Beam diagnostics on the electron beam welding installation at Budker Institute of Nuclear Physics

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Abstract. This paper describes the equipment and methods of the beam diagnostics, namely, the beam current density distribution measuring and the beam position and inclines angle determination. Such a diagnosis is aimed at applying on the electron-beam technological installations, in particular, on the electron-beam welding installations. The paper presents the results of the beam current density distribution measurement, describes the design of the beam position and inclines angle measurement system, and presents the results of preliminary tests of the prototype of this system.

1. Introduction
Nowadays an electron beam is widely used tool both for scientific researches and for different applications. With the development of electron beam technologies the beam quality requirements are increasingly rigorous. Therefore, simultaneously with development equipment for beam generation and transportation the direction of beam quality diagnostics have to be developed. It is the fine-tuning of the beam that ensures the high quality of the manufactured products, and it also affects the repeatability of scientific experiments not directly related to electron beam processing but using electron beam.

One of the practically important electron beam implementations is electron beam welding. To obtain high quality weld seams it is necessary to monitor various electron beam parameters, first of all, the power density distribution in the beam cross-section.

The present work was carried out on EBW installation in Budker Institute of Nuclear Physics SB RAS, Novosibirsk [1]. The installation includes:
- 60 keV electron gun with current up to 750 mA;
- magnetic optical system with ability of deflection and parallel beam shift;
- two-coordinate sample holder with the ability to move;
- seam tracking system based on reflected electron sensing technique.

A significant part of the equipment was designed and manufactured directly at BINP. The work on developing new modules and subsystems is being carried out continuously.

This paper presents the results of the electron beam diagnostic tools development based on the external current collector signal processing.
2. Problem statement
To exam BINP electron guns beam quality the slit and wired detectors are being used [2, 3]. The measuring procedure is based on the following operating principle: a circular beam oscillation is applied to the gun deflecting systems, obtained signal from the detector is observed by an oscilloscope. Measured beam profiles allow estimating beam radial size (the result was 0.6 mm under 2.7 mA current).

Due to increasing the number of works carried out on BINP EBW installation, which require precise beam positioning, a new diagnostics tool realization able measured not only profile but beam power distribution was required.

3. Diagnostic technique choice substantiation
The simplest and widely used types of devices for measuring beam current and determining its profile is contact one. When using this device type, the beam profile is determined from the known speed of movement of the device relative to the beam, the device geometry and the measured time of exposure of the beam to a current collector.

In our case from mentioned type of devices the Faraday cup is considered to be the most suitable collector due to its high current measurement accuracy. While the task is not to measure the total beam current, different masks or diaphragms are placed before the collector. Masks are aimed at highlighting a certain part of the beam. Then the current distribution in the beam cross-section is determined.

As a supporting beam shape diagnostic a luminophore screen visualization could be used. Interacting with luminophore surface electrons lose part of their energy by ionization, in turn, part of the ionization loss is converted into optical radiation. The intensity of visible light from the luminophore surface is proportional to the beam current. Luminophore can be used for subsequent diagnostics with an optical sensor. At the moment of the optical beam diagnostics experiments have not been carried out yet but are planned in the future.

Therefore, the system for current density distribution measuring with a Faraday cup current collector is the only developed beam diagnostic system. The decision on the initial device design was based on the fact that it was planned to carry out beam diagnostics at the small pretuning beam current. Due to the low received power, the small dimensions of the device allow it being in the vacuum chamber constantly and do not impede welding process.

Graphite was considered as the most suitable mask material. Graphite has a high melting point, which allows it being exposed to the beam for a prolonged period. In addition it has a low electron reflection coefficient (~0), resulting in inappreciable signal distortion (for example, copper masks gave a poor signal to noise ratio). And the last important advantage of graphite is that it can be easily processed into complex shape, and this allows producing a replacement item quickly in case of damage.

As a result, a graphite plate with a 0.1 mm diameter round transcentric symmetrical pin-hole was chosen as a mask for the power density distribution system.

4. Beam current distribution measurement

4.1. Measurement procedure

4.1.1. Beam oscillation forming. The beam oscillation in the diaphragm plane is set by periodic changing of magnetic system fields that allows isolating and measuring the beam small part current passing through the diaphragm (See Figure 1).

ADC connected to the shunt \( R \) of the Faraday cup controls the beam position relative to the pin-hole (by ADC reading \( U_r \)). In the beam tracking system the same ADC data are used to measure the secondary emission electrode voltage drop and to observe the surface map [4]. The collected data arrays during scanning are written to a separate text file. Assuming the resistance \( R \) is constant, we find the current at each point \( U_r(x) = I(x)R \).

Analytically, the beam current is calculated by the formula:
\[ I = \int_{-\infty}^{\infty} J(x, y) \, dy, \]

where \( I(x) \) is the instantaneous cylinder current, and \( J(x, y) \) is the distribution of the current density in the beam per unit surface area.

Then, the power distribution in the beam is calculated by the formula:

\[ P(x, y) = J(x, y) U_{ac}, \]

assuming the accelerating voltage is constant.

Beam diagnostics are carried out with a beam current of \( \sim 1 \) mA, since a larger current can destroy the diagnostic system.

**Figure 1.** Measurement procedure scheme

**Figure 2.** Scanning beam oscillation

### 4.1.2. Scanning function

The current values in a pair of magnetic correctors are set through the DAC. The values written to the DAC are set by a periodic function with a smooth current change (up to 500 points) in one direction and sequential bias in the other. The function is implemented in the Elixir functional language.

In each point the voltage drop is amplified and read by ADC. The scan system generates a symmetrical saw tooth signal with the step \( \Delta \). The step value has to be set by operator (see Figure 2). Also operator can set such parameters as the angle of rotation \( \phi \) and the scanning beam oscillation amplitude. For data processing and displaying Python Spyder development environment is used.

### 4.2. Beam current distribution composition algorithm

Scanning is performed on a raster of 250 points per line and \( \sim 100 \) lines per projection. After scanning in one projection, the scanning beam oscillation is rotated by a certain angle \( \phi \) in the range from 0 to 90 degrees (see Fig. 2). For detailed current density distribution performing all the specified projections is required. Usually their number is from 7 to 15.

The noise in the signal of a single scan is too large; therefore, a parameter that controls the number of passes along one scan line was added to the scanning function. Collecting statistics significantly reduces the noise. The beam energy distribution is assumed to be constant over time. However, in order to avoid possible errors it is also necessary to collect statistics for averaging fluctuations in case of energy jump. To obtain reliable data the number of iterations in the existing system must be at least 10. Collecting data for a full beam scan with \( \geq 100 \) scan lines takes about 1 min per projection. Figure 3a shows the result of sharply focused beam current distribution measurement. Figure 3 (b, c) shows two projections of current distribution for an insufficiently focused beam, where the irregular shape of the distribution can be observed in detail.
4.3. Magnetic optics parameters selection algorithm

To select the required magnetic optics elements current values it is necessary to obtain current density distribution in one projection for each of the current values of the focusing lens or corrector. By variating the lens current the optimal focus depending on correspondent counted beam size is set. By variating the magnetic corrector current the anode correction is set according to the change in the waveform and the beam displacement nonlinearity. An example of the magnetic corrector values selection is shown on Figure 4 whence it is obvious that the $y$-corrector current value is set correctly and the $x$-corrector current must be increased.

4.4. Results and discussion

The results of measuring the beam current density obtained with the presented diagnostic system give more detailed information about the beam shape than the data obtained previously on the slit detector [2]. The modified data collection system and the visualizing software simplify the observation of the beam current distribution shape, shorten the setup time and increase its accuracy. As a result, obtaining a better beam quality became possible at the installation.

Currently, the theoretically calculated beam shape (see Figure 5) cannot be distinguished with sufficient accuracy from the image of the beam shape obtained with this diagnostic system. However, the observed similarity of the distribution character indicates that the theoretical predictions were correct. Moreover, the previously observed shape of the defocused beam on the luminophore is visually similar to the projections of an under focused beam obtained by the diagnostic system.
Figure 5. Beam current distribution (axes are co-directed): (a) – simulated at the focusing point by CST; (b) – measured at the welding point.

The principal defect of the system is the operation speed. The complete measurement cycle without iterations takes 2 minutes and that one with reducing noise iterations takes 7-10 minutes. Subsequently the scanning time must be reduced by 1-2 orders.

Image quality is strongly influenced by noise. Not all the noise can be eliminated by increasing the number of iterations. The installation sources of noise are:

- equipment that controls the beam current stabilization by high-frequency grid voltage regulation;
- deflecting system supplies stabilizing the coil current;
- high-voltage power supply stabilization system;
- heating current control equipment.

Only the beam current stabilization can be programmatically disabled at the control program user interface by putting the gun into non-stabilization mode with manual exposure of the grid voltage. All the data presented in this paper were obtained with this mode. Due to the noise that prevents the correct data collection, the results of the beam cross-section power density calculation were not presented in this paper. The calculated order of the power density is known to agree with that expected for the EBW beam.

5. Beam position and beam incline angle measurement system

5.1. Problem statement

We were tasked to develop a universal device for beam position and incline angle determination. This device should be using on electron beam welding facility, and other facilities where we need to know these parameters of electron beam (for example, on the facilities with alfa-magnet developed in our Institute [3]).

5.2. Construction of beam position and beam incline angle measurement system

To solve the problem a small diagnostic device located in electron beamguide was proposed. It displacement could be both closed to anode to check initial spreading of EBW electrons and downstream from the magnetic system, for example, for alfa-magnet facility. The diagnostic system consists of two independent deflecting coils (two-coordinate corrector) and electron collectors located further in the beam transition system. The center region of the device has an opening for a beam passage. The scheme of the device is illustrated on Figure 6.
The electrons collector consists of several lamellas located nearby electrically connected to ADC. Each lamella signal is measured separately of another (see Figure 7a). The lamellas are proposed to be arranged in groups of 4 mirror-symmetrical on both sides, for each of the deflecting system axes. There are 16 electrodes for entire system.

Deflecting coil declines the electron beam along both diameters. When the beam is shifted or tilted, the different currents get to opposite electrodes, both in magnitude and duration. The scanning scheme is shown on Figure 7b. By the difference in the shape of the signals and by which lamellas the more current is detected, the beam inclination or displacement could be determined. To achieve the required accuracy of measurements, the transverse size of the lamellas should be on the order of the beam size (about 1 mm).

5.3. The analysis of the signals from the device

In order to avoid collector lamellas destruction due to heating by the beam the scanning procedure time should be as short as we can. At the moment we didn’t calculate the optimal ratios between ADCs, DACs, power amplifiers for the magnetic system performance, the size and raw material of electrodes, and maximum current for the scanning procedure.

The Figure 8 demonstrates the qualitative dependence of expected signals from the lamellas. Axis x describes the coordinate in the space that corresponds to the magnetic system current. Axis y describes a beam current, which got on the lamellas.

On the Figure 8a is shown the case if the beam propagates the beamguide along the axis without a bias or tilt. The signals are symmetric and equal.

When the beam is biased on Δx from the beamguide center, the result of beam scanning procedure will look like the Figure 8b. Middle point between two corresponding signal peaks indicates the beam shift from deflecting lens magnetic axis.
The beam inclination results in non-equal shapes of the signals, as shown at the Figure 8c. It seems to be possible to calculate the beam incline angle analyzing the signal shapes. The exact formula of this calculation is determined by the geometry and location of electrodes. Moreover, the device is able to show if the beam is defocused (for example, high overlay of signals from lamellas 2 and 4, or smaller signal level from the lamella 3 than signal level from lamellas 2 and 4, or more smooth edges of the signals.)

5.4. Tests of the prototype

The prototype of the device for one magnetic corrector axis with copper lamellas (corresponding to electrodes 2 and 3 shown on Figure 7a) was manufactured and tested. During the preliminary test, there was set the function of slow beam oscillation with a beam current of 1.4 mA in the direction corresponding to the corrector axis. Signals from the lamellas were recorded by the oscilloscope (See Figure 9). The test was also carried out with no current stabilization mode. For extra noise reduction the RC-circuit was made for each electrode. The results obtained indicate the operability of such a device design. However, in this case additional measures are required to suppress high-frequency noise. In the next version of the prototype, the remaining electrodes need to be added in order to verify all of the described abilities, and the noise reduction scheme needs an improvement. As a result of the next series of preliminary tests, it is planned to collect the first database required for developing a user program to analyze signals and display the results for the beam parameters correction.

6. Conclusion

The system of the beam cross-section current distribution measurement was put into operation at the EBW installation. The prototype of the system of beam position and beam incline angle measurement is at the testing stage. Measures were taken to decrease the scanning procedure time and there were
identified further actions for minimizing this time. At the installation the works aimed at modernization of the equipment for accelerating ADC reading speed and decreasing the equipment noises are being carried out.

References

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