode - corona tandis que pour les composantes lentes on ajuste le courant de charge sur la courroie. En vue de déterminer le gain maximum compatible avec une opération stable nous avons adopté une fonction de transfert bien définie pour stabiliser les 2 boucles mentionnées ci-dessus. Ensuite nous avons appliqué cette fonction à l'analyse de la stabilité du système de courte réaction. Bien que le calcul ait été fait avec les paramètres de l'accélérateur *LECH*, la même méthode est facilement applicable à d'autres accélérateurs Van de Graaff.

Abstract. — In the Van de Graaff accelerator *LECH* the deviation of the beam energy from the desired value is detected by the standard analysing system consisting of the 90° bending magnet followed by a pair of slits. The amplified error signal from that slits is used to correct the high voltage at the terminal. Corrections of the fast component of the voltage instability are made *via* the corona-triode and for the slow component *via* adjustment of the belt charging current.

In order to determine the maximum gain factors providing the stable operating conditions we have adopted a definite transfer function for the aforementioned two loop stabilizer. Next we have applied this function to the analysis of the stability of the feedback system. Although the calculation was made for parameters of the accelerator *LECH*, the same method is easily applicable to other Van de Graaff accelerators.

In the Van de Graaff accelerator *Lech* the deviation of the beam energy from the desired value is detected by the standard analysing system consisting of the 90° bending magnet followed by a pair of slits. The amplified error signal from those slits is used to correct the high voltage at the terminal. Corrections of the fast component of the voltage instability are made *via* the corona-triode and for slow component *via* adjustment of the belt charging current. Figure 1 shows the schematic diagram of our accelerator.

The block diagram of the regulating system is shown in figure 2. E_s represents the steering signal determined by the magnitude of the magnetic field in the analysing magnet. The signal E_i represent the energy of the ions at the exit of the accelerator tube. The error signal $\Delta E = E_s - E_i$ in the form of the difference of currents from the exit slits is amplified by the amplifier A.

The accelerator considered as an integrating circuit has the time constant:

$$T_e = C_k \cdot R \quad (1)$$

where:

C_k — the terminal to ground capacity (150 pF)

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FIG. 1. — Schematic diagram of the accelerator *LECH*.

FIG. 2. — Block diagram of regulating system.

R is estimated by the formula:

$$\frac{1}{R} = \frac{1}{R_d} + \frac{I}{U} \quad (2)$$

where:

R_d — the divider resistance

I — the load current (the beam current, the leakage current, etc.)

U — the terminal voltage.

$R_{\min.} = 4.5 \times 10^9 \Omega$ From that $T_e \min. = 0.67$ s
 $R_{\max.} = 42.3 \times 10^9 \Omega$ From that $T_e \max. = 6.35$ s

The response of the terminal to the corona-triode is described by two time constants: T_t and T_t' . The time delay T_t is the minimum ion transit time from the corona points to the terminal, T_t' is the spread of the transit time. If the voltage of the needles of the

corona-triode is rapidly changed, the terminal potential starts to change exponentially with the time constant T_t' after the delay-time T_t . The above time constants have been measured. At 3 MV terminal voltage and at 10 atm gas pressure T_t and T_t' was measured 7 ms and 5 ms respectively.

The response of the slow loop of the stabilizer is described by the belt delay — time $T_p = 185$ ms and by the time constant of the regulated belt charging supply $T_l = 140$ ms.

The other time constants are negligible as compared with the mentioned above. With practically sufficient approximation, the elements of the regulating system can be considered as linear. Linear systems are most easily handled by the use of Laplace transforms. We can write the Laplace transform of the regulator according to the block diagram in figure 2:

$$K(p) = \frac{A}{1 + pT_e} \left[B \frac{e^{-pT_t}}{1 + pT_t'} + C \frac{e^{-pT_p}}{1 + pT_l} \right] \quad (3)$$

where: A, B, C are the zero frequency open loop gains of the chains.

The time constant $T_t' = 5$ ms is small with comparison to the time constant $T_e = 0.67$ s. Therefore the transfer function of the system will be given by the formula:

$$K(p) = \frac{A}{1 + pT_e} \left[B e^{-pT_t} + C \frac{e^{-pT_p}}{1 + pT_l} \right] \quad (4)$$

We have applied this formula to the analysis of the stability of the feedback system. The Laplace transform is simply related to the Fourier transform by a change of variable. The Fourier transform of the regulator is given by the formula:

$$K(j\omega) = \frac{A \cdot B \cdot e^{-j\omega T_t}}{1 + j\omega T_e} + \frac{A \cdot C \cdot e^{-j\omega T_p}}{(1 + j\omega T_e)(1 + j\omega T_l)} \quad (5)$$

The real component of this transform is given by the expression :

$$\text{Re} [K(j\omega)] = \frac{D}{\sqrt{1 + \omega^2 T_e^2}} \{ \text{Re}_1 [K(j\omega)] + k \cdot \text{Re}_2 [K(j\omega)] \} \quad (6)$$

and the imaginary component by the expression :

$$\text{Im} [K(j\omega)] = \frac{-D}{\sqrt{1 + \omega^2 T_e^2}} \{ \text{Im}_1 [K(j\omega)] + k \cdot \text{Im}_2 [K(j\omega)] \} \quad (7)$$

where :

$$D = A \cdot B$$

$$k = \frac{A \cdot C}{A \cdot B} = \frac{C}{B}$$

$$\text{Re}_1 [K(j\omega)] = \cos (\arctg \omega T_e + \omega T_t)$$

$$\text{Re}_2 [K(j\omega)] = \frac{\cos (\arctg \omega T_e + \arctg \omega T_l + \omega T_p)}{\sqrt{1 + \omega^2 T_l^2}}$$

$$\text{Im}_1 [K(j\omega)] = \sin (\arctg \omega T_e + \omega T_t)$$

$$\text{Im}_2 [K(j\omega)] = \frac{\sin (\arctg \omega T_e + \arctg \omega T_l + \omega T_p)}{\sqrt{1 + \omega^2 T_l^2}}$$

where:

D : the gain factor of the fast loop,

k : the fast loop gain to the slow loop gain ratio.

In order to determine the admissible gain factor D and the admissible gain ratio k providing the stable

operating conditions we have applied the Nyquist criterion.

At first we have solved numerically the equation:

$$\text{Im}[K(j\omega)] = 0 \quad (8)$$

The lowest non — zero solution of the equation (8) is the critical frequency ω_{crit} . If the inequality:

$$\text{Re}[K(j\omega_{\text{crit}})] > -1 \quad (9)$$

holds for critical frequency ω_{crit} , the feedback system is stable. The calculation was made for minimum and maximum value of load currents. The results of the calculations are presented in tables.

TABLE I

*The conditions of the stable work
for the two loop stabilizer*

	k	f_{crit} (cps)	D
$T_e = 6.35$ s	1.82	1.65	< 31.4
minimum load	1.6	36.8	< 1 440
$T_e = 0.67$ s	1.89	1.74	< 35
maximum load	1.6	36	< 150

For the time constant $T_e = 6.35$ s (minimum load) and for gain ratio $k = 1.82$, the critical frequency is only 1.65 cps and the admissible gain factor of the fast loop is less than 31.4. In order to increase the critical frequency, the gain ratio should be decreased. For $k = 1.6$ the critical frequency is equal 36.8 cps and the fast loop gain ratio should be less than 1440. For the accelerator running with the maximum load T_e is equal 0.67 s. Then the gain ratio is 1.89, the critical frequency is only 1.74 cps and the admissible fast loop gain factor is less than 35. For the gain ratio equal 1.6 the critical frequency is 36 cps and the maximum gain factor of the fast

loop is less than 150. The above results are in good agreement with the experiment. We have chosen the maximum gain ratio equal 1.6 and the maximum fast loop gain factor equal 100, that is compatible with a stable system in the whole range of load currents.

TABLE II

*The conditions of the stable work
for the one loop stabilizer with the corona-triode.*

	f_{crit} (cps)	D
$T_e = 6.35$ s	35.7	< 1 420
minimum load		
$T_e = 0.67$ s	35.9	< 150
maximum load		

There is a possibility of working with the corona-triode alone (table II). The bandwidth and the gain is then comparable with those discussed above, but the range of stabilization is smaller. The range of two loop stabilizer is approximately 200 kV, while the range of corona — triode stabilizer is at most 50 kV.

TABLE III

*The conditions of the stable work for the one loop
stabilizer with the regulation of the belt charging
current.*

	f_{crit} (cps)	A
$T_e = 6.35$ s	0.83	< 41
minimum load		
$T_e = 0.67$ s	0.96	< 5.45
maximum load		

The work with the slow loop alone (table III) is impossible because the bandwidth and the permissible gain are then far too small ($f_{\text{crit}} = 0.83$ -0.96 cps, the gain less than 5.45).