50 MeV SUPERCONDUCTING ELECTRON LINEAR ACCELERATOR

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Abstract

A superconducting linear accelerator is designed as an electron injector to a compact electron storage ring. Pulse mode of operation is supposed. Acceleration of electrons occurs by electromagnetic energy which is stored in the 2450 MHz TW accelerating structure. RF power pulse length is equal to 10 μs, electron current pulse length is equal to 20 ns. A disc loaded niobium waveguide is used as accelerating structure. The design energy of 50 MeV will be achieved with the accelerating gradient of 25 MeV/m. The design of linear accelerator is completed. Parts of it and prototypes are tested. The machine is in fabrication now.

Introduction

A 600 MeV compact superconducting electron storage ring Siberia-SM [1] is designed at the Institute of Nuclear Physics in collaboration with a research institute of microelectronic industry. This machine will operate as a dedicated synchrotron radiation source for industrial applications. Several types of electron injectors to the storage ring are considered. One of them is a superconducting linear accelerator.

There will be cryogenic equipment at the facility because of usage of superconducting magnets in the storage ring Siberia-SM. Therefore the employment of a superconducting linear accelerator is rather natural. Since the superconductivity is employed, RF power necessary to drive the linac is several times less than that in case of a copper linac. At short pulse mode of operation of superconducting cavities one cannot obtain such a dramatic reduction of RF power as at CW mode of operation. But nevertheless the RF power source is cheaper and more compact in this case.

Pulse mode of operation of the linac with short pulse duration (τ = 10 μs) allows to have an acceleration gradient much higher than in CW superconducting cavities and limited only by the superconductor critical field [2]. It is because thermal processes which usually limit the high field levels in superconducting RF cavities do not play their role at short pulse mode of operation.

Linac design

An LS-band disc loaded niobium waveguide is used as accelerating structure. The structure operates in TW mode with a feedback (Fig.1). The feedback loop and the accelerating structure form a traveling wave resonator. It is necessary to accord a relatively long RF pulse duration with the accelerating structure which has a high group velocity. The accelerating structure has a high group velocity because it should have a rather large beam aperture and the structure with a high group velocity has lower sensitivity to dimension errors. Thanks to no decay of electromagnetic fields along the superconducting structure dimensions of individual cavities are constant for the whole structure.

Electrons are accelerated at the end of the RF pulse by the energy stored in the accelerating structure (Fig.2). The electron current pulse duration (20 ns) is determined by the conditions of one turn injection into the storage ring.

A directional coupler is used for coupling the traveling wave resonator to the klystron. Its coupling coefficient (6.8 dB) is optimal. In this case the energy which goes into the dummy load during driving the structure is minimal and 78% of incident energy is stored in the accelerating structure. A 5 MW klystron is used to drive the linac.

The waveguide has a cross-section of 90×45 mm^2. The main part of it is evacuated. The part of the waveguide near the klystron including a ferrite isolator is gas filled. The feedback loop is placed outside the cryostat and is made of copper. The parts of the waveguide inside the cryostat have a cross-section of 90×28 mm^2, they are made of stainless steel and are copper plated from inside.

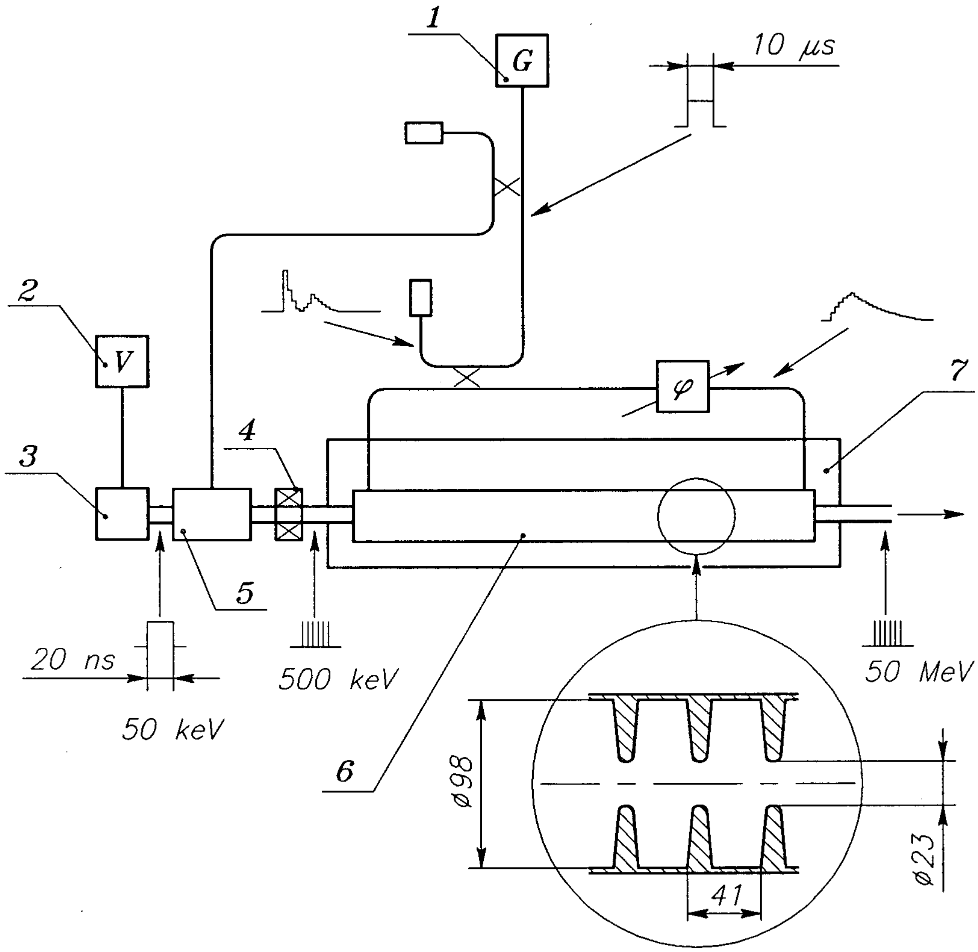

Fig.1: *Skeleton diagram of linear accelerator*

1 - klystron amplifier; 2 - electron gun power supply; 3 - triode electron gun; 4 - focusing lens; 5 - buncher/preaccelerator; 6 - superconducting accelerator; 7 - cryostat.

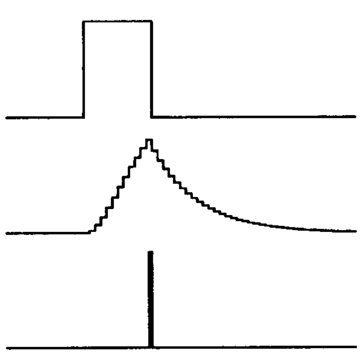

Fig.2:

Time diagrams of driving power, power of electromagnetic wave in the accelerator structure, current of accelerating electrons.

Table 1:

Superconducting linear accelerator parameters

1.	Energy of electrons	50 MeV
2.	Energy spread	± 0.5 %
3.	Electron gun energy	50 keV
4.	Energy of electrons after buncher	0.5 MeV
5.	Electron current	30 mA
6.	Electron current pulse length	20 ns
7.	Repetition rate	0.5 Hz
8.	RF operating frequency	2450 MHz
9.	Operating mode	2π/3, TW
10.	Group velocity / velocity of light	0.0075
11.	Length of superconducting accelerating structure	2 m
12.	Total length of accelerator	3.5 m
13.	Accelerating gradient	25 MeV/m
14.	Peak surface electric field	40 MV/m
15.	Stored RF energy in accelerating structure	35 J
16.	RF power pulse length	10 μs
17.	RF power of klystron	5 MW
18.	Number of recirculations	11
19.	Coupling of directional coupler	6.8 dB
20.	Operating temperature of accelerating structure	4.2 K
21.	Total cryostat heat loss	2.5 W
22.	Liquid helium consumption	3.5 l/h

The main accelerating structure is fabricated of niobium. Its pieces (cylinders cut from seamless tubes and irises) are electron beam welded together after machining and chemical polishing. The whole section has chemical treatment after welding. The section is 1 m long. It consists of 24 regular cavities and a coupler cavity for coupling to the rectangular waveguide. The main accelerating structure consists of two such sections joined together using an indium wire as a RF contact and a vacuum seal simultaneously. It is possible to have a normal conducting RF contact in the superconducting structure taking into account the pulse mode of operation with a very low duty factor ($5\cdot10^{-6}$). According to our estimates the average power dissipated in the contact is about 50 mW. The power loss in the whole structure (at $Q = 0.5 \cdot 10^8$) is approximately the same. It is much less than the heat loss of the cryostat (about 2 W). These figures explain also that there is no need to have an operating temperature lower than 4.2 K for increasing the Q of the structure.

The design of the cryostat containing the accelerating structure is shown in the Fig.3.

A 50 kV triode electron gun [3] is the electron source for the linac. The gun forms an electron current pulse of 20 ns. Then the electron beam goes through a copper buncher [4] which is also a preaccelerator. Therefore at the input of the superconducting accelerator we have electron bunches with a phase length about 30° and an energy of 500 keV. A small part of the klystron power (about 200 kW) is used to drive the buncher.

Table 1 presents parameters of the linear accelerator.

Tuning the accelerator structure

High identity of the individual cells of the accelerating structure is required to ensure good field flatness and high acceleration efficiency. The manufacturing technology cannot afford such identity even with stringent tolerances for machining the parts of cells because there is shrinkage during welding which cannot be totally controlled. Therefore tuning the linac structure after its fabrication is necessary.

A computerized set-up was built for measuring and tuning the accelerator structure (Fig.4). It includes a four probe line (6), a gear (3) for precise positioning the accelerating structure (1), a tuning device (4,5). The four probe line is drived through a coax-to-waveguide transition (8). A sliding short-circuit drived by a step motor can be connected to the line instead of the accelerating structure for calibrations.

A metallic rod (2) is inserted inside the structure along its axis. It detunes a part of cells and the phase of the reflection coefficient is measured [5]. Then the structure moves on a period and the phase is measured again. The phase difference should be equal to 240°. The tip of the rod is separable. It may be either metallic or absorbing.

Tuning the structure is performed by inelastic deformation of its walls [5]. Three rods (4) driving simultaneously by step motors (5) are used for this purpose.

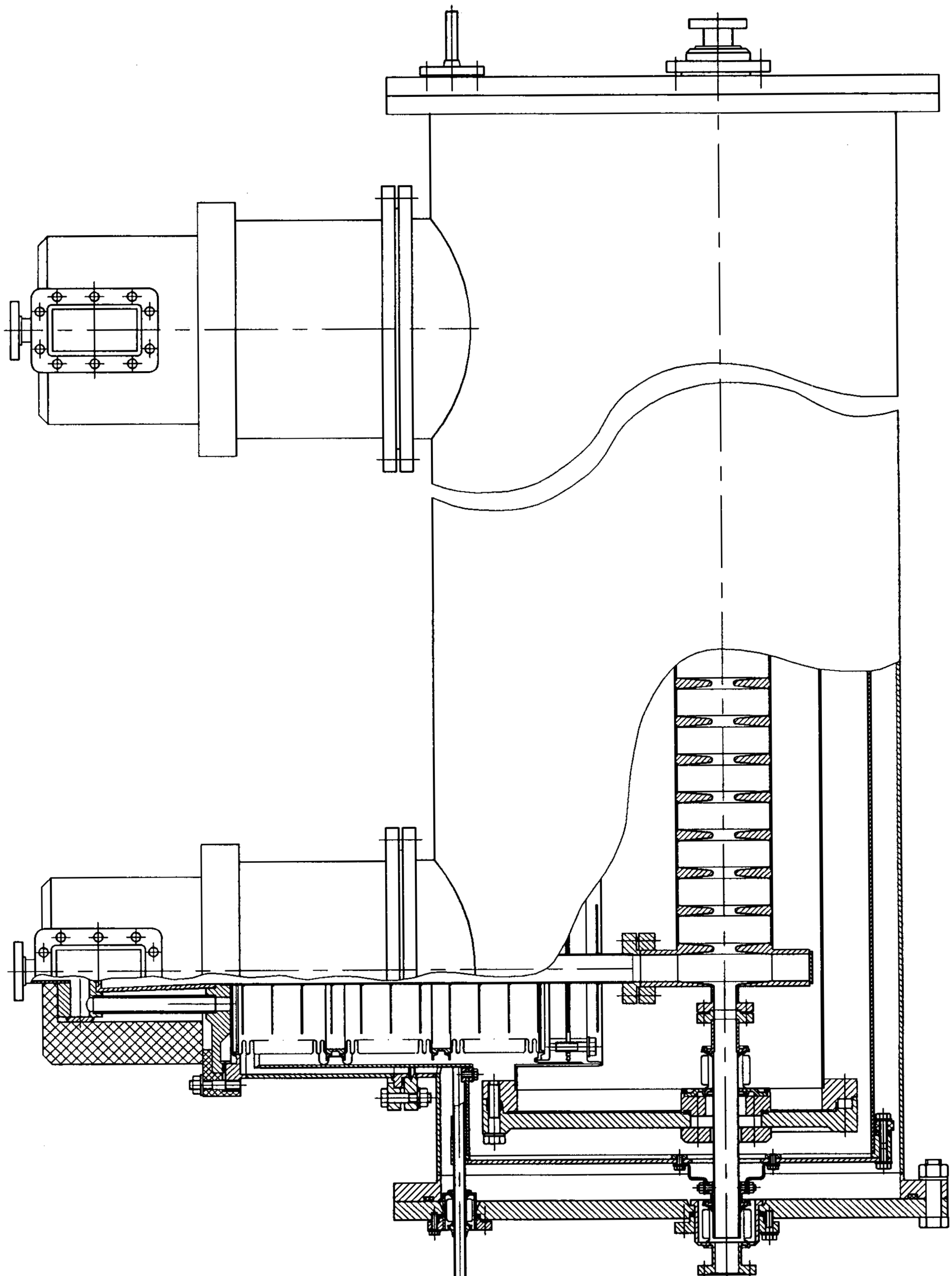

Fig.3: *Design of the cryostat with the accelerating structure*

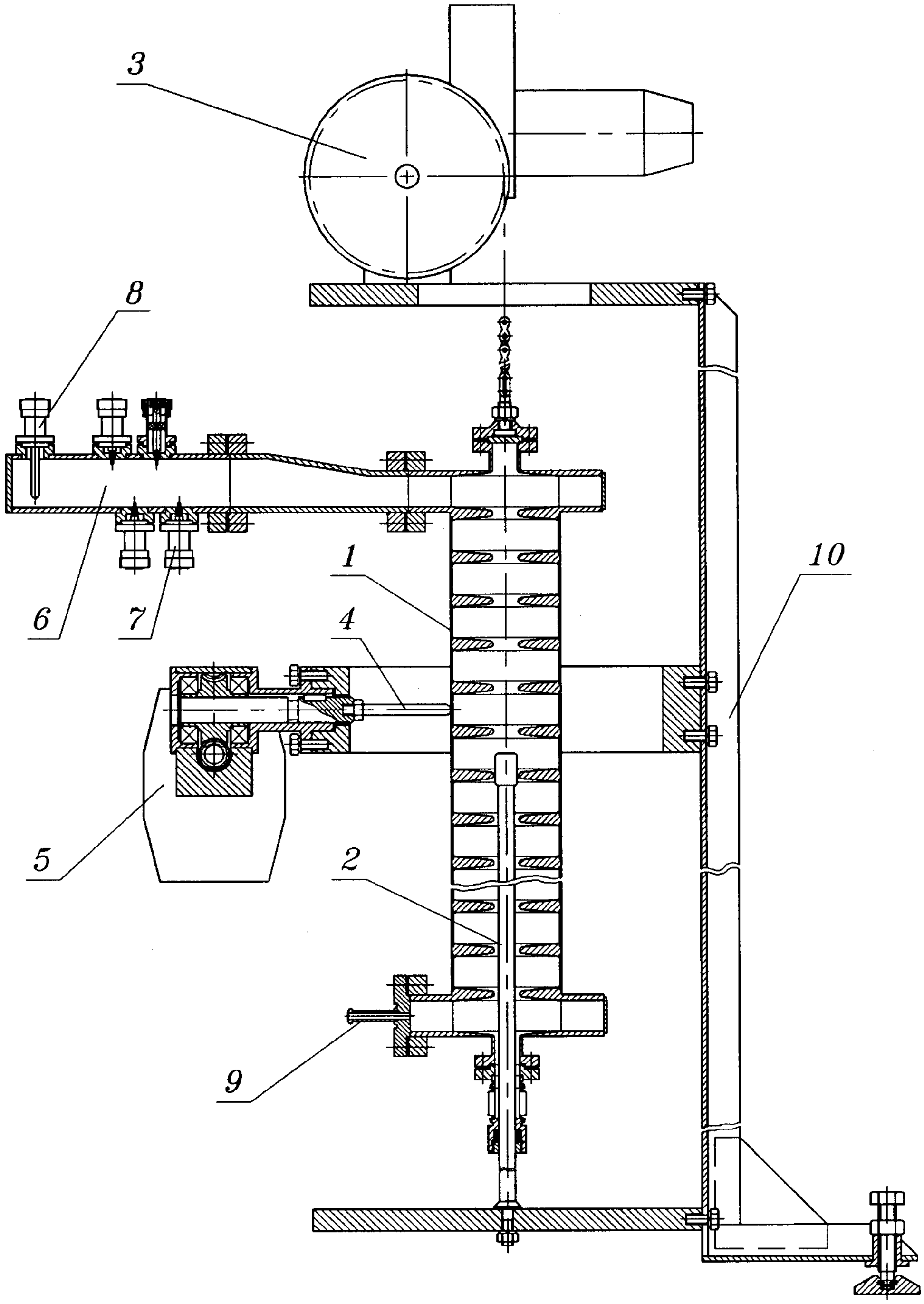

Fig.4: *Design of the set-up for tuning the accelerating structure*

1 - accelerating structure; 2 - detuning rod; 3 - gear for positioning the accelerating structure; 4 - rod for deformation of the structure wall; 5 - gear for movement of deformation rod; 6 - four probe line; 7 - probe; 8 - coax-to-waveguide transition; 9 - pipe unit for pumping out the structure; 10 - frame.

The structure can be evacuated before tuning for better accuracy. This helps to avoid errors caused by air permittivity and by deformation of the structure in consequence of its pumping out.

Tuning the structure is performed at a frequency lower than the nominal operating one taking into account reducing the structure dimensions after its cooling down.

The energy of the accelerated electrons depends on the accuracy of the structure tuning. For this structure at the phase error of ± 2^{o} (corresponding to the cell frequency error of ± $1.3 \cdot 10^{-4}$) the energy of electrons decreases at 5 %.

The set-up was used also for geometry adjustment of the input and output coupler cavities.

Single cell cavity tests

Several single cell niobium cavities at a frequency of 2797 MHz (Fig.5) were fabricated specially for testing the superconducting cavities at high power levels in short pulse mode of operation. The fabrication procedure was similar to the one described in [6]. The Q value of about $5 \cdot 10^{7}$ at T = 4.2 K was measured during the low level tests.

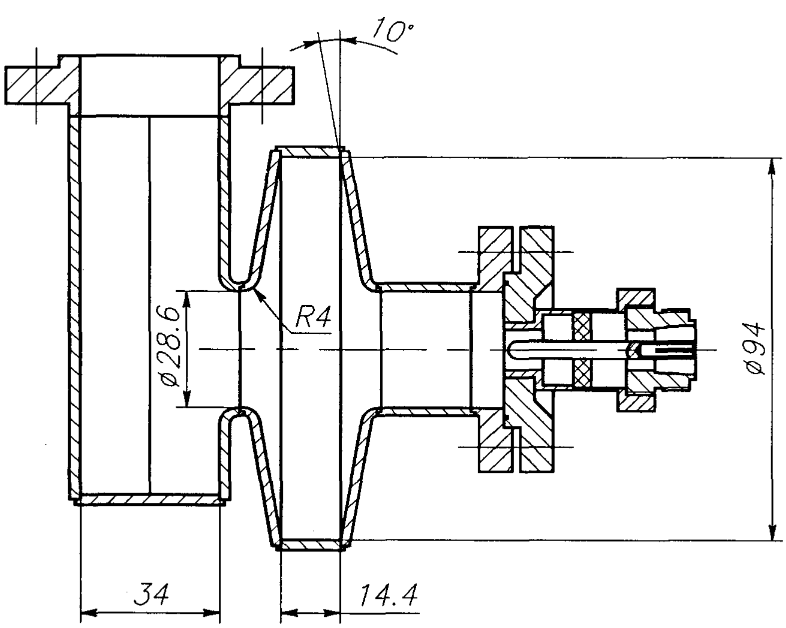

Fig.5:

Single cell cavity for high power pulse tests.

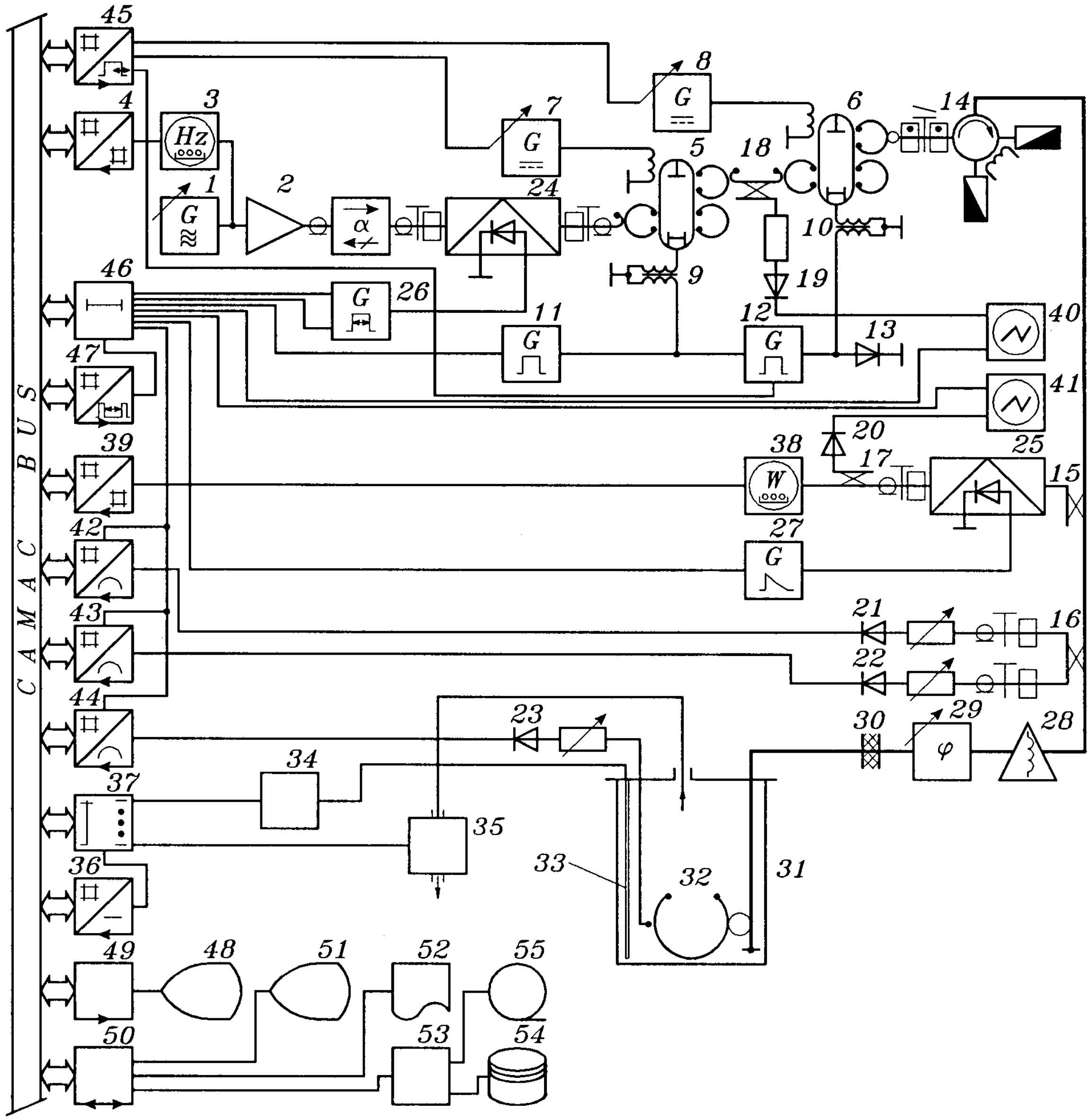

Fig.6: *Block diagram of the setup for single cell cavity tests*

1,2 – master oscillator and amplifier; 3,4 – frequency counter and interface; 5,6 – klystrons with focusing solenoids; 7,8 – power supplies for focusing solenoids; 9,10 – pulse transformers; 11,12 – modulators; 13 – high voltage diode; 14 – ferrite circulator; 15-18 – direction couplers; 19-23 – diode detectors; 24,25 – diode switches; 26,27 – control electronics for switches; 28 – inductive iris; 29 – phase shifter; 30 – ceramic window; 31 – cryostat; 32 – cavity; 33,34 – liquid helium level monitor with electronics; 35 – device for helium evaporating rate measurement; 36 – ADC (16 bit, 20 ms); 37 – analog multiplexer; 38,39 – power meter and interface; 40,41 – oscilloscopes; 42-44 – ADC (8 bit, 50 ns); 45 – code-to-PWM signal converter; 46 – generator of delayed pulses; 47 – timer; 48,49 – colour VDU and interface; 50 – microcomputer; 51 – console; 52 – printer/plotter; 53-55 – central computer with hard disc and tape archives.

The block diagram of the setup for the high level pulse power tests of the cavities is shown in the Fig.6. The cavities are tested in a vertical cryostat which has a diameter of 300 mm and a volume of 60 l. The part of the waveguide placed inside the cryostat is made of a thin stainless steel tube of the elliptical cross-section. It is corrugated for the stiffness and copper plated from inside. The heat loss of the cryostat with the cavity is about 0.7 W.

The coupling of the cavity to the waveguide is very strong in order to obtain high fields in the cavity for a short pulse duration. The loaded Q of the cavity is about 10^4.

The maximum cavity field levels were determined by breakdowns or cavity pulse shape distortion occurrence. Normal pulse shape is shown in Fig.7a, a distorted one is shown in Fig.7b. A possible cause of this distortion is multipactoring.

Up to now one single cell cavity is tested. Tests verified the possibility to achieve high accelerating gradients in superconducting cavities for very short pulses (some microseconds). For a pulse length of 1.5 µs an accelerating gradient of 29 MV/m was obtained.

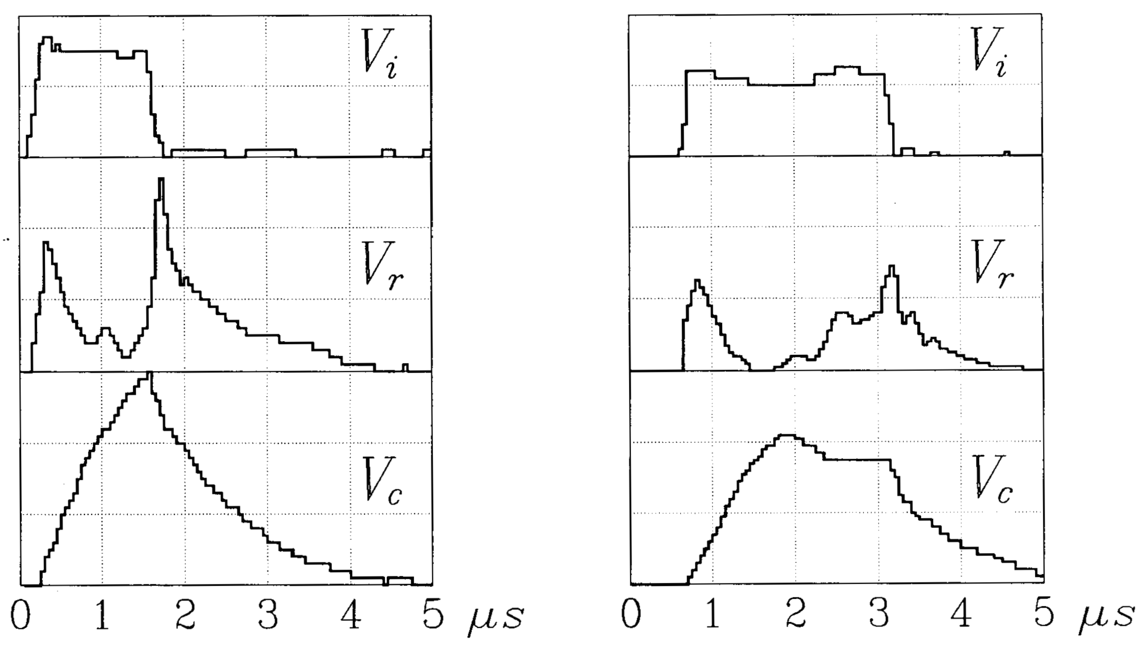

Fig.7: *Pulse patterns of the incident wave field, the reflected wave field and the cavity field.*

a) - normal operation; b) - multipactoring in the cavity.

Conclusion

The design of the accelerating structure, the cryostat, the electron gun, different parts of the linear accelerator is completed. Short pieces of the structure were fabricated for mastering the fabrication procedure. Main parts of the accelerator are being fabricated. Single cell cavities were constructed and tested.

References

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