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# THE DOUBLE DRIFT HARMONIC BUNCHER (DDHB) AND ACCEPTANCE INVESTIGATIONS AT LINAC AND CYCLOTRON INJECTIONS

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*Abstract*

Particle Accelerators demand high particle transmission and reduced longitudinal emittance; hence, effective bunching systems are requested. The concept based on an efficient, compact design called "Double Drift Harmonic Buncher - DDHB" fulfills these two requirements for a c.w. or pulsed beam injection into an RFQ, a DTL, or a cyclotron. The proposal is associated with two buncher cavities separated by a drift space and an additional drift at the end of the system for a longitudinal beam focus at the entrance of the next accelerator unit, whose candidates can be one of those mentioned above. The investigations are focused on exploring accurate acceptance rates. To obtain successful and understandable outputs from the DDHB concept, a new multi-particle tracking beam dynamics code called "Bunch Creation from a DC beam - BCDC" has been developed for detailed investigations of space charge effects. It allows to calculate the transformation of intense dc beams into particle bunches in detail with a selectable degree of space charge compensation at every location. This paper presents the results from various investigations with and without space charge effects.

## INTRODUCTION

Drift tube RF accelerators have restricted input phase acceptance and thus require a bunched beam at the entrance. Although this can easily be achieved with a single buncher cavity, the sinusoidal excitation leads to a growth in longitudinal emittance and limits the beam matching into the subsequent structure. Nowadays, the RFQ is the typical/standard solution for efficient beam forming and pre-acceleration prior to injection into the following accelerator structure. However, due to the sinusoidal excitation, the RFQ needs quite some effort in beam dynamics and advanced hardware to reach the requested emittance goals. Because of the incapability of the current technology for the power levels required in particle accelerators ( from kV to 100 kV range), the ideal alternative of a sawtooth-shaped high-frequency excitation of a single cavity is not an option. In this regard, a spatial separation of the sinusoidal excitation with the fundamental frequency and the higher harmonic is possible for such an aim. In this case, a two-harmonics double drift buncher (DDHB) scheme has been proposed [1, 2], including a compact transverse focusing concept, having several benefits. Small longitudinal emittance or a shorter length are benefits in addition to power consumption and financial perspectives when compared to alternative solutions.

As shown in the schematic in Fig. 1, the main elements are two buncher cavities separated with a drift space, $L_1$,

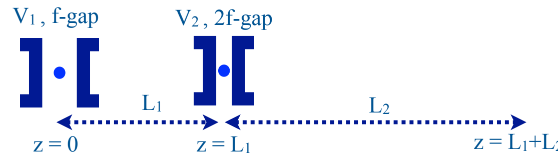


Figure 1: Schematic of the DDHB with four specific parameters.

where the first one is operated at the fundamental frequency with −90° synchronous phase and applied voltage $V_1$, and the second buncher cavity at the second harmonic frequency with 90° synchronous phase and applied voltage $V_2$, respectively. Finally, a second drift $L_2$ at the end of the array is needed for a longitudinal beam focus at the main accelerator entrance. Consequently, the properties of this system for an application can be adjusted depending on the four design parameters $V_1$, $L_1$, $V_2$, and $L_2$, as explained in [3].

Table 1: Range of Parameters For Different Applications

| **Input Energy** [keV] \ **Frequency** [MHz] | $\beta\lambda/2$ [mm] 27 | 54 | 108 |
|---|---|---|---|
| 100 | 81.05 | **40.52** | 20.26 |
| 60 | 62.78 | **31.39** | 15.70 |
| 25 | 40.53 | 20.26 | 10.13 |

The attractive energy range for the DDHB, located between the ion source and the accelerating unit is roughly from 25 keV up to 100 keV. A useful range of fundamental operating frequencies is shown in Table 1. Altogether, this parameter scope results in a set of $\beta\lambda/2$ period lengths, which must be considered with respect to the geometric feasibility of RF buncher cavities. While one design for a 60 keV proton beam at 54 MHz frequency was presented in LINAC'22 [3], in this paper, another design for a 100 keV proton beam at the frequency of 54 MHz is studied. The concept and its limitations for this particular design are investigated by using the in-house developed multi-particle tracking program, Bunch Creation from a DC beam - BCDC, which is dedicated to studying all aspects relevant to low-energy bunch formation.

## BCDC

At linac simulations, the numerical computations are usually restricted to one RF bucket containing a bunched beam.

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Such a definite volume brings a non-physical/artificial effect on space charge calculations as soon as the bunch length fills a large percentage of the RF period $\beta\lambda$, as is the case here. The new multi-particle tracking code BCDC has been developed to simulate bunch formation at low and medium energies and included space charge calculations considering the effects of the next neighbor bunches (NNB). Additionally, the program allows for partial or complete space charge compensation (SCC) in all sections except those with RF electric fields.

The space charge algorithm in BCDC is based on a direct Coulomb grid-grid interaction and electric field calculations by depositing charge density on a Cartesian grid. In order to obtain accuracy, the field computations are longitudinally extended by the main grid size three times larger than the original dimension. The central particle distribution is then copied after each step into the neighbour buckets. Afterward, the resulting fields in the main grid box are recalculated by overlapping the electric fields in the main grid box with those from neighboring regions. By applying this technique, the space charge effect on the borders without (black) or with (red) the adjacent boxes, respectively, can be seen in Fig. 2, and the simulations become realistic.

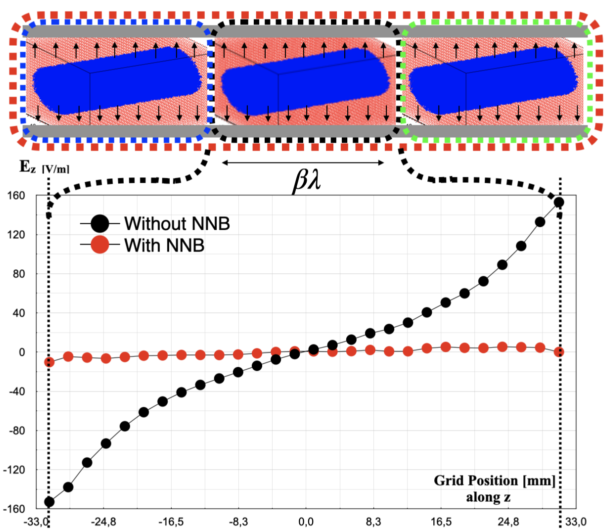


Figure 2: The field calculations without and with the NNB concept.

Furthermore, Fig. 3 shows the results in the absence (symbolized by a triangle) and presence (denoted by a circle) of the NNB concept in which the field computations in a test simulation for a group of distributions with distinct lengths are performed for the sequence of one likely unbunched beam (red) and two bunched ones with a half (yellow) and a quarter (blue) of the primary size. The high $E_z$ fields close to the defined walls are drastically reduced by that concept, especially for the D.C. beam (labeled red). To sum up, the NNB concept is a powerful tool for linac simulations, especially for accurate field calculations at the edges of the buckets.

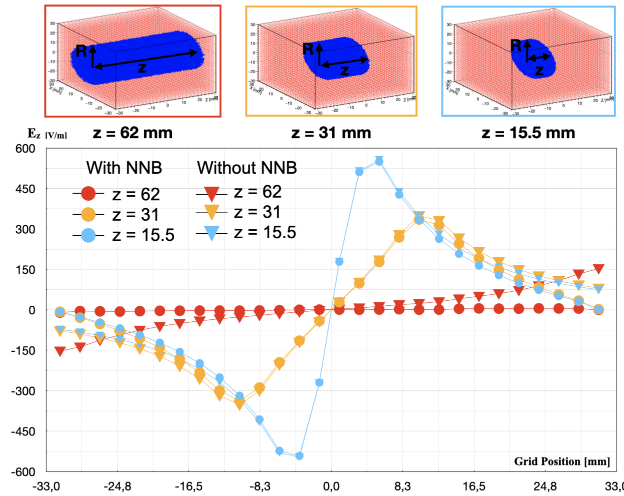


Figure 3: The effects on the field calculations for distinct beam sizes without and with the NNB concept.

In addition to the NNB feature, BCDC has one more aspect, namely the Space Charge Compensation (SCC). Due to the ionization of the residual gas partial space charge compensation will happen along the LEBT, with different percentages before, at, and behind the buncher system. In the simulation shown in Fig. 4, while the compensation degree at the front side of the harmonic bunchers is assumed to be 90% and the value at the section after the buncher is 70%, the region along $L_1$ between the buncher gaps is assumed to be 0%. Since high current beam application is one important purpose of the design, the partial space charge compensation allows to reach higher current levels.

In conclusion, so far, the simulations are linear with respect to energy depending phase shifts. After bringing the BCDC into its final form, comparisons with the standard code TraceWin [4] have been performed and will be continued for further investigations.

## SIMULATION AND DESIGN

Figure 4 shows as an example the simulation of a 100 keV, 30 mA proton beam using a second harmonics double drift buncher to achieve bunch formation, with parameters listed in Table 2.

A quadrupole triplet array from permanent magnets provides transverse focusing. One potential use for this design is injecting the beam into a cyclotron, where the DDHB might be partially embedded into the cyclotron yoke.

The outcome of the setup is a very sharp longitudinal beam focus with very small emittance and a fair capture rate within a total array length of less than 0.8 m. When repeating the simulation for a zero-current input beam, the bunch width is considerably shorter even. Although the concept proves its robustness with respect to beam current, as seen in the acceptance rates for ±3° in Table 2, the comparison of these two designs indicates that the space charge inside the beam helps the bunch formation by capturing more particles into a larger phase width.

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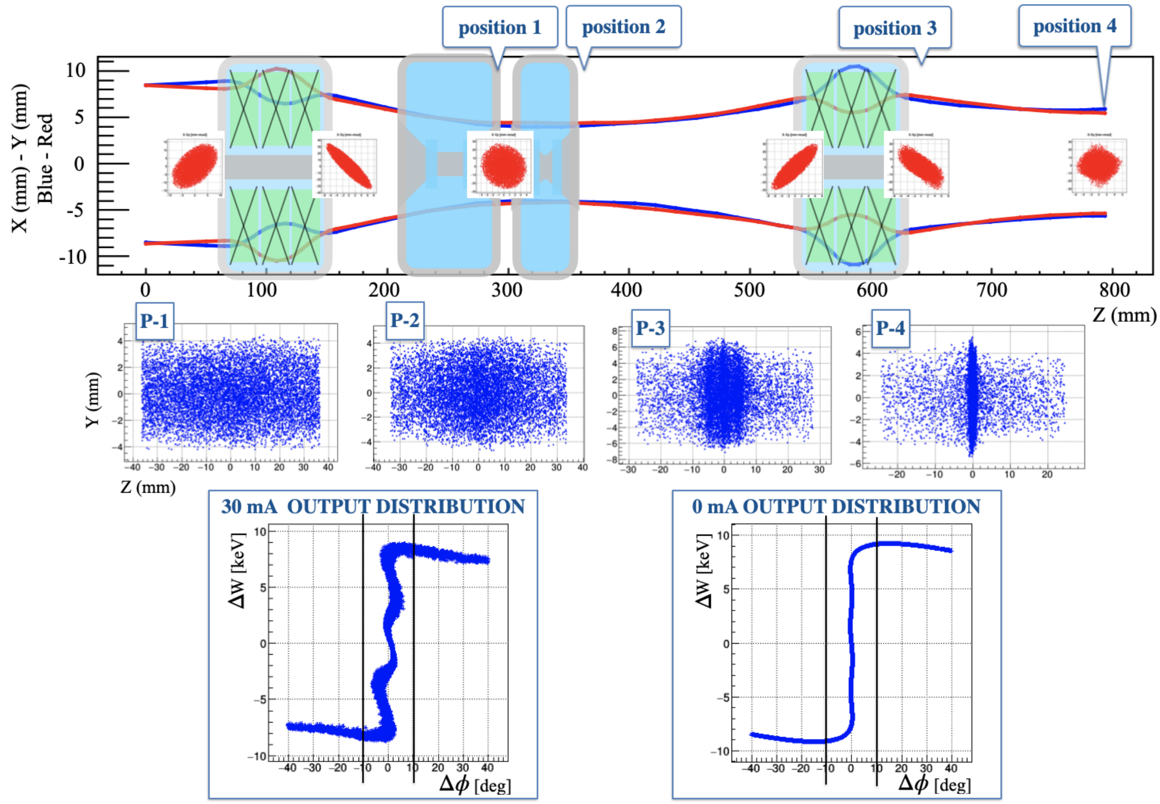


Figure 4: Illustrating an example of one DDHB design simulated with the BCDC code. The upper plot shows the transverse beam envelope for 0 mA. The following four plots in Cartesian coordinates of $Y - Z$ planes indicate the timeline of a bunching formation through the traveling direction. The graphs at the bottom are the output distributions of the longitudinal phase space for 0 mA and 30 mA.

Table 2: Results of the Two Designs of 0 mA and 30 mA

| Parameter | 0 mA Design | 30 mA Design |
|---|---|---|
| $W_s$ [keV] | 100 | 100 |
| Frequency [MHz] | 54, 108 | 54, 108 |
| $I_{beam}$ | 0 mA | 30 mA |
| SCC % | 0 | 90, 0, 70 |
| $L_1, L_2$ [mm] | 80.39, 460.13 | 80.39, 460.13 |
| $V_1, V_2$ [kV] | 4.3, 1.65 | 5.4, 2.35 |
| Capture % $_{\Delta\phi\| \pm 3°\|}$ | 63 | 63 |
| Capture % $_{\Delta\phi\| \pm 10°\|}$ | 69 | 73 |
| $\varepsilon_{x,n,\mathrm{rms}}$ [mm.mrad] | 0.281 | 0.290 |
| $\varepsilon_{l,n,\mathrm{rms}}$ [keV.deg] | 2.135 | 1.56 |

A bunching system in front of an RFQ as realized at ATLAS, Argonne and at FRIB, MSU, Michigan at low currents [5, 6] might also be interesting for higher current projects by using the DDHB concept.

## CONCLUSION

The DDHB concept demonstrates excellent potential for zero-current and high-current applications in LEBT's for a DTL, RFQ, or cyclotron injection where the beams are in the energy range of 25 keV, up to 100 keV, typically. The outcomes are small longitudinal emittance and high capture efficiency of up to 75%. A high-current design for demanding output beam properties can perform for lower currents with similar efficient outcomes by well-tuning the four parameters defined in the DDHB theory as $V_1$, $V_2$, $L_1$, and $L_2$.

Furthermore, the BCDC code allows to study bunch formation in detail. The feature for the degree of space charge compensation (SCC) makes the simulation flexible for comparison with experimental results.

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