Lecture 8
Core Fabrication

Core Fabrication and Assembly Practices

Magnet Installation and Alignment

Introduction

- Conventional magnet performance and quality is dominated by the core design and fabrication.
  - Field quality depends not only on the pole design, but is highly dependent on the mechanical fabrication and assembly tolerances. Design of magnets, including the core assembly practices, often determine the quality of the final product.
  - Magnet to magnet reproducibility require that the iron properties among magnets be uniform.

- The boundaries surrounding magnet design and fabrication go beyond satisfying the physics requirements. Once the magnets have been fabricated and tested, they must be installed and aligned. Consideration of the installation and alignment requirements and procedures must be *built into the magnet design*. In order to install and align magnets, the support system and the system of fiducialization must be built into the *initial* design of the magnets. The cost of *retrofit* is high.
  - Magnet Fiducialization
  - Magnet Support and Alignment

Solid Cores or Laminated Cores

- The choice of solid or laminated cores has *historically* been associated with whether the magnetic field is time varying or steady state.
  - Insulated laminations are *always* used for time varying field magnets in order to reduce or eliminate eddy current effects. Ferrite might be used for fast, low field magnet cores.
- Presently, many *steady state* magnets are assembled with laminated cores.

Economics

- Solid iron yokes are often used in simple, flat pole contour magnets.
  - The cost of laminated cores are often less if the quantity of magnets is large.
    - Die set costs are approximately 50 k$.
    - Costs of laminations is about $1/lamination.
    - Core assembly time is about 2 to 4 m-days/core.
- For complicated yoke shapes, quadrupoles, sextupoles and gradient magnets, the cost of machining solid cores can be prohibitive.

Reproducibility and Symmetry

- The following discussion will assume the use of laminated rather than solid core magnets. Most modern accelerators, even storage rings whose energy are not ramped, use laminated magnets. The reason for this is more than just the economics of fabrication. The driving motivation for using laminations to assemble magnet cores is magnet to magnet *reproducibility and symmetry*.
- Dipole magnets, both flat field and gradient, are usually connected in power supply series. Therefore, it is essential that the magnet be identical among all the magnets at the same current.
- Families of quadrupoles and sextupoles are often connected in series.

- The *BH* characteristics of iron are variable and depend on the chemistry of the iron (dominated by the Carbon content, which is highly variable from heat to heat) and the cold working history of the iron plates or sheets.
- Even from the same heat (where the iron chemistry is identical), the *BH* characteristics or iron can vary because of stratification in the melt depending on whether the iron piece was taken from the head, middle or tail of the pour.
- The iron *BH* characteristics can be different *parallel* and *transverse* to the plate or sheet rolling direction.
  - One usually specifies non-oriented steel when ordering from a mill. However, all steel has some degree of orientation.

Die Sets and Lamination Stamping

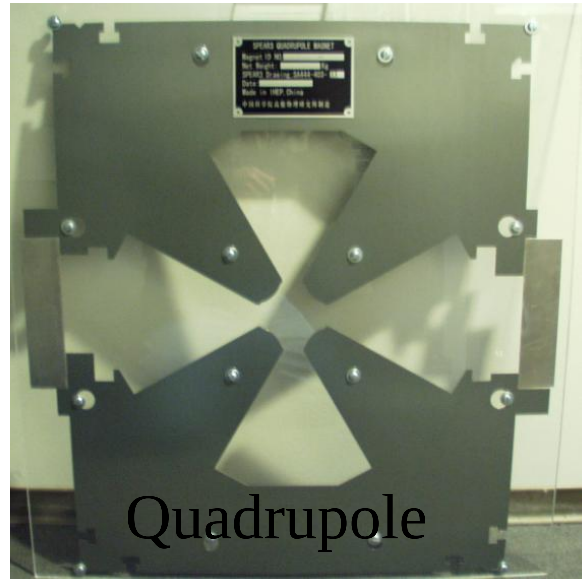
- The design of the lamination should incorporate several considerations regarding material and die wear.
  - The maximum size of the lamination should consider the rolling width of the sheet. Sheets are normally slit from master coils, and the sheets slit from the edges of the coils often are tapered near the edge.
  - The lamination design should avoid sharp internal and external corners. The punch and die pieces have excessive wear at these features. If the design incorporates sharp corners, the die fabricator will often recommend design changes.
  - Tooling should be thick enough to undergo several sharpening procedures during the production stamping.

Lamination Shuffling

- Shuffling is often used to enhance magnet to magnet reproducibility and symmetry.
- The laminations are stacked on pallets for each magnet segment as they arrive. This distributes the *BH* iron variation among each magnet and each segment of each magnet.
  - It is not necessary to wait until all the laminations have been stamped since they can be distributed on pallets as they arrive.
- Laminations *may* be stamped with orientation along and transverse to the rolling direction in order to cancel any directional variation of *BH* behavior.

SPEAR3 Laminations

Gradient Magnet



Quadrupole

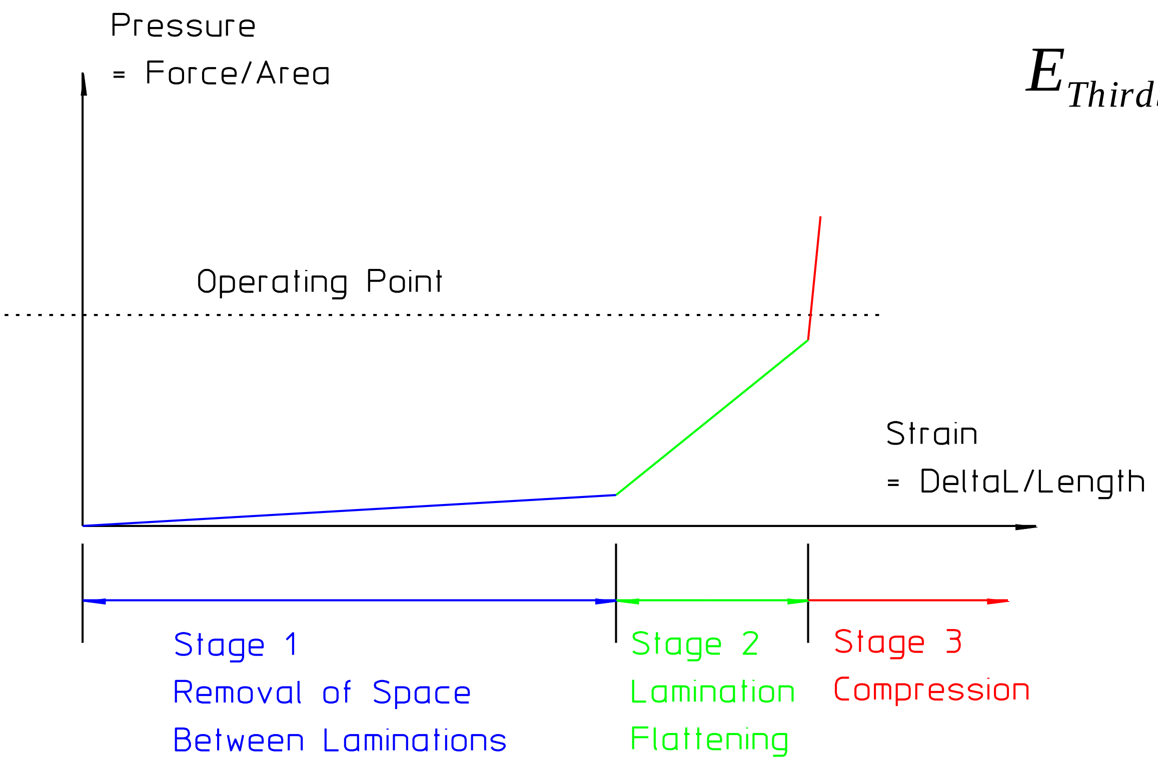
Sextupole

Core Stacking and Compression

- Cores stacked from laminations exhibit certain elastic characteristics. These characteristics are displayed as an effective *elastic modulus* of the stack, which are usually manifest themselves into three stages.
  - Removal of space between the laminations
  - Flattening of the lamination warps
  - Metal to metal compression

$$E = \frac{\frac{Force}{Area}}{\frac{\Delta L}{L}} = \frac{\text{Pressure}}{\text{Strain}} \quad \text{(usually expressed in psi)}$$

Compression Stages



$$E_{ThirdStage} = \frac{Force/Area}{\Delta Length/Length}$$

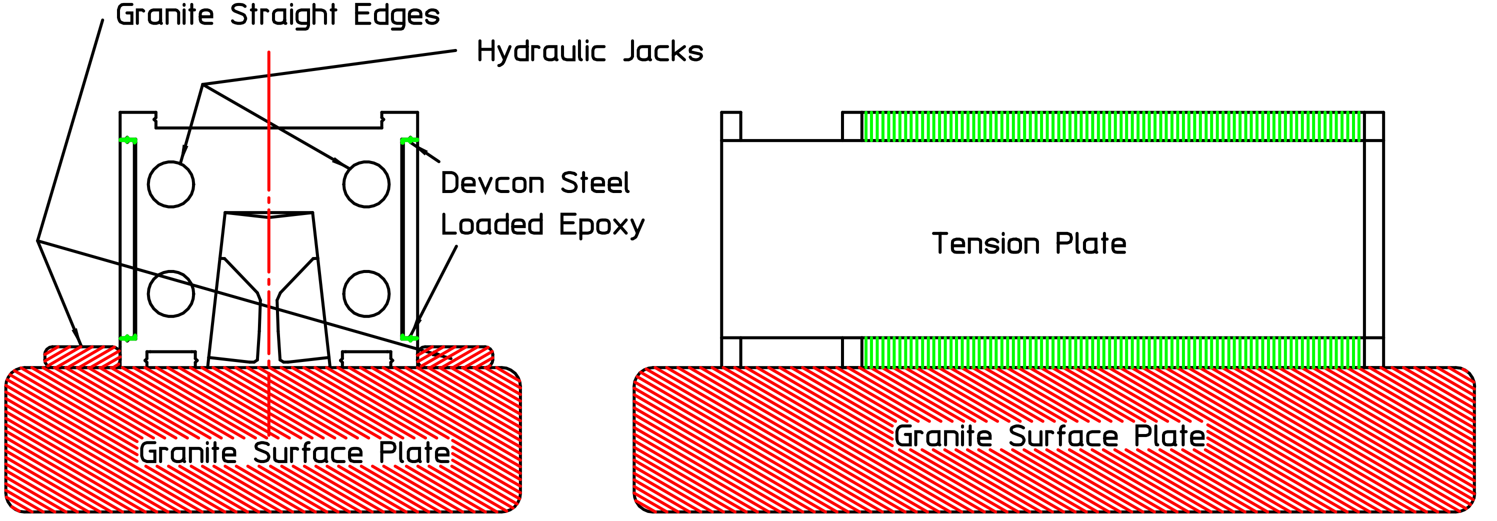
$$= \frac{\sigma}{\varepsilon} \approx 5 \times 10^5 \, psi$$

Maximum pressure at operating point $\leq$ 30 psi.

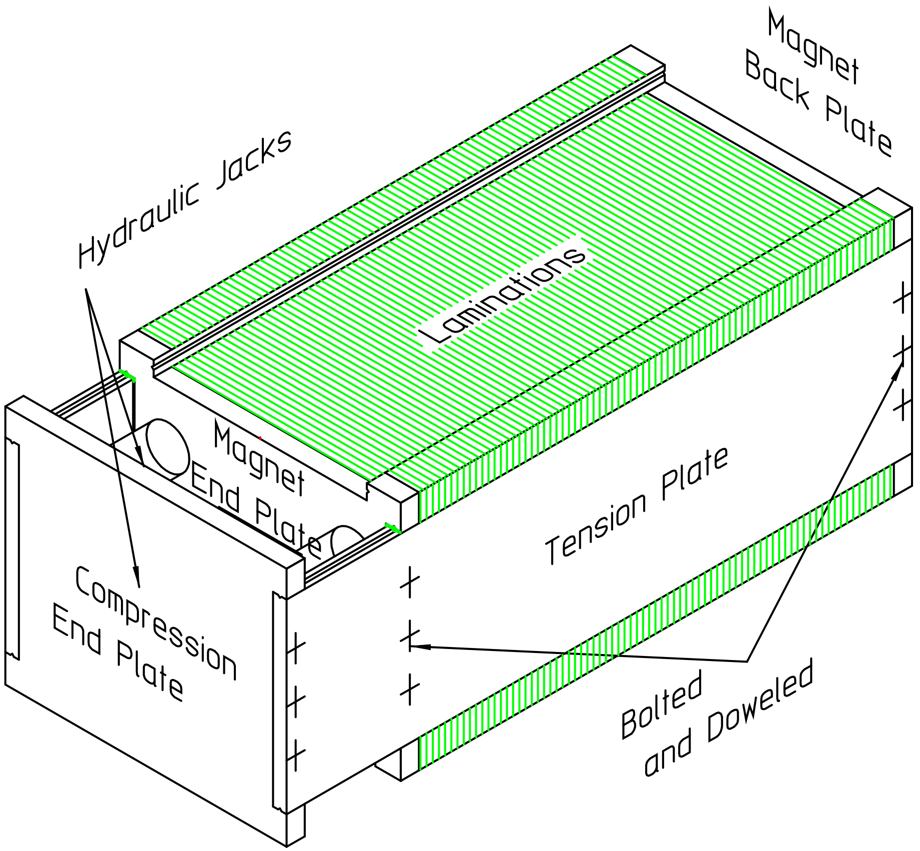
Core Assembly Techniques

- Different techniques are used to assemble cores.
  - Welding
  - Gluing
  - Mechanical Frame Technique
- Welding and gluing are standard assembly techniques.
- The mechanical frame technique is described since it is a fairly novel way of assembling a precise mechanical core which avoids the distortion due to welding and can also be used for fairly long cores.

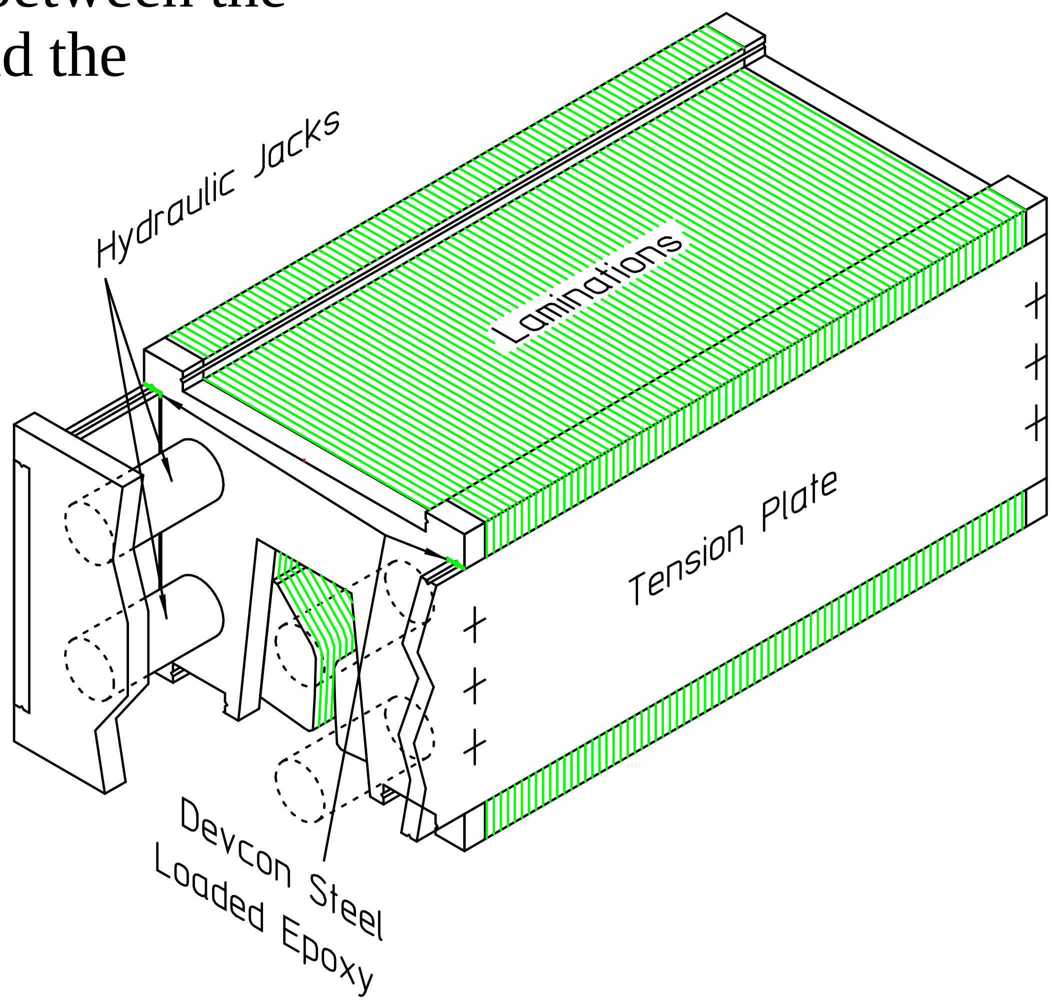
- The mechanical frame technique was first developed for the PEPI Insertion Quadrupoles.
- It has subsequently been used for both the ALS and SPEAR3 Gradient Magnet cores.



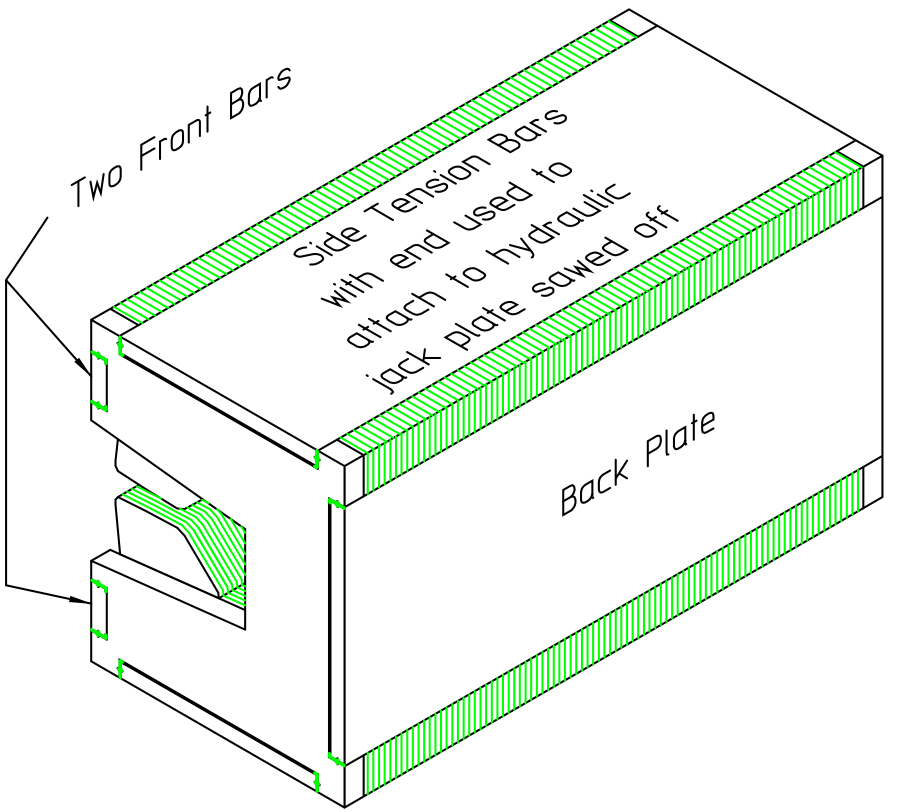
- The magnet back plate and two tension plates are assembled along with the compression end plate and the magnet front end plate.
- The tension plates are drilled with a series of holes so that the compression end plate can be moved as the laminations are stacked in the frame.
- When the final core length is achieved, the end plate is bolted and doweled to the tension plate.



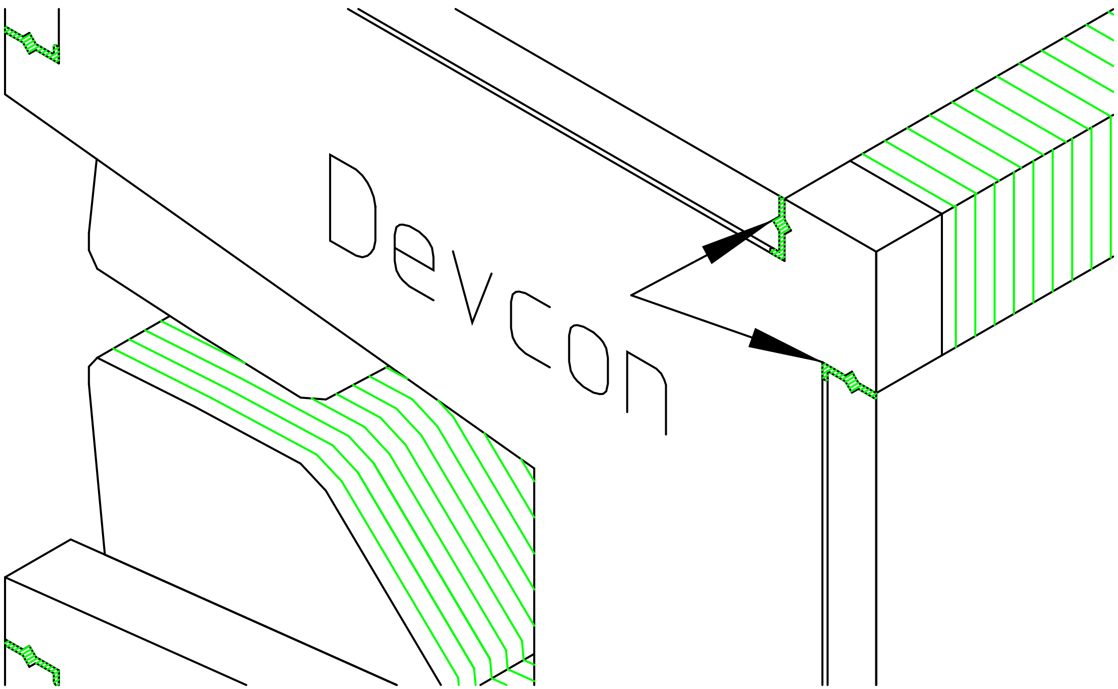
- After the compression, bolting and doweling, the Devcon, steel loaded epoxy is extruded in the v-groove space between the tension plates and the laminations.



- The assembled core is rotated, the back and two front plates are assembled, bolted and doweled to the end plates and the Devcon steel loaded epoxy is applied. Usually, transparent tape is attached to the outside gap in order to prevent the fluid from escaping.

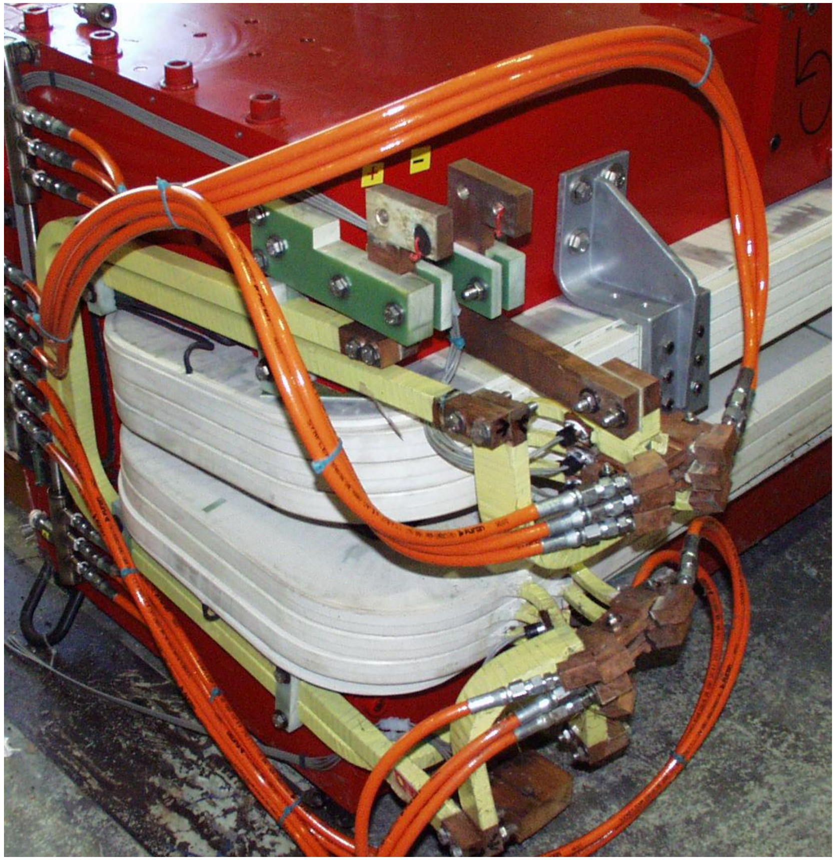


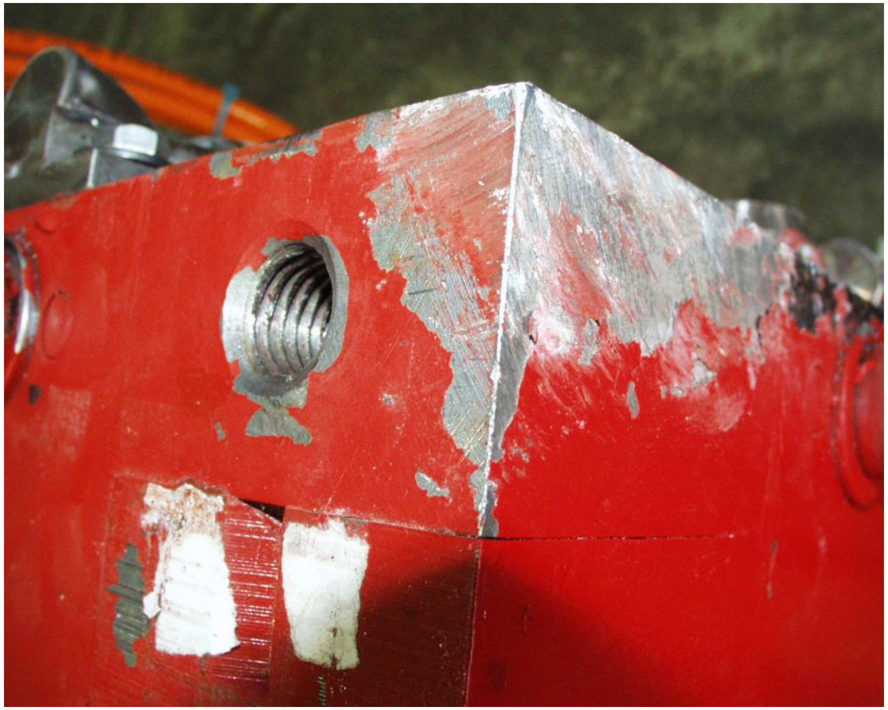
- The steel loaded epoxy comes in a variety of curing times and viscosities. Normally, it is applied with a pressure gun using a long tube to reach into the v-groove gap. Some experimentation is often needed in order to find the best technique for applying this material.



- The magnet cores fabricated in this manner result in a surprisingly robust structure. Shown below is one of the 1.45 meter long gradient magnets that accidentally fell off of a truck while being transported to the raft assembly area.

- While the coil and assembly suffered major injury, the core was undamaged.
- New coils were assembled and the magnet will be installed in the SPEAR3 ring.

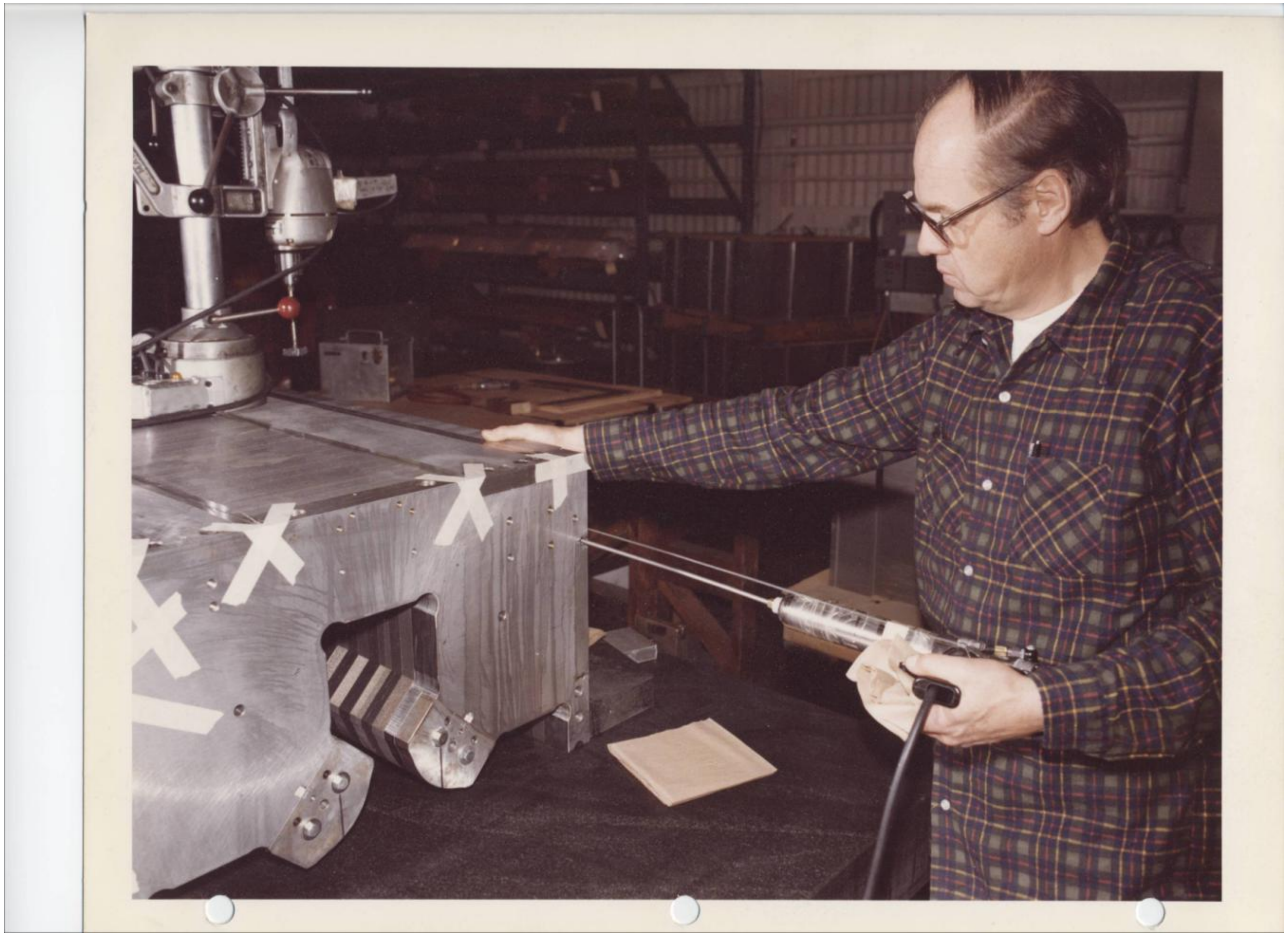




- After the accident, a more secure means of fixing the magnet on the truck was adopted.

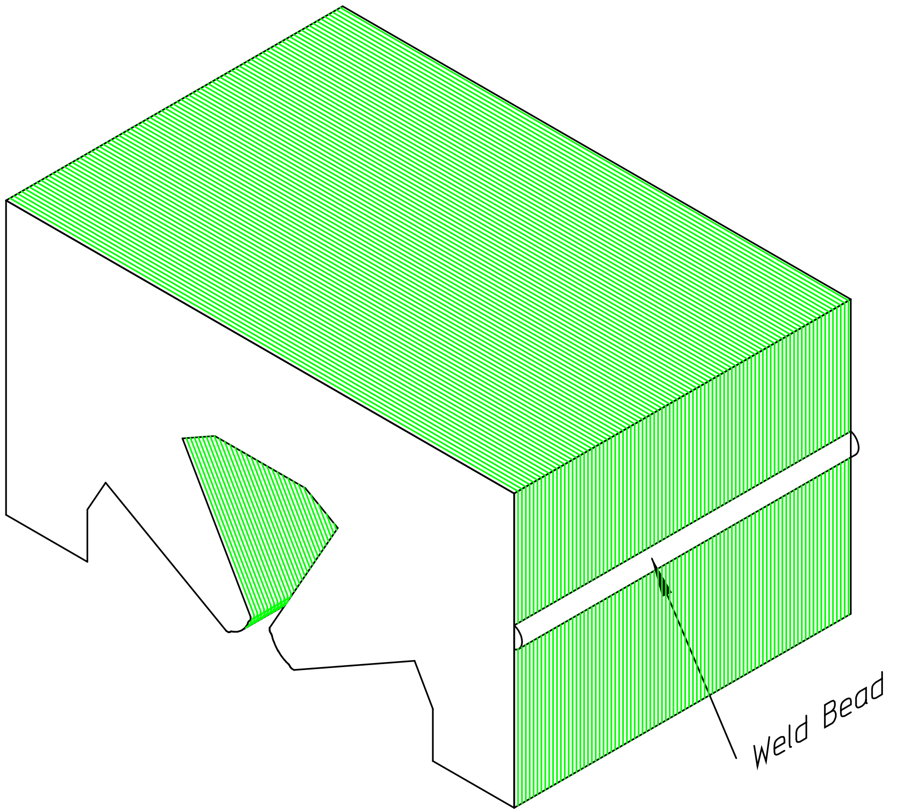
Devcon Application

The photo show the application of Devcon in the V-grooves of the PEPI Insertion quadrupole core using a pneumatic actuator. The outside of the slot is covered with transparent tape.



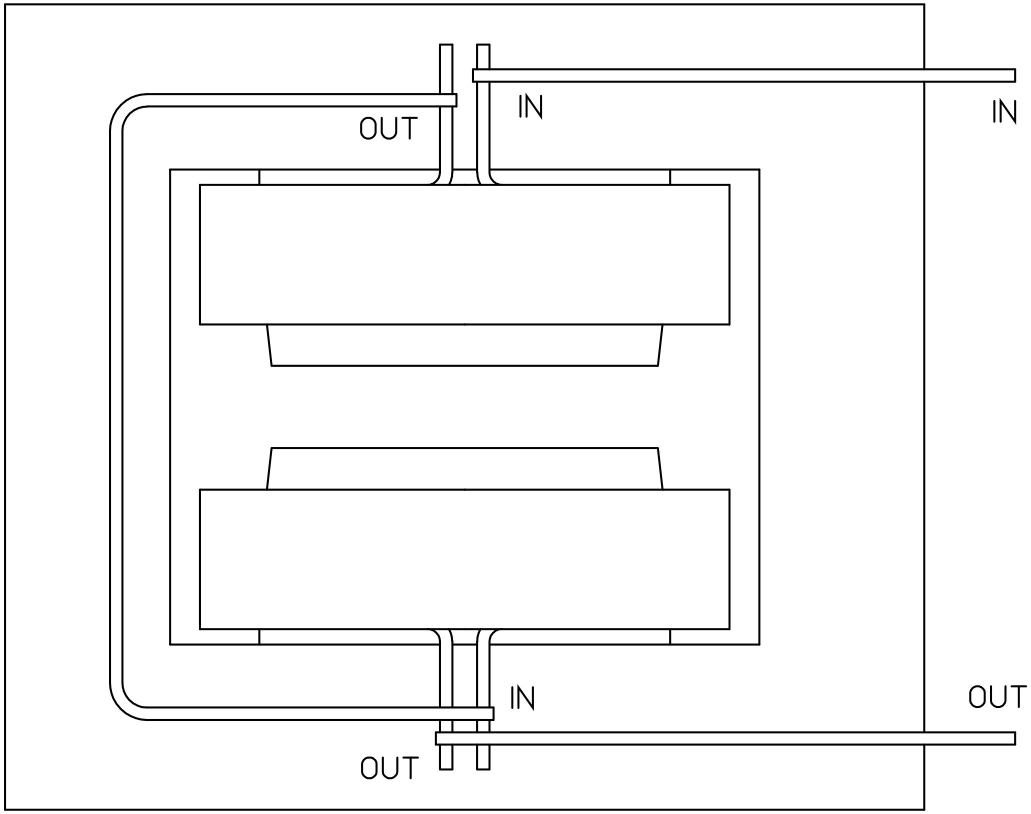
Core Grounding

- For a glued core, each lamination may not be electrically connected to its neighbor. It is necessary to add a small weld bead, electrically connecting all the laminations. The core can then be grounded to a single ground point.



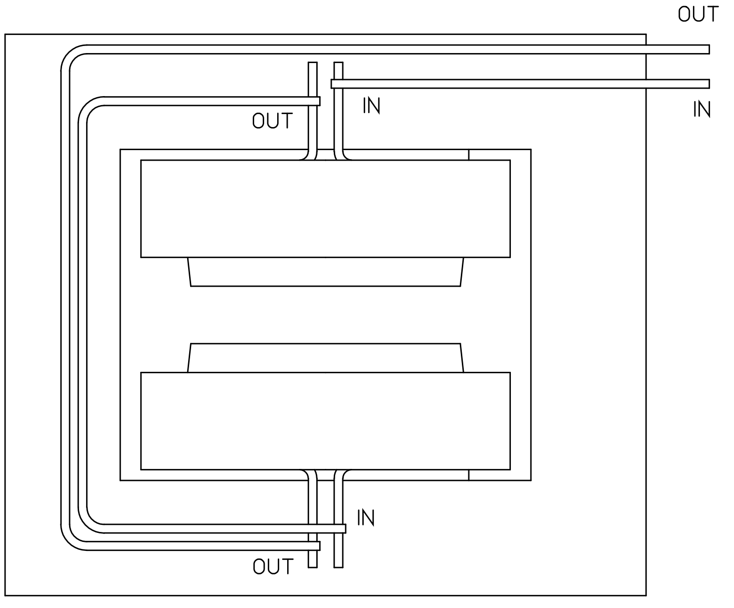
Magnet Bussing

- What is wrong with this picture?



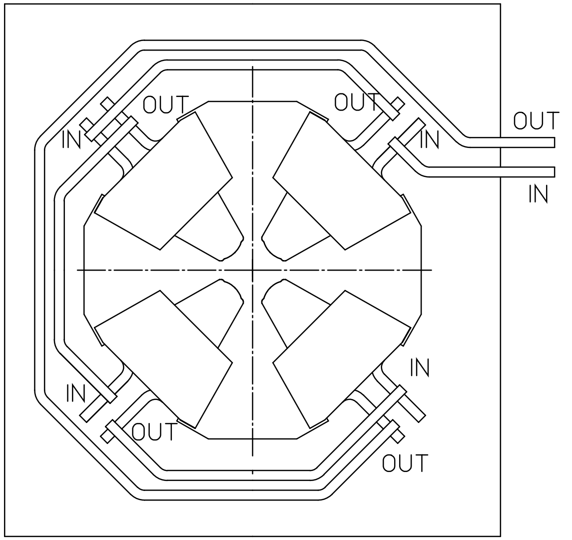
- The electrical bussing connection creates a loop around the beam line, resulting in a small solenoidal field. This longitudinal field can rotate the beam.
- The correct dipole bussing topology is shown below.

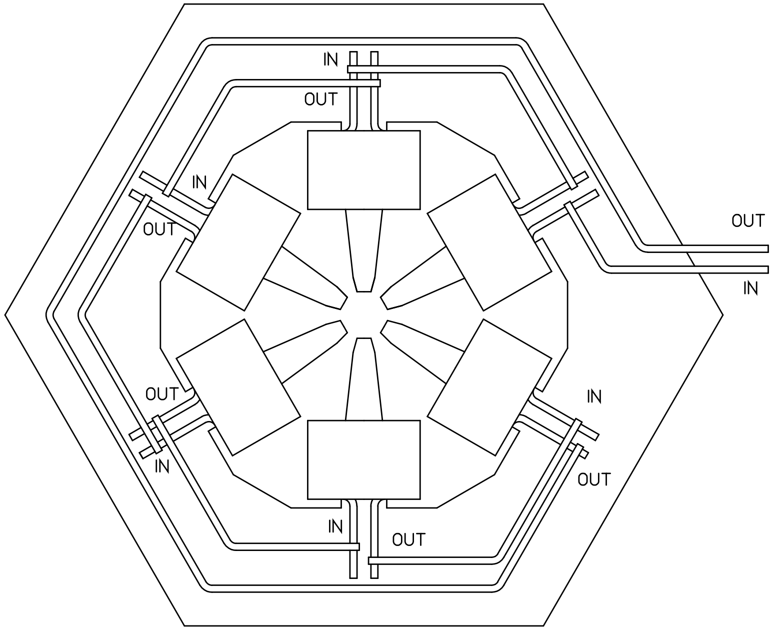
In this geometry, the in and out conductors should be placed close to each other so that longitudinal fields are minimized .



Quadrupole and Sextupole Bussing

- The correct quadrupole and sextupole bussing scheme is shown. Again, it is recommended that the conductors be placed close to each other.





Magnet Fiducialization

- Magnet alignment specifications for accelerators and beam transport lines typically call for $\leq \pm 250\ \mu$ precision transversely and vertically and $\leq \pm 500\ \mu$ longitudinally.
- Rotational tolerances are typically $\leq \pm 0.2$ mrad in roll, pitch and yaw.
- The *centers* of magnets are normally not accessible in accelerators or beam-lines because of the presence of evacuated beam-tubes. Therefore, it is necessary to know the precise positions of external features which can be measured and aligned with respect to the accelerator/beamline coordinate system. These features are called fiducials and the measurement and/or identification of these features with respect to the local magnet coordinate system is called fiducialization.

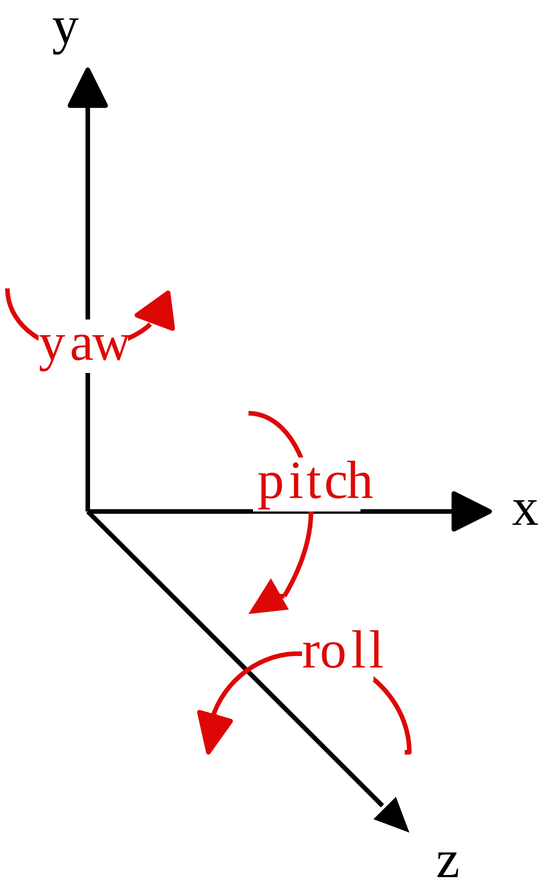
- There are two styles of fiducialization, both used extensively to align magnets.
  - *Generic* fiducialization (Used for PEPII)
    - Generic fiducialization relies on design features of the magnet. Thus, the coordinates of the fiducial features are assumed to be identical among all magnets of the same design family.
    - This method relies on the precise and reproducible positioning of fiducial targets on all magnets.
  - *Pedigreed* fiducialization (Used for ALS and SPEAR3)
    - Pedigreed fiducialization measures the coordinates of fiducial features on each individual magnet.
    - It does not rely on precision or reproducibility in the positioning of targets.
    - It requires that a large database be maintained with all the coordinates of each magnet.

- Fiducialization requires one to adopt and use the language of *metrology*. In this language, three separate features must be defined in three dimensional geometry.
  - The principal plane
    - The principal plane is the plane containing two of the orthogonal coordinate axes. In magnets, this is usually the z (longitudinal) and x (transverse) axes.
  - The principal line
    - The principal line is a line in the principal plane which defines a direction. In magnets, this is usually the z (longitudinal) direction.
  - The principal point
    - The principal point is a point on the principal line and defines the origin of the axes. This is usually the longitudinal center of the magnet.

- The (x, y, x) axes are defined with respect to these constructs.
  - The z axis is in the principal plane and is along the magnet coordinate. The origin of the z axis is at the longitudinal center of the magnet.
  - The x axis is in the principal plane and is perpendicular to the z axis with its origin at the z=0 point.
  - The y axis is perpendicular to the principal plane with its origin at the z=0 point.
  - The (x,y,z) coordinate system is right handed. That is, a right handed rotation from the x to y axis points in the z direction. This is the US convention. The European convention may be the opposite.

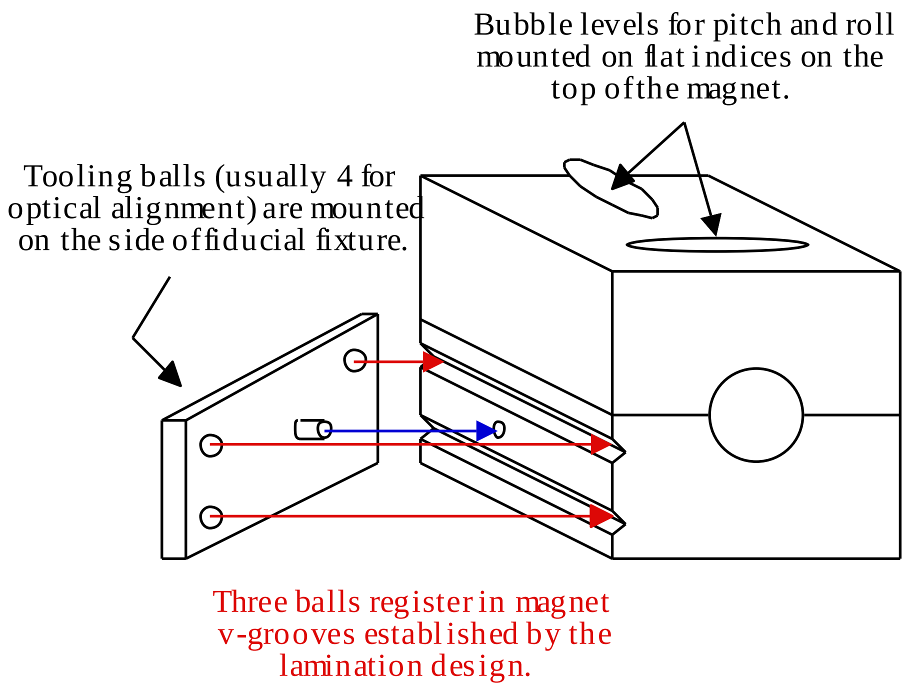
Six Degrees of Rigid Body Motion in Kinematic Systems

- The figures shows the six degrees of freedom, three displacements and three rotations, in the typical three dimensional Cartesian coordinate system.



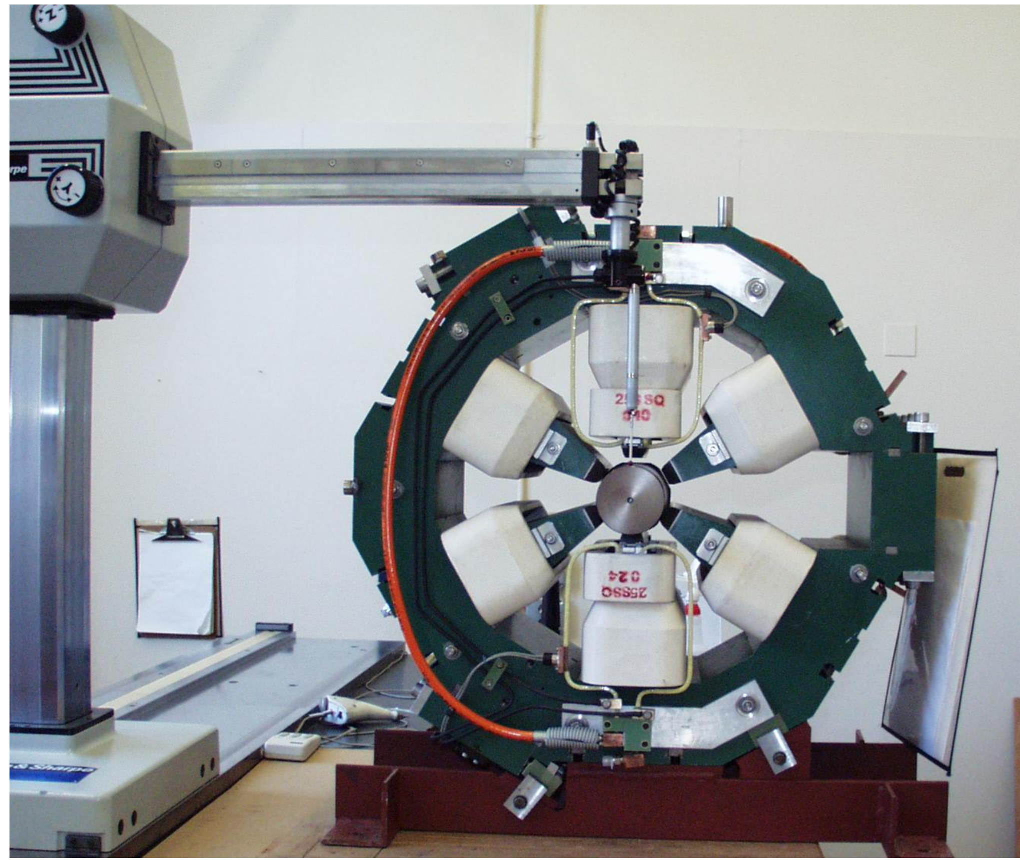
Generic Fiducialization

- The general features of a generic fiducial system using a removable target plate is shown in the illustration. For PEPII, a *single* target plate, moved from magnet to magnet, was used. This removed the error due to fabrication tolerances of constructing several target plates.

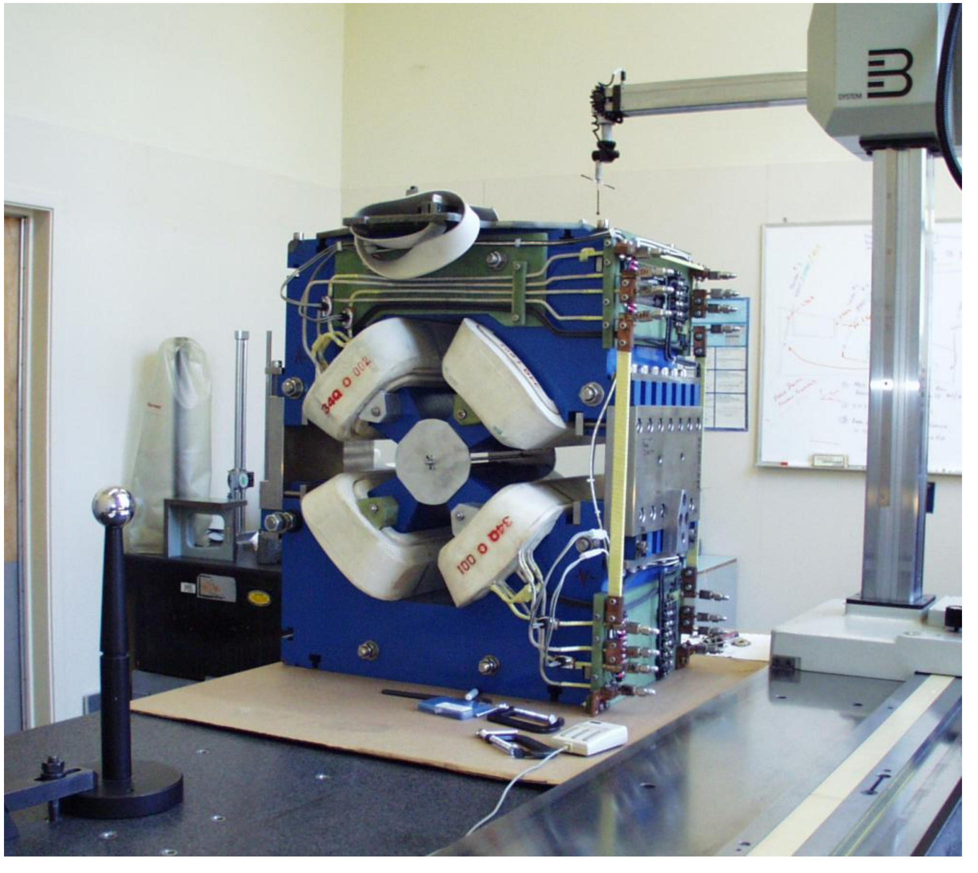


Pedigreed Fiducialization

- The steps used to measure *pedigreed* fiducials for magnets are described.
  - The first photo shows a sextupole mounted on the table of a coordinate measurement machine (CMM). The cylinder mounted in the bore defines the magnet axis.



- The second photograph shows a quadrupole mounted on the CMM. The plate at the end of the poles is placed in contact with flats machined on the poles to establish the longitudinal end of the magnet. A mating plate is mounted at the opposite end of the magnet.



CMM Measurements

- All the measurements are made and recorded in the CMM (u,v,w) coordinate system. This system is defined by the single tooling ball and the various motions of the probe.
  - Several measurements are made on the top of the magnet so that a least square fit to a plane can be computed.
  - Several measurements are made on the surface of the cylinder mounted in the magnet gap so that a least square fit to the axis of the cylinder can be computed.
  - Several measurements are made on the plates mounted on flats on the pole tip at both ends of the magnet so that least square fits to planes can be made at both ends of the magnet.
  - Measurements of the coordinates of each tooling ball are made.

Computations

- The least square fit cylinder axis is computed from the measurements of the cylinder surface.
- The least square fit planes at both ends of the magnet are computed from the plate measurements.
- The intersection of these planes with the cylinder axis is computed. The midpoint of these intersection points is defined as the axis origin.
- The plane established from the measurements at the top of the magnet is moved parallel to itself until the axis origin is in the plane. This is defined as the center of the magnet.
- The projection of the cylinder axis onto this plane is defined as the magnet z axis.

- The x-axis is defined as the direction in the plane, perpendicular to the z-axis, with its origin at the magnet center.
- The y-axis is defined as the direction perpendicular to the plane, with its origin at the magnet center.
- A rigid body translation and rotation of the coordinate axes from the (u,v,w) to the newly defined (x,y,z) is performed on the measurements of the fiducial features.
- These (x,y,z) coordinates are stored and archived for each individual magnet.

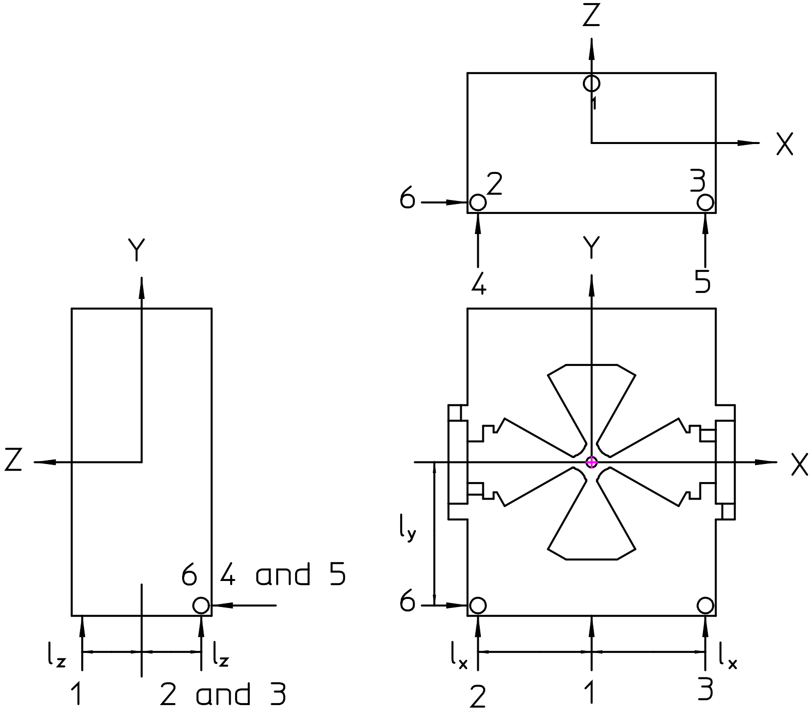
Support and Alignment

- A true kinematic support system must have *at least and at most* six *linearly independent* supports.
- Two examples of kinematic support systems are the six strut support and the three block support systems. The advantages and disadvantages of each system are;
  - Six strut advantage – quickly and easily adjustable.
  - Six strut disadvantage – soft structure, therefore low natural vibration frequencies.
  - Three block advantage – high stiffness leading to high natural frequencies. This is important for photon beam stability in light source accelerators.
  - Three block disadvantage – more difficult to adjust requiring more time.

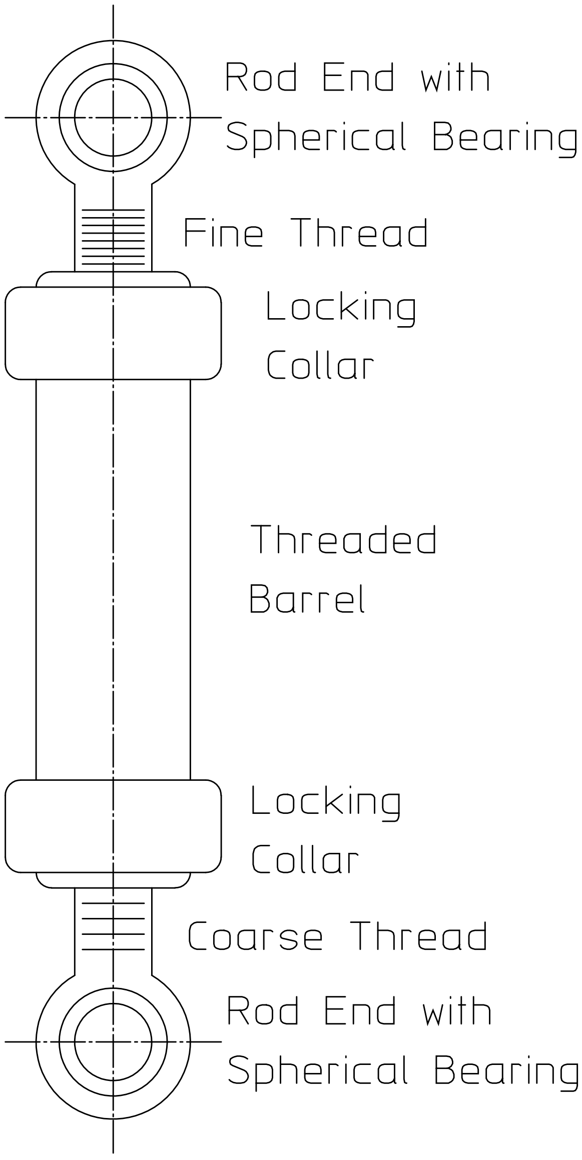
Six Struts

- The location and orientation of six struts is illustrated. Three vertical struts at points 1, 2 and 3 provide vertical adjustment as well as adjustment of pitch (rotation about the x axis) and roll (rotation about the z axis).

Two longitudinal struts at points 4 and 5 provide z adjustment as well as yaw (rotation about the y axis).
One transverse strut at point 6 provides x adjustment.

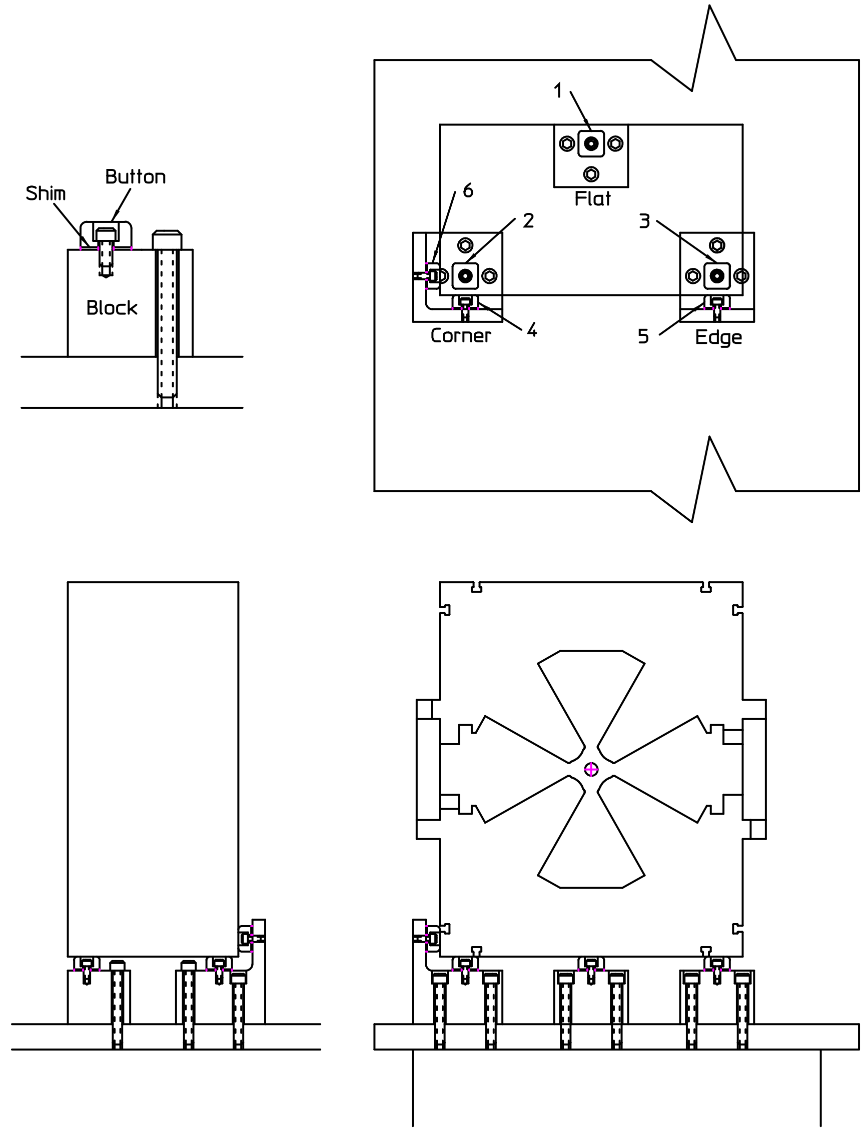


- Each strut consists of a barrel, two rod ends and two locking collars. The rod ends are both right hand thread, but one is fine and the other is coarse. Therefore, each rotation of the barrel provides an adjustment equal to the difference in the pitches of the two threads.



Three Block Support

- There are three support blocks. Each block has buttons which can be machined to a desired thickness.
  - Corner block has x, y and z buttons.
  - Edge block has y and z buttons.
  - Flat block has y button.



- In both the six strut and three block support system, one must make measurements of the location of the magnet and compute the adjustments necessary in the strut lengths or the changes in block thicknesses which need to be made to align the magnet to its desired location.
- The errors in six dimensional space must be made. Δx, Δy, Δz, pitch (rotation about the x axis), roll (rotation about the z axis) and yaw (rotation about the y axis) must be evaluated.
- With these measured values, six linear equations in six unknowns can be written. These equations can be solved for the unknown strut adjustments or changes in block thicknesses to achieve the motions required to correct for the measured errors in the six dimensional space.
- The set of six linear equations in six unknowns is more conveniently written in matrix form. The development of these equations is covered in section 12.2.3 of the text.

$$(M)(s) = (\Delta)$$

The strut adjustments are given by the inverse matrix,

$$(s) = -(M)^{-1}(\Delta)$$

- The matrices in the previous slide are given by,

$$(M)=\begin{pmatrix} 0 & \frac{l_y}{l_x} & -\frac{l_y}{l_x} & 0 & 0 & 1 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 & 0 & 0 \\ -\frac{l_y}{l_z} & \frac{l_y}{2l_z} & \frac{l_y}{2l_z} & \frac{1}{2} & \frac{1}{2} & 0 \\ \frac{l_y}{l_z} & -\frac{l_y}{2l_z} & \frac{l_y}{2l_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{l_y}{l_x} & \frac{l_y}{l_x} & 0 \\ 0 & \frac{l_y}{l_x} & -\frac{l_y}{l_x} & 0 & 0 & 0 \end{pmatrix} \qquad (s)=\begin{pmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \end{pmatrix} \qquad (\Delta)=\begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \\ l_y\theta_x \\ l_y\theta_y \\ l_y\theta_z \end{pmatrix}$$

- The text includes a section on simple calculations to estimate the natural frequencies of a strut system. However, this section, indicating that the motions are eigenmodes and that the frequencies are eigenvalues, is incomplete.
- In general, the matrix expression for the strut adjustments using the six dimensional error vector, use a coordinate system centered on the top of the magnet, the location of the fiducial alignment targets and the expression which describes the various accelerations uses a coordinate system centered at the center of mass of the body.
- In order to write an equation where the eigenvalues (natural frequencies) can be computed easily, the strut adjustment expressions should be rewritten using the same coordinate system used for the accelerations.
- More development of the theory will be included in the next edition of the text.

Closure

- Issues associated with the installation, support and alignment of the magnet can be easily overlooked when considering the design of synchrotron magnets. These issues *must* be addressed at the *beginning* of the design.
- It is difficult, it not impossible, to retrofit features in the magnet if these issues are ignored and the magnets are fabricated without considering installation, support and alignment.

Lecture 9

- The material covered in lecture 9 is reviewed in chapter 10 of the text. Coil winding and potting, as well as testing and adding components for coil operating safety are covered. The principles covered in this chapter includes the specifications and requirements which must be given to the fabrication shops or the manufacturer.