EXPERIMENTS ON LOW ENERGY ELECTRON BEAMS

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The aim is to report experimental results on low energy medium current electron beams in a better agreement with space charge model. The experiments were performed using a laboratory installation specially designed for electron beam (EB) diagnosis and dynamics referred to as DIADYN. It includes a vacuum electron source, a beam channel consisting of two axially symmetric magnetic lenses, as well as two beams profile monitors. Our previously reported investigations were focused on the non-destructive beam diagnosis at the source exit and on the beam dynamics in the transport channel. In the present work we report on hardware adjustments of the EB channel that led to a better agreement between calculated and experimental data. DIADYN proved to be a suitable educational tool for an in depth understanding of EB physical and engineering aspects.

1. INTRODUCTION

Electron beams (EBs) of energies inferior to 300 keV, usually classified as low energy, are found in numerous materials processing applications such as welding; melting; evaporation; curing of coatings on wood panels, floor coverings, magnetic media, printing inks; crosslinking of strand wires or plastic laminates and many others.

Sanderson describes advanced EB welding technologies developed recently at the Welding Institute, a non-profit research entity [1]. It reviews other EB applications such as use of thin films obtained by EB evaporation to produce capacitors, magnetic devices, semiconductors, metal coated plastics, special photographic products, and multi-layer systems for optical devices, or, for example, coating of turbine blades with yttrium-stabilised zirconia. EB melting

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technology is mentioned as used to process refractory metals (tantalum, niobium, molybdenum) and reactive metals (titanium and zirconium), allowing for titanium scrap re-processing to account for approximately 90% of the EB melted tonnage per year. EB irradiation for curing of adhesives and resins is viewed as a technology that can provide significant advantages for aerospace and automotive industries due to low energy consumption, reduced volatile emissions, low-cost tooling materials, and control over curing energy-absorption profile. In addition, EB cured materials have been shown to possess excellent mechanical properties. Pulsed electron beam treatment of advanced bearing materials, such as Al-Pb alloy, uses electron beams in the range 10 to 40 keV.

Continuing interest in low energy EB applications is illustrated also by recent investigations on EB use in nanotechnology. Nano-gratings structures suitable for nanolithography, of 27 nm width, 7 nm separation and heights from 80 to 250 nm, were obtained after exposure to a 30 keV electron beam [2]. Nicholson et al report on a fully computer controlled X-ray source for printed circuit board automated inspection [3]. The source contains an electron gun with a magnetically focussed electron beam intercepting a 15μm air-cooled tungsten foil target behind a 0.5mm thick aluminium window, producing 40 to 160 keV electrons, of the maximum current 0.5 mA. Defects are detected through an intensifier coupled via a large aperture lens to a digital camera. Low-adhesion surfaces are studied with human genome microarrays of 120 nm diameter pits produced by electron beam lithography and 11 nm high columns produced by colloidal lithography [4]. Discrete force sensors fabricated by nanolithography are described in [5].

Electron sources are essential in EB installations. In a recent review paper aimed at vacuum electron sources [6], Zhang et al investigate electron beam emission characteristics from neon, argon, hydrogen and helium in a dense plasma focus device for deposition of thin films, concluding that hydrogen should be the first choice for thin film deposition as it produces the highest beam charge from 50 to 200 keV electrons, neon being the next best choice for energies from 30 to 70 keV [7]. A magnetic deflector for miniaturised electron beam microcolumn systems for e-beam nanolithography is reported in [8].

In our studies [9, 10] we focused on electron beams of energies from 10 keV to 50 keV, and the beam currents from 0.05 A to 1 A. An experimental set-up has been designed and realised to allow investigations for both scientific and educational purposes. By these studies, we supplement studies based on high-energy installations realised in our national laboratories [11, 12]. We concentrated on the beam diagnosis at the source exit and on the beam dynamics in the transport channel. In the present work we report on hardware adjustments of the electron beam channel leading to a better matching between experimental and calculated results.
2. ELECTRON BEAM EXPERIMENTAL SETUP

The electron beam installation for diagnosis and dynamics, called DIADYN, is presented in Fig. 1. It is a classical installation containing an electron gun, magnetic lenses and monitoring devices. The source of the electron beam is of pulse convergent Pierce diode type. It provides a 4 µs beams at 100 Hz, with current intensity in the range 0.05–1A and voltage in the range 10–50 keV. Two magnetic lenses produce an axial magnetic field in the electron beam channel. The beam monitoring unit consists of two beam profile monitors and a sliding Faraday cage (parked inside the vacuum chamber). Also shown in Fig. 1 is the high-voltage probe.

Fig. 1 – Diadyn installation: S – pulsed Pierce diode electron source (10–50 keV, 0.05–1 A, 4 µs, 100 Hz); EBC – electron beam channel, L1, L2 – magnetic lenses; T1…T5 – drift spaces; VR – vacuum room (sliding Faraday cage parked inside); M1, M2 – beam profile monitors; HVP – high-voltage probe.

3. BEAM DIAGNOSIS AND DYNAMICS

Due to their relative low energy, electrons are non-relativistic. Medium beam currents imply consideration of space charge forces. The theory developed by Kapchinskii and Vladimirskii in [13] and Ciuti in [14] is applicable to EB channels with axial symmetry, controlled by magnetic lenses, such as DIADYN. Accordingly, the root-mean-square (rms) value $R$ of the beam radius can be evaluated by the following equation:
\[
\frac{d^2 R}{dz^2} + \eta \frac{B^2}{8U} R - \frac{1}{4\pi \varepsilon_0} \left(\frac{2\eta}{U}\right)^{-1/2} \frac{I}{U^{3/2}} R^{-1} - \varepsilon^2 R^{-3} = 0,
\]

(1)

where \(I\) is the beam current intensity, \(U\) the beam acceleration potential, \(\varepsilon\) is the rms beam emittance, and \(B\) the axial magnetic flux density. The constants in (1) are the electron charge-to-mass ratio \(\eta\) and the electric constant \(\varepsilon_0\).

As indicated by recent results obtained with low energy medium current electron beams [9], in order to have an adequate control of the experiments one needs: 1 a good knowledge of the beam parameters; 2 a well designed electron beam channel, and 3 a correct understanding of the beam dynamics.

In using DIADYN we have concentrated so far on the conditions (1) and (3). We developed a numerical code for non-destructive beam diagnosis, and investigated several beam regimes, by numerical calculations and experimental validation. Results presented in [10] emphasised the importance of condition (2) and made clear that DIADYN needs hardware adjustments of the EB channel. These adjustments, already implemented, prevent the current loss between the electron source and the beam profile monitors. Moreover, as well as observing the paraxial approximation implied by Eq. (1).

A proper experimental determination of the beam radius at two locations, where the two monitors M1 and M2 are placed, as function of the first magnetic lens input power, is a key element in our numerical method. For each lens power the beam profile at the two monitors is read on the oscilloscope. The beam crossing duration and the known scanning velocity of the profile monitor provide the beam radius. A dedicated fitting program uses experimental data and Eq. (1) to find the beam parameters at the source exit. Once the beam parameters are determined, we can investigate the beam dynamics. With two magnetic lenses, as in the DIADYN
set-up, it is possible to vary both the position and the radius of the image crossover. Beam evolution along the channel is shown in Fig. 2.

4. BEAM TRANSMISSION

Experimental and numerical data were not always in good agreement. We presumed that in certain operating regimes part of the beam current was lost along the EB channel. To check this possibility, we compared the current extracted from the electron source with the current transmitted to the monitoring unit.

![Oscillograms of the beam current: left-section T2 upstream from L2; right-section T4 downstream from M1.](image)

The beam current was measured with a Faraday cage, able to slide along the EB channel axis, and parked inside the vacuum chamber during nominal operation.

Oscillograms of the beam current in the section T2, upstream from the second magnetic lens L2, and in the section T4, downstream from the first beam profile monitor M1 are shown in Fig. 3. The beam current, measured through a 10Ω resistor, diminishes by approximately 25%, from 0.21 A at T2, to 0.15 A at T4. The acceleration potential of 31.7 kV can be observed on the first channel oscillogram.

The beam profiles shown in Fig. 4 pinpoint the location of the current loss between the two monitors at a centring diaphragm for the Faraday cage. The beam profile at the first monitor is shown on channel one while the beam profile at the second monitor is shown on channel two, of the oscillograms. Several input lens powers (of L1) that correspond to different applied voltages were investigated. The example in Fig. 4 corresponds to a lens voltage UL1 = 2.3 V.
The difference between left and right sides of Figure 4 resides in the presence of a centring diaphragm inserted between M1 and M2. On the left side oscillograms, the diaphragm is present and the beam current loss is visible in the decrease of the pulse height. On the right side oscillograms, without diaphragm, the pulses at M1 and M2 have about the same height.

5. MAGNETIC LENS REDISIGN AND TESTING

The magnetic lens L2 was redesigned to have better electron-optical properties by: 1 enlarging the spool, which enables a larger paraxial region, and 2 enhancing the field confinement, through lateral flanges and soft iron polar pieces.

A key tool used in the design phase was the numerical program FER1CH [15], based on a finite element code, which allows the calculation of the magnetic field for axially symmetric lenses. FER1CH requires information on the geometry of the beam, magnetic properties of the materials, winding area and ampere-turns. Four possible design solutions are shown in Fig. 5. The sketch based on the geometry V2a and lens photo after welding the spool, and adding the polar pieces, facing, and boring are shown in Fig. 6.

Experimental arrangement used to measure the magnetic field along the second magnetic lens axis is shown in Fig. 7.

The agreement between the measured, and simulated magnetic flux density values of is found very good, except for small differences due mainly to errors in positioning the Hall probe.
Fig. 5 – Four design versions of the magnetic lens. Version V2a: 1 – soft iron flanges, 2 – coil winding, 3 – stainless steel spool, 4 – soft iron polar pieces.

Fig. 6 – Magnetic lens based on version V2a (left); lens after welding the spool (right).

Fig. 7 – Magnetic lens measurement set-up (left); L2 lens axial magnetic flux density $B_z$ versus axial distance (right). The measured values are marked by solid circles, calculated values by solid squares.

6. MODIFIED ELECTRON BEAM CHANNEL

The electron beam channel has been improved by the new design of the second magnetic lens.
Regarding the beam monitoring unit, the operation of the Faraday cage has been optimised by changing the measuring position and the movement system. The key changes in the design of the second magnetic lens are: a larger spool internal diameter; edge flanges from soft iron instead of stainless steel; polar pieces inside the spool, in order to increase the confinement of the magnetic field. The Faraday cage is mounted downstream second magnetic lens and moves perpendicular to the beam axis. The centring diaphragm between the two monitoring units has been removed, to avoid reducing effective width of the EB channel.

7. SUMMARY AND PROSPECTS

Analysis of the previously reported experimental results [9, 10] led to the conclusion that DIADYN low energy medium current electron beam installation needs upgrading work in order to improve measurement accuracy. We focused on the hardware changes needed by the EB channel and the beam-monitoring unit. The main part of the EB channel subject to modifications was the second magnetic lens. The new design of this lens was successfully evaluated and checked by computer calculations. Magnetic flux density measurements were in good agreement with predicted values.

With its improved EB channel and optimised beam monitoring unit, DIADYN is better suited for both theoretical and experimental investigations on low energy EBs diagnosis and dynamics. In addition, DIADYN proved to be a good educational tool for in depth understanding of EB physical and engineering aspects.
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