DESIGN OF AN ELECTRON BEAM ENERGY CONTROL LOOP USING TRANSVERSE DISPERSION

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Abstract

Stability in mean electron beam energy is of highest interest for a number of experiments performed at the ELBE accelerator. Energy drifts affect parameters of the generated Bremsstrahlung spectra, X-rays or infrared light, as well as the beam trajectory at the production targets or through the FEL waveguide, respectively.

In practise, we observe a slow drifting of the effective accelerating field during the first hours after a machine power-up or after switching to different nominal beam energies. Initially, this effect was compensated manually. A first order automation solution has been developed that corrects the resulting energy drift continuously, using a non-intrusive beam position monitor placed in a transversely dispersive part of the beam guide.

This paper describes the beam line setup and the simplified dynamic model of the control loop derived from it. Calculation of controller parameters using standard a standard method is shown. The user interface of the control system and working conditions for the loop are explained. Operational performance and conclusions towards improvements close this contribution.

ENERGY DRIFT OF THE ELBE ACCELERATOR

In fig. 1 the observable drift in fed forward and reflected RF power and thus in beam energy is shown exemplarily. A second order delay behaviour was found to fit the data best using time constants of 30 min and 25 min. The usual method to compensate for this was to adjust the RF gradient value of the last accelerating module ten-minute-wise, until the thermal drift behaviour settles. To indicate a change in energy, a λ/4 strip line beam position monitor (BPM, [1]) placed in a dispersive part of the beam guide, was observed. Intuitively, the first order solution is to perform this correction automatically by a continuous control loop.

THE CONTROL LOOP

System identification

In fig. 2, the elements building the control loop are displayed exemplarily for the Bremsstrahlung beam line of ELBE, where photo activation experiments are most sensitive to the beam energy. The transfer function F_S of the controlled system is the product of:

- the TESLA cavity with a length of 1000 mm

$$F_C = \frac{\partial E_{El} /_{MeV}}{\partial G_C /_{(MV/m)}} = \cos\varphi , \tag{1a}$$

- the bending magnet

$$F_D = \frac{\partial x_1}{\partial E_{El}} = \frac{D_D}{E_{nom}} , \tag{1b}$$

- the drift space

$$F_{Dr} = \frac{\partial x_2}{\partial x_1} = 1 + \frac{D'_D}{D_D} \cdot L_{Dr} , \tag{1c}$$

- the beam position monitor

$$F_{BPM} = \frac{\partial x_2^*}{\partial x_2} = \frac{1}{1 + pT_\Sigma} , \tag{1d}$$

- a low pass filter in the PLC algorithm

$$F_F = \frac{1}{1 + pT_F} \quad \text{with } T_F = 30s . \tag{1e}$$

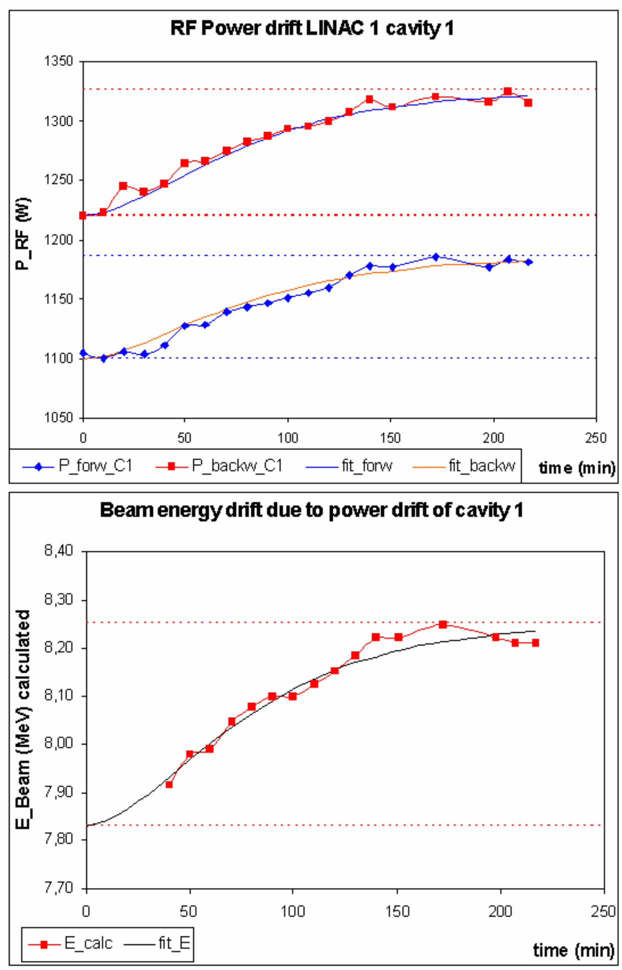

Figure 1a: RF power and mean beam energy drift after start up of the accelerator. (G_{C1} = 10 MV/m, $G_{C2} \approx 0$, E_{nom} = 8 MeV)

Have a look at fig. 3 for the corresponding control loop model. The notations used above are:

φ	RF phase
G_C	RF gradient
x_1, x_2	transverse displacement (horizontal)
D_D	dispersion
E_{nom}	nominal beam energy
D'_D/D_D	horizontal momentum (angul. notation)
L_{Dr}	length of drift space
T_F	filter time constant

Equation (1a) implies the transit time factor of cavity 2 to be unity. The dispersion is a geometric attribute of the dipole and is not derived here in detail. This may be studied with appropriate literature on particle beam optics [i.e. 3, 4]. The delay time T_Σ in equation (1d) is the so called "accumulated delay time" [5], representing all response times of the BPM RF signal transmission, data acquisition and transfer of the BPM results to the PLC (programmable logic control). It was found experimentally to be ≈ 0.3 s. The filter is designed as to eliminate higher frequency parts of the BPM signal, which are small deviations of beam deflection and energy, as well as measurement noise. They may result from local charging up effects in the injector section or RF system modulations and are not handled by this control loop.

Controller Design

Using general rules of structural design for linear control loops [5] a PI controller is used that compensates for the large delay time T_F of the system:

$$F_R = \frac{1 + pT_F}{pT_I} = P + \frac{1}{pT_I} \tag{2}$$

For the resulting second order control loop, the necessary damping D can be calculated by selecting a certain overshoot h_+ that has to be inserted as a percentage:

$$D = \frac{1}{\sqrt{1 + (\pi / (\ln h_+))^2}} \tag{3}$$

The open loop transfer function $F_0(j\omega)$ in frequency domain is calculated by developing $F_0 = F_R * F_S$ towards

$$F_0(j\omega) = \frac{V_S}{j\omega_0 T_I (1 + j\omega T_\Sigma)} \tag{4a}$$

Equating with

$$F_0(j\omega) = \frac{\omega_0^2}{(j\omega)^2 + 2D\omega_0 \cdot j\omega} \tag{4b}$$

and using

$$\omega_0 = \frac{1}{2DT_\Sigma} \text{ and } T_I = \frac{V_S}{\omega_0^2 T_\Sigma}, \tag{5}$$

one can calculate the integration time and the gain of the controller. Here, ω_0 is the eigen frequency of the open loop. This generalized derivation for the controller parameters has been used to meet any ratio of T_F and T_Σ, i.e. if the filter time is modified or one faces data transmission delays other than expected.

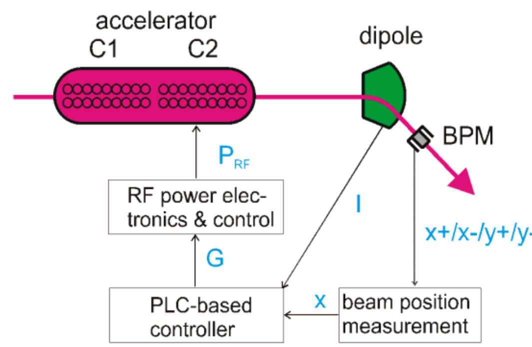

Figure 2: Scheme of the energy stabilization system. (C1, C2: Tesla cavities)

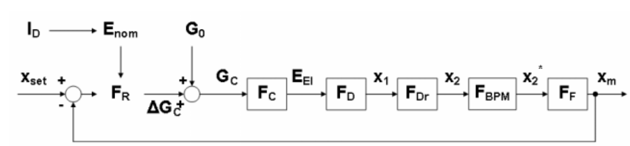

Figure 3: Control loop scheme.

SOFTWARE IMPLEMENTATION

ELBE is run using commercial PLC and visualization technology by Siemens [2]. For implementation into this environment, a standard function block for de facto continuous PI(D) control is used. In every iteration step (period of 500 ms), the required controller parameters are calculated according to the above standing rules from machine parameters. The filter is a simple discrete delay element using the backwards differentiation method with a period of 50 ms. The controller is adaptive in terms of the dependence of the system gain from the nominal energy, which is calculated from the current set value I_D and the design value $(\Delta I/\Delta E)_D$ of the dipole for the nominal deflection radius:

$$E_{nom} = \frac{I_D + I_0}{(\Delta I / \Delta E)_D} \tag{6}$$

Further, a user interface was created for the operating personnel, allowing full control of the loop parameters. The operator can check whether the running conditions are fulfilled (beam is on, the appropriate beam line is selected, a minimum macro bunch length and current are given and pre-alignment has been done). These are switch-off conditions as well, triggering appropriate error messages. When the controller is activated, the actual gradient set value is stored as controller output offset, controller parameters are initialized, and the input due value is set to zero or to the actual BPM reading, respectively. The direct input options for all beam line elements determining beam current, energy or trajectory are restricted.

VERIFICATION

Fig. 4 shows the operation of the control loop over a timescale of 5 hours in the nuclear physics beam line. Over the first 30 minutes of the plot, the machine was set up manually. One can see that from the moment of switching on, the BPM reading stays on a constant base line (curve BPM-X). The remaining higher frequent part of the signal is in the order of +/- 25 µm, corresponding to a value for $\partial E/E_{nom}$ = $2.4 \cdot 10^{-4}$, if this was pure energy modulation. The gradient set value decreases slowly, reflecting thus partly the exponential drift behaviour of the cavities depicted before (curve GRAD_C2).

To check the step responses of the loop, the parameters were varied in different ways (see fig. 5). Attention was paid here on minimizing the overshoot of the gradient set value, which has not been discussed so far. As a result, optimum P values were found be off the calculated values by a factors of 2 to 3. The reason for that is first seen in adding up of errors in the system identification and in beam misalignment (i.e. off-center passing of a quadrupole, yielding unknown deflections). Further, a couple of assumptions had been made, like zero horizontal displacement and momentum of the beam when entering the dipole, as well as on crest operation of the cavity and the experimentally obtained delay time.

CONCLUSION AND LOOK-OUT

Drawing a line, we can state that the method is working properly and as expected and is definitely an upgrade in beam quality and operability for long term experiments requiring higher mean energy stability. Looking at the reproducibility of any aimed time behaviour, there have to be improvements in the future, although the robustness of the loop is fitting our needs. One could develop a more detailed model of the system, containing the disturbing element, but measures taken will be rather a self tuning algorithm for the controller, combined with active horizontal position control and high resolution field measurement, being thus an absolute energy measurement. The necessary technologies are partly already applied at ELBE (NMR measurement). In case of FEL operation, users are rather interested in the infrared wavelength than in the energy, so the intention is to use continuous spectrometry as input for the control loop instead of dispersion.

Figure 5: Optimizing the controller.
(due value with added step function)

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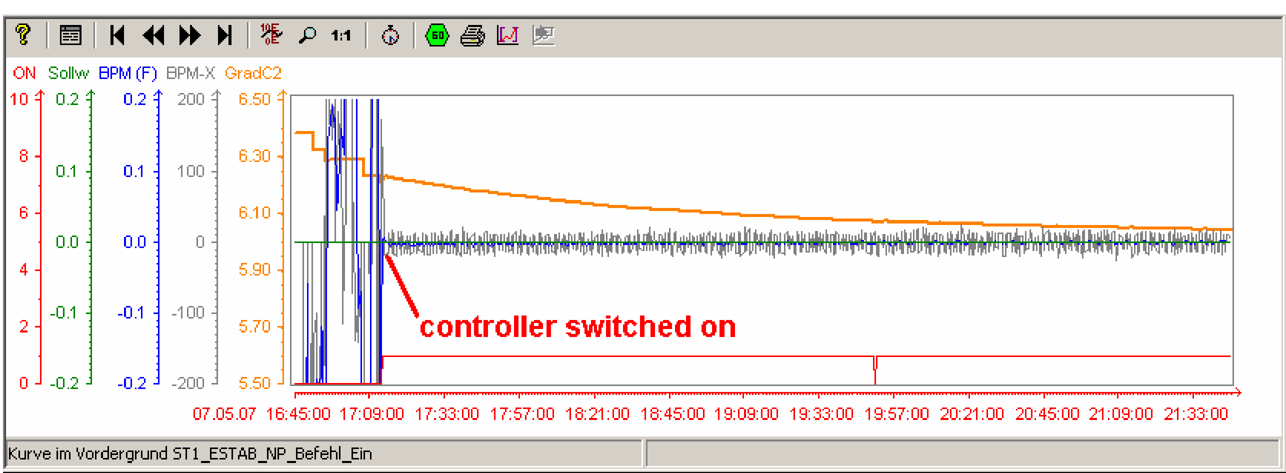

Figure 4: Operation of the energy control loop at E_{nom} = 14.5MeV, G_{C1} = 10 MV/m, I_{Beam} = 450µA in cw mode. ("ON": controller on state, "Sollw": BPM due value, "BPM(F)": BPM reading filtered with 30 sec, "BPM-X": BPM reading, "GRAD_C2": gradient set value for cavity 2 (controller output).