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ZEPTO – Zero Power Tuneable Optics: Permanent Magnet Quadrupoles and Dipoles for CLIC

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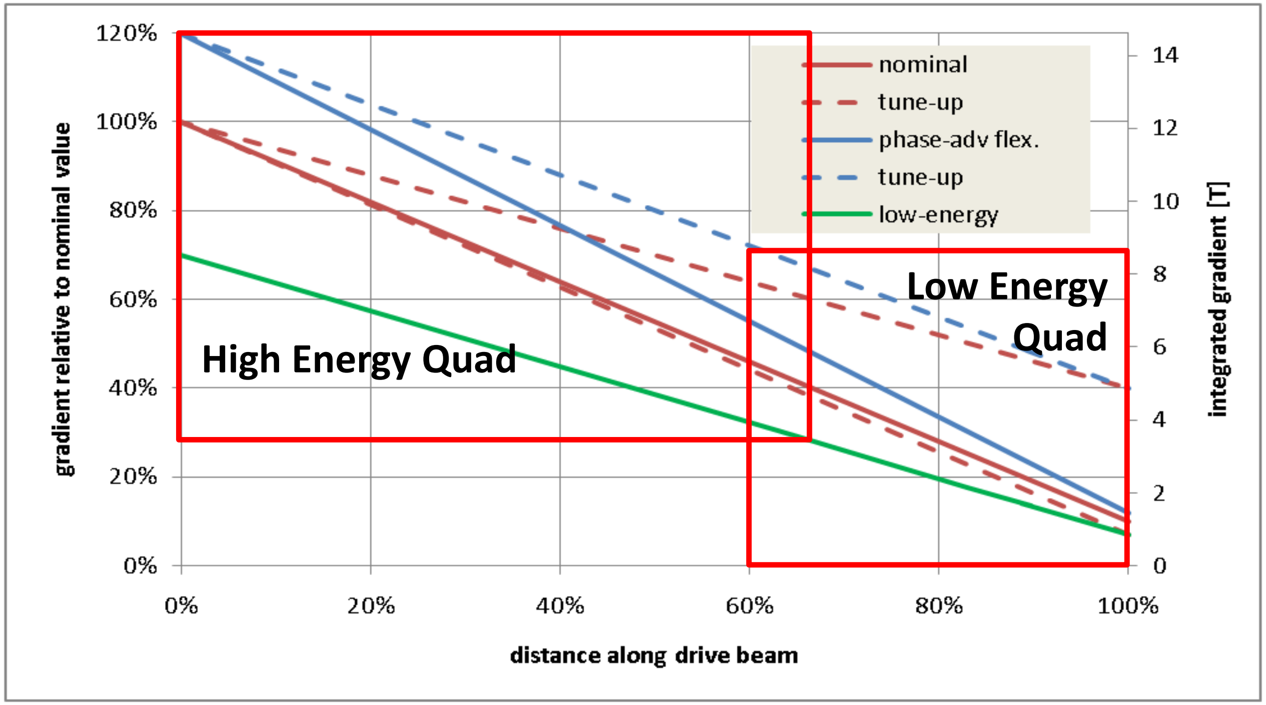
on behalf of Alex Bainbridge, Norbert Collomb, Ben Shepherd, (STFC Daresbury Laboratory) and Michele Modena (CERN)

10th Feb 2017, CLIC Implementation Meeting

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

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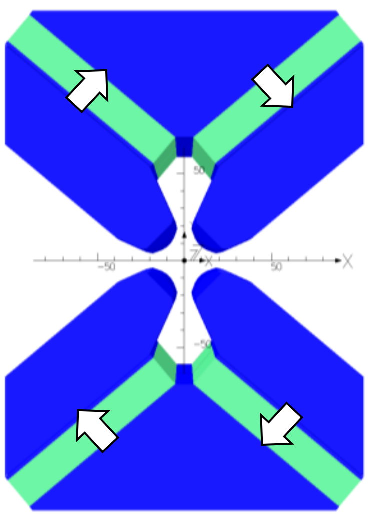
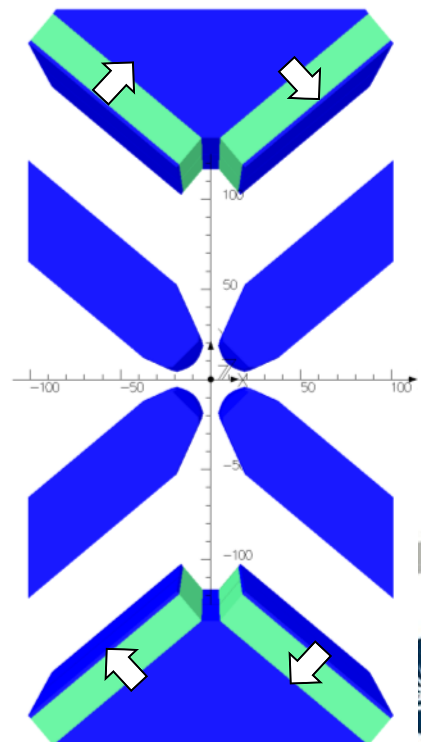
High Energy Quad Design

- **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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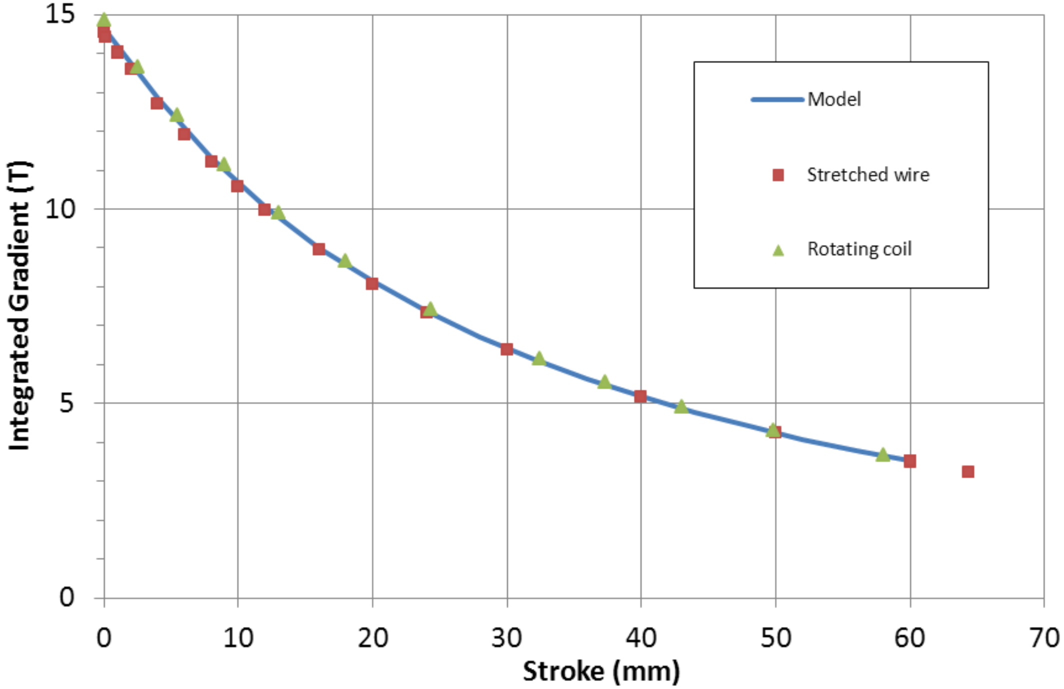
High Energy Quad
Measured Integrated Gradient



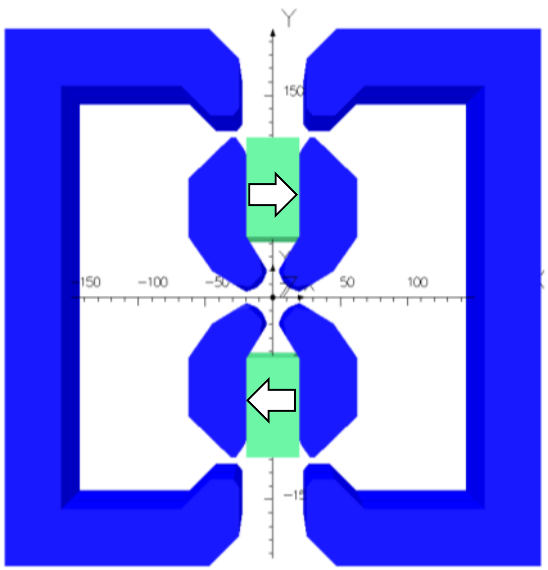
Gradient, Integrated Gradient, and Field Quality all good.

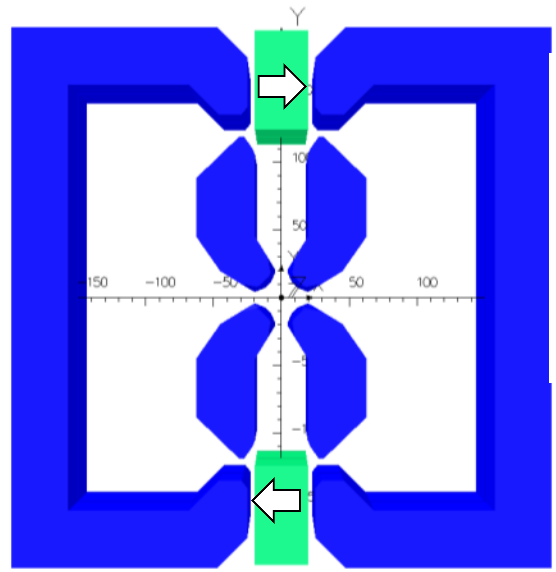
Main issue: Magnet centre moves with motion of PMs

Low Energy Quad Design

- Lower strength easier but requires **much larger tunability range (x12)**
- 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

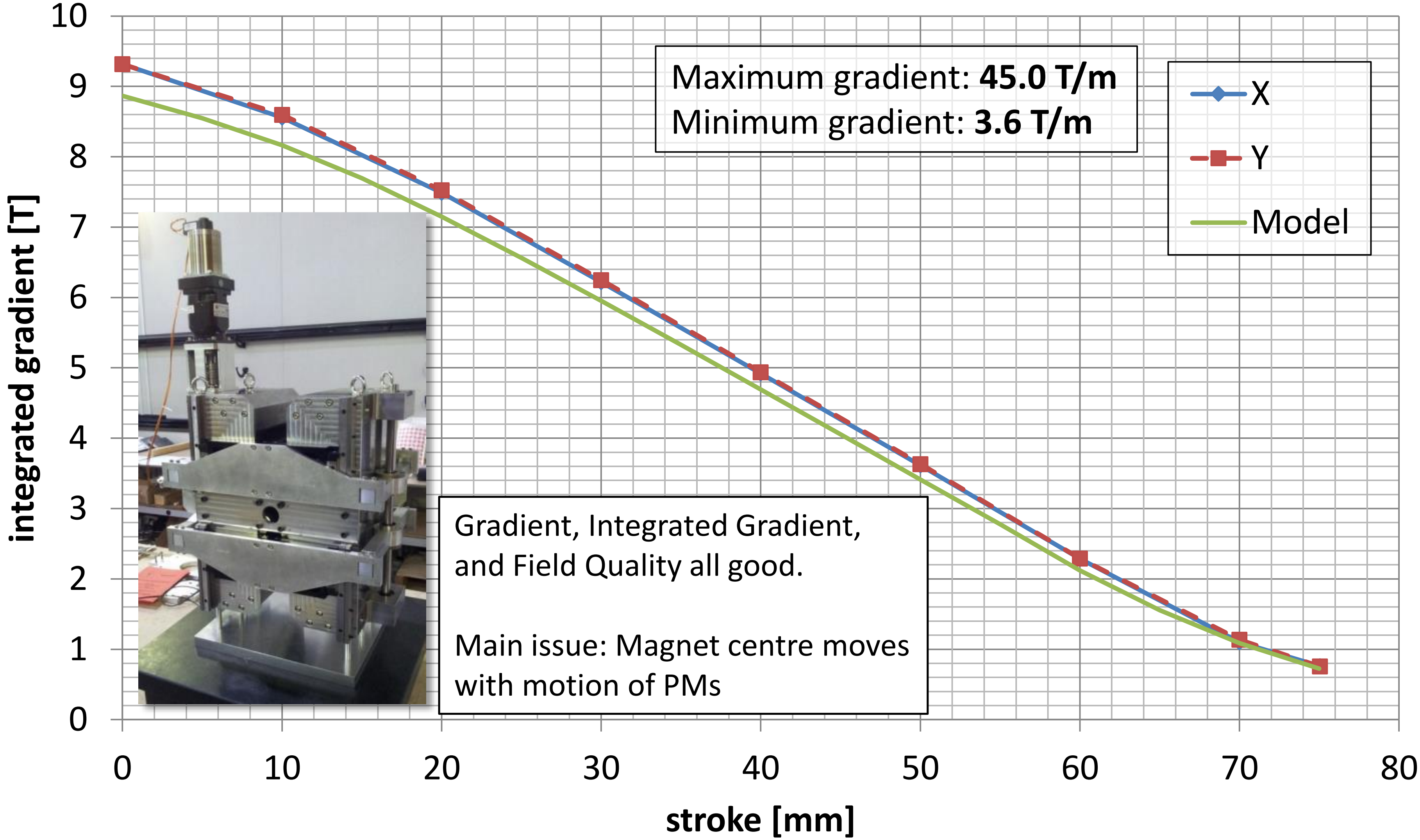




Stroke = 75 mm

Poles and outer shell are permanently fixed in place.

Low Energy Quad
Measured Integrated Gradient

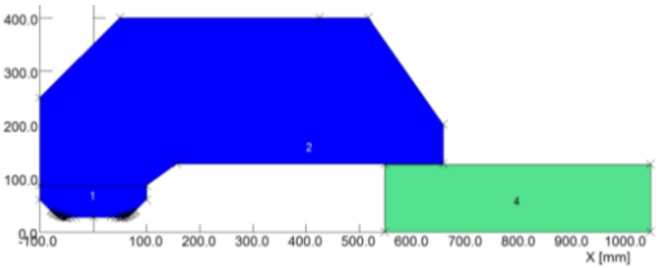


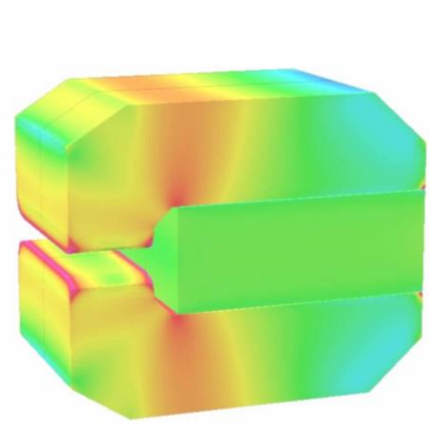
CLIC PM Dipoles

- 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	1×10^{-4}	± 10
DB TAL	576	1.5	**1.6**	**53**	**40 x 40**	**1×10^{-4}**	**50–100**

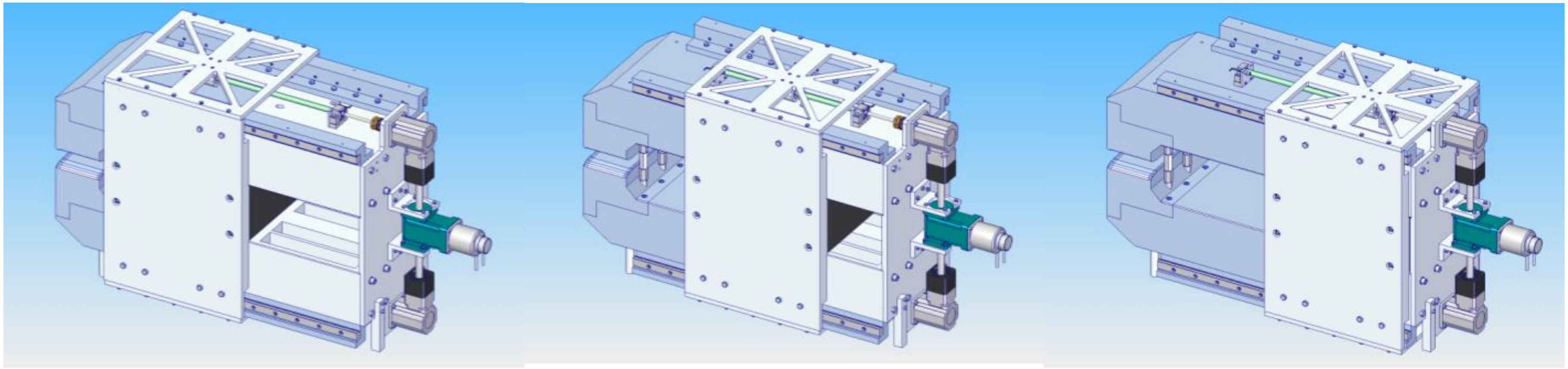
Selected Dipole Design





- *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.



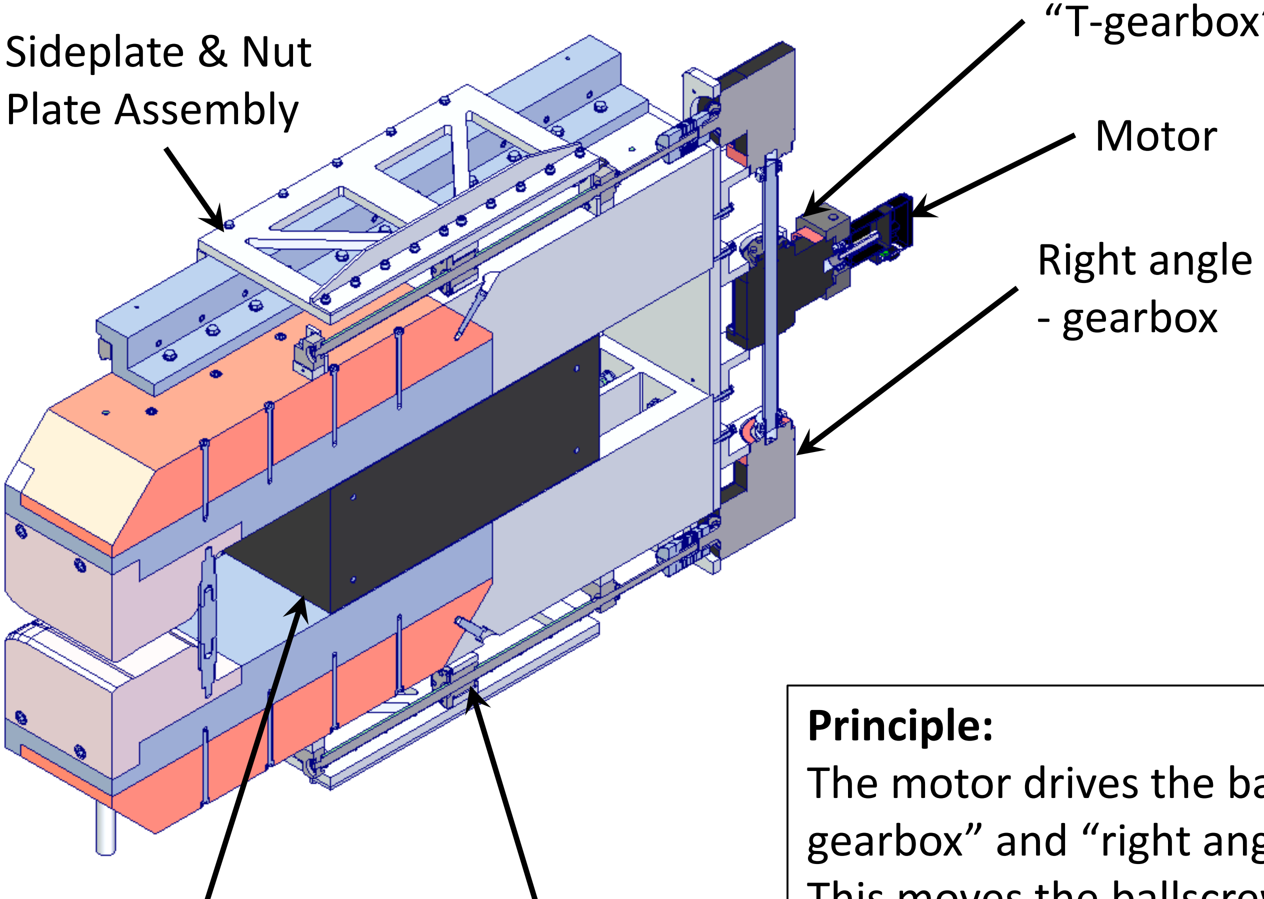
Dipole Prototype

- Original plan was to build a 0.5m version of full size DB TAL magnet
- However, *cost 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 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

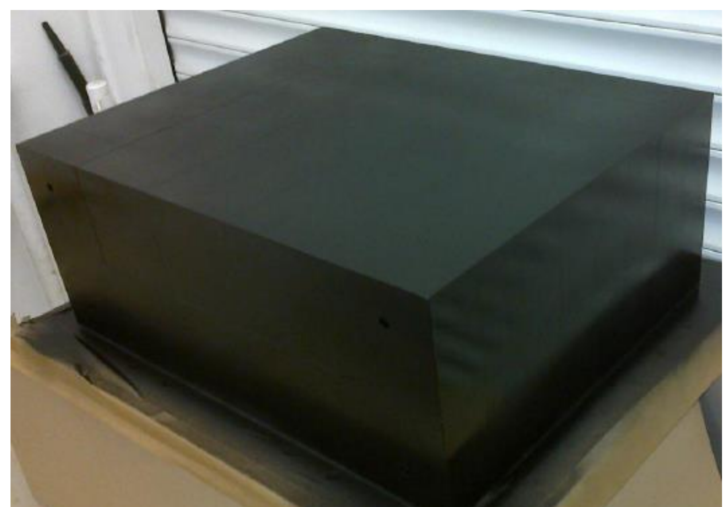


Principle:
The motor drives the ballscrews through a "T-gearbox" and "right angle gearbox".
This moves the ballscrew nut which is connected via the housing to the Nut Plate Assembly.
This in turn moves the permanent magnet via the PM side-plates.

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 (each 100x50x100mm)
- World's largest ever NdFeB PM block?

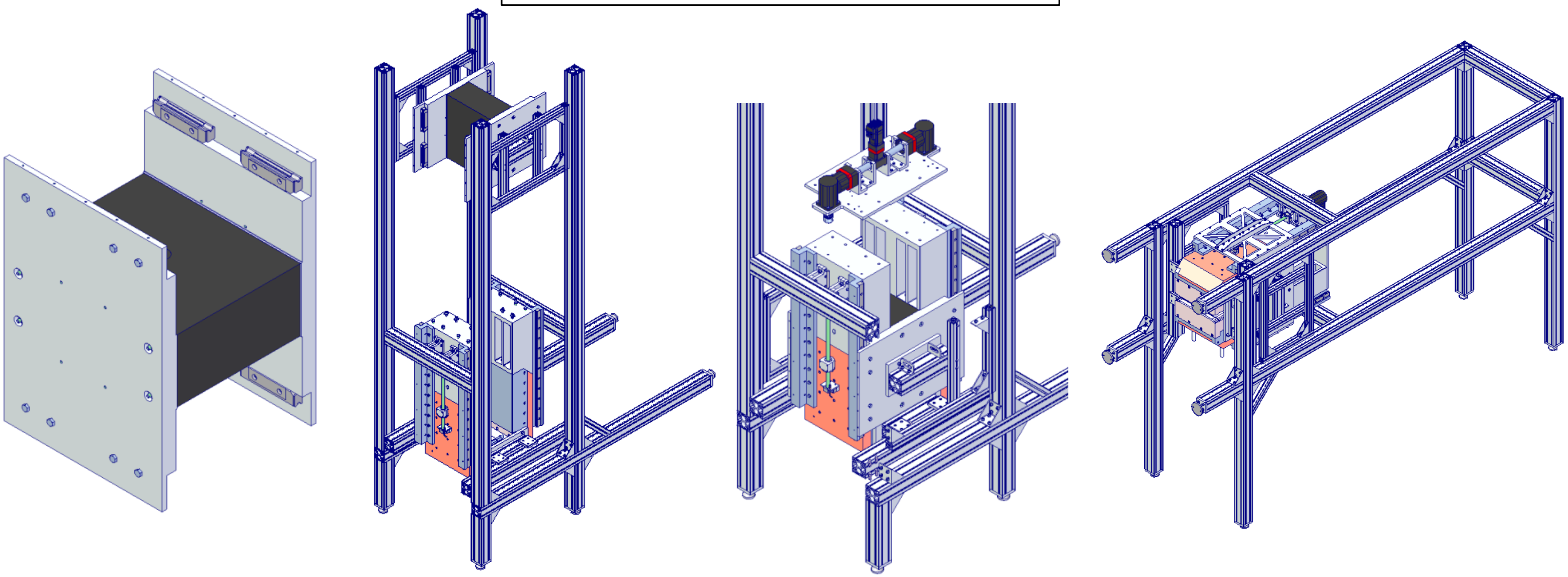


Prototype Progress

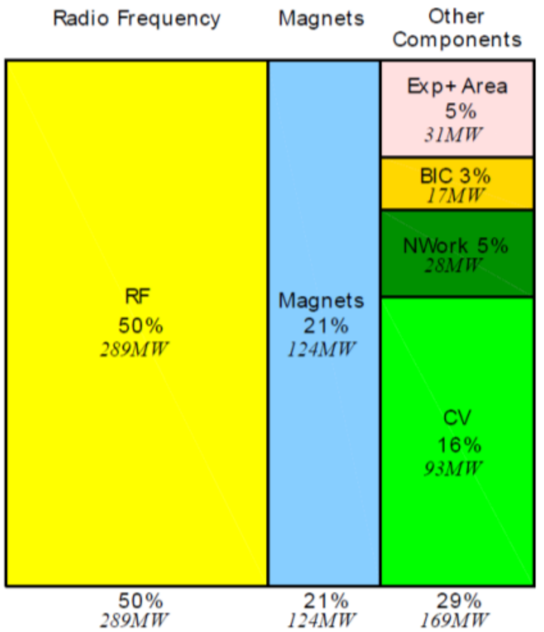
- All externally procured items have been delivered
- Assembly area prepared (non-trivial) – specific safety training has been given to all staff involved
- Assembly anticipated to be complete by early March 2017
- Measurements (at DL only) and Report to follow immediately afterwards

Assembly Sequence



Next Steps

- Work with CLIC beam dynamics team to maximise benefit of PM magnets – starting today!
- Assess which other magnet families within 380GeV CLIC could be PM based to reduce the overall cost and power demand
- Optimise current quad designs to minimise capital cost



Power consumption by technical systems for CLIC 3 TeV

Quick Assessment May 2016

Several promising candidates rapidly identified (another 28MW)

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	62.78	T/m	10%	120%	1E-03	1.0E-04	0.5	17.0
MBTA	Dipole	576	1.5	40	40	1.6	T	10%	100%	1E-03	1.0E-04	21.6	12.4
MBCOTA	Dipole	1872	0.2	40	40	0.07	T	-100%	100%	1E-03	1.0E-03	0.3	0.5
QTA	Quadrupole	1872	0.5	40	40	14	T/m	10%	100%	1E-03	1.0E-04	2.0	3.7
SXTA	Sextupole	1152	0.2	40	40	85	T/m^2	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												

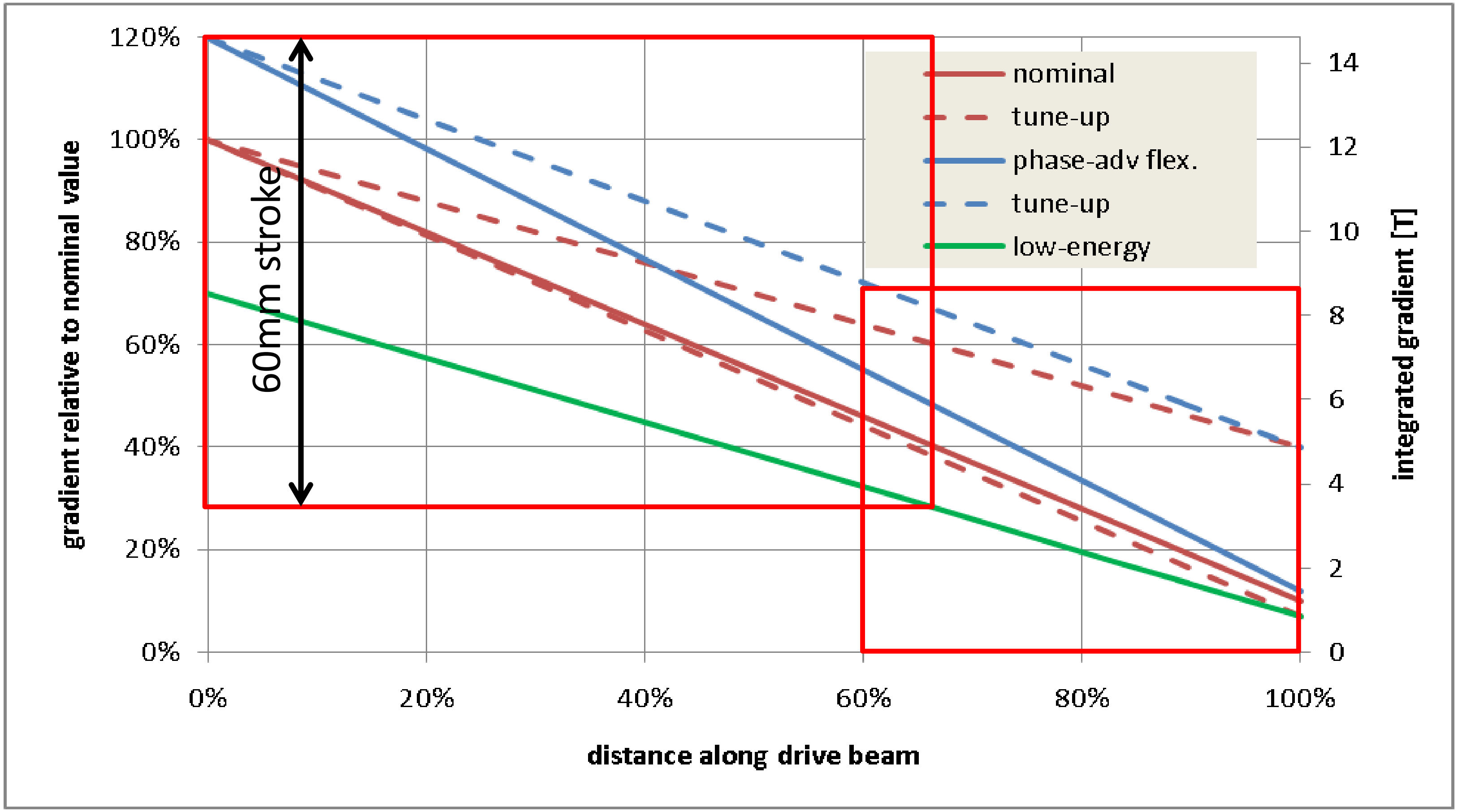
MAIN BEAM

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	0.4	T	100%	100%		1.0E-04	1.8	0.0
D2 Type 1	Dipole	12	1.5	30	30	0.7	T	100%	100%		1.0E-04	5.8	0.1
D2 Type 2	Dipole	666	1.5	30	30	0.5	T	100%	100%		1.0E-04	3.8	2.5
D3	Dipole	16	1.5	500	30	0.5	T	-100%	120%		1.0E-04	3.9	0.1
D4	Dipole	8	1.5	500	30	0.3	T	-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

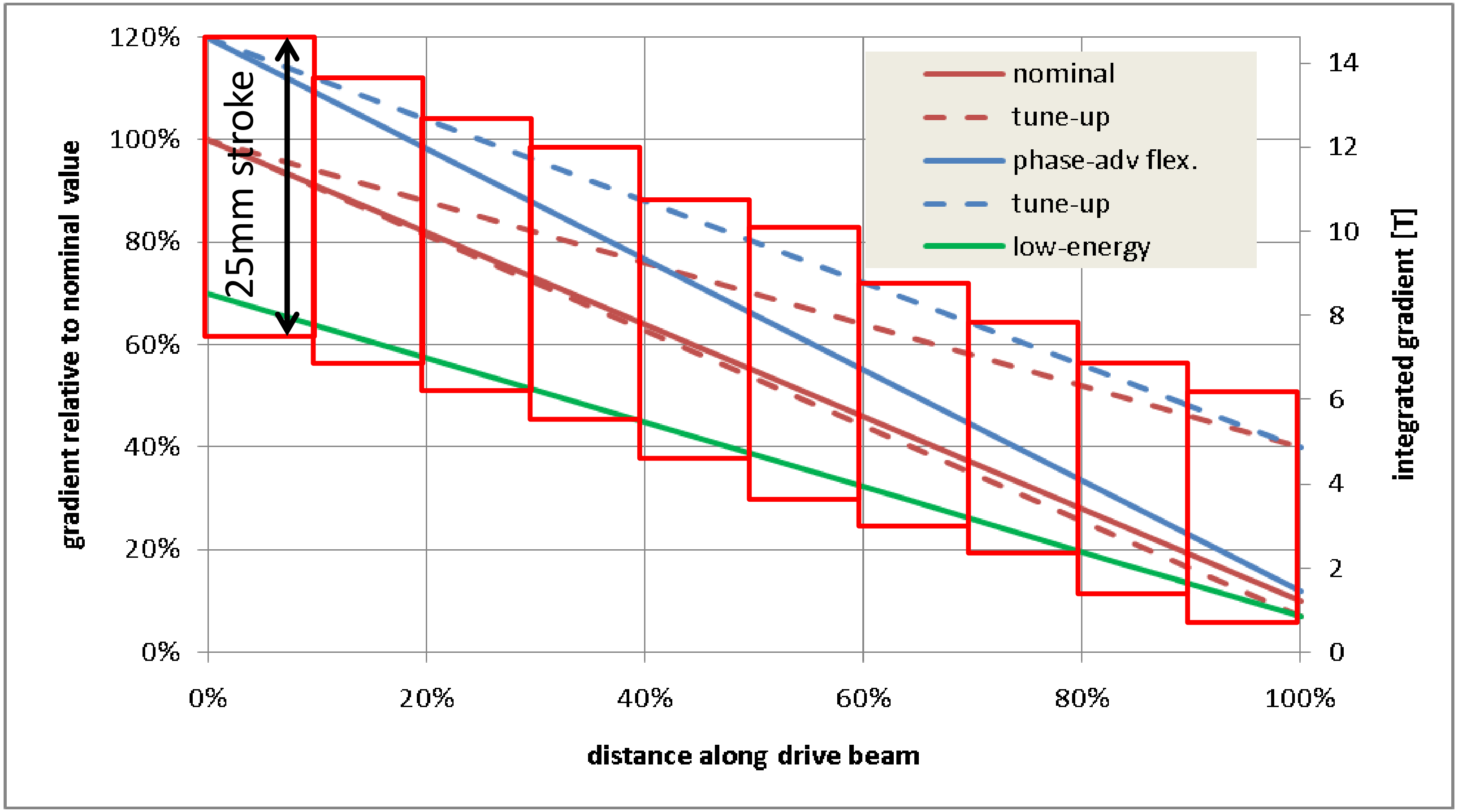
Ring	Type	Magnet type	Total	Effective Length [m]	H	V	Strength	Units	Min field	Max field	Rel Field Accuracy	Higher Harmonics [Tm]	per magnet [kW]	total [MW]
PDR	D1.7	Dipole	76	1.3	160	80	1.7	T	75%	100%	5E-04		37.5	2.9
PDR	Q30L04	Quadrupole	408	0.4	80	80	30	T/m	20%	100%	5E-04		11.4	4.7
PDR	Q30L02	Quadrupole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

Example Cost Reduction



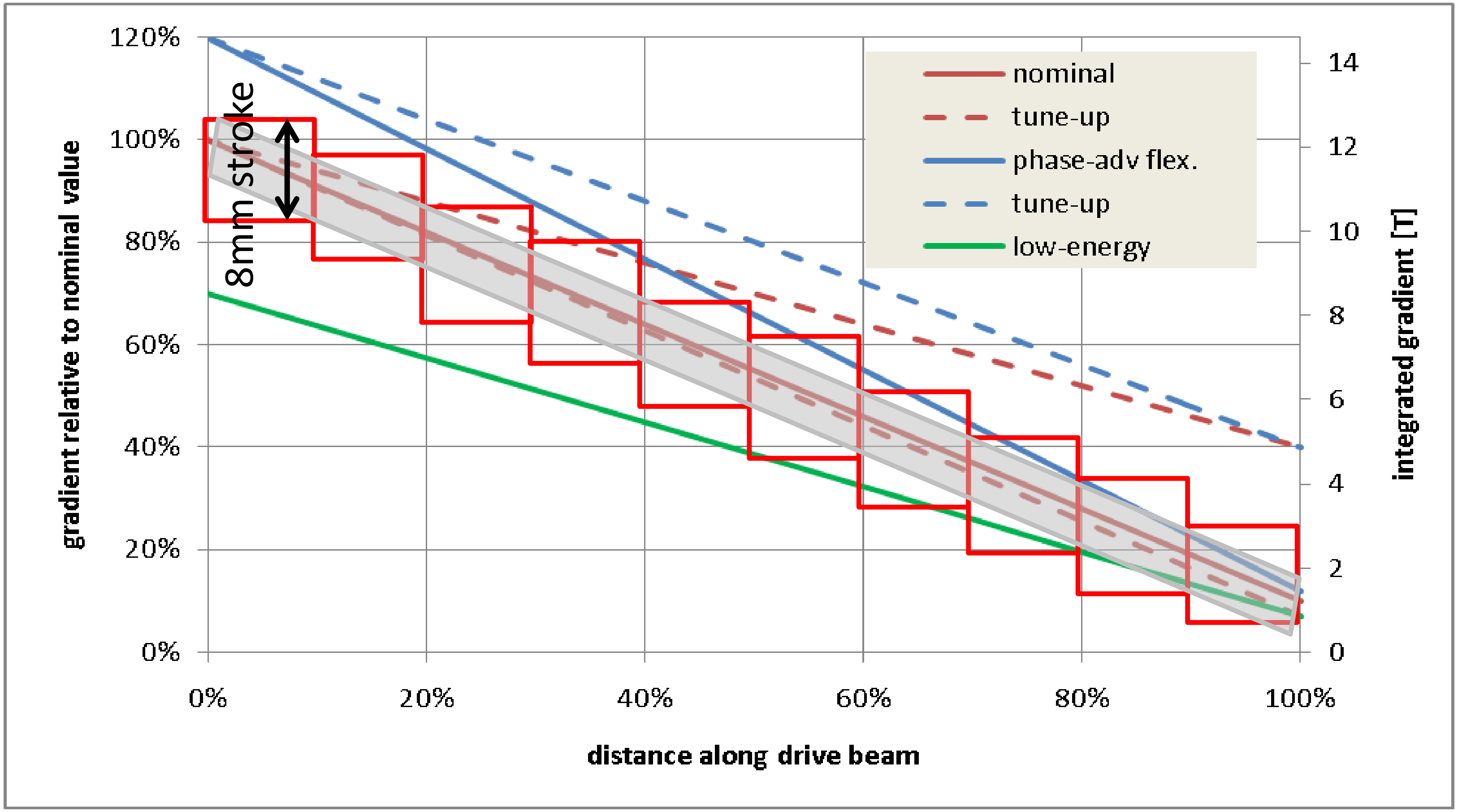
Wide tuneability is expensive – better to limit tuneability

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.

Example Cost Reduction



Restricting the beam requirements will have a big impact

Quad Comments

- ***Quad procurement cost reduction drivers***
  - Simplification of design
  - "Modular" solutions
  - **Reduced tuning ranges** (motion requirements) – e.g. ~8 to 100% has been demonstrated but ~80 to ~100% will allow simpler & cheaper motion system
  - Reduced PM material volumes or cheaper material
  - More relaxed space constraints
  - Reduced magnet aperture, gradient, magnetic length
- PM Quads are generally applicable across CLIC and minimising the requested tuning range will help significantly!

Dipole Comments

- ***Dipole procurement cost reduction drivers***
  - Simplification of design, reduction in forces
  - **Reduced tuning ranges** (motion requirements) – e.g. ~50 to 100% looks just about feasible but ~90 to 100% will be much simpler, cheaper, and more practical to implement
  - Reduced PM material volumes or cheaper materials
  - Reduced magnet aperture, field, magnetic length
- PM Dipoles are much less applicable generally, fixed field straightforward, even modest tuneability (e.g. ~90 to 100%) is difficult.
- Long (e.g. 2m) versions would priobably have to be multiple short versions.
- ***Possible*** "Hybrid" solution?
  - Combination of fixed field PM & tuneable EM dipoles?