DESIGN OF A PREBUNCHER FOR INCREASED LONGITUDINAL CAPTURE EFFICIENCY OF MAMI.*

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Abstract

We present a redesign of the prebunching system at the MAMI-injector, to increase its capture efficiency from the present 10–15% to 40–45% while preserving the high beam quality of MAMI. By analytical methods two different types of prebuncher were investigated: a three cavities fundamental frequency system and a two cavities setup using the fundamental and its first harmonic. The two-cavity design – fundamental and harmonic resonator separated by a strictly defined drift space – was chosen as the solution to be realized. It was computer simulated in detail, taking into account experimental data on the injector linac acceptance.

1 INTRODUCTION

The Mainz Microtron (MAMI) [1] is an 855 MeV cascade of three continuous wave (CW) racetrack microtrons (RTM1-3) with a 3.5 MeV injector linac (ILAC) [2]. A halo-free electron beam with very low longitudinal and transverse emittance [3] is used for precise medium energy nuclear physics experiments and the experimental production of special types of electromagnetic radiation. To get this high quality beam only 10–15% of the guns 100 keV dc-beam pass the compensated double chopper [4]. After longitudinal compression with a standard fundamental frequency prebuncher, the beam is captured and accelerated in the ILAC. Discarding 85–90% of the initial dc-beam is not important for the thermionic gun, but is a waste of precious electrons when the polarized gun [5] with its GaAsP-photocathode is used. Therefore a prebuncher system with distinctly increased capture efficiency, but causing no loss of beam quality, would be highly desirable.

2 GENERAL CONSIDERATIONS.

To satisfy the stringent limitations to the longitudinal and transverse emittances of the MAMI-RTMs, two problems must be solved when designing a prebuncher:

1.) Nonlinear beam distortions in the longitudinal phase space must be minimized, ideally a δ-function-like phase distribution at the longitudinal focus should be obtained for zero initial beam energy spread.

2.) The beam formed by the prebuncher must be matched in the best way to the longitudinal acceptance of the ILAC.

To get a δ-function in the particle phase distribution, a zero length prebuncher must provide the next dependence of the relative particle velocity on the phase of passage φ:

$$\Delta\beta(\varphi) = \beta(\varphi) - \beta_0 = \frac{\beta_0^2\lambda\varphi}{2\pi L_{\mathrm{f}} - \beta_0\lambda\varphi}\,, \qquad (1)$$

where $-\pi \leq \varphi < \pi$, β_0 – relative velocity of the reference particle ($\varphi = 0$), L_{f} – distance from prebuncher to longitudinal focus, λ – rf wavelength. The distribution (1) is asymmetric with respect to zero phase – later particles must be accelerated more, than decelerated corresponding earlier particles. In the further analytical considerations however we will use the linear approximation to (1), valid for $L_{\mathrm{f}} \gg \lambda\beta_0$.

A linear approximation of $\Delta\beta(\varphi)$ for the whole rf period (sawtooth modulation) could be achieved by introducing an infinite number of harmonics to the velocity distribution:

$$\Delta\beta(\varphi) = \frac{\beta_0^2\lambda}{\pi L_{\mathrm{f}}}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n}\sin(n\varphi)\,. \qquad (2)$$

In a real situation one naturally has only a finite number of harmonics to get a best approximation to the linear function within the limited phase interval $-\Delta\varphi_{in} \leq \varphi < \Delta\varphi_{in}$, therefore:

$$I = \int_{\Delta\varphi_{in}}^{\Delta\varphi_{in}}\left[\varphi - \sum_{n=1}^{N} a_n^{(N)}\sin(n\varphi)\right]^2 \cdot \mathrm{d}\varphi \to \min\,. \qquad (3)$$

Particles being out of this interval must be rejected by the chopper system. Taking $\Delta\varphi_{in} = \pm\pi/2$ as a reasonable value, we get the next factors $a_n^{(N)}$ for $N = 1, 2$ and 3:
$a_1^{(1)} = 1.273;\quad a_1^{(2)} = 1.519, a_2^{(2)} = -0.289;$
$a_1^{(3)} = 1.640, a_2^{(3)} = -0.433, a_3^{(3)} = 0.079.$

Would the linear approximation provide a zero length bunch at focus, then the expression in square brackets in (3) is the particle phase deviation from the reference particle phase. These deviations are shown at Fig. 1 for $N = 1, 2$ and 3, the minimum phase lengths are ± 0.3, ± 0.046 and ± 0.008 radian respectively. Naturally the linear approximation itself produces a finite bunch length, shown at Fig. 1 by the parabolic "zero-line" line for MAMI-injector parameters ($\beta_0 = 0.548, \lambda = 0.1224$ m, $L_{\mathrm{f}} \cong 1.5$ m). This deviation however, about 0.017 radian for the $\pm\pi/2$ interval, can be decreased by a small phase shift in the higher harmonics (see 4.2).

* Work supported by DFG (SFB 201)

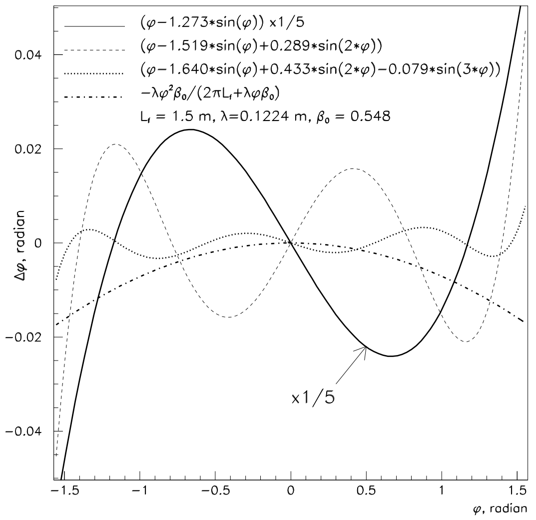

Figure 1: Deviation of particle phases from reference at longitudinal focus for $N = 1, 2, 3$ harmonics. Parabola: error of linear approximation.

3 PREBUNCHER VARIANTS.

Higher harmonics with proper amplitude and sign can be introduced to $\Delta\beta(\varphi)$ by different methods:
by application of gap voltages with higher harmonics;
by usage of several fundamental harmonic gaps, separated by drift spaces;
by a combination of both ways.
Low space charge at CW operation ($q \leq 0.05$ pC/bunch at MAMI) and low beam energy modulation during the prebunching process allow to get rather good first approximations using the methods of ballistic klystron theory. A number of different prebuncher versions were considered with this approach [6], here we present two variants schematically shown at Fig. 2.

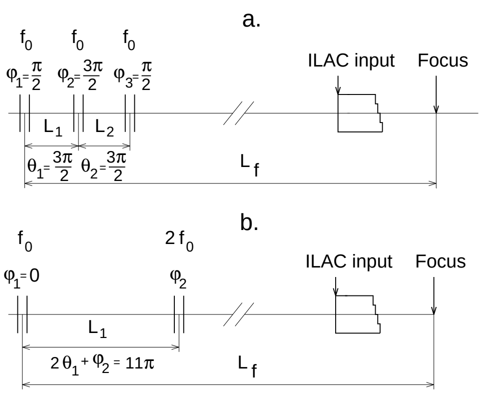

Figure 2: Schematic view of two prebuncher variants (f-frequency, φ-rf phase, θ-transit angle).

3.1 *Three Cavities Fundamental Frequency Prebuncher.*

For this prebuncher variant (Fig. 2a) an rf phase shift of π between neighbouring fundamental frequency gaps was chosen, so it can be realized as a π/2 standing wave structure of three accelerating and two coupling cells, with its inherent high stability of field amplitudes and phases. The transit angle $\theta_1 = \frac{2\pi L_i}{\beta_0 \lambda}$ was taken to be $3\pi/2$ for both drift spaces.

For this choice of parameters the voltage amplitudes at the first and third gap must be equal , and one gets the next formula describing the dependence of the relative electron velocity at prebuncher exit on their phase at the first gap:

$$\Delta\beta(\varphi) \approx \beta_0 \alpha_2 \left[1 + \left(\frac{3\pi\alpha_1}{4}\right)^2\right] \text{x}$$

$$\text{x} \left[\sin(\varphi) - \frac{3\pi\alpha_1^2}{2\alpha_2}\sin(2\varphi) + \left(\frac{3\pi\alpha_1}{4}\right)^2 \sin(3\varphi)\right], \quad (4)$$

where $\alpha_i = \dfrac{eU_{0i}}{\beta_0^2\gamma_0^3 m_0 c^2}$, $U_{0i} - -i^{\text{th}}$gap voltage,

γ_0 – relative beam energy. To get this formula the approximations $\alpha_i \ll 1$ and $\alpha_i\theta_j \ll \pi/2$ were used, and the gaps were considered to be of zero length. A small constant energy shift, which is introduced by this type of prebuncher is omitted in (4). As can be seen, the higher harmonics have the proper sign, but only two free parameters are available to vary their contribution and to get the appropriate position of the longitudinal focus. Thus this prebuncher can produce an intermediate result between the two and three harmonics cases shown at Fig. 1. An undoubted merit is that only two operational parameters, amplitude and phase of the input rf must be controlled. On the other hand the rf power needed is close to 100 W.

3.2 *Two Cavities Two Harmonics Prebuncher.*

A single cavity two harmonics prebuncher [7] would be an N=2-device with rather strong deviations from linearity (Fig. 1). A prebuncher with seperate resonators, shown at fig. 2b, possesses greater flexibility, as can be seen from the formula describing the velocity modulation at its exit:

$$\Delta\beta(\varphi) \approx \beta_0\alpha_1(1 + \alpha_2\theta_1)\text{x}$$

$$\text{x} \left[\sin(\varphi) - \frac{\alpha_2}{\alpha_1(1+\alpha_2\theta_1)}\sin(2\varphi) + \frac{\alpha_2\theta_1}{1+\alpha_2\theta_1}\sin(3\varphi)\right], \quad (5)$$

i.e. we have three free parameters and a third harmonic component of proper sign. An additional condition to be fulfilled is $2\theta_1 + \varphi_2 = (2k+1)\pi (k = 1, 2...)$, where φ_2 is the second gap rf phase shift (at the harmonic frequency) with respect to the first. Even fixing φ_2, one has some freedoom for the choice of θ_1.

For a longitudinal focus position defined by the ILAC acceptance (see 4.2) of $L_{\text{f}} \approx 1.5$ m, we got the next values of the parameters in (5) for the three harmonics case shown at Fig. 1: $2\theta_1 + \varphi_2 = 11\pi$, $\alpha_1 \approx 0.0111, \alpha_2 \approx 0.0031,$ and $\theta_1 \approx 16.42$ rad. These parameters were used as initial guess for a computer simulation by RTMTRACE [8] to match the ILAC acceptance.

4 FINAL CHOICE OF PARAMETERS

4.1 ILAC Acceptance.

The measured ILAC acceptance is shown at Fig. 3a by open squares. It was determined by scanning the longitudinal phase space at the ILAC entrance with a small energy and phase spread probing beam, obtained by closing the chopper collimator aperture. Beam parameters at the ILAC exit were measured simultaneously [9], and the squares at Fig. 3a give the boundary where longitudinal nonlinear beam distortions stayed reasonably small. The bunch-shifting across the longitudinal phase space was done by varying the prebuncher cavity field amplitude and phase. From these acceptance measurements we estimated, that the crossover of the convergent bunch must be about 0.34 m inside the ILAC. The longitudinal emittance at the ILAC entrance must be positioned along the sloping line, with a maximum energy and phase deviation of ± 2.5 keV and$\pm 17°$ respectively. These values define the position of the first prebuncher cavity. To accept $\pm 90°$ of the dc-beam, the center of the first prebuncher cavity gap must be placed at a distance of about 1.46 m from the ILAC entrance. However, the present value of 0.6 m can be increased by the injection path redesign only to max. 1.18 m, thus the maximum accepted phase angle will be $\pm 80°$.

4.2 Results of the Computer Simulation.

In Fig. 3 the longitudinal beam emittance is shown at the ILAC entrance and at the crossover (upper resp. lower picture), with the ILAC field switched off. Initial phase spread was taken to be $\pm 80°$, relative energy spread of the beam at prebuncher entrance ± 10 eV. The transit distance between the f_0-and $2f_0$-cavity was chosen $\theta_1 = 5\pi = 0.168$ m. An additional rf phase shift of about $3°$ of the harmonic cavity was introduced to get a symmetric picture at crossover:$\varphi_2 = 180° + 3°$. Other parameters (Fig. 3a) found in the computer simulation are: $\alpha_1 \approx 0.01199, \alpha_2 \approx 0.0034$, values which slightly differ from the analytical values. The reason is, that in the analytical treatment a zero prebuncher length was assumed. For aluminum cavities with moderate shunt impedance the required rf-power is about 12 W for the first and 2 W for the second cavity.

The sensitivity to parameter settings was extensively investigated. Requirements to the amplitude settings are within $\pm 1\%$, to phase stability $\pm 1°$, with the phase of the second cavity being most sensitive.

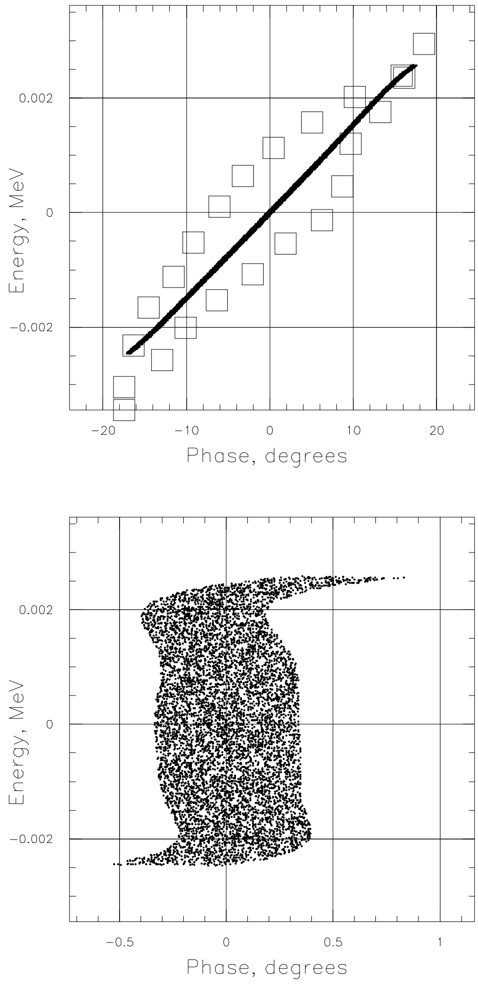

Figure 3: Longitudinal emittance at ILAC entrance and at the crossover. Open squares: measured ILAC entrance acceptance.

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