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Electrodynamics Optimization for Linac's RF Control

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ABSTRACT

Criterion for effective RF control at transient beamloading is developed under the beam dynamics optimization. The control parameters with the accelerating channel total characteristics are optimized for high-duty-factor linac at time-varying injection.

1 Introduction

Main specifications of the high-duty-factor intense beam linacs lead to a need for excellent control of the accelerating fields. Since application [1,2] of the well-known methods, assuming a slow variation of amplitude and phase for the single harmonic approximation of the beam excited field is inadequate for the rigorous solution, detailed analysis [3] defines the effective control at transient beamloading, and the system optimization for the required RF energy with the control errors minimization at the system simplification is developed in [4]. However, the particles dynamics is not considered in an explicit form, so that the principle restrictions on the [3,4] results applicability may impose. In the general case the accelerating resonator external characteristics as well as the control signal are completely defined by F function (Eq.(6) in [3]), and the required criterion for the dynamics optimization can be defined in F terms also, since the excited field carries the particles dynamics information.

2 Electrodynamics criterion

The p-particle energy variation $\mathcal{E}_p(t)$ in the operating mode field can be presented in the correlative form $\frac{d\mathcal{E}_p}{dt} = k_p f_{sy}(t) + g_p(t)$ with the synchronous particle energy derivative $f_{sy}(t)$ reference ($\int_{-\infty}^{\infty} g_p(t) f_{sy}(t) dt = 0$); the sum for P_n particles, which enter the resonator on one of RF periods T, is

$$F_n(t) = \sum_{p=1}^{P_n} \frac{d\mathcal{E}_p}{dt} = K_n \cdot F_s(t) + G_n(t), \qquad (1)$$

$K_n = \kappa_n / P_n$, $\kappa_n = \sum_{p=1}^{P_n} k_p$, and $G_n(t) = \sum_{p=1}^{P_n} g_p(t)$ is uncorrelated with $F_s(t) = P_n f_{sy}(t)$. The residual $F_s - F_n = \sum[f_{sy}(t) - \frac{d\mathcal{E}_p}{dt}]$ signal term for bunching particle is oscillating function with decreasing intensity (as the particle approaches the synchronous one, the mode field effect becomes the same as for the synchronous particle; the particle velocities on an accelerating period are not substantially different, so that the pass from one bunch to another is improbable), while for the losing particle it is just $f_{sy}(t)$ from the loss instant. Thus, the lost particles cause main contribution to the correlation of the residual signal with $f_{sy}(t)$, since most losses take place in the initial part of the accelerating structure. Moreover, symmetrical bunching gives the zero contribution (the term for the particle that overtakes the synchronous is compensated by the particle that lags behind in the energy sense), therewith for vanishing losses the nonzero $\int (F_s - F_p)^2 dt$ value presents the real bunching difference from the symmetrical. So, the losses will be minimized at $\int_{-\infty}^{\infty} (F_s - F_p)^2 dt \to 0$ with $\left| \int_{-\infty}^{\infty} (F_s - F_p) F_s dt \right| \to 0$, the global minimum determines the realizable[1] criterion

$$\int_{-\infty}^{\infty} F_n^2 dt \to \min, \quad G_n \to 0, \quad K_n \to 1; \qquad (2)$$

which represents the necessary conditions for the particles output energy spread minimization also.

3 Implementation

Total energy derivative for N periods beam is defined by Eq.(1) sum, $D_N(\omega) = \sum_{n=1}^{N} \kappa_n e^{-i\omega(n-1)T} f_{sy}(\omega) +$

[1]Minimum minimorum conditions $G_n = 0$, $K_n = 1$ are realized, e.g., for δ-bunched beam. Formally, $F_n = 0$ also delivers zero values, that is consistent with zero losses possibility [5] in RFQ channel without acceleration.

$\sum_{n=1}^{N} G_n(\omega)$. Consider the relationship between the conditions (2) of the particle losses with the output energy spread minimization and $\Psi_N = \int_{-\infty}^{\infty} |D_N(\omega)|^2 d\omega$ minimization under prescribed $\int_{-\Delta}^{\Delta} |D_N(\omega)|^2 d\omega$ value (the same for $|F(\omega)|^2$ integrals since $F(\omega) = -(\omega_r/W_1)D_N(\omega)$, Eq.(6) in [3]). For the single period the noncorrelatedness property

$$\int_{-\Delta}^{\Delta} f_{sy}(\omega)\,(G_1(\omega))^* d\omega + \int_{out} f_{sy}(\omega)\,(G_1(\omega))^* d\omega = 0, \quad (3)$$

where "out" denotes $\omega \in (-\infty, -\Delta) \cup (\Delta, \infty)$, allows to bring Ψ_1 to the out band form, in which Cauchy-Schwarz estimation of $\left| \int_{out} f_{sy}(\omega)\,(G_1(\omega))^* d\omega \right|$ determines Ψ_1 minimum for any prescribed $f_{sy}(\omega)$ at

$$G_1(\omega) = c \cdot f_{sy}(\omega) \text{ at } \omega \in (-\infty, -\Delta) \cup (\Delta, \infty),$$

the arbitrary coefficient $c \leq 0$. The other band signal must remain the same

$$G_1(\omega) = c \cdot f_{sy}(\omega) \text{ at } \omega \in [-\Delta, \Delta],$$

otherwise any additional function to $G_1(\omega)$ in $\omega \in [-\Delta, \Delta]$ will create the infinite time-domain component in the summary signal, that is in contradict with the initial conditions. The last two relations satisfy (3) property at $c = 0$ only, that gives $G_1(\omega) = 0$. Unique Ψ_N minimizing conditions, which do not depend on the number of periods, are $\kappa_n = \text{const}(n)$, $G_n = 0\ \forall n$; that is deduced by induction at Ψ_N minimization for $D_N(\omega)$ form with new $f_{sy}(\omega) \sum_{n=1}^{N} e^{-i\omega(n-1)T}$ reference similarly to the single period case. So, the first two conditions in Eq.(2) are fulfilled for each period; the third can be attained by $f_{sy}(\omega)$ variation (i.e., by accelerating channel characteristics variation), since κ_n remains free.

Therefore, under symmetrical band compensative signal $S_0(\omega) = C(\omega - \omega_0)e^{i\alpha(\omega-\omega_0)} + C(-\omega - \omega_0)e^{-i\alpha(-\omega-\omega_0)}$ consideration, where $C(\omega)$ and $\alpha(\omega)$ are defined in $\omega \in [-y_0, +y_0]$, the value, determined by Eq.(6) in [3] throughout the frequency domain,

$$\int_{-\infty}^{\infty} |F(\omega)|^2 d\omega = \frac{A^2 \int_{-y_0}^{y_0} C^2(\omega) d\omega}{2} + A^2\Lambda + R \quad (4)$$

must be minimized at the prescribed $\Lambda = \int_{-y_0}^{y_0} |F(\omega)|^2 d\omega / A^2$. In Eq.(4) $R \cong A^2 \int_{-\infty}^{\infty} \left|\mathbf{F}\{(V(t) + S_0(t))\cos(\omega t + \varphi)\}\right|^2 d\omega$ presents the energy of uncompensated V excitation [3] and does not depend on $C(\omega)$, $\alpha(\omega)$, and the equation necessitates the required S_0 signal energy $\mathrm{E} = \frac{1}{\pi} \int_{-y_0}^{y_0} C^2(\omega) d\omega$ minimization[2]; which global minimum is just implemented by [3,4] method.

Thus, necessary conditions for the optimal dynamics with minimal required RF energy are obtained if $V(\omega)$ in the compensation band is the spectrum of an amplitude modulated signal only. For unchanged beam current injection the control signal (and the beam excitation) optimization defines the particles energy variation, averaged over the period $\mathcal{E}_{0A}(t)$, [4]. Now the third optimization condition Eq.(2) gives $\mathcal{E}_{SA}(t)/\mathcal{E}_{\text{av}} = \mathcal{E}_{0A}(t)/\mathcal{E}_{\text{out}}$, where $\mathcal{E}_{\text{av}}$ is the average accelerated beam energy; the synchronous particle energy variation, averaged over the period $\mathcal{E}_{SA}(t)$ is indicated in Fig.1 for the upper band optimum on Fig.2 in [4] at nominal beam.

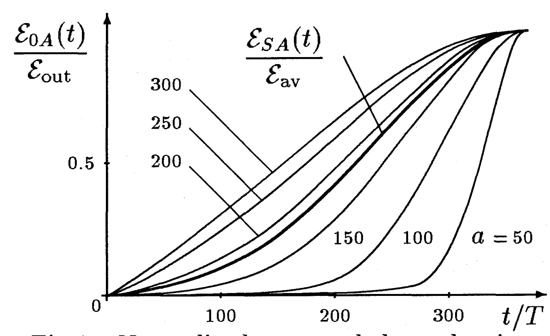

Fig.1. Normalized averaged dependencies of the particles energy $\mathcal{E}_{0A}(t)$ for different a values [4] and of the optimized synchronous particle energy $\mathcal{E}_{SA}(t)$ at $a_{\text{opt}} = 184$, $y_{m\text{opt}}/\omega_0 = 0.022$ for IFMIF RFQ [6,7].

So, the electrodes modulation law at the RFQ design is specified, since for defined synchronous phase the $\mathcal{E}_{SA}(t)$ dependence immediately determines this function.

4 Time-varying injection

In the general case the injected current $i(t)$ is different from the rectangular pulse, the fronts duration τ is finite, so that only the stationary level i_Σ with the pulse start instant may be taken as preassigned. Consider the sum of the delayed rectangular pulses $i_1, \ldots i_m, \ldots i_M$ with very nearly equal durations, which approximates to $i(t)$ at $P \to \infty$ (for the equal NT durations the trailing edge dependence will be $i_\Sigma - i(t - NT)$). The electrodynamics optimization result of the amplitude modulated excitation remains valid for any injection; the synchronous particle energy variation will be the same for any partial beam and for the total $i(t)$ (if the partial and total currents are the same sign) at the single-harmonic dependence of the operating field. Therefore, at the

[2] It is sufficient for prescribed resonator case, but the accelerator channel selection can deliver R minimization, e.g., the π-type has apparent advantages over 2π one.

optimized symmetrical bunching the amplitude modulation carriers will be in phase for the partial and total currents, and the total beam excitation is the sum of the delayed partial excitations. Thus, the optimized control for the total beam remains optimal for any partial beam at the ideal field.

However, at the real control the operating field error for i_m must be smaller than for $i(t)$, since the partial error's accumulation should not exceed the prescribed tolerance. The time-varying beamloading gives no way to attain RF source matching for all t; the attainable matching for $t \geq \tau$ (the same result as for i_Σ) is the best since $NT \gg 2\tau$. Direct verification with the use of these items proves that the optimized [4] bandwidth value with a parameter for i_m particles acceleration remains the same as for i_Σ.

Thus, the envelope $S_v(t)$ of the control signal in the optimized system is the sum of the delayed functions with identical edges, so that the pass to $M \to \infty$ yields

$$S_v(t) = \int_0^t \frac{dI(x)}{dx} s(t-x)dx,^3 \qquad (5)$$

where $s(t) = f(t)/f_s$ is defined by Eq.(11) in [4] with the determined at the total current a parameter; $I(t) = i(t)/i_\Sigma$. Eq.(5) gives the estimation of the control envelope change due to the injection $\Delta I(t)$ variation

$$|\Delta S_v(t)| \leq \sqrt{\int_0^{NT} (\Delta I(t))^2 dt \frac{\Omega}{2\sqrt{\pi}}},$$

where Ω is $\mathbf{F}\{f(t) - f(t-NT)\}$ spectrum width, defined by moment method in [4]; i.e., the required dynamic range is compressed by Ω minimization [4]. For the random variation the mean square deviation of the envelope attains global minimum at minimal Ω. The signal spectrum width for $NT \gg 2\tau$ can be also defined by the moment $\Omega_{Sv}^2 = \int_{-\infty}^{\infty} |S_v(\omega)|^2 \omega^2 d\omega$; at monotone dependencies of $i(t)$ edges the width $\Omega_{Sv} \leq \Omega$ (the equality takes place for the step-function fronts), so that the obtained Ω minimum provides the width minimization in the any case.

5 Conclusion

Developed method of the control optimization at the transient excitation analysis [3] with RF system optimization [4] provides the following crucial results: (1) minimal particle losses with necessary conditions minimizing the beam energy dispersion for prescribed resonator, (2) the minimal required RF source power, (3) the absence of phase (and frequency) modulation in the control signal, (4) minimization of RF source and RF system bandwidths for prescribed tolerances on the field magnitude (the minimized bandwidth is in only a few percents excess over the unrealizable level), (5) a simple implementation of RF system, (6) only a weak dependence of the optimized characteristics on the beam current, (7) minimization of the bandwidth and the required dynamic range compression for the control at time-varying injection.

The (1-4) extremums are global (for (4) item with realizability criterion), so that the better results are provided in accelerating channel which synchronous energy variation is maximally correlated with the determined optimized dependence, if it can not be implemented exactly.

[3] In spite of the convolution form of the result, it is not to be supposed that the system is linear in the general case; the result is demonstrated only for the optimized control.

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