MAGNET PLUNGING SYSTEM FOR THE BEVATRON EXTERNAL PROTON BEAM*

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Summary

As part of a recent 9.6-million-dollar improvement and modernization program, an external proton beam was created for the Bevatron. During the period 1960 to 1963, the equipment necessary to produce this beam was designed, fabricated, and installed. The first external beam emerged from the Bevatron in February 1963.

Introduction

The Bevatron is one of the leading instruments used in high-energy physics research and has occupied this position since starting operation in 1954. In order to maintain this high standing, a recent 9.6-million-dollar improvement and modernization program was undertaken. An important feature of this project was the creation of an external proton beam. The general scheme for producing an external proton beam is based on earlier studies by Wright,[1] Piccioni,[2] Chupp,[3, 4] Wenzel,[4, 5] and Lambertson.[6]

The external proton beam has provided many desirable features:

(a) There is a substantial increase in the flexibility with which experiments can be designed, set up, and run.

(b) In the absence of the limitations of magnetic field and geometry imposed by the Bevatron magnet, the experimenter has a much wider choice of targeting, including the use of liquid hydrogen.

(c) Secondary particles with positive, negative, and neutral polarities are more accessible over a wider momentum range and solid angle.

(d) More accurate monitoring of the beam is possible.

(e) Detectors can be placed closer to targets to study short-lived secondary particles.

Description of Beam Extraction

The extraction scheme used is basically a two-magnet achromatic extraction system[7] with an energy-loss target and two hydraulic devices to thrust the magnets into and out of the Bevatron aperture.

A set of magnets (bending magnet M-1 and focusing magnet Q-1) is placed in the east straight section (Fig. 1). A larger set of magnets (bending magnet M-2 and focusing magnet Q-2) and the energy-loss target (usually a small block of beryllium) are placed in the south straight section. The rest positions of the magnets and target are out of the beam aperture. This is necessary because at injection, the circulating protons occupy most of the 12-in.-high by 48-in.-wide gap of the Bevatron magnet. The target and magnets cannot be placed permanently in position for extracting the protons because they would intercept and destroy the injected beam. During accelleration to full energy, however, the beam size shrinks to 1 in. high by 4 in. wide, and circulates about an equilibrium orbit in the aperture. The magnets are moved into the beam aperture in a programmed fashion so that they follow, but do not interfere with, the decreasing width of the accellerating beam. A short time before extraction, the target flips up to the median of the accelerating gap. By the time the protons have reached the desired energy, the target and magnets are in position. The beam is then steered onto the target (Fig. 1). The particles that go through the target experience a slight decrease in energy, which causes them to execute radial oscillations about a smaller equilibrium orbit. Half a betatron wavelength later (when they are at their minimum radius), the particles enter M-1 and Q-1 in the east straight section. M-1 deflects them 4 in. inward to M-2 and Q-2 (in the south straight section). M-2 then deflects them outward 38 in., where they emerge through a 0.020-in.-thick aluminum "thin window" in the upstream end of the west straight section. A bending magnet M-3 and a doublet focusing magnet Q-3 A & B are placed immediately downstream from the "thin window." M-3 is required to deflect the beam farther outward so it will miss the downstream end of the west straight section.

Because the Bevatron magnet is an "H" type, the geometry is such that it was impractical to deflect the protons outward far enough to miss the leg yokes of the magnet. Therefore, four of these leg yokes were modified to allow the installation of a beam tube (a 4.5-in. o.d. by 4-in. i.d. length of steel tubing) through which pass the protons. The focusing magnets, together with the fringe field of the Bevatron magnet, combine as a quadrupole system to focus the beam at a point approximately 2 ft beyond the leg yokes. Once the protons have been extracted from the Bevatron, the magnets are retracted and the target is lowered to await the next acceleration cycle. The cycle repeats 12 times per minute at the maximum beam energy of 6.2 BeV. A beam extraction efficiency of 50% is attainable at full energy. However, the extraction efficiency that is obtained in actual day-to-day operation is determined by a variety of running conditions and in most cases is less than 50%.

In 1959 the plunging magnet specifications were defined by the Bevatron staff, using both computer programs and the experimental results of early extraction tests.[6] In late 1959, we of the mechanical engineering department were asked to design the magnets and associated mechanical apparatus that would accomplish the extraction of the proton beam.[8, 9] The devices that were constructed to plunge these magnets into the Bevatron aperture and retract them are hydraulic cylinders with a great deal of related equipment, and as part of the improvement program were installed during a 7-month shutdown starting in July 1962.

The Bevatron, by nature, is a very flexible machine, as it must be for the type of research for which it is used. Therefore, the mechanisms that we designed had to be versatile, flexible, easily adjustable, and reliable in order to match the operating conditions of the Bevatron. It is the purpose of this paper to describe the mechanical details and operational features of these plunging devices.

Description of Plunger

The moving system in the east straight section weighs approximately 1500 pounds and the apparatus in the south straight section weighs about 8000 pounds. Both must plunge 28 in. in 750 milliseconds with a high degree of end-position accuracy and repeatability. The actual measured end-position repeatability is 0.0005 in.

The prime mover for these two plungers is a 4-1/8-in.-diameter by 28-in.-stroke hydraulic cylinder operating at 750 psi (Fig. 2) and supplied with oil from an accumulator filled by a vane-type variable-volume pump with a maximum output of 35 gpm. The controller for the 28-in. stroke is comprised of a rotary torque actuator, also supplied with oil from the accumulator, and controlled by a four-way solenoid valve, a control arm, and connecting linkages. The torque actuator moves the control arm as a simple crank, with the rotation being restricted to 180 deg by stops (Fig. 3). This control arm provides the "command" input for the desired magnet position as a function of time. The speed of rotation of the control arm, and therefore the plunge velocity, is regulated in both directions (clockwise and counterclockwise) by flow control valves that govern the flow of oil to the torque actuator. The control arm actuates the linkage, which moves a four-way piston-type mechanical servo valve. The movement of this servo valve controls the oil flow rate from the accumulator to either side of the power piston. At the same time, it vents oil from the other side of the power piston to the return line. However, this valve is also moved by the power piston in such a manner that the piston cannot travel faster or slower than the torque actuator dictates. This provides the mechanical feedback to the servo valve.

Figure 4 shows the start of a plunge. An electrical signal opens the four-way solenoid valve, admitting oil to the torque actuator. Rotation of the control arm and subsequent linkage movement opens the servo valve, admitting high pressure oil to the backside of the power piston. The piston at first remains at rest because of the high magnet inertia. Shortly after the initial servo valve movement, the piston starts to move. Near the end of its stroke, it overshoots the controller position and pulls the servo valve back across the ports, as illustrated in Fig. 5. This motion admits high pressure oil to the forward side of the power piston, at the same time venting pressure from the backside. The piston now comes to rest in a controlled manner in the plunged position, as depicted in Fig. 6. To retract the magnets, the cycle is repeated in the reverse direction.

When the servo valve is pulled across the power cylinder ports, there is a momentary oil blockage which results in a very high pressure surge (2000 to 3000 psi) in the cylinder. We provided pop-off valves (not shown) to relieve this high pressure. They vent the high pressure oil into the return line. The entire combination of controller, accumulator, servo valve, and cylinder is called the hydraulic actuator.

A 6-in. o. d. by 1-in. wall by 13-ft-long chrome-plated probe tube provides the mechanical connection between the hydraulic cylinder shaft and the magnets. A ball joint at each end of the probe tube allows it to adjust to any misalignment and prevents bending of the tube. Since the hydraulic actuator is outside the vacuum tank and the magnets are inside, under a vacuum of 2×10^{-6} mm of Hg, the probe tube passes through a 6-in. chevron-type vacuum seal. The seal is evacuated by a vacuum pump to approximately 10 microns. Lubrication for the seal assembly is by gravity feed from a similarly evacuated 3-gallon reservoir. The chevron seal assembly is mounted on a gimbal ring and bellows combination which allows it to float on the probe tube. This insures that there is no radial load on the seal due to misalignment--a very important factor in seal longevity. The chevron seal—gimbal ring—bellows assembly is held in a housing (not shown), which rests on the frame that supports the plunging mechanism. This frame is supported by a sliding connection at the straight section and by a pin connection at the wall.

The magnets are contained in a steel box that is mounted on a cart and to which the inner ball joint is attached. This cart rides on hardened and ground steel rails that are rigidly mounted inside the east and south straight sections.

Electrical power for the magnets is supplied to the two fixed bus bars shown in Fig. 2. Twenty-four flexible cables are attached to the bus bars and are wrapped (in alternating directions) half way around the cable drum, terminating at two more bus bars on the cable tray. The cable tray is clamped to the probe tube. The cable drum rolls back and forth on the cable tray as the mechanism plunges, and maintains the proper tension on the power cables. The cable tray bus bars extend below the tray and clamp to six water-cooled copper conductors, 5/8 in. o. d. tubing by 0.095-in. wall, that pass through the center of the probe tube. A compression seal in the outer end of the probe tube prevents air leakage around the conductors.

The length of stroke of the plunger is fixed by the design of the hydraulic cylinder. Since one of the requirements of this system is that it be usable for many beam conditions, the position of the magnet at the end of the plunge must be adjustable. We accomplished this by using a worm-gear jack screw powered by a reversible motor. This mechanism moves the complete actuator and probe tube so that the entire 28-in. stroke (and therefore the magnet position) changes its radial position. The power piston still travels to the end of the hydraulic cylinder, so that precise control is maintained. The jack screw can be operated at the plunger or from the Bevatron control room, and moves the magnets at a rate of 2.5 in./min. Total jack screw range is 6 in. The magnet position readout consists of a vernier scale on the magnet cart, a selsyn motor on the jack screw, and a selsyn motor-Veeder-Root counter combination in the control room. The vernier and counter are calibrated to indicate the radial position of the center of the plunged magnet gap. The vernier provides a standard position calibration for the counter. Times of arrival at the plunged and retracted positions are monitored by microswitches, their signals being displayed on an oscilloscope in the control room. A final 1-in. retraction, in addition to the 6-in. range, is provided with the jack screw which pulls a tapered sleeve (not shown) on the probe tube back into an O-ring seal in the wall of the straight section. This backseal maneuver allows us to change the chevron seal without letting the main vacuum tank up to air pressure.

Safety Devices

We have stressed safety, both mechanical and personnel. There is a main power switch for the entire mechanism that must be operated with a key. This key must be obtained from the crew chief, thus insuring that only authorized personnel will operate the equipment.

We have a series of interlocks called a "chain." Warning lights on a control panel indicate any abnormal condition. These interlocks must all be in the permissive condition, which completes the chain, in order for the pump to be started and the magnets plunged. If the pump is running, and any link (interlock) in the chain is opened, the pump trips off and stops the plunger.

As a safety shutdown device, we installed a two-way solenoid-operated valve in the controller oil system. When any of the various safety interlocks mentioned below is actuated, the pump shuts off, the accumulator is vented, and the two-way solenoid valve closes, blocking the flow of oil to the torque actuator. Thus the controller motion is stopped and the servo valve now seeks a neutral position, blocking the cylinder ports. This blocks the power piston and stops all movement. This is called stopping on a "crash-off" basis.

The apparatus can also be "crashed off" manually by pushing either a button on the plunger itself or one in the control room.

We developed crash pads (Fig. 7) to protect the equipment in the event either the magnet or actuator should break loose during the plunge. These crash pads consist of pointed steel pins and sheet steel membranes. If the pins were struck by a part that had broken loose they would in turn puncture the membranes. The kinetic energy of this moving mass would be dissipated as the pins punctured and deformed the membranes.

We actually tested the crash pad that would have to stop the largest mass, the 8000-lb M-2-Q-2 combination. Such a mass was crashed under operating conditions and was decelerated with a loading of only 1.5 g (1.5×32.2 ft/sec^2). One of the most important requirements of these pads is that, should they be actuated, the deceleration must be low so as not to destroy the magnets. We have microswitches on each crash pad so that if one were actuated, the plunger would stop on "crash-off." We should point out that we hope the crash pads are never needed, and because of the conservative design policy that we employed, in all probability they will never be used. However, the protection is there.

The gimbal-ring housing is held in place by two shear pins designed to fail at a load slightly higher than the frictional drag between the chevron seal and the probe tube. If the seal should sieze on the probe tube, the housing would move, shearing the pins. A housing movement as small as 1/16 in. would be detected by a microswitch, and the plunger would crash off. This protection would minimize the damage to the seal or probe tube or both by immediately stopping the plunging motion.

We have a cover (not shown) over the entire 30-ft length of the plunger. This cover is for mechanical and personnel protection when the machine is in operation. If any portion of this cover is open, the chain is broken and the pump cannot be started. The plunging chain is so designed that it must be complete before the magnet power can be turned on. This insures that the bus bars under the cover will not be "hot" when people are working on the mechanism. When the main vacuum tank is at air pressure, the pump cannot be started nor the magnet power turned on. This insures that no one can be injured when working inside the tank by the magnet' s being plunged or energized.

The clearances in the hydraulic actuator are critical. Large temperature variations can cause excessive expansions or contractions in the hydraulic system which will change these clearances and cause erratic operation. Therefore, the oil must be at a minimum temperature of 105° F or the "oil temperature low" interlock will not "make up." The pumps heat up the oil during operation--so much so that a heat exchanger is necessary to control the oil temperature. If the cooling water for this exchanger failed, the oil temperature would rise above the operating temperature. At 140°F an alarm bell would ring in the control room. If the temperature continued to rise to 145°F the pump power would be automatically shut off.

Other interlocks in the chain are for such conditions as oil supply pressure too high, oil supply pressure too low, return oil pressure too high, or oil level in the pump reservoir too low. If the probe tube is in the "back-seal" position, a microswitch breaks the chain. This insures that the equipment will not be plunged out of the seal. We have a smoke detector under the cover, connected to the building fire alarm system. If the detector is activated, the chain is broken, shutting down the equipment and sounding an alarm. There are also limit switches on the jack screw to prevent excessive magnet travel.

We provided a steel locking pin that anchors the power piston shaft to the plunger support frame and is strong enough to resist the full force of hydraulic pressure on the piston. If this pin is in place it insures that the mechanism will not be accidentally plunged. The safety pin also serves a second purpose. There is a vacuum pull of approximately 450 pounds on the probe tube; when the pump is off, there is no pressure on the power piston to hold it in the retracted position. Were it not for the pin, the magnets would be uncontrollably sucked into the Bevatron magnet aperture. We incorporated a spring-loaded, collapsible arm in the controller linkage. If the safety pin is accidentally left in place and the equipment plunged, the controller linkage simply compresses the spring-loaded arm, the power piston does not move, and there is no damage to the mechanism.

Comments

Because Bevatron operating time is extremely valuable, we could not afford to interrupt Bevatron operations with a plunger development program. Therefore, we built a prototype, tested it for one year, and then built the two operational units. The three plungers are identical, so that the prototype is available for spare parts and future development.

When the Bevatron resumed operation in February 1963, the external proton beam was used only 2 or 3 days per week until operational experience proved its dependability. Since July of that year, it has been in constant demand and use.

To date, both east and south plungers have operated 24 months (as of February 1965) and slightly more than 5 000 000 cycles. We changed the chevron seal on the south unit at 5 000 000 cycles, but the original seal in the east unit is still in perfect working condition. We had to change the power piston shaft seal and the accumulator piston seal on both mechanisms at 3 000 000 cycles. We consider the replacements of the seals on the piston shaft and the accumulator piston as normal maintenance.

Future Developments

The plungers were originally designed for a plunge rate of 12 cycles per minute, since this is the Bevatron repetition rate at full beam energy. The Bevatron, however, is capable of higher repetition rates at lower energies. The need has now developed for an external beam at these lower energies with a corresponding increase in plunge rate. Unfortunately the plunger is flow-limited, as the hydraulic pump is operating at its maximum output of 35 gpm at a "rep rate" of 12. The hydraulic power supply unit was designed with two identical pumps of 35 gpm capacity mounted on each end of a double-ended-shaft 20-hp motor. Originally only one pump at a time was to be connected, the other serving as a spare. We can speed up the plungers to 15 cycles per minute by connecting both pumps to the motor simultaneously, having the motor rewound to 25 hp (to handle the increased load of both pumps running together), and making some minor piping changes. We are now in the process of evaluating these modifications on our prototype machine and hope to have the two operational units converted by the summer of 1965.

Acknowledgments

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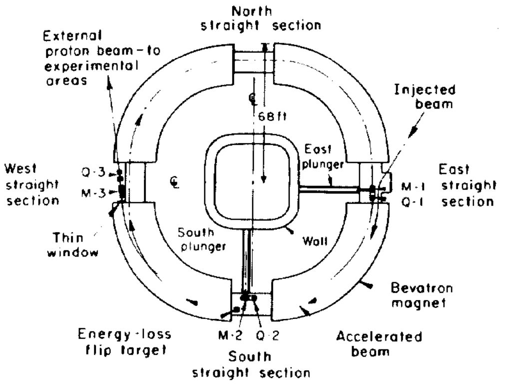

Fig. 1. Layout of the internal deflection system. The circulating beam travels in a clockwise direction.

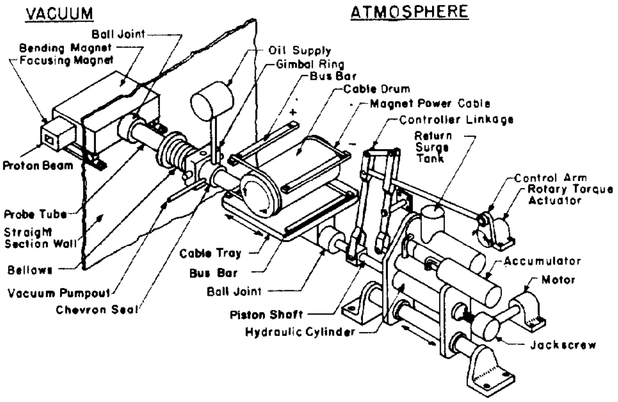

Fig. 2. Plunging mechanism schematic.

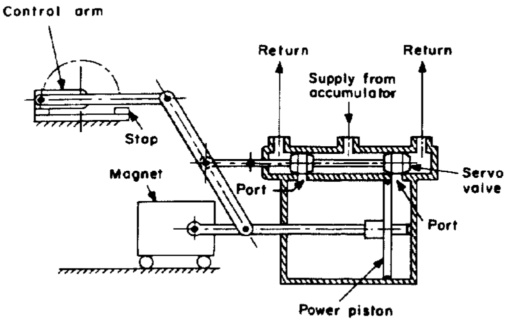

Fig. 3. Schematic diagram of actuator; magnet in retracted position.

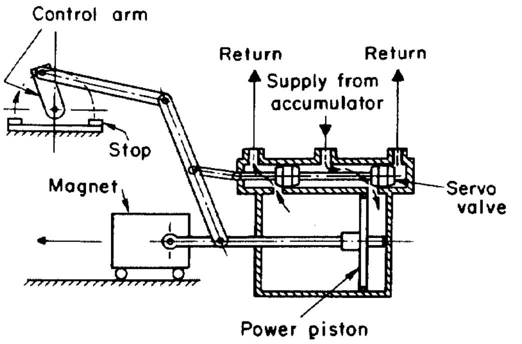

Fig. 4. Exaggerated motion of controller; valve open, magnet plunge starting.

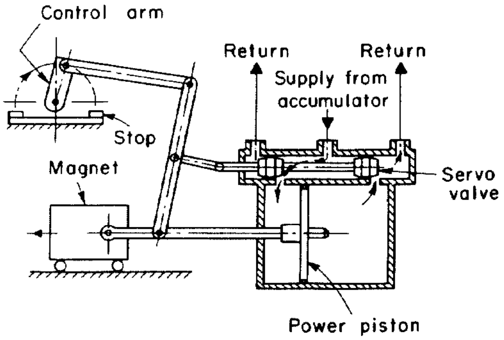

Fig. 5. Exaggerated motion of controller; valve open, magnet plunge stopping.

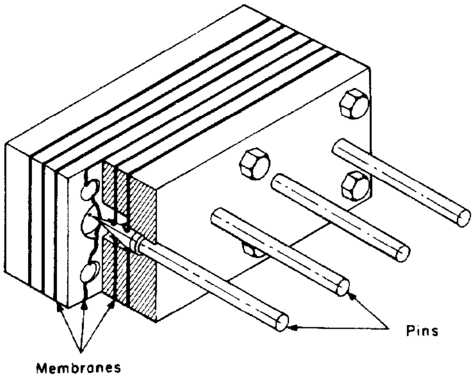

Fig. 7. Crash pad.

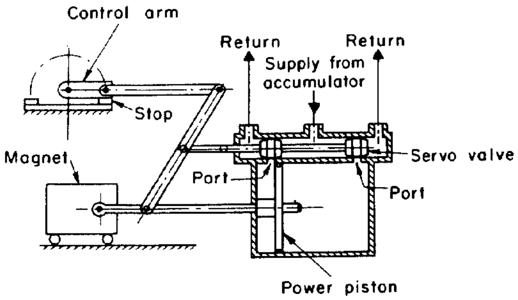

Fig. 6. Schematic diagram of actuator; magnet in plunged position.