LOW ENERGY BUNCHING WITH A DOUBLE GAP RF BUNCHER

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Abstract

A compact double gap bunching system for low energy proton beams is presented. The system is designed for the bunching of a low current proton beam (less than 50µA) with anenergy of 10 keV. The buncher operates at 150 MHz and bunches without significantly changing the beam energy. The beam is generated by an Electron Beam Ion Source and has to be bunched for the subsequent acceleration in a 150 MHz linear accelerator. The buncher contains two short gaps and an RF electrode inbetween. Thus the full length of the buncher in the beamline is in the range of 2 cm. The location of the bunch focus depends on the buncher power. The bunched beam was analysed at a distance of 550 mm with a fast faraday cup. The bunching effectivity was determined as 50%, which means that 50% of the protons of the beam were located in bunches with a width of 60°, which is a reasonable value of acceptance for a conventional accelerator cavity. Some theory and detailed results will be presented.

INTRODUCTION

Electron Beam Ion Sources (EBIS) with permanent magnets are compact ion sources with high operational stability. Therefore they are a good choice for compact accelerator systems as desired e.g., for particle therapy. Due to their limited proton output efforts have to be made to get high particle throughput of the accelerator system in order to achieve sufficient particle numbers delivered at the patient. The presented low energy buncher has a compact footprint and is realised with low cost and technical effort for the RF hardware as well as for the mechanical double gap structure. With a bunching effectivity of 50 % it contributes to get as much particles to the patient as possible.

As another advantage, a bunched low energy beam might enable a system to deflect each bunch in x- and y-direction individually. This could be leveraged to manipulate the particle numbers of each bunch individually prior to the injection into the accelerator.

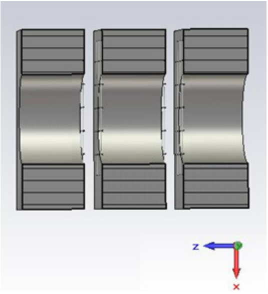

Figure 1: Schematic of buncher structure

WORKING PRINCIPLE

The buncher consists of 3 cylindrical electrodes with two gaps between them(similar to an electrostatic Einzel lens) which have to be passed by the ions.The sinusoidal 150 MHz RF signalis applied to the central electrode, while the outerelectrodes are grounded. The central electrode is designed with properties close to a 50 Ω system, therefore the applied RF power of 0-200 W results in a maximum voltage of 0-140 V at the gaps. For 10 keV protons this means an energy change of less than 2 %. Copper grids at the ends of the electrodes ensurethat the electric fields do mainly have a z-component, so that lens effectsare small and the particles are just accelerated or decelerated in z-direction by the voltageU(t_0) between the electrodes.

$$U(t_0) = U_{\max} \sin(\omega t_0) \tag{1}$$

The distance between the two gaps equals to the distance which the ionstravel in a half RF cycle. That means that particles pass the first and second gap at the same phase of the RF.The velocity modulation of the 1st and 2nd gap then adds up to (see [1])

$$\Delta v(t_0) = T \frac{2qU(t_0)}{mv_0} \tag{2}$$

With the gap length *D*and the transit time factor *T*

$$T = \frac{\sin(D\omega/2v_0)}{D\omega/2v_0} \tag{3}$$

Due to the varying acceleration and deceleration the last particles in anRF cycle will travel faster and the first particles will travel more slowly after passing the buncher. This causes the faster particles at the endto catch up with the slower ones, which will fall back, and thus they meet ina ”bunch” after a certain flight distance (the bunch focus) before the fasterparticles get ahead and the bunch becomes broader again.The particle current $I_L(t_0)$ at a certain distance L from the gap is then no more constant(see [2]) :

$$I_L(t_0) = \frac{I_0(t_0)}{1 - X\cos(\omega t_0)} \tag{4}$$

Where $I_0(t_0)$is the particle current at the buncher (depending on the ion source this is assumed to be constant) and X is the bunching factor:

$$X = \frac{\omega L}{v_0}\frac{2TqU_{\max}}{m v_0^2} \tag{5}$$

Theoretically (4) leads to infinite currents at the bunch focus (X=1) and behind (X>1). For a realistic scenario with space charge, realistic electrical fields (not 100 % homogeneous at the gaps) and a beam with a transverse and longitudinal emittance (i.e. a distributionof v_0) this does of course not occur.

EXPERIMENTS

Buncher Hardware

The buncher system is realized with a so called zero-length CF 100 flange which contains the central drift tube electrode and 4 grids with a mesh constant of 1 mm, two of them contacted tothe central drift tube and two of them contacted to the ground. The central drift tube is connectedto two transmission lines which are connected to SMA-feedthroughs whichcan be approached from outside the vacuum to get the RF power in and out of the system. The buncher is designed for aproton energy of 10keV, which equals to a proton velocity v_0 of 0.0046 c. At the operating frequency of 150 MHz the distance Dbetween the two gaps has to be 4.61 mm to get the right phase.The buncher flange was installed in a low energy beamlinesubsequent to the EBIS and a Wien filter. The EBIS produces ion pulses of 2 µs length (compared to the bunching frequency these are macro pulses, see Figure 2) which then pass the Wien filter and the buncher. The 150 MHz buncher “cuts” the macro pulses into small 6.6 ns pulses.

Measurement Setup

The bunched beam was analysed with a Fast Faraday Cup (FFC) at the distance L=550 mm. The FFC has a 2 mm beam entrance hole and twoSMA terminals, which are matched to 50 Ω. The FFC itself is a 50 Ω system as well,which means that an RF proton current with an amplitude of 1 µA inducesan RF signal with a voltage amplitude of 50 µV. The FFC was connected to two broadband RF amplifiers in series with a gain of app.27 dB each. The amplified signal was then analysed with an oscilloscope. Due to very weak signals and a lot of noise the signal was averaged over300 sweeps. An important issue for averaging is appropriate triggering. The triggering was done with two triggers. One trigger signal comes from theion source electronics and indicates the time when the ion source is openedand a 2 µs long pulse comes out. The second trigger comes from thesinus slope of the buncher RF and makes sure that the phase is right. Thecoincidence of both trigger conditions then triggers the oscilloscope.

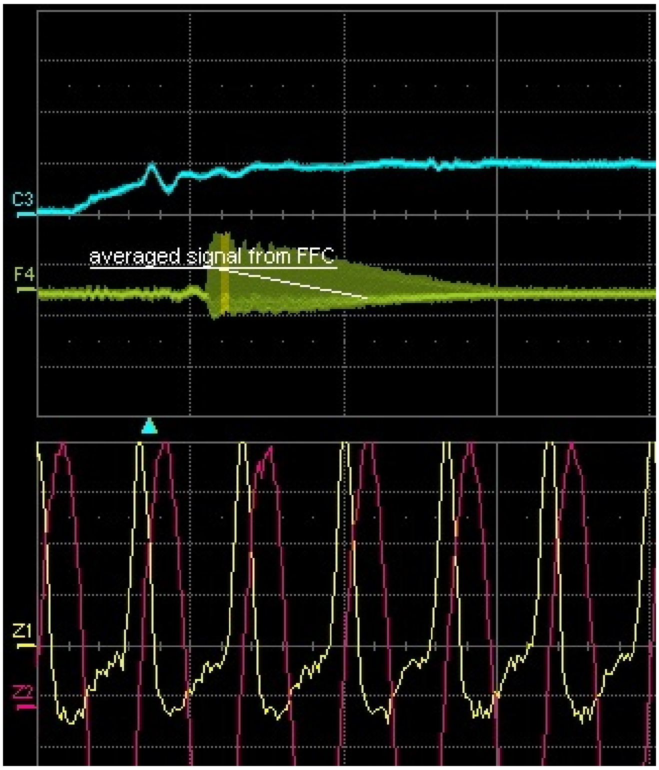

Figure 2: Screenshot from the oscilloscope. The upper graphic shows the blue trigger signal from the ion source and the bunched (150 MHz) ion source pulse with a total pulse length of 2 µs as measured on the FFC. The lower graphic shows a zoom (200x) into the bunched beam (yellow) and the attenuated sinus slope from the buncher (red) which is used for the triggering

Reconstruction of signals

Actually the whole signal transmission between FFC and oscilloscope hasan influence on the signal. The attenuation and amplification of the cablesand amplifiers depends on the frequency and the phase does also depend onthe frequency. Furthermore the amplifiers (bandwidth 0.1-18 GHz) do nottransmit low frequency or DC fractions of the signal. This means that all thefrequency fractions belonging to the ion source macro pulse (between 0 and500 kHz) are cut off. This makes it impossible to measure the DC current.Thus the low frequency and DC parts of the signal were measured separatelywith other amplifiers (bandwidth 0-1 MHz). The background signal (i.e. with no current from the ion source) fromthe FFC and the transfer characteristics of the cables and amplifiers werealso measured separately. Then the measured signals were corrected in an 8step process:

- The background was subtracted from the signal
- The spectrum was calculated via Fast Fourier Transformation (FFT)
- Phase and amplitude of each frequency were corrected with the characteristics of cables and amplifiers measured before

- The corrected signal (as it originates from the FFC) was calculatedfrom the corrected spectrum via inverse Fast Fourier Transformation(iFFT)
- The voltage signal at 50 Ω was converted into a current signal
- The current signal was integrated over time to determine the averagecurrent
- The average current was compared to the DC current measured withthe low frequency amplifier
- An offset was added to the FFC current signal so that the average current becomes the same as the DC current measured with the low frequency amplifier

The outcoming corrected signals are then identical to the proton currentwhich enters the FFC. This means that the bunching effectivity (i.e. thepercentage of beam current which is concentrated in the peaks of a distinctphase portion) can be determined from them.

Results

To determine the bunching effectivity and the optimal RF power somebeam measurements with the FFC were made at several power levels. Themeasured signals were then corrected as explained before and thebunching effectivityfor several phase fractions was calculated (see Figure 3). Thebest bunching effectivityis given for a buncher power of app. 45 W. Fora phase acceptance of a resonator which might be in the range of60-70 degrees, the buncher has an effectivity of 50 %.

The maximum peak proton current at the FFC was measured for 45 W buncherpower (remember equation (4): theoretically the peak current becomes infinite at the bunch focus). The measured peak current of 5.5 µA is more than three times as high as the constant current of app. 1.5 µA from the ion source before the bunching.

Actually the buncherhas an influence on the beam parameters. The emittance in x- and y-direction does grow with buncher action, but the effect is very low. The measured emittance at 60 W buncherpower was app. 5 % higher than without buncher action.

CONCLUSION

The presented buncher is a very effective, robust and compact solution which requires low investment in RF hardware as well as in the mechanical structure of the buncher itself. The small footprint and the achieved bunching effectivity of 50 % make it very interesting for compact accelerators. The bunch focus can be chosen very flexible via the RF amplitude applied at the buncher electrode. The concept of bunching the beam at low energies prior to injection into the first resonator is very promising. Especially the possibility of manipulating individual bunches prior to injection into a resonator makes this approach interesting.

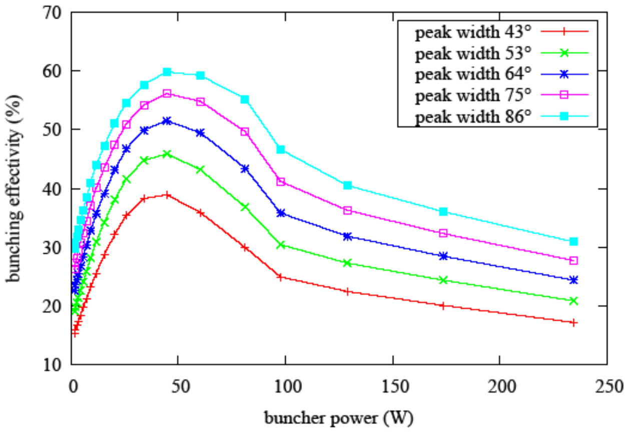

Figure 3: The bunching effectivity at L=550 mm from the buncher for several power levels and phase acceptance values (peak width)

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[1] H. von Jagwitz, “Untersuchungen zur Physik und Strahlcharakterisierung eines Ioneninjektionssystems füreinneuesKonzeptvonmedizinischen Kompakttherapiebeschleunigern“, Diplomathesis, TU Dresden 2011

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