이온 가속기의 인젝터 전원 장치 및 제어 시스템

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Power Supply and Control System for Injector of Ion Accelerator

Abstract - Injector of high voltage or linear ion accelerator is intended to generate, extract and form beam of certain species with required parameters at the entrance of accelerating structure or, for low energy case, directly in the processing chamber (end station). Injector is the main part defining the ion accelerator performance and reliability. Its power supply and control system (PSCS) features are conditioned by placing the injector equipment at high voltage potential and by complexity of the plasma-beam load. The injector's PSCS should provide:
- Transmission of electric power onto high voltage (h/v) terminal;
- Obtaining of required output characteristics for injector equipment operation;
- Transmission of the operational data and start/stop signals from h/v terminal to control cabinet;
- Rremote control of injector;
- Withstanding the high voltage breakdowns and X-ray radiation;
- Compatibility with other equipment.

The paper is concerned with analysis of injectors' PSCS structure and description of the system developed for 50 keV, 20 mA heavy ion injector.

I. INTRODUCTION

Ion beams of various elements with energy from several keV to several MeV are widely used for semiconductor circuits processing, surface modification of various materials, neutron generation, material characteristics analysis [1]. In general, high voltage or linear ion accelerator employed include the following main parts:
- Ion injector (ion generation, beam extraction and initial forming, ion mass separation);
- Accelerating system (if energy more than 40-60 keV required);
- Beam transport line (focusing, mass analysis and deflecting, scanning);
- End station (target holding and manipulation, load/unload, irradiation process monitoring).

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Based upon long term experience in R&D of various accelerators some thoughts concerning design of PSCS and brief description of the system recently developed for 50 keV, 20 mA heavy ion injector will be presented below.

II. MAIN UNITS OF PSCS

Structurally injector's PSCS consists of supply units placed at ground potential, supply units placed in h/v terminal, h/v sources, device for transmission power onto h/v terminal and injector's control system.

2.1. Transmission of electric power onto high voltage (h/v) terminal

The chart 1. represents main types of high voltage insulated devices are being used in ion accelerators to supply with electric power equipment placed at high voltage potential. Various types of insulating transformers or motor-generators with insulating shaft are conventionally employed in high voltage ion accelerators and injectors of linear accelerators to supply h/v terminal and/or ion source terminal with electric power. In Van-de-Graaf accelerators electric generator driven by charging band or chain is used for the same purpose. In some cases it is possible to use capability of dc accelerating voltage source employed to transmit ac power. Some remarks concerning possible use of different devices are presented in Table 1. The choice of method to transmit electric power depends on many factors but use of high frequency is always preferable.

2.2. High voltage source

Inductive and capacitive cascade generators with gas or oil insulation are conventionally used as dc h/v sources up to several MV output voltage. The former mainly employed when big output power (up to hundreds kW) is required while latter - for precision application where small voltage ripple and high stability are required.

As in case of power transmission devices use of high frequency is preferable. Use of modern electronic components such as power IGBT and MOSFET transistors, high frequency h/v diodes and capacitors allow to create quite simple, compact and reliable power precision h/v source consisting of capacitive cascade generator, fed by high frequency inverter, and voltage stabilizer.

Use of high frequency voltage to feed high voltage source has several advantages. They are following:
- Small dimension and weight of h/v source;
- Small output voltage ripple;
- Small stored energy $\left(\frac{CU^2}{2}\right)$
- Repairable;
- Simple design and making.

2.3. Power supply and control units placed in h/v terminal

In general it includes power supply for ion source, gas inlet, initial beam forming, mass-separator and vacuum system. Its design must provide proper feedbacks, protection and withstanding of h/v breakdowns in accelerating structure. Arrangement of power supply units is important to eliminate electronics failures during h/v breakdowns.

2.4. Injector control system

Control of supplies placed at high voltage potential may be realized through individual insulating transformers, by means of insulating rods (with manual or motor drive), by opto-electronic devices through light guides and using multichannel fiber-optic transducer. Measurement of parameters of the units placed in h/v terminal - visual (measuring devices placed at front panel in the h/v terminal), through television camera and using multichannel fiber-optic receiver. The only use of multichannel fiber-optic transmission system allows to realize fast feedbacks across whole accelerator, such as space positioning of ion beam or stabilization of its current by variation of one or several discharge parameters and provide full computer control, manual or automatic.

III. PSCS FOR 50 kV, 20 mA HEAVY ION INJECTOR

PSCS for 50 kV, 20 mA heavy ion injector T-5010 intended for use in ion implanters and isotope separators has been developed. The injector includes Freeman type ion source equipped with four electrode accel/decel system, beam current measuring system and vacuum system [2]. The PSCS provides autonomous operation of the injector and can be easily extended or incorporated into PSCS of complete machine.

Structurally, the power supply and control system developed includes ion source PS (ISPS), high voltage PS (HVPS) and control system. It based upon use high frequency mains (about 20 kHz) for supplying the equipment placed in the h/v terminal and capacitive cascade generator - accelerating voltage source. The employment of high frequency gives several advantages: sharply decrease in both dimensions and weight of the equipment; less value of stored energy in high voltage cascade generators thus increase reliability of the electronics when high voltage breakdowns in ion extracting and accelerating structures happened; also it is allow to consider new design of some supply units. The PSCS structure is shown in Fig. 1.

3.1. H/V PS

The H/V PS is intended for transferring power from ground to h/v terminal and to provide ion source extracting system with required voltages.

3.1.1. 50 kV insulating transformer (IT) with 20 kHz operating frequency and 4 kW transferring power have been developed to supply with mains the equipment placed in high voltage terminal. A special technology is required for manufacturing conventional insulating transformers with solid insulation between primary and secondary windings. Use of high frequency allowed to design simple and cheap transformer by employing high voltage cable for making secondary winding. We used 50 kV cable 幹Â-50/1 type. It has about 10 mm in diameter when removing external PVC coating and grounding copper screen. Only 10-15 turns for secondary winding is necessary for the frequency chosen. Completed with multisectional ferrite core it has dimensions Ø250x100 mm. IT is supplied by 300 V, 20 kHz voltage from noncontrolled power inverter (PI).

3.1.2. The accelerating voltage source is 5-stages Cockcroft-Walton symmetrical capacitive voltage generator (CG). It is provides output voltage up to 50 kV with 0.05% instability including ripple for load current up to 20 mA. It is supplied with 20 kHz voltage from controlled inverter (CI). The output of CG is connected with high voltage terminal through antisurge resistor R_{as} to decrease current in case of vacuum breakdown. The precision h/v divider (VD) is used for measurement and stabilization of accelerating voltage.

3.2. ISPS

ISPS provides ion source and extracting system with required controlled voltages, and supplies piezoelectric gas flow controller (GFC) and cooling fans with 50 Hz local mains. It includes cathode heater unit (CHU) /dc 5 V, 200 A/, discharge supply unit (DSU) /dc 150 V, 5 A/, furnace heater unit (FHU) /dc 30 V, 30 A/ and extracting supply unit (ESU) /dc 25 kV, 10 mA/. Each unit consists of transistor regulator operated in pulse-width modulation (PWM) mode, and output circuit. The PWM frequency is twice of mains' one, ea. 40 kHz. Each unit has current (CHU, DSU, FHU) or voltage (ESU) feedback. The regulators are controlled from 8-channel digit/analog converter. Matching unit (MU) includes low frequency inverter /50 Hz/, electronic circuits required for matching ISPS and fiber-optic transmission line and special circuit for thermocouple signal amplification.

3.3. Control system

Control of the injector operation and measurement of all the necessary parameters is executed from control rack. The fiber-optic system is used to control the equipment placed inside high voltage terminal and measurement of ion source parameters. It includes two sets of 8-channel transducer (FOT), receiver (FOR) and communication line (FOCL).

The PSCS developed is designed so to be easy extended or included in complete accelerator power supply and control system. In the last case such subsystem like feedback for stabilization of beam current on the target by means of acting upon discharge parameters of ion source, or others required can be added. The system allows also to realize automatic control through serial port RS232 or others.

Function and parameters of main PSCS's units are tabulated in Table 2. Layout of T5010 Injector is shown in Fig.2.

IV. CONCLUSION

The following aspects should be considered when designing state-of-the-art power supply and control system for injector of applied or research ion accelerator: Use of high frequency (10-40 kHz) voltage for feeding power supply units including h/v sources (extracting, accelerating, focusing) and units placed in h/v terminal is strongly recommended. It allows to create compact, quite simple, reliable and cost effective system. Employing of modern high frequency semiconductor devices such as power IGBT transistors allows to design compact, reliable and quite simple high frequency voltage inverters with power up to several tens of kilowatts thus covering the injectors' power range required including such power injectors as plasma heating injectors for tokamak installations or oxygen injectors for SIMOX implanters.

High frequency insulating transformer with solid insulation and ferrite core is considered to be most appropriate device for transmission power onto h/v terminal. High frequency symmetrical capacitive cascade generator provides small output voltage ripple and at the same time small value of stored energy, so substantially enhancing reliability of power supply units placed in h/v terminal. To withstand h/v breakdowns in accelerating structure, careful arrangement of elements and proper safety circuits should be provided when designing power supply and control system placed in h/v terminal.

The only use of multichannel fiber-optical communication system allows to realize necessary accelerator's feedbacks (like stabilizing of beam current on the target), parameters monitoring and automatic control. Based upon above mentioned remarks, complete precision PSCS for 50 kV, 20 mA heavy ion injector has been developed. One year operation of the injector showed its reliability and flexibility.

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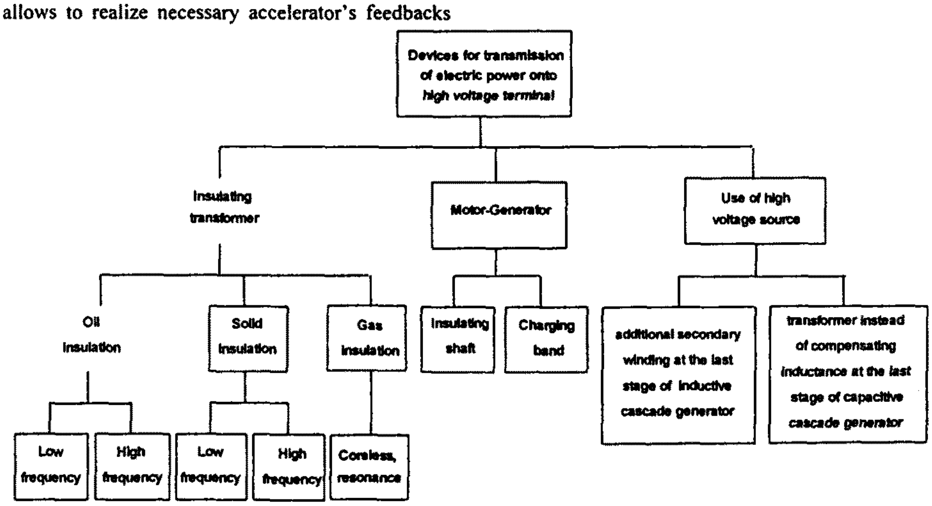

Chart 1. represents main types of high voltage insulated devices

N	Power transmission device	Application in accelerators	Advantages	Disadvantages
1.	Motor-generator with insulating shaft	Opened type h/v machines for 200-500 keV	Quite easy to make it for 500 kV insulation and more; Transmitted power is defined by choosing the proper motor and generator and can be as high as tens kW	Careful mechanical design and precision working is required Increased noise; Low frequency of output voltage if using commercial generators (50 Hz and 400 Hz is only available).
2.	Insulating Transformer			
2.1.	Oil insulation. a/. Low frequency (50 Hz)	Opened type h/v machines for 150-500 keV; 20-150 keV Injectors for single-stage and tandem h/v accelerators and linear accelerators	Wide range of transmitted power is available; Can be made for 500 kV insulation and more; Reliable	Low frequency of output voltage; Big dimensions and weight; H/v feedthrough is required (plus proper h/v cable, if installed remotely); Special safety requests for oil containing equipment
	Oil insulation. b/. High frequency (20 kHz)		High frequency of output voltage; Decreased dimensions and weight;	Frequency converter is required at the input; H/v feedthrough is required (plus proper h/v cable, if installed remotely); Special safety requests for oil containing equipment
2.2.	Solid insulation. a/. Low frequency (50 Hz)	20-150 keV Injectors for single-stage and tandem h/v accelerators and linear accelerators	Decreased dimensions and weight compare with 2.1.	Special technology is required; Nonrepairable secondary winding; Difficult to make for more than 200 kV insulation
	Solid insulation. b/. High frequency (20 kHz)	20-15 keV Injectors for single-stage and tandem h/v accelerators and linear accelerators	High frequency of output voltage Small dimensions and weight	Special technology required; Nonrepairable secondary winding; Difficult to make for more than 200 kV insulation; Frequency converter is required at the input
2.3.	High frequency resonance coreless transformer	Closed type h/v machines for 300-2000 keV	Compact; Quite simple design; Can be made for 500 kV insulation and more	Difficult to make for more than few kW transmitted power
3.	Use of high voltage source			
3.1.	Additional secondary winding at the last stage of inductive cascade generator	H/V electron accelerators	Special power transmitting device is not required	Transmitting power is limited to about 1 kW; Output voltage changes proportionally to high voltage, so special stabilizer is required; Low frequency of output voltage
3.2.	Transformer instead of compensating inductance at the last stage of capacitive cascade generator	1-5 MeV tandem accelerators	Special power transmitting device is not required	Transmitting power is limited to about 1 kW; Output voltage changes proportionally to high voltage, so special stabilizer is required.

Table 1. Comparison of different electric power transmission devices

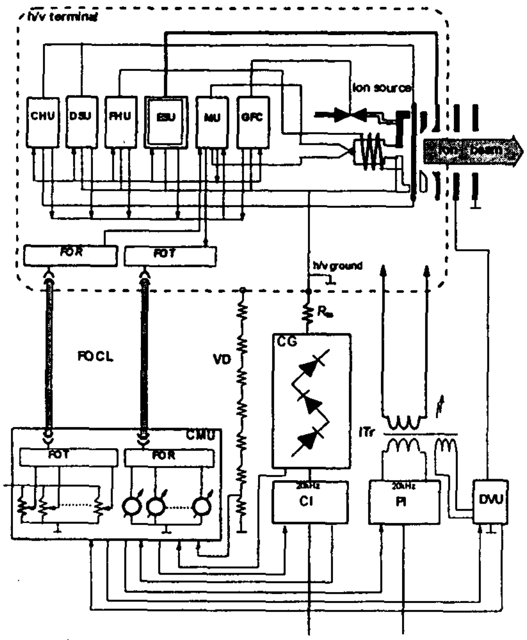

Fig. 1. Structure of Power Supply and Control System for T-5010 Heavy Ion Injector

		Unit functions	Unit parameters
1.	H/V terminal		
1.1.	CHU	Cathode Heater Unit -- heating of thermionic emission cathode	dc 5 V, 200 A, 1% instability including ripple, current feedback
1.2.	DSU	Discharge Supply Unit -- plasma generation in ExH magnetron geometry discharge	dc 150 V, 5 A, 1% instability including ripple, controlled voltage and current feedback, variable slope of V-A dependence
1.3.	FHU	Furnace Heater Unit -- oven heating for evaporation of various working substances	ac 20 V, 30 A, 1% instability, current feedback
1.4.	GFC	Gas Flow Controller -- control of working or support gas flow into ion source discharge chamber through two channel piezoelectric regulator	dc 1.5 kV, 0.1 A, 1% instability including ripple, voltage feedback
1.5.	MU	Matching Unit -- matching ion source power supply and control signals with fiber optic system	
1.6.	ESU	Extracting Supply Unit -- supply of ion extracting electrode with proper potential	dc −25 kV, 10 mA, 0.5% instability including ripple, voltage feedback
1.7.	FOR	Fiber Optic Receiver -- converts optical codes into analog control and measuring voltages	8 channels; successive codes receiving
1.8.	FOT	Fiber Optic Transmitter -- converts analog control and measuring voltages into optical codes	8 channels; successive codes transmission
1.9.	FOCL	Fiber Optic Communication Line -- transmission of control signals onto h/v terminal and measuring signals from h/v terminal to CMU	2 fiber-optic cables. Length - up to 300 m.
2.	CMU	Control and Measuring Unit -- control of injector units and display its current parameters	Manual control through precision potentiometers. Computer control is available.
3.	CG	Cascade Generator -- capacitive voltage multiplier -- accelerating voltage source	dc +50 kV, 30 mA, 0.1% instability including ripple, voltage feedback
4.	CI	Controlled Inverter -- supplies CG with controlled input ac voltage	500 V, 20 kHz, 2 kW,
5.	VD	High Voltage Divider -- measuring of accelerating voltage	50 kV, 0.25 mA
6.	ITr	Insulating Transformer -- transmission of electric power onto h/v terminal	4 kW, 20 kHz, 50 kV insulation between primary and secondary windings
7.	PI	Power Inverter (noncontrolled) -- supplies ITr with HF input voltage	300 V, 20 kHz, 5 kW
8.	DVU	Decelerating Voltage Unit -- supplies the initial beam forming system with decelerating potential	dc −5 kV, 10 mA, 0.5% instability including ripple, voltage feedback

Table 2. Main units of T5010 Injector's PSCS

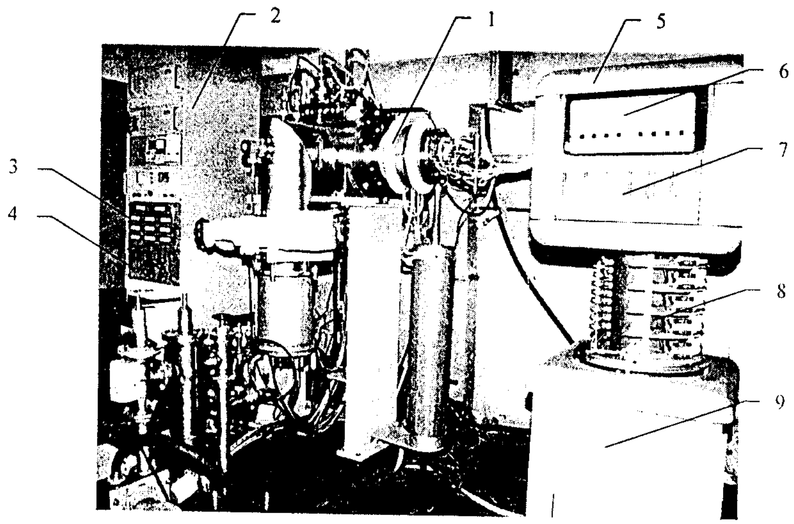

Fig. 2 T-5010 Heavy Ion Injector Layout
1 - Ion source with extracting system; 2 - Control cabinet; 3 - Control and measuring unit; 4 - Control and signaling unit; 5 - High voltage (h/v) terminal; 6 - Gas flow controller; 7 - Ion source power supply; 8 - 50 kV, 30 mA cascade generator (CG); 9 - Cabinet for 20 kHz-inverters, CG h/v transformers and 50 kV insulating transformer.