Drive Beam Quadrupoles

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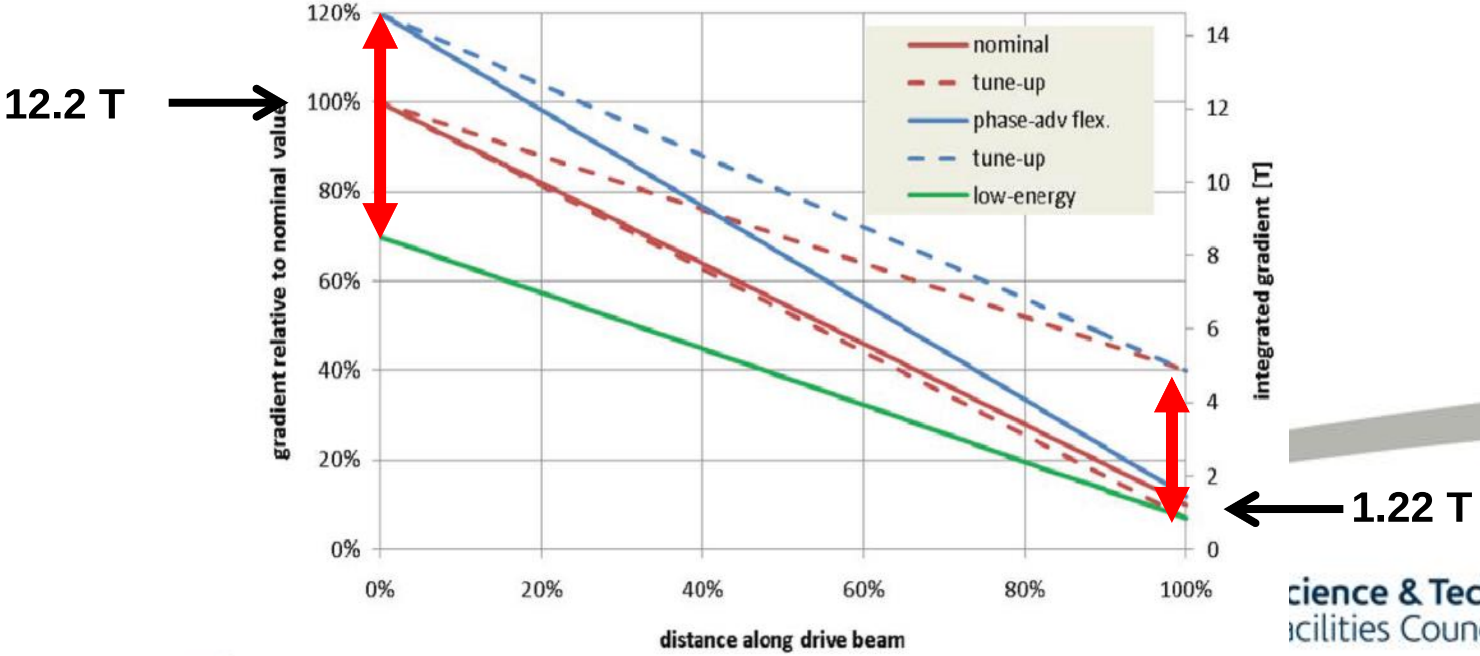
Current Work Programme

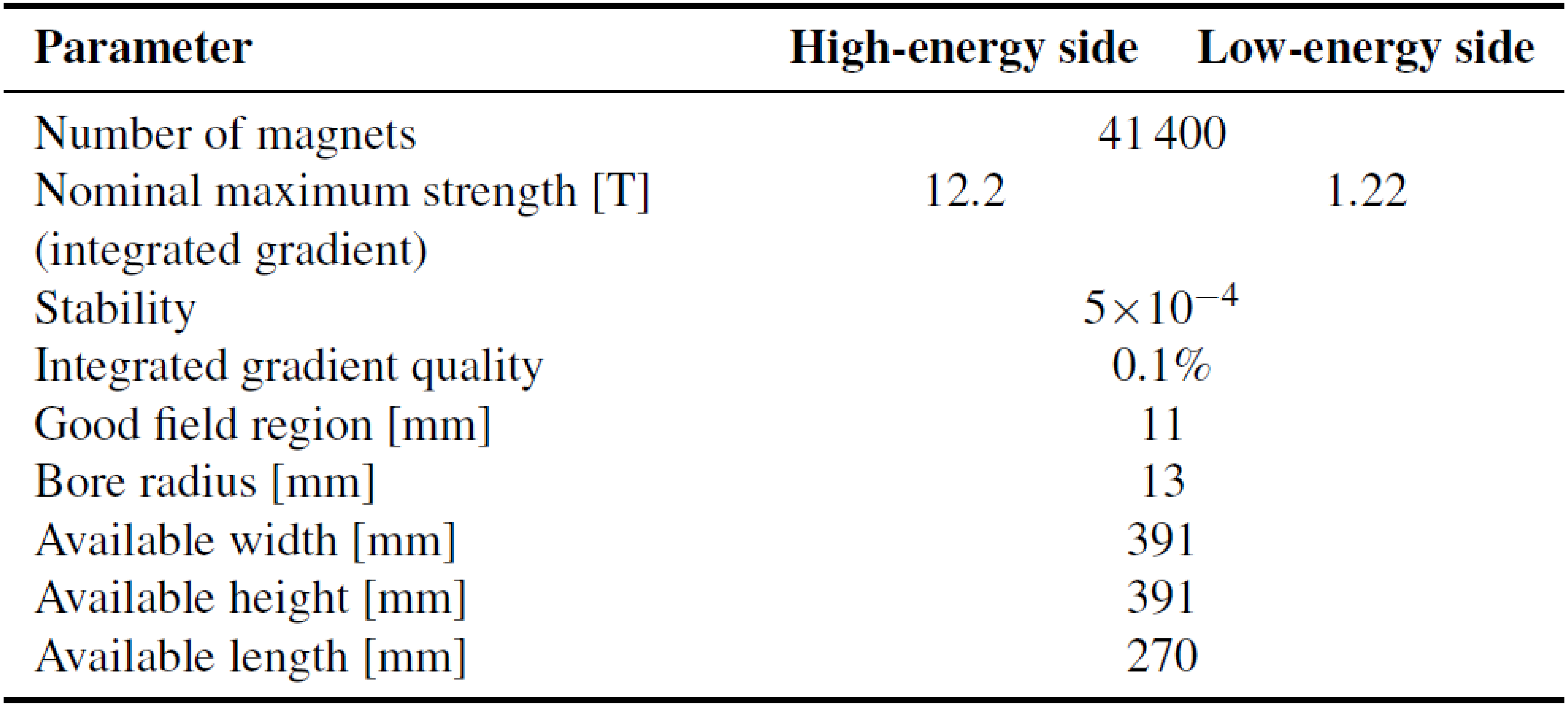
- **Objectives:**
  - Design, assemble and test a tuneable permanent magnet quadrupole of sufficient strength and quality for the high energy end of the drive beam (2.4 GeV).
  - Design, assemble and test a tuneable permanent magnet quadrupole of sufficient strength and quality for the low energy end of the drive beam (0.24 GeV).
- **Deliverables:**
  - A high strength (for a beam energy of 2.4 GeV), tuneable, permanent magnet quadrupole prototype (31/3/12)
  - A report covering the design and test results of the high strength prototype (30/9/12)
  - A low strength (for a beam energy of 0.24 GeV), tuneable, permanent magnet quadrupole prototype (30/9/13)
  - A report covering the design and test results of the low strength prototype (31/3/14)
  - Mass production assessment

Quadrupole Tunability

- The **nominal** maximum integrated gradient is 12.2T and the minimum is 1.22T
- For operational flexibility each individual quadrupole must operate over a wide tuning range
  - 70% to 120% at high energy (2.4 GeV)
  - 7% to 40% at low energy (0.24 GeV)



Quadrupole Specification



Parameter	High-energy side	Low-energy side
Number of magnets	41 400	
Nominal maximum strength [T] (integrated gradient)	12.2	1.22
Stability	5×10^{-4}	
Integrated gradient quality	0.1%	
Good field region [mm]	11	
Bore radius [mm]	13	
Available width [mm]	391	
Available height [mm]	391	
Available length [mm]	270	

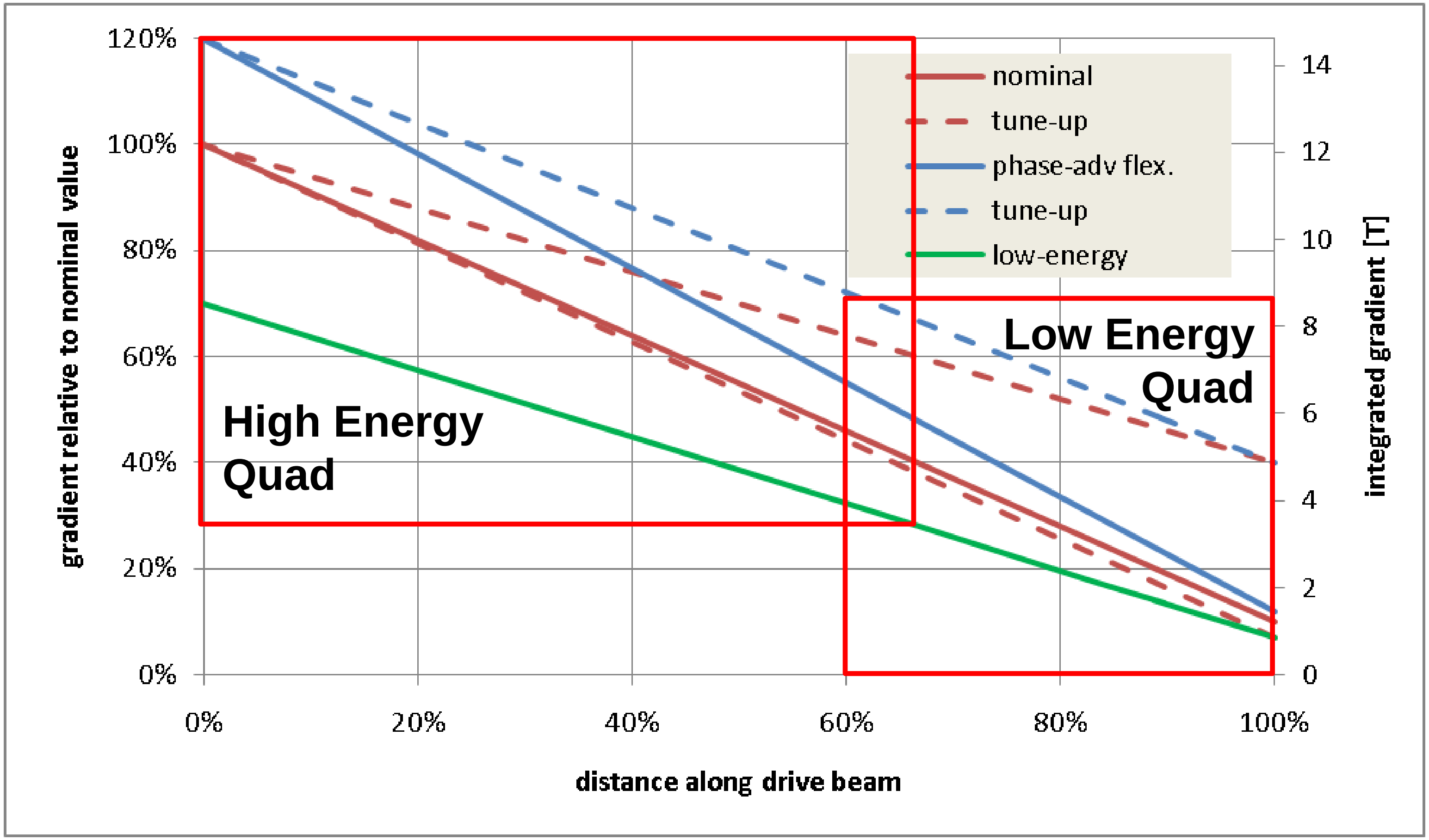
Permanent Magnet Option

- The integrated magnet strength requirement is very challenging (given the space constraints) for a conventional electromagnet
- The nominal power consumption for the EM version will be **~13MW** in nominal mode and up to **~34 MW** in tune-up mode
- Total Power Load limit to air within the tunnel is only **150 W/m** (all components)
- A PM quad would potentially have many advantages
  - Vastly reduced electrical power
  - Very low operating costs
  - No cooling water needs
  - Very low power to air
- We have been investigating the PM option for the drive beam in detail

Permanent Magnet Challenges

- There are many existing PM quadrupole examples
- The combination of high strength, large tunability, high field quality, and restricted volume meant that a new design was required
- Additional challenges for PM include possible **radiation damage**, field **variation with temperature**, PM strength **variation from block to block** (material and engineering tolerances)
- The complete tuning range (120% to 7%) could not be met by a single design
- We have broken the problem down into two magnet designs – **one high energy and one low energy**

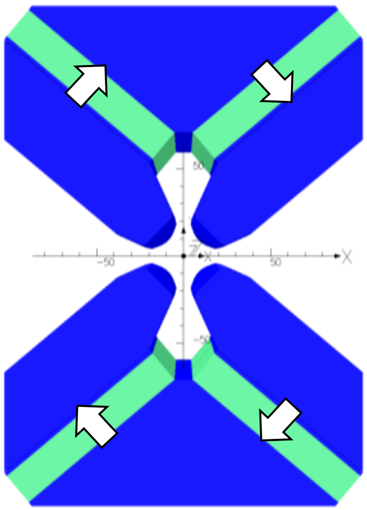
Quadrupole Types



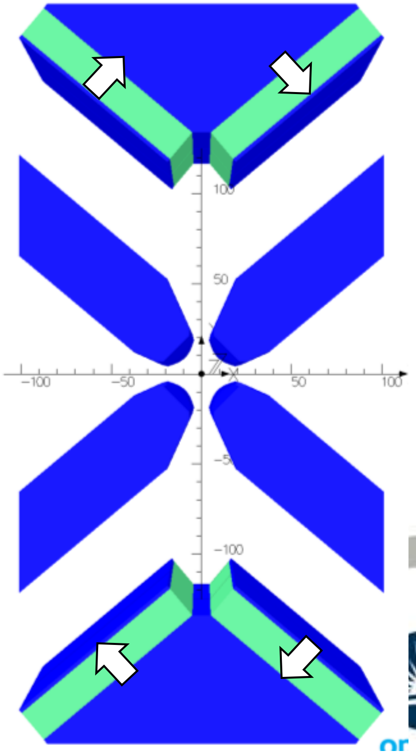
High energy quad – Gradient very high
Low energy quad – Very large dynamic range

High Energy Quad Design

- **NdFeB** magnets with **B_r = 1.37 T** (VACODYM 764 TP)
- 4 permanent magnet blocks each 18 x 100 x 230 mm
- Mounted at optimum angle of 40°
- Max gradient = **60.4 T/m** (stroke = 0 mm)
- Min gradient = **15.0 T/m** (stroke = 64 mm)
- Pole gap = 27.2 mm
- Field quality = ±0.1% over 23 mm

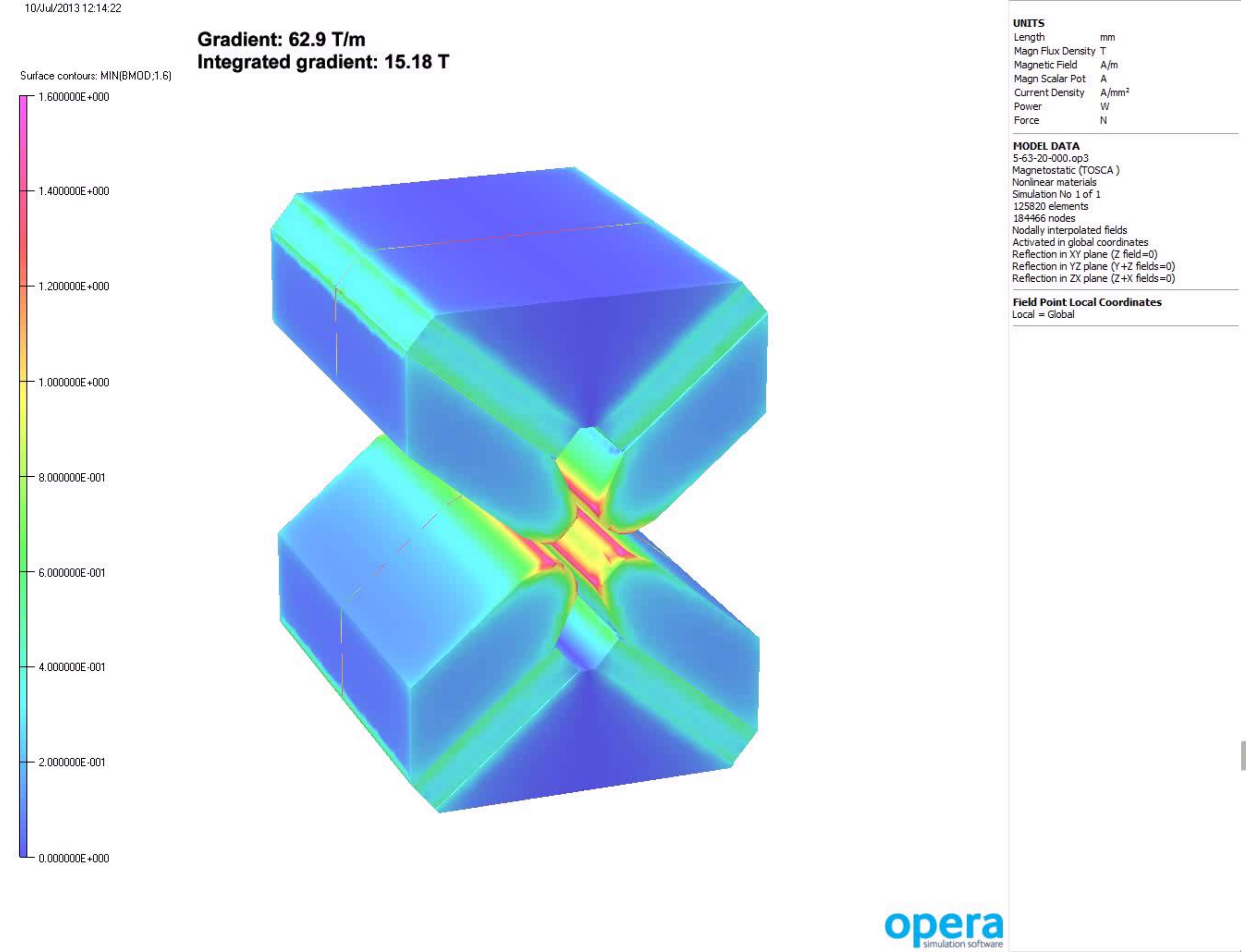


Stroke = 0 mm



Stroke = 64 mm

Poles are permanently fixed in place.



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Gradient: 62.9 T/m
Integrated gradient: 15.18 T

Surface contours: MIN(BMOD;1.6)

UNITS

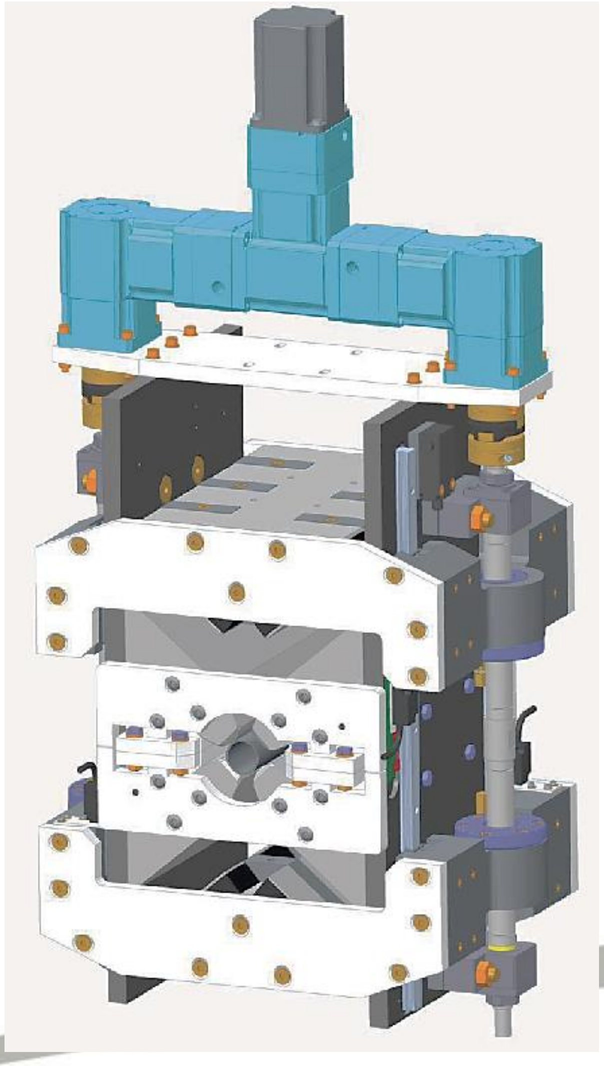
Length	mm
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Current Density	A/mm²
Power	W
Force	N

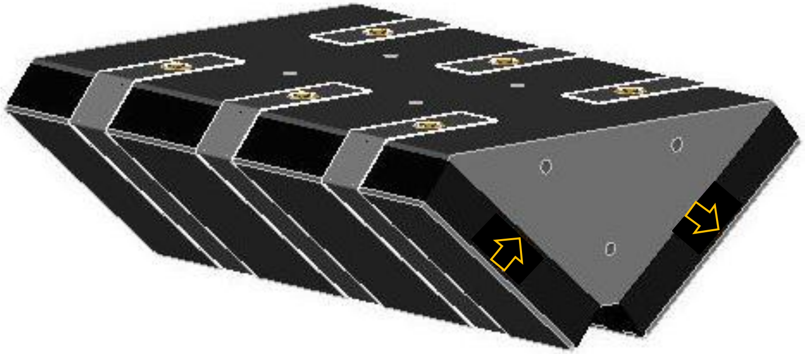
MODEL DATA
5-63-20-000.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
125820 elements
184466 nodes
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in YZ plane (Y+Z fields=0)
Reflection in ZX plane (Z+X fields=0)

Field Point Local Coordinates
Local = Global

Engineering of High Energy Quad

- Single axis motion with one motor and two ballscrews
- Two linear encoders to check position on both sides with 1μm accuracy
- Maximum force is 16.4 kN per side, reduces by x10 when stroke = 64 mm
- PM blocks bonded to steel bridge piece and protective steel plate also bonded
- Steel straps added as extra security





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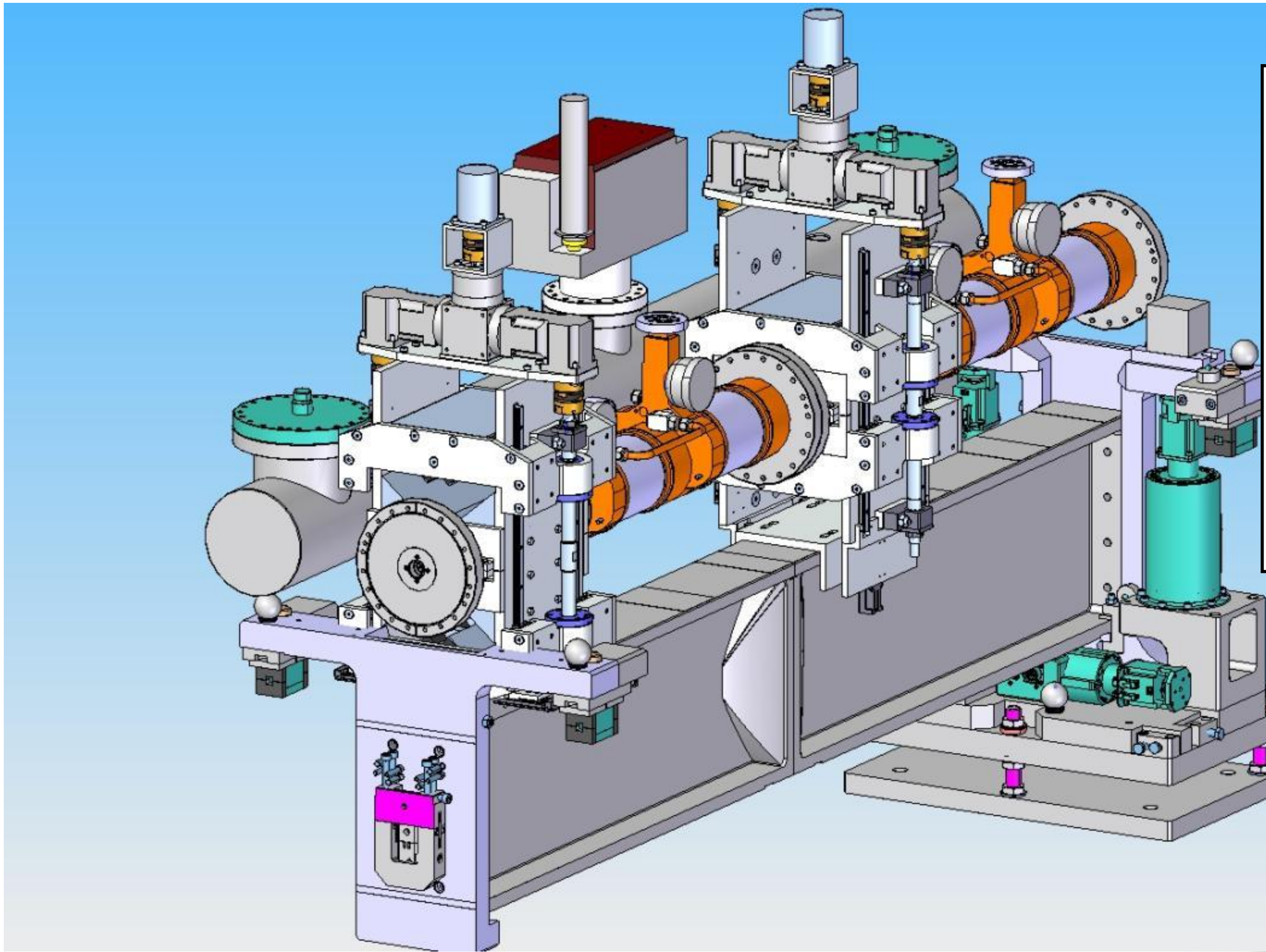
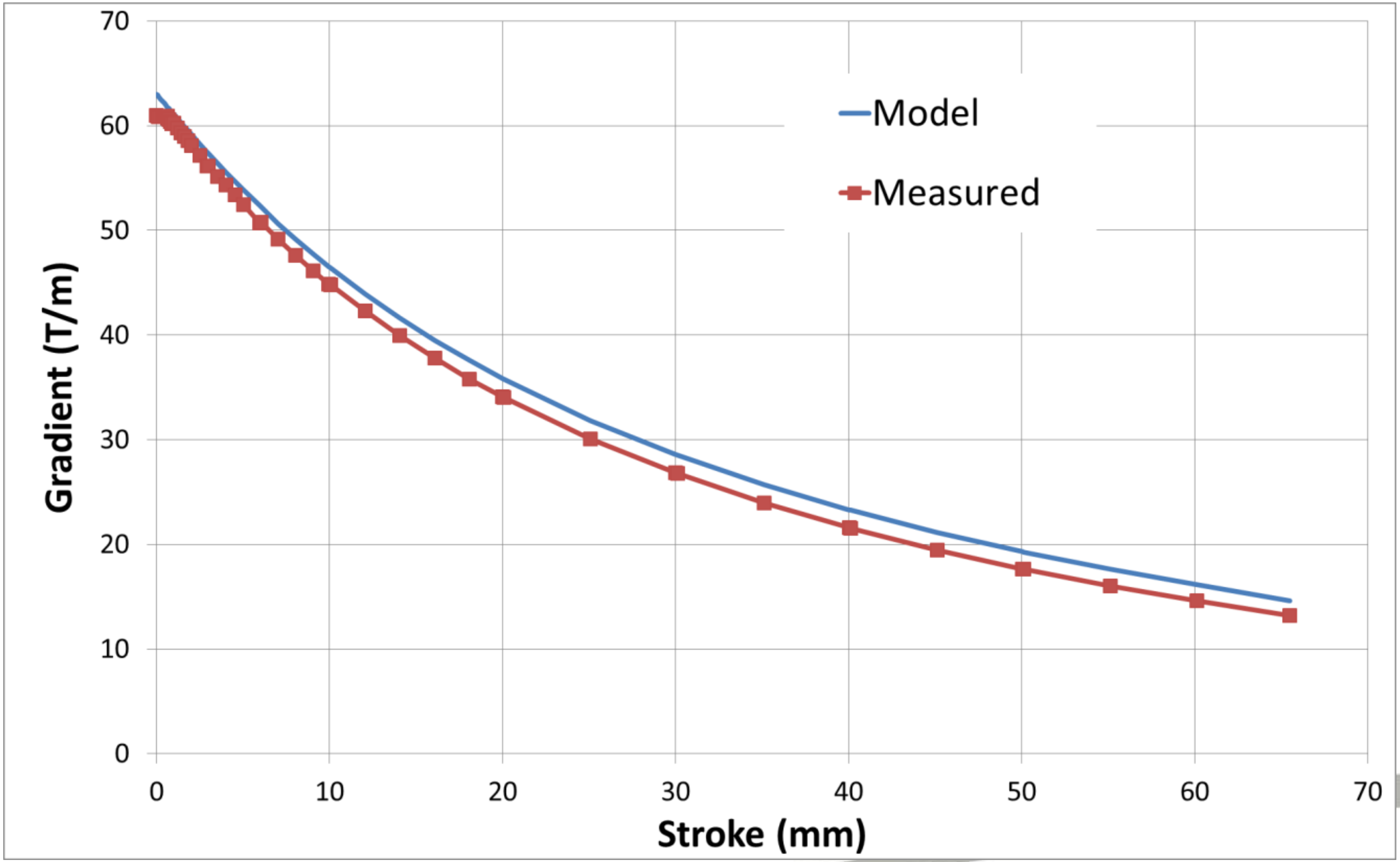
PM Quads in CLIC



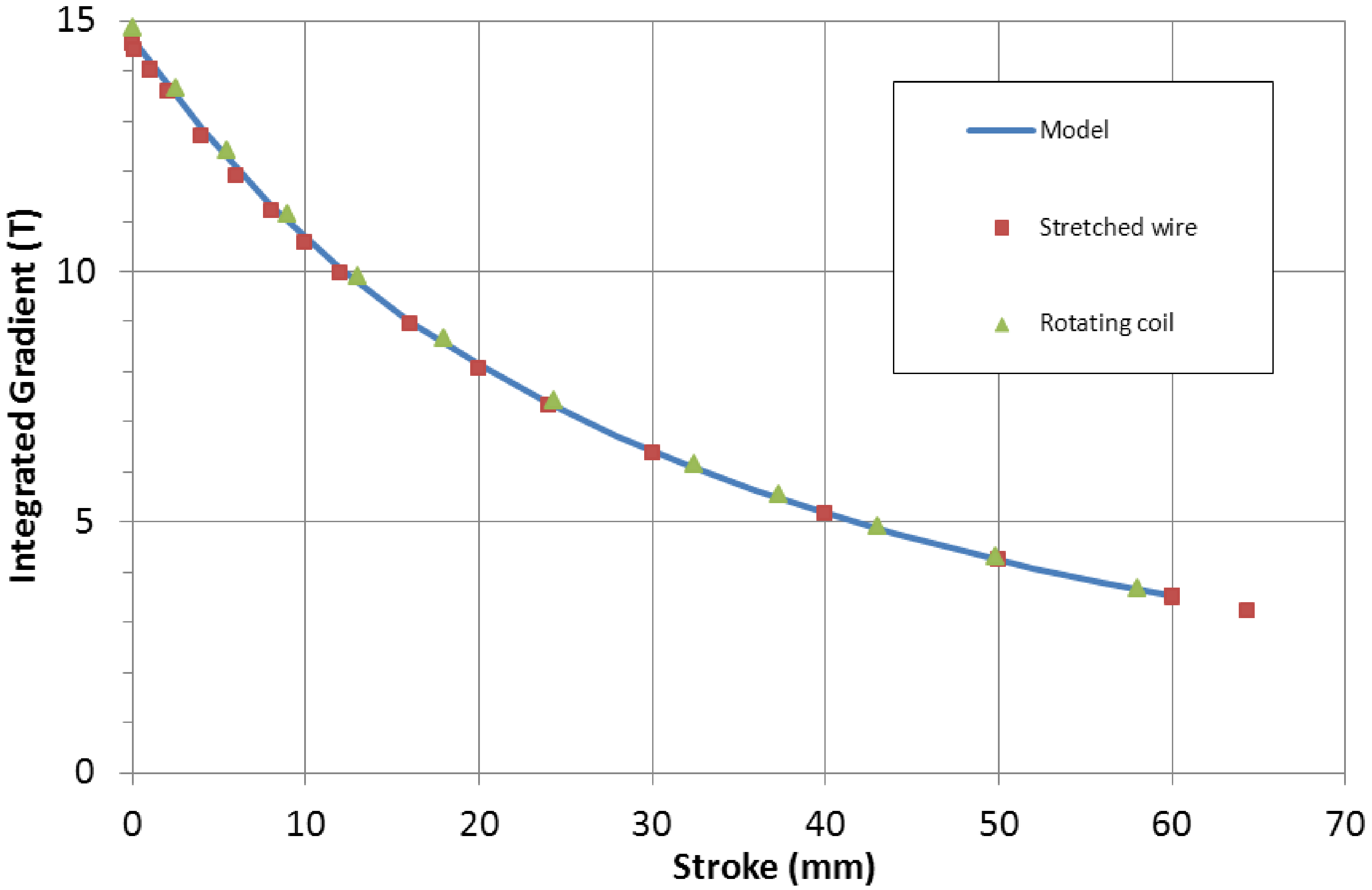
Very tight space constraints
Our designs were constrained by having to fit into predefined volume. We would benefit from relaxation in some areas if this is possible in the future.

Assembled Prototype

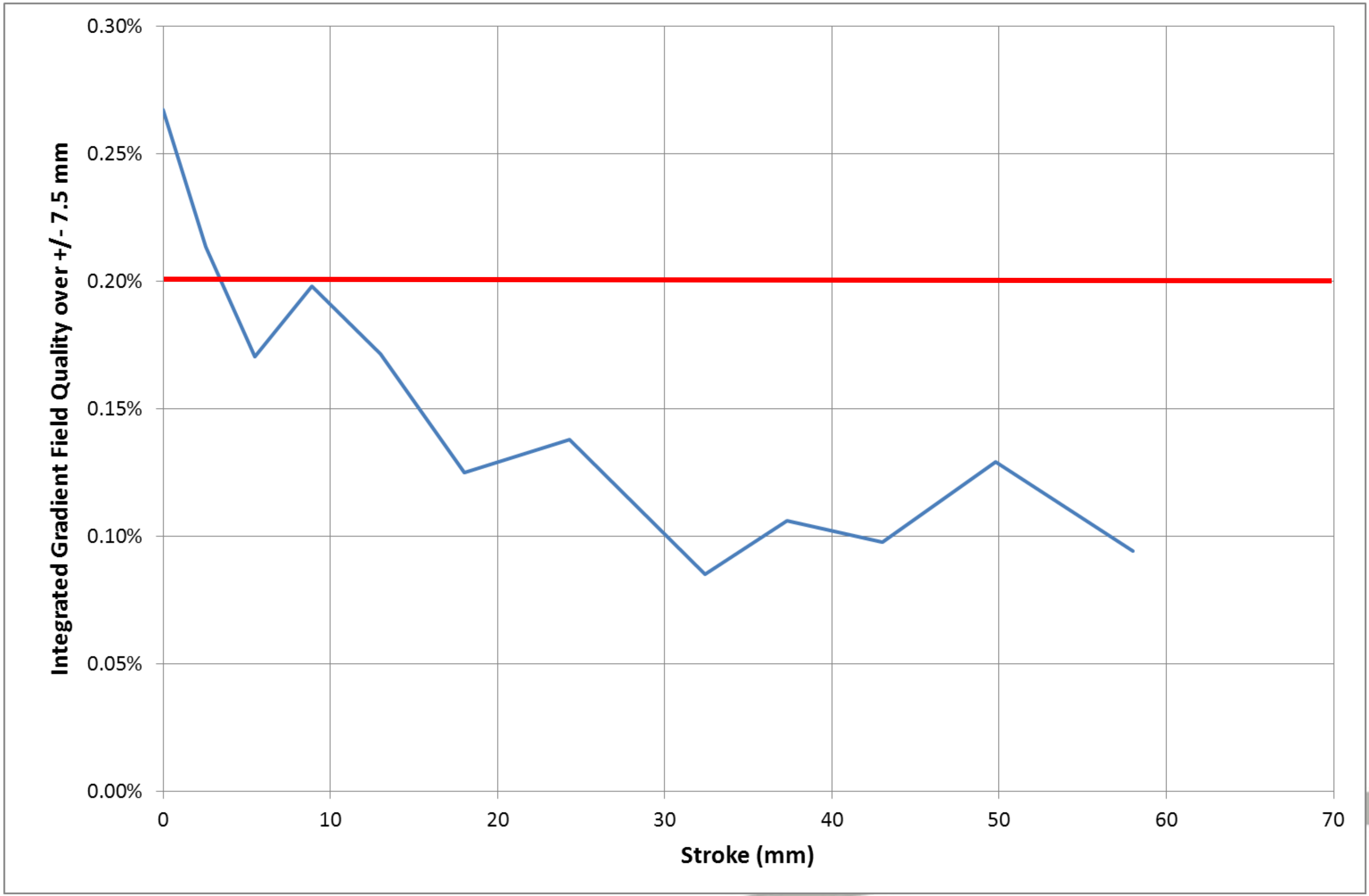
Measured Gradient



Measured Integrated Gradient



Measured Field Quality



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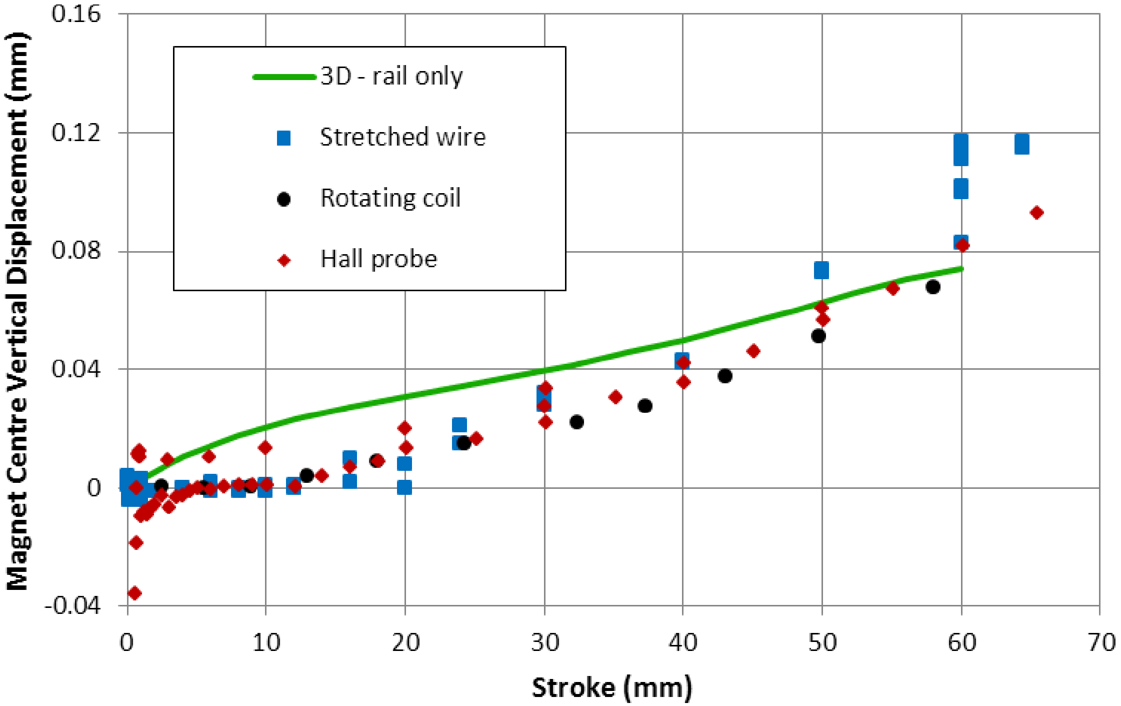
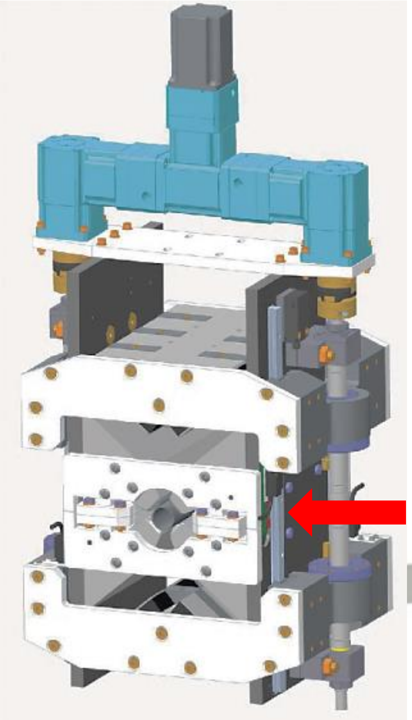
Magnet Centre Movement

- The magnet centre moves upwards by **~100 μm** as the permanent magnets are moved away
- 3D modelling suggests this is due to the rails being **ferromagnetic** (**μ_r ~ 100**, measured) and **not mounted symmetrically** about the midplane – should be easy to fix
- Motor/gearbox assembly may also be a contributing factor

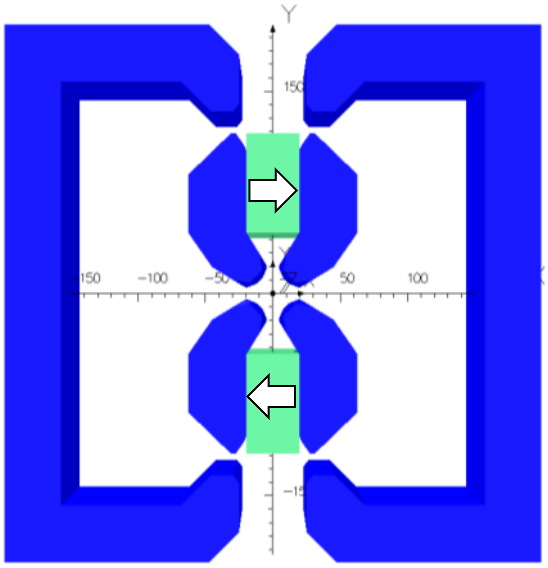


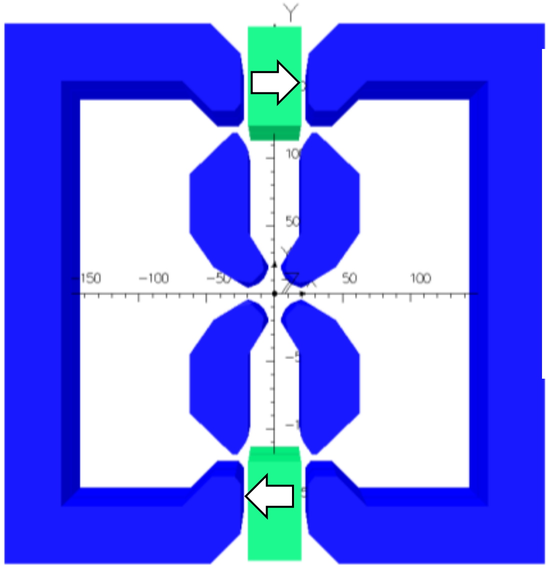


Low Energy Quad Design

- Lower strength easier but requires **much larger tunability range (x10)**
- Outer shell short circuits magnetic flux **to reduce quad strength rapidly**
- **NdFeB** magnets with **B_r = 1.37 T** (VACODYM 764 TP)
- 2 permanent magnet blocks are 37.2 x 70 x 190 mm
- Max gradient = **43.4 T/m** (stroke = 0 mm)
- Min gradient = **3.5 T/m** (stroke = 75 mm)
- Pole gap = 27.6 mm
- Field quality = ±0.1% over 23 mm

Stroke = 0 mm





Stroke = 75 mm

Poles and outer shell are permanently fixed in place.

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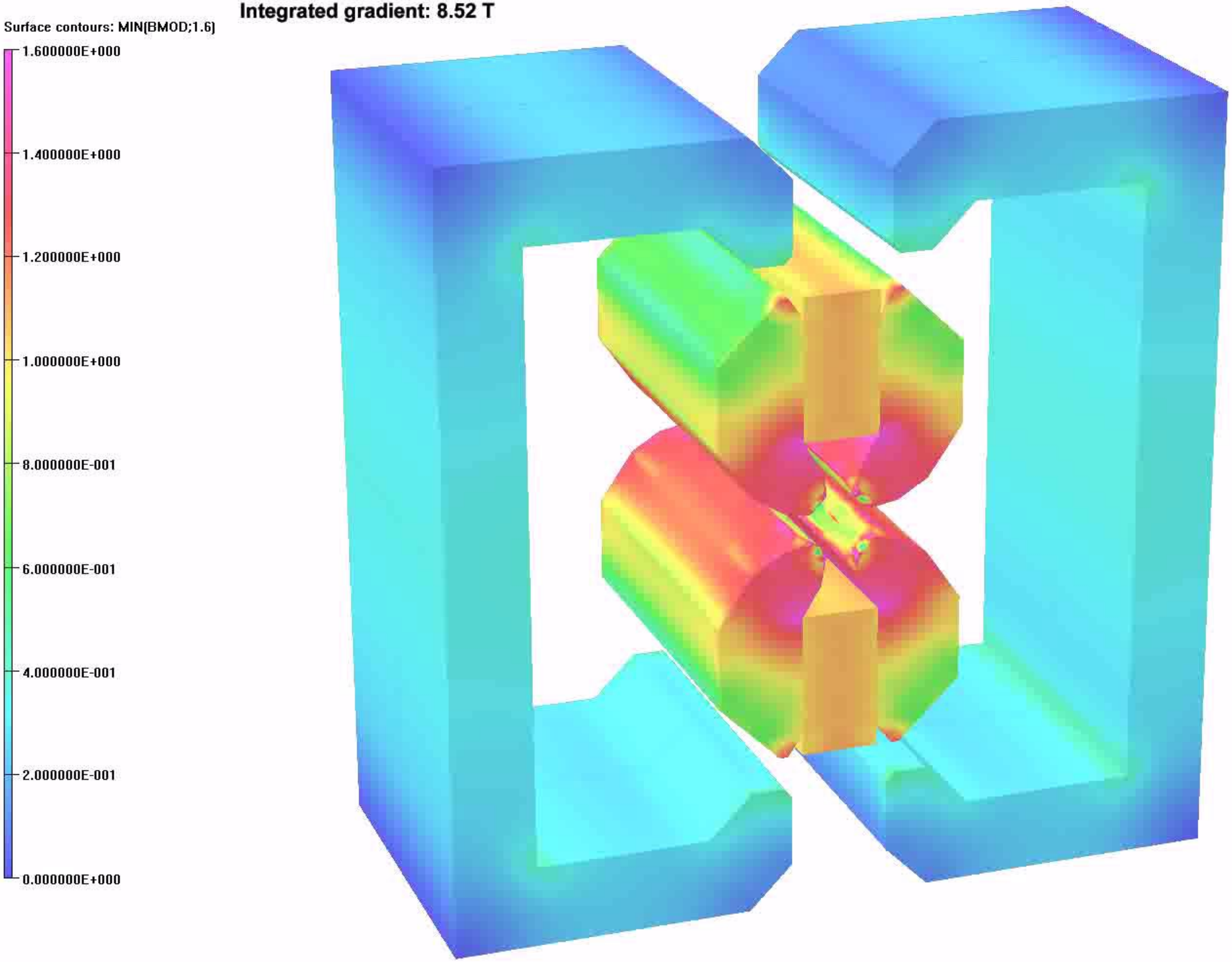
Gradient: 41.68 T/m
Integrated gradient: 8.52 T

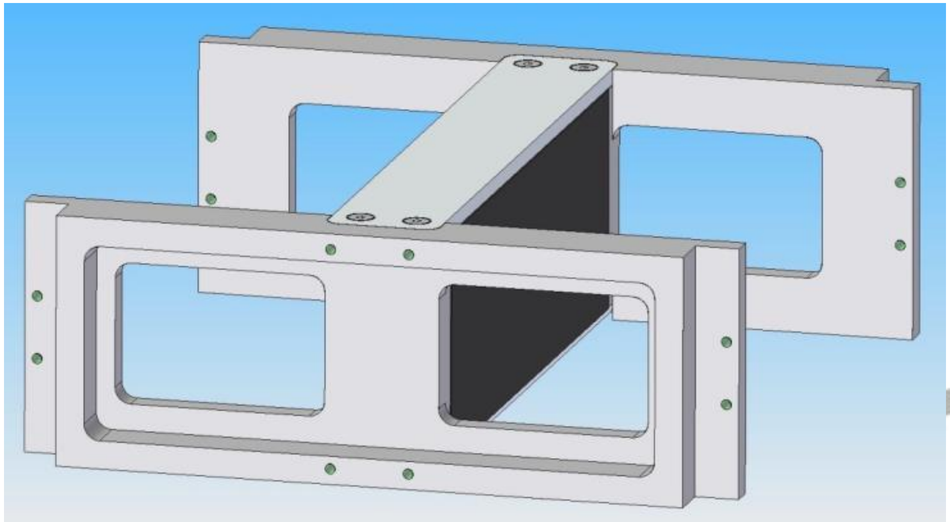
Surface contours: MIN(BMOD;1.6)

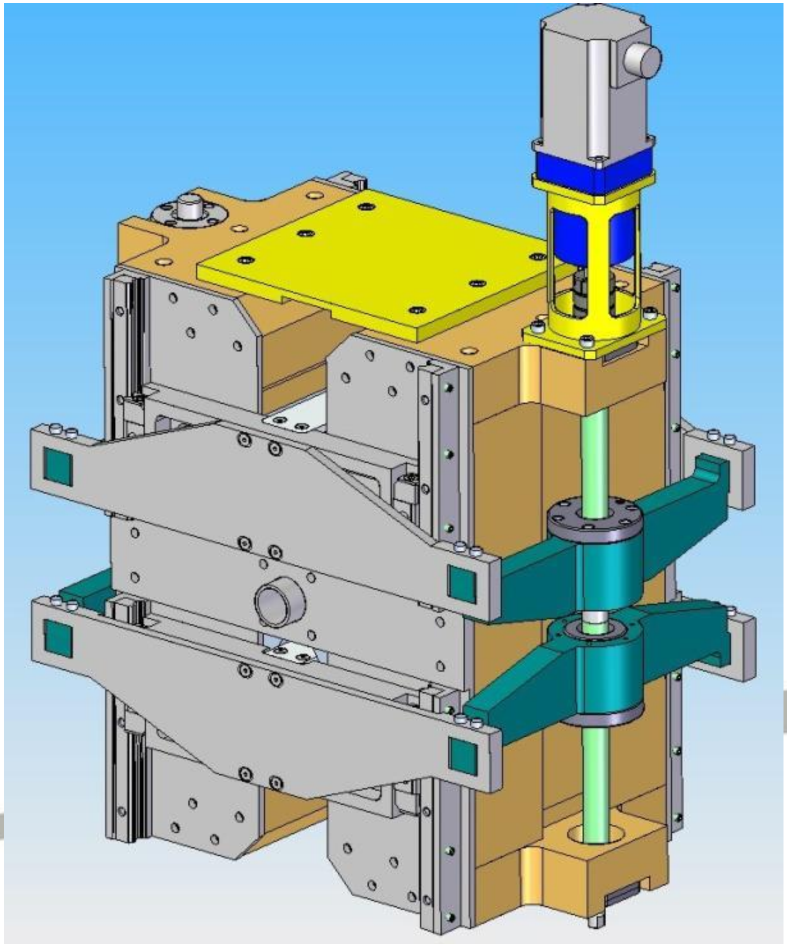


Opera

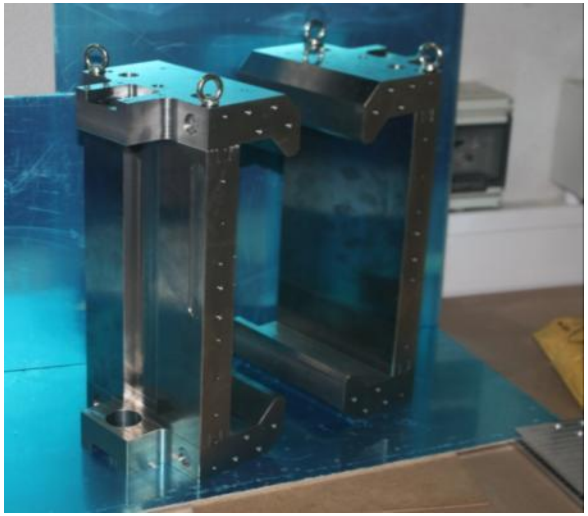
Engineering of Low Energy Quad

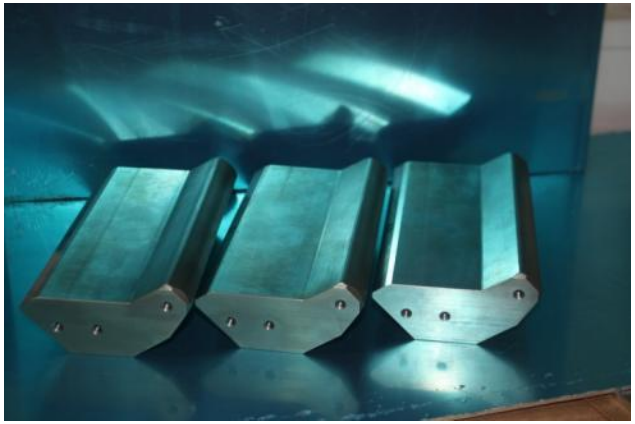
- Simplified single axis motion with one motor and one ballscrew
- Two linear encoders to check position on both sides with 1μm accuracy
- Maximum force is only 0.7 kN per side
- PM blocks bonded within aluminium support frame



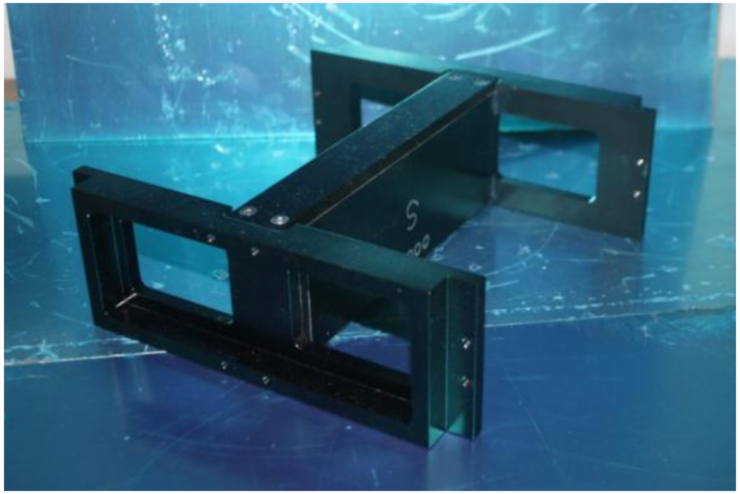


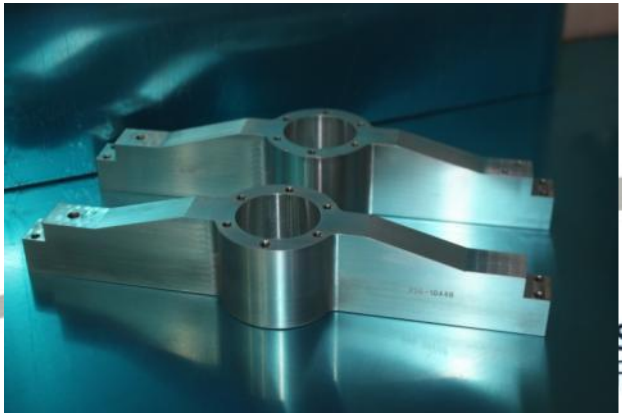
Assembly Now Starting at Daresbury





Measurements at DL due to start in 8 weeks





Mass Production Assessment and Costings

- Face to face discussions have been held with the suppliers of the major components of the high energy quad
  - Permanent magnets
  - Motion system
  - Machined parts
  - Rails and ballscrews
- All suppliers have been extremely helpful and willing to spend time suggesting improvements, learning lessons from the prototype, to make mass production more practical and cost effective
- They will all provide cost estimates for high volume orders before end 2013
- No show stoppers identified that would prevent high volume production on realistic timescales

Current Work Programme

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  - (Mass production assessment)

All deliverables expected to be achieved

Resources

- Contract 4/2011 to 3/2014

	CERN Contract	CERN Actual to Sept 13	STFC Contract	STFC Actual to Sept 13
Manpower	5.08 s-y	4.1 s-y	0.92 s-y	0.41 s-y
Material, travel, freight, etc	-	-	£59k	£78.2k

- High energy prototype cost £39.7k + VAT
- Low energy prototype cost £23.6k + VAT
- Jigs & Fixtures ~£9k

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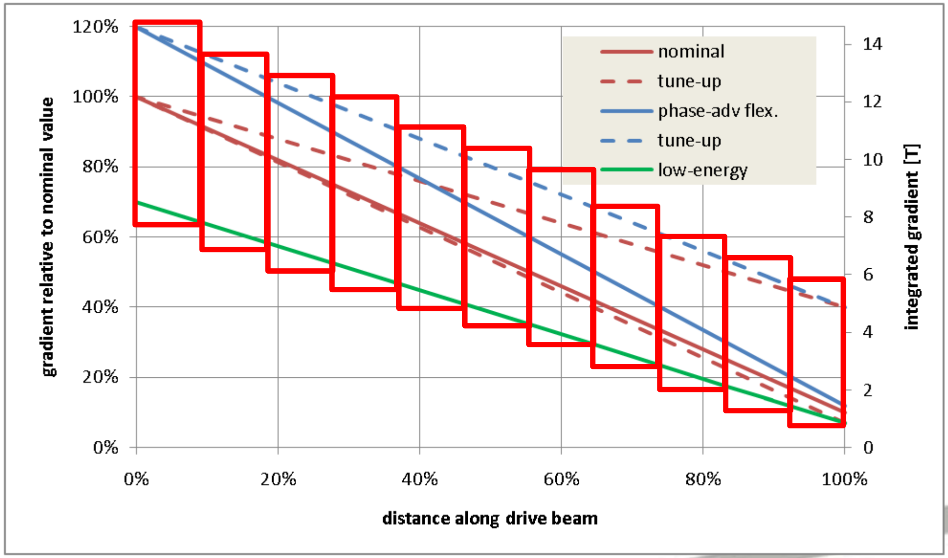
Future Plan (1)

- **Proposed Programme:**
  - Modify high strength quad prototype to improve field quality and reduce magnet centre motion to acceptable level.
  - Modify low strength quad prototype to achieve specification (if required).
  - Consider in detail possible magnet design refinements to tailor solutions better to each energy with the aim of reducing the tuning ranges required and so allowing simpler tuning mechanisms such as the use of low power coils or motion of only a fraction of the permanent magnet blocks



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Future Plan (2)

- **Proposed Programme:**
  - Design and demonstrate, in one of the existing prototypes, a passive temperature compensation scheme to ensure the magnet strength is stable at the operating temperature
  - Iterate the detailed mechanical and electrical designs to address features such as fiducialisation and closed loop vs open loop motion control.
  - Value engineer the designs to ensure they provide the required performance at the optimal cost, including the need for mass production.
  - Design and demonstrate, in one of the existing prototypes, the ability to provide beam steering adjustment to the level specified for the drive beam.

Proposed Deliverables

- 2014-15
  - Field quality and magnet centre motion specification achieved for both prototypes
  - Iteration of designs and selection of number of quad types completed
- 2015-16
  - Temperature compensation demonstrated
  - Beam steering capability demonstrated
- 2016-17
  - Value engineered designs compatible with mass production completed

Resources

- 2011 – 2014 Contract

	CERN	STFC
Manpower	5.08 s-y	0.92 s-y
Material, travel, freight, etc	-	£59k

- 2014 – 2017 Request

	CERN	STFC
Manpower	4.0 s-y	2.33 s-y
Material, travel, freight, etc	-	£68k