

## SIMULATION SOFTWARE FOR NEW TYPE OF CHARGED PARTICLES ACCELERATOR

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*This paper presents a simulation software useful for developing a new type of charged particles linear accelerator, in order to optimize the overall dimensions and weight, as well as reducing the energy consumption. Also, these accelerators will be capable of accelerating different ion species, at different final energies.*

*With the simulation software, all constructive parameters can be varied and calculations of corresponding speed profiles and energy gain of the particles can be performed. Results from using the simulation software are presented, which demonstrate the possibility of obtaining compact accelerators by using successive high voltage pulse power supplies.*

**Keywords:** simulation software for accelerators, compact linear particle accelerator

### 1. Introduction

With new knowledge about nature on a microscopic scale, the need to find tools to investigate this new world appeared. One of these tools was the use of charged particles, as projectiles accelerated to large enough kinetic energy to interact with the substance at the atomic scale and provide information about the nature and structure of the matter investigated [1][2].

Some of the active areas of research in the field of modern accelerators, both at high and low kinetic energy, can be listed: production of short-lived radioisotopes for medical diagnosis, pulsed X-ray radiography, analysis of trace elements for biology and archeology, elemental and structural analyses for micro and nano structured materials and many others [3][4].

In this paper a simulation software is proposed, which helps the user obtain a design for a compact type of accelerator for charged particles.

The novelty of the design is related to the replacement of the RF technique of acceleration with the use of very compact, high voltage pulse power supplies, connected to successive accelerating intervals and triggered at convenient time intervals, according to the arrival of particles in the accelerating regions.

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The simulation tool was developed to define the speed profile of an ion which is accelerated in successive gaps, in which square or half sine pulses of different amplitudes and delays are applied.

With this tool, the user can define different accelerating geometries which can be used as a starting point in designing a constructive solution, according to overall constraints, in order to obtain particles at specific energies from 0.1 MeV up to 3 MeV, or even more.

## 2. Principles Used in the Simulation Software

The main aspect in accelerators technology is represented by the means of producing high electric fields. One of the first solutions for DC high voltage sources is through mechanically carrying electrostatic charges (Van de Graaf or Pelletron generators, as well as the Cockcroft-Walton multiplying rectifiers). For non DC high voltage sources, a solution is represented by the RF resonant cavities working at tens or hundreds of MHz and HV, pulse generators like the Marx generators and vector inversion generators (VIG) [5][6][7].

It is suitable to mention an important problem of DC accelerators, which is the size of the insulation of the HV platform, when higher voltages are used [6]. For particle accelerators using resonant structures like resonant cavities at frequencies of tens or hundreds of MHz, the size is again a problem, because the resonant cavities also have important dimensions / heights.

Insulation and size related problems, arising for potentials greater than 1MV, have conducted to new kinds of accelerators, where the charged particles are traversing many smaller *accelerating gaps*, with electrical fields applied, followed by spaces without electric field (*drift tubes*).

The systems where energy gain is obtained by reiterated accelerating forces over a linear trajectory are known as *linear accelerators* or *linacs*. The most suggestive example is Wideroe's original structure [8] in which a series of cylindrical tubes are aligned in a vacuum site being alternating connected to a RF source (Fig. 1) [9].

The linac mentioned has a main characteristic which is that the accelerated particles must be synchronous with a proper phase of the RF field, which leads to a stable acceleration over the entire length of the linac. [10] Obvious, this synchronism is in strong relationship with the speed profile of the particles and as a consequence, it is fulfilled only for one ion specie and for a unique final energy.

Such accelerators, used mainly in fundamental physics researches at energies of hundreds of MeV up to TeV (Large Hadron Collider-CERN), are not compatible with the field of applied physics. For such applications there is a

strong need for versatile accelerators, capable to accelerate different ion species, at different final energies.

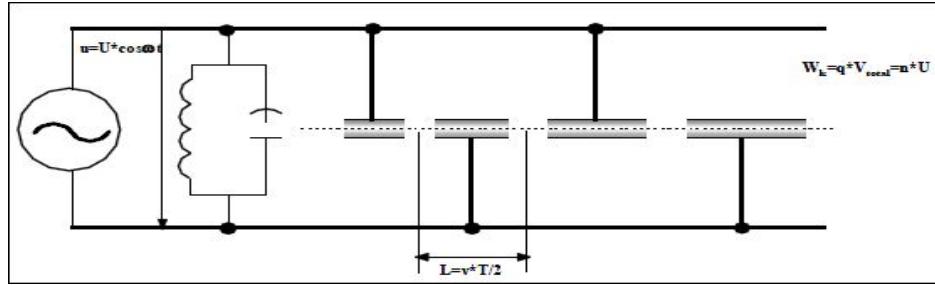


Fig. 1. Wideroe's accelerating structure

The paper envisages a new approach in the linac technology, in terms of replacing the RF excitation of a resonant cavity, with individual HV pulse generators, which have to be synchronized according to the speed profile of different ion species. In this way, it would be possible to use a number of HV generators, each up to maximum 500kV (which are commercially available), to excite a smaller number of gaps, in order to obtain final energies up to 3MeV or even more.

In such case, the length of the drift tubes could be minimized according to the minimum available delay for successive firing of HV generators. Another advantage of such accelerating structure is the possibility to change the final energy from maximum (all the HV generators active) to the minimum voltage level of one of the HV generators, by not exciting the other corresponding gaps.

To design such accelerating structure (Fig. 2) it is necessary to have a simulation tool in which all the parameters (square or half sine pulses applied at different amplitudes and delays, charge and mass of the ion being accelerated) can be varied and calculations of corresponding speed profile and energy gain have to be performed.

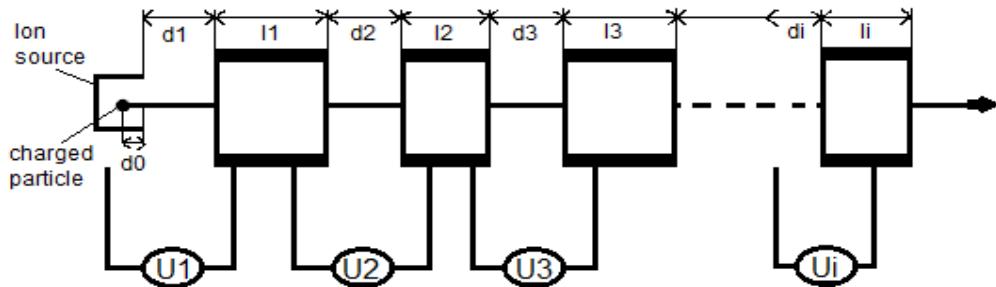


Fig. 2. Accelerating structure with successive gaps excited with delayed HV generators, according to the speed profile of the charged particle being accelerated

According to the notation in Fig. 2, the following definitions are used:

- $d0$ : the space from the ion source until the charged particle reaches the accelerating space of gap no. 1
- $di$ : length of gap no. i (distance over which the charged particle is accelerated by the applied electric field)
- $li$ : the length of the drift tubes (distance over which the charged particle is not accelerated)
- $Ui$ : the value of the HV pulse biasing gap no. i

### 3. The Software Simulation Tool

In this chapter is presented the software application developed for simulating the behavior of the accelerated particles in a linear accelerator.

The software tool was developed in order to simulate the final acceleration of the particles, using different values for parameters like number and position of gaps, the length of drift tubes, intensity and shape of the pulses applied in the gaps and the appropriate delays between the pulses.

The formulas behind the simulation are from Newton's laws of motion for particle dynamics, because we don't have relativistic speeds. The intensity of the electric field (1) and the acceleration of particles (2) obtained from electric forces of the applied electric fields are calculated on the X axis of the particles' movement.

$$E = \frac{F}{ne} = \frac{m * a}{ne} = \frac{m * S}{ne * t^2} \quad (1)$$

$$a(t) = \frac{F}{m} = \frac{ne * E(t)}{m} = \frac{ne * U(t)}{m * S} \quad (2)$$

In formula (1) :  $E$  – intensity of the electric field,  $F$  – Electric Force,  $ne$  – charge of the accelerated ion in a beam,  $m$  – mass of the particles,  $a$  – acceleration,  $S$  – distance travelled by the particles,  $t$  – time.

In formula (2) :  $a$  – acceleration of the particles,  $U$  – voltage of the applied field,  $S$  – distance travelled by the particles.

The formula used in the software for calculating the energy of the particle ( $W$ ) at any moment in space and time is:

$$\frac{dW}{dt} = ne * \frac{d}{dt}[U(t) * S(t)] \quad (3)$$

The application is constructed to simulate 3 successive gaps. If we need to simulate the behavior of a charged particle linear accelerator with more than 3 gaps, the results from the first simulation (the first 3 gaps) can be used as initial

parameters for another simulation, and thus being able to make simulations for any number of gaps.

The software environment chosen for this purpose is National Instruments' LabVIEW.

### 3.1. The Interface

First of all, in the LabVIEW application a HMI (Human Machine Interface) screen was needed in order to visualize the data and input the parameters.

The interface presented in Fig. 3. has two regions: one for the input of values for different parameters and one for the visualization of the effect on the particle beam and on the shape of the accelerator.

The input of values is located in the left and in the bottom part of the screen. On the left are the parameters linked to the initial setup: number of elementary charges of the particles in the beam ("n charges"), atomic mass of the particles ("A [uamu]"), shape of the electric pulse ("Half sine On or Off"), initial energy of the particles ("E0 [eV]") and some other parameters which help the functioning of the program and specially the level of granularization of the calculations ("maximum number of points", "dt").

In the bottom part of the screen are located parameters related to the electric fields applied in each of the three gaps: length of the gap ("gap [m]"), value of the electric pulse applied in the gap ("Upk [V]"), duration of the electric pulse applied in the gap ("pulse t [s]") and the moment at which the pulse is applied ("pulse delay [s]").

The visualization is also presented in two areas on the screen. The central graph represents the energy of the accelerated particles, in each gap and between them (the yellow thick lines represent the energy of the particles in the gaps).

Also on the graph, the intensity and shape of the electric fields applied in the gaps are represented (with red lines). The white line represents the distance covered by the particles and its associated Y-axis is on the right of the graph.

The second visualization that the simulation tool offers is the design of the linear accelerator, represented in a vertical position in the right part of the screen.

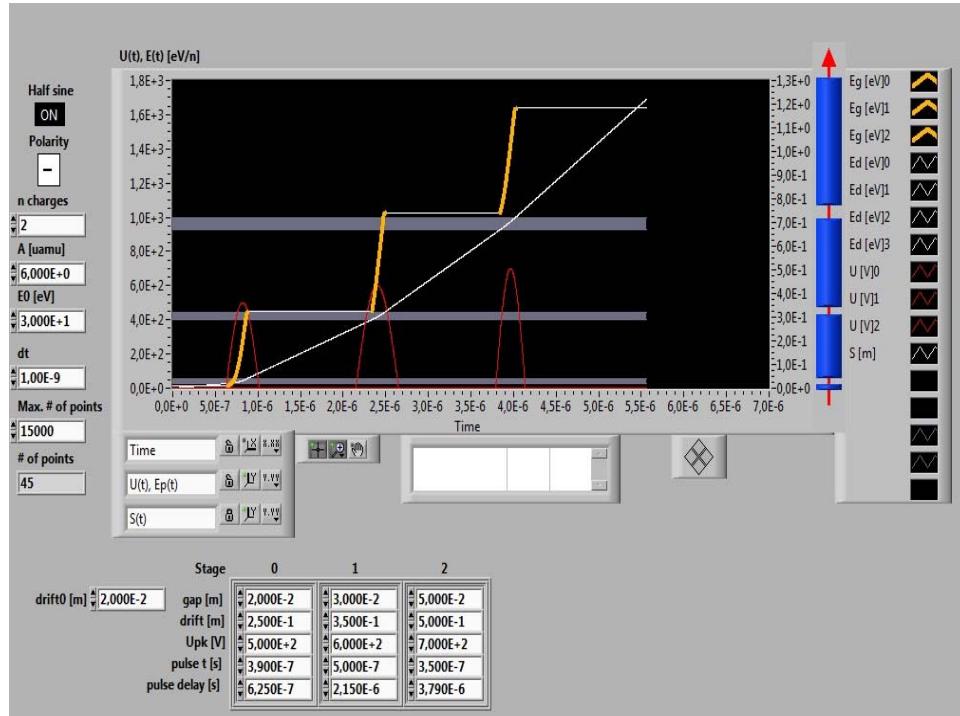


Fig. 3. The user interface of the software simulation tool

### 3.2. The Code Diagram

As any LabVIEW application, the program has two parts: the interface and the code (the diagram) behind it (Fig. 4).

The diagram of the application is structured in 3 parts:

- processing of the input data for implementing the formulas (left part of the diagram),
- using the formulas in order to create results for each discrete moment (centre-left part of the diagram),
- preparing the graphs for the visualization of results (right part of the diagram).

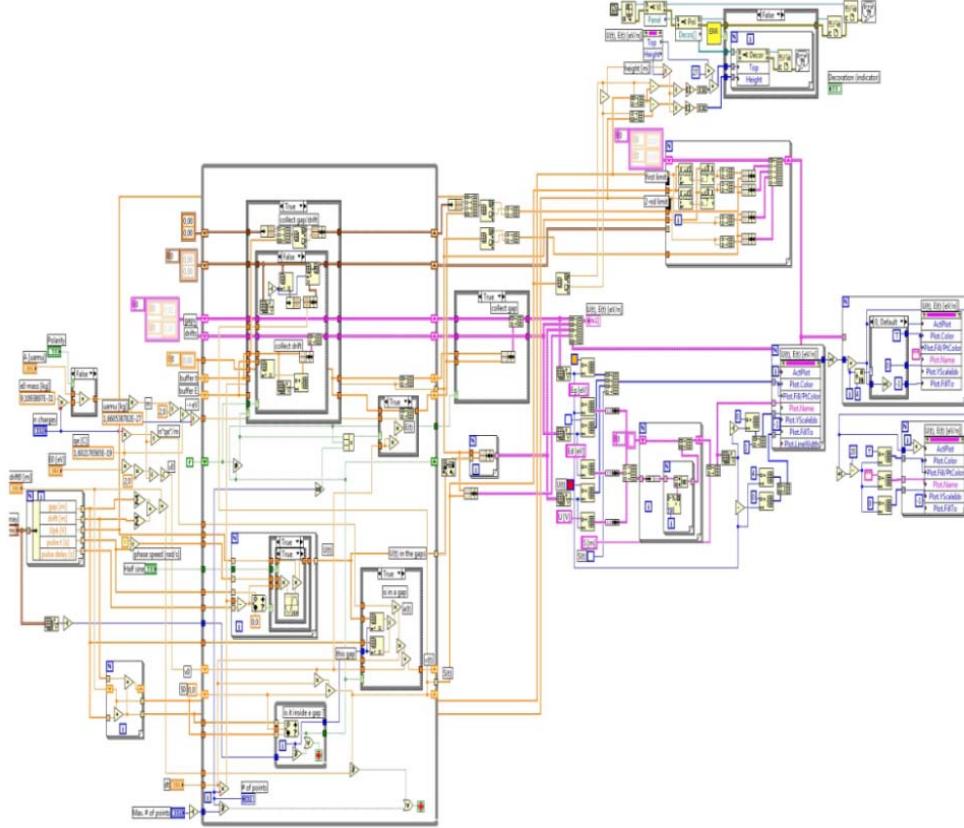


Fig. 4. The code diagram of the software simulation tool

The values which were inserted in the interface are received in the left part of the diagram. Using additional operators, the formulas presented above (1), (2) and (3) are constructed for each spatial point.

In the center part of the diagram, for every point on the axis which is travelled by the particles, the energy is calculated, taking in consideration if the particles are situated in or outside a gap. If they are in a gap, their energy is increased. After the beam travelled through the gap, all the results and values of parameters are returned again to this repetitive section of the program. As stated before, the program is designed to make calculations for three successive gaps.

After the three gaps have been transited, the results are sent to the graphs (the right part of the diagram). Different properties of the graphs are set here, from the names of the curves (the graph legend) to the style and colors, length of the axes. Also the visual representation of the linear accelerator is defined here, based on the positions and distances from the input data.

#### 4. Results

Many simulations made with the presented software demonstrated the possibility to design and build a new, very compact, kind of accelerator, dedicated for applied physics, which can accelerate different ion species at different energies. A relevant example (Fig. 5) is the acceleration of  ${}^4\text{He}^{+2}$  ions at 3MeV, such beams being very useful for material analysis and characterization by Rutherford Backscattering Spectroscopy.

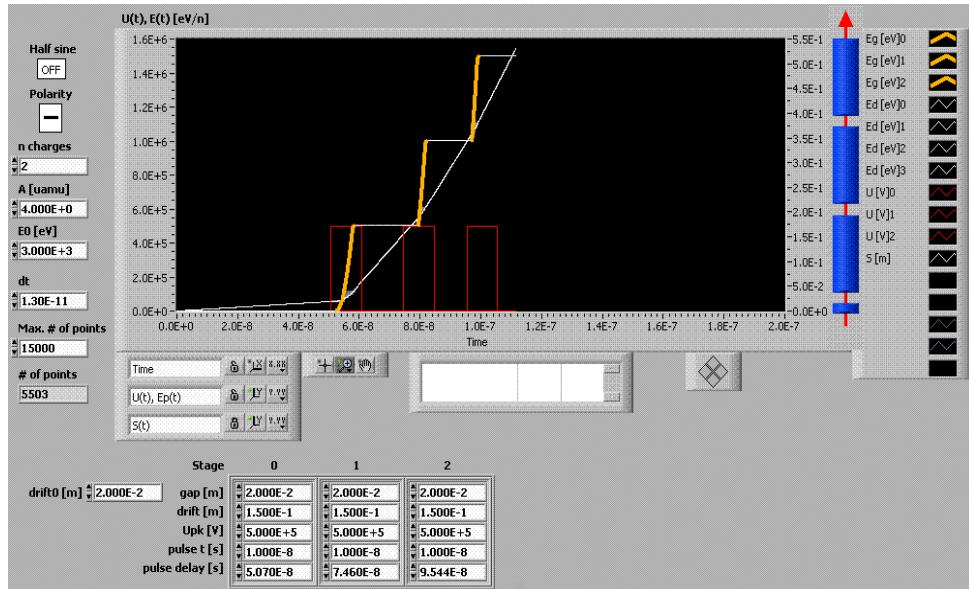


Fig. 5. Simulation for acceleration of  ${}^4\text{He}^{+2}$  ions at final energy of 3MeV

The geometry of the accelerating structure from Fig. 5 was chosen after some attempts. The results, presented in Table 1, show that this geometry and HV pulses parameters can be used to accelerate ions with different masses and charge states. The only parameter that must be changed is the delay between HV pulses. By also changing the amplitude of the HV pulses, the energy can be varied continuously in a wide range. The widths and amplitudes of the applied electric pulses were chosen in respect to the characteristics of the existing commercial solutions for HV pulse generators [11][12][13].

In this respect, we started by analyzing the motion of different ions, at different charge states, in a single gap excited at voltages from 200kV, up to 500kV, with pulses of different widths and shapes. Based on the obtained data, the length of the gaps was optimized in correlation with the pulse duration (width). This correlation has to assure the accelerating potential during the travel of the ion

through the gaps. Further simulations and analysis were done to correlate the length of the drift tubes with the corresponding delay time of firing the gaps.

Table 1

**Results obtained using the simulation software, with 3 gaps**

Geometry (according to the notations in Fig. 2): d0=2cm, d1=2cm, l1=15cm, d2=2cm l2=15cm, d3=2cm, l3=15cm; <b>TOTAL=53cm</b>					
Ions	Energy [MeV]	HV pulse			Delay Times [ns]
		U [kV]	Shape	Duration [ns]	
${}_1H^{+1}$	1.5	500	rectangular	10	tl1=25, tl2=38.5, tl3=51
${}_4He^{+2}$	3	500	rectangular	10	tl1=50, tl2=75, tl3=95.5
${}_6Li^{+2}$	3	500	rectangular	10	tl1=65, tl2=93, tl3=117
${}_{14}N^{+2}$	3	500	rectangular	10	tl1=100, tl2=146, tl3=179
${}_4He^{+2}$	1.2	200	rectangular	10	tl1=50, tl2=90, tl3=120

The results from Table 1, with a physical structure of only 53cm, are showing the feasibility of the proposed solution for a new type of accelerating structure and also how useful is the simulation software in optimizing its constructive and functional parameters.

## 5. Conclusions

This paper presents a software simulation tool which calculates the energy of the accelerated particles at each moment in time and space, in order to determine the best input parameters of constructing and operating a compact linear accelerator.

The purpose of this approach is to minimize the total length and energy consumption of the accelerator and also being able to accelerate different ion species at different energies.

The main constructive solution is to replace the RF excitation of a resonant cavity with HV pulse generators, which can be fired independently, depending on the characteristics of the accelerated particles.

The presented results demonstrate the possibility to obtain accelerated beams of different ion species (H, He, Li, N, etc.), at continuously variable energies up to 1.5MeV/charge, using a physical structure of only 53cm.

This approach leads to multiple advantages:

- smaller overall size of the accelerator (25% of the length of the smallest experimental tandem accelerator [14]) and much more as RF linacs, because the lengths of the drift tubes are not in relation with the RF period;
- versatility greater than in RF linacs: different types of ion species can be accelerated at different energies, because the different speed profiles of ions are harmonized by the moment at which the HV generators are fired;

- reduced energy consumption (10-20 kW comparable with more than 50 kW for tandem accelerators and few hundred kW for RF linacs), because each HV pulse generator supplies a very high resistive load and a small capacitive load (moderate peak power). Also, a small ratio of pulse width over a high period of repetition time, minimizes the overall energy consumption.

Further works in developing the simulation tools for such simulators have to be done in order to define the spatial distribution of the electric field in the gaps and to optimize the ion optics along the acceleration path.

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