Powered Magnets, DB Formation and Decelerator

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International Workshop on Linear Colliders 18-22 October 2010

Outline

1. Drive Beam Linac Quadrupole
   – Requirements and constraints
   – Initial design
   – The new “long yoke” proposal
   – Magnetic field calculations
   – Field quality
   – Conclusions
2. Drive Beam magnets for Delay line, Combiner rings, Turn-around, Transport to tunnel, Long transfer line and injector linac
   – Preliminary electromagnetic design
   – Cost estimate
   – Conclusions

CLIC Drive Beam Quadrupole DBQ

> 40’000 quadrupole magnets along the Drive beam linacs required

The beam energy decrease requires variation of integrated field gradient in the range between 12.18 T (“Nominal value” at the starting of the Decelerator, high energy side) and 1.218 T(10% of nominal, at the end, low energy side)

“Ultimate” strength for high energy side: 14.6[T] -120% of nominal

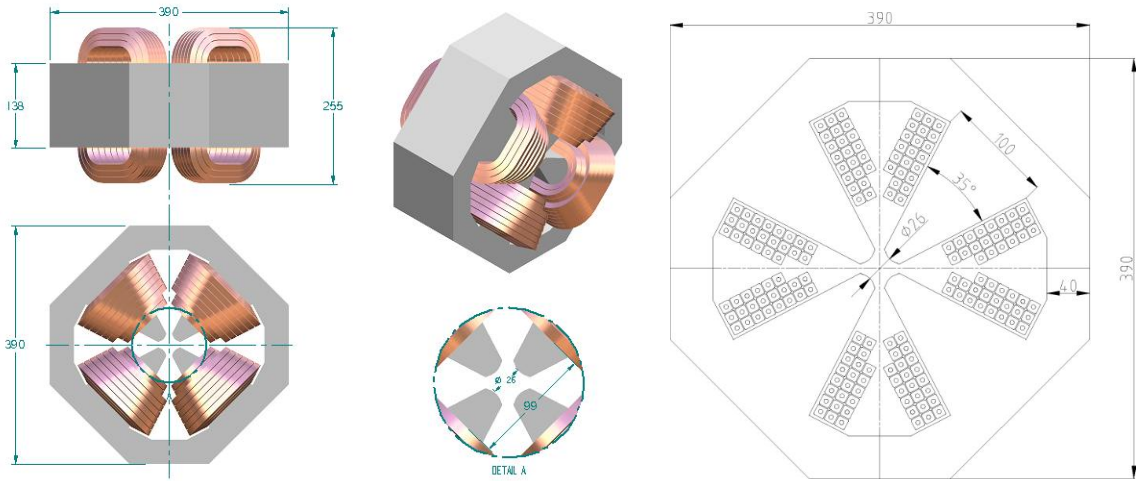
Aperture and field requirements

– Integrated gradient range:	1.218 [T] - 12.18 [T] (14.6[T])
– Nominal gradient	81.2 [T]
– Magnetic length	150[mm]
– Aperture radius:	13 [mm]
– Good field region	11 [mm]
– Integrated gradient quality	0.1%
– Available longitudinal space:	< 290 [mm](at the coil level)

Keep heat dissipation into tunnel as low as possible

- Water cooling

Initial design

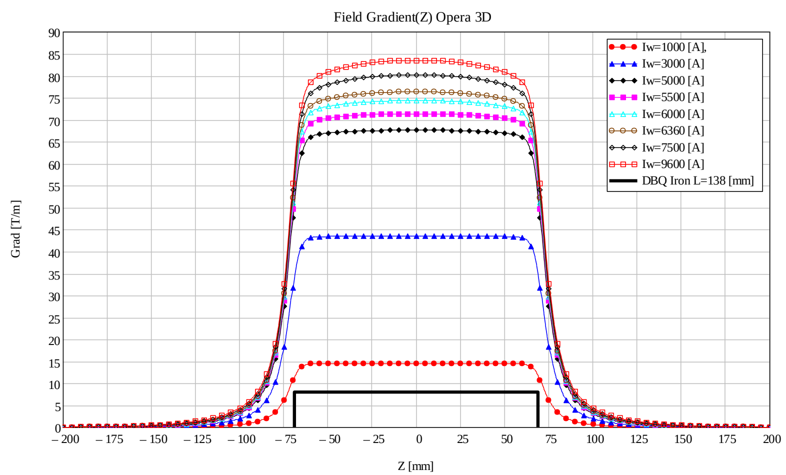


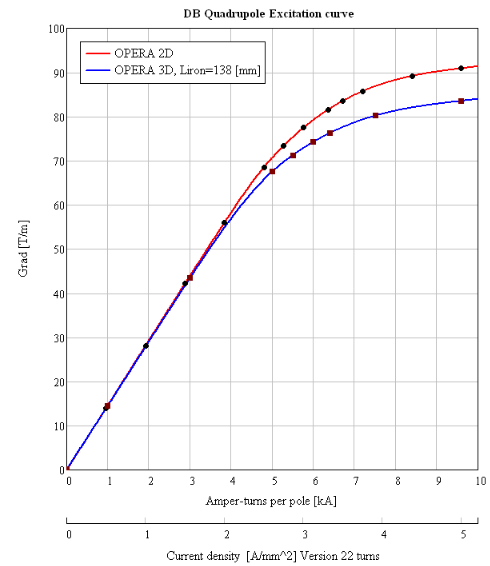
Nominal integrated gradient 12.18 T

Aperture radius:	13 mm
GFR:	11 mm
Magnetic length:	150 mm
Nominal gradient:	81.2 T/m
Number of turns:	20
Nominal current:	400 A

3D modelling suggested that, due to the short magnet length, the central gradient was not as high as the 2D model(end effects).

<u>The requested gradient 81.2[T/m] achievable at Iw=8000[A] only !</u>





Coil structure is too complicated

Big bending radius 35 mm for the selected conductor 10×10, Ø=4

Bad field quality (end effects dominated for the max gradient)

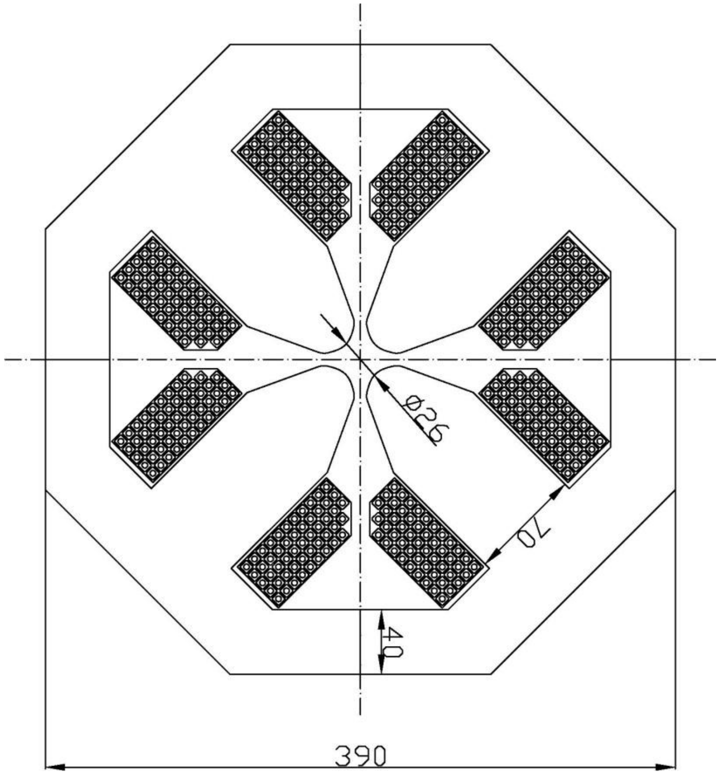
New proposal

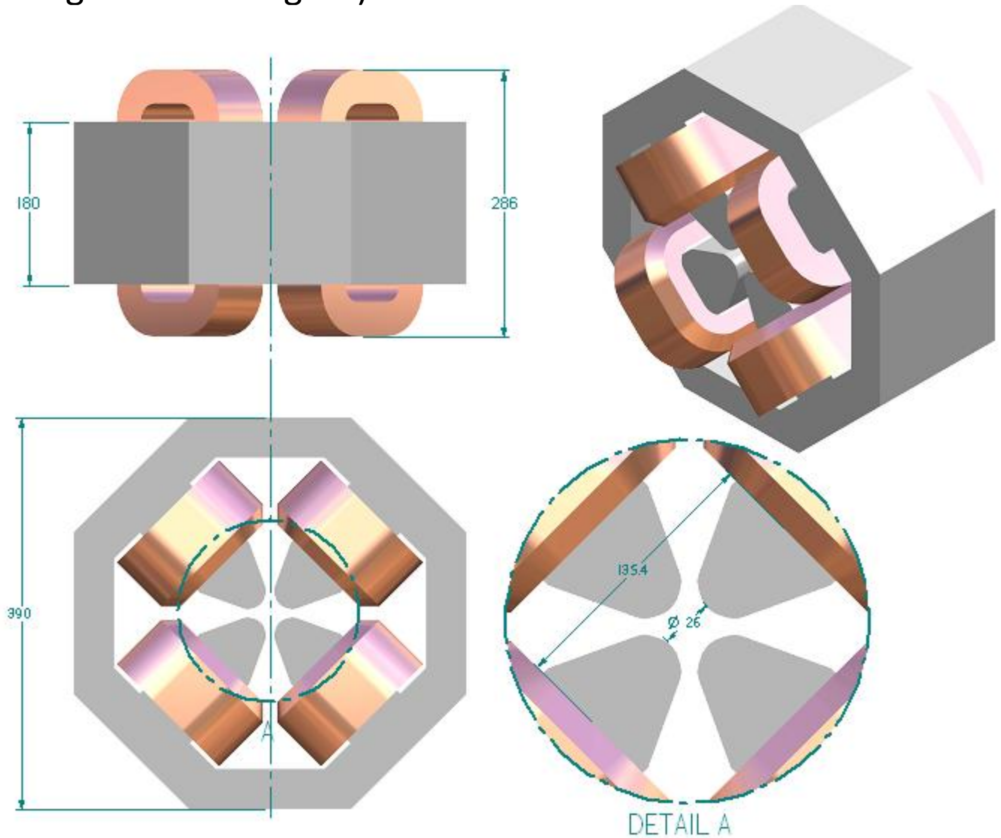
- Increase the iron length(as much as possible taking into account the available space) to achieve the requested integrated gradient =12.18[T] at smaller current:

$$GL = Leff \times Grad(0) = 150[mm] \times 81.2[T/m] = 194[mm] \times 62.8[T/m] = 12.18[T]$$

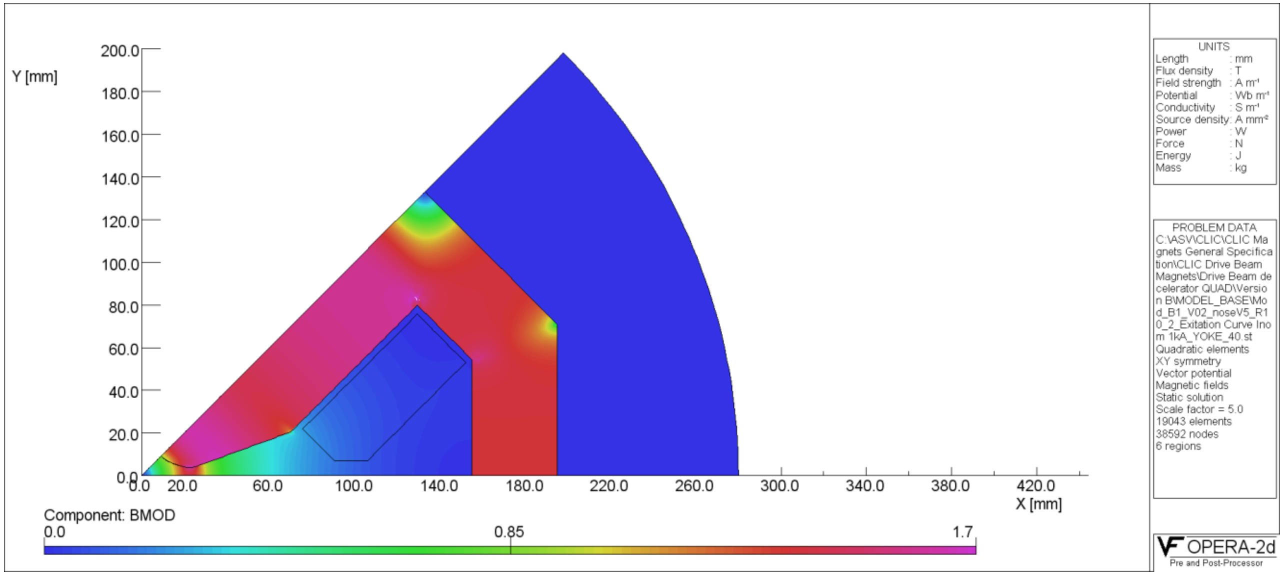
$$Liron(new) = Leff(new) - 2Rb \times 0.45 \approx 180[mm]$$

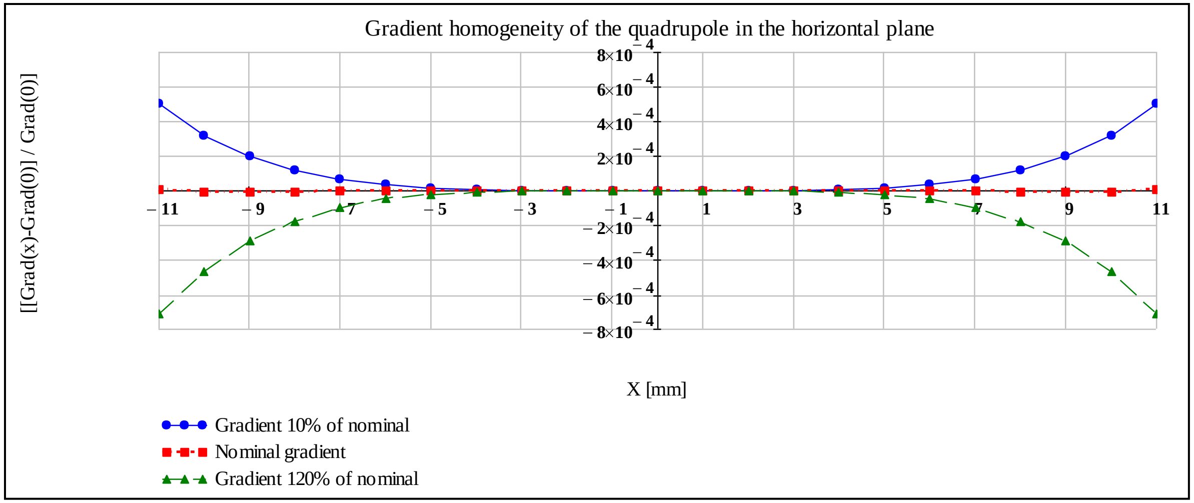
- Conductor type has been changed from 10×10mm Ø=4mm 20 turns to 6×6 Ø=3.5mm 52 turns=> Smaller bending radius 18mm(smaller total length of the magnet).



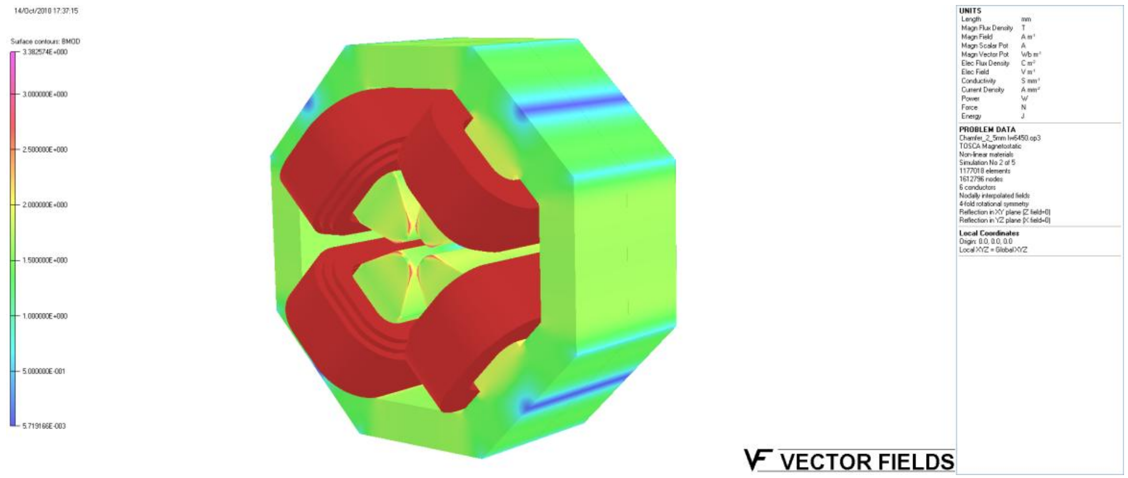


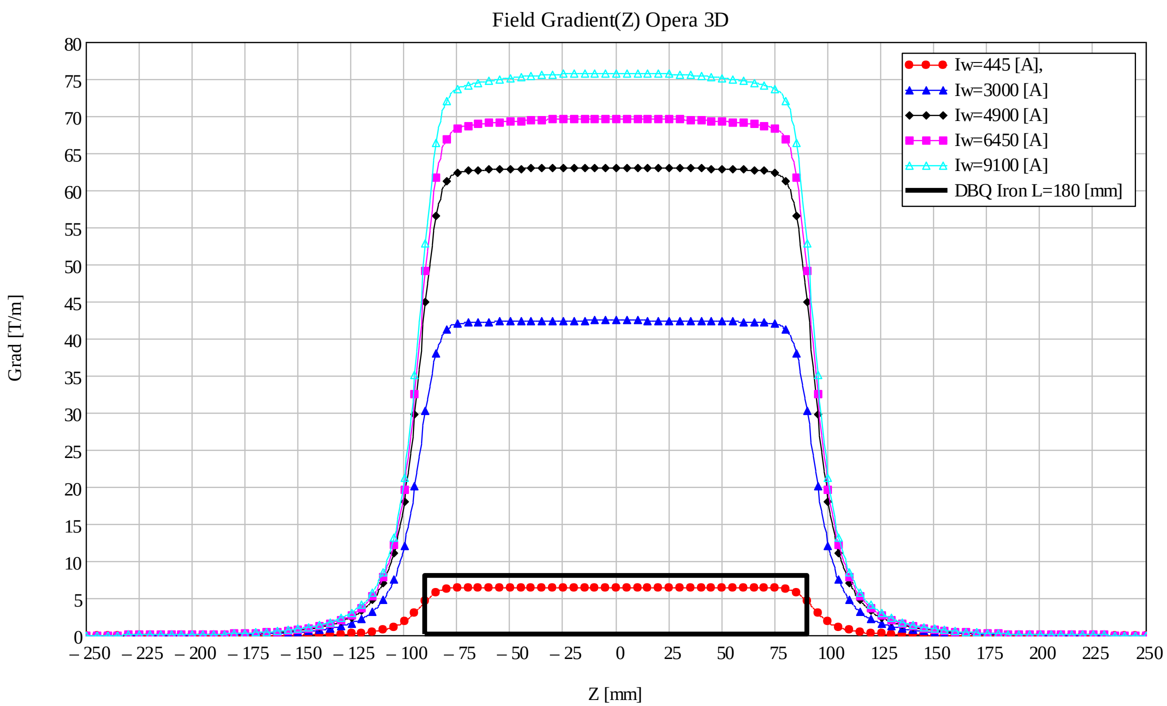
2D magnetic field calculations & field quality



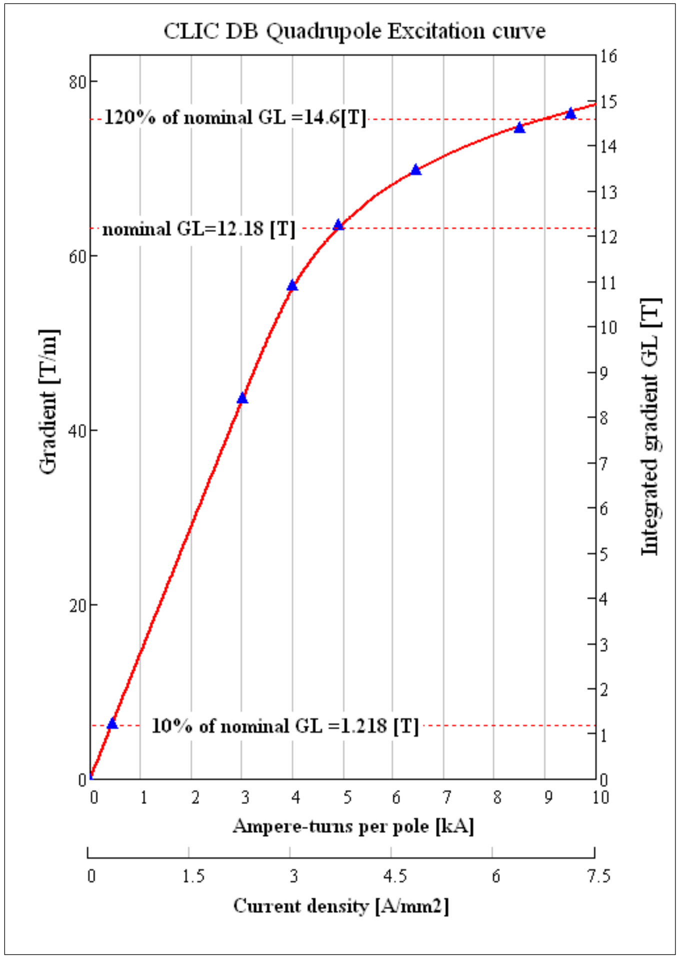


3D Magnetic Field Calculations



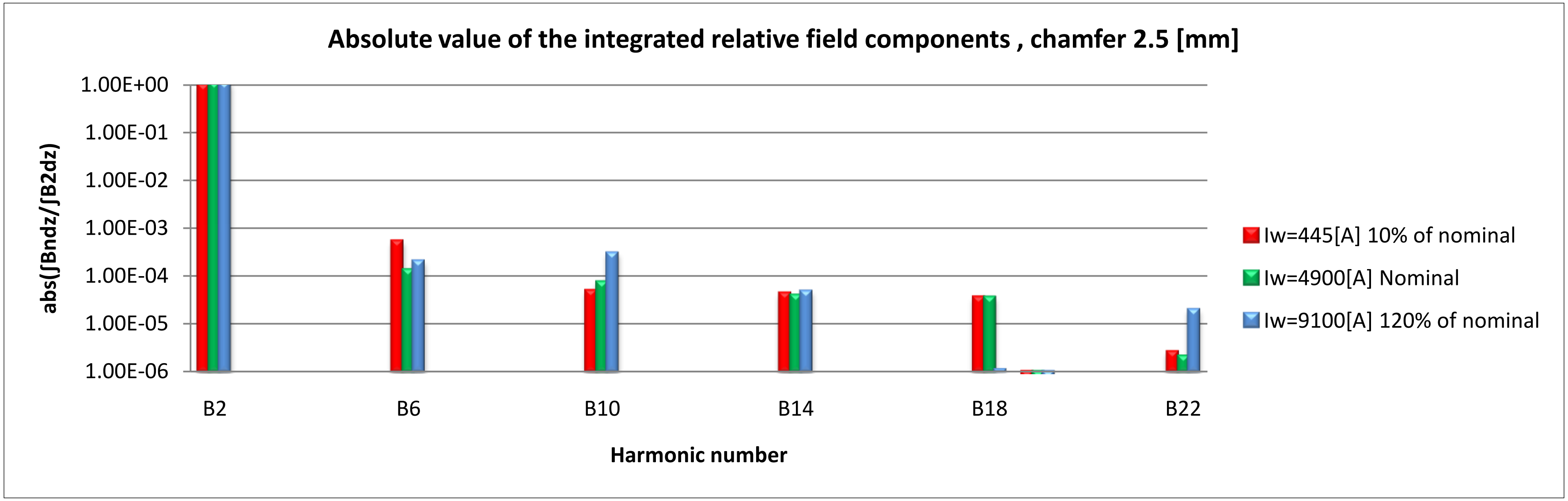


Excitation curve & main parameters

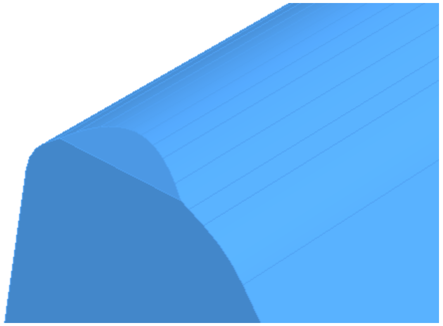


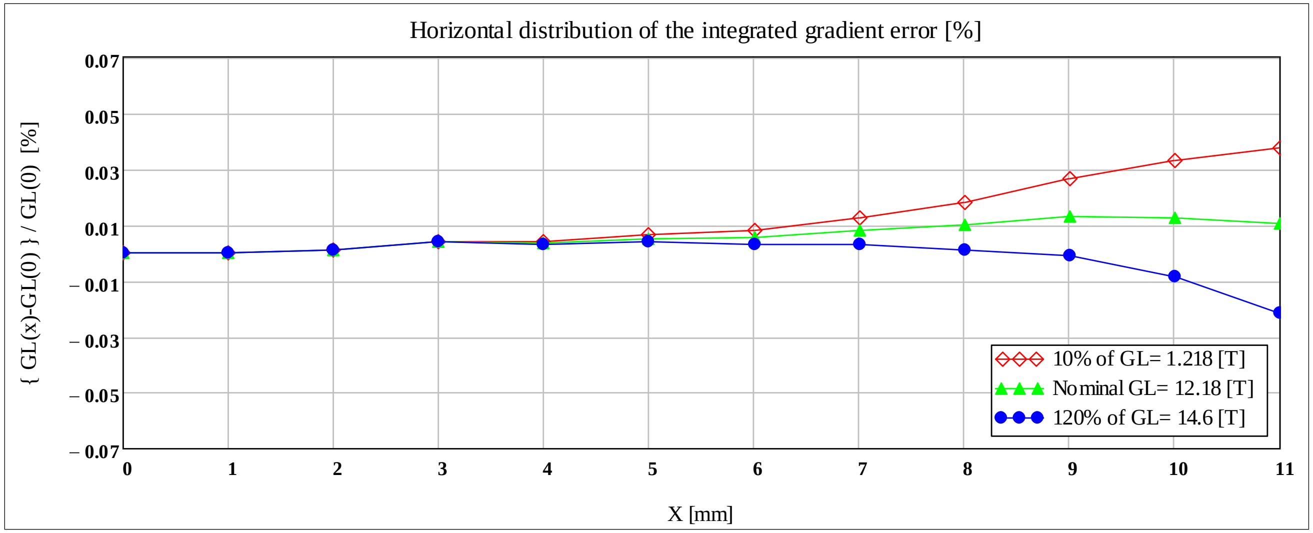
CLIC DB Quadrupole Parameters	Units			
		MAGNET		
Magnet size **H×S×L**	[mm×mm×mm]	390×390×286		
Magnet mass	[kg]	149.2		
Full aperture	[mm]	26		
Good field region(GFR) diameter	[mm]	11×2=22		
		YOKE		
Yoke size **H×S×L**	[mm×mm×mm]	390×390×180		
Yoke mass	[kg]	29.4×4=117.6		
		COIL		
Hollow Conductor size	[mm]	6×6, Ø=3.5		
Number of turns per coil		52		
Total conductor mass	[kg]	31.6		
		Operation mode		
		10% of nominal	**Nominal**	**120% of nominal**
Effective length	[mm]	194.7	194	192.5
Gradient at Z=0	[T/m]	6.26	62.78	75.85
Integrated gradient ∫Gdl	[T]	1.218	12.18	14.6
Integrated gradient quality in GFR	%	0.04	0.01	0.02
		Electrical parameters		
Ampere turns per pole	[A]	432	4840	9100
Current	[A]	8.3	93	175
Current density	[A/mm^2]	0.3	3.6	6.8
Total resistance	[mOhm]	99	99	99
Total inductance	[mH]	40	40	40
Voltage	[V]	0.82	9.2	17.3
Power	[kW]	0.007	0.86	3.03
COOLING		**Air (natural convection)**	**Water**	**Water**
Cooling circuits per magnet			4	4
coolant velocity	[m/s]		1.1	1.9
cooling flow per circuit	[l/min]		0.6	1.1
Pressure drop	[bar]		2.2	5.7
Reynolds number			4122	8210
Temperature rise	[K]		5	10

Field quality 3D for various Integrated gradient values, chamfer 2.5 mm



Chamfer height: 2.5mm





Conclusions on DBQ design

- The electromagnetic design of the CLIC DB quadrupole has been presented
- The proposed design fulfill the requirements: Available space, integrated gradient up to 120% of nominal value 12.18[T]
- To study the end field effects the 3D model of the magnet has been constructed
- The 3D field analysis shows that the minimum integrated field error is mandated for the chamfer height 2.5mm and it stays below the requested value 0.1% at GFR=11[mm] for the full range of the integrated field gradient (1.218[T]-14.6 [T]).

Drive Beam magnets for Delay line, Combiner rings, Turn-around, Transport to tunnel, Long transfer line and injector linac.

Type	Magnet type	Total	Effective Length [m]	Aperture H/V [m]	Shape	Strength	Range %	Rel Field Accuracy	Higher Harmonics [Tm]
				Note 0				Note 1	Note 2
MBTA	Dipole	576	1.5	0.04/0.04	circular	1.6 T	10-100	1.00E-03	1.00E-04
MBCOTA	Dipole	1872	0.2	0.04/0.04	circular	0.07 T	-100/100	1.00E-03	1.00E-03
QTA	Quadrupole	1872	0.5	0.04/0.04	circular	14 T/m	10-100	1.00E-03	1.00E-04
SXTA	Sextupole	1152	0.2	0.04/0.04	circular	85 T/m^2	10-100	1.00E-03	1.00E-03
MB1	Dipole	184	1.5	0.08/0.08	circular	1.6 T	10-100	1.00E-03	1.00E-04
MB2	Dipole	32	0.7	0.08/0.08	circular	1.6 T	10-100	1.00E-03	1.00E-04
MB3	Dipole	236	1	0.08/0.08	circular	0.26 T	10-100	1.00E-03	1.00E-04
MBCO	Dipole	1061	0.2	0.08/0.08	circular	0.07 T	-100/100	1.00E-03	1.00E-03
Q1	Quadrupole	1061	0.5	0.08/0.08	circular	14 T/m	10-100	1.00E-03	1.00E-04
SX	Sextupole	416	0.2	0.08/0.08	circular	85 T/m^2	10-100	1.00E-03	1.00E-03
SX2	Sextupole	236	0.5	0.08/0.08	circular	360 T/m^2	10-100	1.00E-03	1.00E-04
QLINAC	Quadrupole	1638	0.25	0.087/0.087	No data	17 T/m	No data	No data	No data
Note 4			Note 3	Note 5					
MBCO2	Dipole_CO	880	1	0.2/0.2	circular	0.008 T	-100/100	0.002	2.80E-05
Q4	Quadrupole	880	1	0.2/0.2	circular	0.14 T/m	10/100	0.002	2.80E-05

0) Aperture H, V: Vacuum Chamber inner full aperture. Add 2(1.5+5) = 1.3e-2m for vac.ch&bake-out
1) Relative field accuracy: tolerance for the transfer function of the main field component (strength x length)
2) Higher harmonics: max integrated field of all higher harmonics at a reference radius r = 0.01 m (radius of the good field region)
3) The length given is indicative for MBCO2 & Q4. There is no longitudinal constraint. Only the integrated strength must be granted
4) Overall EXTERNAL transverse dimensions and weight of the magnet must be made small (transverse dimension < .4 x .4 m). A 'yoke-less' magnet must be considered
5) Add 6e-3 to diameter for vacuum chamber thickness, no bake-out in magnets

List of magnets for CLIC Drive Beam, B. Jeanneret , 20/04/2010

- In total 12096 magnets of 14 different types required.
- At this stage only a preliminary design is needed as an input for the cost estimate, conception and dimensioning of technical services like electricity and cooling water distribution.

Preliminary Electromagnetic design

- Required ampere-turns per pole NI: defined by the formula (1)

  where: R is the quadrupole, sextupole aperture radius or half gap for dipole, n is the order of magnet (Dipole-1, Quadrupole-2, Sextupole-3), η-magnet efficiency=0.95.

$$NI = \frac{[\frac{B}{R^{(n-1)}}] \times R^n}{n \times \mu 0 \times \eta} \qquad (1)$$

- Pole overhang for H-Dipole(unoptimized) (2)

  where: h is the half gap, GFR-good field region radius, ΔB/B- field tolerance at GFR.

$$a = (-0.36 \ln \frac{\Delta B}{B} - 0.9) \times h \qquad \text{- } pole\ overhang \qquad (2)$$

$$Xpole = GFR + a \qquad \text{- } pole\ coordinate$$

- Pole overhang for Quadrupole and Sextupole by conformal transformation from dipole space
- Iron Yoke length: $\boxed{Lyoke = Lmag - 2Rk}$

  Lmag - is the magnetic length, R is the quadrupole, sextupole aperture radius or half gap for dipole, k is the specific constant for Dipole k=0.56, Quadrupole k=0.45, Sextupole k=0.33.

•Average turn length for the coil ≈ 2.5Liron(then this value will be updated for the selected conductor type)

•Current density < 5 A/mm^2 (To minimize the power consumption)

•Cooling: Temperature rise <20K, Turbulent flow, Pressure drop <10 Bar , water speed < 3m/s

•Conductor selection: standard hollow conductor types from "Luvata www.luvata.com catalog", taking into account requirements for cooling and electrical parameters.

•2D calculations by OPERA VF(to confirm the field strength level and field quality, inductance calculation)

•Table with the main parameters

Result of the preliminary design

Dipole MB3, PBS [2.3.2]

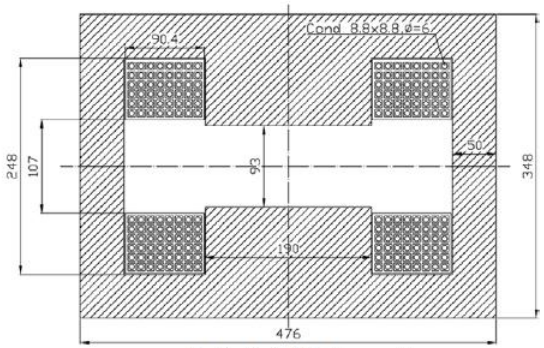


Fig 13. Dipole MB3 Cross-section

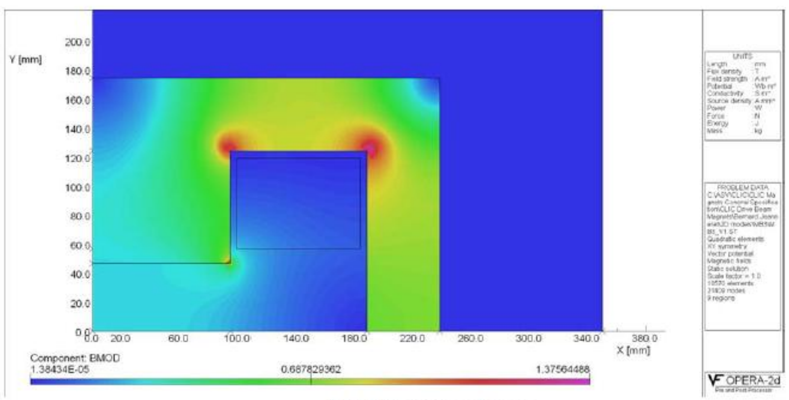


Fig 14. Opera 2D model view

Parameters	UNITS	
Magnet type		Dipole MB3
Full aperture	[mm]	80+2×(1.5+5)=93
Good field region diameter	[mm]	10×2=20
Effective length	[mm]	1000
Strength	[T]	0.26
Pole field	[T]	0.26
	YOKE	
Yoke length	[mm]	948
Yoke cross section area	[m^2]	0.051×2=0.102
Yoke mass	[kg]	760
	USED STEEL	
Steel block size **H**×**S**×**L**	[mm×mm×mm]	348×476×948
Used steel mass	[kg]	1236
	COIL	
Conductor type	"Luvata"[ID number-6843]	8.8[mm]×8.8[mm], Ø=6[mm]
Conductor mass per 1 m	[kg/m]	0.43
Number of turns per coil		48
Number of pancakes/coil		1
Average turn length	[m]	2.7
Total conductor length	[m]	2.7×48×2=259.2
Total conductor mass	[kg]	111.5
	Electrical parameters	
Ampere turns per pole	[A]	10'130
Current	[A]	211
Current density	[A/mm^2]	4.37
Total resistance	[mOhm]	100
Total inductance	[mH]	34.7
Voltage	[V]	21
Power	[kW]	4.5
	COOLING	
Cooling circuits per magnet		2
coolant velocity	[m/s]	1.1
cooling flow per circuit	[l/min]	1.87
Pressure drop	[bar]	4.18
Reynolds number		9454
Temperature rise	[K]	17

COST ESTIMATE

- Defined magnet parameters as an input for the cost estimate.
- This amount includes the raw materials and components, tooling, manufacturing and assembling.
- The estimated costs are based on analytical formulas and experience from magnet projects in the recent past.
- For the large quantity production of components the manufacturing cost was reduced by applying the learning curve

Table of input parameters for the cost estimate

Number of magnets
Magnet Type: Dipole-1/Quadrupole -2/Sextupole-3
Yoke length [mm]
Yoke height [mm]
Yoke width [mm]
Yoke weight [kg]
Used steel weight [kg]
Conductor height [mm]
Conductor widht [mm]
Coil length/magnet [m]
Number turns per coil
Number of pancakes per coil
Coil weight/magnet [kg]

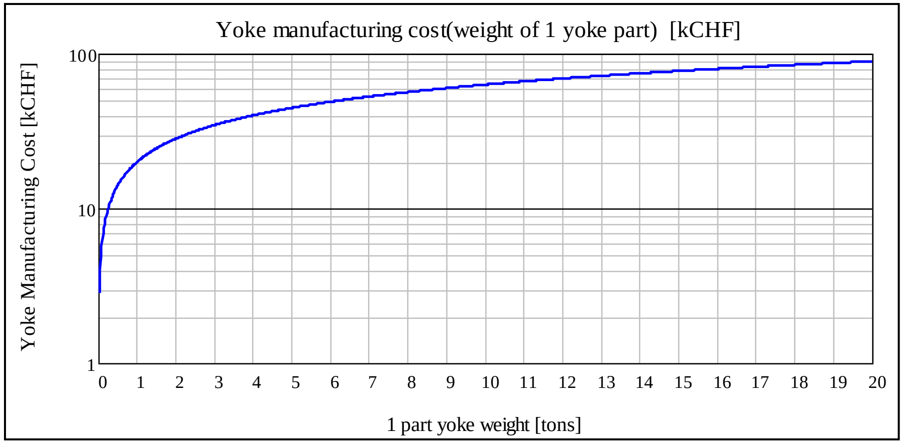
Cost estimate

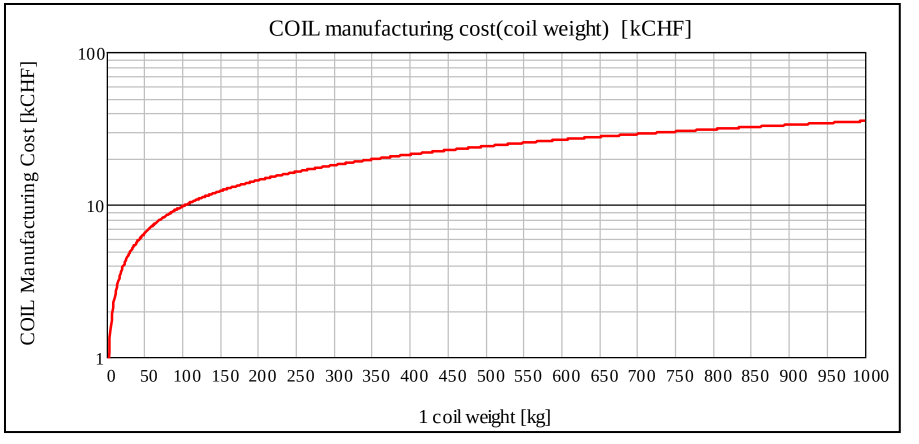
- Material:
  - Steel sheets(used steel mass) : 2 CHF/kg
  - Copper conductor(conductor mass): 20 CHF/kg
- Fixed cost
  - Punching die (yoke cross section)
  - Stacking tool (yoke mass)
  - Winding (turn length)
  - Molding (coil volume)
- Manufacturing cost
  - Yoke manufacturing (Yoke mass/Yoke parts)
  - Coil manufacturing(One Coil mass)
- Assembling(Magnet mass)
- Learning curve(for big series):

$$C(n) = \frac{[C(1)] \times n^{1+\log_2^a}}{(1+\log_2^a)} \quad \text{- cumulative cost of first } n \text{ units}$$

$$C(n)/n = \quad \text{- Average unit cost of first } n \text{ units produced}$$

Magnet type	Dipole	
Costs for	1st magnet	Average unit
Number of magnets	236	236
Used steel mass/magnet [kg]	1236	1236
Yoke mass/magnet [kg]	760	760
Coil mass/magnet [kg]	111.5	111.5
Tools costs		
Total Tooling COSTS [kCHF]	40.1	40.1
Material Costs (Steel+Copper)		
TOTAL material/magnet [kCHF]	4.702	4.702
Manufacturing costs(Yoke+Coil)		
TOTAL manufacturing/magnet [kCHF]	42.375	37.221
Magnet Assembly [kCHF]	8.856	8.856
TOTAL		
Total Costs/magnet [kCHF]	56.103	50.949
Total Costs [kCHF]	13240.251	12024.037





Conclusions

- Preliminary design and cost estimate of the CLIC Drive Beam magnets has been completed.
- In total 12096 magnets of 14 different types have been considered.
- The total power consumption of all magnets is about 45MW.

Type	Magnet type	Number of magnets	COST(1st Magnet) [kCHF]		COST(Average unit) [kCHF]		Power consumption [kW]	
			Per magnet	TOTAL	Per magnet	TOTAL	Per magnet	TOTAL
MBTA	Dipole	576					21.6	12441.6
MBCOTA	Dipole	1872					0.25	468
QTA	Quadrupole	1872					2	3744
SXTA	Sextupole	1152					0.075	86.4
MB1	Dipole	184					42	7728
MB2	Dipole	32					25	800
MB3	Dipole	236					4.5	1062
MBCO	Dipole	1061					0.4	424.4
Q1	Quadrupole	1061					5.9	6259.9
SX	Sextupole	416					0.5	208
SX2	Sextupole	236					3.3	778.8
QLINAC	Quadrupole	1638					6.3	10319.4
MBCO2	Dipole	880					0.313	275.44
Q4	Quadrupole	880					0.543	477.84
TOTAL		**12096**						**45073.78**

Technical note, EDMS: 1082761

ATS/Note/YYYY/NNN
edms no: 1082761
July 26, 2010

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A&T Sector Note

PRELIMINARY DESIGN AND COST ESTIMATE OF CLIC DRIVE BEAM MAGNETS REQUIRED FOR THE: DELAY LINE, COMBINER RINGS, TURN-AROUND, TRANSPORT TO TUNNEL, LONG TRANSFER LINE AND INJECTOR LINAC.

Alexey Vorozhtsov / TE-MSC

Keywords: CLIC, magnets, normal-conducting, magnet design, cost estimate

Summary
This document describes the preliminary electromagnetic design and cost estimate of the warm magnets required for the CLIC Drive Beam.

Acknowledgment

I would like to express my gratitude to Davide Tommasini, Michele Modena and Bernard Jeanneret for their help and useful discussion.

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