PULSE HIGH-CURRENT RF ACCELERATORS FOR SINGLE-TURN INJECTION INTO A SYNCHROTRON

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1. INTRODUCTION

In 1959, the construction of a high-current synchrotron B-3M with external electron injection was begun [1]. For this accelerator, electron injection at a current in excess of tens of amperes and an energy of not less than 1 MeV was required. The duration of the injected electron burst (pulse current) must be long enough to fill the synchrotron chamber which, for an equilibrium orbit length of 700 cm and relativistic electrons, is roughly 20 nsec. The deviation of electron energy in the cluster from the mean value must not exceed ±0.5 percent.

The pulse power of the injector beam is tens of megawatts. In order to obtain such a high power, the beams utilize an electric field energy stored over a time which is much longer than the electron pulse length. G. I. Budker and A. A. Naumov proposed several types of accelerators based on this principle, some of which were developed in the Institute of Nuclear Physics of Siberian Branch, Academy of Sciences USSR. The necessity of a comparatively rapid construction of an injector of such a type required the use of previously checked principles, where the radio-frequency tank circuit serves as the energy storage for the electric field. A suitable accelerator was proposed and is described by a group of authors [2].

In order to increase the current pulse length of the accelerated particles while maintaining sufficiently rigid requirements on electron energy homogeneity, it was necessary to greatly decrease the frequency of the rf voltage in comparison with the case which is treated in another article [2]. The Physical-Technical Institute of the Academy of Sciences Georgian SSR undertook the development of an injector having an energy of 3.5 MeV and a current of about 100 A. A group of co-workers at this Institute proposed the construction of an injector which was used as the basis of further work. Subsequently, the preparation of the injector began to significantly fall behind in comparison with the preparation of the accelerator itself for reasons which were beyond the control of the workers. This caused us to look for a means of preparing simplified injectors of this type with the aim of assuring an initial working cycle for adjusting the accelerator.

In the Institute of Nuclear Physics of Siberian Branch, Academy of Sciences USSR, an injector was prepared in a short time using a long coaxial line as the resonant circuit. With the aid of this injector, the initial operations were carried out for the investigation of the electron-optical properties of the accelerator and the channeling device. Roughly a year later, this injector was replaced by the more effective so-called "small spiral" type prepared at the Physical-Technical Institute of the Academy of Sciences of the Georgian SSR. The basic injector having an electron energy of 3.5 MeV and a current of about 100 A has still not been prepared.

Work on injectors of the type which have been described here was done by A. A. Naumov.

2. BLOCK DIAGRAM OF THE COMPLEX OF ACCELERATION DEVICES

Both types of injectors have an identical block diagram for the equipment complex (Figure 1). The pulsed two-stage rf generator excites the tank circuit of the injector. A portion of

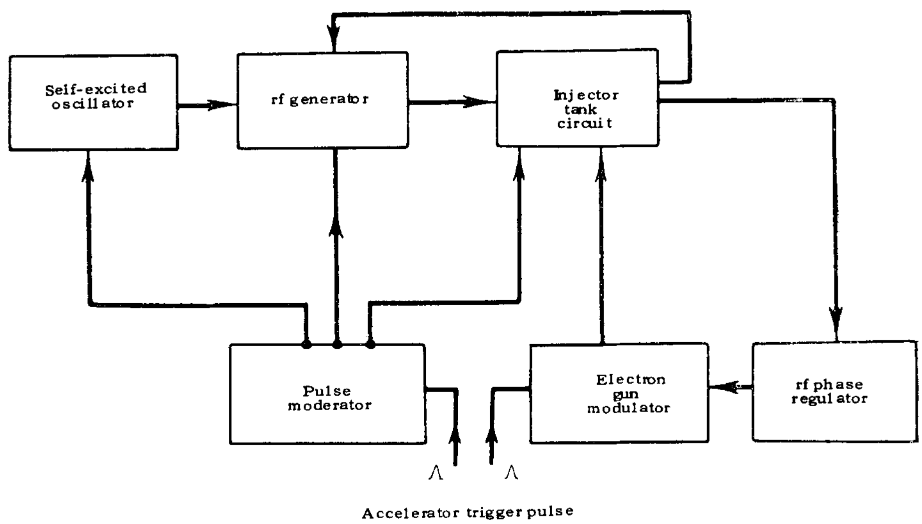

Figure 1

the power for exciting the rf amplifier is drawn off from the resonator cable. The pulsed self-excited oscillator with internal feedback is used for the preliminary excitation of the resonator, i.e., the crossover in a region of low Q for small rf voltage amplitudes (multivibrator). The pulse modulator supplies the rf generators. The modulator of the electron gun serves for triggering this gun which is inoperative during the period for storing rf power in the resonator. The recording unit for the rf phase performs synchronization of the gun triggering time in proper phase for the rf voltage. Both types of injectors may operate with a pulse repetition rate of 12.5 times per second.

3. CONSTRUCTION

The resonator for an injector of the first type is a coaxial quarter wave line, 1, (Figure 2) loaded by the condenser whose plates form a special cap 2 of the inner electrode on one side of the line and the bottom and walls of the outer electrode on the other. A significant reduction in the natural frequency of the resonator is associated with an increase in the inductance, caused by excessively large dimensions. The reduction in natural frequency by increasing the capacitance by lengthening the accelerating gap induces an electrical loss and an increase in the power necessary for exciting the resonator. The length of the accelerating gap in the given case in chosen on the basis of a proposed gradient of the order of 100 kV/cm. This value was chosen on the basis of an analysis of the operation of different types of linear accelerators and cyclotrons. The construction is simplified when the resonator is positioned vertically and there is no necessity for massive fittings associated with the construction of highly rigid elements. The latter fact permits us to use thin copper walls for the internal and external electrodes for the resonator and greatly simplifies the alignment fittings.

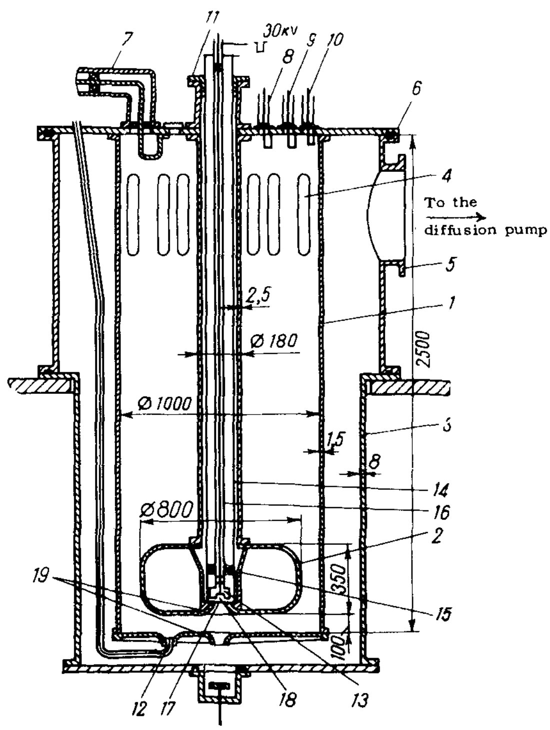

Figure 2

The entire resonator is placed in a length of a standard steel tube of large diameter, 3, which acts as a vacuum jacket. In order to create the necessary pumping conditions for the outer electrodes, the resonator has longitudinal slits, 4, located at the level of the evacuating collar of the pump, 5. The accelerator is evacuated by one oil-vapor pump of the type BA-8-5 with a nitrogen trap having four jalousie series and cooled walls for avoiding the migration of the oil from the pump to the evacuated chamber. A feeder for the rf supply of the resonator, 7 and 8, a rf cable for feedback, 9, and a measurement cable, 10, are flange-mounted to the upper cover of the resonator, 6. All of the feeders are connected to the resonator by coupling loops. The connection to the main feeder may be changed, without impairing the vacuum, by using special movable shields on the loops. The internal electrode is water-cooled (soldered tubes) while the external electrode is cooled by radiation. In order to measure the voltage across the accelerating gap, a capacitor transducer, 12, located in the bottom cover of the external electrode is used. All of the overall dimensions are given in Figure 2.

The construction of a tank circuit for an injector of the second type is shown schematically in Figure 3. The solenoid of the copper tube, 1, is inside the steel cylinder, 2, evacuated from below by a diffusion pump of the type BA-8-5 through a trap similar to the one described above. The upper portion of the solenoid is attached to flange, 3, appearing at the same time as the cap of the steel cylinder. A vacuum-tight insulator, 4, for introducing the central electrode of the feeder connected to the generator is fastened to the flange.

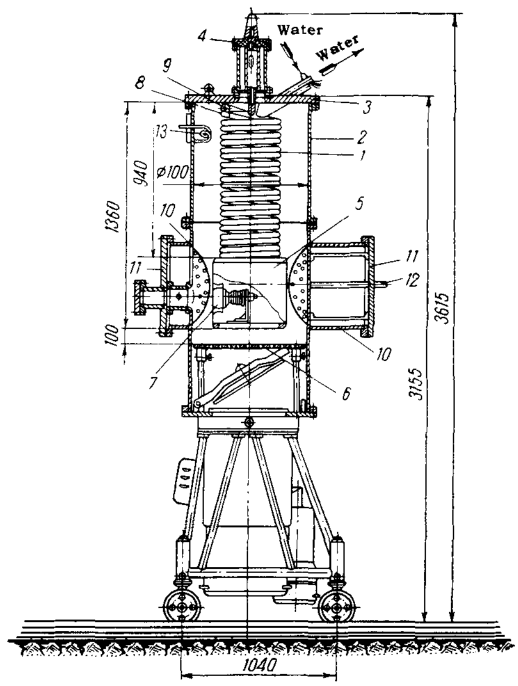

Figure 3

A special cap, 5, is fastened to the lower portion of the solenoid, appearing as one of the electrodes for the tank circuit condenser. The other electrodes are the walls of the steel cylinder and the screen, 6, having apertures for evacuation. Inside the cap is an electron gun, 7, and certain components of the control circuits for the electron gun. The latter are in a special vacuum-tight housing forming a single chamber with the internal chamber of the solenoid tube. Cables, 8, for feeding the gun, pass through it. The connection to the electron gun is accomplished by terminals in the vacuum-tight insulators fastened to the housing cover. The solenoid is water-cooled by a special tube, 9, soldered along the entire length of the solenoid.

In the lower portion of the steel cylinder, the connecting pieces, 10, are cut into its wall for extracting the beam and for access to the electron gun. The connecting pieces are closed off by the vacuum-tight flanges, 11. The capacitor transducer, 12, is mounted on the flanges for measuring the potential across the accelerating gap. The coupling loop, 13, is used for supplying rf power to the feedback loop. A drawback to a resonance circuit construction of this type is the inconvenience in changing the cathode of the gun (an operation associated with breaking down the vacuum in the accelerator) and rigidity of the small helix associated with it. The latter circumstance makes it difficult to adjust the electron-optical system of the gun and requires the accelerator to be mounted on a shockproof base.

4. ELECTRON GUNS

The electron gun for an accelerator of the first type, 13, (see Figure 2) is fastened to the end of the tube, 14. With its aid, the gun is introduced into the adaptor cavity of the central electrode for the resonant circuit. A special vacuum lock, 11, permits us to extract the gun without destroying the vacuum in the accelerator itself. Inside the tube of the gun, there is a vacuum seal, 15, and a shaft, 16, which carries the power to the cathode heater, water for cooling the cathode leads, and the triggering pulse leads. The ribbon cathode of lanthanum hexaboride, 17, has an area equal to 1 cm^2. The anode of the gun is constructed in the form of a grid, 18. The gun current per pulse is about 25 A. Focusing of the electron beam in the accelerating gap is carried out by an electrostatic lens formed by two electrodes, 19, mounted on the cover of a central rod of the resonator and on the cover of the external electrode.

The electron gun for an accelerator of the second type does not differ fundamentally from the one described. It has a cathode in the form of a 1.5 cm disk with a lanthanum hexaboride coating. Heating of the cathode is carried out by electron bombardment from a special heater. The gun current per pulse is about 40 A.

5. RADIO DEVICES

A two-stage rf power amplifier with feedback through the resonator is used for supplying the resonator. Feedback of such a type is a safe method for eliminating the amplitude excursions of the rf voltage due to detuning of the natural frequency of the resonant circuits during warmup [3].

The output stage of the rf amplifier is a grounded grid circuit with two type GK-5A tubes operating in parallel, while the input stage uses the same circuit with one type GK-5A tube. The generator can deliver a useful power of more than 6 MW to the load for a pulse anode voltage equal to 25 kV. The pulse length of the modulator is determined by the time necessary for the voltage rise in the circuit and is 150 μsec. The rf amplifier is connected to the resonator feeder having an electrical length of 0.1 wave length.

In an injector of the first type, a modulator which was described earlier was used [3] while in an injector of the second type, a modulator utilizing partial discharge of the storage capacitance through gas-discharge tubes was used. The subsequent increase in pulse amplitude was carried out by a transformer. A separate self-excited oscillator whose signal is very weakly coupled to the input of the basic amplifier served for the initial excitation of the resonator.

The power of the self-excited oscillator is several kilowatts.

6. MEASUREMENT OF CERTAIN PARAMETERS

It is of interest to look into the Q of the resonators for a specific working pressure ($5 \cdot 10^{-6}$ mm Hg) and a high voltage at the accelerating gap. The Q was measured according to the damping factor of the rf oscillations in the resonator for the rapid cutoff of the generator tubes and by the power balance method.

Table of Comparative Resonator Characteristics

Comparative characteristics	Resonator type		
	coaxial	spiral (small)*	spiral (basic)*
Tank height, mm....	2500	1500	2500
Tank diameter, mm..	1000	700	2000
Maximum accelerating voltage, MV..	1.1	1.5	3.5
Maximum gradient, kV/cm............	110	150	110
Specific rf power for obtaining an accelerating voltage of 1 MV, MW..............	1.25	2.00	0.6
Resistance leading to a voltage peak, ohms.......	80	250	500
Equivalent resistance leading to a voltage peak, ohm.............	$4 \cdot 10^5$	$2.5 \cdot 10^5$	10^6
Q.................	5000	1000	2000
Resonant frequency, Mc.......	14.5	6.4	3.0
Length of burst with an electron energy spread of $\pm 0.5\% \times 10^{-9}$ sec..	3	7	15

*Calculated data (obtained during manufacture).

The Q of the resonators for high voltages turned out to be equal when calculated from the losses in a metal and when measured at low voltage and atmospheric pressure. The voltage across the accelerating gap was measured by a capacitance transducer and agreed very closely with the measured electron energy. The combined electrical parameters of the injector types described here are given in the table of comparative resonator characteristics.

The accelerated electron current at a probe located at the input guide was 16 A per pulse in an injector of the first type, a pulse equal in length to one half the period of the high frequency, while in an injector of the second type, the current was equal to 25 A.

A positive feature of the accelerators described is the feasibility of also obtaining a large mean power for the electron beam. This is explained by the feasibility of using relatively low frequency generator tubes at a large mean power (250, 500 kW) in the rf generator. Depending upon the operating regime (requirements on the energy spectrum and relationship between the mean energy and value for the accelerated particle current), the mean power in the beam may vary from tens of kilowatts to hundreds of kilowatts. The strong γ radiation of such a beam may be used for industrial needs.

The following participated in developing the separate components of the described injectors: the co-workers of the Institute of Nuclear Physics of Siberian Branch, Academy of Sciences USSR, V. A. Borisov, I. A. Samokhin, V. G. Gnidenko, A. P. Afonin, A. V. Makienko, V. P. Alekseev, L. I. Kol'chenko, and the co-workers of the Physical-Technical Institute of the Academy of Sciences Georgian SSR, V. I. Vishnevskii, Ya. R. Abas-Ogly, V. E. Zelenin, M. I. Matrosov, Yu. Sh. Venediktov, V. N. Rybin, G. M. Sigidin.

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