DEVELOPMENT AND TESTING OF POWERFUL HIGH-VOLTAGE ELECTRON ACCELERATOR FOR ENERGY-INTENSIVE INDUSTRIES

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Abstract

The report describes the results of the development and testing of the Electron-23 high-voltage high-power accelerator rated for an accelerating voltage of 1 MV and beam power up to 500 kW at the "NIIEFA" testing facilities.

The accelerator is intended for industrial processing of flue gases from thermal power stations with the aim to reduce concentrations of nitrogen and sulfur oxides. It may also be used for other energy-consuming processes, such as treatment of wastewaters for their decontamination or processing of natural gases for their conversion into engine fuel. [1]

BRIEF DESCRIPTION OF THE ACCELERATOR

General view of the accelerator with the beam forming and extraction device is schematically shown in Fig.1.

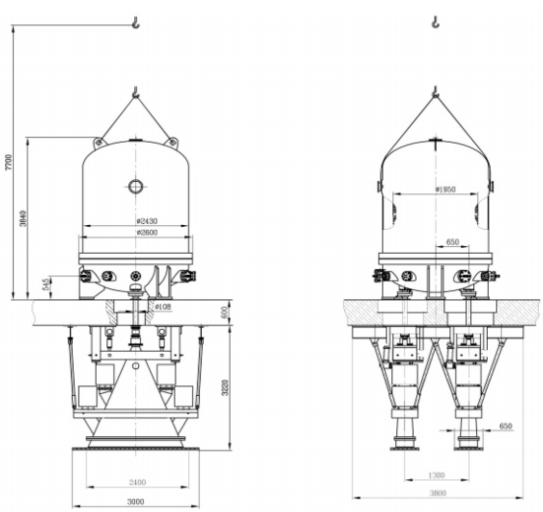

Figure1: General view and main parameters of the «Electron-23» accelerator.

The high-voltage (HV) generator, electron source and accelerating tube (AT) are placed inside a metal vessel filled with a pressurized insulating gas. A three-phase transformer-rectifier with a closed magnetic core and parallel feeding of cascades is used as a HV generator of the accelerator «Electron–23». Such a high-voltage source has a wall-plug-efficiency higher than 90% and practically no restrictions on power. The magnetic core of the HV generator is a construction symmetrical in space and consisting of 3 vertical rods and 2 horizontal annular yokes closing the magnetic flux. Three primary windings are located on the core rods, encircled with electrostatic screens and are star-connected with a power supply. Three secondary windings consist of separate coils located coaxially with primary windings. Each three coils of the secondary winding are located at one level on different magnetic core rods. They are star-connected and together with 6 diodes form a 3-phase bridge rectifying cascade [2, 3]. In the DC voltage, all twenty seven cascades are connected in series.

The majority of the accelerator components facing the HV gap is made of insulating materials with a high-resistive conducting coating. As a rule, these elements are made of stainless steel to prevent short-circuiting around the magnetic core of the HV generator; for this reason their construction is technologically complicated. The use of insulating materials with a high-resistive coating allows us to simplify the construction and considerably reduce the manufacturing cost of these elements.

A diode-type electron source with a lanthanum hexaboride emitter of 13 mm diameter is used in the accelerator. Emitter holders are made of anisotropic pyrolytic graphite that prevents chemical interaction of the emitter with emitter-holders and provides reduction of the filament power of the electron source down to 100 W [4]. The 1st electrode of the AT serves as the electron source anode. The source filament is fed from a special winding located on the magnetic core of the HV generator. The electron beam current is controlled and stabilized from the low voltage side.

The AT consists of alternating ceramic insulators and metal electrodes forming a vacuum-tight connection. A resistive voltage divider is placed outside the tube on its electrodes. A distinctive feature of the accelerator' design is location of the AT in parallel with rods of the HV generator magnetic core inside a common vessel. Such an engineering solution allows overall dimensions to be decreased, but, requires shielding of the AT against stray magnetic fields produced by the HV generator. To achieve this, electrodes of the AT are made of permalloy, and a distance between them is rather small (12, 5 mm), resulting in the reduction of the stray magnetic field on the AT axis approximately by a factor of 100 [5].

General view of the AT installed in the accelerator is shown in Fig. 2. The accelerator design also enables installation of one more AT in the same high-pressure vessel. Tests of the machine were carried out with a single tube.

The irradiation field forming system consists of an electromagnetic lens, beam scanning device and device for the beam extraction to the atmosphere. The beam scanning device comprises longitudinal and transverse

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scanning electromagnets for the beam fast transport to any of 4 extraction windows. The magnetic core of the beam scanning device is made of ferrite, which excludes its corrosion in aggressive ozone environment.

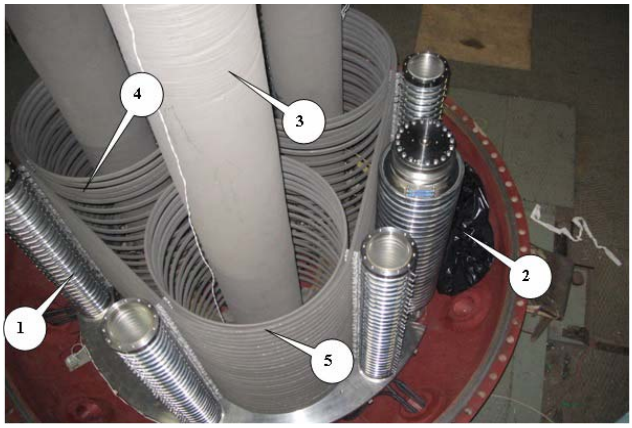


Figure 2: Support columns (1), AT with electromagnetic screens (2), magnetic cores of the HV rectifier primary winding phases (3), gradient rings (4) and electromagnetic screens (5).

The device for the beam extraction to the atmosphere is made separate from the accelerator vacuum chamber (see Fig. 3) and is electrically isolated from it. Electric signal from this device is fed to a unit visualizing the beam position in extraction windows. Four water-cooled extraction windows with a supporting grid are installed at the flange and are closed with metal foil.

Figure 3: Beam extraction device of the «Electron-23» accelerator at a test facility in NIIEFA.

The accelerator is supplied from the 3×380 V, 50 Hz mains and is connected directly to it without any voltage regulators. When the accelerator is switched on, firstly a 10 kVA autotransformer is used to increase high voltage up to a nominal value of 1100 kV. After that, the accelerator is re-switched to be fed directly from a power transformer; and the autotransformer is off.

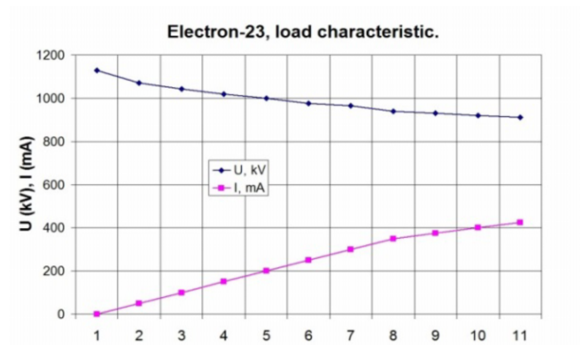
The accelerator is equipped with an industrial computer-based automatic control system. Design technical parameters of the «Electron-23» accelerator are given in Table1.

Table1: Parameters of the «Electron-23» accelerator

Parameter	Value
Range of accelerating voltage control, MV	0,8-1,0
Accelerating voltage instability (excluding 50 Hz ripples), %, not more than	±5
Electron beam current, mA	0-500
Electron beam current instability, %, not more than	±2
Accelerator rated power, kW	500
Electron beam scanning length, cm	240
Non-uniformity of electron beam current linear density 10 cm from extraction foil, %, not more than	±10
Electron beam scanning frequency, Hz	≥300
Electron beam wall-plug efficiency at 500 kW rated power, %	≥90
Annual operating time, %	≥90

ADJUSTMENT AND TESTING RESULTS

As already mentioned above, in the process of the accelerator testing it was supplied from the power transformer without any voltage regulator. The open-circuit voltage in this case is 1100 kV; the leakage current is not more than 3 μA. When operating under load, (HV) depends on the load current; the load characteristic is shown in Fig.4. A max attained load current is 420 mA and it is limited by the beam extraction device; at this current the voltage drop is 210 kV, i.e. 19 % of its initial level.



Note: without energy regulation

Figure 4: Load characteristics of the accelerator.

The accelerator operation on an industrial facility without voltage regulation is possible only if it operates in one mode, for example, when processing flue gases of thermal power stations. Advantages of such a solution are lower cost and higher efficiency.

However, in most cases, the use of a voltage regulator is necessary; note that they are commercially produced for a power of up to 1,8 MW.

In the process of the accelerator testing, HV rectifiers of SDL-130 type failed from time to time because of occasional breakdowns of the HV structure. After analyzing the mechanism of the rectifiers' failures, a

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protection method developed for accelerators of the ELV series (INP, named after Budker) was applied [6]. According to this method, protection chokes were calculated, manufactured and installed in 14 cascades nearest to the HV part of the rectifier. After this no more failures of HV rectifiers were observed.

The beam current instability for one hour of operation does not exceed 1% of its preset value. No failures in the operation of the electron source and its power supply system were observed.

The AT in the idle regime provides safe operation without voltage breakdowns of up to 1200 kV level. As the AT in this accelerator is located in stray magnetic fields of the HV generator, the beam passage through the tube and in the vicinity of it was of special interest, particularly with the load increasing. In the process of the accelerator testing with the 420 mA beam current, the influence of the magnetic stray fields on the beam was not observed. No beam current presence was also registered on the AT electrodes.

In the course of the adjustment works at beam currents of 5-50 мA, it turned out that the beam trajectories looked like some curved lines instead of straight ones, and their shapes differed in different extraction windows. This fact did not allow the extraction window area to be properly used and hindered increasing of the electron beam current. Under the tests, 3 factors responsible for the scanned beam position distortion were found:

- when the beam entered the scanning device not in the center, the beam trace in extraction windows was in the form of an arc. This distortion was corrected by placing correcting electromagnets on the electron guide.
- the stray magnetic field produced by ion pumps also influences the electron beam trajectory. To reduce this influence, magnetic screens were mounted around the ion pumps.
- the influence of the variable magnetic field produced by power current-carrying cables on the beam position was observed at load currents in the HV generator primary windings higher than 500 A. To lessen this influence, each phase cables were laid in pairs. That allowed the beam distortion to be reduced by several times.

As a result of the works performed, the width of the scanned beam in extraction windows was enlarged to 40 mm, which allowed the beam current to be increased up to 420 mA.

Various types of foils were tested in the beam extraction device. Initially we used an Al foil of the AMD type of 80 μ thickness and Ti foil of the VT-1 type of 50 μ thickness. With the AMD foil, we attained the electron beam current close to the design value. However, because of low corrosion resistance and mechanical strength of Al, such a current can be obtained only for a short period of time. With the Ti foil, a beam current of up to 250 mA was obtained in the long-term mode at an accelerating voltage of 960–1100 kV.

Under real conditions the accelerator should operate for a long time without foil replacement. Thus, to provide the 500 мA beam current, one more AT with an electron source should be placed inside the high-pressure vessel, and the accelerator should also be equipped with one more system for the beam extraction to the using Ti foil.

CONCLUSIONS

Based on the results of adjustment and testing of the «Electron-23» HV accelerator, the following conclusions can be drawn:

1. The AT can be located in parallel with the rods of the 3-phase transformer-rectifier magnetic core inside a common vessel. When shielding the AT with electrodes made of permalloy, the influence of magnetic stray fields on the beam passage through the AT was not observed at beam currents of up to 420 мA.
2. The usage of components made of insulating materials with a high-resistive coating in the HV structure provides its necessary electric strength, allows us to simplify the accelerator design and reduce the cost of its manufacturing. Power of 250 kW was attained on the accelerator with a single beam extraction device.
3. The 500 kW power can be provided by installing one more AT inside the same high-pressure vessel and by inserting one more beam extraction device. It was shown that these measures will allow safe operation of the accelerator in energy-intensive industrial radiation processing.

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