Pulsed particle beam high pressure/shock research in India

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Abstract. We have two major facilities for particle beam driven shock wave/high pressure generation. One being AMBA and the other being 1.2MJ capacitor bank RUDRA. Apparatus for Mega-Ampere Beam Application which is known as AMBA is now with India and the experiments are being planned from the facility for the shock wave and high pressure studies using the AMBA for intense light-ion beam generation and then bombarding them on a flyer target. To enhance the AMBA machine to double the output current is also under consideration. AMBA is a pulsed power source which delivers 50kJ of energy in 50ns with 1.7 MV minimum peak voltages maintained as an average of various shots in the case of positive polarity output in a suitable ion-diode. The output impedance of the AMBA machine is 2.25ohms and hence it is a 1.5 TW machine. With peak power densities up to ~1TW/cm², and proton ranges in condensed matter of 10 to 20 μm, specific energy depositions of several MJ/g at deposition rates of the order of 100 TW/g are obtained. This way the AMBA system can be used as a shock wave generator in both, direct drive and impact experiments. We also have 1.2MJ capacitor bank capable of delivering 3.6MA peak current at 44kV charging voltage to be used for Magnetized target fusion based on z-pinch regime of target material compression. The related diagnostics for the system, which are currently being developed, are mentioned in the present paper. Both the systems and the high pressure experiments to be conducted are described in the paper. A brief detail on the plasma focus devices, which also produce shock waves using particle beams, is also presented in the paper.

1. Introduction
The shock wave studies are mostly done using gas-gun, rail-gun and electric-gun [1] or high-power lasers [2]. Similarly the particle beams have also shown the potential of driving the projectiles to a velocity as high as 10km/s using electron and ion-beams. AMBA setup in India will be one of this kind of facility for the particle beam generated shock/high pressure studies. The other major facility RUDRA which is 1.2 Megajoule capacitor bank is also the largest capacitor bank facility of its kind for the similar experiments.

2. AMBA pulsed power machine:
The AMBA generates a high-voltage output pulse and applies to the ion-diode working as load in the following steps:
(1) A capacitor bank of 50 energy storage capacitors, connected in a Marx generator circuit, is DC charged to a level of up to 200KV (using a ±100 KV);
(2) The Marx generator is electrically triggered and generated impulse charges a water-insulated intermediate storage capacitor in a time period of about 800 ns;

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The energy is transferred for the second time to a 2.25-Ω PFL in about 175 ns;

(4) The PFL is discharged by a low inductance switch generating an output pulse that is finally conducted to the load by a matching 2.25-Ω transmission line.

Figure 1. AMBA component assembly scheme

Figure 2. AMBA electrical Schematic

Figure 3 AMBA; MARX erection scheme

Figure 4. AMBA; Marx bank assembly

2.1 The AMBA machine: Marx Generator

The primary energy storage is a 25-stage Marx generator, which can store 250 KJ at maximum charge level. Each stage of the Marx generator consists of two numbers of energy storage capacitors of 1 microfarad charged from a bipolar power supply up to ± 100KV. In each stage a spark gap switch is also present which is pressurized with sulfur hexafluoride gas. All the 25 stages are arranged in a hybrid Marx circuit. This scheme derives its name from the fact that it combines the features of the capacitance Marx circuit and the resistively triggered Marx circuit.

The mechanism referring to these designations causes the spark gaps to successfully break down and discharge the generator into its load. In the capacitance Marx circuit, high-voltage transients generated by the firing of previous stages are coupled through stray capacitances to succeeding spark gaps, causing them to break down. In the resistively triggered Marx circuit, each spark gap contains a triggering electrode connected to successive stages through a coupling resistor. As each stage fires, one trigger pulse is generated that is applied to the unfired spark gap. The hybrid circuit uses both of these mechanisms to achieve very reliable Marx triggering during the operation at less than 50% of the self-firing voltage. Components of the hybrid Marx are arranged in such a way that the current discharge path doubles back on itself in zigzag fashion and, by so doing, maintain a relatively low generator inductance.
The basic schematic of a representative portion of a hybrid Marx generator is shown in Figure 3. The circuit in this figure is simplified by omitting the charging circuits. The Marx circuit is suspended in the insulating oil in seven columns of three stages and in two columns of two stages. The nylon suspension straps are attached to the capacitors with special quick-release mechanisms to facilitate ease of installation and removal. The generator is positioned off-center within the tank to reduce electric fields in the vicinity of the capacitor bushings and to allow space for servicing. Figure 4 is the photograph of the Marx generator. A small two-stage Marx trigger circuit suspended in the Marx tank triggers the Marx generator. The trigger circuit is dc charged to 90kV (±45 kV) and is triggered by another trigger generator. The output of the Marx trigger circuit is resistively connected to the trigger electrodes of the first three spark gaps of the main Marx generator, while the remaining spark gaps are resistively coupled to each other.

2.2 Pulse Forming lines
The output pulse of the pulsed power system is generated in three stages: (a) energy is transferred from the Marx generator to a water-insulated intermediate storage capacitor in about 800 ns; (b) it is then transferred a second time to the PFL in less than 200 ns; (c) the charged PFL then is discharged to the load through a matching transmission line. This three-stage process allows for a more efficient design of the pulse-forming system by taking advantage of the time dependence of the electrical breakdown of water.

The intermediate storage capacitor is a coaxial transmission line with dimensions chosen to minimize the electric stress in the water. The minimum electrical stress occurs for an infinite line when the ratio of the diameters of the two conductors is equal to the constant e. This ratio would represent an impedance of 6.7 Ω with water which is used as the dielectric. The optimum value is more on the order of 4.5 to 5 Ω because of local field enhancements at the ends of lines and the polarity effects. The intermediate store impedance for the system is chosen at about 5 Ω, and length is chosen so that the capacitance is about 16 nF when fringing fields at the ends are taken into consideration. Transfer of energy form the intermediate store to the PFL is accomplished with a self-closing water spark gap on the axis of the machine between the two lines. This switch has one fixed electrode and one that is adjustable by means of a hydraulic actuator controlled from outside of the machine. The operating voltage then is raised or lowered by remotely increasing or decreasing the distance between the electrodes. The output impedance of the PFL is 2.25 Ω and the electrical length is 50 ns. The PFL is also charged at nominal power to 3.6 MV, the same level as that of the intermediate store. A low inductance switch at the output end of the PFL generates the output pulse by discharging the PFL into the first transmission line. Triggering electrodes are located on the output switch between the main electrodes, which are connected to a master trigger switch. Each trigger electrode is maintained at a potential that reduces field enhancement at its edge during the time that the PFL is being charged. When the desired voltage level is reached on the PFL, the master-trigger switch closes, abruptly...
changing the potential of each of the trigger electrodes. A large field enhancement is produced at the edges of the trigger electrodes, thereby initiating rapid closure of the output switch. The output pulse is conducted from the PFL to the diode through two lengths of matching 2.25-Ω transmission lines that are separated by a pre pulse switch. This pre pulse switch consists of 11 gas-pressurized spark gaps that are adjusted to withstand the pre pulse voltage levels, but rapidly synchronously break down when the main output pulse arrives. Following the pre pulse switch is the second length of transmission line, which connects to the diode assembly.

The system with similar parameters as that of AMBA is used as a shock wave generator in both direct drive and impact experiments [3,4] , delivering up to 40 kJ of proton beam energy to a 7- to 10-mm-diameter focal spot. With peak power densities up to ~1 TW/cm², and proton ranges in condensed matter of 10 to 20 μm, specific energy depositions of several MJ/g at deposition rates of the order of 100 TW/g are obtained. Aluminum foils of 10 to 30 μm thickness had been accelerated to velocities beyond 12 km/s. Within an uncertainty of ~5%, the threshold pressure was found to be 64 GPa for aluminum, 136 GPa for copper, 86.5 GPa for titanium, and 252 GPa for molybdenum. We will use this system as a shock wave generator for further study in the field of hypervelocity impacts and equations of state. The experiments that will be done include the Hugoniot measurements and measurements at unloading of shock-compressed state down to the vaporization region. Figure 5 presents the images of ion-diode and Marx capacitor bank of the AMBA machine. To generate high-power focused ion beam pulses, electrical energy is converted into particle beam energy in ion diodes. With peak proton energies of ~1.7 MeV, specific power densities of up to 200 TW/g and energy densities of several MJ/g can be realized at ~40 ns FWHM. The massive energy deposition in a zone of 5-10 mg/cm² leads to fast vaporization and ablation of the material and causes intense compression waves to propagate into the residual part of the target. In this way thin foil plates with a thickness of several tens of micrometers can be accelerated to velocities larger than 10 km/s.

We are also trying to upgrade AMBA machine to AMBA+ which will have two AMBA machines driving a single load simultaneously and thereby increasing the output power.

3. RUDRA 1.2Megajoule Capacitor Bank:

A capacitor bank named RUDRA is installed and commissioned in our laboratory. The 1.2MJ capacitor bank consists of 24 nos. of capacitors with stored energy of 50kJ each. At the charging voltage of 44kV, each capacitor can deliver a peak current of 150kA and the voltage reversal is limited to 10%. The equivalent series inductance (ESL) of the capacitor is rated as 70nH. In order to segregate the coulomb transfer loading on switches and to minimize the effective circuit inductance, the capacitor bank is subdivided into modules. There are six modules and four nos. of capacitors are connected to each module by parallel plate transmission line assembly (which further couples to Railgap switch). The individual Railgap switches are capable of transferring maximum 10 coulombs.
of charge at a peak current of 750kA with a jitter of <2ns. The output of all modules terminates to
centralized collector plate through RG218 cables. The schematic of implemented configuration of
1.2MJ Capacitor Bank and the actual modular layout of bank has been shown in Fig. 6 and Fig.7
respectively. Other than RUDRA capacitor bank we also have small energy capacitor banks.
RUDRIKA is another capacitor bank of 136kJ and is faster bank capable of delivering 3.6MA in short
circuit configuration. It is shown in figure 8.

![RUDRIKA: 136kJ capacitor bank](image)

CHANDI (80kJ) and CHANDI-II (160kJ) capacitor banks are shown in figures 9 and 10 respectively.

![CHANDI (80kJ) Capacitor Bank](image)

![CHANDI-II (160kJ) Capacitor Bank](image)

We are upgrading the RUDRA Capacitor bank to RUDRA-II to make a 2.4 MJ capacitor bank which
will have double the energy as compared to RUDRA bank and will be capable of delivering near
double the currents. The application of this capacitor bank for high pressure studies is mainly in the
fields of high energy plasma focus and in the z-pinch implosion studies. In the z-pinch implosion by
high current capacitor banks, a cylindrical metallic target is compressed using the interaction of z-
direction current with the theta-direction magnetic field. The targets are usually thin metal cylinders or
a metallic coating on some cylindrical insulator. The current is passed through these cylinders. As the
z-current interacts with the theta- magnetic field, the liner starts imploding. At the end of this radial
motion, the plasma collides with itself in small radius column and kinetic energy gets converted to
thermal energy increasing the temperature and pressure in the interaction region.
We are following two schemes for theta-pinch type high magnetic field/pressure generation which are depicted in figures 11 and figure 12 respectively. With RUDRA capacitor bank, we presently have 500 Tesla pulsed magnetic field facility and we aim to extend it to 700 Tesla by making RUDRA-II capacitor bank in case of directly driven single turn coil configuration. Using Flux compression scheme we expect to get 1000 Tesla by using RUDRA-II capacitor bank. Presently we are getting uneven compression, as is shown in figure 13, and working for achieving uniformity in compression. Other application of the capacitor bank is MTF/MAGO [5] like experiment which involves particle driven shock and high pressure research. In the direction of plasma focus also the capacitor bank is aimed to be used for generation of ion sheath, acceleration of it to create a plasma focus spot. In the both phases of acceleration namely axial acceleration phase and radial compression phase, the velocities of plasma sheath are very high and shock waves propagation takes place during the event.

4. References

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