SLAC Pub 7061

A DESIGN LIBRARY OF MAGNET SUPPORTS
-A PROPOSAL-*

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Preface

Although the ideal and universal support system has not been invented yet, there are many implementations which fulfill most of alignment's requirements. However, inventing a new support system seems to represent the last design challenge, why would we otherwise witness so many new attempts. Already Plato reminded his scholars that one should learn from the past. Unfortunately, learning from previous designs and implementations doesn't seem to carry much attraction. Or it is that we, the customers, are not doing our job by letting the design engineer know what we would like to see done, what we think works, and what is already there.

This contribution is an initiative to create a reference for support systems which exist in our laboratories and we know do work. Such an undertaking will require everybody's active support and feedback. I already have to thank my peers at many laboratories who helped me put together this first draft. Only if a more or less complete library of existing designs can be compiled with easy access to drawings can we then hope that the support system design competition looses its challenge.

1.0 Introduction

As alignment tolerances get ever tighter, the interplay of alignment with mechanical engineering becomes ever more important. In fact, accelerator alignment has advanced so far that mechanical uncertainties now exceed observational uncertainties. Of the mechanical issues bearing

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upon alignment, one of the most crucial is the magnet supports; these must provide both stability and a fineness of motion substantially exceeding the final alignment tolerances.

Magnet supports are the interface that allows mechanical mounting of components and their subsequent alignment to a nominal position in three-dimensional space. Supports thus provide two functions: that of a spacer to bring the component close to its ideal position, and that of a fine motion system to enable the surveyor to move the component to its ideal location within the required tolerance.

It is essential to understand that Magnets, Supports, and Survey and Alignment are interrelated. Ideally, one person would be responsible for all these functions. In larger projects, beyond the scope of one such manager, the responsible parties must be in regular communication. A magnet designed without supports in mind can be quite impossible to hold onto.[1] A support system that holds the magnets up, but requires a hammer to operate, renders impossible the achievement of tight tolerances. Magnets, Supports, and Survey and Alignment must be designed as a system.

1.1 Spacers

Components, with their adjustment systems, are rarely mounted directly to the floor or to an elevated concrete structure. Instead, girders or individual stands are used to hold a component at its approximate position and elevation above the floor. These spacers serve as the backbone on which the more precisely machined adjustment systems can be mounted.

1.1.1 Girders

A girder is a strongback or platform onto which a group of components can be mounted at beam height. Girders simplify the installation in cases when many small components need to be supported immediately adjacent to one another. The major advantages of a girder support system over individual stands are:

- The girder isolates individual components from ground settlements, since the whole group of components moves up or down together. Any settlement can be corrected by adjusting the position of one girder, rather than many support stands.

- To bring the magnet poles as close as possible to the beam in the latest generation of machines, the clearance between the pole tips and the vacuum chamber is very small, allowing little motion of the magnet with respect to the chamber. A global position adjustment of individual components requires many iterations and much time, unless all the components are mounted together and move as one monolith.
- As vacuum chambers become increasingly complex, it is often impossible to achieve and retain the correct shape in the production process. Whereas magnet supports should generally be kinematic (i.e., provide only the minimal number of constraints), for vacuum chambers, a heavily overconstrained system is often required so that the chamber can be pushed and pulled into shape. Such a system will work satisfactorily only if all constraints connect to the same reference body. This eliminates the use of individual stands.
- Girders can be filled with water to increase their thermal capacity, thereby slowing the rate of response of the girder to temperature variations.
- Girders can be preassembled in a shop before installation. All of the magnets and the vacuum chamber for a girder are installed and aligned to the final relative tolerance in a local girder coordinate system. Water-cooling manifolds and hoses are assembled on the girder at this stage, as are the connections of electrical circuits. All this work can be done in a production line environment rather than the tunnel, making it more efficient and of higher quality, with a more reliable inspection.[2] Installation of the preassembled girder in the tunnel is also significantly faster.

There are two primary types of girders: steel box and concrete. Concrete girders (Fig. 1) feature two I-beams cast into a rectangular cement block and machined flat. The rail system formed by the I-beams supports the beam line components. This system is widely used at SLAC. Concrete girders have a significant cost advantage, but great care must be taken during the construction and cement curing process, for slow creep and hairline cracking can severely hamper the monolithic quality of the finished girder. The other girder type (Fig. 2) is the stress-relieved structural-steel box girder. During the machining of the top and bottom plates, all the mounting holes can be quickly, cheaply, and accurately drilled and tapped by NC machines, obviating the need for lengthy prealignment and for manual drilling and tapping of mounting holes.

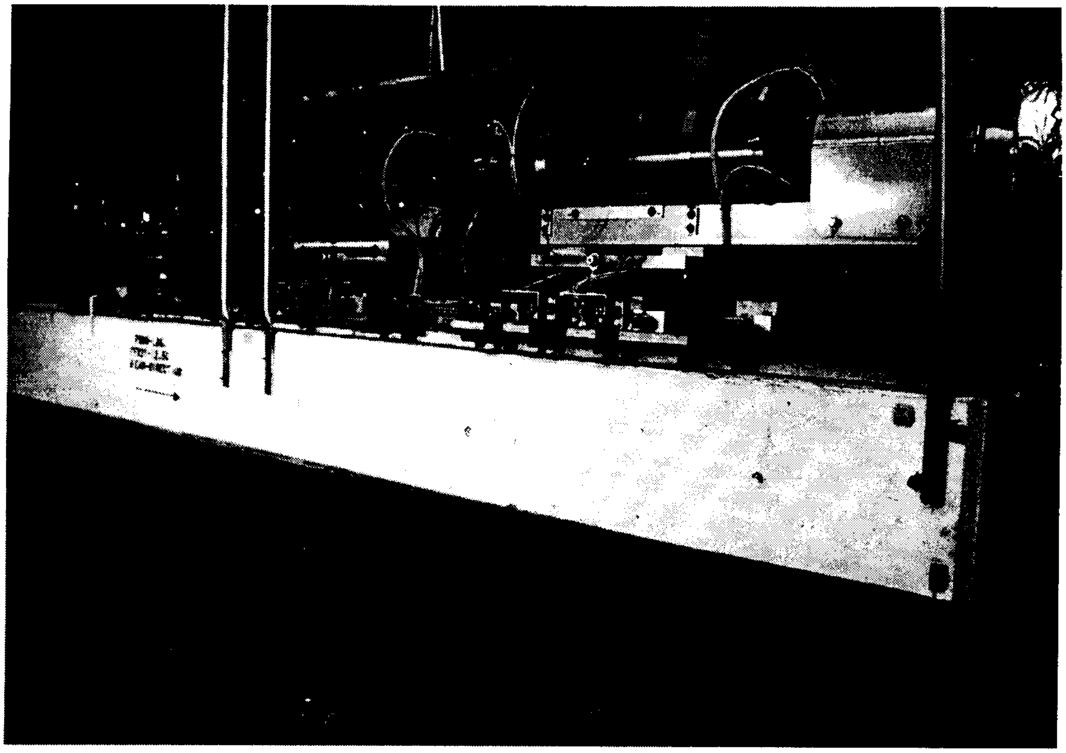


Fig. 1. Concrete girder as used in SLAC Final Focus.

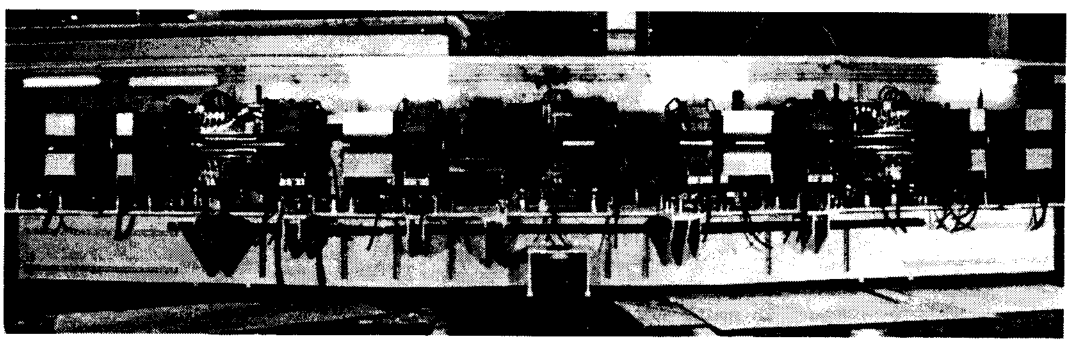


Fig. 2. Steel girder as used in LBL ALS. Photo courtesy of Lawrence Berkeley Laboratory, University of California

1.1.2 Individual Stands

Individual stands are generally used in situations where components are more spread out; e.g., transport lines. The simplest form of stand is a length of pipe with plates welded to the top and bottom (Fig. 3). The diameter of the pipe is of course a function of stand height and component load.

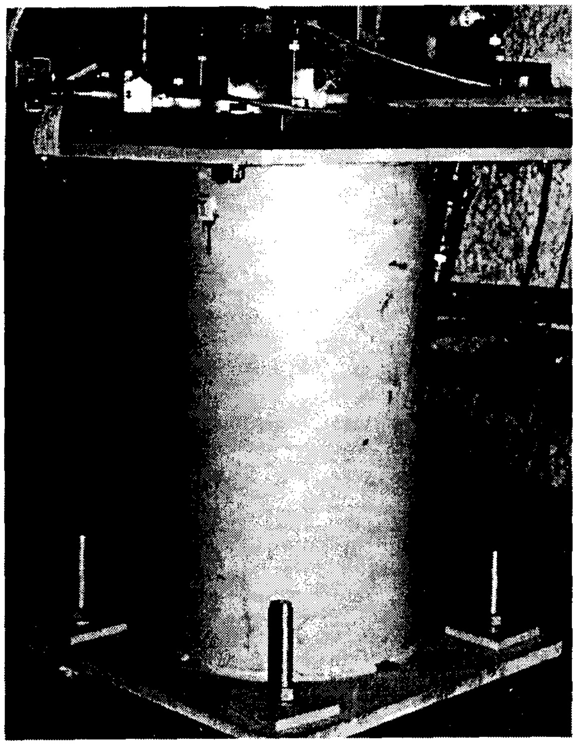
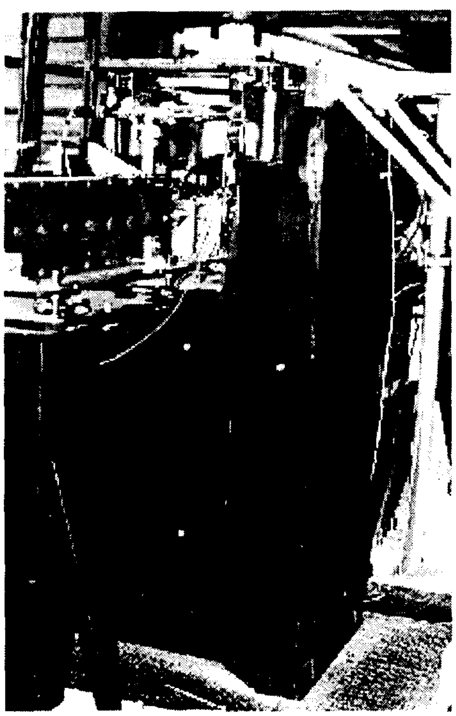


Fig. 3. Individual steel stand

More sophisticated stands are used at SLAC in the FFTB. These stands are made of Anocast, a granite epoxy which gives the stands the appearance of a granite block molded to the specifications of the particular application.[3] In effect, the Anocast stands become a hybrid of stand and girder. In the FFTB some Anocast stands support a group of magnets while still maintaining the typical cross section of an individual magnet stand (Fig. 4a and 4b). Measurements confirm that these stands have much better damping qualities of vibrations at higher frequencies than steel stands. Furthermore, their thermal mass dampens expansion due to variations in the ambient temperatures. Costs for steel and Anocast stands are comparable.



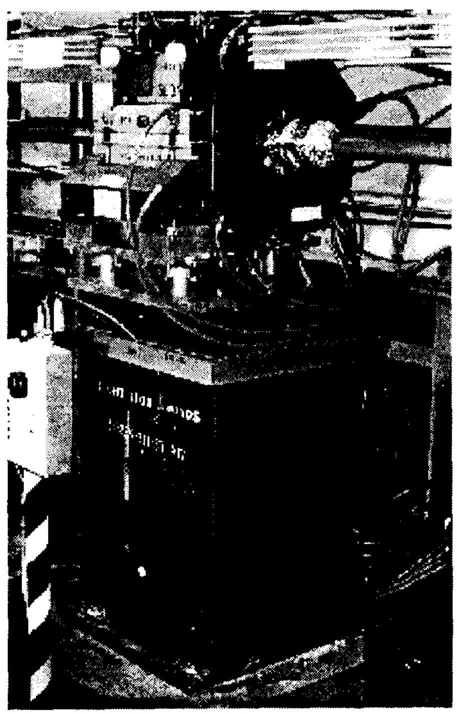


Fig. 4a and 4b. Anocast stands in SLAC FFTB

1.2 Manual Adjustment Systems

All beam components need to be moved and fixed at accurate locations by adjustment mechanisms. These systems should include the following design features:

- Adequate alignment precision: for precise adjustibility, the system's resolution should be ten times the required alignment tolerance.
- Orthogonal motion: there should be no cross coupling between the axes for small adjustment motions. For large motions, any existing coupling must be predictable.
- Kinematic mount: an overconstrained system induces stress into the support and/or component, resulting in a deformation of the component.
- Stability: the support should provide a stiff base when locked down where incidental contact will not cause movement of the magnet. It should also not deform the component during adjustment.
- A small footprint: as real estate is usually at a premium, components must often be placed very close together.
- Vibrational stiffness: typical ground motion frequencies should not be amplified by the support system.

There are two general types of adjustment mechanisms. The most common type separates the horizontal adjustment from the vertical degree of freedom. The second type combines horizontal and vertical adjustments into one system, usually implemented in a six strut layout that holds the component in a kinematic suspension. Other implementations are the CERN Adjuster System and its derivative, the CEBAF 3-D Cartridge, and the SLAC 3-D stage.

1.2.1 One and Two-Dimension Systems

To separate the horizontal from the vertical, a horizontal plane is generated by adjusting the height of three vertical standoffs. In its simplest implementation, the standoffs are either shim stacks or threaded rods. In the case of shim stacks, shim stock is added or removed until the plate is horizontal and the component at its ideal height, a lengthy, iterative process. Where threaded rods are used, the mounting plate rides on three screw nuts that are threaded on vertically mounted rods. Turning the nuts provides vertical translations along the Y-axis and two rotational degrees of freedom, pitch (rotation around the X-axis), and roll (rotation around the Z-axis).

On this horizontal plate slide one or two plates on which the component is mounted. These plates move under the force of adjustment screws to adjust and fix the Z (in beam direction), X (perpendicular to Z), and yaw (rotation around the Y-axis) degrees of freedom. The adjustment screws are often designed in a push-push arrangement (Fig. 5) with two opposing screws pushing on both sides of the component in a colinear arrangement. To achieve a translation, one side is loosened and the other tightened. Tightening both screws locks the position. Often the stand has only one sliding plate; in this case, the X and Z adjustments are not independent, since all adjustment screws must be loosened to permit sliding of the plate. Fine adjustment in the orthogonal direction is usually lost, and must be touched up again. Precise alignment with only a single sliding plate and push-push screw arrangement usually requires many iterations.

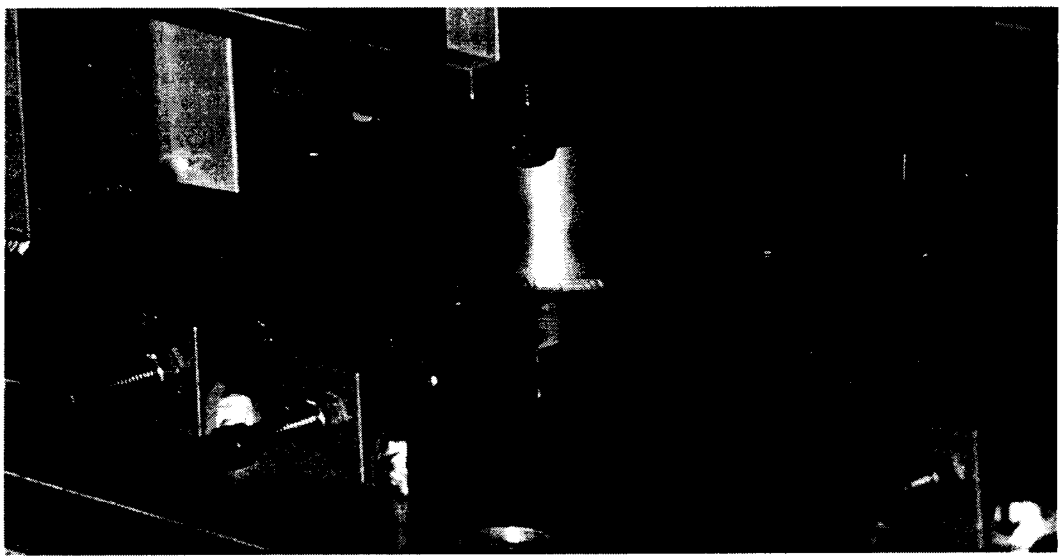


Fig. 5. Push-push screw arrangement

This basic design can be refined by replacing the above described horizontal and vertical adjuster with more sophisticated variations. The addition of spherical washers between the horizontal plate and the adjustment nuts makes the system move more smoothly. If the system is designed to carry higher loads, machine screw jacks (Fig. 6) are available that fit almost any application while still providing fine adjustment motion. Less expensive, but more limited in range, are wedge jack adjusters that are made of two wedges with the two sloped planes riding on each other. A horizontal motion pushes the upper wedge higher on the inclined plane, thereby providing a vertical motion. Wedge jack adjusters are available off the shelf in many load travel combinations. The push-push

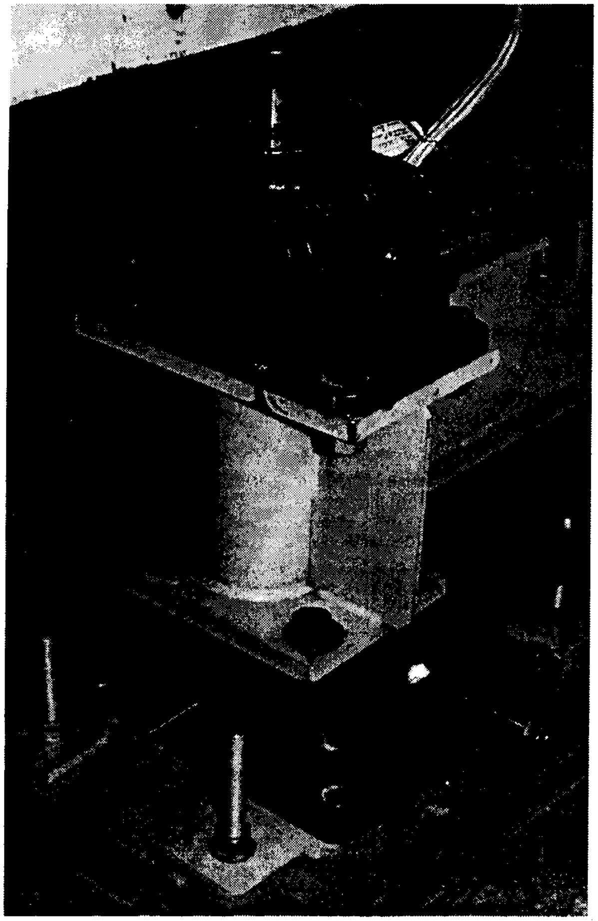


Fig. 6 Machine screw jack support.

Six-strut system A kinematic suspension can be created by arranging six adjustable length links in a 3-D truss. The three vertical struts adjust and hold the vertical translation, and the pitch and roll rotations. The three other struts (Fig. 8) are placed in the horizontal plane, two in one direction, and the third perpendicular. These three adjust and hold the X and Z translations and the yaw rotation. The orthogonal arrangement of the struts minimizes coupling in motion. Struts are length-adjustable rigid members with spherical joints at each end. A strut will support

screw arrangement can be improved by a turnbuckle/rail-slide design. The two push screws are replaced by one turnbuckle, which provides both the push and pull force. The fixed end of the turnbuckle can slide on a rail oriented parallel to the other adjustment axis in order to allow two-dimensional adjustments. This design is still relatively simple and inexpensive, while complying with all the above listed requirements. To support the girders in the storage ring of the Argonne Photon Source, a combination of wedge jack adjusters (Fig. 7) and turnbuckle-type horizontal adjustment was used.

1.2.2 Three-Dimension Systems

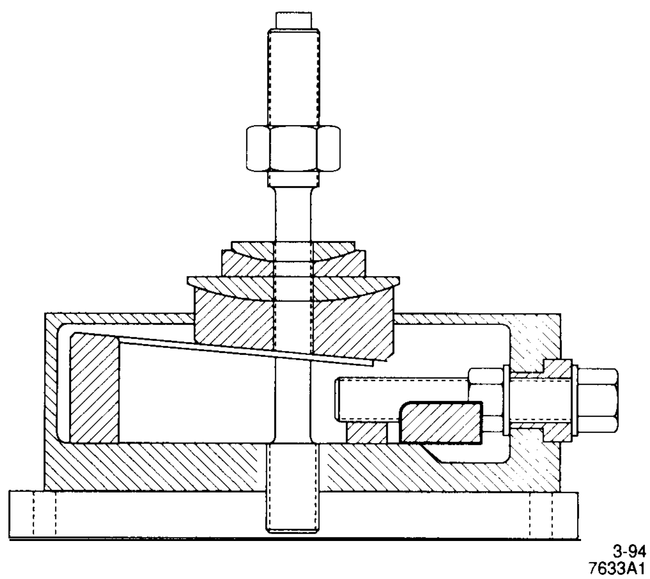


Fig. 7. Wedge jack adjuster as use in APS

only an axial load, in axial compression or tension. The spherical joints at either end ensure that a strut never experiences loads in any other direction. Since all struts are in axial compression or tension, they provide very rigid support.

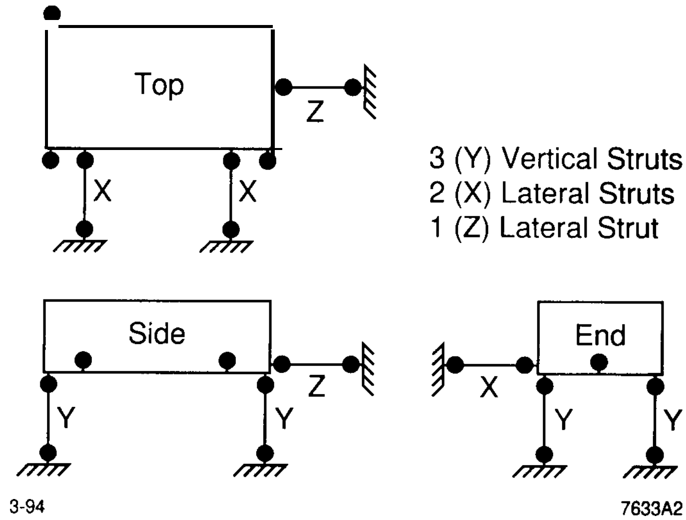


Fig. 8. Kinematic suspension

1.2.3 Typical System Implementations

Advanced Light Source (ALS) strut system. All components and girders at the Advanced Light Source at the Lawrence Berkeley Laboratory are supported by strut systems[4] (Fig. 9), as is the Spherical Grating Monochromator at the SSRL. The struts used for the support systems are not normal stock items. To avoid the backlash present in all regular spherical joints, the spherical rod end bearings have been squeezed in a controlled way to generate friction, which only a specific break-away torque can overcome. A shaft collar has been added at the end of each tube into which the rod end bearings thread. A portion

Fig. 9. ALS strut supports. Photo courtesy of Lawrence Berkeley Laboratory, University of California

of the tube, at each end, is turned down and slit in two directions so the shaft collar will squeeze the female thread against the male thread of the rod ends to remove any backlash in the threads. The rod end bearings are all right-hand threads with one coarse thread and the other a fine thread. creating a differential threaded device which allows very high resolution adjustments. For the support of heavy

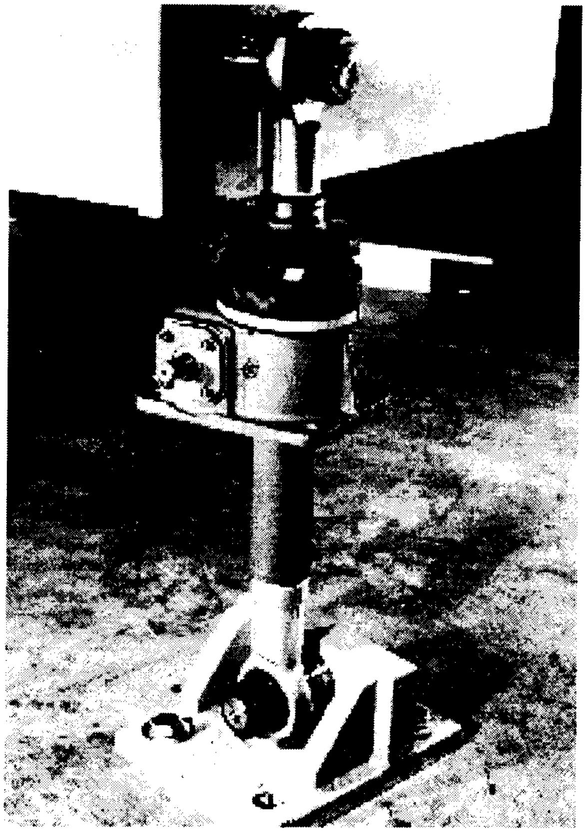


Fig. 10. ALS 5-ton machine screw jack strut.

Fig. 11. ALS 20-ton machine screw jack strut.

Photos courtesy of Lawrence Berkeley Laboratory. University of California.

loads, the tube and differential threads are replaced by an appropriately rated machine screw jack (Figs. 10, 11).

CERN cartridge. The CERN Adjuster System[5] consists of three cartridges that utilize a combination of the principles in the two styles discussed above. The improvement over the first style mechanism is that the sliding feature is replaced by the three vertically-oriented links of the kinematic suspension. The first or main cartridge works as follows (Fig. 12): the piston-ended link pivots in a socket at the bottom of the base and floats within a hollow cylindrical projection from that base. At the top, the link pivots in and supports a cap whose outer skirt drapes over the cylindrical projection. The device to be positioned is placed on this cap. The cap is driven horizontally by four bolts threaded through the skirt of the cap, which press against four flats machined into the cylindrical projection. Lateral and longitudinal adjustment is achieved with one of these pairs of opposing push-push screws. As one bolt is loosened and the opposite bolt tightened, the cap glides easily, rocking on the vertical link. The sockets in which the link is mounted consist of cylinders in the base and cap that are tilled with urethane rubber. Four screws in the base and four screws in the cap drive in and out of this volume, compressing the rubber and driving the link or the cap higher or lower respectively, providing the vertical adjustment. The second cartridge lacks one set of opposing screws and the third cartridge lacks both sets, leaving no restraint on the cap, allowing it to float and provide only vertical adjustment. The three cartridges are placed in a triangular pattern with the set of opposing screws of the second cartridge parallel to one set of screws in the main cartridge. Use of all three cartridges provides pitch, roll, and yaw adjustment. One advantage of the CERN Adjuster System over the kinematic suspension is that there is much less coupling between the adjustments, so that alignment is more easily obtained.

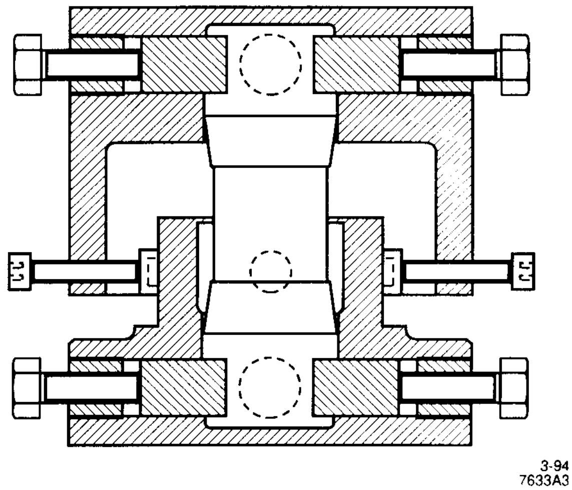


Fig. 12. CERN cartridge adjuster

<u>CEBAF cartridge</u> The CEBAF cartridge[6] uses many of the features of the CERN Adjuster System design. Three identical cartridges are attached to a stand through specially bored mounting holes. Each cartridge consists of a vertical cylinder and a cap (Fig. 13). The device to be adjusted is fastened to the caps of the three cartridges. The hollow, vertical cylinder has two opposing flats on its outer wall at the top, and a threaded hole in its bottom, into which is threaded a set screw. Turning this screw raises the cap, via a vertical rod through the cylinder. Lateral adjustment is by a pair of opposing screws through the skirt of the cap, registering against the flats on the cylinder. The cap glides over easily while rocking on the vertical rod. The cartridges are mounted on the stand such that the flats on two cylinders are parallel to each other and the flats on the remaining cylinder are

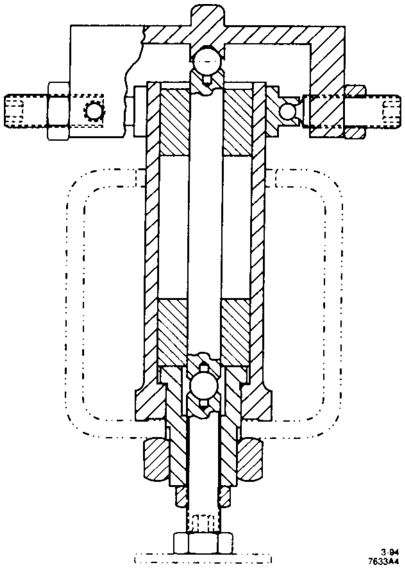


Fig. 13. CEBAF cartridge adjuster

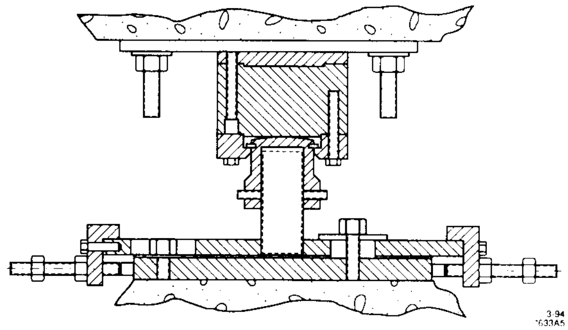


Fig. 14. SLAC Damping Ring girder support

perpendicular to the other two, providing lateral, longitudinal, and yaw adjustment. With this orientation, all degrees of freedom are constrained with no overconstraint. Locking of the movement of all screw threads is provided by locknuts.

SLAC damning ring girder support This design contains the most basic adjustment system construction elements, a push-push screw arrangement combined with a threaded rod[7] (Fig. 14). The girder is supported by three feet. Each foot's baseplate is bolted and grouted to the floor in an approximately horizontal position. Atop this baseplate sits a sliding plate that can be moved relative to the baseplate by the force of a two-dimensional push-push screw arrangement. A short fine-threaded rod of substantial diameter is mounted to the sliding plate at its center. A cap-shaped nut, riding on the threads over the top of the rod, provides the vertical adjustment. The girder is mounted to this nut in a way which prevents any horizontal backlash, while still permitting it to be turned. The system is locked in the horizontal dimension by a bolt holding the sliding plate to the baseplate, and in the vertical dimension by a set screw which prevents the cap nut from turning. While this system allows relatively high resolution adjustment of heavy loads, the total system is significantly overconstrained, and must therefore be operated with great caution.

SLAC Final Focus girder support This design is similar to the Damping Ring supports. but avoids the overconstraints[8] (Fig. 15). The push-push screw arrangement is replaced by one-dimensional stages: two feet have stages oriented for lateral adjustment, while the stage at the third foot provides longitudinal motion. To decouple the cross-motion between stages, the supports are fixed to the girder in only one horizontal dimension, which is accomplished by a rail slide system. The vertical adjustment is functionally the same as on the support discussed above.

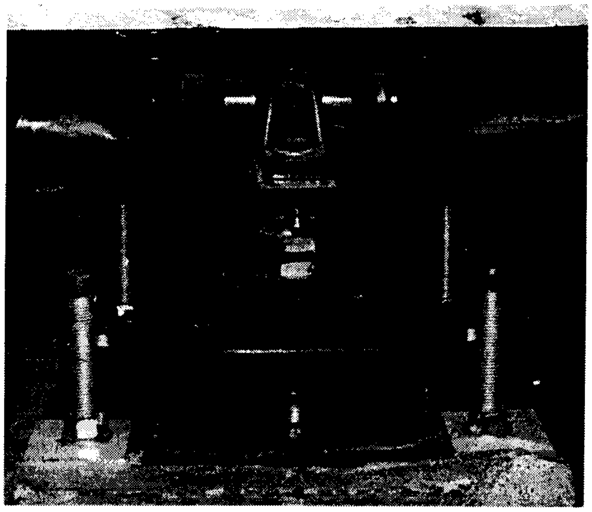


Fig. 15. SLAC Final Focus girder support

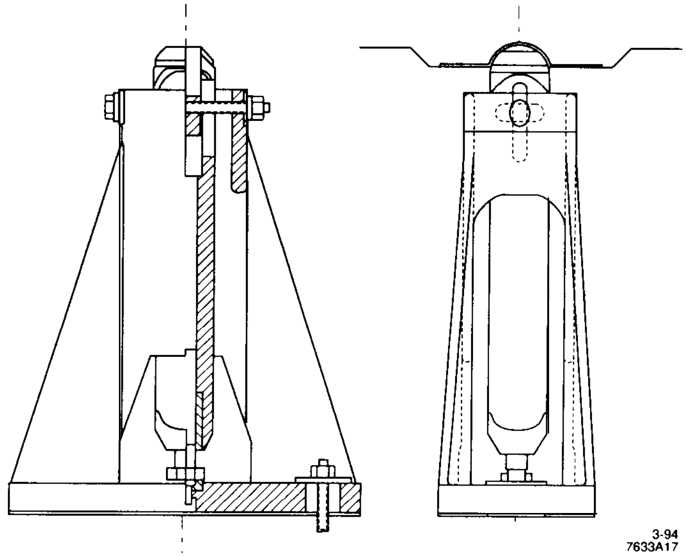


Fig. 16 CERN LEP Dipole support

CERN LEP dipole support This system[9] can provide kinematic support to a wide variety of applications, from small magnets to heavy girder modules. The general idea and functionality are taken from the CERN cartridge design, but with the vertical adjustment replaced by an adjustable-length link (Fig. 16). To minimize motion correlation, the link is made as long as possible, subject to the restraints of the specific application.

SLAC 3-D stage This is an adjustment system tailored to support a variety of components, from small quadrupoles to long narrow bends that are to be positioned to tight tolerances[10] (Fig. 17). The horizontal degrees of freedom are provided by a baseplate/sliding plate arrangement. To avoid overconstraint, the adjustment motion is created by three semitumbuckles, in which one end is a conventional rod end bearing, but the other end is a threaded stud (Fig. 18). Two of these semitumbuckles provide the lateral adjustment, and a third gives the longitudinal adjustment. The spherical rod end bearings are threaded into blocks bolted to the base plate. The spherical bearing end is threaded onto a rail that is mounted on the baseplate perpendicular to the rod's adjustment direction. This arrangement allows the sliding plate to be adjusted in one dimension, while maintaining the adjustment in the other horizontal dimension. The vertical adjustment is created in a similar way. Three spherical

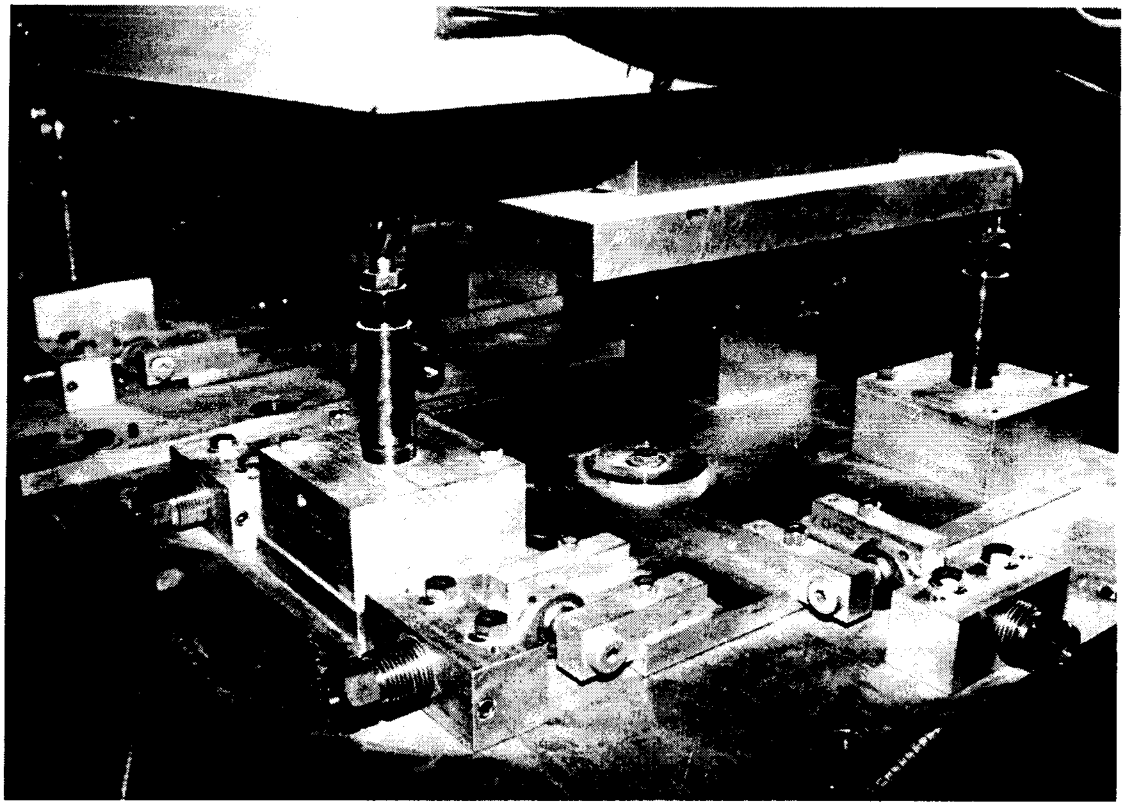


Fig. 17. SLAC 3-D stage

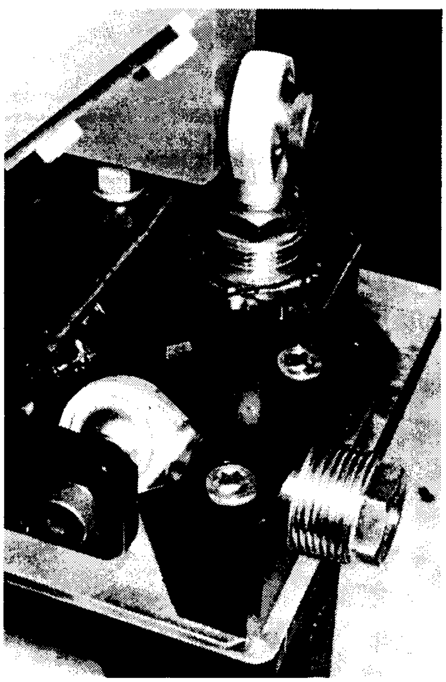


Fig. 18. Lateral adjustment layout

rod end bearings are bolted vertically into blocks mounted to the sliding plate. Bolts through the spherical rod end bearings support the component.

DESY PETRA single component support system This system[11] has been used to support quadrupoles on single stands and long dipoles on two single stands at either magnet end in the PETRA ring. The underlying scheme is now widely used in other machines at DESY. Shown below in Fig. 19 is a quadrupole sitting with three pads on three vertical screws that provide height, roll, and pitch adjustments. In the horizontal plane, two struts allow mo-

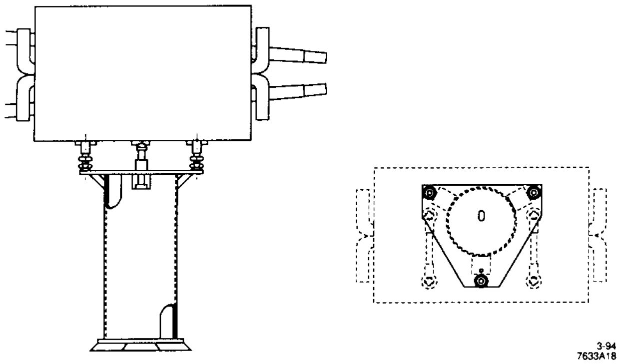


Fig. 19. DESY PETRA support system

tion perpendicular to the beam. No adjustment capability along the beam axis is provided. To create a kinematic mount between the pads and screws, one screw head is resting in a groove, while the other two pads are flat.

1.3 Motorized Adjustment Systems

SLAC FFTB magnet positioners The FFTB magnet positioners[12] differ from conventional positioning stages used in instruments and machine tools. The mechanism is designed to support loads exceeding 1 ton, while still providing smooth motion, free of hysteresis, at the micron level. The design is simple and sufficiently reliable for large scale use in the remote positioning of hundreds of magnets. Conventional crossed-slide leadscrew positioning stages are not appropriate for this application. High-resolution piezoelectric positioners[13] cannot meet the load and range requirements. The remote magnet positioning mounts used in the FFTB kinematically support the magnets on roller cams. The magnet rests under gravity in a cradle formed by the cams (Fig. 20). This type of kinematic support is similar to the Kelvin Clamp[14] used in laboratory optics and instrumentation. The V-blocks and flat plates fixed to the magnet make point or line contact with the outer bearing races of the roller cams. Rotation of the eccentric camshafts shifts the magnet position. This type of kinematic support, where the number of contact points balances the number of degrees of spatial freedom, has the advantage of avoiding all free play between the magnet and mount. The magnet always rests in contact with all of the supporting cams, regardless of their position. No precise mechanical dimensions are needed to insure zero play. No clamping forces, other than gravity, can distort the magnet's shape. The magnet can be removed from the mount and replaced without realignment.

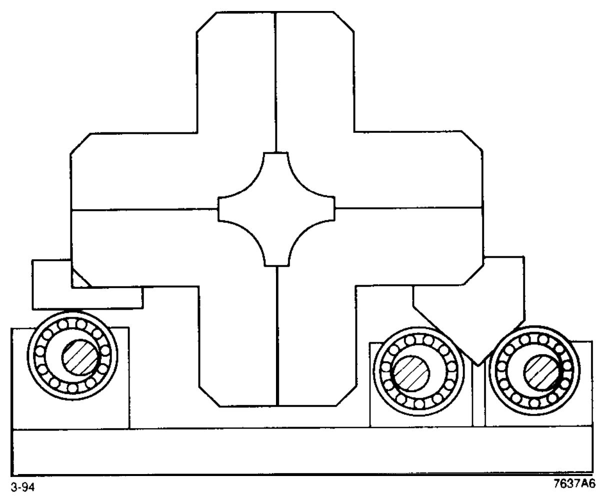


Fig. 20. Magnet positioning mount with roller cams

During operation, only the inner eccentric shaft of a support cam rotates under motor control. The outer cam bearing race remains in contact with the magnet as shaft rotation lifts the magnet. In such a system, failure of the control system will only cause the cam to cycle around again. Magnet motions are strictly bounded by the design geometry. Limit switches are not needed for over-travel protection. All support cams are arranged so that gravity applies a load torque to each cam shaft drive train. This torque removes all backlash, except at the extremes of cam lift. All parts move by pure rolling motion, and are free of the hysteresis typical of intermittent and reversing sliding motion. This mount can adjust the horizontal and vertical position of the magnet, as well as the magnet's roll angle around the beam axis. The magnet's longitudinal position along the beam line, as well as its alignment to the beam direction in this implementation are fixed in the support mount, and not remotely adjustable. Figure 21 shows the three-motor positioning mount used to support FFTB quadrupole magnets. Kinematic roller cam supports can be applied to a variety of geometries. The barrel containing the final triplet of quadrupole lenses for the Stanford Linear Collider is supported on five roller cam supports. This 5-m-long 6-ton assembly is remotely adjustable in pitch and yaw, as well as roll, vertical, and horizontal position.

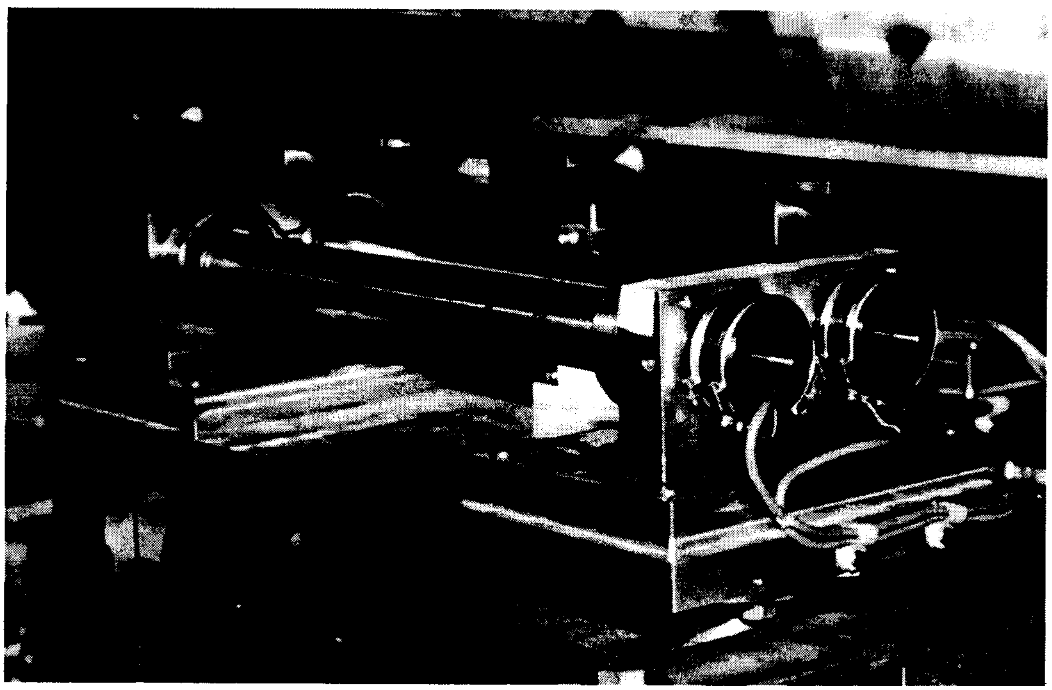


Fig. 21. FFTB magnet remote positioner

ESRF servo-controlled jacks Predicted ground motion of more than 1 mm per year led to the development of a remote vertical alignment system. A computer-controlled hydrostatic leveling system was installed in the storage ring with three measurement stations on each girder. These girders are kinematically supported by three vertical motorized screw jacks, which are interfaced to the control system. The horizontal adjustment is provided by a gear-driven X-Z stage mounted on top of the vertical jacks.[15] First results indicate that it takes about two minutes to map the entire ring, and then only two hours to vertically align all girders.[16]

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