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HARMONIC BUNCH FORMATION AND OPTIONAL RFQ INJECTION

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Abstract

With the aim of reduced beam emittances, a pre-bunching concept into an RFQ or a DTL has been developed. The structure has been designed by using a two harmonics double drift buncher which consists of two bunchers: the first one is driven by a fundamental frequency whereas the other is excited with the second harmonic including a drift in between. This well-known "Harmonic Double-Drift-Buncher" is reinvestigated under space charge conditions for RFQ, cyclotron, and for direct DTL-injection. There are significant benefits for this design such as to catch as many particles as possible from a dc beam into the longitudinal linac acceptance, or to reduce/optimize by up to an order of magnitude the longitudinal emittance for low and medium beam currents. In accordance to these advantages, a new multi-particle tracking beam dynamics code has been developed which is called "Bunch Creation from a DC beam - BCDC". In this paper we present this new code and some stimulating examples.

INTRODUCTION

A source generates continuous particle beams, which need to be bunched before injection into the main part of an rf accelerator. This task can be performed either by a stand alone buncher cavity or by an RFQ. Both alternatives must fulfill certain design requirements like high transmission rates combined with low beam emittance. RFQs are common bunch forming systems. However, harmonic bunchers especially for low and medium current proton and ion beams at linac injection have also some potentials at special requirements like providing really small longitudinal emittance or a shorter length than the RFQ. Besides of this, the RF power need of a buncher cavity is in general much smaller than for an RFQ, which leads to an attractive, cost efficient alternative. Multi harmonic buncher systems have already been used at Argonne ANL-ATLAS [1] and by many others like FRIB at MSU in East Lansing [2, 3]. Based on the existing experience, we developed a two-harmonics double drift buncher (DDHB) scheme including a compact transverse focusing concept. In this paper, the DDHB concept as well as a new code for mutli-particle tracking, BCDC, are explained briefly and an optimized example obtained by this new tool is presented in detail. The motivation of the development for the new beam dynamics code is the detailed study of the space charge action during bunch formation.

CONCEPT OF DOUBLE DRIFT HARMONIC BUNCHING SYSTEM

The ideal energy modulation is achieved by a saw-tooth waveform. A saw-tooth signal of amplitude V_{st} leads to the following energy spread when starting with a mono-energetic and continuous beam:

$$\Delta W_i = q \cdot V_{st} \cdot \frac{\Delta\phi_i}{\pi} \tag{1}$$

As seen in the formula, there is a linear dependence between the particles' energy ΔW_i and its relative phase, $\Delta\phi_i$. However, generating a direct saw-tooth waveform is not possible due to incapability of power electronics with current technologies. An approximate saw-tooth voltage can be obtained with a combination of a sine-wave and its superposition of higher harmonics. One option is to overlap the fundamental and the higher harmonics in one buncher cavity at one location, which mathematically corresponds to the Fourier analysis of the sawtooth [4]. However, the technical realization of such multi-harmonic bunchers (e.g. by combination of two or three $\lambda/4$ resonators [1]) is quite ambitious. Instead of that, the DDHB concept [5] adopted in our proposal is to use two bunching cavities each operated at one harmonic frequency (f or $2f$) and separated by a drift space L_1, as schematically shown in Fig. 1. The length L_2 serves as an additional parameter for a longitudinal beam focus at the position $z = L_1 + L_2$.

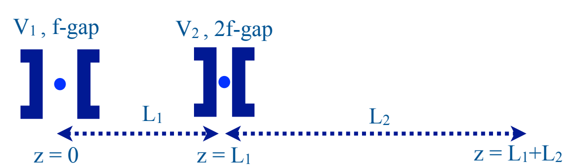

Figure 1: Schematic of the DDHB with four specific parameters.

In the simplified model as shown in Fig. 1, the first buncher cavity operated at the fundamental frequency f and the synchronous phase -90 deg is located at position $z = 0$ and has the gap voltage V_1. This pure sinusoidal signal leads to the following energy variation for an initially mono-energetic and continuous beam [6]:

$$\Delta W_i(\Delta\phi_i(0)) = q \cdot V_1 \cdot \sin(\Delta\phi_i(0)) \tag{2}$$

Along the drift L_1 between the buncher cavities only the relative particle phases $\Delta\phi_i$ are transformed due to the energy modulation of the beam, described by the following formula (with beam current effects neglected):

$$\Delta\phi_i(L_1) = \Delta\phi_i(0) - \frac{\omega\, L_1}{\beta_s^3 \gamma_s^2\, c} \cdot \frac{\Delta W_i(\Delta\phi_i(0))}{W_s} \tag{3}$$

The effect of the second accelerating gap at double harmonic $2f$ with a synchronous phase of +90 deg is given as:

$$\Delta W_i(\Delta\phi_i(L_1)) = \Delta W_i(\Delta\phi_i(0)) - q \cdot V_2 \cdot \sin(2\Delta\phi_i(L_1)) \tag{4}$$

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where V_2 is the applied voltage of the second buncher cavity. Finally, the contribution of the drift L_2 causes one more time a transformation on the "new" relative particle phases $\Delta\phi_i(L_2)$ by following the same Equation 3.

The study of the concept is based on finding a correlation between these four variables. As can be seen from the Equations 2 to 4, a good synthesis of the voltages V_1 and V_2 in combination with ratio of L_1 to L_2 defines the degree of filamentation or "wiggling" of a beam which is an indicator for output emittance and determines the number of particles of that beam into an acceptance ratio for the next accelerator unit as shown in Fig. 2. By the combination of these four parameters, every particular design could be adopted to either smallest output emittances or maximum capture efficiencies (at least 70% − 80%). As a result, the idea of DDHB demonstrates great potentials for outstanding applications like being positioned upstream of a DTL, an RFQ or a cyclotron.

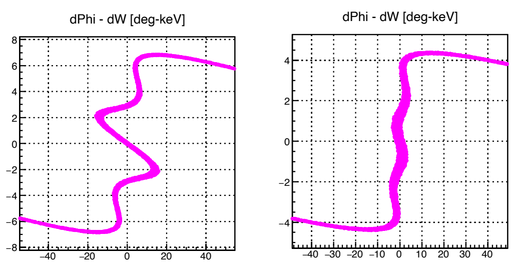


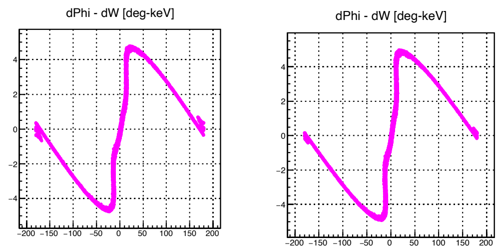
Figure 2: The graphs show the output of longitudinal phase spaces for a 60 keV, 0 mA proton beam fulfilling the different aims for various applications of the subsequent accelerator units.

In addition to all, this simplified setup can be extended by using multi-gap resonators (2 to 4 gaps each, typically) with total voltages in the range of the single gap voltages V_1 and V_2.

BCDC

A multi-particle tracking code, BCDC, has been developed for the dedicated task of simulating the bunch formation at low energies including space charge calculations and considering the effects of the next neighbored bunches (NBB). Moreover, a partial or up to 100% space charge compensation degree can be defined in all sections except those with rf electric fields. There is no such a tool available, which combines all the above-mentioned properties.

The main BCDC code components are the particle generator, which provides several basic particle distributions such as waterbag 6d, uniform 4d+2d, etc., the implementation of essential accelerator elements which are the accelerating gap (thin gap approximation), the drift space as well as the magnetic quadrupole lens and finally the space charge routine.



(a) NBB is deactivated. (b) NBB is activated.

Figure 3: The graphs show the longitudinal phase spaces with and without the effects of neighbored bunches (NBB) for a 60 keV, 15 mA proton beam in 30 mm radial and 62.7 mm longitudinal sizes of the grid box.

The space charge algorithm is based on a direct Coulomb grid-grid interaction: The macro particles are distributed on a Cartesian grid and the electric field components are calculated on the grid points from the charge density on the grid. In this way, the complexity of the algorithm can be reduced and is depending on the number of grid points and not on the macro particle number. The effect of the next neighbored bunches is calculated by extending the main grid box longitudinally to the next and to the previous cell. The total field of the main box is then calculated by superposition with the neighbored cell fields. This of course increase the calculation complexity by the factor of three. The importance of the next neighbored bunches effect is clearly visible by the example shown in Fig. 3: As soon as a continuous beam starts getting bunched, the particles at the top and the bottom of the bunch will "see" the full space charge and build some artificial "satellites" in the particle distribution (Fig. 3a). With the contribution of the next neighbored bunches included, this artificial effect is almost fully compensated (Fig. 3b). It is important to note that all steps during programming have been validated by two well-known beam dynamics codes; TraceWin [7] and LORASR [8].

SIMULATION AND DESIGN

One simulation example applied on a 60 keV, 15 mA proton beam demonstrating an effective phase focusing by a second harmonic double drift buncher is shown in Fig. 4, with the corresponding parameters listed in Table 1. The transverse focusing is provided by a quadrupole triplet array. Very compact layouts could be realized by using permanent magnets. The longitudinal beam focus with very small emittance and high capture rate is achieved within less than 0.7 m only. One application for such a setup is the injection into a cyclotron. In this case, the DDHB could be partially embedded into the cyclotron yoke. This system is very well suited for increasing the cyclotrons' injection efficiency, since it delivers a well-focused, low emittance and high current input beam.

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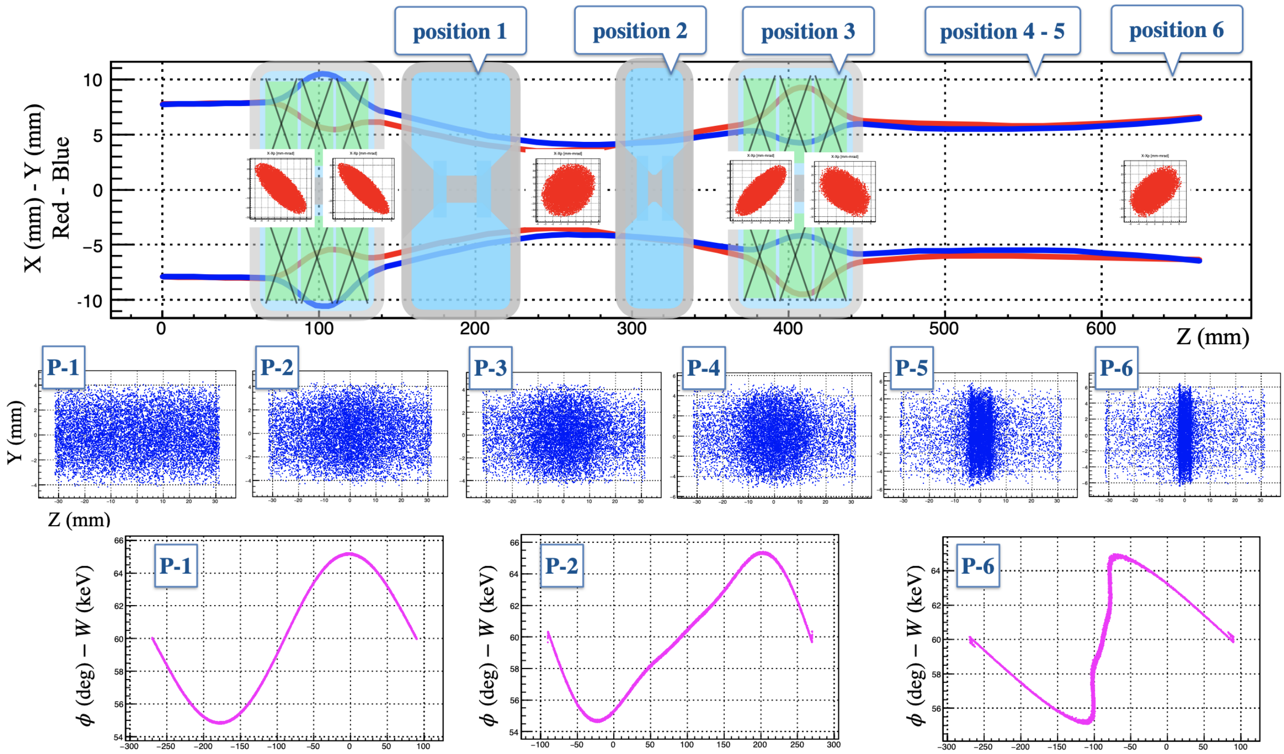

Figure 4: An example of a DDHB design simulated with the BCDC code. The upper plot shows the transverse beam envelope. The six plots in Cartesian coordinates at the middle indicate bunching formation through the traveling direction. The graphs at the bottom are longitudinal phase spaces at the critical positions.

Table 1: Parameters of the example shown in Fig. 4.

Parameter	at section 1	at section 2
W_s	60 keV	—
Frequency	54 MHz	108 MHz
I_{beam}	15 mA	15 mA
L_1, L_2	73.35 mm	458 mm
V_1, V_2	2.6 kV	1.2 kV
Capture Ratio	—	72.24 %
	in	**out**
$\epsilon_{x,n,\text{rms}}$	0.268 mm.mrad	0.273 mm.mrad
$\epsilon_{l,n,\text{rms}}$	0.0287 keV.deg	1.515 keV.deg

CONCLUSION

The concept of DDHB has been developed by the close relation of the two voltages at the bunchers V_1, V_2, and two drift spaces L_1, L_2. The application of the idea for different types of injection into a DTL, an RFQ, or a cyclotron has excellent potentials for beams in 10 to 100 A keV energy range and currents up to a few 10 mA as outputs with high capture efficiency (70% – 80% depending on the L_1/L_2–ratio) and small longitudinal emittance. Moreover, the BCDC simulation code considering the effects of the next neighbored bunches has been developed, benchmarked and reliably on process. The implementation of NBB makes this code unique for the task of studying bunch formation at low energies.

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