The ZEPTO project: Tuneable permanent magnets for the next generation of high energy accelerators.

Alex Bainbridge, Ben Shepherd, Norbert Collomb, Jim Clarke.

STFC Daresbury Laboratory, UK

Michele Modena**, CERN**

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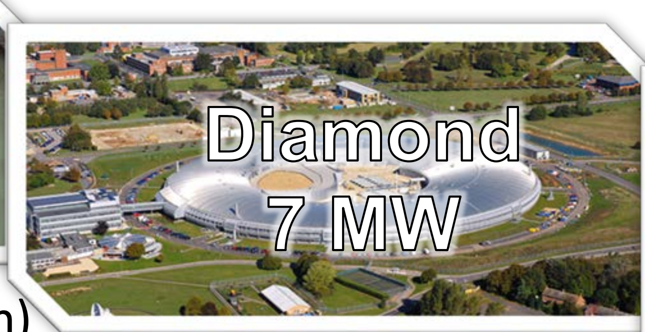
ZEPTO – An Introduction

ZEPTO (Zero Power Tuneable Optics) project is a collaboration between CERN and STFC Daresbury Laboratory to save power and costs by switching from resistive electromagnets to permanent magnets.



(Total facility consumption)

CERN

Peak 200 MW!
This is a third of the total consumption of Geneva!

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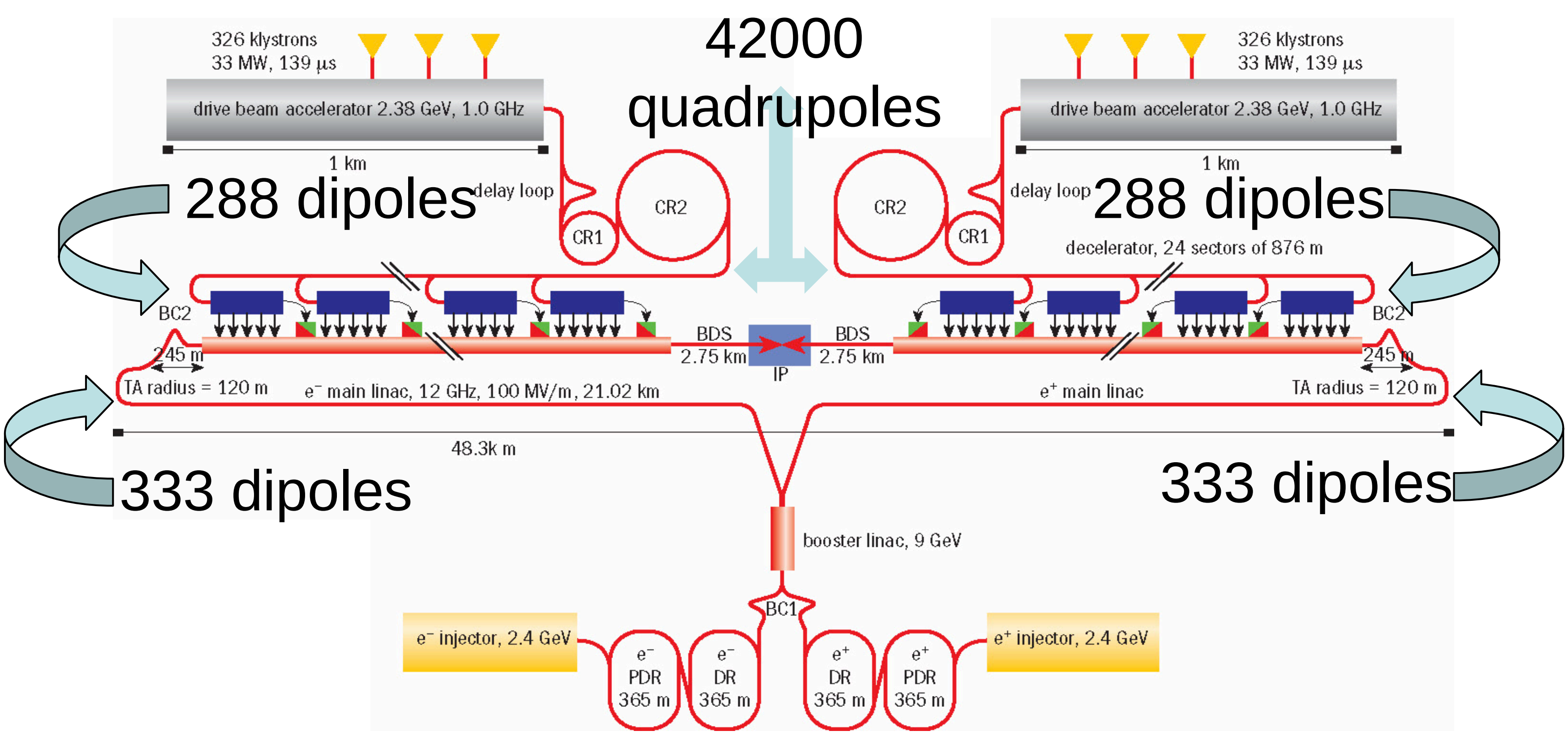
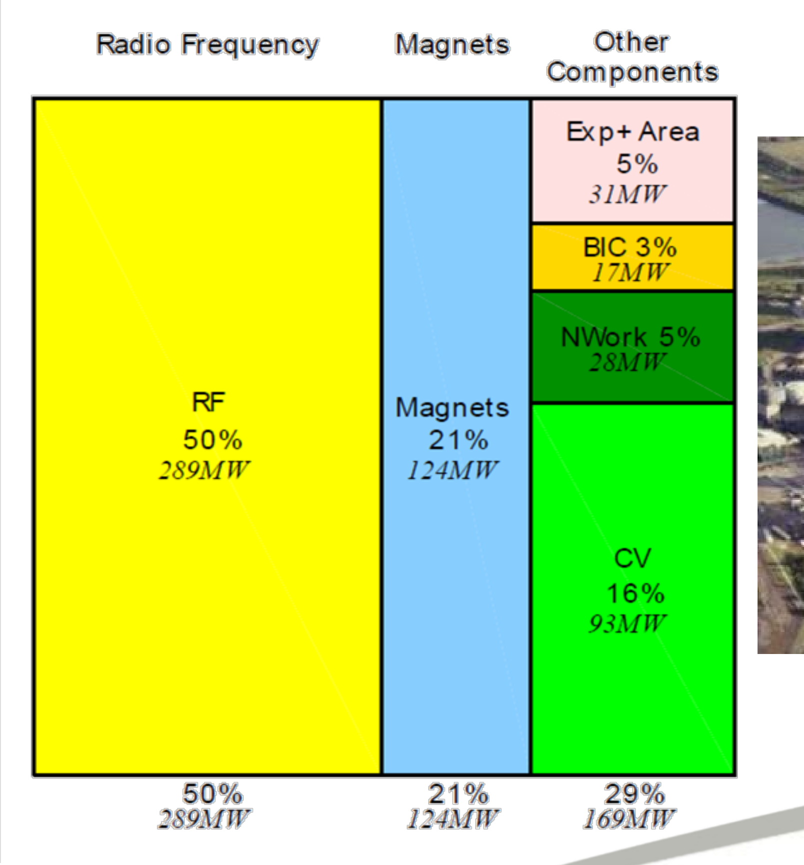
Motivation - CLIC



Motivation - CLIC

The plan to use normal conducting systems on CLIC will result in high electrical power consumption and running costs.



The Challenge

Magnet Type	Number	Length	Strength	Range	0.1% good field	Power/total
Drive Beam Quads	41400	0.2 m	63 T/m	100-10%	26x26 mm	20 MW
Drive Beam Dipoles	576	1.5 m	1.6 T	100-50%	40x40 mm	12.4 MW
Linac Quads	1061	0.5 m	14 T/m	100-10%	80x80 mm	6.3 MW
Linac Quads	1638	0.25 m	17 T/m	100-10%	87x87 mm	10.3 MW
Main Beam Dipoles	666	1.5 m	0.5 T	100%	30x30 mm	2.5 MW
Damping Ring Quads	408	0.4 m	30 T/m	100-20%	80x80 mm	4.7 MW
Damping Ring Quads	408	0.2 m	30 T/m	100-20%	80x80 mm	3.3 MW
Chicane Dipole	184	1.5 m	1.6 T	100-10%	80x80 mm	7.7 MW
Chicane Dipole	236	1 m	0.26 T	100-10%	80x80 mm	1.1 MW

Can we use permanent magnets to save power?

Measurement Capability

Granite Hall probe bench

- 3-axis micron positioning.
- Single and multi-axis probes.
- Rotatable to cancel planar Hall effect.

Calibration magnet

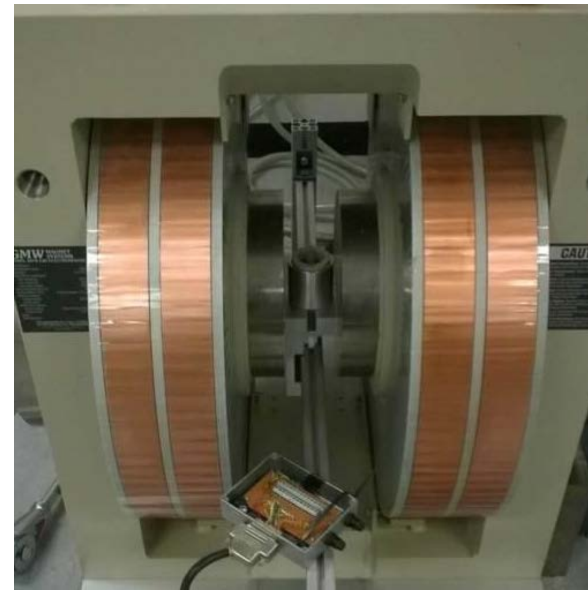
- with NMR probe

Stretched wire bench

- With laser alignment

Rotating coil

- Compensated coil option



Quadrupole Prototypes

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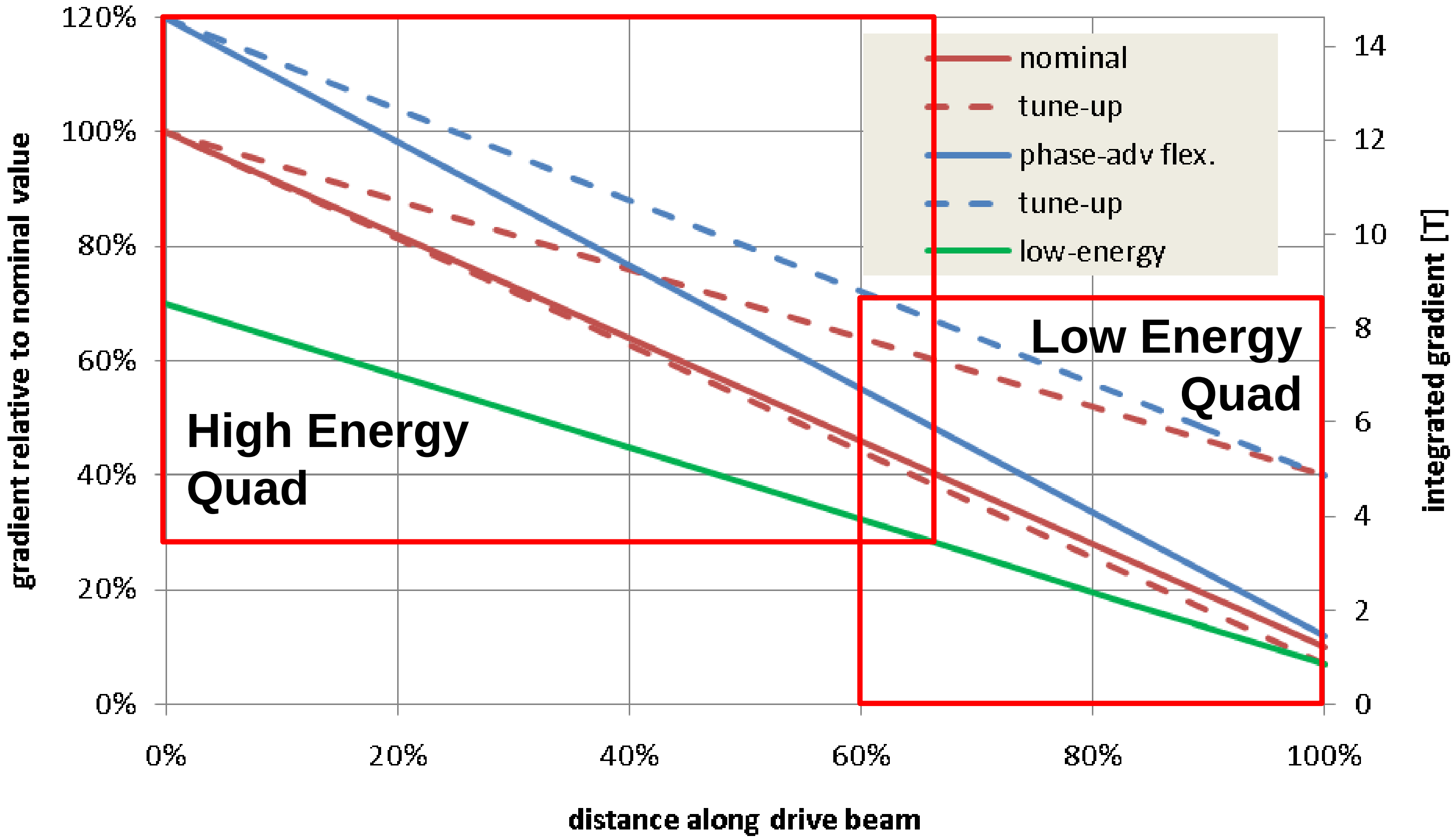
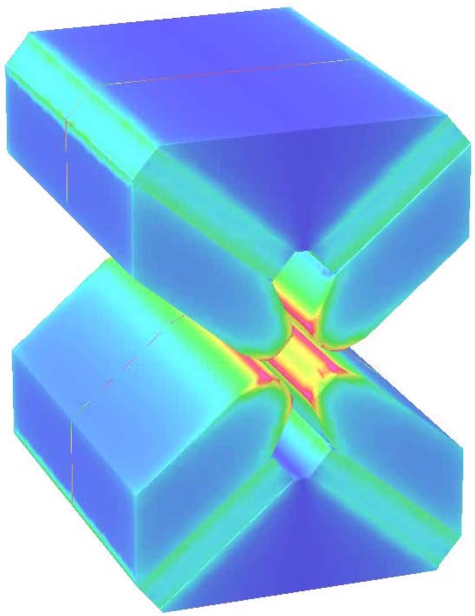
Quadrupole Prototypes



2 different magnet designs to deal with high energy and low energy regions!

High Energy Quadrupole



- Max gradient = 60.4 T/m
- Min gradient = 15.0 T/m

- Pole gap = 27.2 mm
- Field quality = ±0.1% over 23 mm
- NdFeB magnets with B_r = 1.37 T (VACODYM 764 TP)

- 4 permanent magnet blocks each 18 x 100 x 230 mm

opera simulation software

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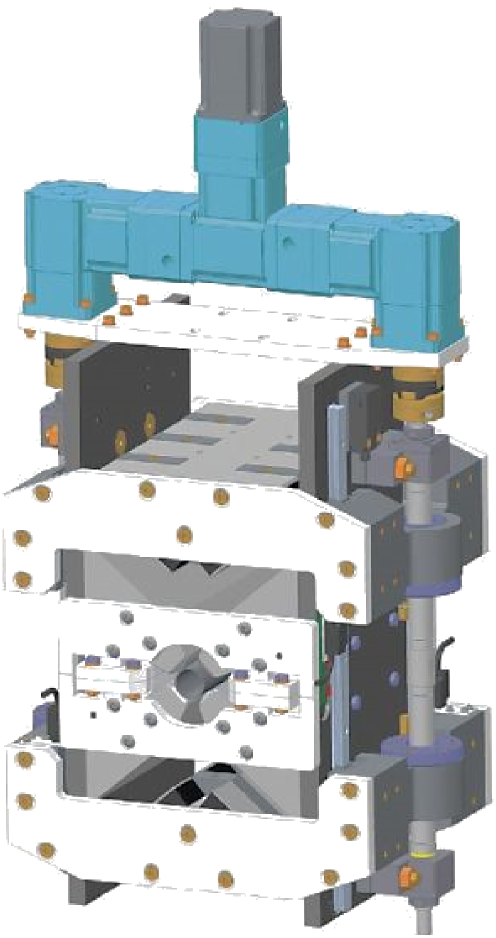
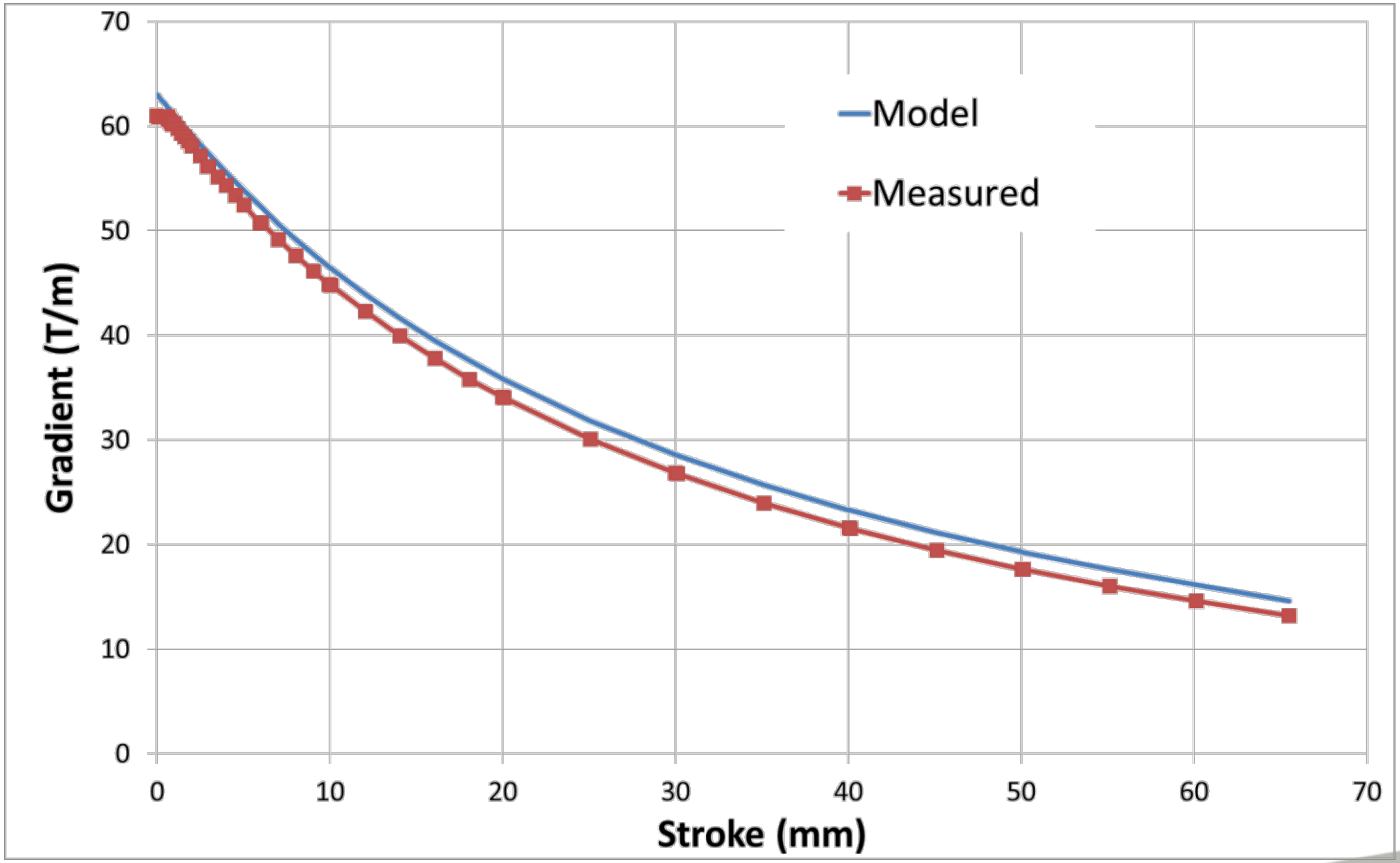
Engineering



- Single axis motion with one motor and two ballscrews
- Maximum force is 16.4 kN per side, reduces by x10 when stroke = 64 mm
- PM blocks bonded and strapped to steel bridge piece, protective steel plate also bonded

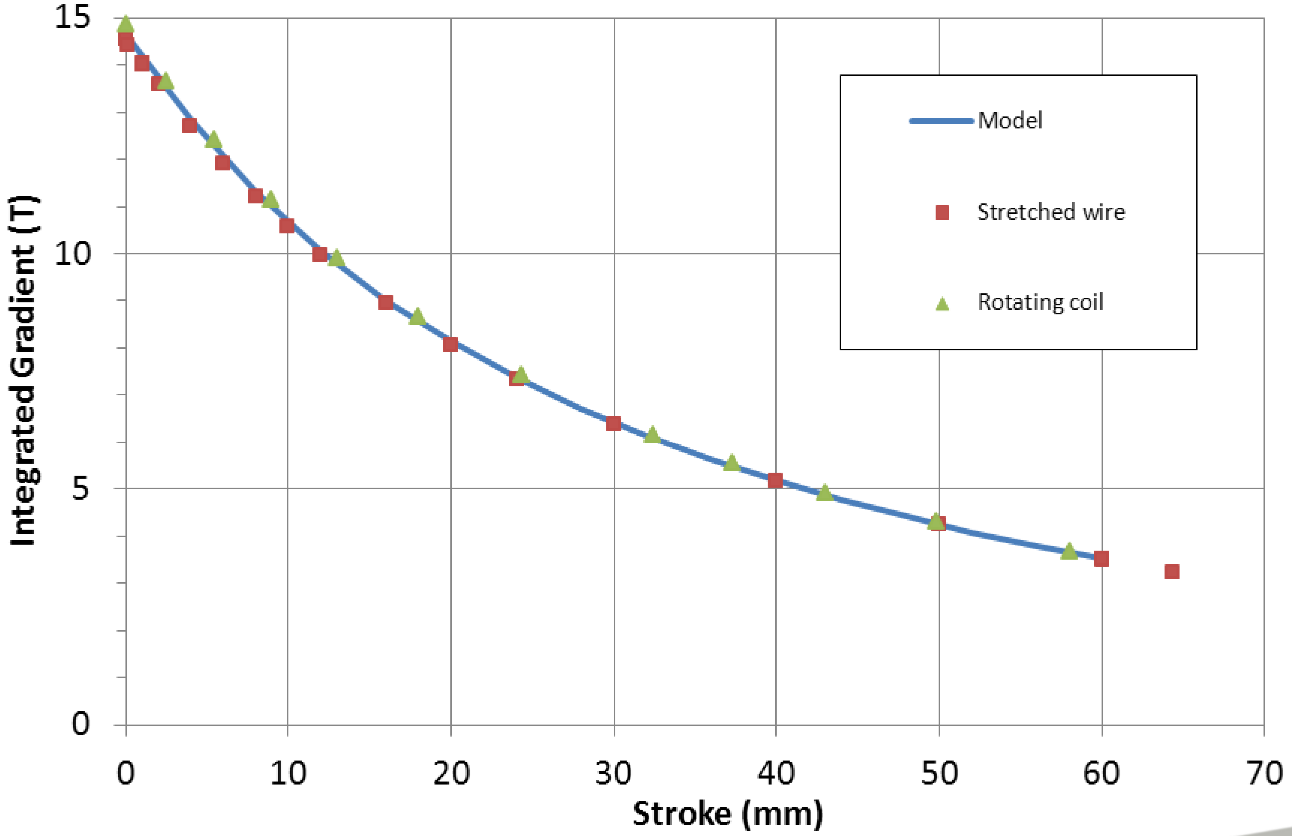
Measurements



Gradient determined by Hall probe measurements across full useful width of magnet

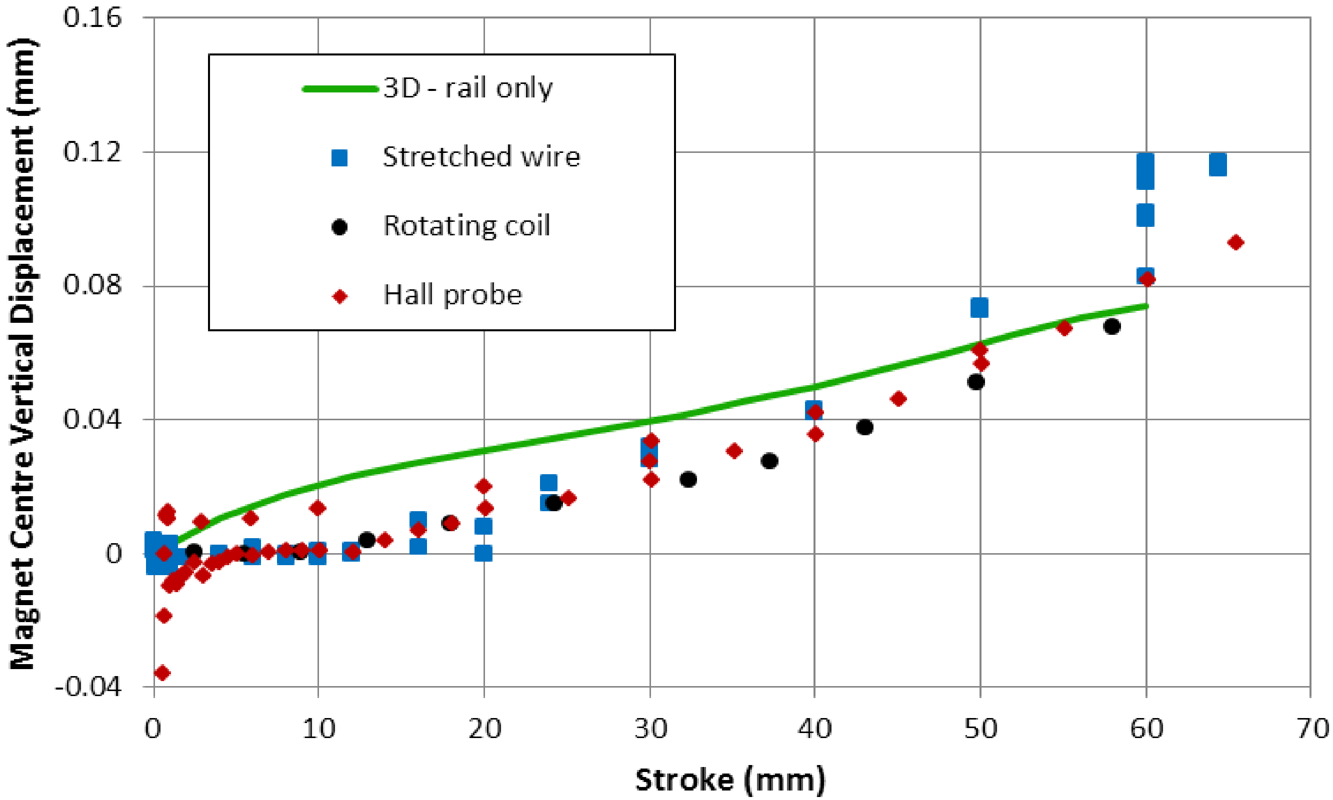
(±11.5 mm)

Measurements



Integrated gradient determined by stretched wire measurements across full useful width of magnet (±11.5 mm) and rotating coil over ±7.5 mm

Magnetic Center



The magnet centre moves upwards by ~100 µm as the permanent magnets are moved away

Able to detect this by 3 measurement techniques

Compared to 3D model of ferromagnetic rail in motion….

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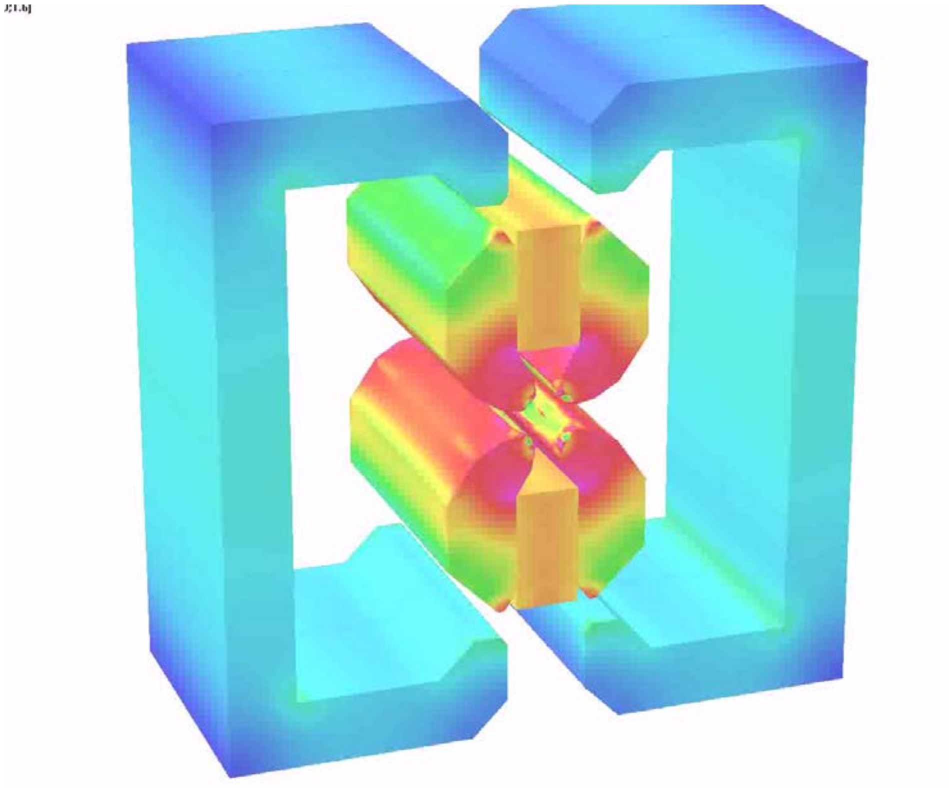
Low Energy Quadrupole

Stroke = 75 mm



- Max gradient = 43.4 T/m
- Min gradient = 3.5 T/m

- Pole gap = 27.6 mm
- Field quality = ±0.1% over 23 mm

- NdFeB magnets with B_r = 1.37 T (VACODYM 764 TP)
- 2 PM blocks are 37.2 x 70 x 190 mm

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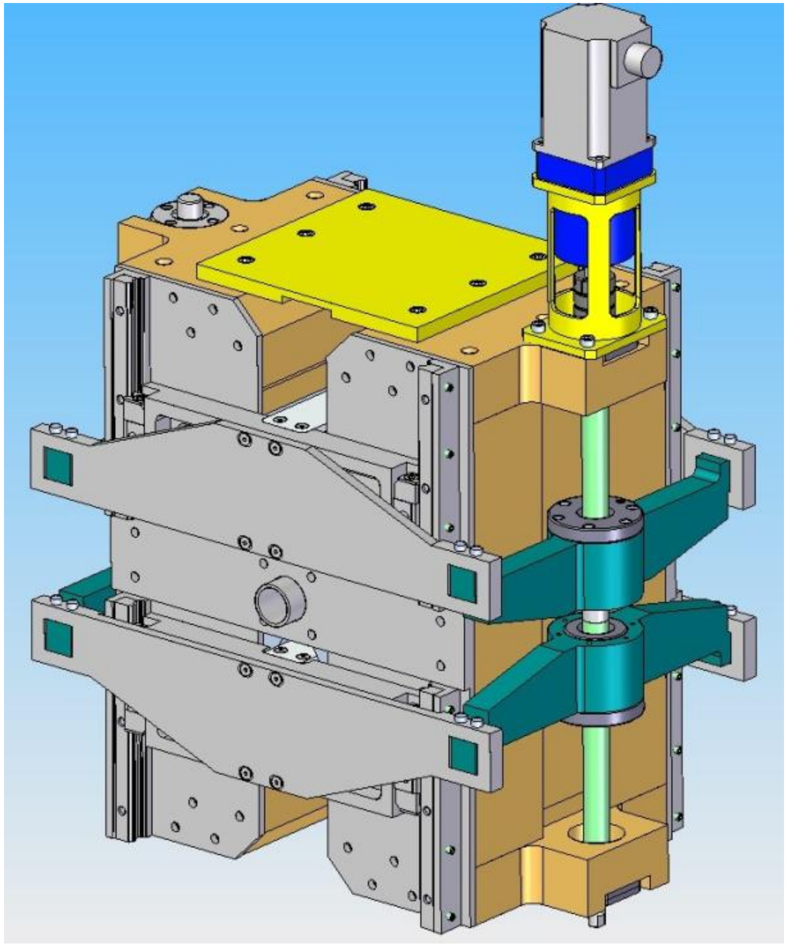
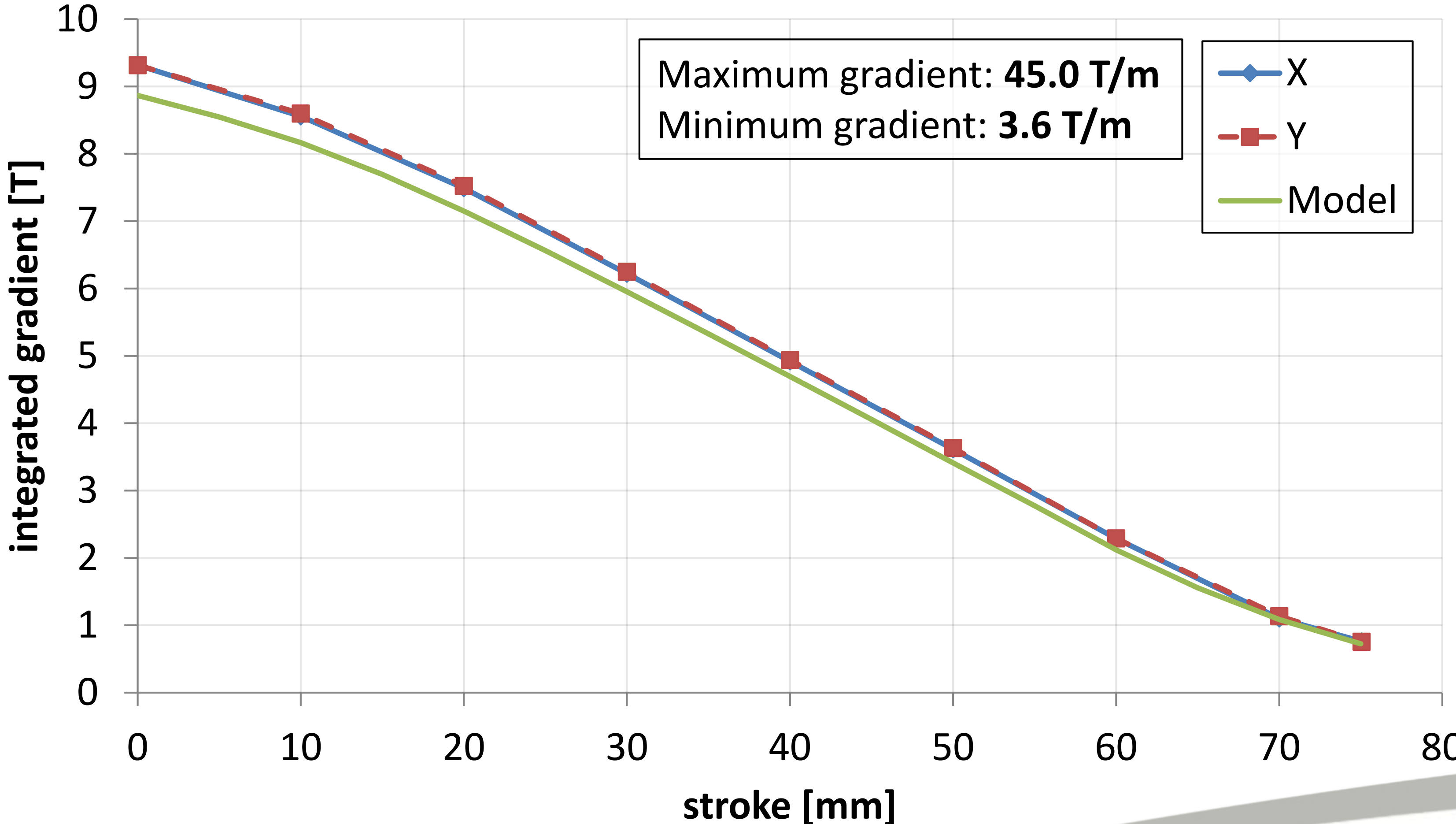
Engineering

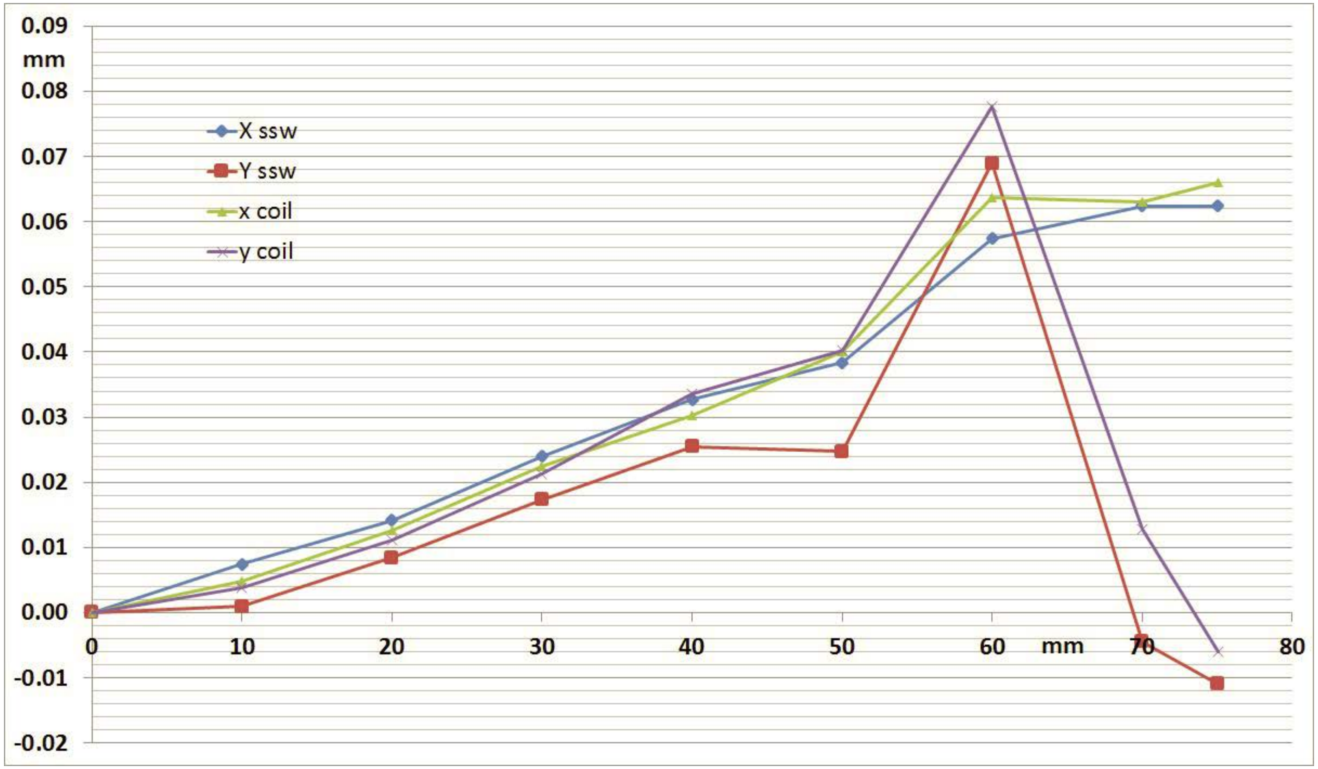


- Single axis motion with one motor and one ballscrew
- Maximum force is only 0.7 kN per side
- PM blocks bonded within aluminium support frame

Measurements



Measurements



2 measurement methods (stretched wire, rotating coil)

X axis moves in one direction, misalignment of outer shell?

Y axis moves up and then back down. Harder to explain…

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Dipole Prototype

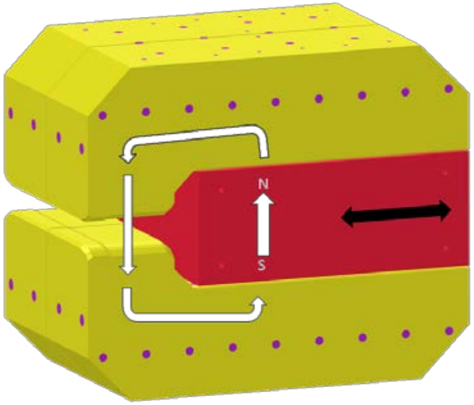
Dipole Prototype

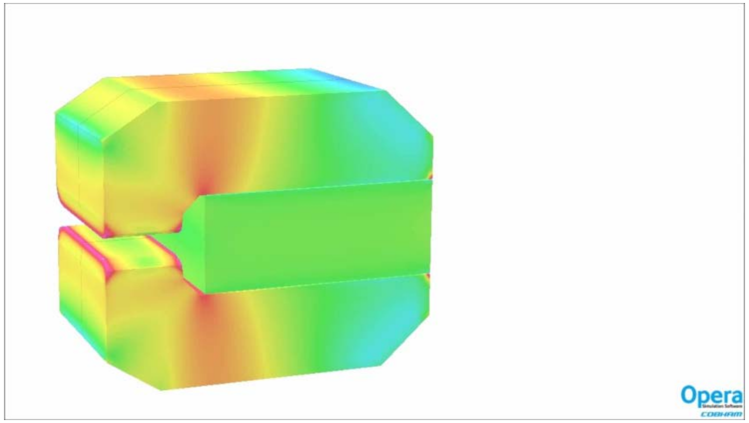
- Original plan was to build a 0.5m version of full size DB TAL magnet
  - Not possible within available budget (£100,000)
- So, instead we are building a scaled version
  - Cost dominated by one off PM block costs (>50%)
  - Will still demonstrate the tuneable PM dipole principle as well as achieving the same field quality and the same relative tuning range.

Type	Length (m)	Max Field Strength (T)	Pole Gap (mm)	0.1% good field (integrated)(mm)	Range (%)
DB TAL	**1.5**	**1.6**	**53**	**40 x 40**	**50–100**
Original Prototype	0.5	1.6	53	40 x 40	50–100
Scaled Prototype	0.4	**1.1**	**40**	**30 x 30**	**50–100**

Dipole Prototype

- Focus on the most challenging case (576 dipoles for drive beam turn-around loop).
  - Length 1.5 m, strength 1.6 T, tuning range 50-100%
- Settled on C-design that uses a single sliding PM block to adjust field





- Advantages:
  - Tunes without changing gap!
  - PM moves perpendicular to largest forces
  - Curved poles possible

Magnet Block

- Magnet block dimensions are **500x400x200 mm**, with 4 holes on 400mm axis for mounting rods.
  - Constructed from 80 individual blocks (each 100x50x100mm) in resin

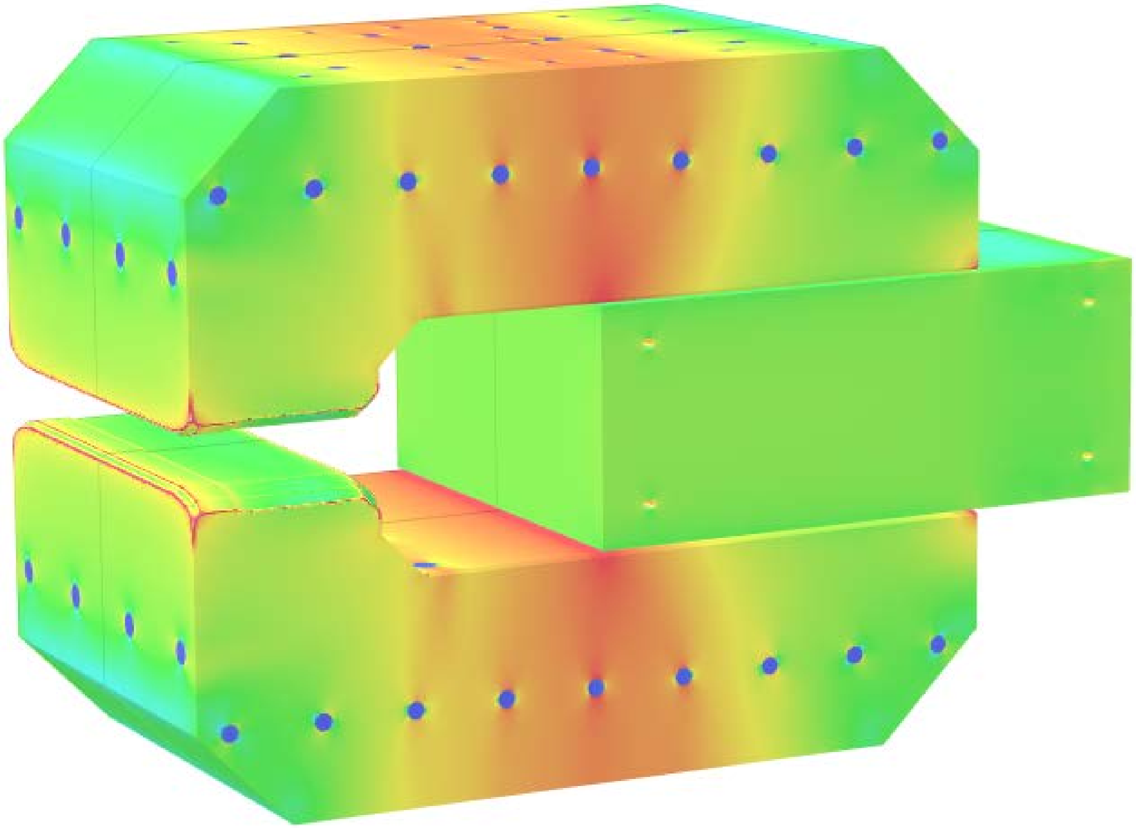
- Manufactured, measured & delivered by Vacuumschmelze
- Magnet material **NdFeB, Vacodym 745TP**
- **Br 1.38T min, 1.41T typical**

Modelling

Magnet simulations performed in OPERA 3D

Mesh deals with small gaps and non-magnetic fasteners

Not component deflection



MODEL DATA
Position 150.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
4202266 elements
2036289 nodes
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in ZX plane (Z+X fields=0)

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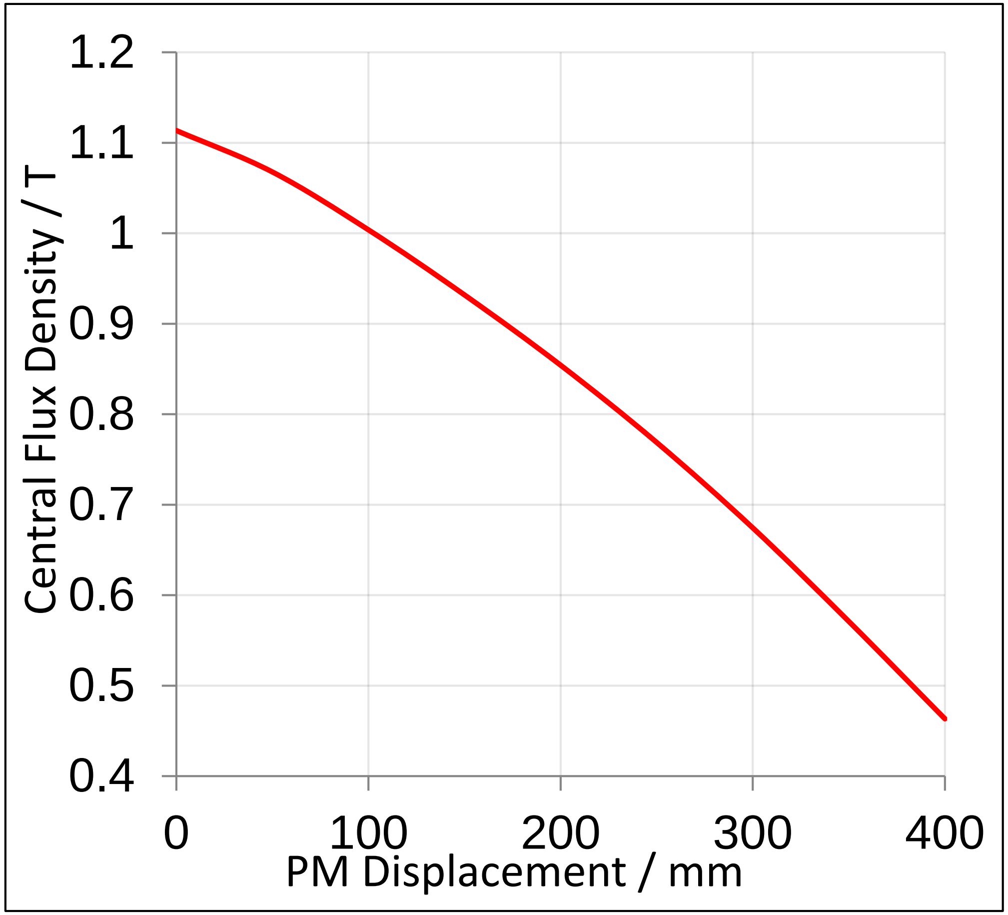
Predicted Flux Density

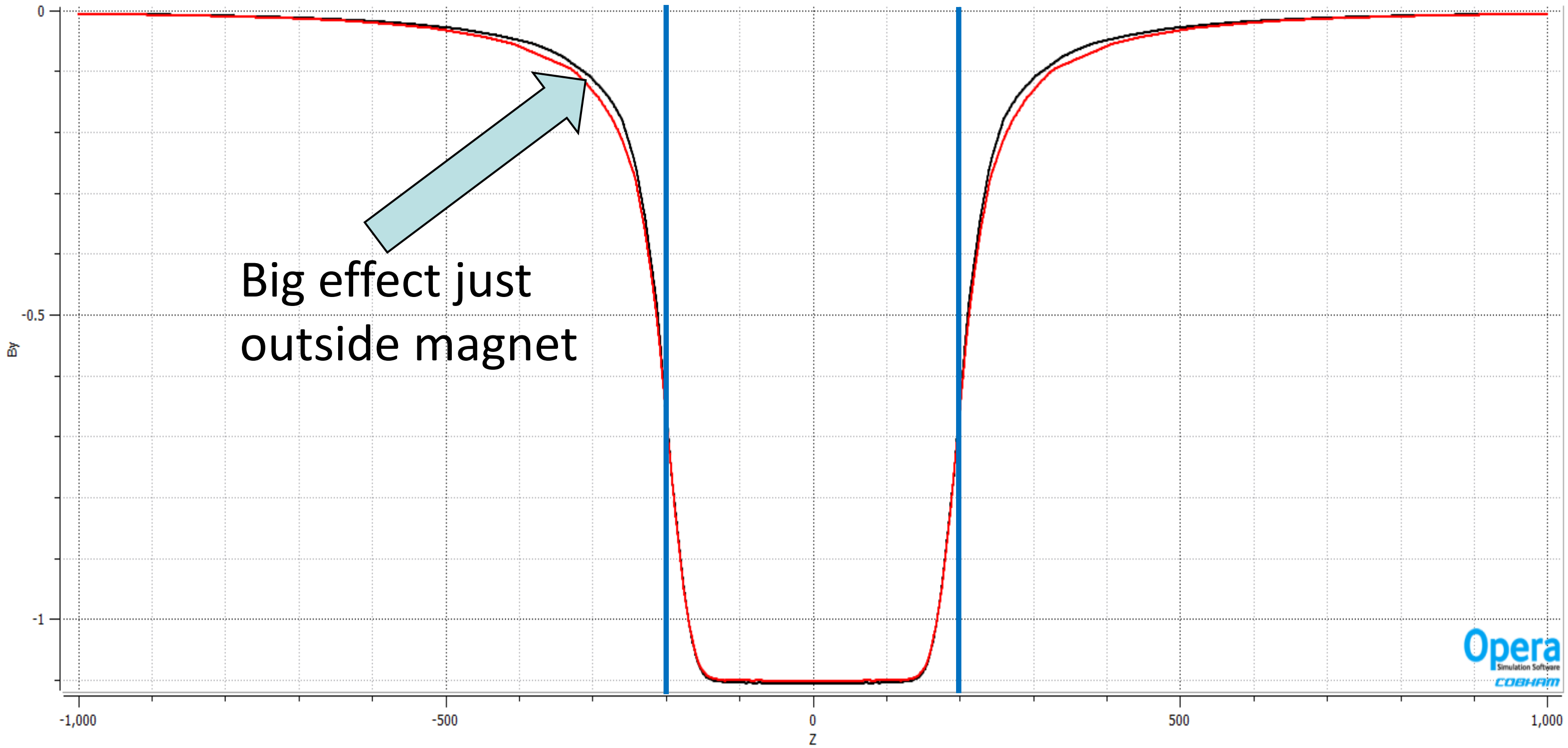


Predicted magnetic flux density at the geometric center of the magnet as a function of block displacement.

OPERA's 2 calculation methods agree to within the width of the fitting line.

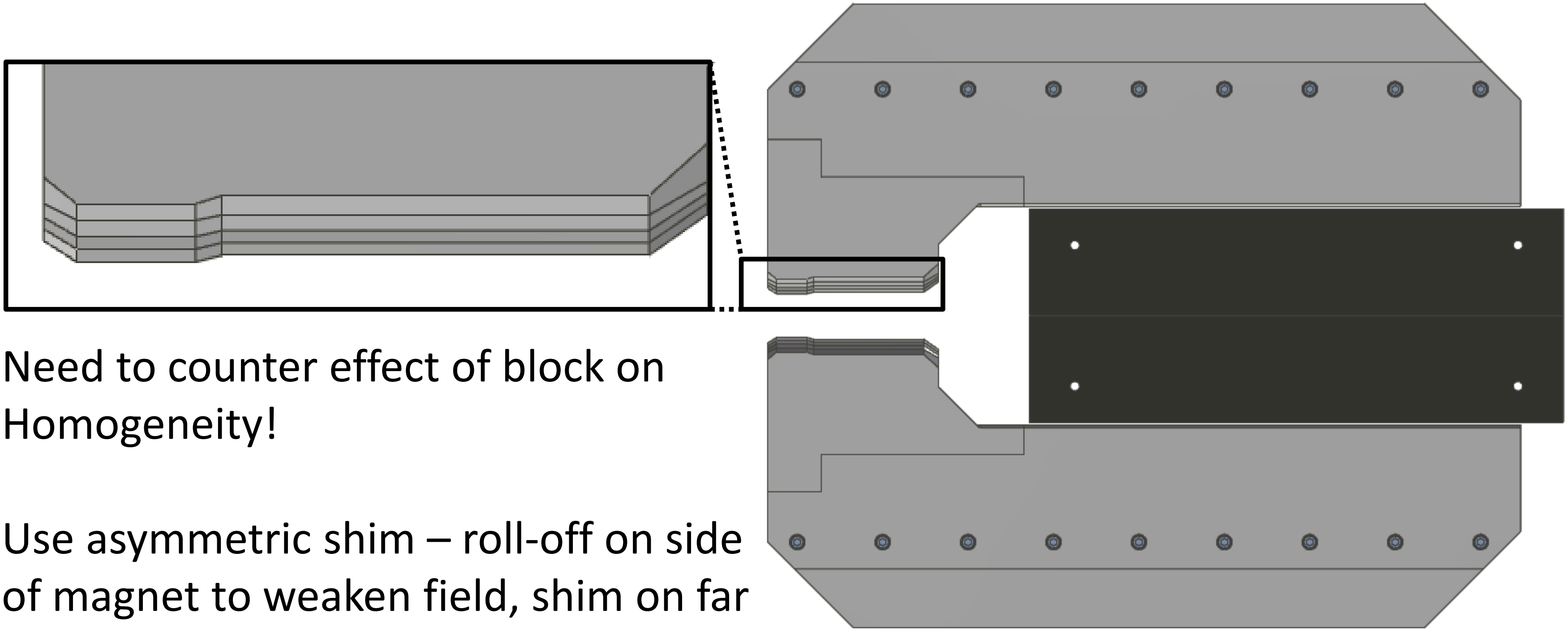
50 % tuning mark reached at 355 mm displacement.

Longitudinal Profile



Block affects longitudinal field profile differently at different positions in beam pipe.

Shim Structure



Need to counter effect of block on Homogeneity!

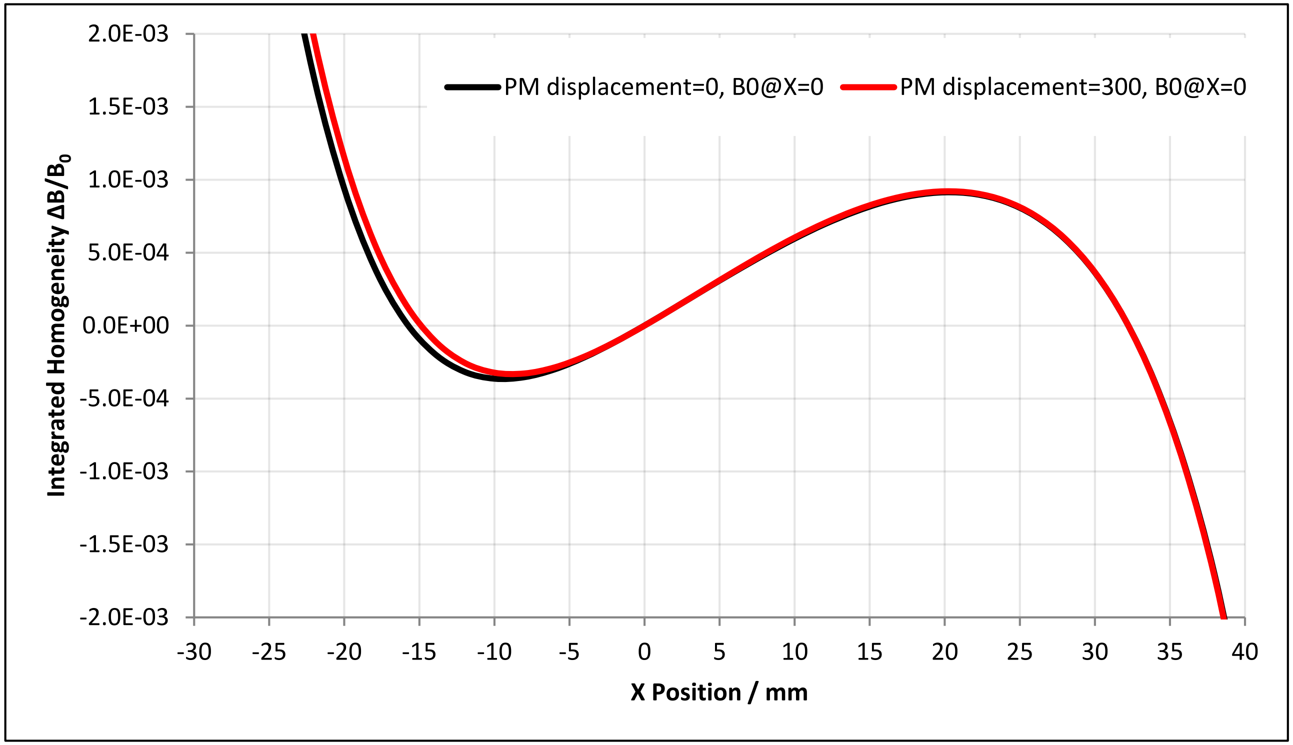
Use asymmetric shim – roll-off on side of magnet to weaken field, shim on far side to strengthen.

Effect on higher harmonics? Likely adds quadrupole effect – rotating coil measurements interesting!

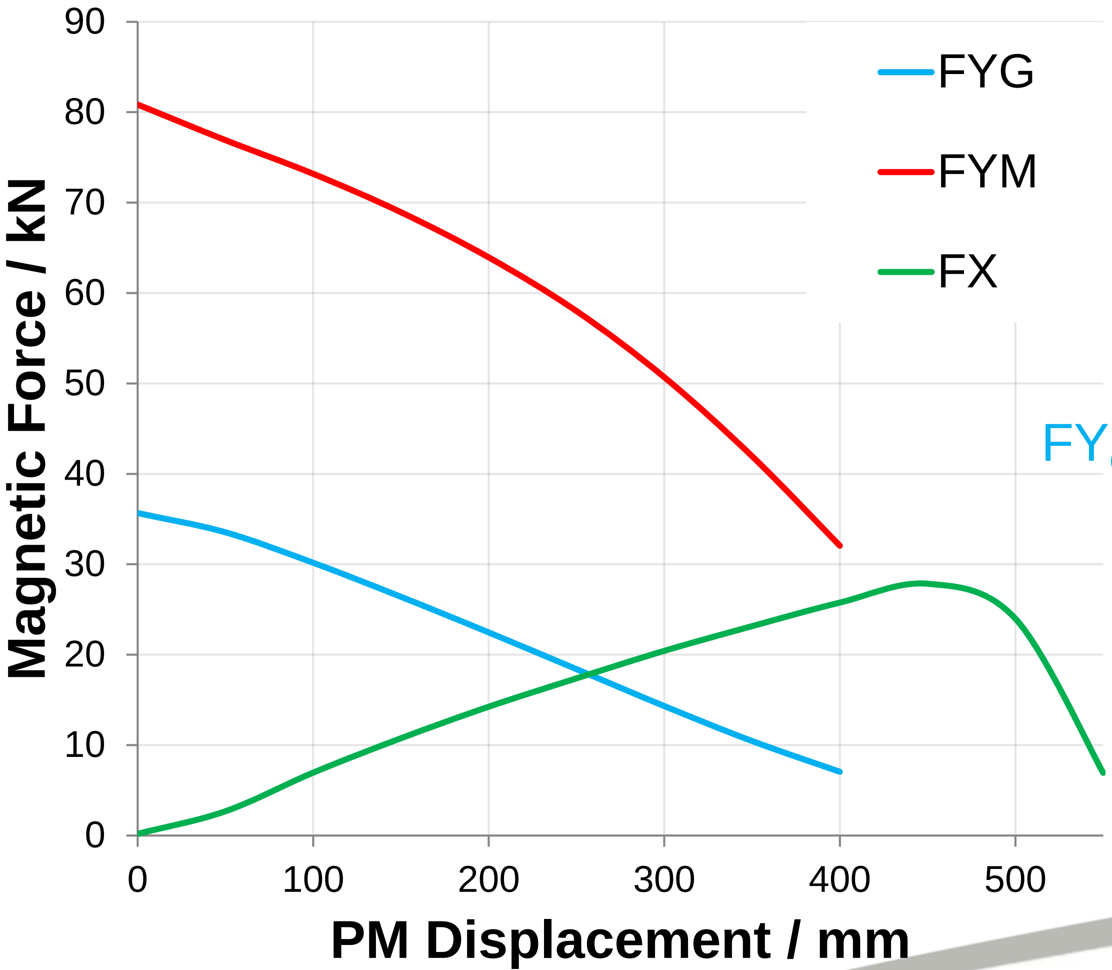
Integrated Homogeneity

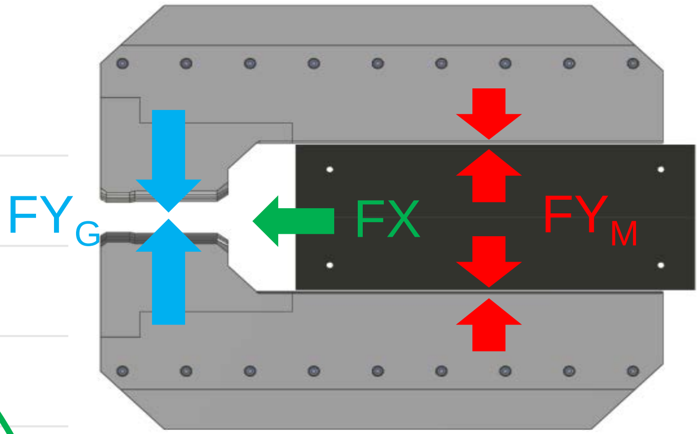
The optimised pole design meets the target to 20mm each side of the beam axis.

Balancing pole shape with saturation makes homogeneity relatively independent of PM block position.



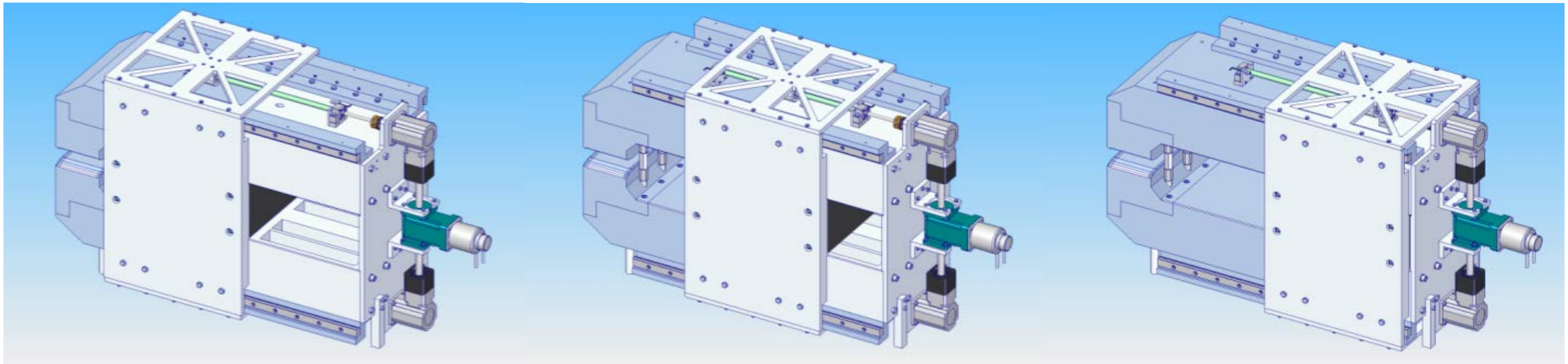
Magnetic Forces

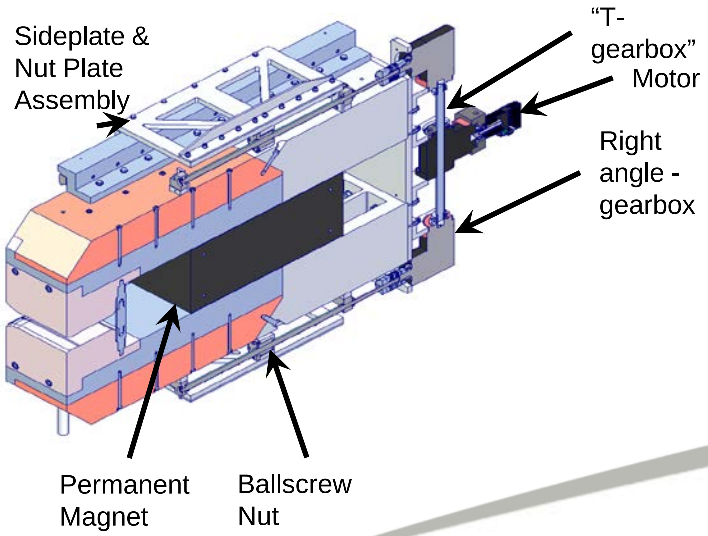




Engineering

- Sliding assembly using rails, stepper motor and gearbox.



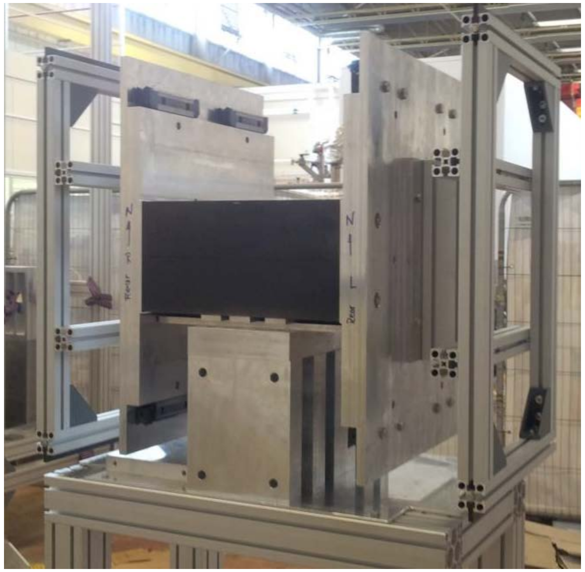


3 support rods hold jaws of magnet fixed
Can be independently adjusted

Poles held 2 mm from surface of block

Assembly

- Magnet assembly is currently underway – proving difficult!



Measurement Plan

- Forces – Load cell on assembly crane

- 3D grid using Hall probe bench
  - Hall probe of central field vs magnet position
  - Integrated field vs X for different magnet positions
  - longitudinal profile for different magnet positions

- Stretched wire bench to backup field integral measurements

- Rotating Coil (compensated to remove dipole component)
  - Very interested in effect of asymmetric shim – F-type quadrupole?
  - Sextupole component ?

Conclusions

- Tuneable permanent magnets are becoming a reality, merging the versatility of electromagnets with savings in operating costs (both financial and environmental) and infrastructure.

- Two quadrupole prototypes have been designed, built and measured, demonstrating the required gradient range and giving good agreement with models. A dipole is under construction.

- There is an additional measurement challenge over conventional electromagnets – moving ferromagnetic components results in shift of magnetic axis or changing homogeneity.

Acknowledgements

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