MATCHING OF RFQ BEAM WITH PERIODIC FOCUSING STRUCTURES

Vorobjov I.A., Kolomiets A.A.
ITEP, 25, Bolshaja Cheremushkinskaja, Moscow 117259, Russia

Abstract

The methods of transverse and longitudinal matching of RFQ beam with different types of accelerating structures in linacs are considered. The possibility to eliminate the mismatching due to time dependence of RFQ output beam emittance is discussed.

Introduction

The using of RFQ as initial part of linac allows to design high intensity high duty cycle accelerators. Usually special matching channel (sometimes including buncher) is installed between RFQ and the following structures for beam matching. However there is the possibility to provide six-dimensional matching RFQ output beam with following accelerating structures, which can have different operating frequencies and focusing periods, without intermediate matching channels. The matching can be provided only by appropriate choice of output part of RFQ channel parameters. It allows to achieve both static and dynamic (we mean it as elimination of time dependence of output RFQ beam emittance) transverse matching. The additional bunching needed for beam recapture into following structures with higher operating frequencies also can be provided in RFQ structure.

Static transverse beam matching

We shall estimate quality of matching by coefficient k, introduced in [1]:

$$k = 1 + \sqrt{c^2 - 4}, \quad c = \frac{\rho^2}{\sigma^2} + \frac{\sigma^2}{\rho^2} + \left(\rho\frac{d\sigma}{d\tau} - \sigma\frac{d\rho}{d\tau}\right)^2, \quad (1)$$

where σ is value of normalized matched envelope (absolute value of Flouqet function), ρ - value of normalized mismatched envelope, τ - dimensionless time $\tau = t/T_f$, T_f - ratio of period focusing length to syncronous particle velocity.

Coefficient k is defined by main maximum of mismatched envelope, and shows how it is necessary to increase acceptance to prevent particle losses of mismatched beam. For ideal matching $k = 1$.

Normalized frequency of transverse oscillations is defined by absolute value of Floquet function [1]: $\nu = 1/\sigma^2$.

For perfect transverse matching it is necessary to provide equal particle oscillations frequencies in both channels. In this case the distribution of space charge is keeping constant that prevents emittance growth.

Equal lengths of focusing periods

This case corresponds for example to FODO focusing period in DTL with operating frequency twice higher then in RFQ.

The calculations [2] carried out for RFQ and DTL focusing channels with equal phase advances $\mu_{0RFQ} = \mu_{0DTL}$ showed that for beam crossover at RFQ output (correspondingly at DTL input) extreme absolute values of Floquet function are identical for both channels if in DTL lens length to focusing period ratio $d/s = 0.5$. It is true for whole first stability region. If $d/s = 0.1$ mismatching coefficient $k = 1.05$ in focusing plane for $\mu_0 = \pi/2$. If beam at RFQ output has maximum envelope slope then $k = 1.37 (d/s = 0.1)$. These results are obtained for zero beam current. The calculations showed that for zero current (phase advance $\mu_0 = 0.8$),as well as for depressed phase advance $\mu/\mu_0 = 0.57$ normalized extreme frequencies ν_{min} and ν_{max} are varying in such way that beam matching is being kept in the investigated region of currents.

So, existence of crossover at RFQ output is necessary condition for beam matching. If phase advances and focusing periods lengths are equal then matching coefficient non critically depends on period structure in wide range of beam currents and phases of transverse particle oscillations.

Equal RF frequencies

This case corresponds to two times longer focusing period in DTL. It requires the corresponding increasing of absolute values of Floquet function at RFQ output. It can be achieved by increasing of average distance between opposite electrodes. However, it is impossible to change properly the envelopes in both transverse planes if average distance is the same in both planes. To decrease particle losses it is better to match maximum values of envelopes. It is difficult to obtain perfect matching in wide range of normalized frequencies ν. The simulation [2] showed that for best results average distance should be changed along structure following the relation:

$$R_0(n) = R_0(0) + 0.5 \cdot [R_0(N) - R_0(0)] \cdot (1 - \cos\frac{\pi n}{N}).$$

The dependence of matching coefficient k on number of cells N included in output matcher is presented at Fig.1. The results of simulations for different laws $R_0(n)$ showed

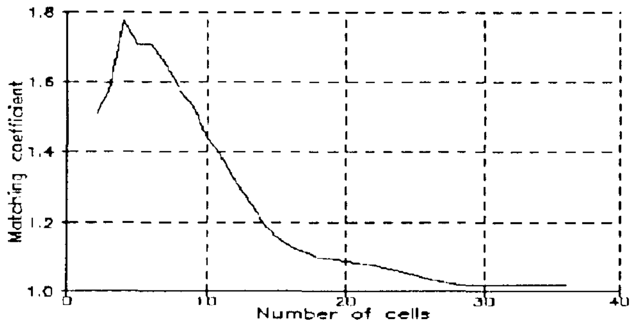

Fig. 1: Matching coefficient k dependence of adiabatic matcher length.

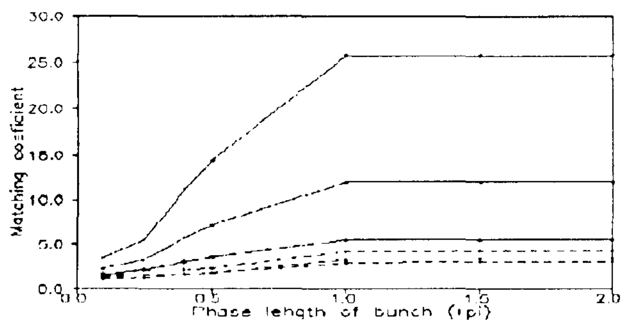

Fig. 2: Matching coefficient k dependence of bunch phase length $\delta\phi_b$ for different phase advance depressions before (----) and after (- - -) matching

that output matcher can be considered as adiabatic one only for $N > 34$. However mismatching does not exceed 15% for $18 < N < 34$ with above mentioned law $R_0(n)$.

Dynamic transverse beam matching

Influence of beam parameters time dependence on matching

Beam crossover at the RFQ output is provided while bunch center is passing the RFQ output at time moment corresponding maximum electrode voltage. Emittances of particles, which are passing the RFQ output at other moments, differ from crossover.

The matching coefficient k in dependence of bunch phase length for different phase advance depressions is given at Fig.2 by solid lines. The coefficient is calculated for central and end parts of bunch at RFQ ISTRA [3] output. The maximum value of $k \approx 25$ corresponds only $\approx 10\%$ overlapping of ellipses representing beam emittances.

This effect can be considered as increasing of effective emittance at RFQ output. The calculations showed that at RFQ ISTRA effective emittance increases in factor 1.7 for focusing plane and 1.4 for defocusing one. The measurements of time integrated emittance at RFQ ISTRA output [4] are in good agreement with calculated values.

Correction of RFQ output beam parameters

To eliminate dependence of RFQ output beam parameters of time it is possible to use the known methods of dynamic matching [5,6]. However it leads to considerable distortion of quadruple symmetry of RFQ output beam and increases its envelopes, that makes impossible connection of RFQ and DTL without matching channel.

We proposed an alternative method to decrease dependence of RFQ output beam parameters of time [7,8]. It consists in using a short RF quadruple lens installed after RFQ with appropriate relation between its focusing strength K_m^2, length l_m and RF phase with RFQ focusing channel parameters μ and σ. The phase shift $\Delta\phi$ between RF fields in lens and RFQ is given by the following relation:

$$\Delta\phi = \frac{\pi}{2} - \pi f t_m + 2\pi n,$$

where $n = 0; 1; 2; ....,$
f - frequency of RF oscillations in matching lens;
t_m - time while particles move through matching lens.

The relation for matching lens and RFQ parameters has the following view:

$$\frac{\Delta\varphi_b}{4\pi\sigma^3} + \frac{\tau_m}{\sigma^3} - \sqrt{2}\mu sin\frac{\Delta\varphi_b}{2} + \frac{4K_m^2}{\pi}sin(\frac{\Delta\varphi_b}{2})sin(\pi\tau_m) = 0$$

where $\tau_m = t_m/T_f$,
$\Delta\varphi_b$ - bunch phase length

This relation is obtained by envelope equation integration in approximation of small changing of Floquet function $\sigma \approx const$ along bunch length in absence of Coulomb repulsion.

The values of coefficient k after dynamical matching according to numerical optimization results are plotted in Fig.2 by dashed lines. The values of normalized envelopes X, Y and their angles $dX/d\tau, dY/d\tau$ at phase plane before and after matching are given in Table 1 for instantaneous emittance corresponding to synchronous particle.

Time integrated emittances corresponding to the RFQ output and matching lens output simulated by 1000 macroparticles per bunch without Coulomb forces are shown in Fig.3(A,B).

Table 1. Parameters of central phaze ellips befor and after matching

	Befor matching		After matching			
a	X	Y	X	$\frac{dX}{d\tau}$	Y	$\frac{dY}{d\tau}$
0.	0.93	1.37	1.02	0.39	1.36	0.13
0.94	1.08	1.58	1.18	0.38	1.57	0.20
1.88	1.24	1.80	1.34	0.38	1.80	0.26

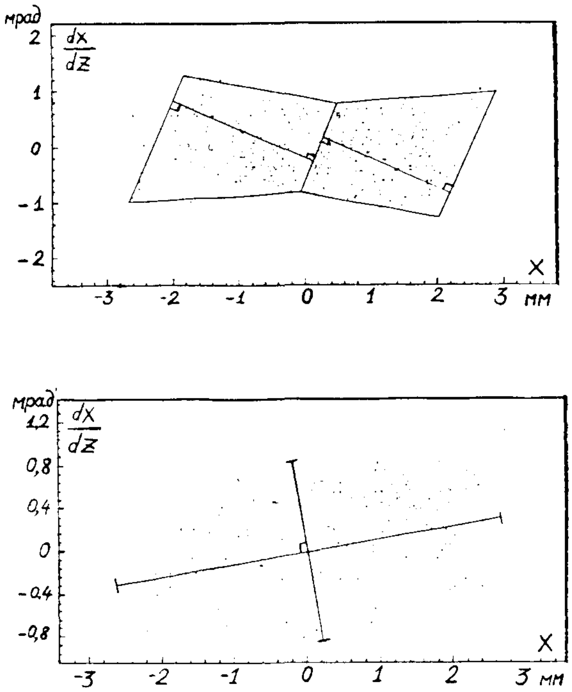

Fig. 3: Bunch phase potraits at the RFQ end (A) and matching lens end (B)

One can see that emittance corresponding RFQ output produced by ellipses with different orientation. The emittance border is shown by solid lines. The time integrated emittance corresponding matching lens output has practically elliptical shape. It formed by instanteneous ellipses with overlapping close to 90That is in agreement with preliminary envelope method calculations. Areas of approximated phase volumes, shown in Fig.3, are $9.9 cm \cdot mrad$ and $6.9 cm \cdot mrad$ and relative phase volumes increasing are 1.65 and 1.15 accordingly, that proves significant decreasing of beam parameters time dependence.

Longitudinal matching

There is no difficulties to recapture beam from RFQ into DTL if RFQ and DTL have the same operation frequencies. In case of higher frequency in DTL additional bunching is often needed. For example for ISTRA linac it is necessary to decrease bunch phase length in factor 1.6 to inject it into linear part of DTL input separatrix.

The estimation showed that this additional bunching for ISTRA can be achieved by using additional section with synchronous phase $\varphi_s = -90^0$. The length of this section is 0.86 m, modulation factor is increased up to 2.4 to provide 1/4 wave length of longitudinal particle oscillation frequency [9].

The additional bunching in RFQ not only provides the possibility to use higher frequency in DTL, but also decreases the dependence on time of output RFQ beam emittance and makes the dynamic matching easier.

Conclusion

The six-dimensional matching of the RFQ output beam with accelerating structures with periodic focusing is possible in wide range of accelerated currents, for equal and different operating frequencies in RFQ and DTL with different types of focusing period, without using special matching channels between RFQ and DTL. The matching is achieved only with appropriate choice of RFQ and DTL parameters.

The optimum transverse matching requires the beam crossover at RFQ output in both transverse planes. The adiabatic transformation of RFQ beam parameters allows to match it with different types of DTL focusing periods.

It is possible to decrease considerably mismatching caused by dependence of time of RFQ output emittance using very simple method of dynamic RFQ output matching.

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