Industrial Challenges of Compact Magnet Production

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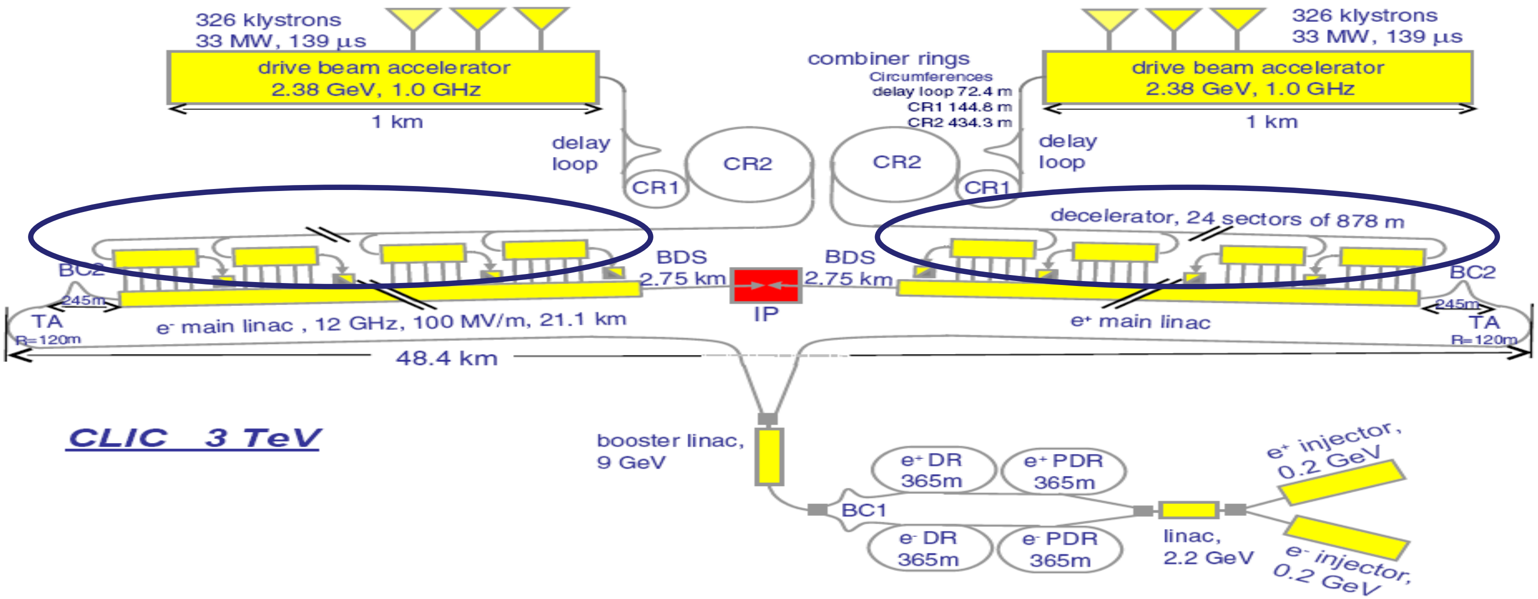
Agenda

1. Abstract
2. The prototypes
3. Lessons learned
4. Industrialisation
5. Conclusion

1. Abstract

The CLIC-UK collaboration between CERN and STFC produced two prototypes of permanent magnet based quadrupoles to cover the large tuning range (15 - 60 T/m and 4 - 43 T/m respectively) required for the CLIC Drive Beam Decelerator. The space envelope and accuracies to achieve the demanding parameter challenges have been addressed during the production of the prototypes. Assembly sequencing, accuracy analysis and an investigation into industrial capabilities in both metrology and manufacture/assembly led to a proposal in the efficient and specification meeting "mass-production". Manufacture and assembly of the prototypes provided the identification and foundation of techniques and methodologies essential for large scale industrial manufacture.



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2. The prototypes

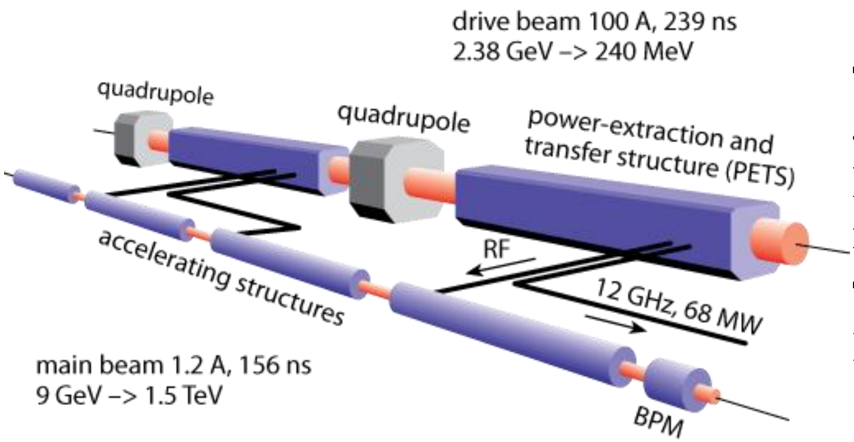
2.1 CLIC Requirements

2.2 Magnet specification

2.3 High Strength prototype

2.4 Low Strength prototype

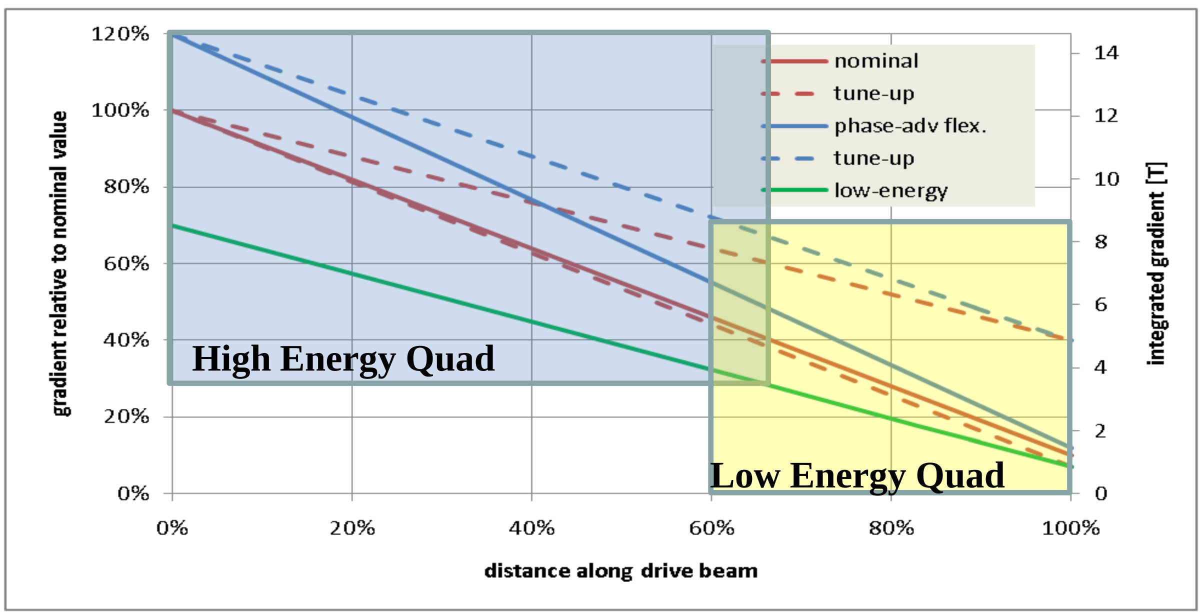
2.1 CLIC Requirements



CLIC DBD Quadrupoles

The CLIC drive beam decelerator requires a total of around 41400 quadrupoles to focus the beam along its 42km length (2 x 21km, where 21km consist of 24 sectors x 876m module strings).

There are two Quadrupole Magnets required per 2m long Drive Beam module (Modules: type 1, type 0 and type 4).



Large range of integrated gradient (1.22 – 14.6T) requires at least two different PM Quadrupole designs.
The nominal max integrated gradient is 12.2T and the min is 1.6T

For operational flexibility each individual quadrupole must operate over a wide tuning range:

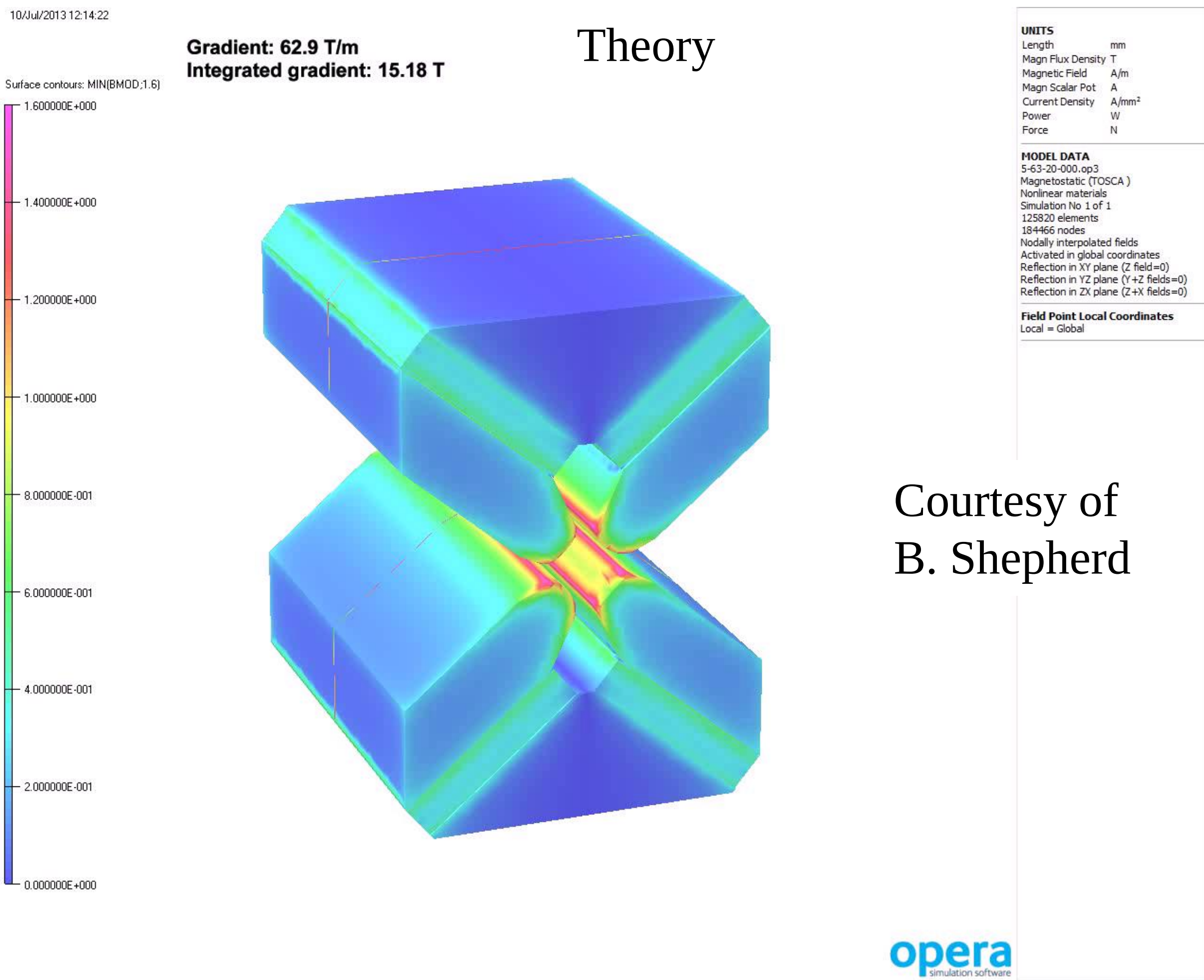
70% to 120% at high energy
7% to 40% at low energy

2.2 Magnet Specification

Parameter	*Specification*		High-strength version		Low-strength version	
Inscribed radius	*≥ 13 mm*		13.6 mm			
PM size			18 x 100 x 230 mm		37.2 x 70 x 180 mm	
PM angle			40°		90°	
Magnet Pole Length	*≤ 230 mm*		230 mm		180 mm	
Maximum stroke			64 mm		75 mm	
Integrated gradient	*14.6 T*	*0.9 T*	14.6 T	4.4 T	8.5 T	0.6 T
Relative to nominal	*120%*	*7%*	120%	30%	70%	5%
Good gradient region (0.1%)	*±11.5 mm*		±12.0 mm		±12.0 mm	
Movement precision			10 µm			
Relative strength precision	*$\leq 5 \times 10^{-4}$*		3.2×10^{-4}	1.7×10^{-4}	6.5×10^{-5}	7.6×10^{-4}
Force on moving section			16.4 kN	1.0 kN	0.7 kN	0

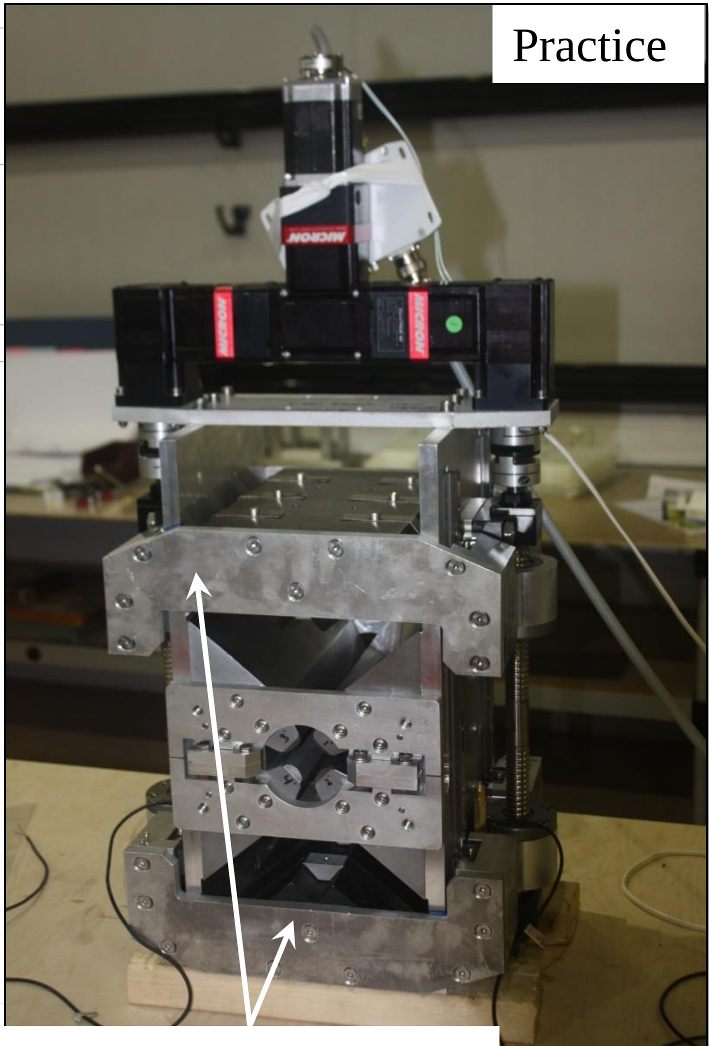
2.3 High Strength prototype

Theory



Courtesy of
B. Shepherd

Practice



Complete Prototype.
Note the "open jaws".

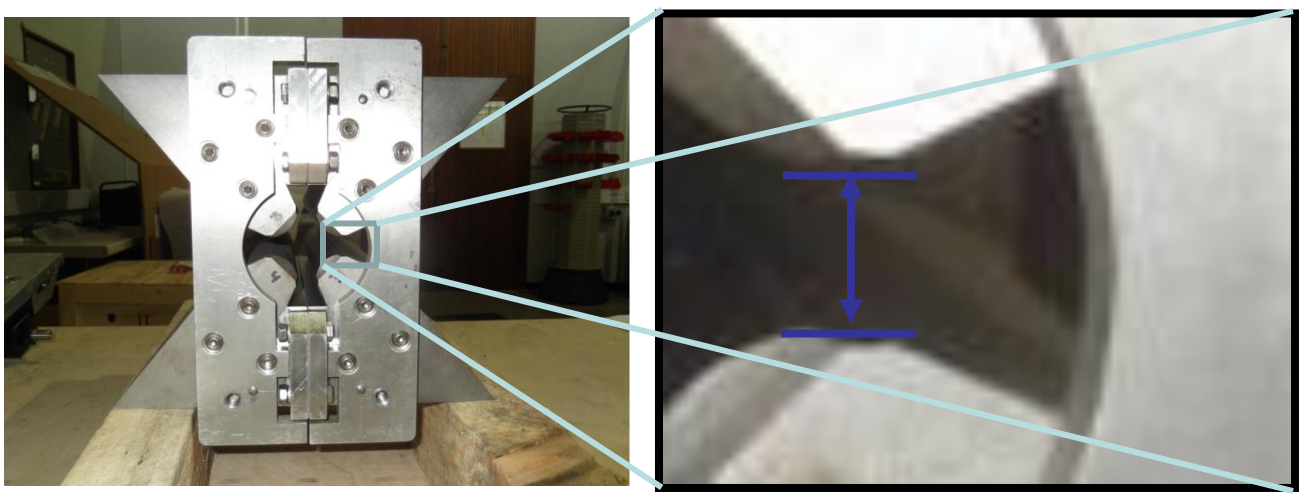
2.3 High Strength prototype

The High Strength version is conveniently broken down into four subassemblies.

1. The core
2. Side-plates
3. Permanent Magnet cap
4. Motor - gearbox

1. The Core

Hypothesis: field quality is controlled by poles (not PMs), so are they where they should be? Measured pole gaps using ceramic slip gauges. Found discrepancies in all measurements.



Nominal: 9.03mm

1	←8.790→	3
↑		↑
9.153		9.251
↓		↓
2	←8.910→	4

2.3 High Strength prototype

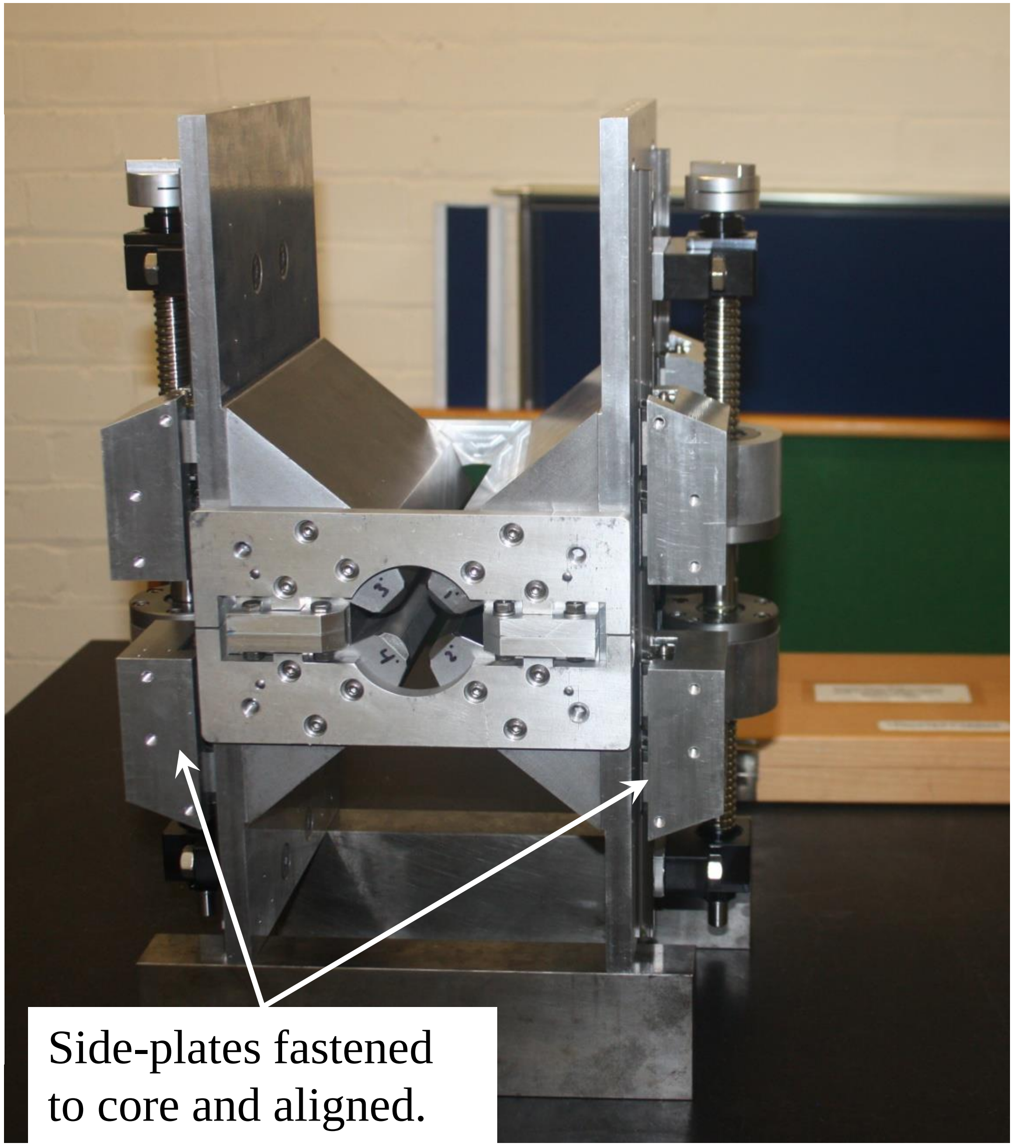
2. The Side-Plate

Two "identical" side-plate assemblies.
Challenges include:
Parallelism of "Left-Right Hand Threaded" Ballscrews in both rotational degrees of freedom and accurate positioning relative to each other and the core in all 3 planar degrees of freedom.

Synchronisation between the left and right hand side was critical.

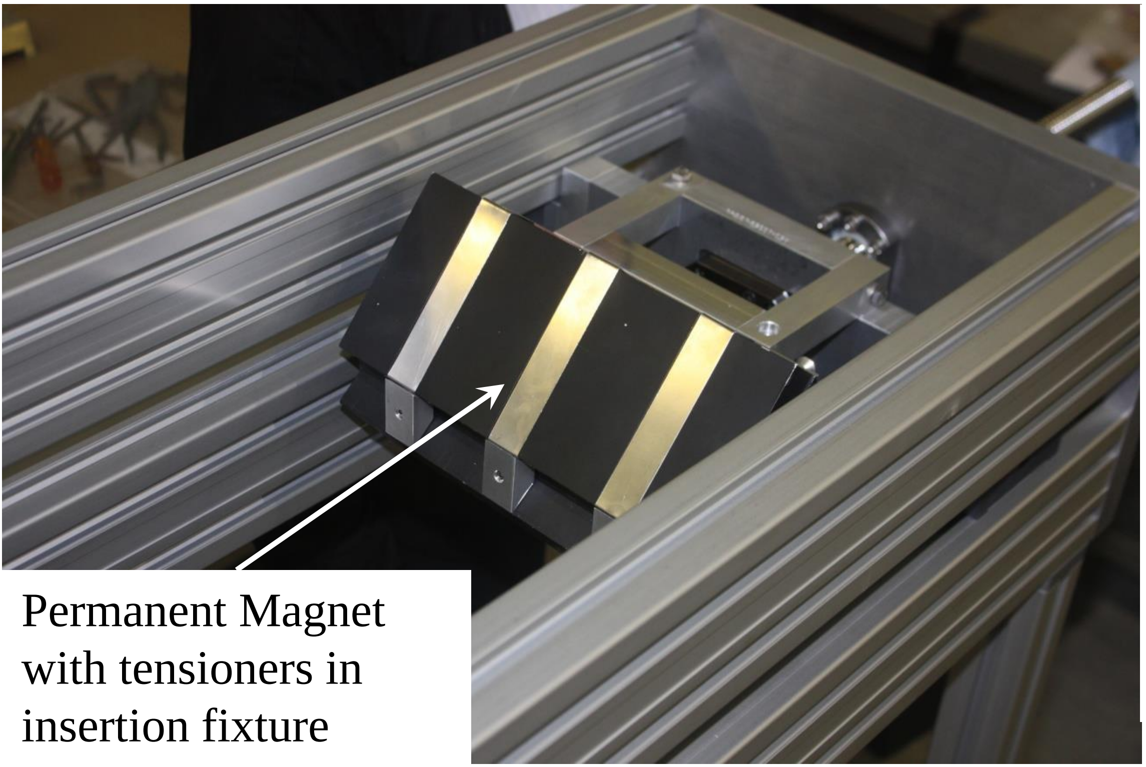
Now less important as other parts have features to permit adjustment.

Supplier will deliver complete units with relevant metrology data.


Side-plates fastened to core and aligned.

2.3 High Strength prototype

3. The Permanent Magnet Cap



Permanent Magnet with tensioners in insertion fixture

Mechanical accuracies less critical than other sub-assemblies. Larger tolerances permitted.

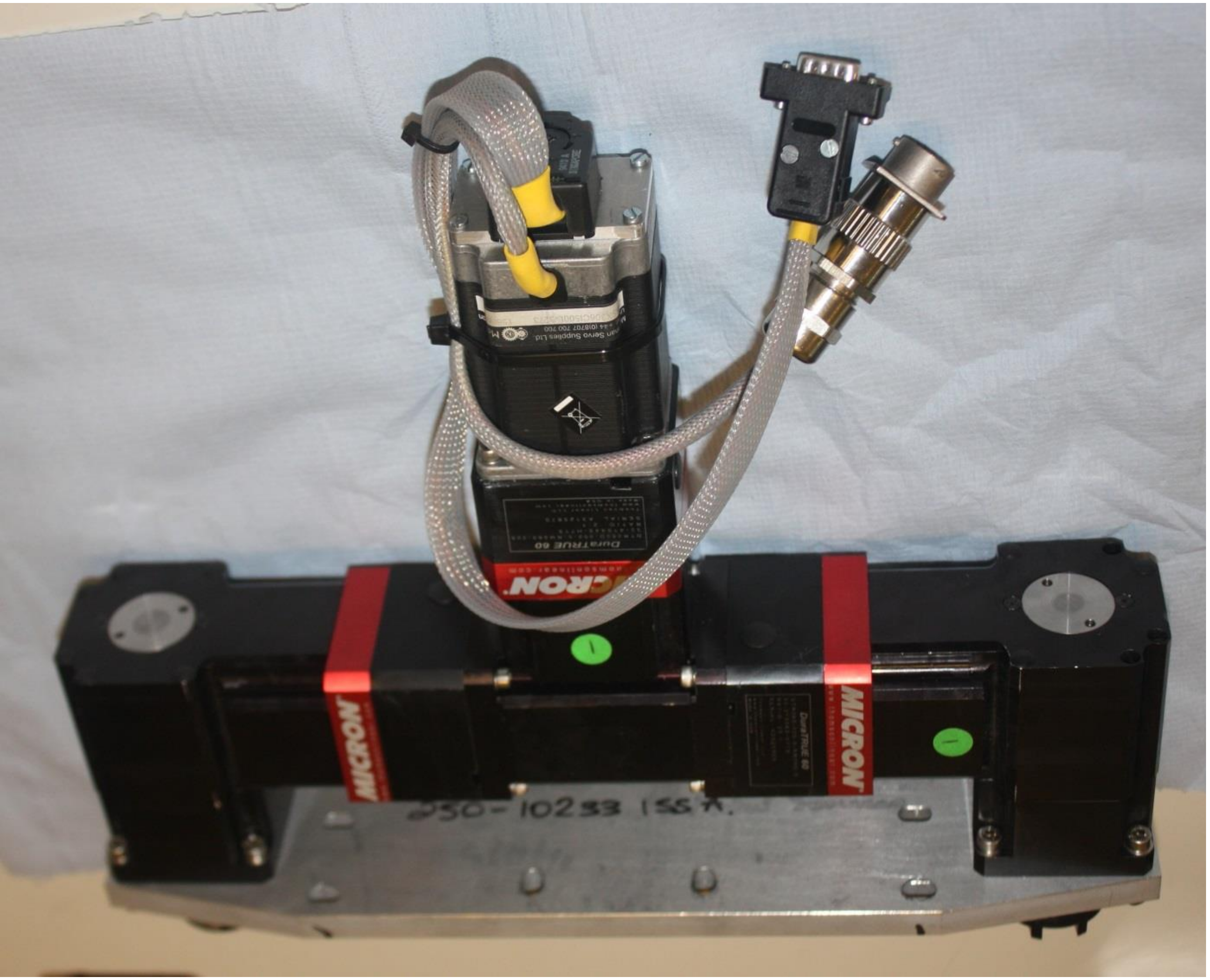
Magnetic performance requires pairing per cap.

Supplier will deliver complete units with relevant metrology data.

Caps require pairing in final assembly to prevent magnetic axis offsets.

2.3 High Strength prototype

4. The Motor - Gearbox



High accuracy systems specified.

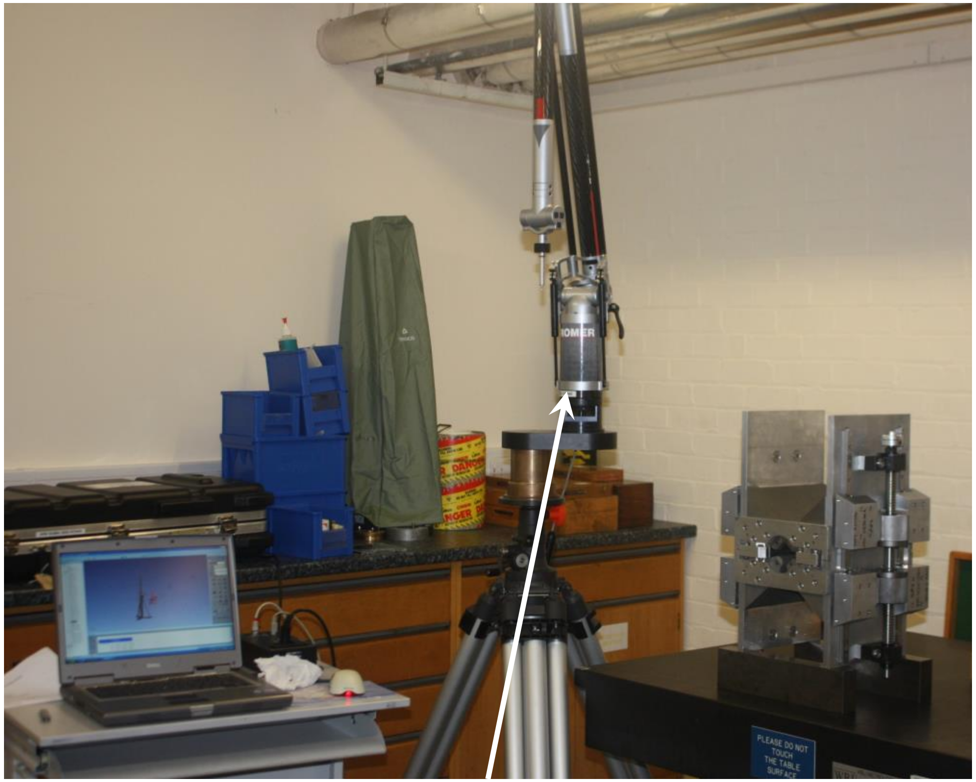
Stepper motor (400 steps per revolution) with rotary encoder mounted on top.

“T-Gearbox” with a 2:1 ratio coupled directly onto 90° gearbox (25:1 ratio) with an overall rotational error range of approximately ±8 arc seconds.

Output axis alignment reasonably tight tolerance. Axial centre distance less important as the large torque precision backlash coupling will cater for this.

2.3 High Strength prototype

The Challenges



Coordinate Measurement Machine utilised at every step of the assembly process.

During the assembly of the prototype almost continuous measurements were taken.

This data in conjunction with magnetic measurement data permitted the identification of areas where the tolerances needed to be tightened whilst others could be relaxed.

This iterative process furthermore permitted the assembly process analysis, which in turn resulted in the improvement of accuracies due to design changes.

Manufacturing methods have been discussed with suppliers clearly outlining the specification and further improvements are identified.

2.3 High Strength prototype

Summary

The thorough documentation of the High Strength Prototype assembly, measurement, analysis and iteration identified areas of improvement not only from a performance point of view, but also the “large” scale production.

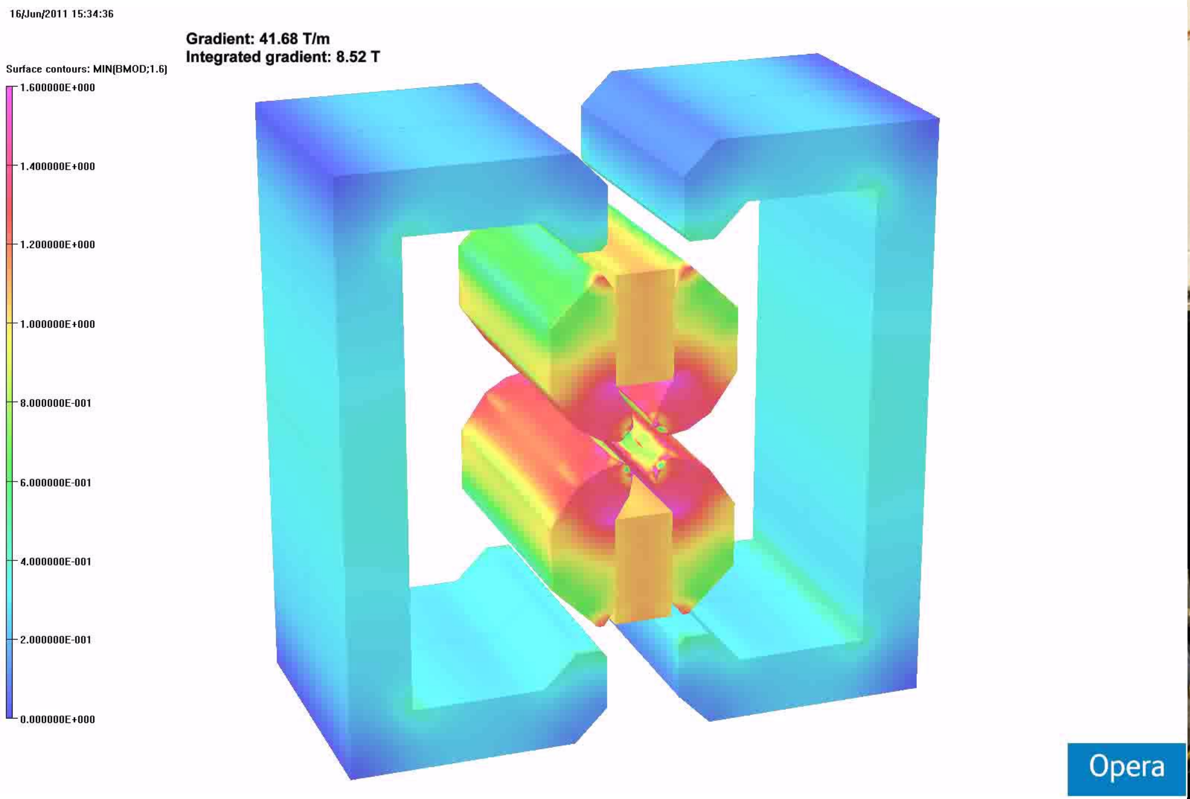
Close liaison with suppliers provided ideas and suggestions to speed up the manufacturing process and assembly, and at the same time achieving better accuracies than the prototype. For instance the core can be wire eroded in the assembled condition. Subsequently accuracies remain well within the ±10μm around the nosepole, plus time to manufacture can be quartered. Furthermore, expensive optical comparator and positioning equipment could be eliminated.

Design features, such as additional tooling holes and adjustment provisions aid in the final assembly process. Here, optical self centering or laser interferometer equipment in conjunction with 6 axis position systems (closed loop) will ensure accurate final assembly. These will also eliminate the “human error” element and faster assembly.

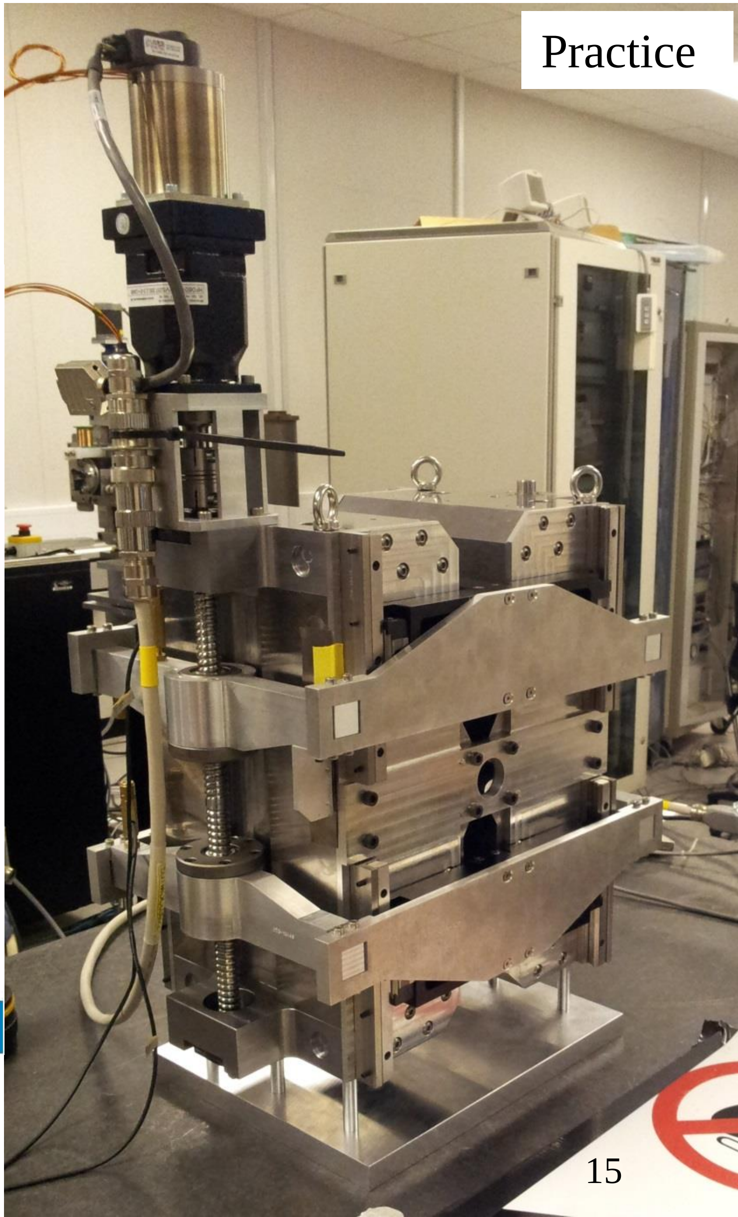
2.4 Low Strength prototype

Completely different design where the Permanent Magnet is drawn out from the yokes towards a shroud, essentially creating a short circuit for the flux.

Theory



Practice



2.4 Low Strength prototype

The Low Strength version can't be broken down into convenient subassemblies unfortunately. There are however five lower level subassemblies.

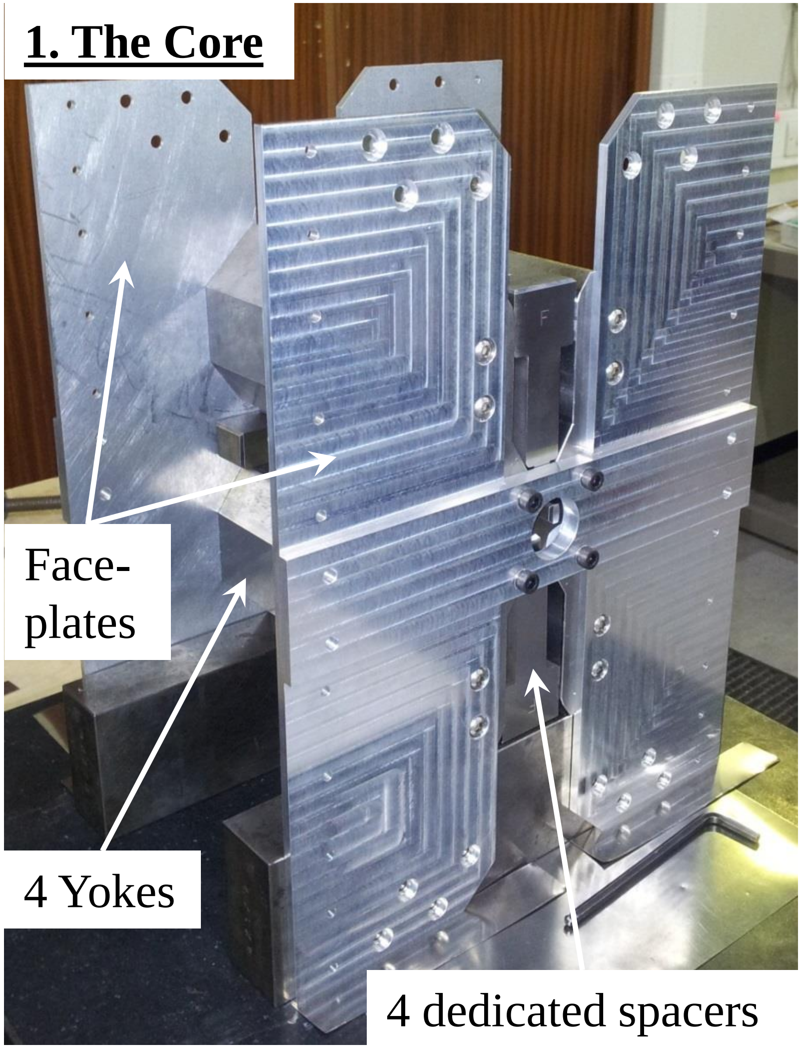
1. Core
2. Permanent Magnet Frame
3. Motor – Gearbox
4. Shroud - Drive Side
5. Shroud – Guide Side

1. The Core

The 4 yokes have an additional complication in terms of positioning. The PM receptacle needs to be aligned as well as the nosepole to a fairly tight tolerance (±0.05mm and ±10µm respectively) relative to each other.

Dedicated spacers (to the nearest 5µm have been used for the prototype. This is unfeasible for production.

A dedicated optical scanning and positioning system will need to be developed or a less desirable post assembly machining methodology must be adapted.



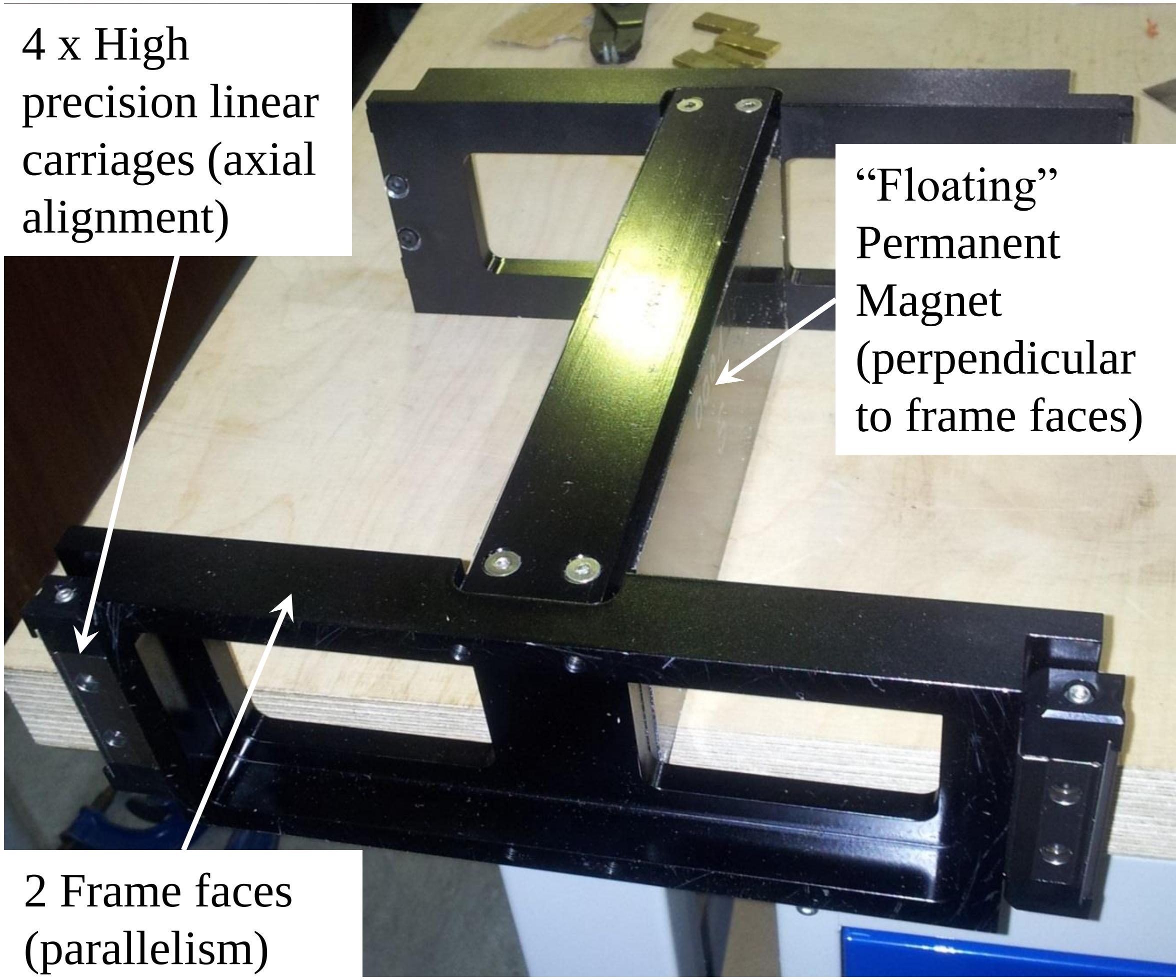
2.4 Low Strength prototype

2. The Permanent Magnet Frame

Discussions with the permanent magnet supplier about the industrialisation have shown that this subassembly requires few “semi-critical” mechanical parameters to be controlled.

Assembly is reasonably easy using semi-automated machinery in conjunction with closed loop optical measurement systems.

The supplier delivers complete units with metrology data.



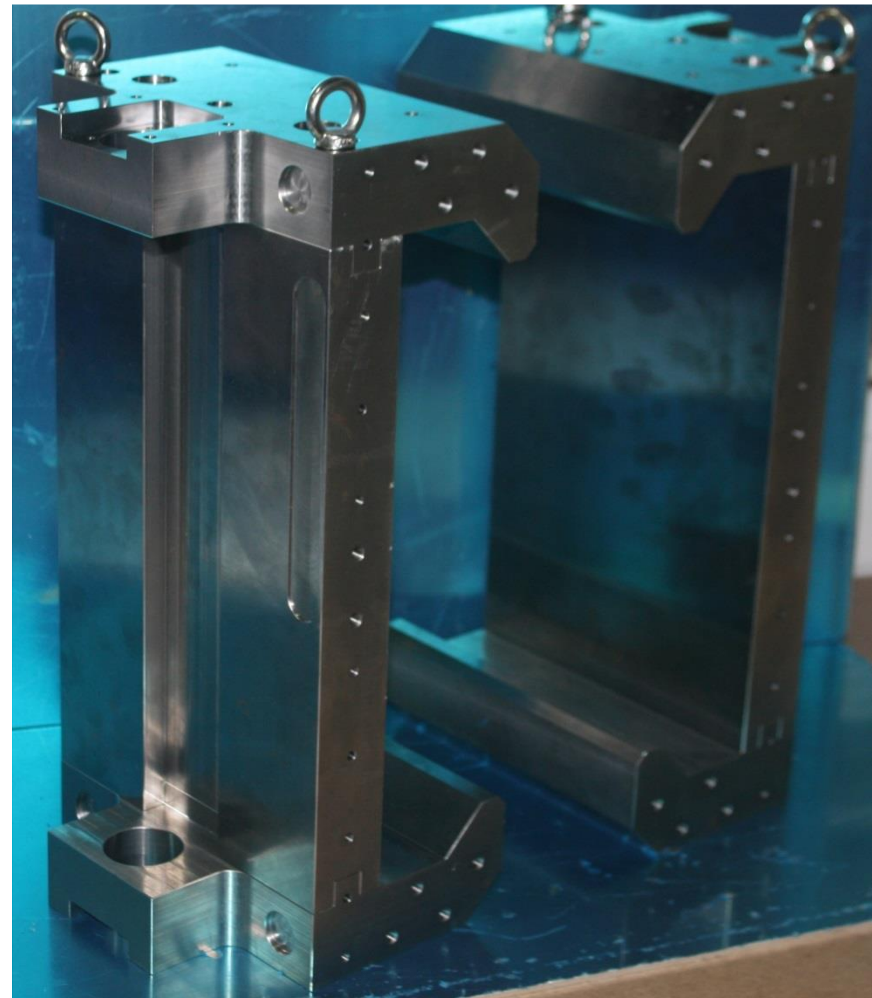
2.4 Low Strength prototype

3. Motor-gearbox

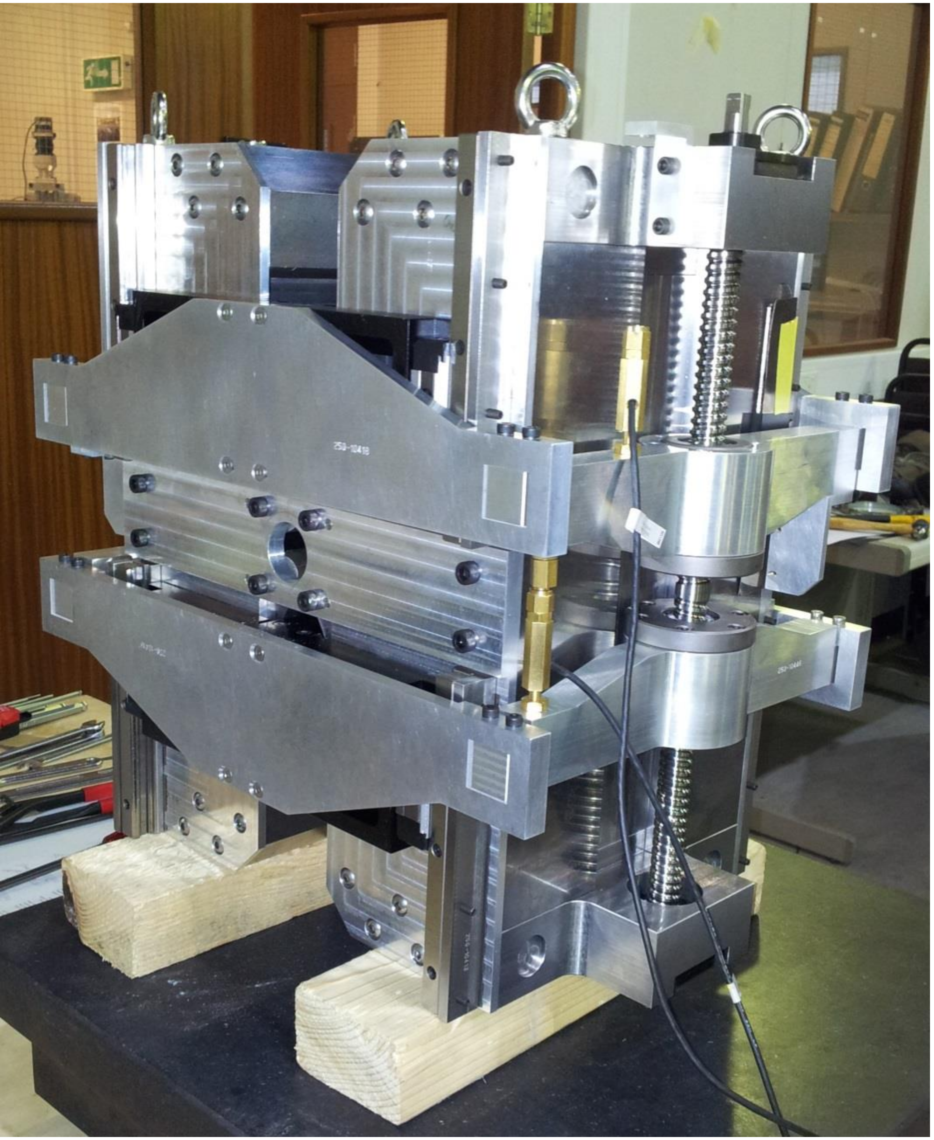
Straight "off-the-shelf" units and supplied assembled as depicted above.

Precision machined shrouds ensure magnetic axis "symmetry" horizontally (X-plane) and vertically (Y-plane).

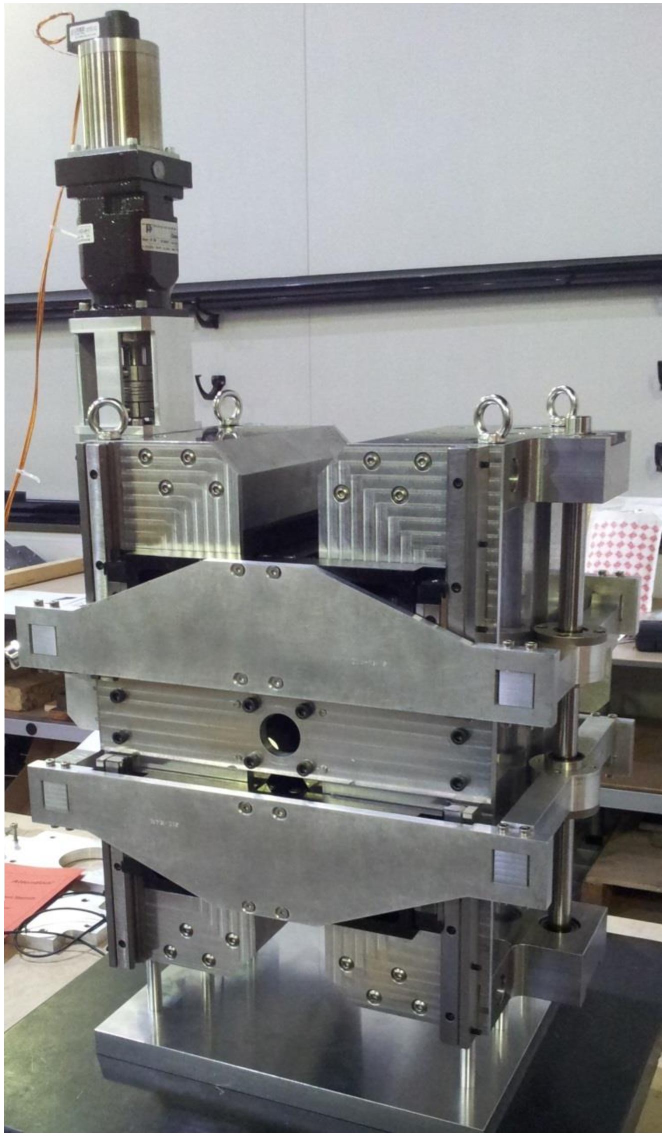
4 & 5. Shrouds – Drive (left) & Guide (right)



2.4 Low Strength prototype



Now the difficult part of the assembly; bringing it all together and ensuring items are aligned (vertically and horizontally) and spacing from the "imaginary centre" is equal in all directions.



2.4 Low Strength prototype

Summary

The Low Strength Prototype design principle is very different from the High Strength version.

All “pre-assembled” items require careful alignment and positioning relative to each other.

This in turn demands almost constant measurements; at least after each assembly step.

A continuous design review was carried out during the assembly process, which in turn has lead to a “large” number of areas of improvement suggestions.

Close collaboration with suppliers has increased this number and the overall conclusion is that individual components need to have tight tolerance specification.

It is essential to utilise optical self centering or laser interferometer equipment, edge recognition modern ‘shadow graphs’ in conjunction with 6 axis position systems (closed loop) to ensure accurate final assembly.

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3 Lessons learned

3.1 High Strength version

Design:

1. High forces (up to 17kN per side) was considered a concern initially.
2. Potential risks included one side of one cap disengaging prior to other side (skewing).
3. Steps (stroke) too large to achieve required magnetic characteristic.
4. Both sides synchronised via single motor and “identical” motion system.
5. High forces causing undesired mechanical deflections.
6. Design may not fit in the permissible envelope.

The list is long,   BUT the design is sound and performs better than expected.

3 Lessons learned

3.1 High Strength version

Manufacture/Assembly:

1. Initially assumed very tight tolerances are required on manufactured and assembled items to achieve overall performance.
2. Found that system can be broken down into 4 distinct subassemblies.
3. Core can be manufactured as one subassembly – time saving and increased accuracy.
4. Additional assembly features and adjustment permitted the relaxation of tolerances.
5. Eliminated the need for expensive assembly tooling (Laser Interferometer, Edge recognition “shadow graph”, closed loop positioning systems (still desired but not essential) and dedicated visual shape recognition (Optical Comparators) system.

3 Lessons learned

3.1 High Strength version

Logistics:

1. The number of High Strength Quadrupoles required based on a 60:40 (HS:LS) division out of the total requirement of 41400 equates to 25000 over a period of 3 years, meaning a production of 33 per day.
2. Shipping subassemblies from their relative source country needs to be carefully orchestrated and during discussions with suppliers the advice to have dedicated containers on a rolling schedule was given.
3. Protection of goods (environment), ensuring accuracies are retained (i.e. vibration) and distribution advantages are achieved by this; it aids furthermore in the Just In Time final assembly.

3 Lessons learned

3.1 High Strength version

<u>Final Assembly/Testing:</u>

1. Final assembly is relatively straight forward with the proposed finished subassemblies arriving on site.
2. Some pairing will be required (PM cap & Side-plate) based on the supplier metrology data.
3. Each system will undergo testing to provide a magnetic characteristic map and physical positioning information.

3 Lessons learned

3.2 Low Strength version

Design:

1. Completely different principle compared with High Strength version.
2. Forces for motion system very low.
3. Only one side is driven, other side is a “slave” arrangement.
4. Magnet can’t be “split” to permit insertion of vacuum vessel.
5. Component number count high, but reasonably simple.
6. Motion system “behind shroud, thus less likely to have an adverse influence on magnetic characteristics.

3 Lessons learned

3.2 Low Strength version

Manufacture/Assembly:

1. Tight tolerances are required on manufactured and assembled items to achieve overall performance.
2. Final assembly requires dedicated closed loop metrology and positioning system.
3. Post-subassembly machining may be required.
4. Alignment of 3 linear motion subsystems with 3 subassemblies critical, each relative to each other in all 6 degrees of freedom.
5. PM insertion delicate and may have to be carried out by a skilled person.
6. Vertical equality adjustment of system must be carried out by a skilled person.

3 Lessons learned

3.2 Low Strength version

Logistics:

1. The number of Low Strength Quadrupoles required is 16700, equating to a production rate of 22 complete units per day (same assumptions as per HS version).
2. No special transport packaging is required except for the Permanent Magnet subassembly. This will follow similar arrangements as the HS version.
3. There is a need to have metrology data for all subassemblies. Sorting at the final assembly plant may have to be carried out to ensure pairing is correct for symmetry reasons.

3 Lessons learned

3.2 Low Strength version

Final Assembly/Testing:

1. Final assembly is rather "complex" as a good number of components are required to be assembled at the final stage.
2. Measurements have confirmed that the nosepole shape and position relative to each other is critical (20µm). An optical comparator system in a close loop arrangement to a 6 axis positioning system.
3. Testing will be as per High Strength version and final adjustments may need to be carried out by a skilled person.

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4 Industrialisation

4.1 High Strength version

4.1.1 The Core:

Manufacture will be such that the yokes, "yoke-wedges" and face-plates are machined using CNC machining centres. These items are then assembled before the precise nosepole shape and position is produced using Electro Discharge Machining.

4.1.2 The Side-plate:

The linear motion supplier will manufacture the components required (side-plate, brackets, ball-screw and LM rails. Their expertise in assembling such systems is ensuring alignment of these components to specification (theirs and ours).

4.1.3 The Permanent Magnet Cap:

Somewhat more demanding than the mechanical components. The Permanent Magnet Blocks need to be mechanically accurate AND magnetically. The supplier has provided assurance that each block will be measured, sorted and paired accordingly.

4 Industrialisation

4.1 High Strength version

4.1.3 The Permanent Magnet Cap (continued):

Each cap will have metrology data (magnetic and mechanical) to enable "cap-pairing" during final assembly. This is to ensure vertical symmetry.

4.1.4 The Motor-Gearbox assembly:

The Motor-Gearbox assembly is supplied ready to mount onto the final unit. The electrical connections use standard plugs and sockets to interface with the control system (one per 6 motors) for the motor and encoder.

4.1.5 Final assembly:

Few additional items (to the above) are required in the final assembly and with appropriate jigs, fixtures and tooling this process takes little time. Adjustment and testing is also relatively simple, but will be somewhat more time consuming.

4 Industrialisation

4.2 Low Strength version

4.2.1 The Core:

Manufacture will be such that the yokes and face-plates are machined using CNC machining centres. The yokes are then individually finished using Electro Discharge Machining. Assembly requires precise positioning and will be carried out using optical equipment with feedback for a 6 axis positioning system. Prior to fastening and securing the face-plates, end machining may be required. Despite this being the most time consuming subassembly the supplier is certain timescales can be met.

4.2.2 The Permanent Magnet Frame:

The PM Frame has mechanical and magnetic specifications. Mechanical parallelism and perpendicular relationships need to be quite accurate. The magnetic characteristics are such that metrology data is required for each that pairing in the final assembly is carried out without delay. Assurance from the supplier has been received to confirm the rate and quality for these units does not pose issues.

4 Industrialisation

4.2 Low Strength version

4.2.3 The Motor-Gearbox assembly:

As with the High Strength motor gearbox assembly, this subassembly will be received ready to be installed. Electrical connections are standard components from motor and rotary encoder to control system.

4.2.4 The Shrouds:

The shrouds are assembled from “simple” manufactured items. Alignment of the top and bottom sections is however important. Post assembly machining (front and rear faces) may be required to ensure squareness. Furthermore, sorting according to “size” will guarantee the magnetic characteristics to remain symmetric.

4 Industrialisation

4.2 Low Strength version

4.2.5 The Quad assembly:

In the first instance the shrouds and core are brought together and positioned relative to each other using optical comparator machines (e.g. Nikon HORIZON or V-series) and autocollimators (Tayler Hobson, Ultra range) or micro alignment telescopes. This will provide RMS planes (horizontal and a vertical) for future reference.

The linear motion system is fastened to the assembly and aligned as per manufacturer specification. The previously established planes serve as the datum regarding alignment, important!

The importance of the above is evident when inserting the PM magnetic frames. These must be positioned so that they are symmetric (left-right) over the entire stroke distance. Also a small clearance “air-gap” on each side is essential (prevents undesired friction). Connector bars permit the vertical adjustment (symmetry reasons) and cater for variations in the manufacture.

4.2.6 Final assembly:

The motor-gearbox and few additional items are required in the final assembly and with appropriate jigs, fixtures and tooling this process takes little time. Adjustment and testing is reasonably simple, but will be somewhat more time consuming than the HS version.

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5 Conclusion

In conclusion, the CLIC Drive Beam Decelerator Permanent Magnet Quadrupole requirement calls for at least two different design solutions.

The High Strength solution covers 60% of the requirement (3.5T – 14.8T Integrated gradient; 1:4.5 ratio).

The design is such that manufacture and assembly are reasonably straight forward.

Analysis of the prototype assembly process, performance and design has resulted in a revision that relaxes previously tight tolerances.

Close liaison with suppliers has taken this a step further and subsequently cost and lead times have been reduced.

5 Conclusion

The Low Strength solution covers the remaining 40% of the requirement (0.45T – 8.8T I.G.).

To cater for the large adjustment range (1:11 ratio) the design is distinctly different to the HS version.

This solution involves high accuracy machined components to be assembled at different stages.

Alignment of these and the linear motion system is challenging.

It requires a dedicated “metrology – positioning” closed loop assembly system in addition to skilled professionals for final adjustment meaning it will be time consuming.

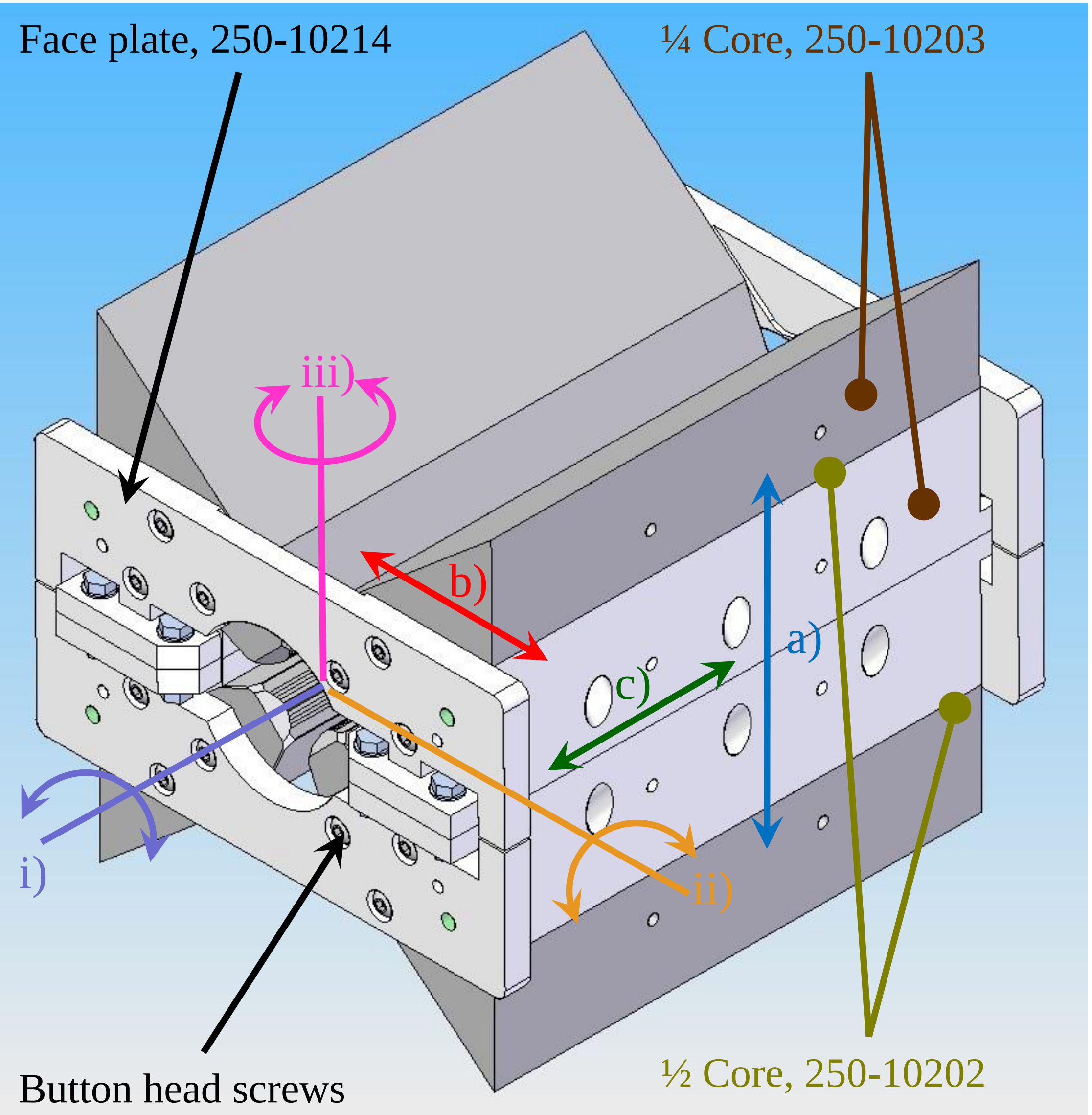
Improvements to the prototype have been identified to alleviate some of the complexity and close tolerance requirements.

Both CLIC Permanent Magnet Quadrupole solutions can be manufactured in the time scale stated at the beginning.

Question time

Backup slides

Assembly to measure; first instance: core (250-10201):



Need to eliminate 6 degrees of freedom of the 'two halves':

1. The 3 linear motions:
   a) Up and down
   b) Left and right
   c) Back and forth

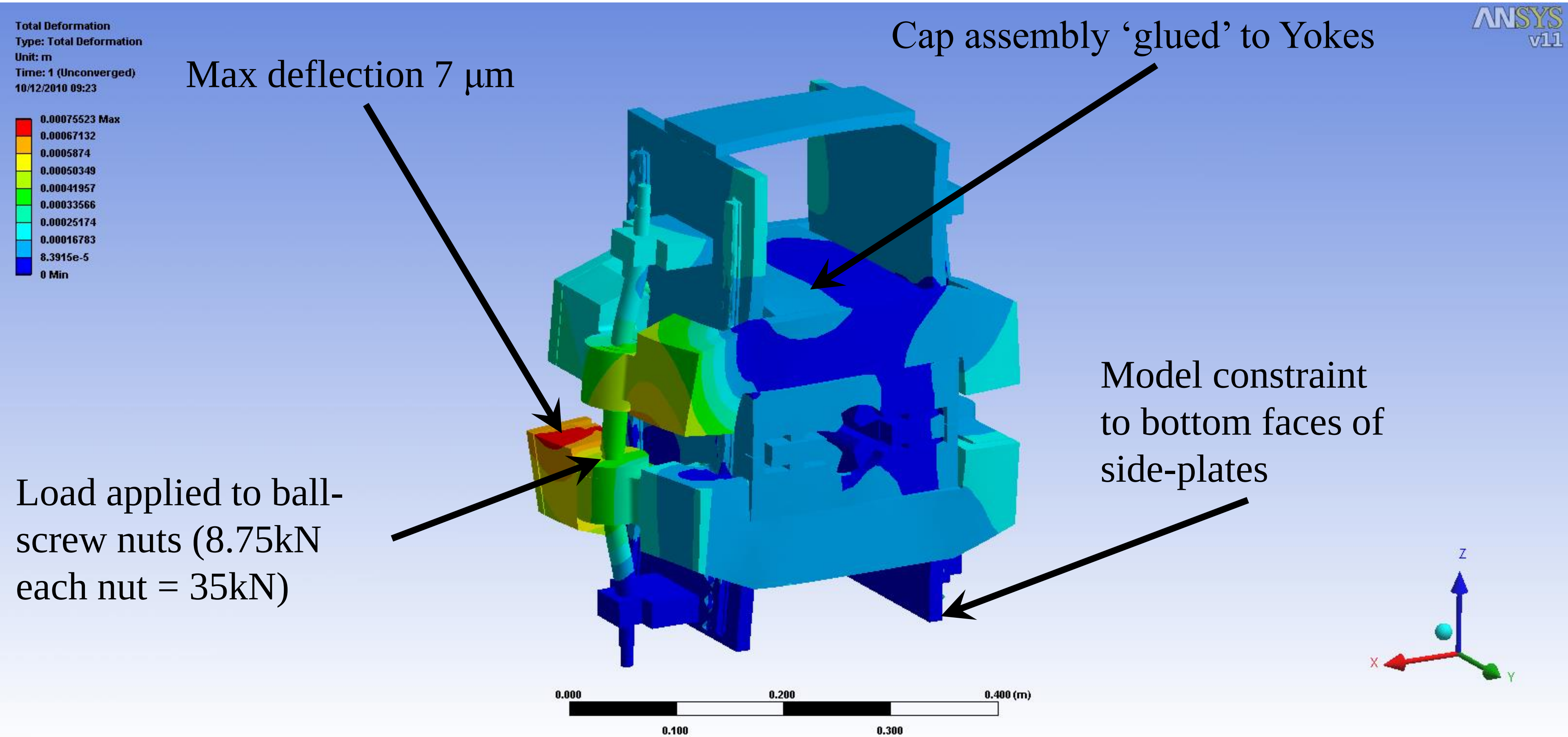
2. The 3 rotational motions:
   i. Longitudinal centre axis
   ii. Transverse centre axis
   iii. Vertical centre axis

3. Tolerance in Button head screw holes large enough to adjust core accordingly.

4. Ensure the quadrupole aperture diameter is 27.2mm.

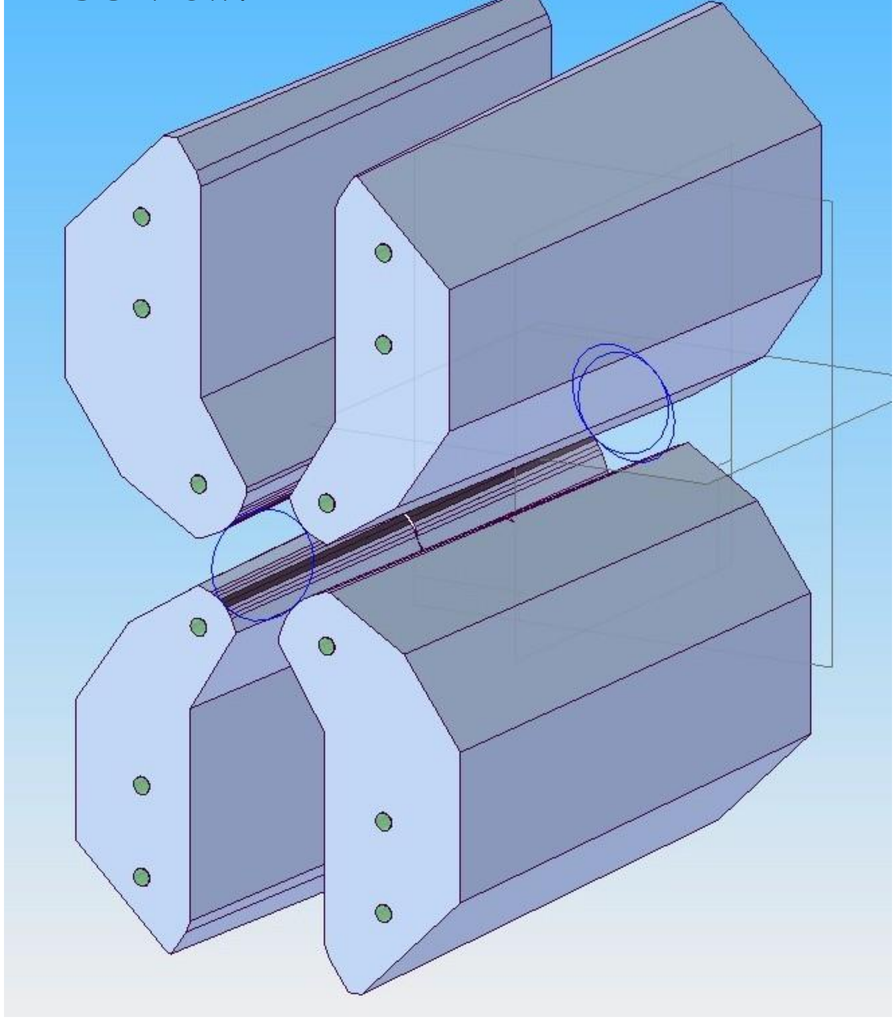
Provisional Analysis – Complete Model

All parts working together, i.e. Ball-screw and nut with Linear Motion rails provides a feasible design that is within the specified tolerance range of 10 μm.

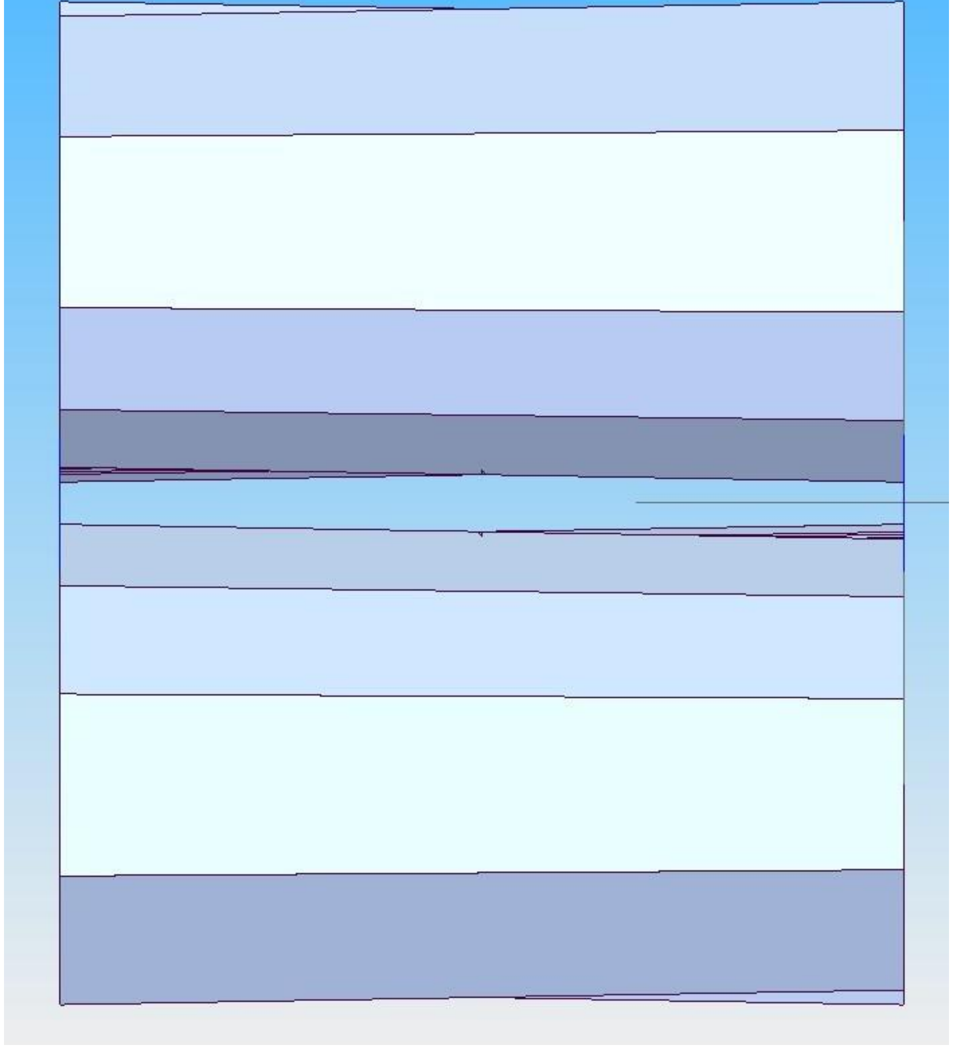


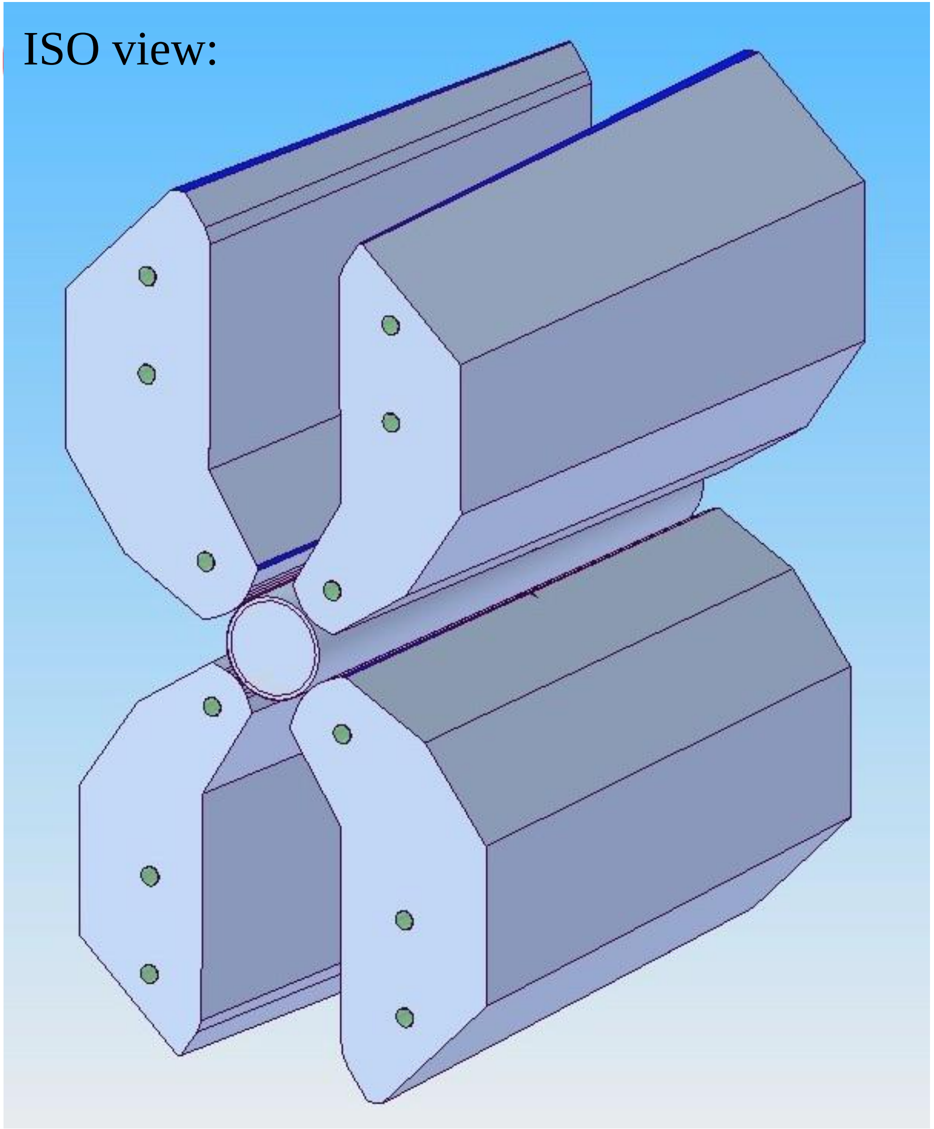
Assembling the yokes in their current shape would result in parallel end faces as intended. The important feature of the magnet is however the inscribed nose pole radius. We would retain the average over the length aperture with opposite ovals at the ends – not acceptable.

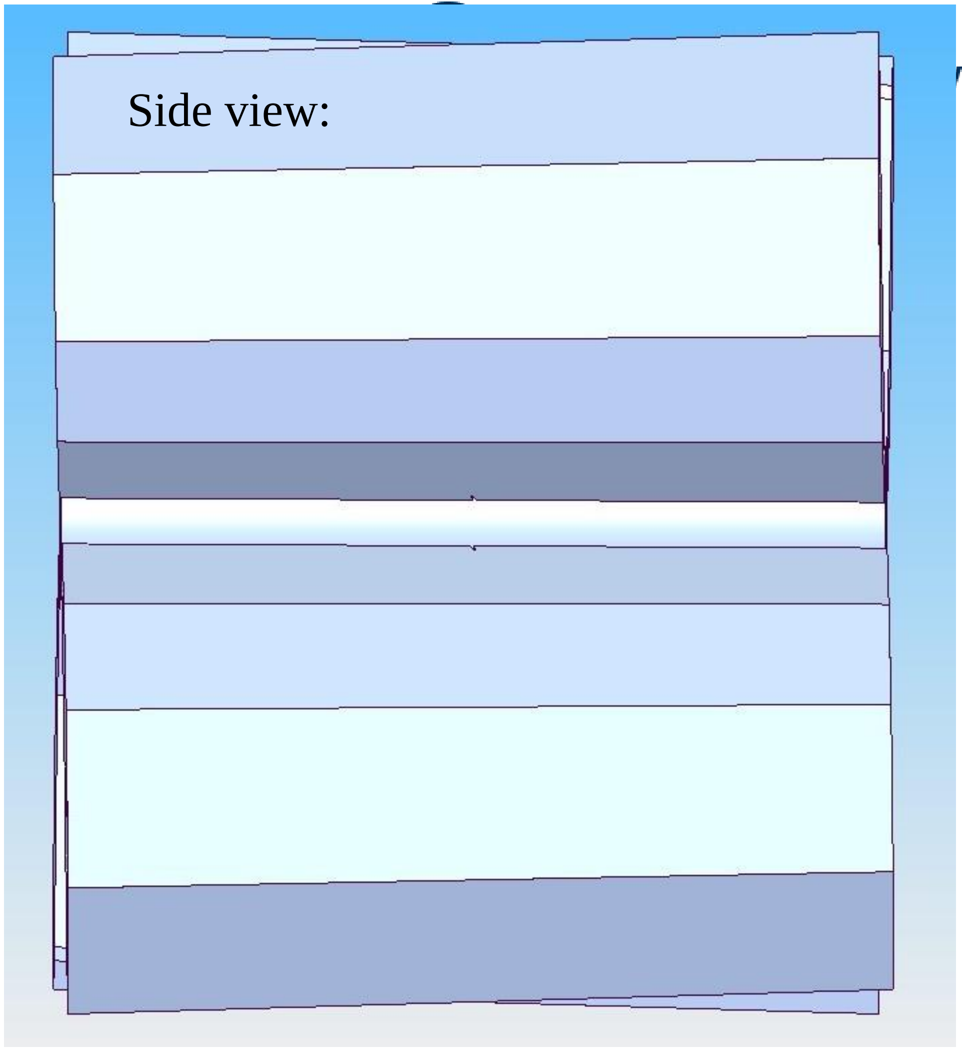
ISO view:



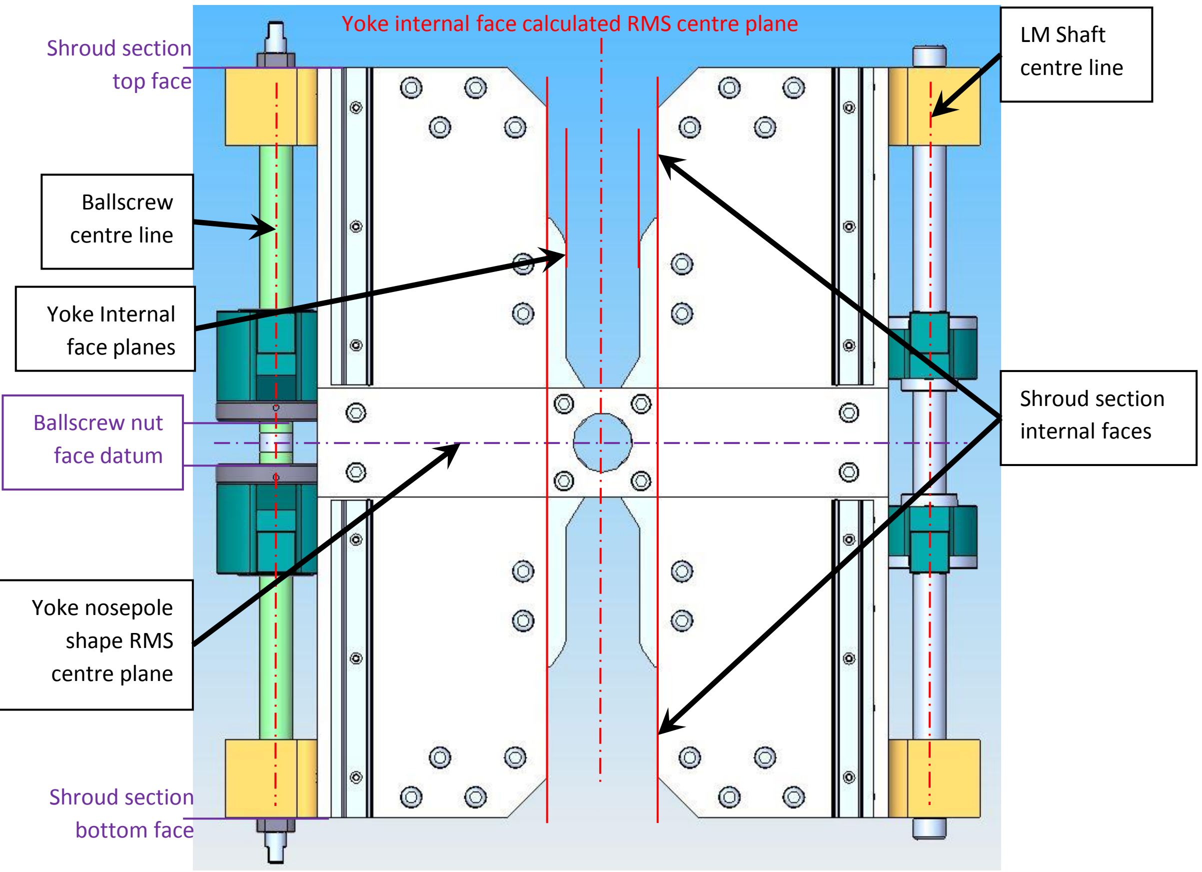
Side view:

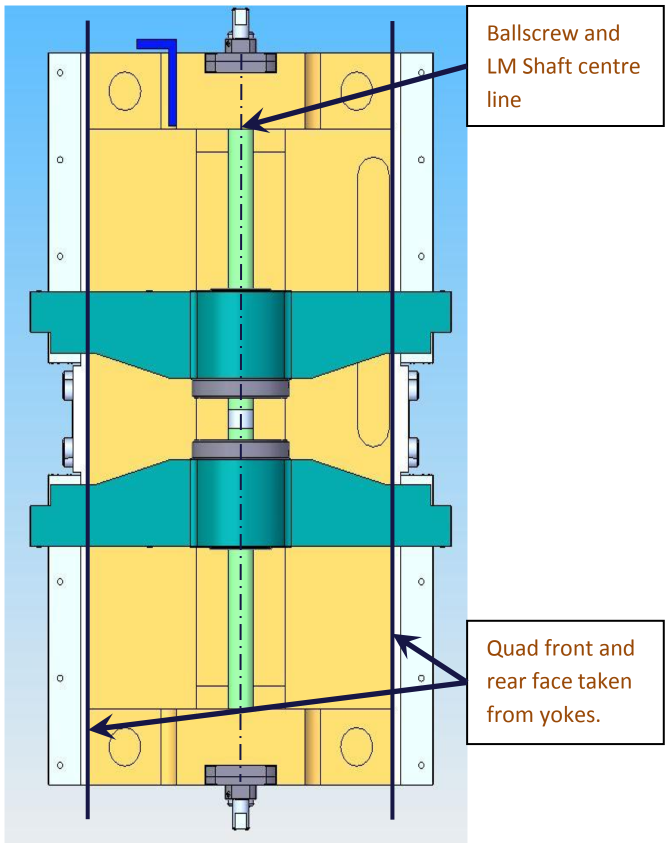


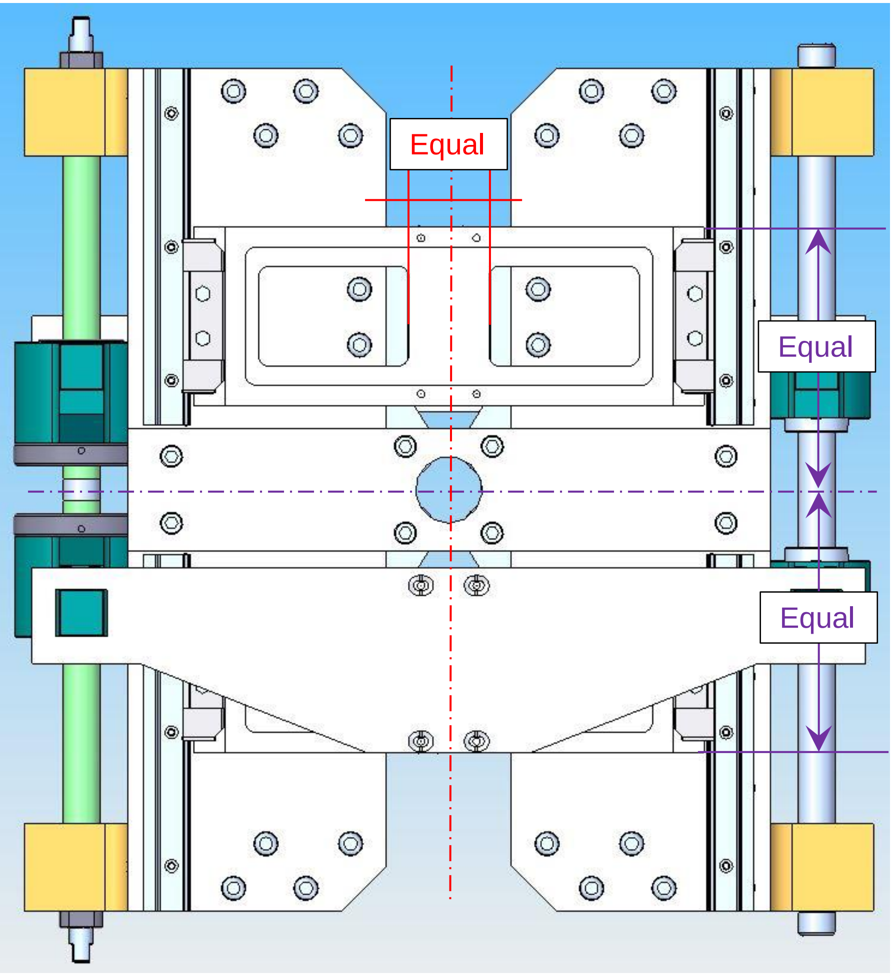




We need to “straighten” the nose pole aperture by tilting the yokes at a 45 degree plane.
Drawback; end faces are now angled and would need to be ground square.
Top faces are also “out-of-square”. This would influence the magnetic characteristics.


Yoke internal face calculated RMS centre plane
Shroud section top face
Ballscrew centre line
Yoke Internal face planes
Ballscrew nut face datum
Yoke nosepole shape RMS centre plane
Shroud section bottom face
LM Shaft centre line
Shroud section internal faces


Ballscrew and LM Shaft centre line
Quad front and rear face taken from yokes.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