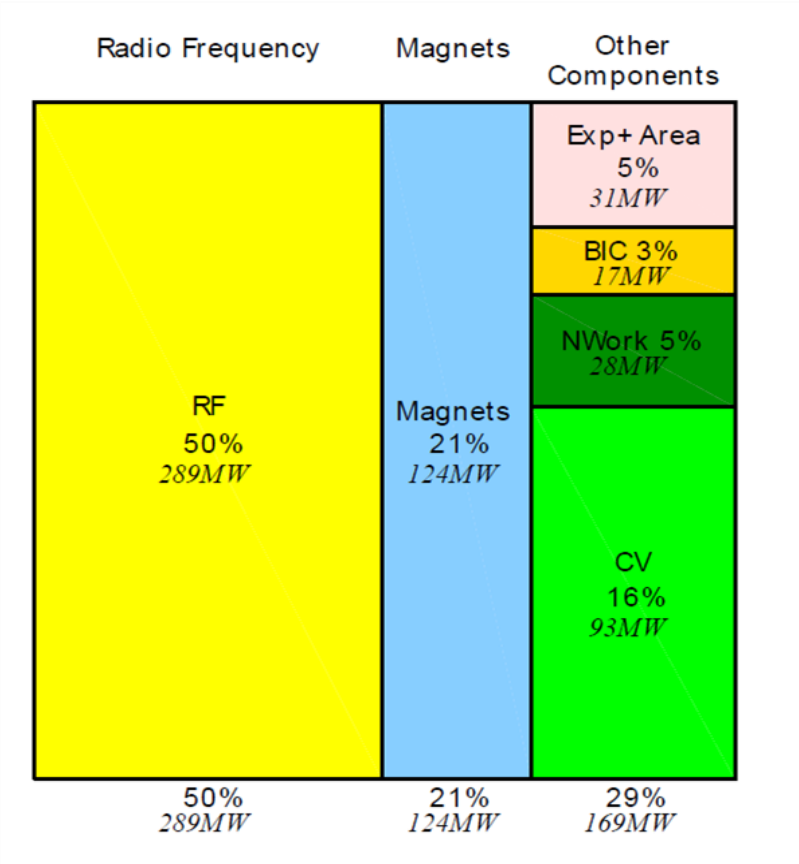
Update on the ZEPTO project: Prototype adjustable permanent magnets for CLIC

Alex Bainbridge[1], Ben shepherd[1], Jim Clarke[1], Norbert Collomb[1], Michele Modena[2]

1: ASTeC, STFC Daresbury Laboratory, UK
2: CLIC project, CERN

Intro + motivation

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



124 MW projected for resistive electromagnets alone….

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.

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Potential targets

DRIVE BEAM

Type	Magnet type	Total	Effective Length [m]	H	V	Strength	Units	Min field	Max field	Rel Field Accuracy	Higher Harmonics [Tm]	per magnet [kW]	total [MW]
DBQ	***Quadrupole***	***41400***	***0.194***	***26***	***26***	***62.78T/m***		***10%***	***120%***	***1E-03***	***1.0E-04***	***0.5***	***17.0***
MBTA	***Dipole***	***576***	***1.5***	***40***	***40***	***1.6T***		***10%***	***100%***	***1E-03***	***1.0E-04***	***21.6***	***12.4***
MBCOTA	Dipole	1872	0.2	40	40	0.07T		-100%	100%	1E-03	1.0E-03	0.3	0.5
QTA	Quadrupole	1872	0.5	40	40	14T/m		10%	100%	1E-03	1.0E-04	2.0	3.7
SXTA	Sextupole	1152	0.2	40	40	85T/m²		10%	100%	1E-03	1.0E-03	0.1	0.1
MB1	***Dipole***	***184***	***1.5***	***80***	***80***	***1.6T***		***10%***	***100%***	***1E-03***	***1.0E-04***	***42.0***	***7.7***
MB2	***Dipole***	***32***	***0.7***	***80***	***80***	***1.6T***		***10%***	***100%***	***1E-03***	***1.0E-04***	***25.0***	***0.8***
MB3	***Dipole***	***236***	***1***	***80***	***80***	***0.26T***		***10%***	***100%***	***1E-03***	***1.0E-04***	***4.5***	***1.1***
MBCO	Dipole	1061	0.2	80	80	0.07T		-100%	100%	1E-03	1.0E-03	0.4	0.4
Q1	***Quadrupole***	***1061***	***0.5***	***80***	***80***	***14T/m***		***10%***	***100%***	***1E-03***	***1.0E-04***	***5.9***	***6.3***
SX	Sextupole	416	0.2	80	80	85T/m²		10%	100%	1E-03	1.0E-03	0.5	0.2
SX2	Sextupole	236	0.5	80	80	360T/m²		10%	100%	1E-03	1.0E-04	3.3	0.8
QLINAC	***Quadrupole***	***1638***	***0.25***	***87***	***87***	***17T/m***		***No data***	***100%***	***No data***	***No data***	***6.3***	***10.3***
MBCO2	Dipole_CO	880	1	200	200	0.008T		-100%	100%	2E-03	2.8E-05	0.3	0.3
Q4	Quadrupole	880	1	200	200	0.14T/m		10%	100%	2E-03	2.8E-05	0.5	0.5

Obvious targets

Likely targets

Possible targets

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Potential targets

MAIN BEAM

Type	Magnet type	Total	Effective Length [m]	H	V	Strength	Units	Min field	Max field	Rel Field Accuracy	Higher Harmonics [Tm]	per magnet [kW]	total [MW]
D1	*Dipole*	*6*	*1*	*30*	*30*	*0.4T*		*100%*	*100%*		*1.0E-04*	*1.8*	*0.0*
D2 Type 1	*Dipole*	*12*	*1.5*	*30*	*30*	*0.7T*		*100%*	*100%*		*1.0E-04*	*5.8*	*0.1*
D2 Type 2	*Dipole*	*666*	*1.5*	*30*	*30*	*0.5T*		*100%*	*100%*		*1.0E-04*	*3.8*	*2.5*
D3	Dipole	16	1.5	500	30	0.5T		-100%	120%		1.0E-04	3.9	0.1
D4	Dipole	8	1.5	500	30	0.3T		-100%	120%		1.0E-04	2.3	0.0
Q1	Quadrupole	268	0.3	30	30	63T/m		98%	100%	1E-03	1.0E-04	1.7	0.5
Q2	Quadrupole	223	0.3	30	30	45T/m		60%	100%	1E-03	1.0E-04	1.2	0.3
Q3 Type 1	Quadrupole	318	0.15	30	30	36.6T/m		77%	100%	1E-03	1.0E-04	0.9	0.3
Q3 Type 2	Quadrupole	73	0.2	30	30	39T/m		77%	100%	1E-03	1.0E-04	0.8	0.1
Q3 Type 3	Quadrupole	202	0.3	30	30	37T/m	?		100%	1E-03	1.0E-04	0.6	0.1
Q4 Type 1	Quadrupole	44	0.075	30	30	16T/m		83%	100%	1E-03	1.0E-04	0.2	0.0
Q4 Type 2	Quadrupole	110	0.15	30	30	16.2T/m		74%	100%	1E-03	1.0E-04	0.2	0.0
Q4 Type 3	Quadrupole	230	0.2	30	30	18T/m		79%	100%	1E-03	1.0E-04	0.3	0.1
Q5	Quadrupole	87	0.075	30	30	7.6T/m		53%	100%	1E-03	1.0E-04	0.1	0.0
Q6	Quadrupole	192	0.36	30	30	0.3T/m	?		100%	1E-03	1.0E-04	0.0	0.0
SX2	Sextupole	520	0.2	30	30	1200T/m²	?		100%	1E-03	1.0E-04	0.1	0.1
SX1	Sextupole	16	0.2	30	30	3000T/m²		63%	100%	1E-03	1.0E-04	0.3	0.0

Obvious targets

Likely targets

Possible targets

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Potential targets

DAMPING AND PRE-DAMPING RINGS

Type	Magnet type	Total	Effective Length [m]	H	V	Strength	Units	Min field	Max field	Rel Field Accuracy	Higher Harmonics [Tm]	per magnet [kW]	total [MW]
D1.7	Dipole	76	1.3	160	80	1.7T		75%	100%	5E-04		37.5	2.9
Q30L04	***Quadrupole***	***408***	***0.4***	***80***	***80***	***30T/m***		***20%***	***100%***	***5E-04***		***11.4***	***4.7***
Q30L02	***Quadrupole***	***408***	***0.2***	***80***	***80***	***30T/m***		***20%***	***100%***	***5E-04***		***8.2***	***3.3***
S300	Sextupole	204	0.3	80	80	300T/m^2		0%	100%	5E-04		1.2	0.2
ST0.3	Steerer	312	0.15	80	80	0.3T		-100%	100%	5E-04		1.5	0.5
SkQ5	Skew Quad	76	0.15	80	80	5T/m		-100%	100%	5E-04		0.8	0.1
CFM D1.7Q10.5	Combined Dipole/Quad	204	0.43	100	20	1.4T		75%	125%	5E-04		2.4	0.5
				0	0	10.5T/m							0.0
Q75	Quadrupole	1004	0.2	20	20	75T/m		20%	100%	5E-04		0.8	0.8
S5000	Sextupole	576	0.15	20	20	5000T/m^2		0%	100%	5E-04		0.2	0.1
ST0.4	Steerer	712	0.15	20	20	0.4T		-100%	100%	5E-04		0.4	0.3
SkQ20	Skew Quad	96	0.15	20	20	20T/m		-100%	100%	5E-04		0.2	0.0

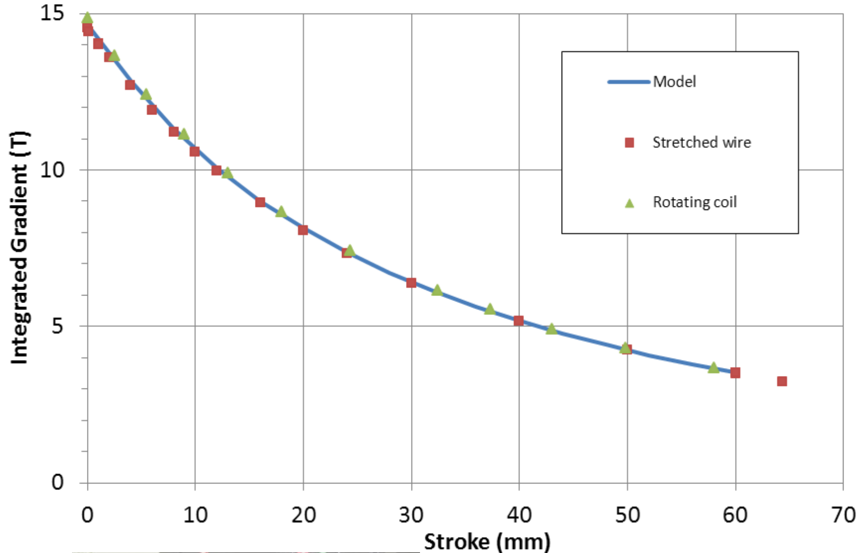
Obvious targets

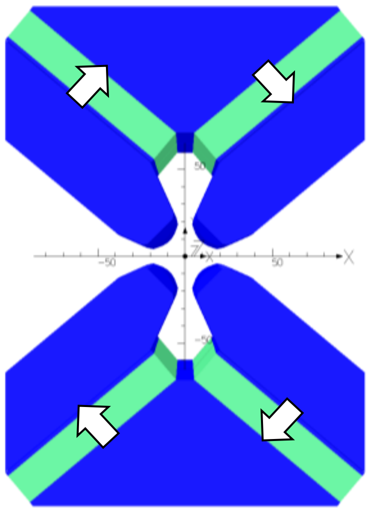
Likely targets

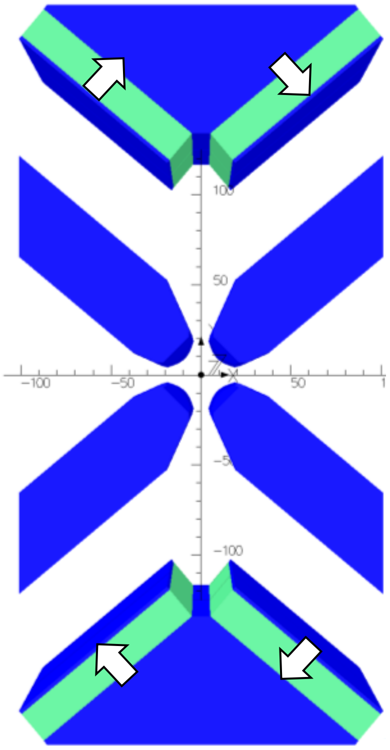
Possible targets

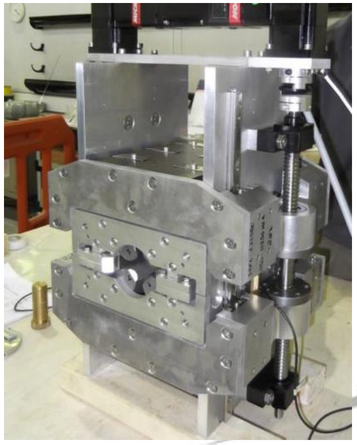
High strength quadrupoles

High strength quadrupole (tunes 60.4 to 15.0 T/M) to replace 41400 DBQ's. Uses 4 NdFeB blocks (18x100x230 mm) with Br=1.37, requires 64 mm motion range.







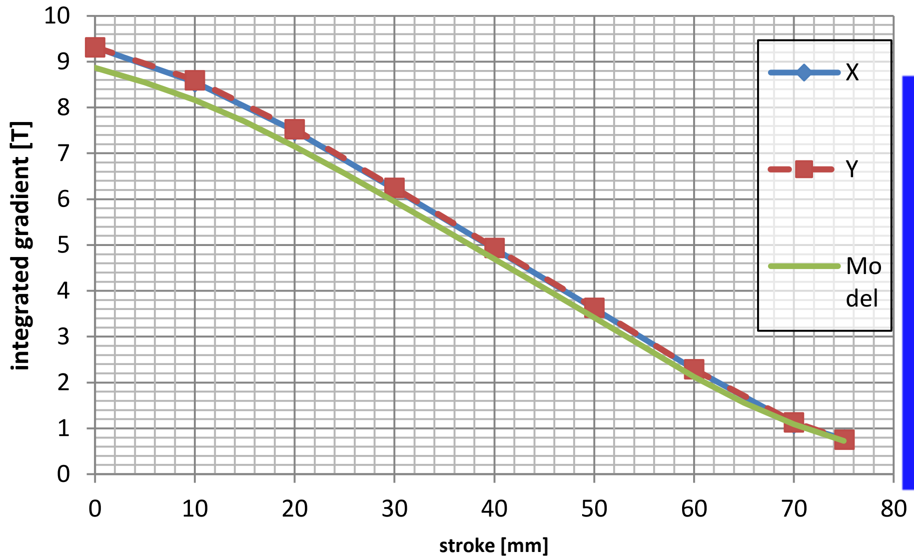


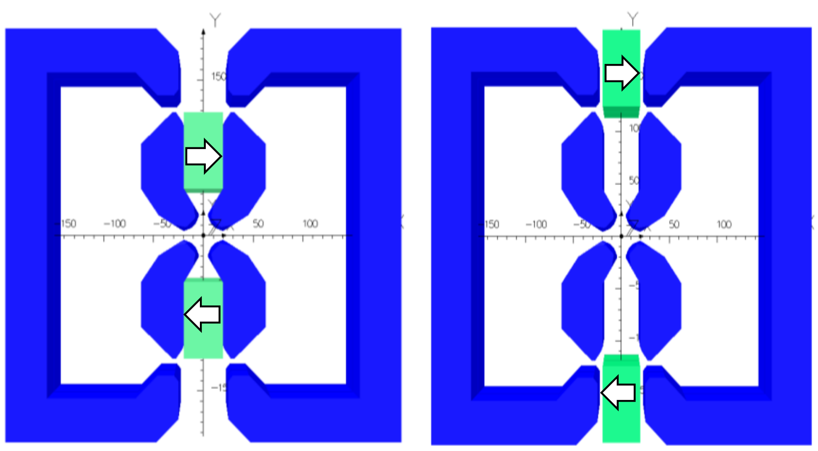
Built and tested at Daresbury
Finished in 2015

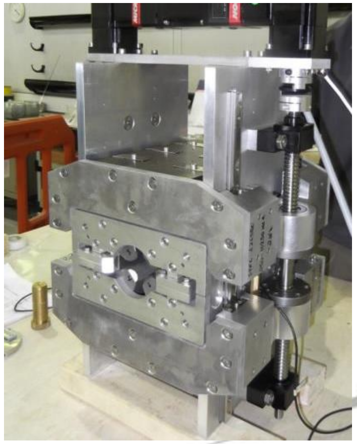
Meets all requirements

Low strength quadrupoles

Low strength quadrupole (tunes 43.4 to 3.5 T/M) to replace Q1, QLINAC, Q30L04 and Q30L02. Uses 2 NdFeB blocks (37.2x70x190 mm) with Br=1.37, requires 75 mm motion range.







Built and tested at Daresbury
Finished in 2015

Meets most requirements but magnet center moves with PM's – Still not resolved

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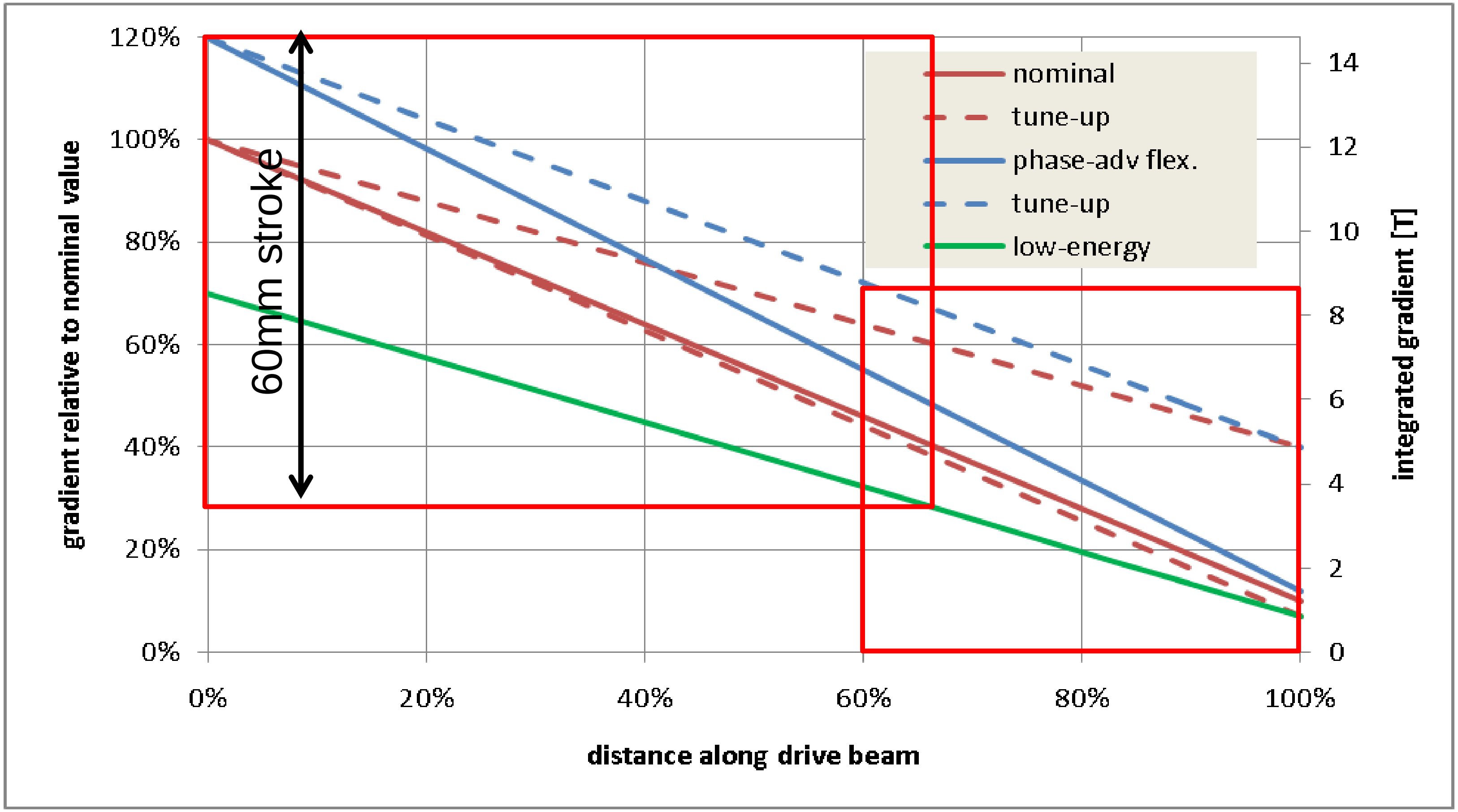
Quadrupole Implementation



Large tuning range requires complex motion and control system
Big effect on build cost per magnet

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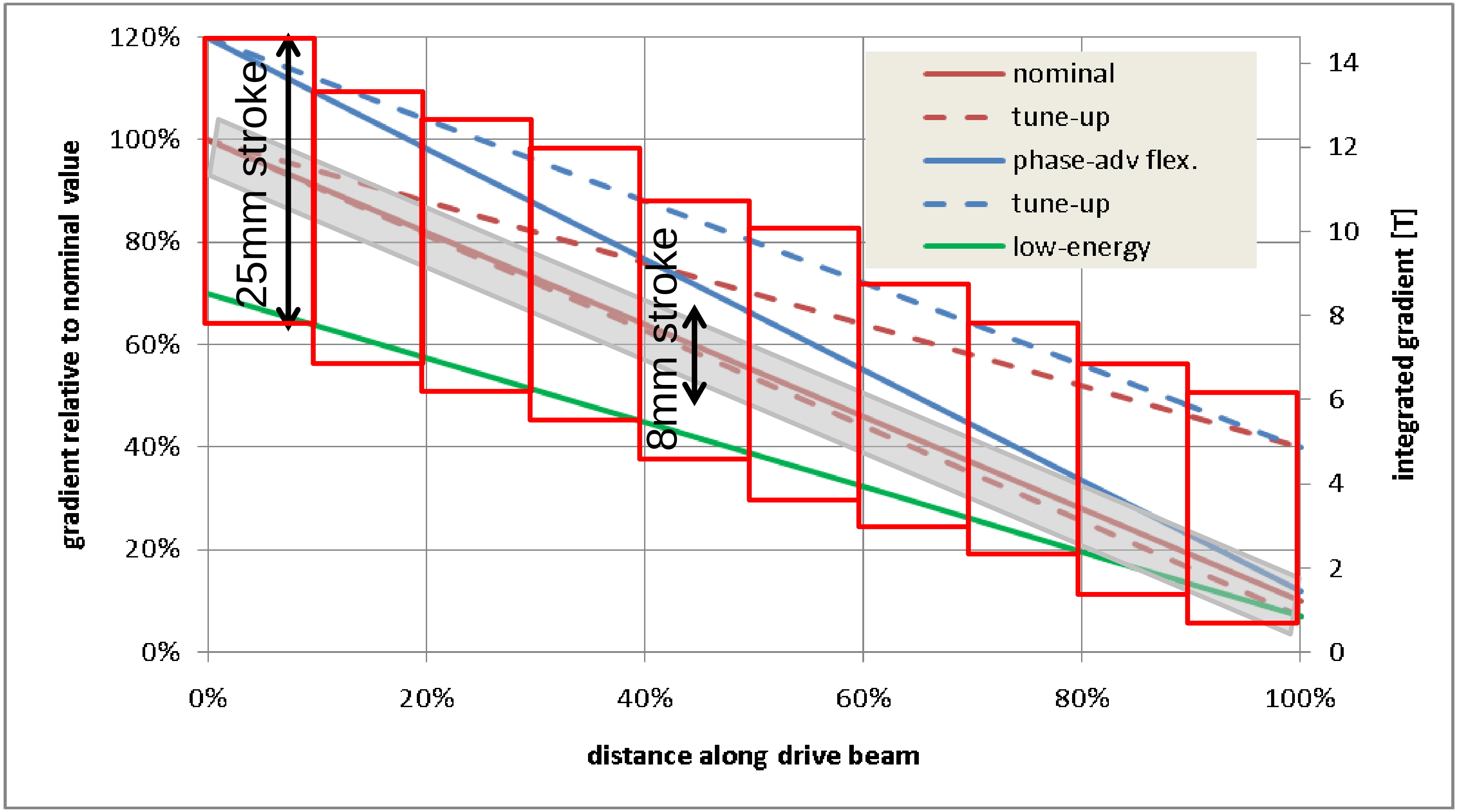
Quadrupole Implementation

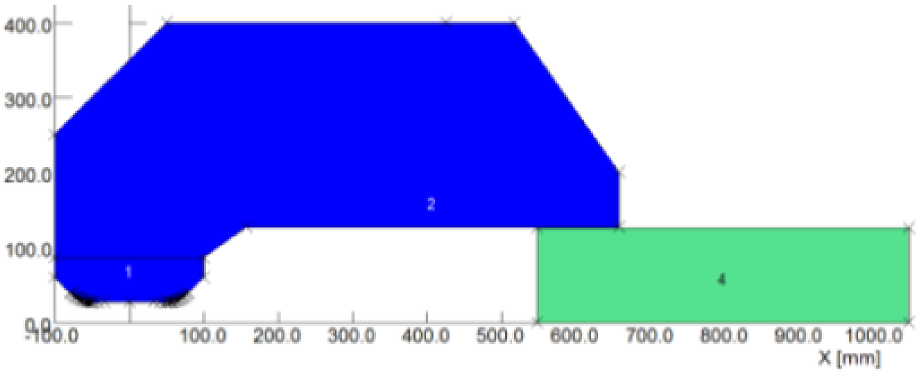


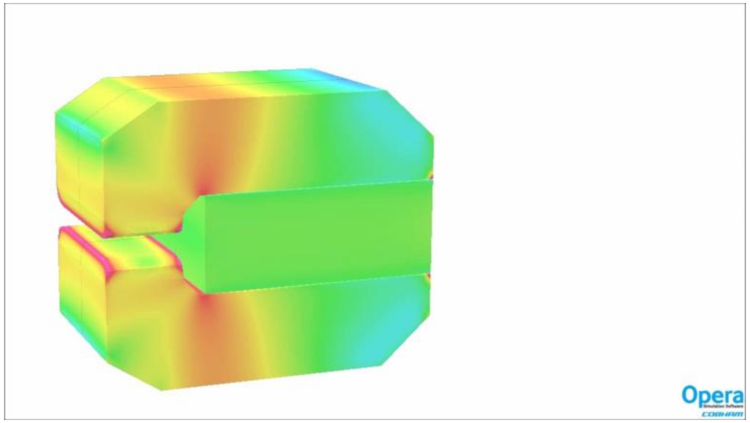
Reducing the stroke will help keep things cheap. Have 10 magnet types instead of 2 but keep modular – same intrinsic design but with different PM block sizes for example. Restrict beam requirements for even bigger impact on cost!

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:
  Single simple PM
  PM moves perpendicular to largest forces – can be moved easily
  Curved poles possible

Dipole Prototype

- Original plan was to build a 0.5m version of full size DB TAL magnet
- However, cost exceeded available budget
- 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)	Good Field Region (mm)	Field Quality	Range (%)
DB TAL	**1.5**	**1.6**	**53**	**40 x 40**	**1×10^{-4}**	**50–100**
Original Prototype	0.5	1.6	53	40 x 40	1×10^{-4}	50–100
Scaled Prototype	0.4	**1.1**	**40**	**30 x 30**	**1×10^{-4}**	**50–100**

Note: Scaled Prototype weighs ~1500kg
PM block is ~350kg!

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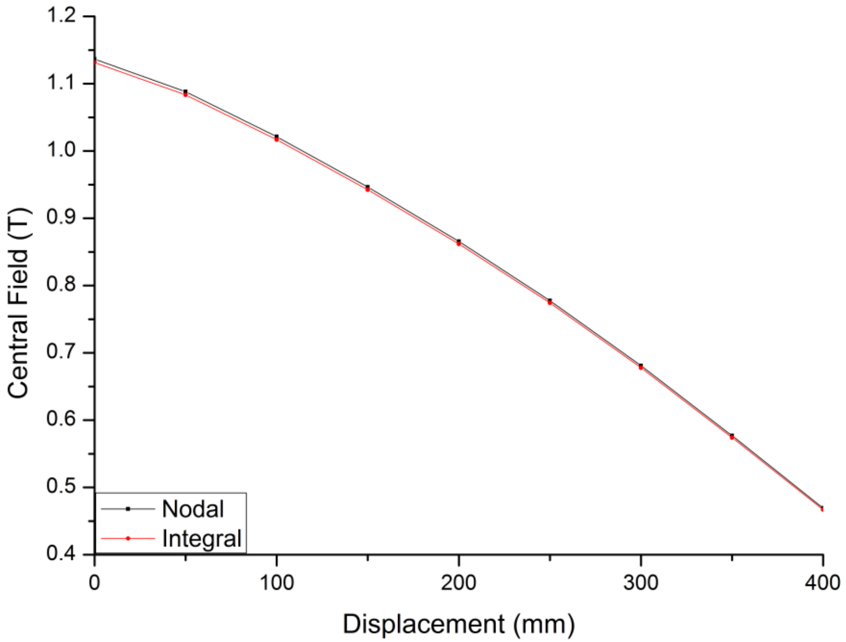
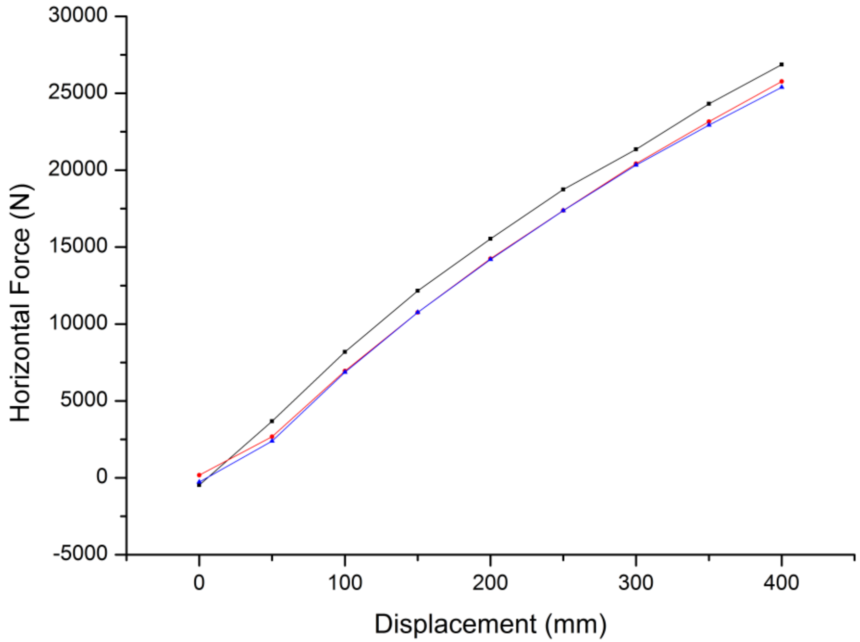
Dipole Prototype

- Scaled prototype extensively modelled (non-linear FEA, OPERA)
- Results predict 50% tuning range with 400 mm stroke





- Force between magnet and pole predicted as >120 kN
  - Simply not feasible to separate poles
  - Mechanical design compensates for static force

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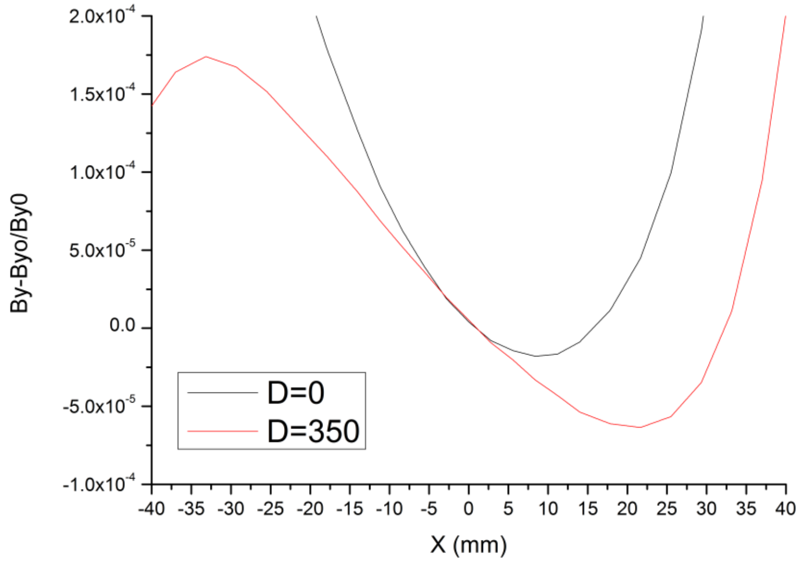
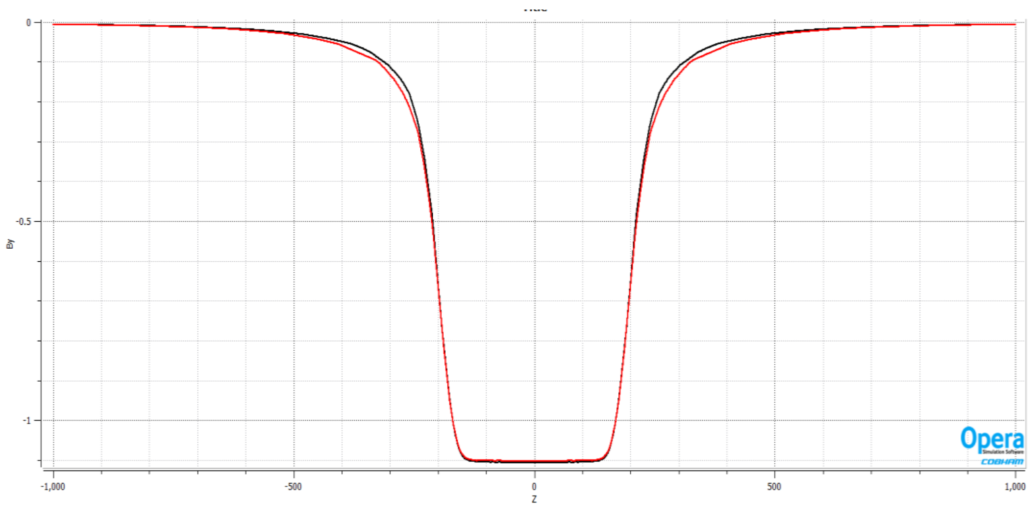
Dipole Prototype

- Homogeneity of integrated field quality difficult to achieve as field from magnet block extends far beyond magnet itself – would clamping plates help in the full size model?





- Homogeneity inside magnet itself is excellent but on approach and exit electrons closer to the magnet block feel a larger field – cumulative effect severe over several magnets
  - Beam pipe shielding?

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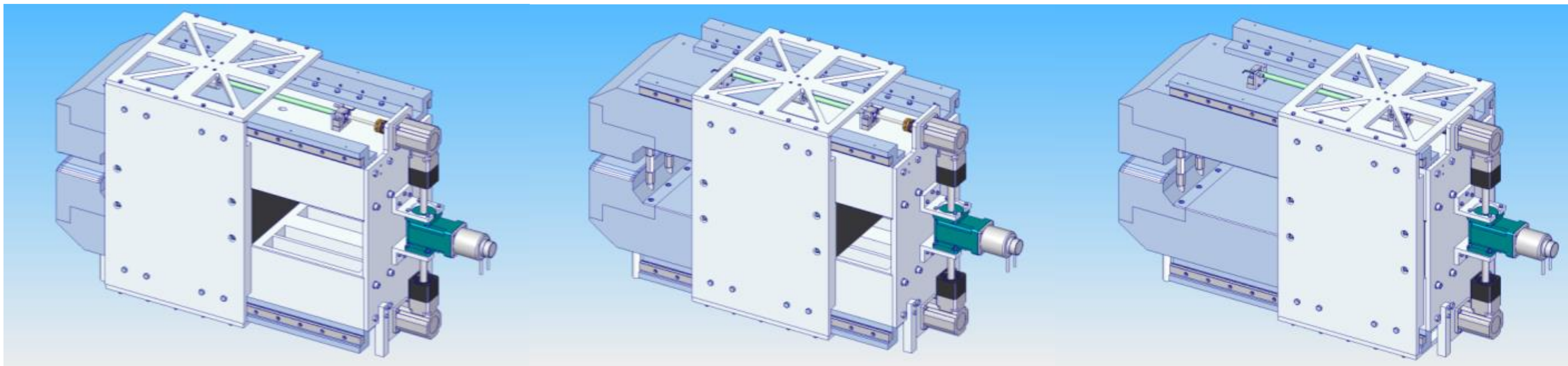
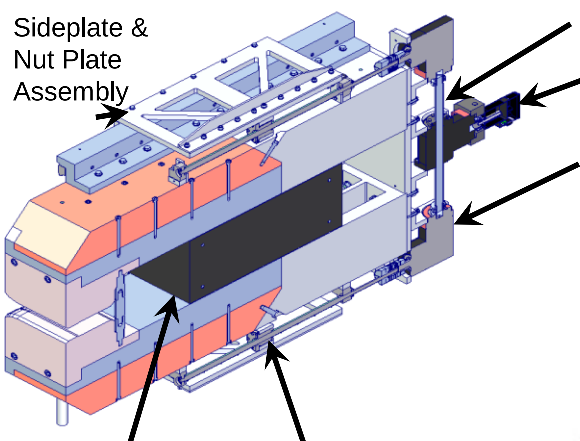
Dipole Prototype

- Sliding assembly using rails, stepper motor and gearbox.
- Should cope with horizontal forces (peak >27 kN) and hold the magnet steady at any point on a 400 mm stroke.





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

Poles held 2 mm from surface of block

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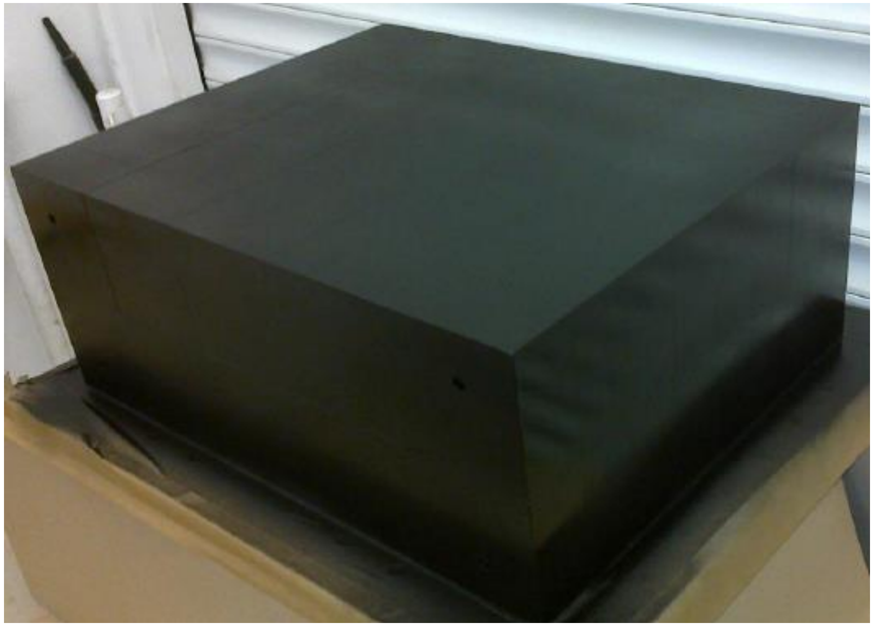
PM Block

- Manufactured, measured & delivered by Vacuumschmelze
- Magnet block dimensions are **500x400x200 mm**, with 4 holes on 400mm axis for mounting rods.
- Magnet material **NdFeB, Vacodym 745TP (Br 1.38T min, 1.41T typical)**
- Constructed from 80 individual blocks (each 100x50x100mm) in resin
- World's largest ever NdFeB PM block?



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Assembly

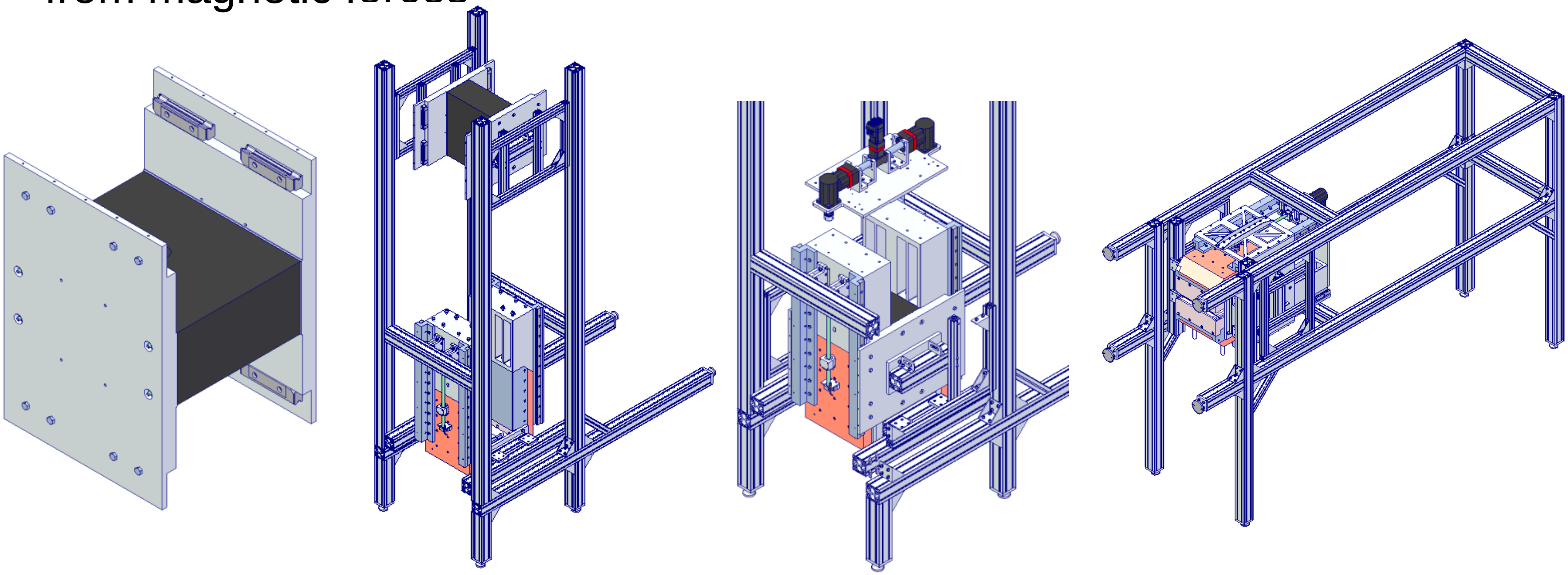
All components manufactured and delivered. Assembly area prepared with safety precautions!

Insertion of block into pole pieces due next week!

Assembly sequence

Assembly requires a purpose built tilting aluminium frame

Block must be lowered into poles vertically to allow crane to take strain from magnetic forces

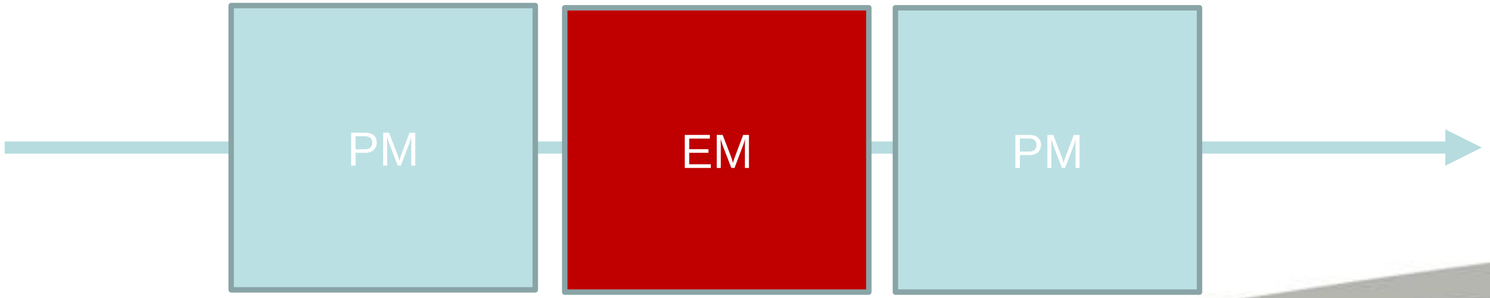


Assembly is a slow and careful process. Frame is built and most parts in place but each step is checked and double checked!

Dipole limitations

- The forces in the scaled down prototype are already very difficult to manage – and this was the best option!
- Assembly is already a dangerous process, extending the length and increasing the field to 1.6 T will make forced between magnet and pole impossible to deal with!
- Reduce tuning range, reduce cost through simpler motion system!

- For longer magnets will almost certainly have to split into 3 separate dipoles – possible hybrid solution?



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Conclusions + Future

- Work on PM quads completed with great success, but costs for CLIC could be reduced in reality by a larger number of narrower tuning ranges.
- Design of dipole is complete, all components have been ordered and assembly is happening now! Field mapping due in very near future.
- Already agreed another 2 years of collaboration to perform more generic examinations of where permanent magnets might be used.
- Klystron solenoids given as a suggestion, already ruled out after quick simulation reveals poor field quality.
- Focus on further dipole technologies – in particular how do we extend the prototype to full size whilst keeping forces manageable and the block buildable and movable?