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PROJECT ANALYSIS OF A TWO-CHANNEL TECHNOLOGICAL INDUCTION ACCELERATOR FOR COMMERCIAL APPLICATION

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The results of the project analysis of an electron two-channel induction accelerator are presented in the paper. Determination technological parameters of the accelerator blocks is carried out. Apart from that, general characteristics of the installation proposed for practical realization are estimated. It is shown, in particular, that a commercial system of high-efficiency and relatively compact can be constructed for purification of wastewater and natural water on the basis of the proposed accelerator.

Introduction

As it is known, charged particle accelerators have found more and more practical application in the modern civil industry. In this connection the systems for defectoscopy in machine building (especially in heavy industry) can be mentioned as well as the electron-beam equipment for decontamination of wastewater, sterilization of medical and biological preparations, and plastic mass polymerization is also well-known.

But, possibilities of wide implementation of the electron-beam technologies into civil industry till today are limited due to the shortage of commercially accepted technological accelerators. This can be explained by the fact that most of existing today accelerators have been developed historically in the framework of relevant nuclear programs. Therefore, they were designed for specific applications. As a result these accelerators do not meet completely some specific requirements of civil industry, including, for instance, pharmaceutical or food industry. On the other hand, electron-beam technological systems proved their high commercial efficiency. This means that today a topical problem is elaboration of purely civil design of accelerators. The main purpose of the paper is to demonstrate such a possibility. The project of two-channel linear induction accelerator (TLINAC) is chosen here as a convenient example of this.

Two-channel induction electron accelerator

Two-channel linear induction accelerator of electron beam consists of a set of functional blocks including the following:

– the injector of electron beam;
– the pulsed power driving system;
– the acceleration system;
– the system of control and protection;
– the auxiliary systems (vacuum system, cooling system etc).

Each block, in turn, contains several sub-blocks with a corresponding set of elements. The choice of a real design scheme of each block is accomplished on the basis of relevant numerical analysis and computer simulation of main working processes. These analysis and simulation involve:

– electrical engineering calculations;
– electrodynamic analysis;
– heat transfer calculation;
– mechanical calculation;
– simulation of control and protection of each block;
– analysis of compatibility with other blocks.

A system for control and measurement of working parameters of all the mentioned blocks is projected, too. The structure scheme of TLINAC considered is shown in fig. 1.

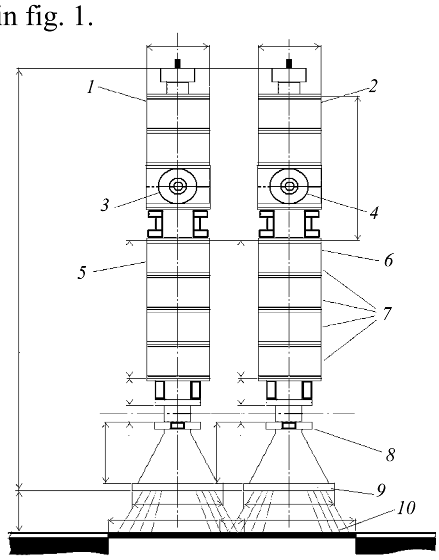

Fig. 1. Arrangement of the two-channel induction accelerator:
1, 2 – the injector of electron beam; *3, 4* – the high vacuum pump (magnetic discharge type); *5, 6* – the acceleration block; *7* – the sections of the acceleration block *5, 6; 8* – the quadruple magnetic system for the beam expansion; *9* – the output diaphragm; *10* – the zone of product processing

The project parameters of the elaborated accelerator are given in tab. 1.

Table 1

TLINAC general parameters

Parameter	Value
Beam current (peak), kA	1,0
Output beam energy, MeV	2,2
Total voltage of the injector (peak), kV	600
Beam diameter, mm	80
Axial electric field, kV/m	500
Pulse duration, ns	100
Inductor’s primary voltage, kV	25
Magnetic core diameters (int./ext.) mm	150 / 280
Inductors efficiency	0.44
Vacuum system productivity, liters/s	350
Total mass of magnetic cores per section for 100 kV, kg	57,4
Focusing magnetic field in solenoids, T	0.09
Magnetic induction swing, T	1.5
Rate of remagnetization, T/ms	15
The output beam power (average), kW	50
Diameter of the vacuum channels, mm	90
Number of acceleration sections	2x5
Number of cores per section	8
Material of the magnetic cores	MetGlas 2605 CO

A general view of the system considered is shown in fig. 2.

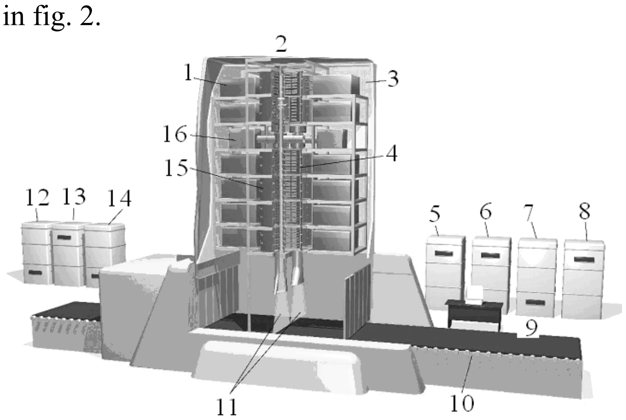

Fig. 2. General view of the system for water sterilization on the basis of TLINAC:
1 – pulse power supply blocks; *2* – injector; *3* – radiation protection; *4* – water cooling; *5* – charged unit; *6* – auxiliary electronics and current source block; *7* – power supply unit for focusing solenoid; *8* – relay block of control system; *9* – working place for the operator; *10* – conveyer; *11* – Electron beams; *12* – gas cooling; *13* – water cooling control unit; *14* – thyratrons power supply; *15* – pulse power supply block; *16* – vacuum station

According to our calculations, the main expenses for the production of TLINAC include the cost of magnetic materials for cores (fig. 3). That is why especial attention has been paid to the magnetic inductors and relative problems.

Calculation of the inductor system

Efficiency K of the inductor system depends essentially on the core design. With regard to this, it can be represented in the form in case of no disposition of core, and in the form in case of radial disposition of core [1]:

$$K(\Delta B) = \left(1 + \frac{\pi q}{i \cdot \Delta B}\left\{D + \frac{U}{h} \cdot \frac{t}{\varphi \Delta B}\right\}\right)^{-1};$$

$$K_1(\Delta B) = \left(1 + \frac{\pi q}{i \cdot \Delta B}\left\{D_1 + 2(1+k)\frac{U}{h}\frac{t}{\varphi \Delta B}\right\}\right),$$

where ΔB is a swing of the magnetic induction; q is the local heat losses per unit of core material volume; i is the beam current (output current of inductor system); D (or D_1) is an inner diameter of the magnetic core; U is the voltage of the inductor primary winding; h is the width of magnetic strip used for core manufacturing; U/h is the strength of longitudinal electric field; t is the pulse duration; φ is the fill coefficient in the cross-section of the core; k is the ratio of radial gap between cores δ to the difference of their diameters: $2b$, $k = \delta/2b < 1$.

Efficiency of the inductor system for different strength of longitudinal electric field is shown in fig. 4.

Power of the heat losses in the cores is stipulated by the remagnetization effect and it has a minimum on the remagnetization rate (fig. 5).

Total mass of cores $M(y)$ as the function of the rate of remagnetization $y = dB/dt$ can be determined as:

$M(y) = \rho\pi\ (E/y)\ (d + 10^{-3}\ (u/h\ y\varphi)),$

for the case of no radial disposition of cores, and

$M(y) = \rho\pi\ (E/y)\ [D_1 + 2\cdot 10^{-3}\ (1+k)\ (u/h\ y\varphi)],$

for the case of radial disposition of cores.

The value E is the output energy of electron beam measured in MeV.

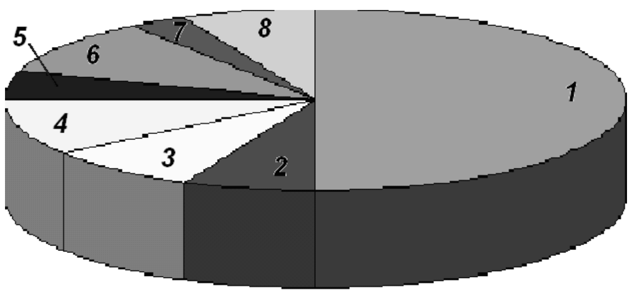

Fig. 3. Diagram of expenses for constructing the TLINAC:
1 is the cost of magnetic material MetGlas (50 %); *2* – the final manufacturing of inductors (7%); *3* – the focusing solenoids (8 %); *4* – the vacuum system (10%); *5* – the cooling system (5%); *6* – the pulsed power supply system (10%); *7* – the engineering (3%); *8* – the design work (7 %)

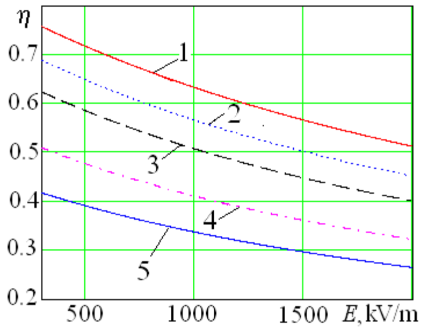

Fig. 4. Dependencies of the efficiency of the inductors system with radial disposition of cores on the longitudinal electrical strength for different swing of induction Δ B:
1 – Δ B = 1,0; *2* – Δ B =1,25; *3* – Δ B = 1,5; *4* – Δ B =2,0; *5* – Δ B = 2,5T

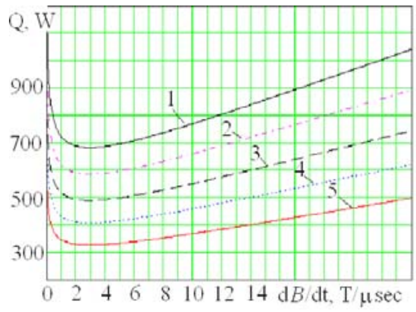

Fig. 5. The power of total losses Q in the magnetic cores for the design of doubled cores with radial disposition as the function of the rate of remagnetization dB/dt:
1 – Δ B = 2,1 T; *2* – Δ B = 1,8 T; *3* – Δ B = 1,5 T; *4* – Δ B = 1,2 T; *5* – Δ B = 1,0 T

Corresponding dependence for the case of no radial disposition is shown in fig. 6.

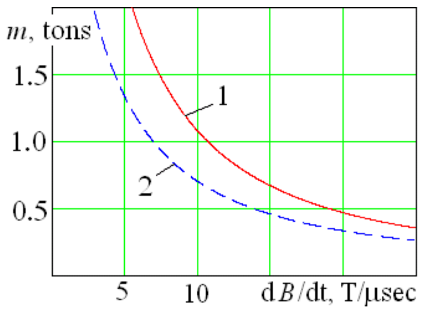

Fig. 6. The total mass of the cores material in inductor system for 1 MeV of the beam acceleration (with no radial disposition of cores) as a function of remagnetization rate y = dB/dt:
1 – corresponds to U_1 = 50kV; *2* – U_1 = 25kV

Determining the technical parameters

The main function of the injector is formation of initial acceleration beam, which is then accelerated within the acceleration unit. In the considered case this is the electron beam with energy 600 keV, peak current pulse up to 1…1,5 kA and the pulse duration 100…140 ns.

The injector structure includes the following design elements:
– the pulsed transformers for the output voltage 400 and 200 kV, respectively;
– the cathode unit;
– the system of focusing solenoids;
– the vacuum chamber with high vacuum pump;
– the sensor of pulsed current of beam.

The source of electrons is accomplished as the diode with flat cathode and anode and one more additional accelerating gap. Parameters of cathode are provided in tab. 2.

Table 2

Parameters of cathode

Parameter	Value
Cathode diameter, mm	100
Length of cathode interval, mm	35
Allowable micro-perveance of beam	3
Voltage pulse on the inductor, kV	25
Duration of voltage pulse, ns	140
Pulse repetition, Hz	100
Voltage on the cathode interval, kV	400
Length of the acceleration gape, mm	90
Maximal voltage on the injector, kV	600
Current of the cathode emission, кA	1,5
Output current of injector, кA	1
Maximal emittance of beam after passage of anode grid, cm·rad	0,25

The magnetic cores of the inductor have the radial disposition for two parts of the following geometry (taking into account the insulation thickness).

The large part of the core has inner diameter ID = 460 mm and outer diameter OD = 680 mm, the smaller part of core has ID/OD = 200 mm/420 mm. The cross section area of the core is the same for both parts: 32 x 110 mm.

The ferromagnetic material METGLASS 2605 SC (a 14 µm thick and 25 mm wide strip) is used for manufacturing the cores. The insulating film between layers is made of polycarbone strip that is 4 µm thick and 27 mm wide.

Power of the losses for remagnetization is not more than 305 W in the smaller part of core and 560 W in the larger part of the core, the pulse duration in the injector is taken 140 ns at frequency of repetition 100 Hz.

The total power of losses in the volume of all cores is 11,4 kW.

Heat transfer out of the cores is provided by forced circulation of the gaseous cooler SF_6 along the lateral sides of cores.

This gas is used simultaneously as an insulator within the injector induction block.

The sketch of injector block for TLINAC is shown in fig. 7.

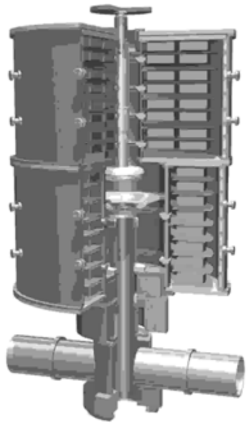

Fig. 7. The general view of the injector block

Dynamics of the electron beam

The saving of the beam parameter during its passage through accelerator needs a special analysis of beam dynamics with regard to its peculiarities of interaction with the accelerating and focusing fields. Direct current in the solenoids is considered as a means for keeping the beam parameters. The profile of the solenoid magnetic field in the acceleration channel is shown in fig. 8 (system parameters are provided in the tab. 3).

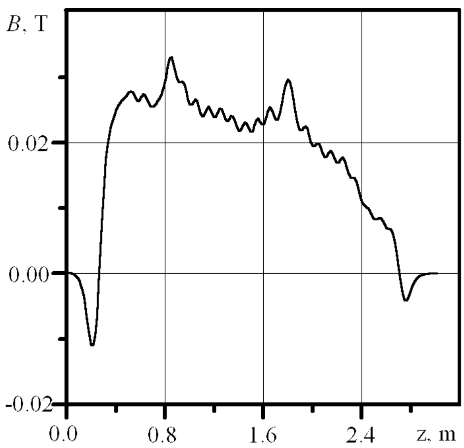

Fig. 8. Dependence of longitudinal component of magnetic field in the system

The computer simulation of high current beam dynamics has been realized using the algorithm described in work [2]. Parameters of the electron beam are given in tab. 3.

The results of computer simulation of the electron beam dynamics are shown in fig. 9. Parameters of the beam are presented in tab. 3. As can be seen, transversal dimensions of the accelerated beam (i.e., its diameter) are staying in the acceptable borders not exceeding the channel diameter. This provides a possibility to transit the electron through the acceleration channel without any essential beam losses.

Conclusion

The research and designer work accomplished allows to prove the main idea about possibilities of developing an especially commercial version of the linear induction accelerators.

This conclusion is important because traditionally such a class of accelerators has been regarded as an element of military systems (for instance, in the well-known "Star Wares" program).

Relevant project analysis shows that technologies, which have been developed in the framework of that program, can be used successfully for purely commercial purposes.

Apart from that the project analysis of the concept of multi-channel linear accelerators [3] is accomplished in the paper.

This is done in the example of TLINAC for the beam output energy 2,2 MeV, the pulsed beam current 1 kA, and the mean power 2x25 kW.

As the analysis showed, these parameters are promising for utilization of the TLINAC in a number of technological applications in civil industry and medicine, mainly as facility for sterilization and decontamination of different products [4; 5].

At the same time, the analysis accomplished showed that the concept of multi-channel arrangement of accelerators in itself looks very promising for further commercial development.

Table 3

Parameters of the electron beam

Parameter	Value
Beam current, kA	1,0
Initial energy of electron beam, keV	600
Output energy of electron beam, MeV	2,2
Impulse duration, ns	100
Initial beam diameter, cm	8,0

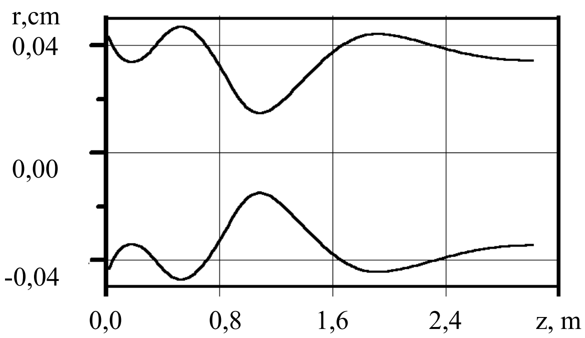

Fig. 9. The bending line of electron beam on the longitudinal coordinate along the full path of acceleration

Firstly, because this allows to solve a series of rather topical existing difficulties connected with the problems of forming especially high current relativistic electron or combined electron-ion or ion-ion beams.

Secondly, because additional use of the undulation concept [6–10 opens a good prospect for constructing relatively compact and at the same time, very powerful systems for various important commercial applications.

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Проектний аналіз двоканального технологічного індукційного прискорювача для комерційного застосування

Наведено підсумки проектного аналізу двоканального лінійного індукційного прискорювача електронів. Визначено технічні параметри головних вузлів і виконано оцінку загальних характеристик пристрою, що пропонується для практичного застосування в комерційних технологічних системах. Показано, що за своїми параметрами прискорювач є придатним для створення на його основі достатньо компактних і ефективних комерційних систем для виконання операцій очищення промислових викидів, стічної та природної води й стерилізації медичних препаратів і харчових продуктів.

В.В. Кулиш, В.Т. Чемерис, И.В. Губанов, А.А. Подворный

Проектный анализ двухканального технологического индукционного ускорителя для коммерческого использования

Приведены результаты проектного анализа двухканального линейного индукционного ускорителя электронов. Определены технические параметры основных узлов и выполнена оценка общих характеристик установки, предлагаемой для практического применения в коммерческих технологических системах. Показано, что по своим параметрам ускоритель пригоден для создания на его основе достаточно компактных и эффективных коммерческих систем для выполнения операций очистки промышленных отходов, сточных и природных вод и стерилизации медицинских препаратов и пищевых продуктов.