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THE CASCADE TRANSFORMER FOR THE HIGH-VOLTAGE ELECTRON COOLING SYSTEM FOR THE NICA COLLIDER

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Abstract

The 2.5 MeV electron cooling system for the NICA collider (JINR, Dubna) will use cascade transformers for distributing the power among the sections of the high-voltage column and for transferring power to the high-voltage terminal. The design of the cascade transformer and the measurements of its prototype are described.

INTRODUCTION

The NICA collider is designed to operate ion beams with energies up to 4.5 GeV/u [1]. In order to increase the ions accumulation efficiency and ions lifetime in the collider the electron cooling system must provide 2.5 MeV electron beams [2]. The designed electron cooling system uses the guiding magnetic field along the entire transport channel of the electron beam, including the high-voltage column. Magnetic coils and the power supply for electron collector constitute the major power consumption of the high-voltage column.

There are several common ways to transfer the electrical power to high-voltage regions, described in [3]. Methods involving the transmission of mechanical energy are not suitable for the new electron cooler, as some of them require larger space, entail the power consumption overhead or tend to be unstable. Instead, the electron cooling system will use a cascade transformed with high coupling coefficient between cascades, which transfers power from section to section through electrically isolated windings (Fig. 1).

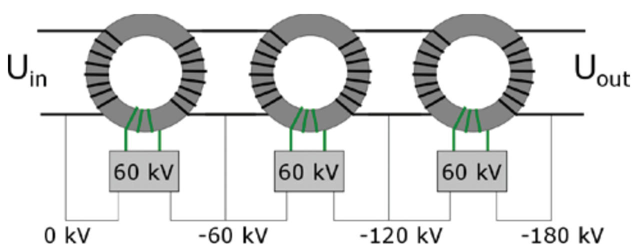

Figure 1: The schematic diagram of a power transferring cascade transformer.

A single high-voltage column includes two cascade transformers with 42 sections each: for transferring power to the high-voltage terminal and for distributing the power among the column sections.

POWER CONSUMPTION OF THE HIGH-VOLTAGE COLUMN

Each section of the high-voltage column (Fig. 2) has two coils for creating 500 G longitudinal magnetic field for focusing the electrons. The power consumption of a single coil is about 100 W. The electronics in a section together with high-voltage power supplies takes additional 220 W. Another consumer is the high-voltage terminal. It includes a 10 kW power supply for the collector rectifier and a 5 kW solenoid for focusing a low energy electron beam. The design parameters of the high-voltage column related to power consumption are presented in Table 1.

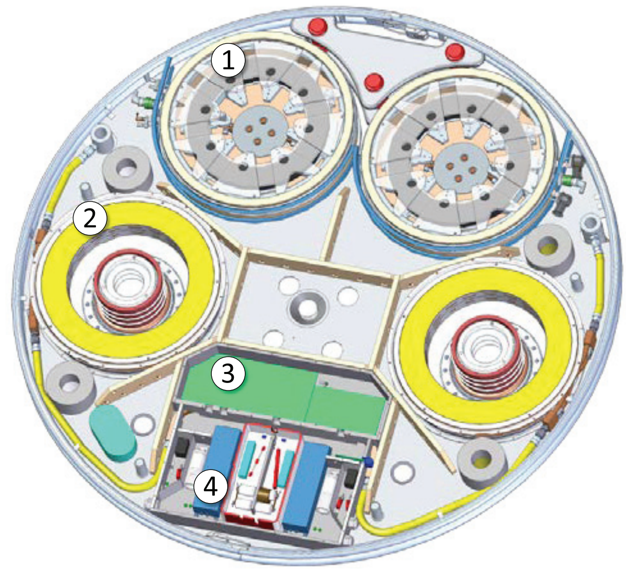

Figure 2: Section of the high-voltage column: (1) a single ring of the cascade transformer, (2) a magnetic coil for creating a guiding magnetic field in the accelerating tube, (3) control electronics, (4) high-voltage power supplies.

Table 1: Power Consumption of the High-Voltage Column

Consumer	Power
Magnetic coils of a section	200 W
HV power supply per a section	120 W
Control electronics per a section	100 W
Collector rectifier	10 kW
Control electronics of the HV terminal	700 W
Magnetic coils in the HV terminal	5 kW
Sections of the HV column	17.6 kW
HV terminal	15.7 kW

DESIGN OF THE CASCADE TRANSFORMER

The cascade transformer consist of 42 sections stacked one onto another with 6.4 cm period. To prevent overheating of the transformer during its operation, it is placed inside an oil-cooled tank (Fig. 3). As voltage between adjacent sections of the transformer reaches 60

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kV, the tank is a set of alternating shielding metal and insulating ceramic rings.

Each section includes a ring-shaped magnetic core, power transferring windings and a set of capacitors for compensating the leakage inductance. One set of windings is used to receive electrical power from the previous section of the cascade transformer, and another is for transferring power to the next section. As voltage between these two set of windings is 60 kV, it is necessary to add an insulating gap between these set of windings as well as between windings and the magnetic core (Fig. 4). These gaps leads to the presence of leakage inductance that can be compensated by adding capacitors to the power transferring windings.

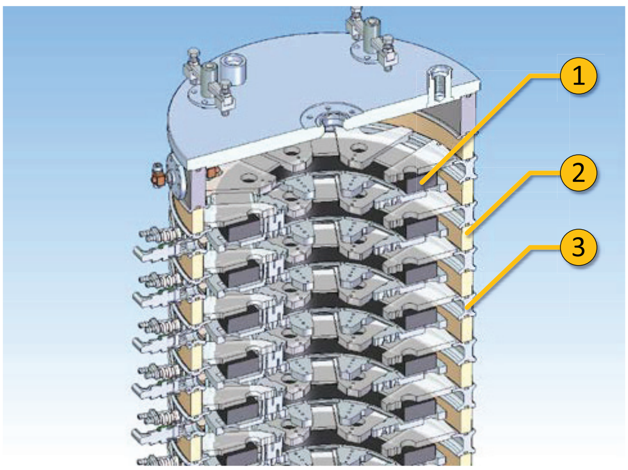

Figure 3: The design of the cascade transformer (for simplicity, windings and other electronic components are not shown): (1) a section of the cascade transformer, (2) ceramic rings for insulating adjacent sections, (3) duralumin shields.

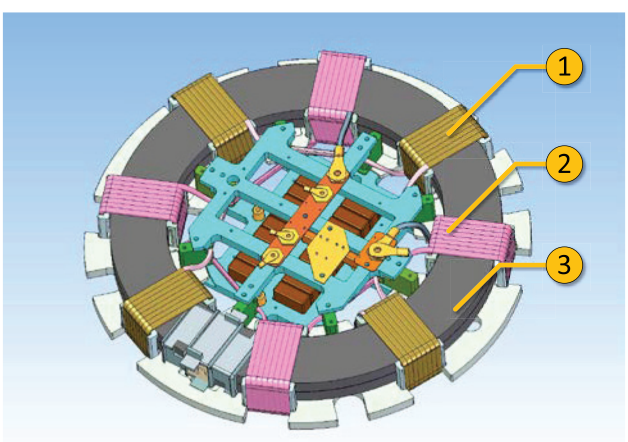

Figure 4: The design of the section of the cascade transformer: (1) windings for receiving electrical power from the previous section of the transformer, (2) windings for transferring power to the next section, (3) a magnetic core of the transformer section.

The similar cascade transformer design were used in the COSY electron cooler [4]. The main difference is that the windings are split into more groups and connected in series (the transformer section of the COSY cooler has two groups of winding connected in parallel). The design parameters of the new cascade section are listed in Table. 2.

Table 2: Parameters of the Cascade Transformer Section

Parameter	Value
Magnetic core shape	Ring
Magnetic core inner radius	10 cm
Magnetic core outer radius	14 cm
Magnetic core thickness	2 cm
Magnetic core material	5BDCP
Number of windings	2
Winding wire type	Litz wire AWG38
Number of winding turns	7×4
Height of a wind turn	3 cm
Width of a winding turn	6 cm
Winding length	6.3 m
Wire electrical resistivity	$17.24\cdot10^{-6}$ Ohm·mm
Wire section	5.7 mm^2

MEASUREMENTS OF THE PROTOTYPE

For verifying the design parameters of the cascade transformer, a three-section prototype was tested (Fig. 5). The parameters of interest are the remagnetization losses, which describe the amount of heat produced by the transformer in the idle regime, the section efficient pass-through resistance, and the leakage inductance of the transformer sections affecting the transformer efficiency.

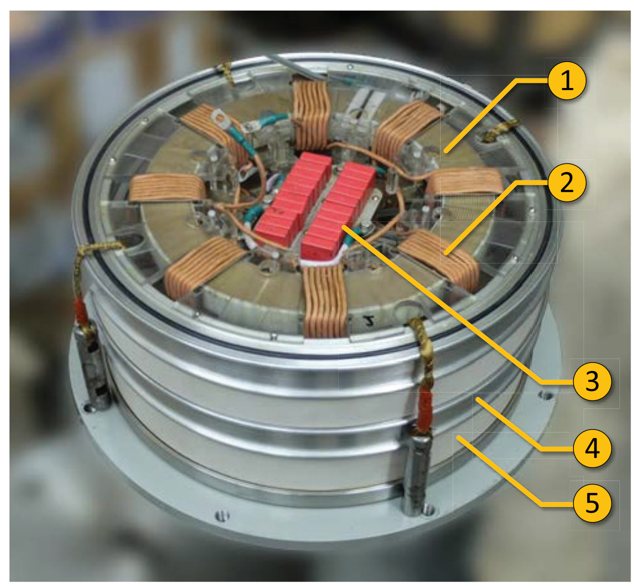

Figure 5: A three-sections prototype of the cascade transformer: (1) a magnetic core, (2) windings, (3) capacitors for compensating the leakage inductance, (4) duralumin shielding rings for decreasing the leakage inductance, (5) ceramic rings for insulating adjacent sections.

The cascade transformer can be represented using its equivalent circuit (Fig. 6). The working frequency of the transformer is chosen so that the capacitors connected to

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the winding of the transformer section compensate the reactive impedance caused by the presence of leakage inductance. The capacitors placed after each section in order to lower the voltage drop from one section to another.

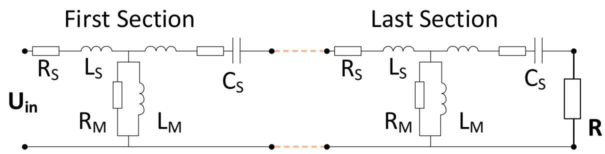

Figure 6: The equivalent circuit of the cascade transformer: (L_M) magnetization inductance, (R_M) load representing the remagnetization losses of a magnetic core, (R_S) losses in the windings, (L_S) leakage inductance, (C_S) capacity for compensating the leakage inductance, (U_{in}) input signal, (R) active load of the transformer.

As the transformer efficiency varies with the working frequency, the frequency response measurements can be used to retrieve the parameters of the transformer. We used frequency response of the transformer pass-through impedance by feeding the transformer with harmonic signal and measuring the output signal on the active load of the transformer. Given the active load and the shape of the input and output signals, one can calculate the impedance of the cascade transformer. At some frequency, the leakage inductance is compensated by the capacitors, and the transformer impedance reaches its minimum corresponding to the active losses in windings. To get a more accurate estimation of the transformer parameters we can fit the measure frequency response function with the curve, calculated with assumption that all transformer sections have similar parameters (Fig. 7). The measured leakage inductance of a single winding is approximately 25 µH. The magnetization inductance was measured the similar way, but with capacitors connected in parallel to the windings and was about 40 mH.

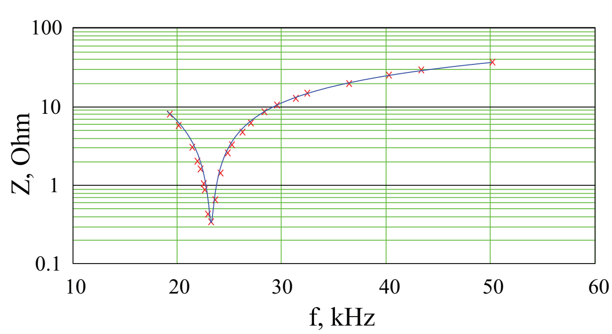

Figure 7: The frequency response of the prototype pass-through impedance (three sections): the red points are measured values of the pass-through impedance and the blue curve is the fit.

Another way to measure losses, which occur during the transformer operation, is to measure the amount of heat that transformer produces. Such experiment was conducted by measuring the heating of the oil, which was used for cooling the transformer loaded to 8 Ohm resistor (Fig. 8). The input voltage is 500 V (rms), input current is 44 A. Given the oil flow 0.1 l/s and its temperature grows about 5.5 degrees, the estimated amount of heat is 240 W per section. At idle, the heating, measured the same way, is about 40 W. So, the pass-through impedance of the transformer can be calculated as (240W - 40W) / $(44A)^2$ $\approx$ 0.1 Ohm. Electrical parameters of the transformer sections are listed in Table 3.

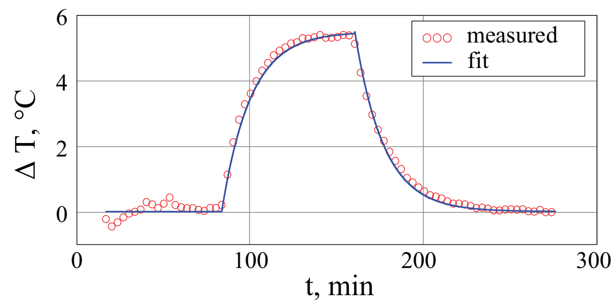

Figure 8: The heating curve of the oil used to cool the sections of the transformer. The current in the transformer windings is 44 A. The input voltage is 500 V. Oil flow is 0.1 l/s.

Table 3: Electrical characteristics of a single section of the cascade transformer.

Parameter	Value
Working frequency	23.2 kHz
Pass-through active impedance	0.11 Ohm
Magnetization inductance	40 mH
Leakage inductance	50 µH
Remagnetization losses	2.5 kOhm
Capacity of compensating conductors	0.94 µF

CONCLUSION

The new cascade transformer with distributed power transferring windings is designed for the high-voltage electron cooling system of the NICA collider. Thermal and electrical tests conducted on the 3-section transformer prototype shows that a single 42 sections cascade transformer is capable of providing more than 18 kW or 16 kW for distributing power along the sections of the high-voltage column or transferring the power to the high-voltage terminal correspondingly.

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