Features of the new VON ARDENNE BeamGuidance system

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Abstract. With the Variocathode EB Gun series completed in 2004 and the fully digital control of High Voltage Power Supplies introduced in 2014, the focus of EB product development has now been directed to the BeamGuidance System. This year, the new VON ARDENNE BeamGuidance will be implemented for the first large EB melting furnace and EB production coater. Based on standard industrial hardware components, a completely new signal processor and HMI software was developed. Sophisticated procedures implemented on the signal processor calculate all dynamic beam scanning sequences for multiple EB guns in real time including automatic figure movements, coordinate transformations and dynamic corrections. Although the beam scanning sequences are defined with discrete coordinates, the new BeamGuidance allows for both quasi-digital (point to point) and analog (continuous) electron beam movement. With further new key features like synchronization of multiple beams, synchronization to external events and extended time and power distribution based figure manipulations, the new BeamGuidance System provides a new quality for control of EB processes.

1. Introduction
The previous BeamGuidance software was released in 1998 and served 20 years for all VON ARDENNE electron beam processes. While the basic core of the software remained unchanged, adaptations for new Windows operating systems (Windows XP, Windows 7, Windows 10) and new signal processors (FOX30/FOX32, M44, ADWIN) had to be implemented.

First released without automatic moving figures, the “track” function was one of the most important additions made already in 2000. Further functions based on specific customer or process requirements were implemented step by step. During the last years, it became evident that the further maintenance of the old software with new operating systems and hardware platforms as well as extension by new features will become inefficient or almost impossible. Some of the later added functions did not perform fully consistently and resource conflicts could not be completely eliminated anymore.

Beginning in 2015, requirement and task lists were assembled and the development of new software from scratch was initiated in 2016.

2. System layout and functional blocks
VON ARDENNE electron beam systems consist of three main, well integrated functional elements:

- Electron Beam Gun;
- High Voltage Power Supply;
- BeamGuidance System.
Such Electron Beam Systems are part of complete VON ARDENNE coaters or furnaces [1-3] and are integrated into customer machines as well.

Figure 1. Basic layout of electron beam systems.

Because of the modular design of VON ARDENNE electron beam systems and the many different applications, the process controllers are not considered to be an integral part of the BeamGuidance software. The BeamGuidance software offers an open interface to process controllers that can be implemented:

- on a master plant computer or
- as a separate process on the BeamGuidance computer.

The BeamGuidance software itself consists of two separate parts:

- the program of the digital signal processor (DSP) and
- the HMI program running on an industrial PC.

When starting the BeamGuidance software at the PC, the DSP program will be loaded from the PC into the DSP as well. Then the DSP in general runs as a stand-alone-system. However, active communication to the HMI PC program is monitored and any interruption of communication will shut down all EB guns for personal and process safety.

3. Key features of the new BeamGuidance software

3.1. Hardware platform and system requirements

As a first step before the software development, different hardware platforms, software development tools and programming languages have been investigated to evaluate possible solutions different from the past hardware platforms and software solutions. In particular, several real-time hardware platforms with associated operating system were examined.
3.2. Procedures executed by the digital signal processor

With previous BeamGuidance systems, the signal processor only performed the major task to continuously send the pre-calculated scanning patterns of one or more EB guns to the signal amplifiers. Certain control functions were implemented onto the DSP as well. However, all dynamic features like manual or automatic figure manipulations including the coordinate transformation have been calculated by the PC program. That is why the two different timers:

- very stable DSP clock and
- not fully predictable Windows program timer could result in non-consistent behaviour, especially for automatically moved figures by so called tracks.

A fully consistent and predictable time behavior for scanning beams became a high-priority task for the new software development. The solution is to use only the very accurate and stable time basis of the DSP with the consequence to now implement all dynamic or time-based procedures within the DSP program.
Using a TiCo process (TiCo is an additional built-in timing processor of ADwin-Gold-II system) in parallel with two CPU processes, the limitation of the existing ADwin-Gold-II model is almost reached by executing the following functions:

1. Generation of digital watchdog signal.
2. X-Y-Z channel output with maximum 100 individual figures per gun and 10 000 coordinate triples per figure (data matrix of 3×106 coordinates).
3. One track per figure with 10 000 coordinates per track for automatic figure movement. Tracks can turn the figure with respect to the track path.
4. Calculation of Z channel based on X and Y data.
5. Coordinate transformation for X and Y channel by polynomial of 3rd order.
6. Dynamic compensation of variations of acceleration voltage Ub for X and Y channel based on measured real values of acceleration voltage.
7. Dynamic correction of frequency response characteristic of the electromagnetic system from amplifier to deflection coil.
8. Output of 8 digital signals for each X-Y-Z data triple.
9. Synchronization of scanning sequences of multiple guns with 8 independent groups.
10. Synchronization to mains frequency.

The resulting minimum output rate is:
- 5 µs for one EB gun controlled by one DSP without calculation of a Z coordinate or
- 10 µs for two EB guns per DSP without calculation of a Z coordinate and
- 10 µs for one EB gun per DSP with calculation of the Z coordinate.

This output rate is fast enough to control all typical, and sometimes very specific, VON ARDENNE electron beam processes. The expected developments for the DSP processor promise even faster output rates in the near future.

Some of the above mentioned functions shall be explained in more detail.

3.2.1. Digital watchdog signal. Despite the fact that the DSP is able to maintain a continuous periodical repetition of the loaded scanning sequence it is essential to supervise the executed DSP program as well as the active communication to the HMI program running on the Windows PC. For that reason, the DSP switches an output bit every 200 µs resulting in a digital 2.5 kHz watchdog signal. A circuit in the Beam Guidance Basic Rack (lens and deflection amplifier unit with power supplies and control units) receives the watchdog signal and resets the main equipment status bit upon interrupted watchdog signal. This measure serves to immediately switch off the electron beam(s) in case of stopped DSP program or lost communication.

3.2.2. Analog output channels X-Y-Z. The complete beam scanning procedure is a defined sequence that is repeated continuously. During the repetitions, changes to the scanning sequence may occur initiated by external events (e.g. operator, process controller) or internal pre-defined manipulations (e.g. track movements). To precisely control the electron beam process, the whole beam scanning sequence is divided into individual sections – the figures. All external and internal manipulations affect the figures as the smallest unit of the whole technological recipe.

The deflection signals X and Y are transmitted from the PC program. To create new technological recipes, X-Y figure templates can be loaded from a huge library. The Z channel is calculated by the DSP out of the X and Y data and can represent the signal for a dynamic lens. A maximum of 8 analog output channels are available per DSP to control additional dynamic position correction coils or a stigmatic system of one or two guns, if necessary.

3.2.3. Tracks. Similar to figures, tracks consist of X-Y coordinates, however, they are not scanned by the beam directly. A track can be a property of a figure and moves and turns a whole figure. Since tracks are now executed by the DSP program, the beam scan along figures and the figure movement by the track happens on the same DSP clock and results in a fully determined beam path over time.
The PC program allows the selection of various track stepping modes. The current position of a track is read back into PC and the figure is appropriately visualized on PC screen.

3.2.4. Coordinate transformation. The transformation of process coordinates to deflection coordinates is realized by polynomial of 3rd order. Since tracks can move figures with output of every X-Y coordinate, the coordinate transformation has to be calculated with every output cycle of 5 or 10 µs.

The polynomial of 3rd order allows for correct beam scan on a target plane even if the electron beam passed a non-linear magnetic bending field. The conversion matrix represents a double folded plane (figure 3).

3.2.5. Dynamic compensation of acceleration voltage variations. The resulting deflection angle of an electron beam within a defined magnetic field depends on the speed of electrons determined by the acceleration voltage Ub. Instabilities of the acceleration voltage like ripple modulate the speed of electrons while being deflected by a scanning regime. The speed modulation is converted into a beam path modulation overlapping the intended and defined beam path.

Especially with SCR driven high voltage power supplies, remaining ripple of the acceleration voltage is a compromise between size of the smoothing capacitor and stored energy that will be released during gun arcing events. The larger the beam deflection angle with remaining Ub ripple, the more noticeable the beam path modulation will appear.

The DSP software reads the actual value of Ub, which typically has a periodic component. From current value and historic values an optimal compensation signal is calculated and applied to actual X-Y output coordinates.

![Figure 3. Coordinate transformation with polynomial of 3rd order; transformation mesh (a) and transformed live scanning sequence (b).](image)

3.2.6. Dynamic correction of frequency response characteristic. Every electromagnetic system for electron beam deflection consists of amplifiers, cables and deflection coils with certain installation conditions. Due to the specific total frequency response characteristic of these components, the real beam deflection will differ from the original values that are transmitted from the DSP program.

With experimentally determined or calculated frequency response characteristic of the system, a correction of the deflection signals can be realized by Fourier transformation of the scanning sequence.
and adding the inverse system frequency response characteristic. After the reverse transformation, the corrected time-based deflection signals are obtained.

Disadvantages of this correction method are:
- Significant time consumption for the two transformations;
- Result and correct compensation only valid for a static periodical scanning sequences.

To overcome the disadvantages, a new approach was realized for the new DSP software.

The implementation of a digital IIR filter of 3rd order. This filter has a fairly simple structure and quickly processes the X and Y data within every output cycle. In contrast to the Fourier transformation, the filter represents an approximation function with the following advantages:
- Fast and simple operations;
- Precise enough signal correction;
- Applicable for changing scanning sequences including online figure manipulation or adding/removing of figures;
- Parameter changes and restart possible during run time.

3.2.7. **Synchronized digital signal output.** To generate information about the status of the beam scanning sequence 8 digital output signals are sent by the DSP in parallel to the analog X-Y-Z output channels. The status of the 8 bits could be defined by the PC program for each individual X-Y-Z coordinate, e.g. to realize a coordinate counter as fastest application. Currently, these status bits can be defined by the HMI program only for each individual figure.

Other usages of such synchronized digital signals are:
- Sequence start trigger and sequence counter;
- Masking of certain scanning figures;
- Releasing of beam pulses to defined process spots;
- Triggering and synchronization of measuring equipment.

3.2.8. **Gun Synchronization.** For melting and coating processes with multiple EB guns in one joint process area, synchronization of individual scanning sequences is required to maintain stable technological processes.

In the past, one or more defined “master guns” restarted the scanning sequences of their “slave guns” at the same time with its own sequence restart. This procedure worked well as long as the individual sequence durations remained fixed and of the same duration or whole time fractions.

The new software calculates all figure and sequence manipulations at the DSP and is now able to maintain gun synchronization even during changes to the “master” and “slave” scanning sequences. For instance, switching a manual hot spot on/off will not cause an active synchronization to get out of the defined time sequence. Phase synchronization between synchronized guns is automatically restored as soon as synchronized guns have the same sequence length.

Up to 4 independent synchronization groups can be defined that are triggered by any of the running beam scanning sequences of up to 8 EB guns. Furthermore, four external synchronizing sources can control the scanning sequences. In a configuration matrix of the PC program, the “master guns” or external synchronization channels are assigned to the “slave guns”. The internal and external trigger signals are exchanged via a signal bus between all DSPs of the EB system. One external trigger channel is reserved for sequence synchronization to the mains frequency.

3.3. **Functions of the HMI PC Program**

The program running on the Windows PC is the basic operator interface of the BeamGuidance system. It loads the specific program to the DSP and maintains all data interfaces. One BeamGuidance PC with HMI program can control up to 8 EB guns.

The active user interface language is selected by the Windows language control. The HMI uses common and intuitive symbols as control elements to minimize the use of text, e.g. for menu and table headers.
All functions are grouped in menus of different levels of operator activities:
- User and permission management;
- Process supervision and control;
- Creation and management of beam scanning sequences;
- Recipe and process step management;
- File operations;
- Support functions.

3.3.1. User and permission management. For the different kinds of electron beam processes, there are various customer requests for user levels and handling of operational permits. Such requests result from the need of reproducible processes and products as well as from legal demands related to certified processes and products.

To meet all the various customer demands, the new BeamGuidance software provides a flexible concept of user and permission management.

Every user has to log on at the Windows operating system with their own user name and password. The BeamGuidance software identifies every user by its Windows log on account. Each user is assigned to a BeamGuidance user group like “administrator”, “supervisor” or “operator”. Only members of the highest level user group can assign users to the BeamGuidance user groups.

Each individual function of the BeamGuidance software is marked with a function identifier. All function identifiers are now assigned to several permission groups of certain logical function families. These permission groups are finally linked with the user groups. Since all the permission and user assignments can be made by the user of the highest user level a fully flexible user and permission management is realized.

3.3.2. Process supervision and control. The HMI screen contains an oscilloscope window of variable size and location. All elements related to the beam scanning sequence are displayed in this window and can be manipulated by the following methods:
- Mouse and keyboard input at the “process area” window;
- Manipulations via the operator panel;
- Graphical manipulations by mouse input at the “oscilloscope” window (ref. paragraph “Summary and Outlook”);
- Automatic manipulations by a process controller or via the external interface.

All other process parameters like set and actual values of the HV power supply and lens parameters including the T-Meter trends (supervision of cooling water temperature increase) are displayed in a separate “process data” window. From that window, manual changes of specified parameters can be applied.

3.3.3. Creation and management of beam scanning sequences. The “process data” window allows to design complete electron beam processes from scratch. All functions are displayed in a logical manner and guide the user through the design steps (figure 4). After having defined the process area by limits, the particular mode for each EB gun scanning sequence has to be defined. The new software allows for time and power determined sequence control as well as mixed sequence modes:
- fixed sequence time with beam power control of individual figures;
- fixed gun beam power and sequence time adjustment based on defined power of individual figures.

Figures are the basic element to design a scanning sequence. They can be newly created, loaded from a template library or imported from customer sources. A huge extendable library of figures is provided with the BeamGuidance software. The beam scanning starting point and direction of movement is indicated by an arrow. When selecting a template, all turned and mirror-inverted versions can be chosen and loaded (figure 5).
3.3.4. Analog and digital beam scan. A unique feature of the new BeamGuidance is the possibility of “analog” and “digital” beam scans. All defined X-Y scanning sequences consist of consecutive discrete, digital coordinates. With a fixed output rate, these coordinates are transmitted via D/A converters to the deflection amplifiers. The input signal of the amplifiers typically represents a step function while the electromagnetic deflection system smoothens the step function into a more or less continuous beam movement on the target due to its inductivity.

The new BeamGuidance allows to send both “digital” step functions or correct “analog” signals to the amplifier input. In “analog” mode the created deflection signal moves with constant speed between consecutive coordinate points regardless their position and distance. With each figure coordinate the BeamGuidance can switch between “analog” and “digital” mode. This allows for specific selection of the desired mode and unique technological features.

“Analog” output is enabled as standard mode. With specific figure properties, the “digital” jump mode can be activated for the following conditions (figure 6):

- jump between all figure coordinates;
— jump from figure end to next figure start;
— jump from end to start of same figure in case of repetitions.

The input pattern to the deflection amplifiers for two spiral figures in “analog” and “digital” mode is shown in figure 7. Both figures are scanned one after the other with the same output rate. Between both figures the beam jumps in “digital” mode as well.

**Figure 6.** Figure properties and selection of “digital” jump modes.

**Figure 7.** Simultaneous scanning of two spiral figures in “digital” and “analog” mode.

### 3.3.5. Tracks.
Another key feature of the VON ARDENNE BeamGuidance are automatically moving figures on so called “tracks”. This feature has already been provided by the former software version since 2000. While in the previous version an independent timer on the PC calculated the movement of one or more figures on the track path, the beam scan was determined by the DSP output rate. The two disadvantages of the previous solution disappear with the new BeamGuidance software:

— Tracks represent figure properties and moving figures are now fully predictable and completely calculated by the DSP.
— There is no track update data traffic between PC and DSP anymore that can be disturbed by the Windows operating system.

### 3.3.6. User interface details.
Numerical inputs are realized by the “NumericUpDown++” control that enables easy value changes just by mouse activities (figure 8). When clicking into the parameter window, the digit pointer appears at the last changed digit. Left/right arrows shift the digit pointer and up/down arrows change the value of the digit. This method enables parameter changes of different step sizes without any configured step resolution.

**Figure 8.** NumericUpDown++ control principle (a) and software realization (b).

### 3.3.7. Recipe and process step management.
A snapshot of all active scanning sequences as well as additional process parameters represents a technological recipe that can be saved, loaded or managed. However, most coating or melting processes have to be carried out as chronological steps of different scanning sequences and process parameters like changes of beam power, acceleration voltage, beam
focus etc. Such a sequence of recipes can be managed as process steps. The BeamGuidance will support the creation of subsequent process steps including the time- or event-controlled execution (ref. paragraph “Summary and Outlook”).

3.3.8. File operations. File operations serve to load, save and manage technological recipes. All information is saved in text files of a specific format. This allows editing recipes “offline” without running BeamGuidance software.

3.3.9. Support functions. Explanations of complex functions are available via intuitive graphics directly at the corresponding function (ref. picture 6) or as tool tip hint popping up when the mouse pointer stays on a control element. Further information and help will be provided under a separate support menu (ref. paragraph “Summary and Outlook”).

3.4. Interface to process control and data acquisition systems

3.4.1. Operator Panel. Operator panels are provided for only the process control functions and include basic control elements for the HV power supply as well (figure 9). The display shows all parameters of the function that has just been activated. All operational parameters can be accessed by scrolling through the screens.

The functions of the operator panel are enabled according to the user level and its permissions. Creation, modification or management of recipes is not possible from operator panels.

![Figure 9. Standard operator panel for one EB gun.](image)

3.4.2. Computer network, remote and service access. The BeamGuidance software is embedded into a communication network shown in picture 1. All data of the EB System is saved in the central data block located in the PLC of the HV Power Supply. With two sub-networks – an internal and a public one – full data exchange via the PLC data block as well as protection of the internal processes can be maintained.

The process controller shall preferably run at the external plant computer. It communicates to the BeamGuidance by loading set values into the data block or sending commands to the BeamGuidance HMI program. As an option, a process controller can run as additional process on the BeamGuidance PC.

For service purposes, a separated and protected gateway is embedded into the BeamGuidance system and allows remote access to the whole EB system including HV power supply.

4. Conclusion and Outlook

The introduced BeamGuidance software represents a completely newly created software tool to design and manage electron beam processes and will be released in two steps. First implementations for about
5 active projects including a large melting furnace and production coater comprise all standard functions of the software and are available from now. As a second step, enhanced and optional features will be completed and released by the end of the year. This includes graphical editing of all geometrical elements on the process screen.

Six patents are pending for new solutions implemented into the new BeamGuidance software.

The used hardware platform does not require any customized installations and is independent from new releases of the operating systems. Ethernet communication will ensure a long lasting layout concept and support. With the used up-to-date software development tools, a continuous improvement and maintenance of the released BeamGuidance software is expected for at least the next 10 years.

The new BeamGuidance software can be applied not only to VON ARDENNE electron beam systems but also to other new or existing systems.

References
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