Prototype of multi-filament electron curtain accelerator (postprint)

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Abstract

In this paper, we present a prototype electron curtain accelerator featuring a high voltage of 200 kV, an average beam current of approximately 20 mA, and a beam width of about 600 mm. Various aspects of the physical and mechanical design of this facility are thoroughly discussed, in conjunction with 3D software modeling and simulation. Furthermore, efforts have been made to modulate the cathode structure to effectively improve electron beam uniformity.

Full Text

Preamble

Prototype of Multi-Filament Electron Curtain Accelerator

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Abstract
This paper presents a prototype electron curtain accelerator capable of producing a 200 kV electron beam with an average current of approximately 20 mA and a beam width of about 600 mm. Several physical and mechanical design aspects of this facility are discussed in detail, incorporating 3D software modeling and simulation. Efforts to modulate the cathode structure have been undertaken to effectively improve electron beam uniformity.

Key words
Vertical electron curtain accelerator, Cathode structure, High voltage

Introduction

Electron curtain accelerators play an important role in numerous industries, including printing, curing, coating, and packaging, where they enhance product quality while reducing volatile organic compounds to protect the global environment [1 3]. Drawing upon extensive experience from previous products at Nuctech Co., Ltd., our division initiated development of an electron curtain accelerator in early 2012, in cooperation with the Beijing Institute of Graphic Communication. The target specifications were a 200 kV electron beam with approximately 20 mA beam current and 600 mm beam width. This paper aims to provide insight into the design considerations throughout the R&D process and report the latest advancements of our prototype.

2 Physical Design

Electron curtain accelerators are low-energy electron accelerators primarily composed of a high voltage power supply, vacuum system, electron source and accelerating system, shielding system, nitrogen inerting system, and process control system, as shown in Fig. 1 [Figure 1: see original paper].

2.1 High Voltage Design

We have developed a DC high voltage power supply in collaboration with a leading X-ray machine manufacturer to meet our specific requirements. This supply can generate up to 200 kV and 20 mA with less than 10% voltage ripple, as shown in Fig. 2 [Figure 2: see original paper]. The high voltage cable from the transformer passes through an oil chamber to reach cylindrical conductors connected to the filaments, which are mounted on a round glass plate that separates the vacuum chamber from the oil chamber. The output high voltage cable inserted into the high voltage feed on the oil chamber contains three conductors: one for the high voltage base, another for the filament, and the last for grid bias voltage. A cone-shaped high voltage connector with conductors at the top surrounded by insulating epoxy has been adopted to minimize potential electrical breakdown. Throughout the system, whether in vacuum or oil, the high voltage cable is shielded by tubular stainless steel conductors serving as grading rings.

The main body of the L-shaped vacuum and oil chamber is constructed from stainless steel, with a lead shell covering the vacuum chamber (Fig. 3 [Figure 3: see original paper]). A vertical window membrane is positioned opposite the oil chamber to avoid electric field distortion that would occur near the vacuum pump pipeline junction at the bottom of the vacuum chamber. To facilitate installation and replacement of components, the chambers feature four openings in total—three on the vacuum chamber and one on the oil chamber. O-ring Viton seals with low outgassing rates are used for vacuum sealing. A ceramic plate seals the oil chamber while isolating the high voltage from the chamber wall at ground potential. Designers also utilize four ceramic columns to support the filament housing at high voltage. Inspection windows are strategically positioned to observe potential high voltage breakdown phenomena in both vacuum and oil chambers.

2.2 Vacuum Design

Three primary challenges must be addressed in vacuum design: vacuum sealing, vacuum sparking, and vacuum material selection. The first concern follows national vacuum design standards, which are comprehensively documented in most vacuum handbooks. The second issue relates to critical static electric field distribution around high voltage conductors and conductor surface roughness in both vacuum and oil chambers, which can be addressed through electromagnetic simulation and manufacturing techniques. Last but not least, material selection for vacuum components is critical, as outgassing rates, electrical breakdown characteristics, and high voltage insulation performance are all intimately related to material properties under vacuum conditions.

Materials used in the vacuum chamber include tungsten alloy for filaments, copper for filament conductors, stainless steel for filament housing and supports, glass disks and ceramic cylinders for insulation, and molybdenum for grid poles.

2.3 Filament Design

Multi-filament cathodes with grid structures within the filament housing were carefully designed to generate uniform beam distribution outside the window membrane [4]. Compared to single longitudinal cathodes, multi-filament configurations offer superior performance in beam width expansion and uniformity. To minimize distribution modifications caused by thermal expansion of heated filaments, a vertical fixation scheme was adopted, as shown in Fig. 4 [Figure 4: see original paper], wherein the electron beam is accelerated horizontally by the high voltage.

When electrons emit from the filaments, they first pass through an extracting grid that controls beam current. The electrons then traverse a secondary grid that not only uniformizes their distribution at the foil window but also shields the filament from high voltage sparks in the high acceleration region, as illustrated in Fig. 5 [Figure 5: see original paper].

Satisfactory beam dynamics were achieved through simulation using the CST Studio Suite package [5], as shown in Fig. 6 [Figure 6: see original paper]. The filament housing contains eight 10 cm long cathodes arranged in parallel with 7.5 cm spacing. The exterior diameter of the filament housing is 18 cm, while the inner diameter of the vacuum chamber is 50 cm. The two grids share the same potential, approximately +100 V relative to the cathodes, while the repeller is biased at -2 V relative to the grids. In practice, a motor in the control panel box enables remote tuning of the grid voltage.

Approximately 60% of the accelerated electron beam successfully penetrates the titanium foil. The total electron beam current is about 21 mA when the filament structure is biased at -200 kV relative to earth. Under these conditions, the maximum electric field in vacuum is approximately 7.5 MV/m near the rounded corner of the second grid, which is below the critical electric field of 9 MV/m in vacuum.

2.4 Ti Foil Window Design

When electrons are accelerated by the high electric field between the filament housing and exit window, they must penetrate the window membrane to irradiate products within a nitrogen atmosphere. Two primary design considerations are electron beam transparency and heat dissipation on the foil. Since thinner titanium foil results in lower power deposition, a 10 m titanium foil is employed, absorbing approximately 300 Watts of heat. A copper rectangular plate with a series of perpendicular slots supports the foil in vacuum, fixed by pressure to the edges of the support plate covering the slots and vacuum exit window.

A good method to concentrate more electrons in the central region and reduce beam loss on the vacuum wall is to shape the upper and lower boundary portions of the filament housing to create a converging electric field, as shown in Fig. 5 [Figure 5: see original paper].

3 Simulation and Prototype Status

Through careful calibration of the filament structure, the prototype electron curtain accelerator system has completed installation and is currently undergoing high voltage conditioning. Initial issues with ceramic and glass plate high voltage breakdown have been resolved through manufacturing process modifications.

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