Permanent Magnet Quadrupoles and Dipoles for CLIC

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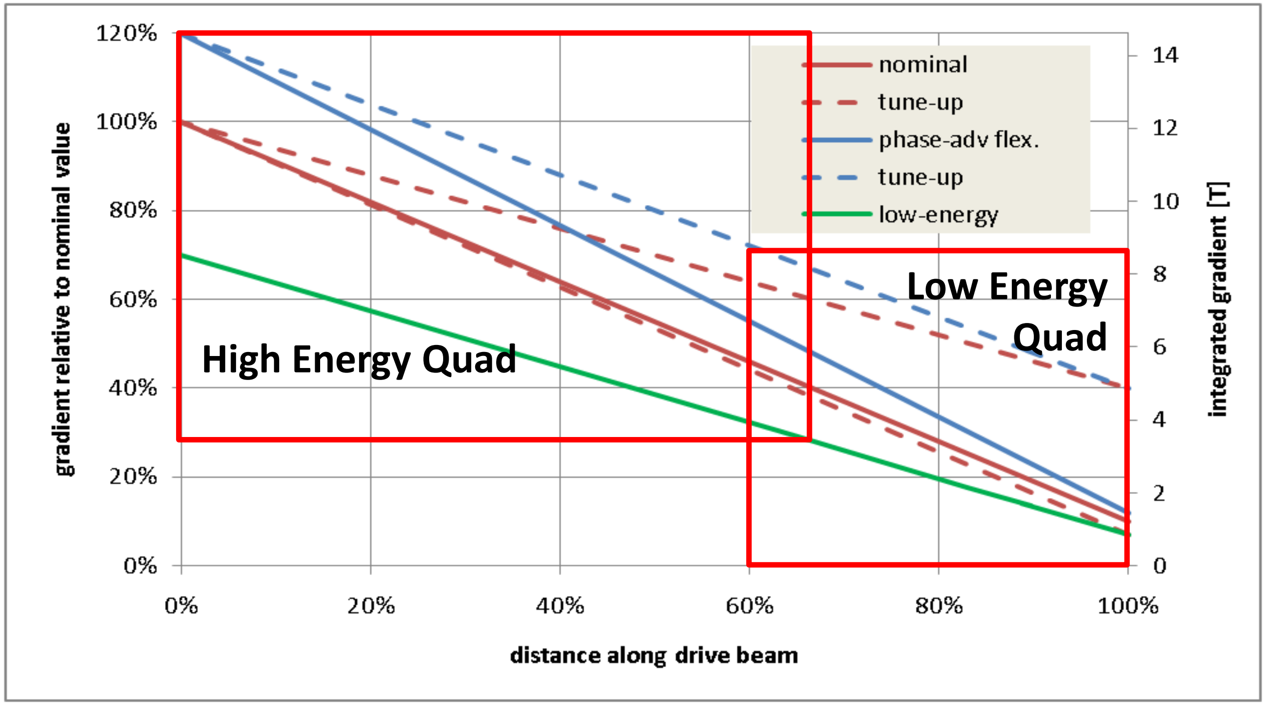
10th Jan 2017, Oxford

PM Quad Recap

- We have developed PM alternatives for the Drive Beam Quads
  - Two types were successfully prototyped to cover the full range required

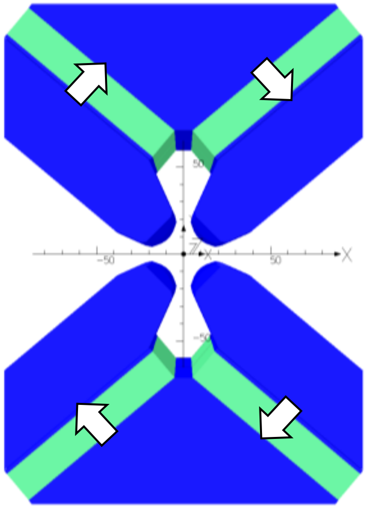


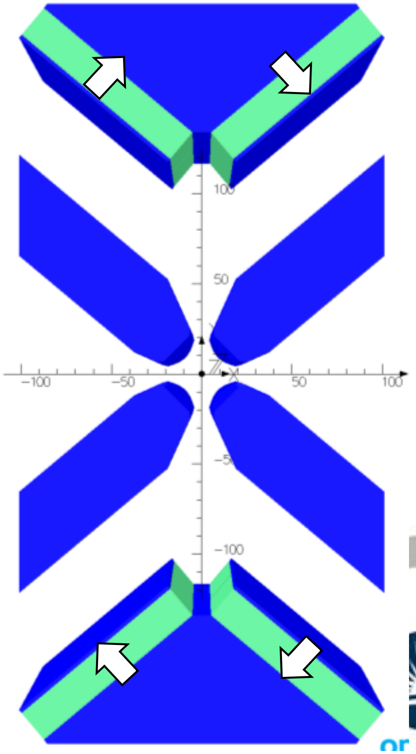
High energy quad – Gradient very high
Low energy quad – Very large dynamic range

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

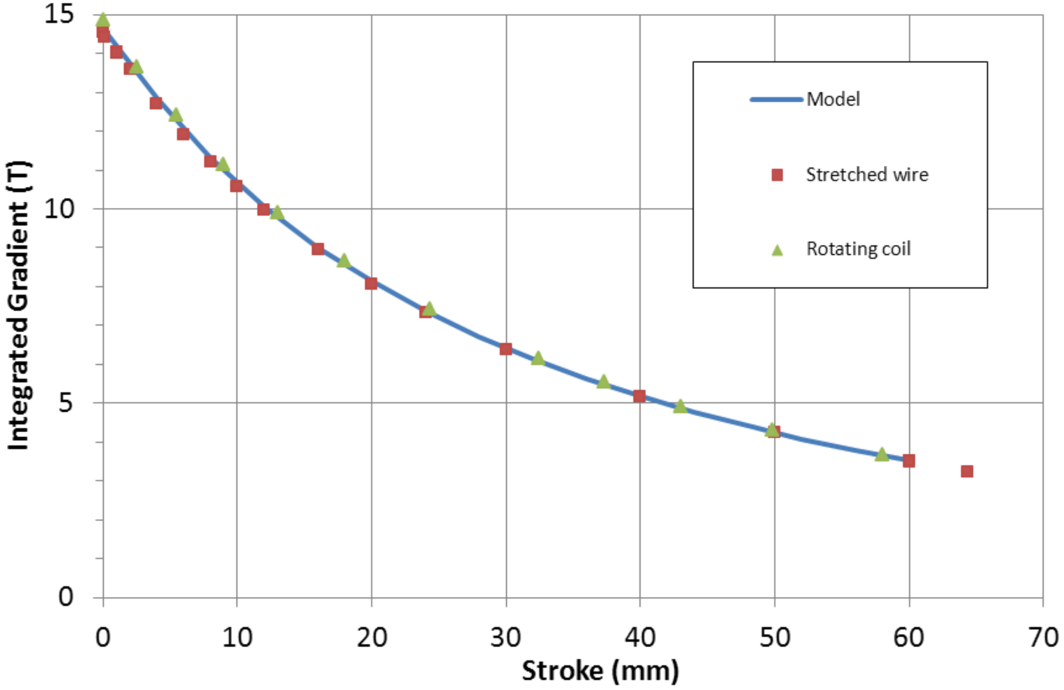




Stroke = 64 mm

Poles are permanently fixed in place.

High Energy Quad
Measured Integrated Gradient

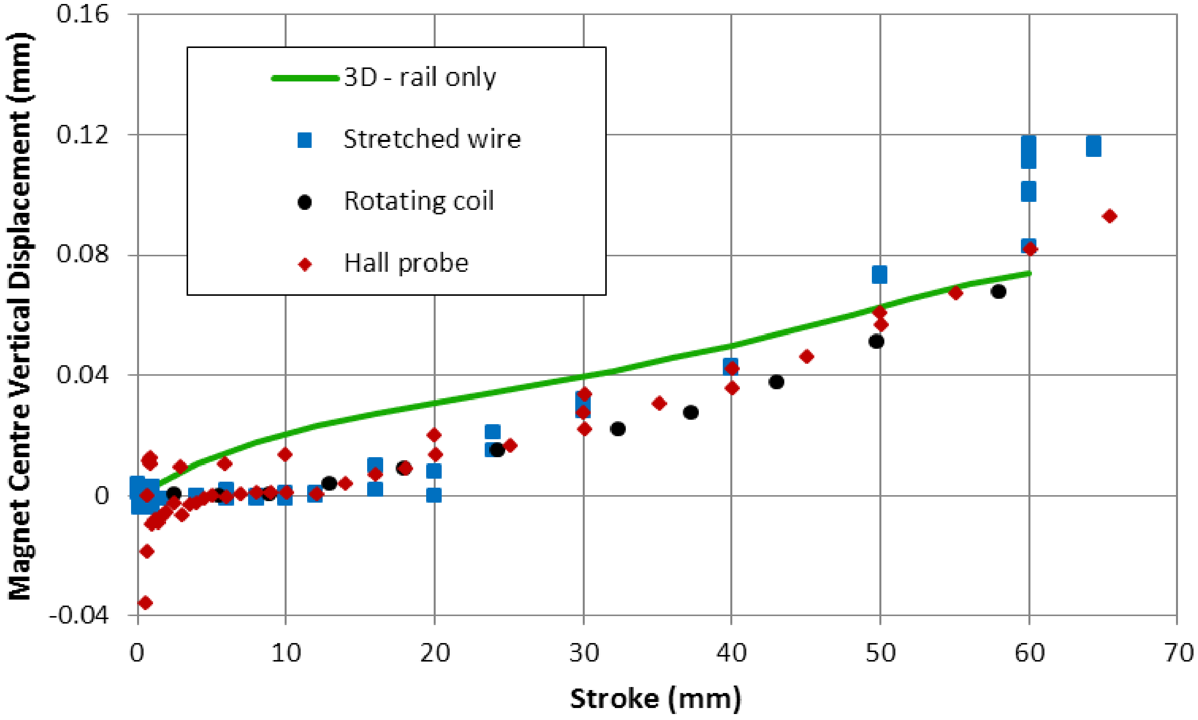


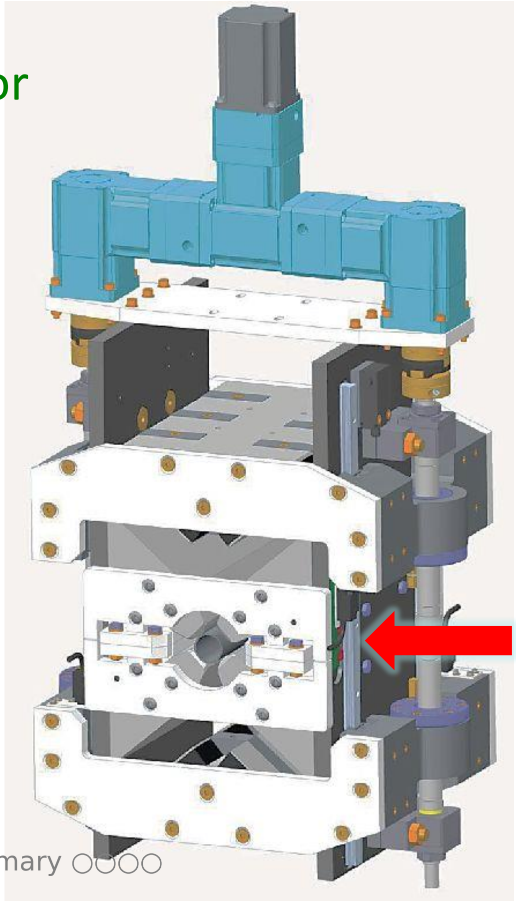
Gradient, Integrated Gradient, and Field Quality all good.

Main issue: Magnet centre moves with motion of PMs

Magnet Centre Movement

- The magnet centre moves upwards by **~100 µm** as the permanent magnets are moved away by 64mm
- 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

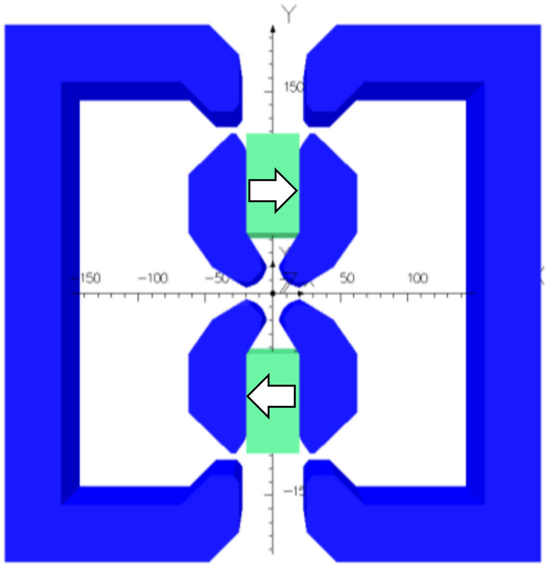


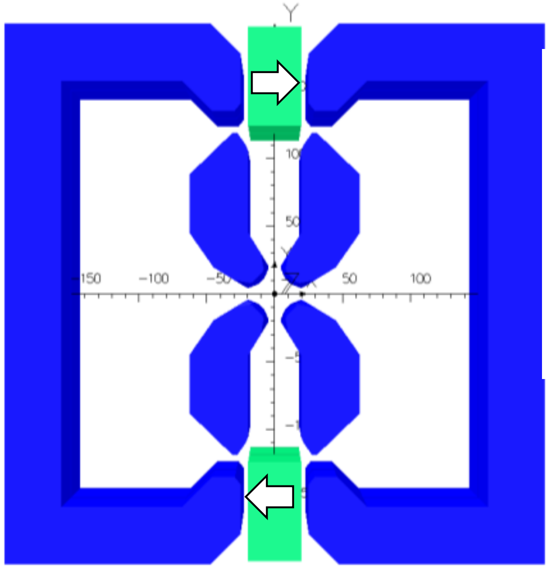


Low Energy Quad Design

- 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

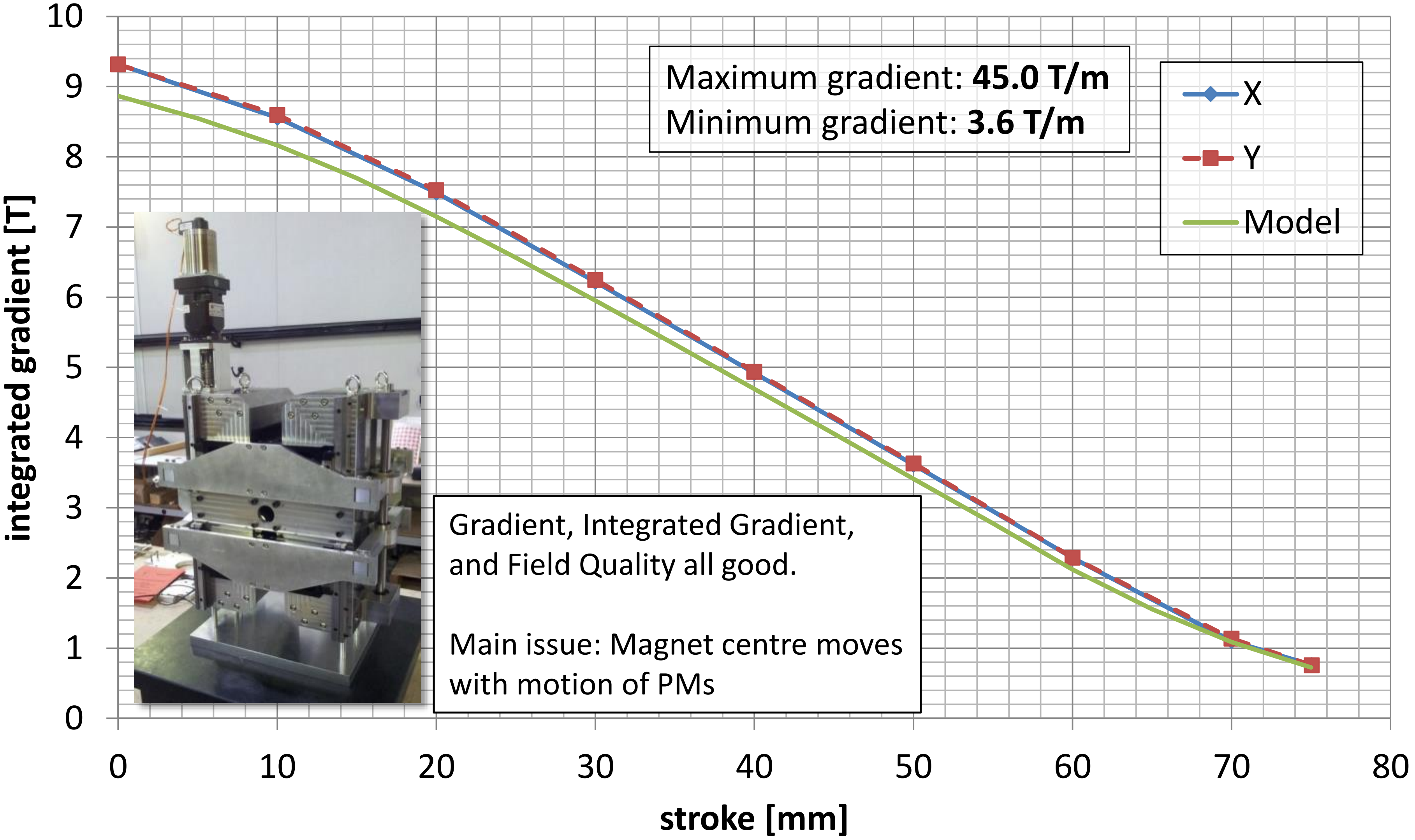




Stroke = 75 mm

Poles and outer shell are permanently fixed in place.

Low Energy Quad
Measured Integrated Gradient

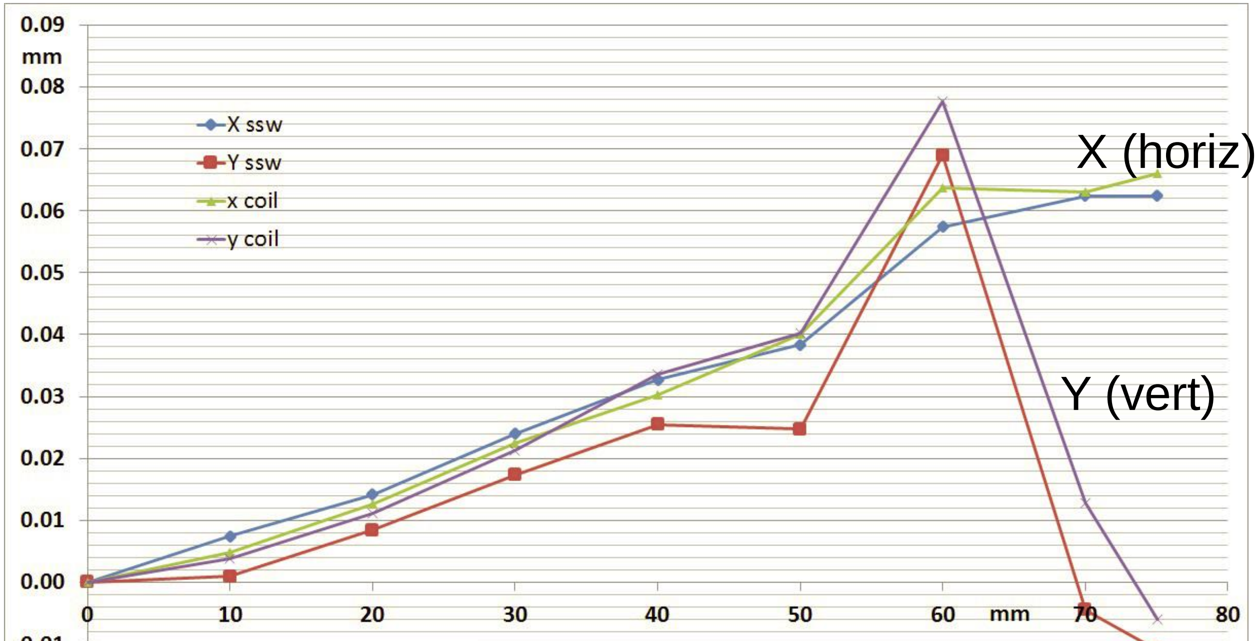


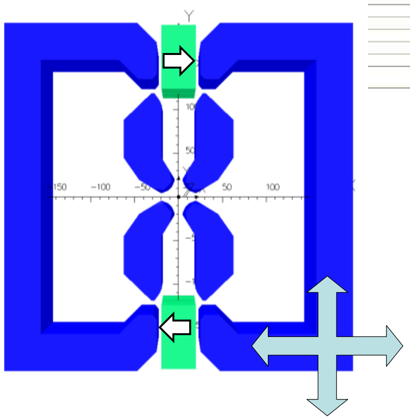
Maximum gradient: **45.0 T/m**
Minimum gradient: **3.6 T/m**

Gradient, Integrated Gradient, and Field Quality all good.

Main issue: Magnet centre moves with motion of PMs

Measured Axis Movement





- Good agreement between measurement methods
  - stretched wire
  - rotating coil
- X axis moves in one direction
  - Possible misalignment of outer shell?
- Y axis moves up and then back down
  - Harder to explain this…
- We believe this motion is a mechanical rather than a magnetic effect

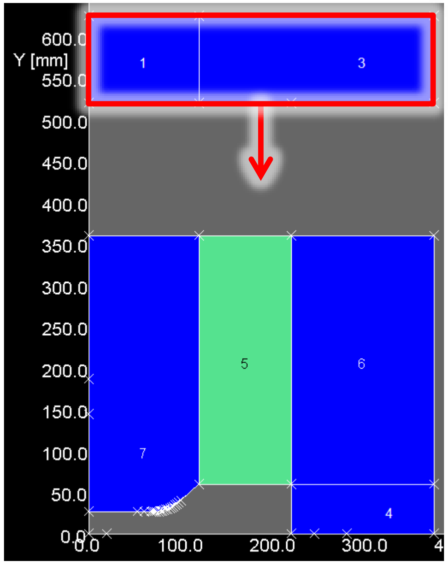
The magnet centre moves diagonally by up to **~100 µm** as the permanent magnets are moved away by 75mm

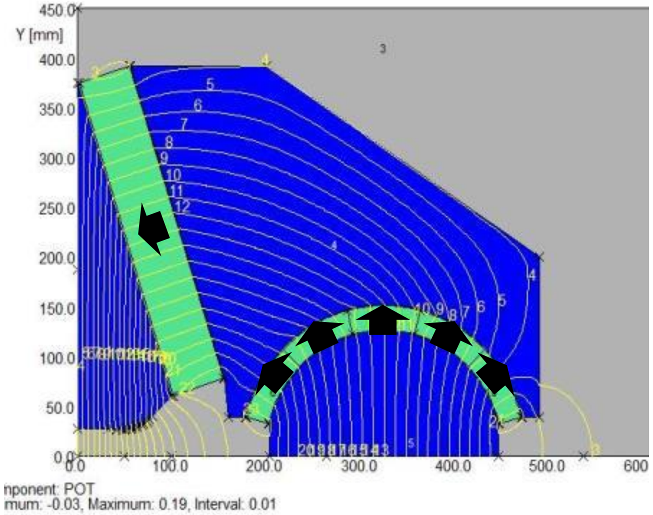
CLIC PM Dipoles

- Next we have investigated PM dipoles
  - Drive Beam Turn Around Loop (DB TAL)
  - Main Beam Ring to Main Linac (MB RTML)
- Total power consumed by both types: **15 MW**
- Several possible designs considered for DB TAL (the most challenging of the two test cases)

Type	Quantity	Length (m)	Strength (T)	Pole Gap (mm)	Good Field Region (mm)	Field Quality	Range (%)
MB RTML	666	2.0	0.5	30	20 x 20	1 x 10^{-4}	± 10
DB TAL	576	1.5	**1.6**	**53**	**40 x 40**	**1 x 10^{-4}**	**50–100**

(Some of the) Dipole Options Investigated

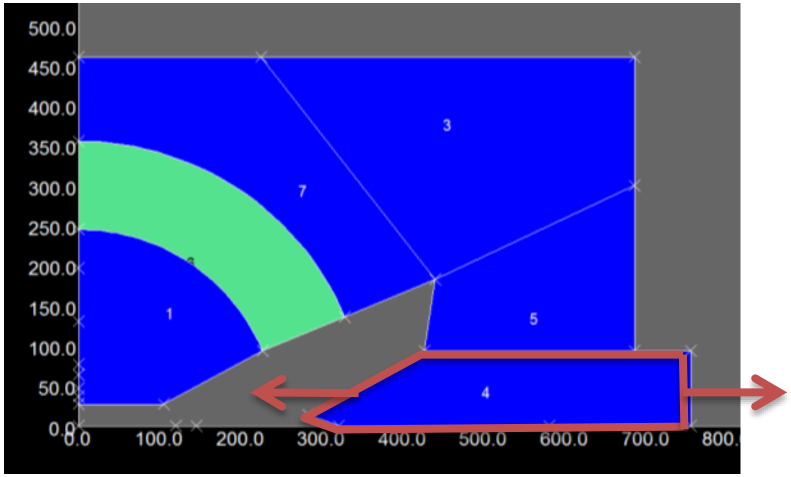




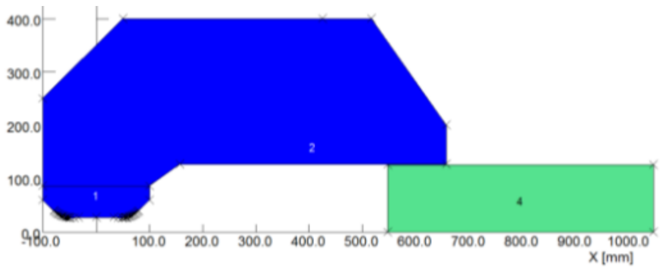
Tuning by rotating steel and PM assembly *→ Huge torque required*

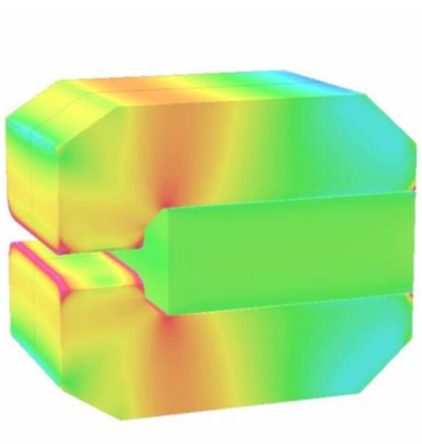
(Design from SPring-8 (Watanabe, IPAC'14)) Tuning by moving top plate *→ Huge vertical forces*

Tuning by moving steel plate to short circuit flux *→ Large forces and field quality concerns*



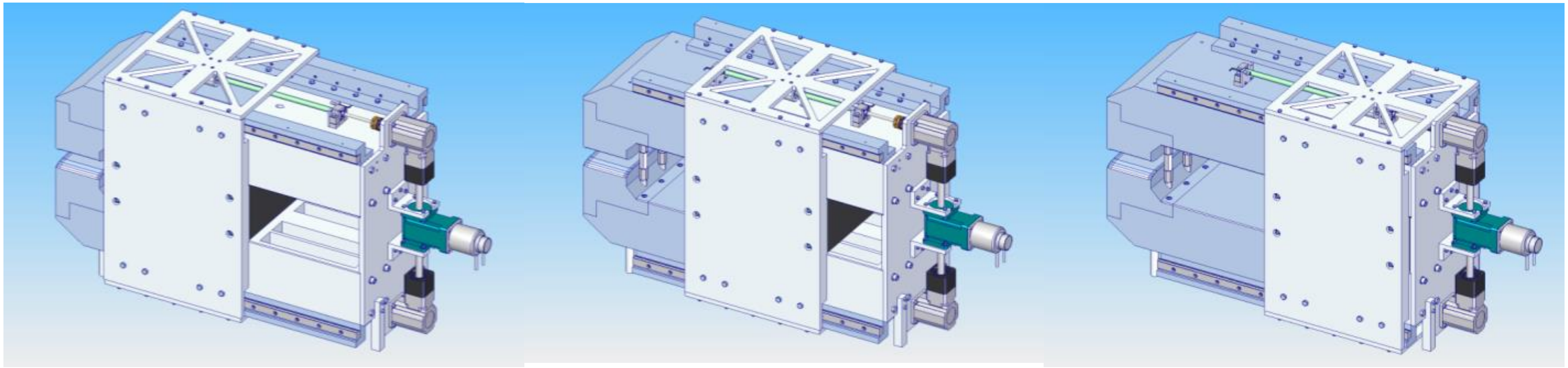
Selected Dipole Design





- *Sliding PM in backleg*
- *Similar to low energy DBQ*
- *Rectangular PM*
- *Forces manageable*
- *C – shape possible*
- *Curved poles (along beam arc) possible*
- *Wide*
- *Large stroke*

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



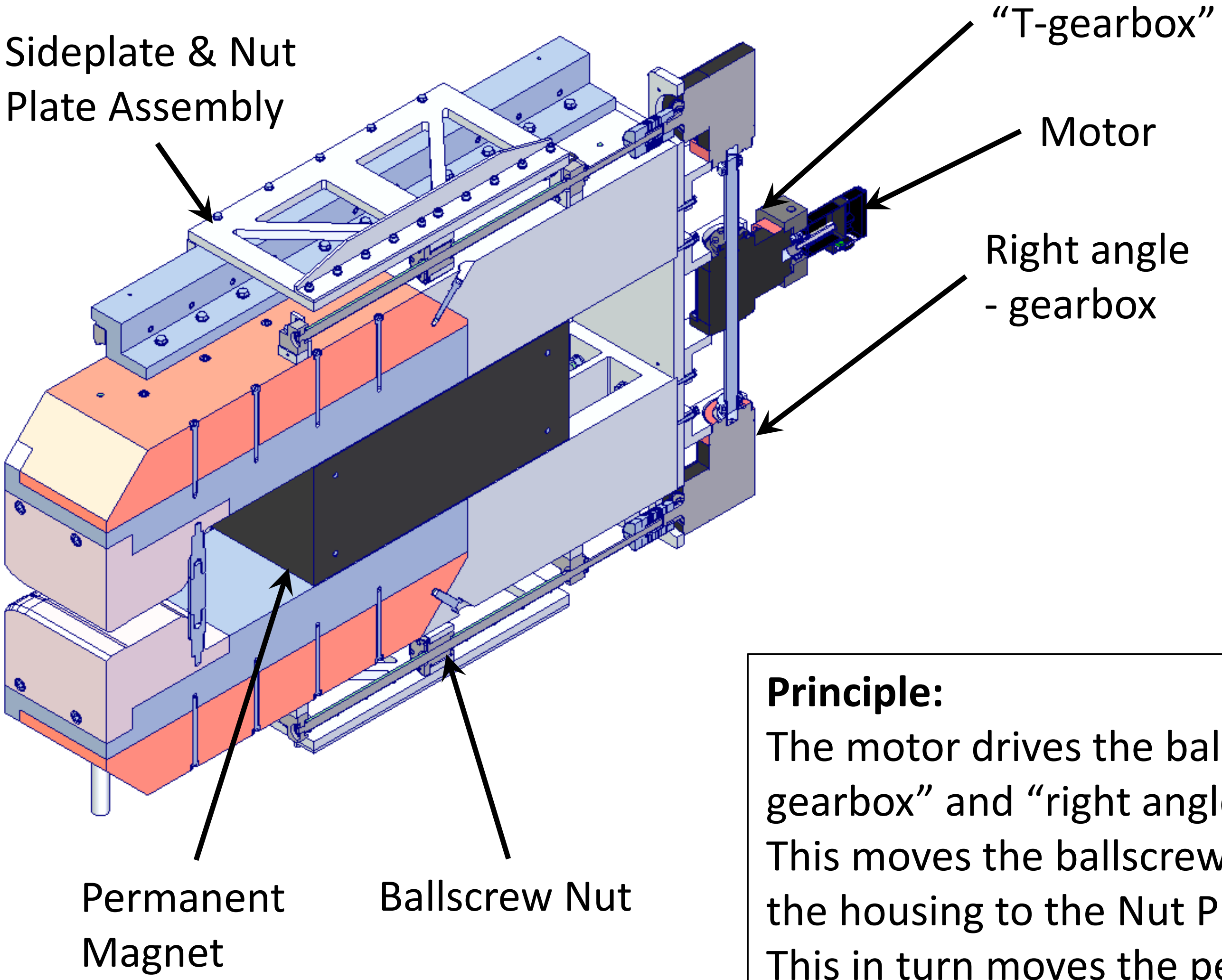
Dipole Prototype

- Original plan was to build a 0.5m version of full size DB TAL magnet
- However, *cost far exceeded* available budget (£100k)
- 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 have 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!

Prototype Dipole Overview

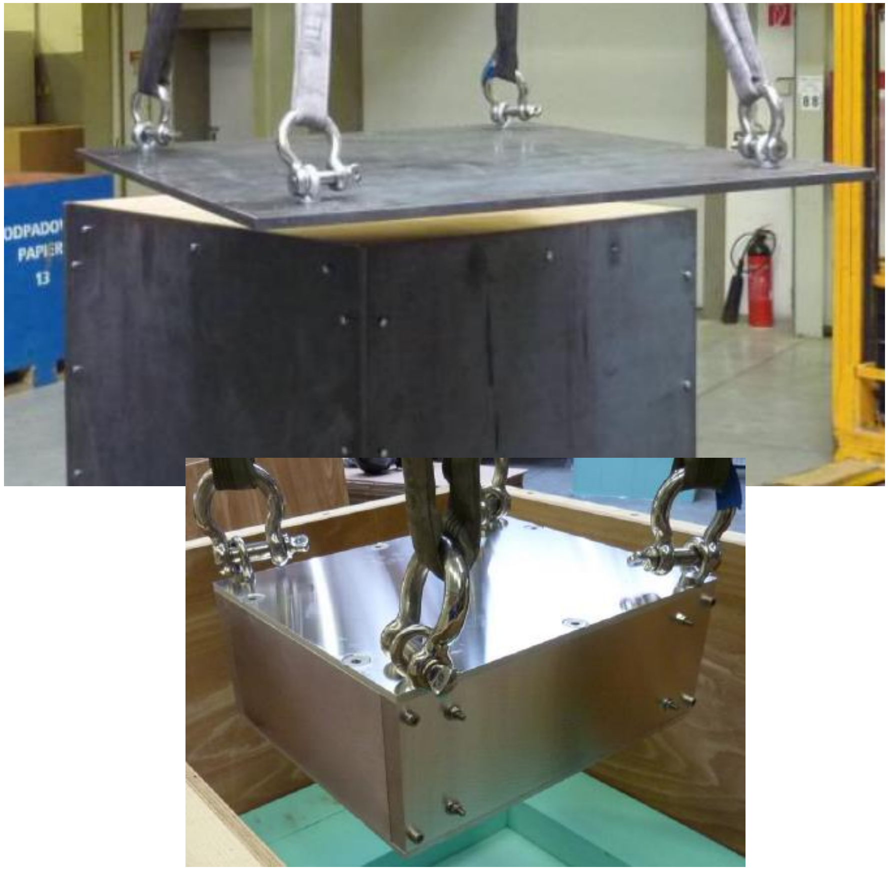


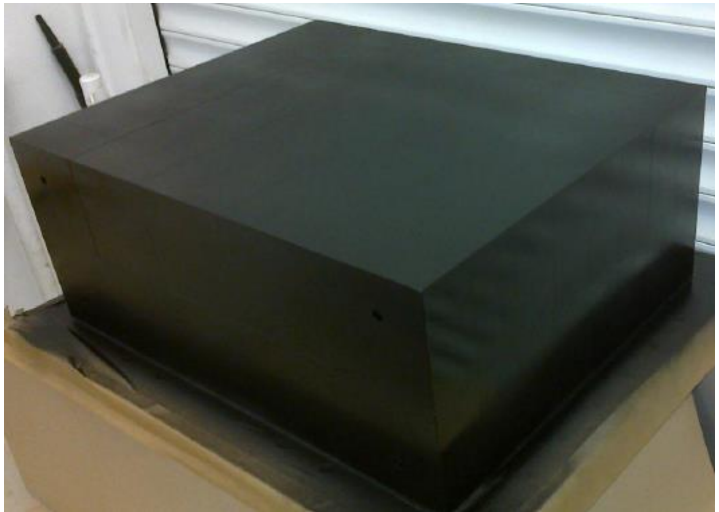
Section View

Principle:
The motor drives the ballscrews through a "T-gearbox" and "right angle gearbox".
This moves the ballscrew nut which is connected via the housing to the Nut Plate Assembly.
This in turn moves the permanent magnet via the PM side-plates.

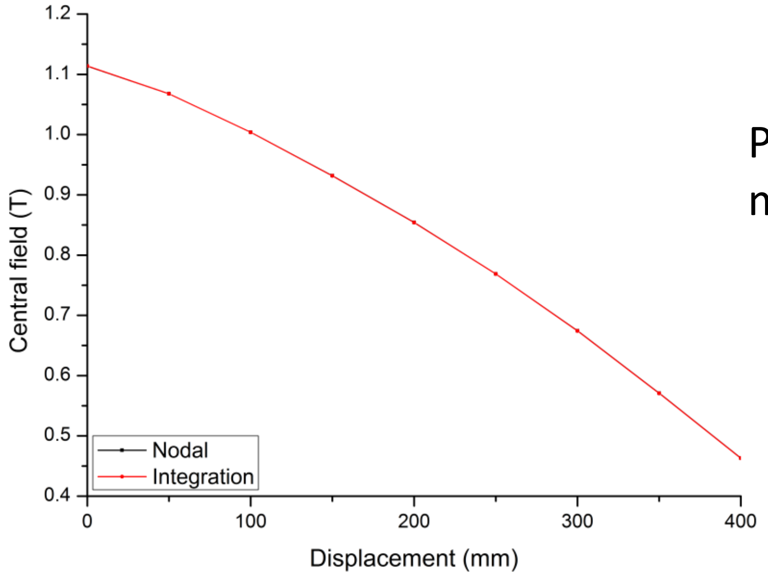
PM Block Details

- Manufactured, measured & delivered by Vacuumschmelze
- Magnet block dimensions are **500x400x200 mm**, with 4 holes on 400mm axis for mounting tie rods.
- Magnet material **NdFeB, Vacodym 745TP (Br 1.38T)**
- Constructed from 80 (large!) individual blocks glued together (100x50x100mm)



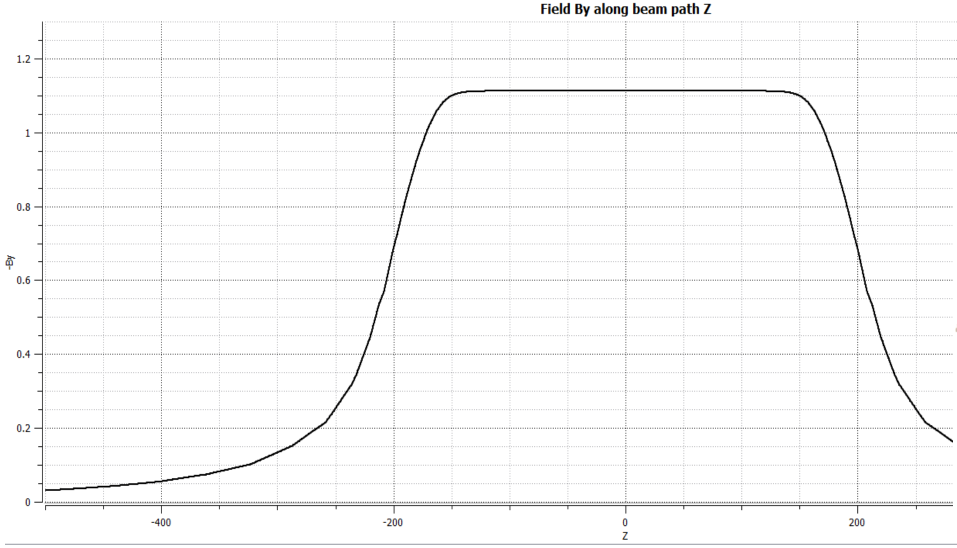


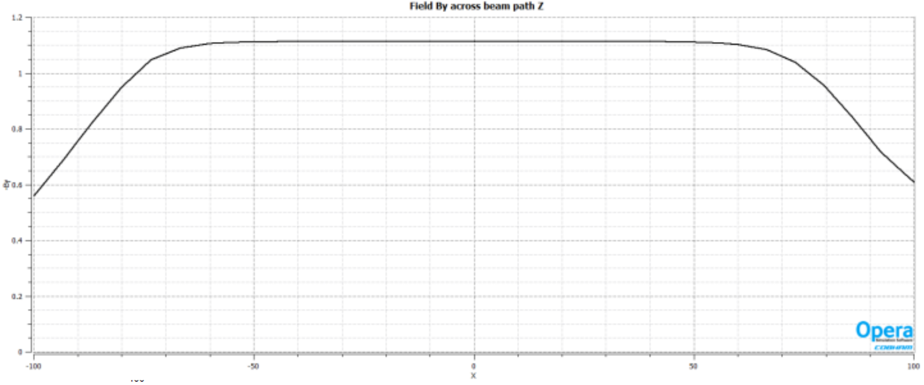
Predicted Field Strength



Peak field 1.11 T with field reducing to 50% at magnet retraction of approximately 370 mm

Field is uniform along the beam path and transverse to it

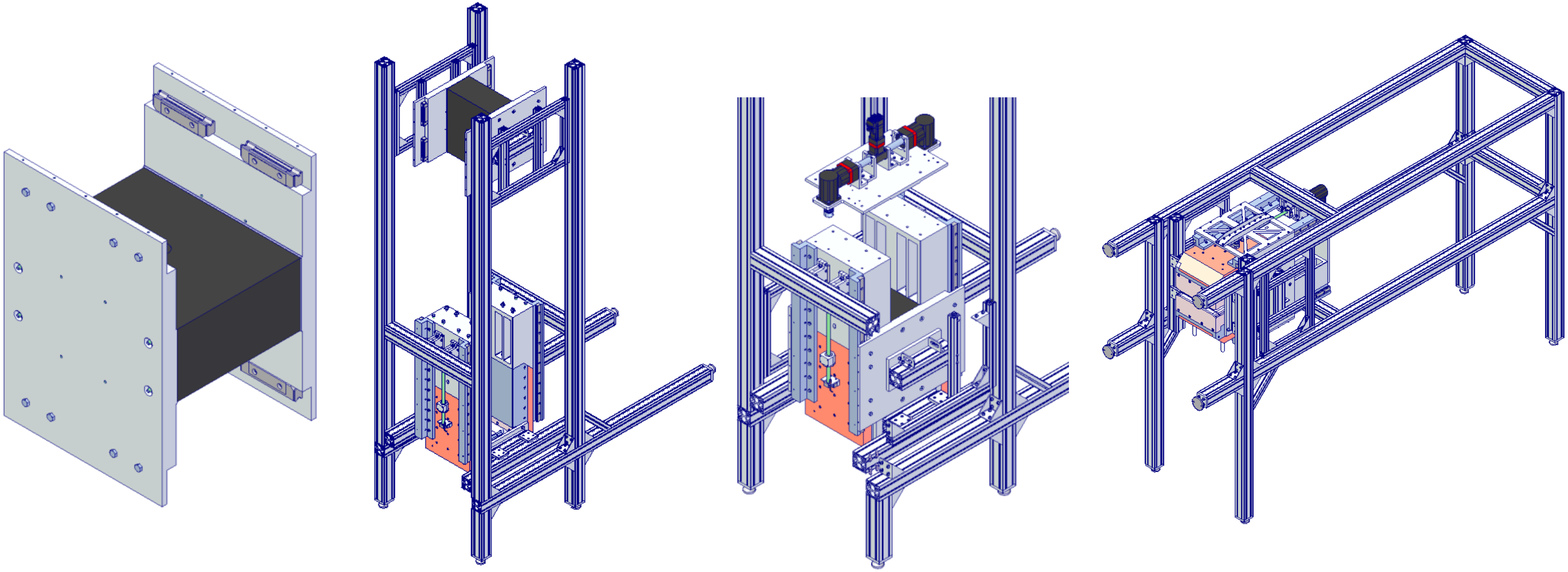




Prototype Progress

- All externally procured items have been delivered
- Assembly area being prepared (non-trivial) – specific safety training has been given to all staff involved
- Assembly anticipated to be complete by early March 2017
- Measurements (at DL only) and Report to follow immediately afterwards

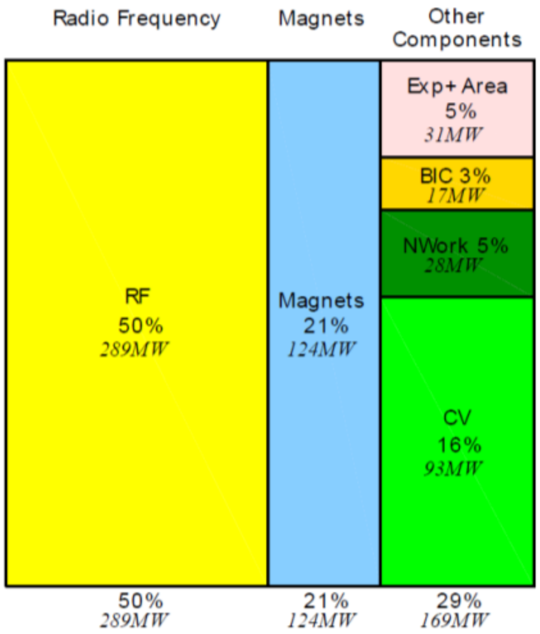
Assembly Sequence



Future Work

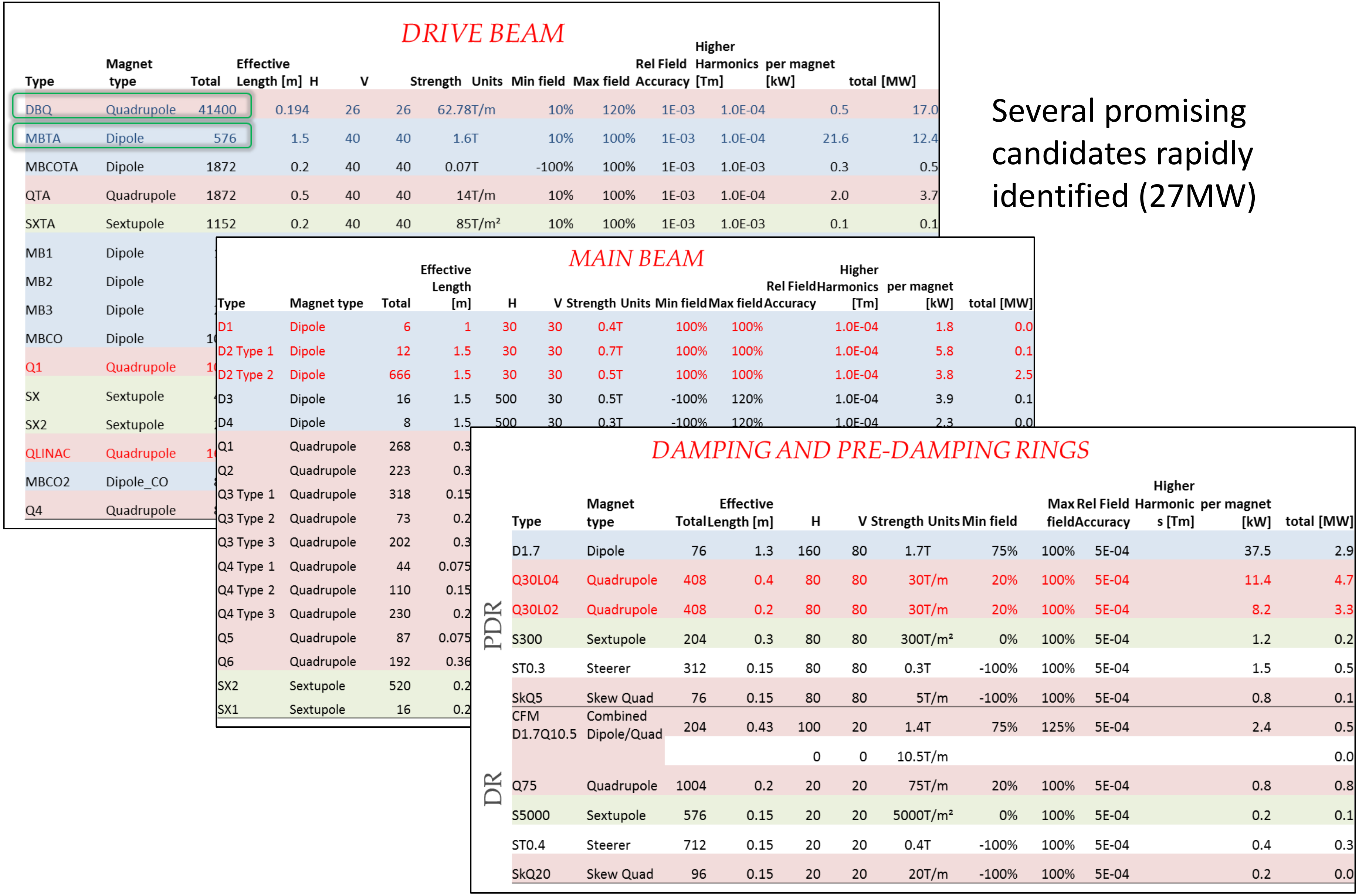
CLIC Accelerator Study – Report from the 2016 Review Panel

- "For the ESU [European Strategy Update], priority should be given only to developments aimed at cost and power reduction; an example are the permanent magnet quadrupoles that can potentially provide a 10% power reduction if implemented generally for the CLIC magnets. The Panel was however surprised of their high cost related to the complex design required for field adjustment and encourages the CLIC team in looking for simpler designs, involving both beam dynamics experts and magnet designers."



Power consumption by technical systems for CLIC 3 TeV

Quick Assessment May 2016



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												
MB2	Dipole												
MB3	Dipole												
MBCO	Dipole												
Q1	Quadrupole												
SX	Sextupole												
SX2	Sextupole												
QLINAC	Quadrupole												
MBCO2	Dipole_CO												
Q4	Quadrupole												

MAIN BEAM

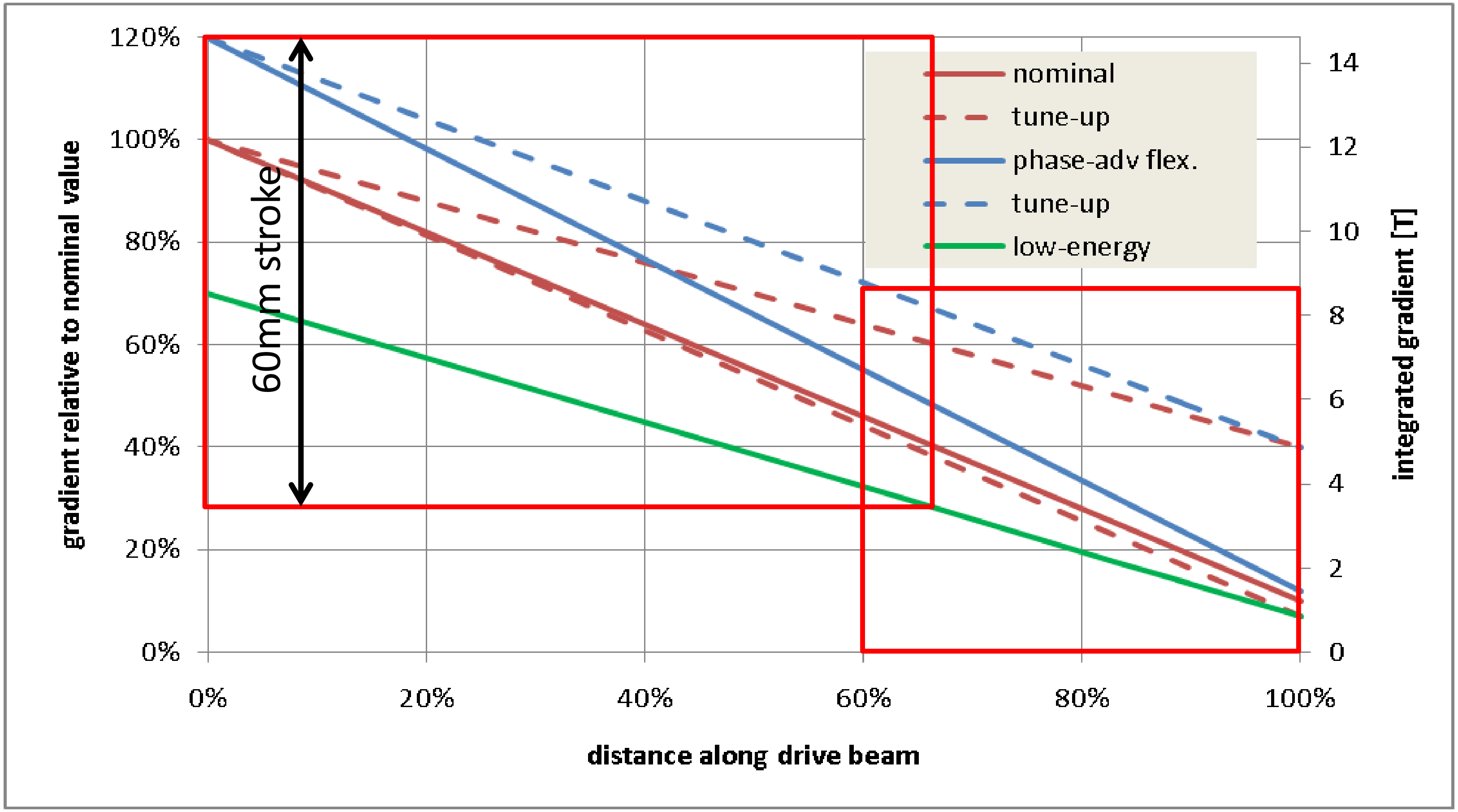
Type	Magnet type	Total	Effective Length [m]	H	V	Strength	Units	Min field	Max field	Rel Field Accuracy	Higher Harmonics [Tm]	per magnet [kW]	total [MW]
D1	Dipole	6	1	30	30	0.4T		100%	100%		1.0E-04	1.8	0.0
D2 Type 1	Dipole	12	1.5	30	30	0.7T		100%	100%		1.0E-04	5.8	0.1
D2 Type 2	Dipole	666	1.5	30	30	0.5T		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										
Q2	Quadrupole	223	0.3										
Q3 Type 1	Quadrupole	318	0.15										
Q3 Type 2	Quadrupole	73	0.2										
Q3 Type 3	Quadrupole	202	0.3										
Q4 Type 1	Quadrupole	44	0.075										
Q4 Type 2	Quadrupole	110	0.15										
Q4 Type 3	Quadrupole	230	0.2										
Q5	Quadrupole	87	0.075										
Q6	Quadrupole	192	0.36										
SX2	Sextupole	520	0.2										
SX1	Sextupole	16	0.2										

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]
PDR	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/m²		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
DR	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/m²		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

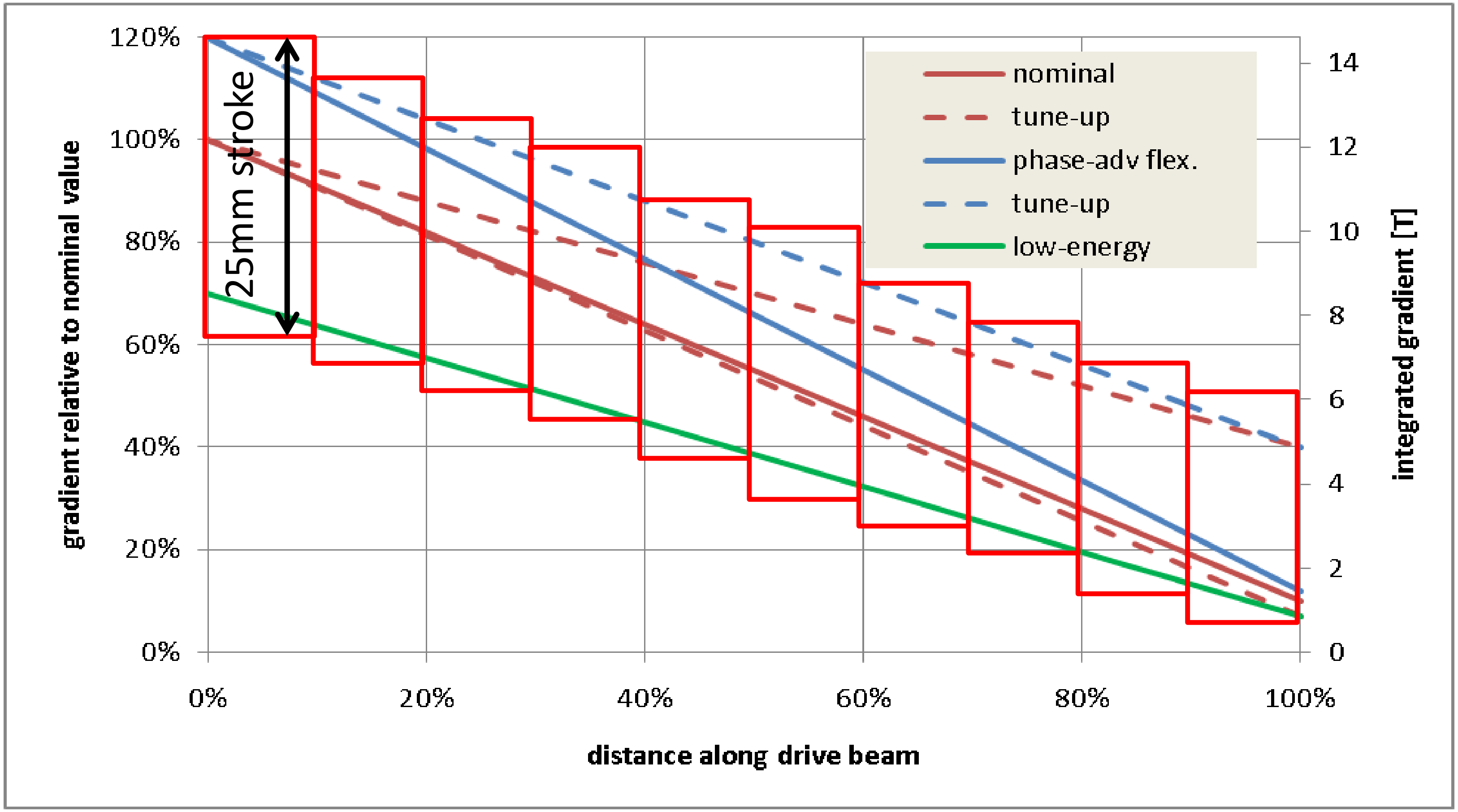
Several promising candidates rapidly identified (27MW)

Example Cost Reduction



Wide tuneability is expensive – better to limit tuneability

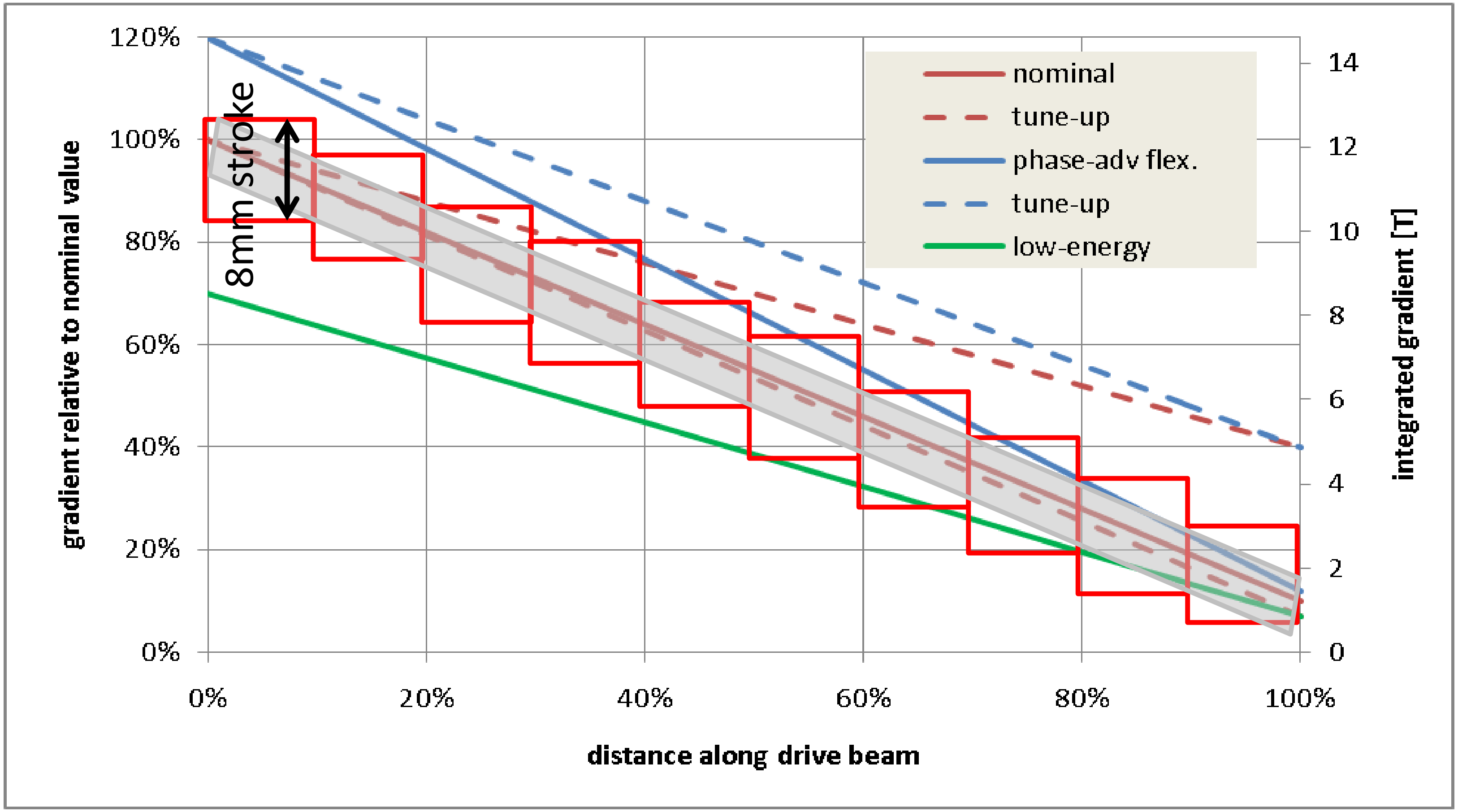
Example Cost Reduction



Reduced range of motion will help significantly – magnets can be modular – same intrinsic design but with different PM block sizes for example.

Magnet centre motion will reduce accordingly (though we would expect to fix this anyway!)

Example Cost Reduction



Restricting the beam requirements will have a big impact – need to iterate with beam dynamics/lattice designers

Future Work Proposal

Paper Studies for Cost and Power Reductions:

- Explore ***procurement cost reduction*** options for PMs
  - Simplification of design
  - “Modular” solutions
  - Reduced motion requirements
  - Reduced PM material volumes
  - Specification iteration with lattice designers
- Explore wider applicability of PM quads & dipoles across CLIC for ***operational cost and power reductions***
  - Work with lattice designers, providing guidance on PM feasibility, to optimise baseline – tweak lattice to suit PMs?
  - Assess **new magnet table** and select suitable magnet families for PM magnetic & mechanical assessment
    - Confirm cost and feasibility based upon current solutions
- Question: Which option of CLIC should we focus on?

Resources

Two year paper study

- CERN Request
  - 18 months of effort (£150k)
    - 12 months engineer
    - 6 months magnet designer
  - Travel (£5k)
  - **Total £155k**
- STFC Funded
  - 9 months of effort (£75k)
    - 3 months engineer
    - 6 months magnet designer
  - **Total £75k**