D.V. Efremov Institute, STC "SINTEZ", Plasma-Facing Components Laboratory

Proposal

on R&D work "Shock wave simulation in liquid-metal targets"

1. Introduction

The large-scale project of the “Muon Collider” required that a new-generation target device be developed, which will provide an appreciable lifetime during interaction with a powerful beam of high-energy protons. The selected concept of a target in the form of a liquid metal jet collinear to the extracted beam, comply with the main requirements imposed on the target unit, but one of the important problems is the behavior of the liquid metal target after interaction with the proton beam.

Energy left by the beam in the target after interaction about 1 ns long duration is converted partially to shock waves that disturb the surface of liquid metal and might cause the target to fail. Fragments of the failed target might damage the target unit elements, in particular 20T solenoid and make circulation difficult in the liquid-metal loop that forms the targets with a frequency of 15 Hz. Computer modeling of interaction between the target and beam does not give the detailed description of the process, therefore experimental investigation of behavior of liquid metal surface under radial shock waves is to clarify this situation.

The D.V. Efremov Scientific Research Institute of Electrophysical Apparatus has got a wide experience in developing various electrophysical apparatus. Thus, the facilities UTRO (θ-pinch, with parameters I_{max}~1.5 MA, $U_{discharge}$~80-100 kV, dI/dt~10^{11} A/s, τ_{pulse}~10 μs) and LIRA-M (pulsed electron accelerator, $I_{discharge}$~100 kA, U_{pulse}~450 kV, τ_{pulse}~0.5 μs) have been developed and manufactured at the Institute. A wide experience has been also acquired in developing high-voltage switches (high-pressure and vacuum), facilities with plasma and explosive foil opening switches (facilities UTRO-M, IREN, FOBOS). Various electromagnetic pumps (MHD-type) with a flow rate from 2.5 to 3600 m^3/h and a pressure of 0.4-1.6 MPa, as well as electromagnetic valves have been developed and manufactured. They are intended mainly for pumping over liquid sodium and potassium in nuclear facilities and reactors at temperatures of 300-500°C. There is also experience in working with liquid gallium and mercury.

The test facility LIS-12 operates at the Institute, which is intended for testing of superconducting wires in the magnetic field with an intensity up to 12 T and energy of ~1.6 MJ. The superconducting magnet with a field up to 7 T operates at the Institute, the like magnet was delivered to the firm “Quantum Design” (USA).

The staff operating the VIKA-M stand facility have acquired exceptional skills in high-speed diagnostics (two-dimensional field shooting with a speed up to 4 million shots per second) and laser interferometers.

2. Mechanisms of shock wave generation in liquid metal jet

The analysis of methods of production of appreciable rapid-growing forces in small volumes shows the electrodynamic capacitor systems to be preferable. Medium scale pressures inside the metal jet can be produced by generating a strong pulse magnetic field, higher pressure in-site will require phase transitions in conductors, i.e. an electric explosion. Strict time constraints on generation process duration, less than 1 μs, i.e. hundreds or even tens of nanoseconds, impose, in its turn, constraints on inductance of the discharge circuit. A low-inductance coaxial load, one end of which is shorted and the other is connected to a pulse-current generator, comply with these requirements to a greater extent. In case an electric explosion is used, a design for fast replacement of the load unit should be provided.

3. Brief description of the facility (Fig. 1.)

The facility includes:

1. Liquid-metal loop with a vacuum pump, flow pipe, flow nozzles for organization of the jet around a shock-wave generator, loop heating system with Ga used, a filter for purification from oxidation products, system for collection and evacuation of splashes during jet destruction (Fig. 2.). A receptacle-suppressor of kinetic energy of the jet and a tank for drain of and filling the loop with liquid metal are also provided. To replace the loading unit it is necessary to drain liquid metal from the loop connected to the tank through the system of communicating vessels.
2. Capacitor with a low-inductance collector and controlled capacitance. Controlled capacitance is need for changes of energy and profile of shock wave.
3. Load unit for connection to collector of various generator types. Fig.3 shows one of the version of a shock-wave generator, where a wave is generated by a pulsed magnetic field. This version is easy to change for a wire-explosion generator that develops higher pressures of the shock wave.
4. Quick-operating switch.
5. Power supply for capacitor.
6. The vacuum system is intended:
   - to facilitate filling with and drain of liquid metal from the loop;
   - to provide convenience when using an inert gas (pumping, not blowing);
   - to provide tightness necessary for work with toxic materials;
   - to reduce intervals of metal purification process.
7. The diagnostic complex comprises the high-speed camera for recording of the following phenomena:
   - metal surface vibrations;
   - drop detachment and jet decomposition;
   - measurement of radial and axial velocities of the jet, fragments and drops.

   The complex provides:
   - electric measurements of current and voltage for control over energy input of the jet;
   - measurement of the falling jet velocity;
   - measurement of liquid metal temperature.

   (Note. A laser interferometer can be used to measure the jet surface velocity.)
8. The control system comprises:
   - meters for discharge voltage and vacuum;
   - control systems of the vacuum lock valves, pump for liquid metal pumping over and lighting for the high-speed camera;
   - system for emergency energy extraction from the capacitor;
   - start-up system for fast switch-on.

Note:

In the process of designing the construction may undergo changes. Possible is the version, when the jet falls on the shock-wave generator (the inverse version of the facility) and the jet can be discontinuous, i.e. switched by fast-acting lock valves. The design provides also for easy-to-replace flow nozzles to vary the diameter of the falling jet.
The final selection of the generator design (wire explosion or not) will be made on the basis of the results of simulation and first experiments.

4. Time step.

1. Replace the load node on capacitor collectors with the new one, install the switch from above.
2. Test the load unit for tightness, prepare the switch for work at high voltage.
3. Pump the vacuum chamber.
4. Fill the loop with liquid metal.
5. Set the flow rate providing the jet with necessary parameters, visual control through the vacuum viewport.
6. Select the required capacitance of the capacitor, charge to the required voltage.
7. Start to necessary recording speed of high-speed camera.
8. Provide lightning of the jet. - High-speed shooting (photograph) requires an intense lighting of the shooting site. For this purpose use is made of pulse gas-discharge lamps synchronized in time with the work of the high-speed camera and shock-wave generator.
9. Start up the shock-wave generator synchronously with the camera.
10. Switch off the high-speed camera.
11. Switch off the pump of the liquid-metal loop.
12. Evacuate liquid metal from the loop into a tank.
13. Puff atmosphere into the vacuum chamber.
14. If necessary, clean or replace the viewports with all due precautions taken, since liquid metal is toxic.
15. Disassemble the switch.
16. Remove remainders of the load unit.
17. Assemble the vacuum chamber.
18. Remove the recorded photographs out of the camera for further development, scanning and analysis and reload it for the next experiment.

5. Estimated cost of facility development

1. The shock-wave generator with the capacitor, collector, switch, load node, charging device - USk$ 30.
2. Vacuum chamber equipped with an open loop with liquid toxic metal, system for pumping and filtration of emissions to the level of sanitary norms - USk$ 20.
3. Loop for liquid metal circulation with a pump, jet former, receptacle-suppresser of jet kinetic energy, tank, loop heating system - USk$ 20.
4. Materials - USk$ 10.
5. Diagnostics, control - USk$ 95.

Total cost: USk$ 95.

The cost of experiments, as well as the related safety measures, when operating with liquid metals, will depend on the scope of necessary research works.

6. Future upgrade

Later on, while expanding the scope of investigations it is possible to install coils of pulse magnetic field, to perform detailed investigations into the jet behavior using piezoelectric transducers located in the area of acoustic contact with the jet. When analyzing the signal spectra from these transducers it is possible to study the cavitation phenomena inside the jet (invisible for the high-speed camera).

Dates of facility start-up after the signing of the contract - 6 months.

7. Communication

For any questions, discussions and proposals please, contact with:

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Figures:

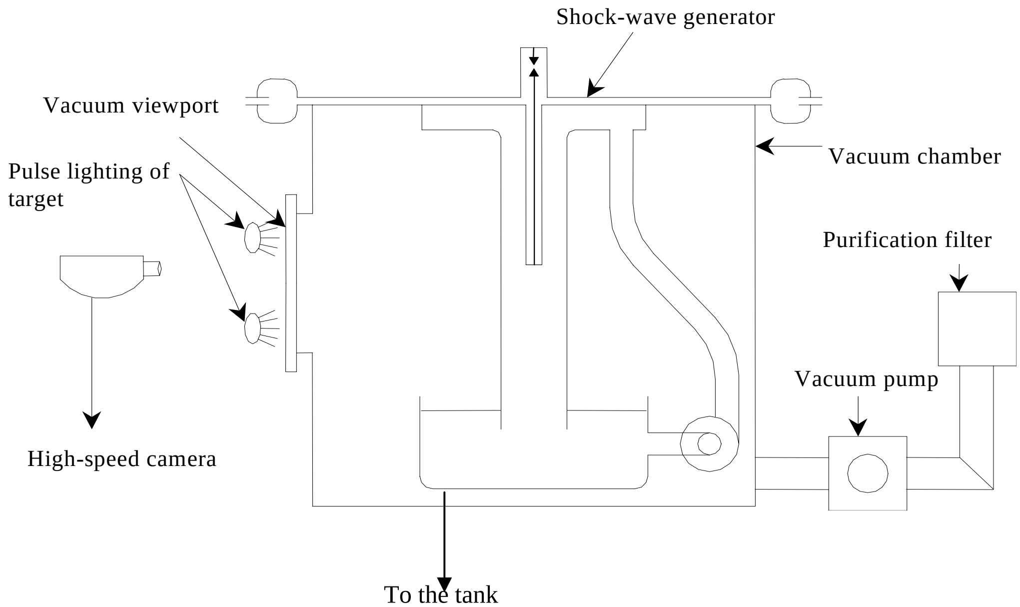

Fig. 1. General view

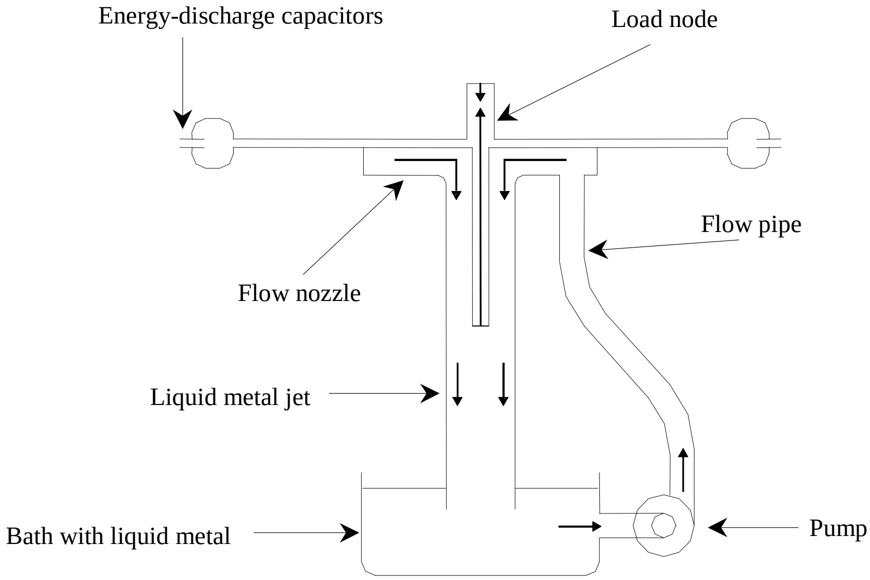

Fig. 2. Liquid metal loop

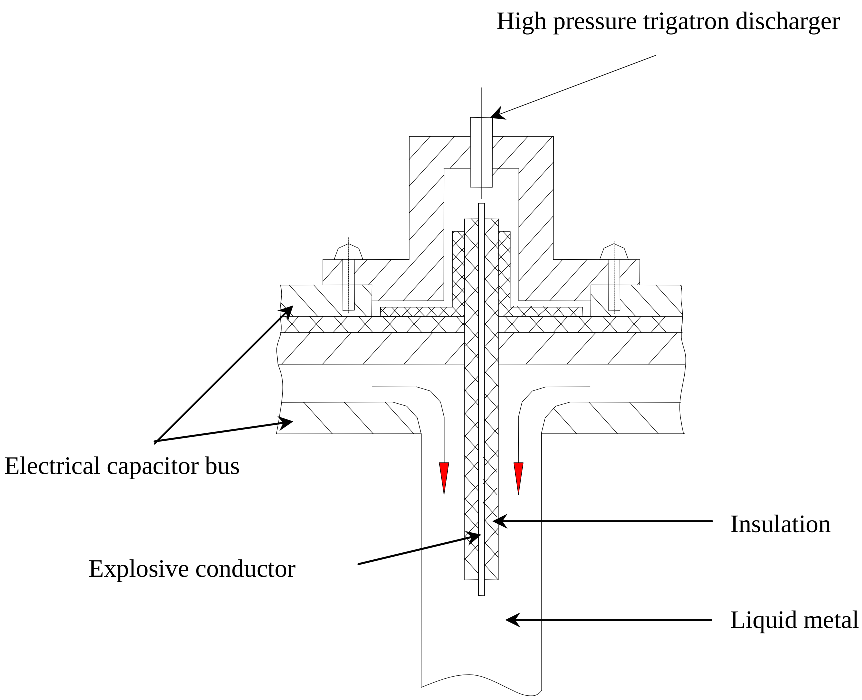

Fig.3. Load unit. Variant with reverse current over jet