

# A novel setup for the pulsing and energy enhancement of a positron beam

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**Abstract.** We propose a detailed concept to raise the total energy of a positron beam by an amount of at least 10 keV. The setup consists of a combination of a pre- and a main-buncher which is able to convert the continuous remoderated positron beam of NEPOMUC into pulses of about 2.5 ns width with a repetition rate of 5 MHz. This pulsed beam is suited for a new setup which elevates the beam energy by rf-fields. In contrast to existing rf-accelerators, the new setup has only negligible influence on the transversal beam phase space.

## 1. Introduction

By tuning the implantation energy of a positron beam it is possible to perform depth resolved measurements from the surface into the bulk of the investigated sample. This is one of the prime advantages of monoenergetic positron beams over the bulk studies performed with  $\beta^+$  emitters. The beam energy is usually adjusted by biasing the source, the sample or both according to the desired implantation energy. However, in some cases this method is not possible for technical reasons.

The remoderated positron beam at NEPOMUC has a kinetic energy of about 20 eV [1] with respect to ground potential. Hence the implantation energy at the instruments has to be tuned by the sample potential. This is e.g. not possible at the PAES system [2] at NEPOMUC, as there the (re-) emitted low energy charged particles are in the scope of interest and the detector can not be biased to the same potential as the sample.

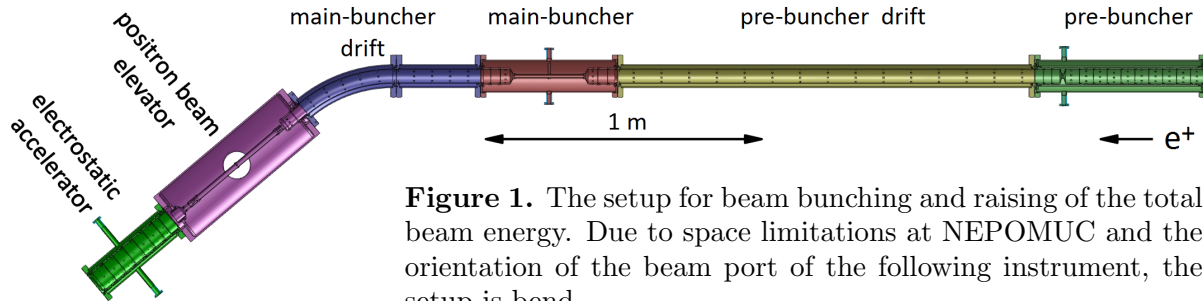
A completely different approach is to raise the total beam energy by using time dependent fields. In common rf-accelerators the kinetic energy is enhanced due to the potential difference between two succeeding electrodes which are charged by an appropriate rf. These accelerators are designed to provide charged particle beams of several MeV or more and substantial precautions are made to ensure the transversal stability of the beam. As the implantation energy in depth resolved positron measurements is usually limited to energies below about 30 keV, a more compact design, which has a much lower effect on the transversal phase space of the beam, is proposed here.

## 2. Experimental setup

The presented setup can be divided into three parts with distinct assignments (see Fig. 1). Firstly, the continuous beam is converted into a pulsed beam by a combination of a pre-buncher and a double gap main-buncher. In the second step the potential energy is raised by using a



rf-electrode and in the last section the potential energy is transformed into kinetic energy by an electrostatic accelerator. As the second component enhances the potential energy it is called positron energy *elevator* to emphasize the difference to a classic rf-accelerator.



**Figure 1.** The setup for beam bunching and raising of the total beam energy. Due to space limitations at NEPOMUC and the orientation of the beam port of the following instrument, the setup is bend.

### 2.1. Positron beam bunching units

The bunching is based on the time-dependent modulation of the beam energy. The energy modulation occurs at the gap between two electrodes where e.g. on the second one a time dependent potential is applied. In the common double gap approach a third electrode follows and hence a time dependent field appears again<sup>1</sup>. If the modulation function has a rising and a falling edge and the length of the center electrode is matched to the mean energy of the positrons, the energy modulation at both gaps leads to a compression of the positron beam. It can be shown, that the time dependency of the energy modulation  $eU_m(t)$  at one gap has to have the following form:

$$eU_m(t) = eU_0 \left( \left( \frac{1}{1-t/t_0} \right)^2 - 1 \right) \quad (1)$$

where  $e$  is the elementary charge,  $eU_0$  the kinetic energy of the reference particle and  $t_0$  the time it needs for the drift  $d$  after which the time focus appears. If the time  $t_0 = d/\sqrt{2e/mU_0}$  is sufficiently long this expression can be approximated linearly to:

$$eU_m(t) \approx 2eU_0 \frac{t}{t_0} = \sqrt{8/m} (eU_0)^{3/2} \frac{t}{d} \quad (2)$$

A sine wave has a rising and a falling edge which are approximately linear and is easy to generate as well as to amplify. Thus it is often used as a modulation function despite the fact that only a fraction of the function leads to a correct energy modulation of the positrons and therefore a high background is generated.

**2.1.1. Pre-Buncher** To avoid the background, a pre-buncher was developed, which modulates only at the second gap. The potential difference at the first gap is spread over several gaps formed by a number of electrodes called equalization drift (ED). If the transit time  $\tau_{pb}$  equals the reciprocal of the repetition frequency  $f_{pb}$ , the energy modulation of the positrons during the pass of the ED is averaged to zero. Using such a buncher, the modulation function does not have to have a rising and a falling edge and an arbitrary function can be used which approximates the function given by equation (1) as exactly as possible or even accounts for higher order effects not regarded by this equation. Although such a function is obviously better suited for bunching purposes, it is more demanding to generate and to amplify. However, a high amplitude is necessary to minimize the aberrations and to attain a sharp time focus. Hence the pre-buncher

<sup>1</sup> Single gap bunchers which are based on  $\lambda/4$ -resonators are several meters long for frequencies below 50 MHz.

is only used to compress as many positrons as possible into a bunch which is just short enough to fit the linear parts of the following sine wave buncher. One design object was to keep the repetition rate  $f_{pb}$  low.  $f_{pb}$  depends on the ED length  $l_{ed}$  and the mean energy of the positrons  $e\bar{U}_{pb}$  is as follows:

$$1/f_{pb} = \tau_{pb} = \frac{l_{ed}}{\sqrt{2e\bar{U}_{pb}/m}} \quad (3)$$

As all electrodes are attached to the rf, the total capacity should be small and hence  $l_{ed}$  should not be larger as about 500 mm. By regarding about 15 eV as a lower limit for  $e\bar{U}_{pb}$ , a minimum repetition rate of 5 MHz is feasible. With equation (2) and assuming a modulation energy of about  $eU_{pb} = 10$  eV and an unchanged mean energy the drift length is about  $d_{pb} = 1.4$  m. Rearranging equation (2) and substituting the energy spread of the primary beam  $\Delta E_p$  for the modulation energy  $eU_m$  leads to the chromatic aberration  $\tau_c$ :

$$\tau_c = \frac{\Delta E_p d_{pb}}{\sqrt{8/m} (eU_0)^{3/2}} \quad (4)$$

The chromatic aberration is in this case the main reason for the finite extension of the time focus and amounts to about 20 ns if a reasonable energy spread of 1 eV is used.

*2.1.2. Main-Buncher* The main-buncher is built up in the same way as those used in the PLEPS [3] or in the Munich SPM [4]. It consists of three electrodes, where the first and the last are biased to a fixed potential  $U_b$ . The center electrode forms together with a coil a resonating circuit and oscillates with the frequency  $f_b$  and an amplitude  $\hat{U}_b$  around the potential  $U_b$ . In order to keep the chromatic aberrations low, the mean energy of the positrons after the time focus of the pre-buncher and therefore also during the pass through the main-buncher has to be considerably higher as the maximum energy modulation at the pre-buncher. To ensure both a high mean energy  $eU_b$  and a short center electrode, the main-buncher is operated at a multiple of the frequency of the pre-buncher. By choosing 20 MHz each fourth main-buncher cycle is used for further beam compression. Using a 250 mm long center electrode leads to a pass energy of about 284 eV. By the resonant amplification, a peak to peak voltage of 100 V can be easily achieved. However, since the beam is pre-bunched, the maximum potential difference which acts onto the positron beam at the first gap, shrinks to about 95 eV. Inserting this value into equation (4) and regarding  $eU_{pb} = 10$  eV as an upper limit for the energy spread in front of the main-buncher, the chromatic aberration  $\tau_{cb}$  of the main-buncher amounts about 1.5 ns. The deviations of the sine wave from equation (1) lead to an additional, the so called spherical aberration  $\tau_{sb} \approx 0.63 f_b^2 \Delta t_b^3$ . It is dependent from the time frame  $\Delta t_b$  during which the modulation field acts onto the pre-bunched beam. Inserting the estimated width of the pre-bunched pulses results in 2 ns for  $\tau_{sb}$  and therefore to a total aberration  $\tau_b = \sqrt{\tau_{cb}^2 + \tau_{sb}^2}$  of about 2.5 ns.

## 2.2. Positron beam energy elevator

The energy elevator is built up in the same way as the main-buncher above. In contrast to the main buncher, the parameters of the elevator and the beam are matched to each other, so that the gaps are field free in first order approximation when the positrons pass them. Hence, the kinetic energy of the positrons is not altered there and the transversal phase space keeps almost unaffected. The passing through the center electrode lasts half of one period and therefore the positron gains a potential energy equal to twice of the amplitude of the applied sine wave.

To attain the aspired amplitude of  $\hat{U}_e = 5$  kV the power losses in the resonating circuit have to be very low. Too high losses would overload the primary sine wave generator or amplifier and would further result in an exceeding heating of the resonating components, especially of those

within the vacuum. By using the identity  $1/2 L \hat{I}^2 = 1/2 C \hat{U}_e^2$  of the maximal stored energy in the coil with the inductance  $L$  and in the capacitor with the capacity  $C$ , the effective power  $P_{\text{eff}}$ , which the amplifier has to provide, can be calculated:

$$P_{\text{eff}} = \frac{1}{2} R \hat{I}^2 = \frac{1}{2} R \frac{C}{L} \hat{U}_e^2 = \frac{1}{2} \omega_0^2 R C^2 \hat{U}_e^2 \quad (5)$$

$\hat{I}$  and  $R$  are amplitude of the current and the total resistance, respectively. Hence, to attain a high amplitude with low power  $R$  and  $C$  have to be small. By finite element simulations and preliminary measurements it could be shown, that a total resistivity of about  $0.3 \Omega$  and a capacity of about 20 pF are reasonable assumptions. With these values and an repetition frequency of again  $f_e = 20$  MHz an amplitude of 5 kV can be achieved with a 24 W amplifier.

To minimize the pulse length at both gaps and therefore the perturbation of the transversal and longitudinal phase space, the beam is accelerated in front of the elevator and passes it with about 730 eV. Due to the higher energy, the center electrode has to have a length of about 400 mm. Nevertheless, the pulse width is at the gaps elongated from the formerly calculated 2.5 ns to about 2.7 ns. This finite width results in an unintended energy modulation of about 18 eV at each gap. If these energy modulations and those of the bunchers are treated as independent from each other, a total energy spread can be estimated by the sum of their squares to about 98 eV. It should be emphasized, that the low potential difference of maximal 18 eV at the gaps has a completely negligible influence onto the transversal phase space of the beam.

### 2.3. Electrostatic acceleration

To preserve the pulse width after the energy elevation, the positrons have to be accelerated immediately after the energy elevation. Therefore, a first acceleration of a few hundred eV is made right after a short exit electrode of the elevator. However, in order to keep the perturbation of the beam low, the main acceleration to about 10 keV is done over seven electrodes spaced over a total distance of about 320 mm.

## 3. Conclusion

It could be shown, that the combination of the novel pre-buncher and the double gap main-buncher is in principle suited to generate highly efficient short pulses of about 2.5 ns with a repetition rate of 5 MHz. Due to the shortness of the pulses, the proposed positron beam elevator is able to raise the total energy of the beam by at least 10 keV with negligible influence onto the longitudinal and the transversal phase space. The calculations here are based on formulas widely used in the field of pulsed particle beams. A deeper insight of the system can only be gained by trajectory calculations leading to a detailed phase space analysis which have already been started.

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