Progress with FFS magnets for CLIC, ILC and ATF2

M. Modena, CERN

Acknowledgments:

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Introduction

Inside the CLIC R&D and since 2010, we have started design studies and some prototypes procurements to investigate the most critical magnets of the CLIC complex (QD0 and others of the BDS; DBQ; MBQ; PCL, etc.).

As concerning the CLIC, ILC and ATF Beam Delivery Systems (BDS) these are the subjects here presented:

*- CLIC **QD0**: Due to the challenging working parameters and layout, we decided to procure a "short prototype" . This was done in 2011-2012.*

*- Some critical assembly aspects of the QD0 design will be now addressed with a CLIC **SD0** prototype that is based on the same concept. We are now completing the detailed design.*

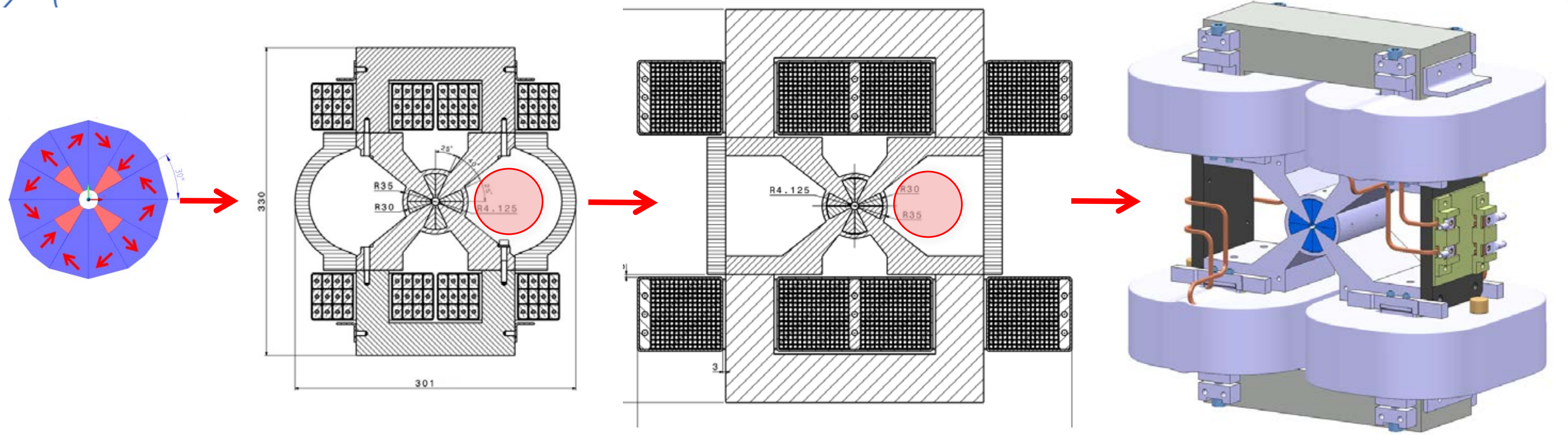
*- Recently, we did the exercise to investigate the solution proposed for the CLIC QD0 with **ILC** working parameters.*

*- **ATF:** Since 2011 we were contacted for a possible upgrade of **QD0** and **QF1** and few weeks ago also for the design of two **OCTUPOLES**.*

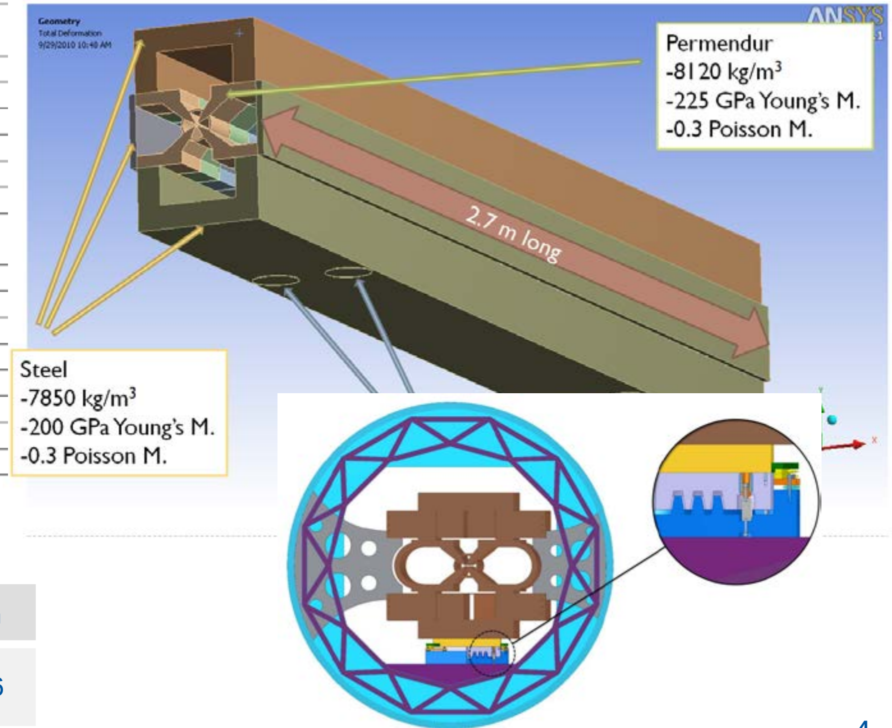
Outline:

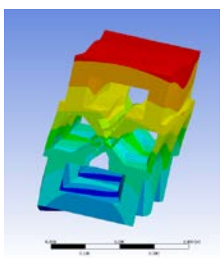
1) CLIC QD0 status
2) CLIC SD0 Status
4) A hybrid QD0 for ILC ? (basic conceptual design)
5) Upgrade of QD0 for ATF
6) OCTUPOLES for ATF

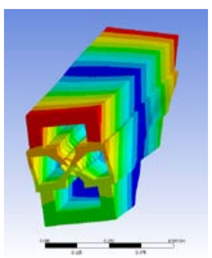
CLIC QD0 design in one slide



CLIC QD0 Main Parameters		100mm prototype	Real magnet 2.7m
Yoke			
Yoke length	[m]	0.1	2.7
Coil			
Conductor size	[mm]	4×4	4×4
Number of turns per coil		18×18=324	18×18=324
Average turn length	[m]	0.586	5.786
Total conductor length/magnet	[m]	0.586×324×4=760	5.786×324×4=7500
Total conductor mass/magnet	[kg]	26.8×4=107.2	265.2×4=1060.8
Electrical parameters			
Ampere turns per pole	[A]	5000	5000
Current	[A]	15.432	15.432
Current density	[A/mm²]	1	1
Total resistance	[mOhm]	896	8836
Voltage	[V]	13.8	136.4
Power	[kW]	0.213	2.1

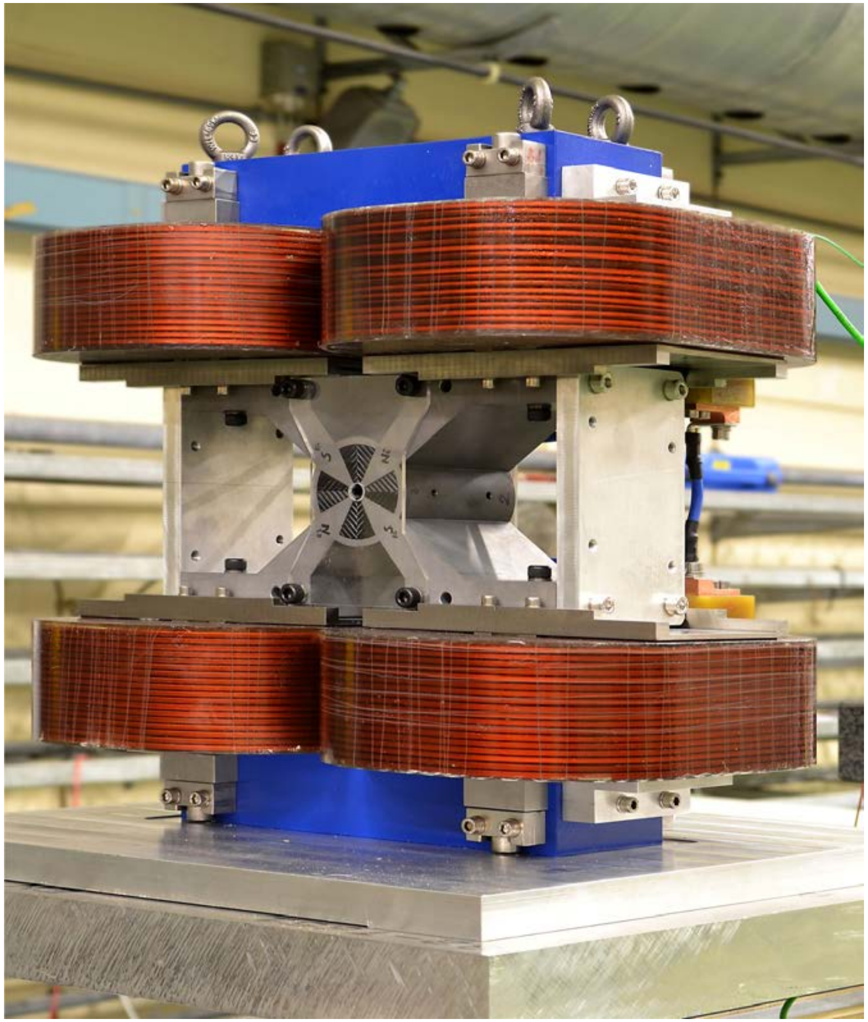






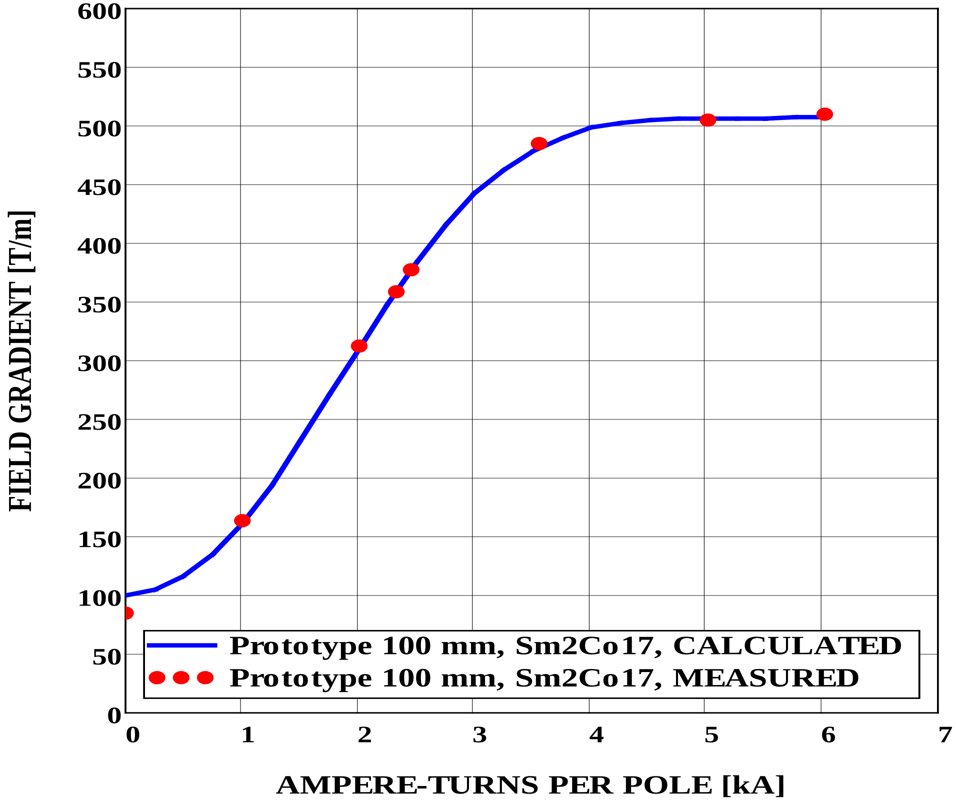
Mode	1st	2nd	3rd	4th
Freq [Hz]	190	260	310	366

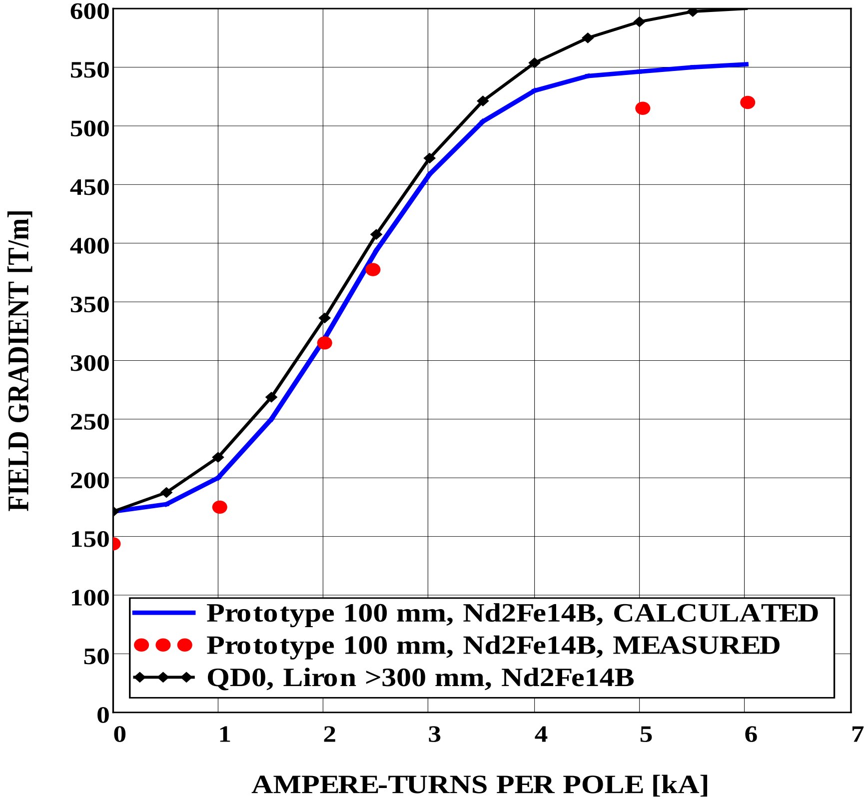
- A **short QD0 prototype** (for CLIC 3TeV layout) **was built** at CERN in 2010-2011.
- **Objective**: validate the Hybrid Magnet design proposed:
  PM blocks - Permendur core structure - coils for tunability (low current density).
- **Two** campaigns of measurements were done in 2012 with two different QD0 configuration:
  - in January 2012: the QD0 equipped with $\mathbf{Nd_2Fe_{14}B}$ blocks
  - in August 2012: the QD0 equipped with $\mathbf{Sm_2Co_{17}}$ blocks .
- **"Vibrating Wire"** MM method was the only available due to the small magnet radius



Main Parameter	*Value*
Nominal field gradient	575 T/m
Magnetic length	2.73 m
Magnet aperture (for beam)	7.6 mm
Magnet bore diameter ** Assuming a 0.30 mm vacuum pipe thickness*	8.25 mm*
Good field region(GFR) radius	1 mm
Integrated field gradient error inside GFR	< 0.1%
Gradient adjustment required	+0 to -20%

COMPUTED Gradient (blue curves) and MEASURED Gradient (red dots) (extrapolated from the INTEGRATED GRADIENT effectively measured), with **Sm_2Co_{17}** blocks (left) and **$Nd_2Fe_{14}B$** blocks (right).





- **Sm_2Co_{17}** blocks: very good agreement with the FEA computation.
- **$Nd_2Fe_{14}B$** blocks: a difference of ~ -6% is visible.

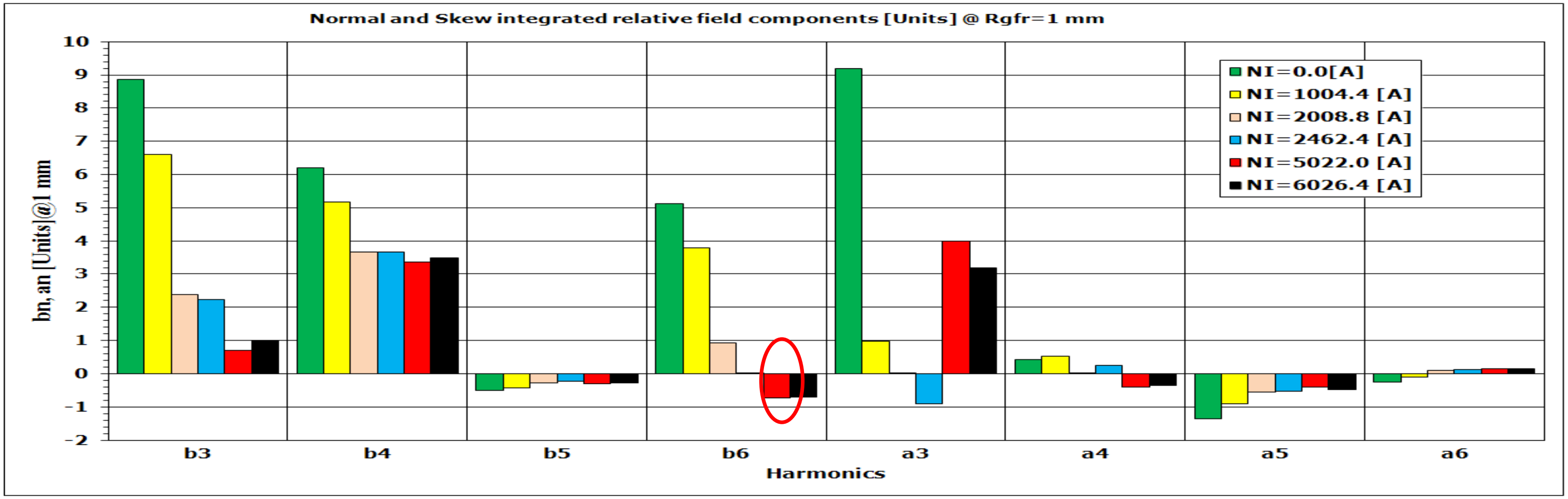
  Having excluded an effect due to the B-H characteristic of Permendur (we take into account the real measured B-H curve of the raw material) we think that the difference is due to quality (magnetization module and/or direction) of the $Nd_2Fe_{14}B$ blocks. → We should get more indication on this by measurements of each PM insert (each one done by 4 blocks) with a 3D measuring device (based on Helmholtz coils) under purchasing by the Magnetic Measurements Section .

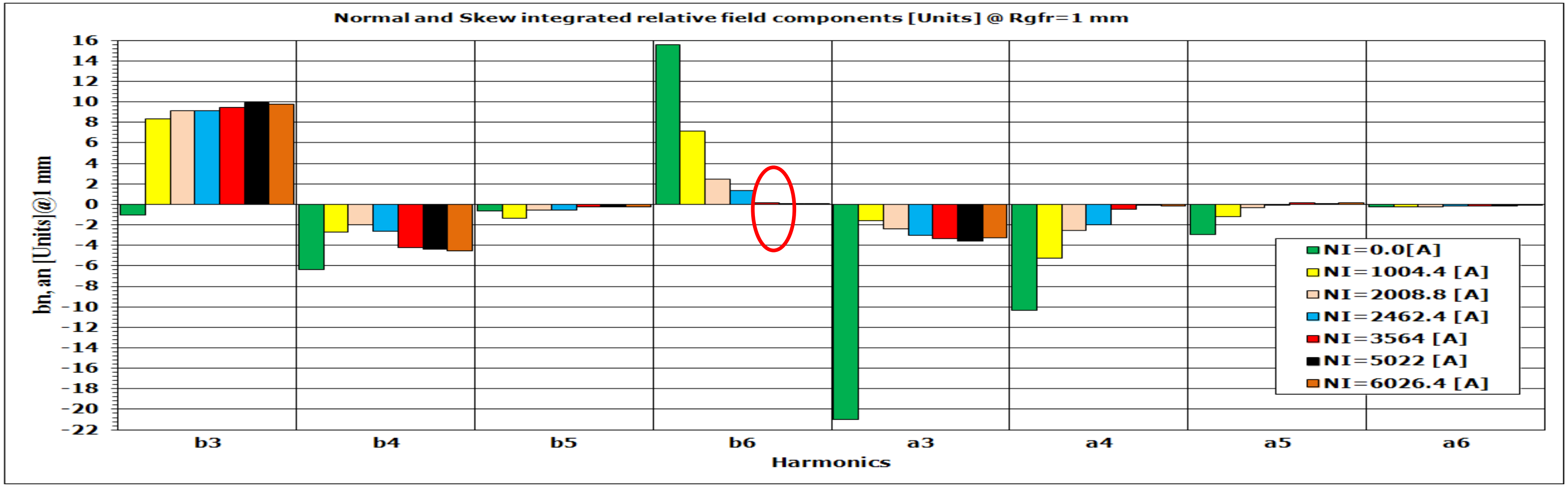

Helmholtz coil


3D Helmholtz coil

Prototype FIELD QUALITY (given as magnetic harmonic content, multipoles) versus the magnet powering: $Nd_2Fe_{14}B$ (upper graph), Sm_2Co_{17} (lover graph).

NOTE: the first "permitted" multipole is b6: at NI=5000A we compute b6=1.4 units (NdFeB) and b6=0.7 units (SmCo).





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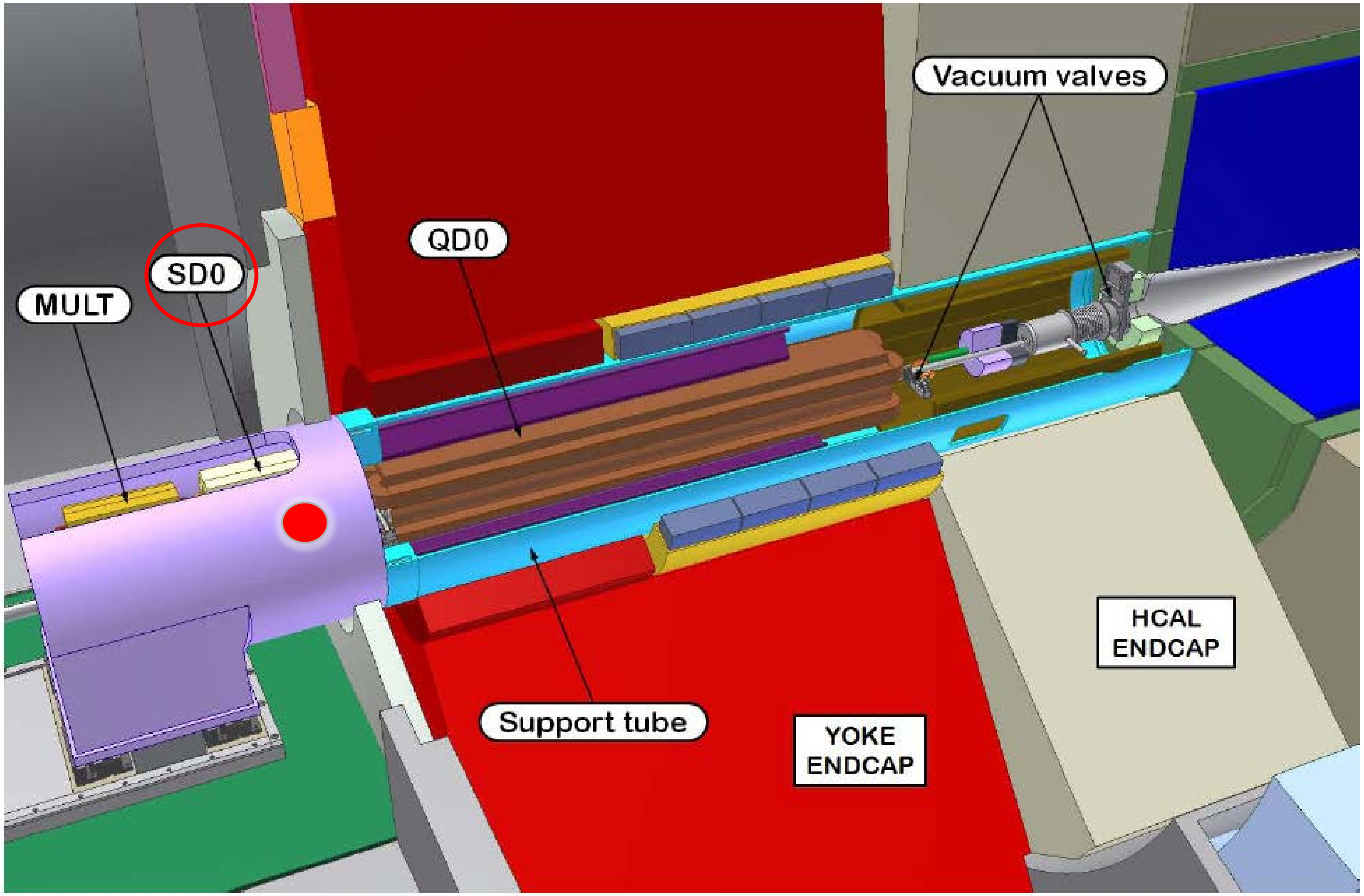
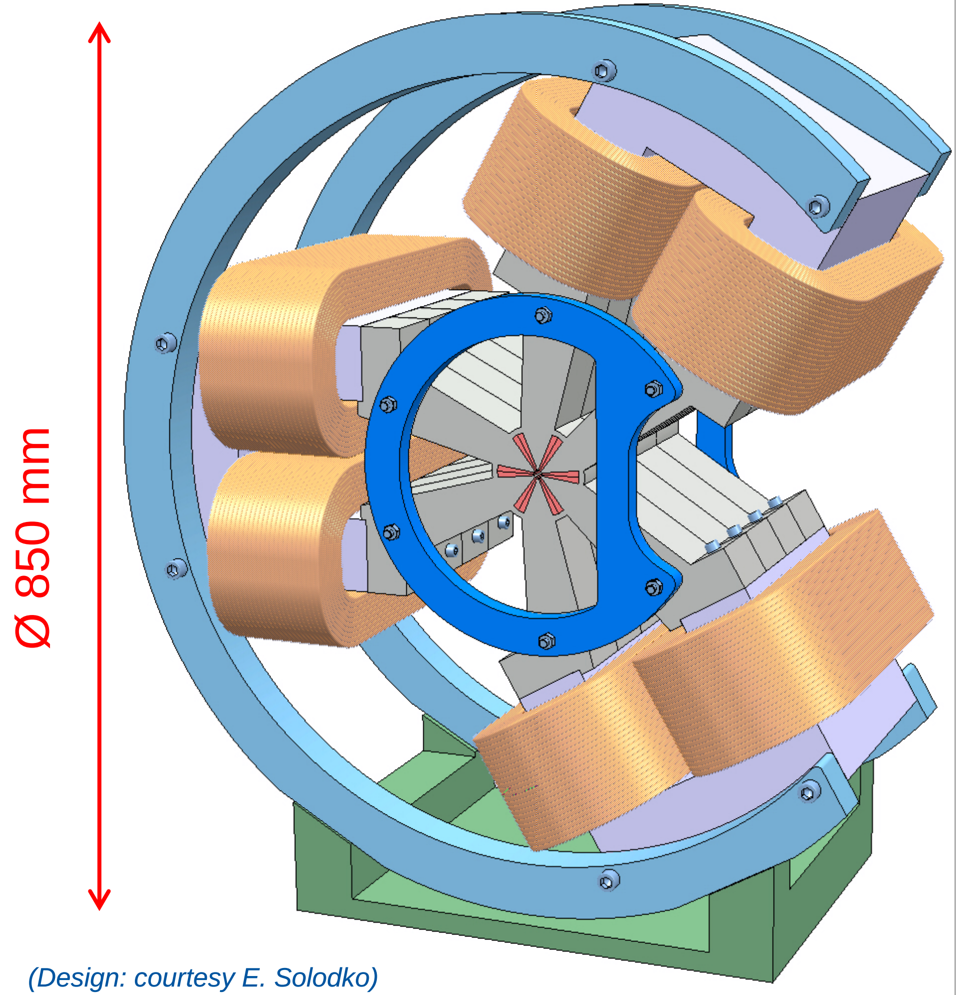
- **SDO** can be also considered a BDS critical magnet as it is requested with the stronger as possible gradient.
- It is the last magnet of the BDS placed on the tunnel, just at the border with the experimental Hall
- Being much shorter and not placed inside the Detector, the magnet has less tight geometric boundary conditions.

Parameter	*Value*
Inner radius	4.3 mm
Nom. Sext. Gradient	219403 T/m2
Magnetic Length	Lm: 0.248 m





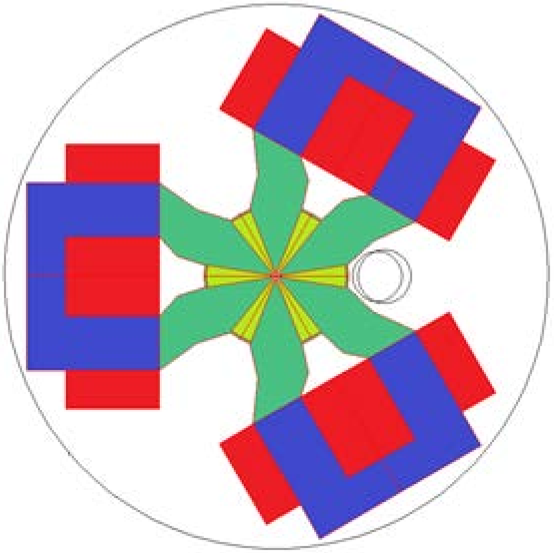
(Design: courtesy E. Solodko)

We are starting now the final design and procurement of components will follow.
Most probably we will procure individual components and coils and final assembly will be done at CERN.

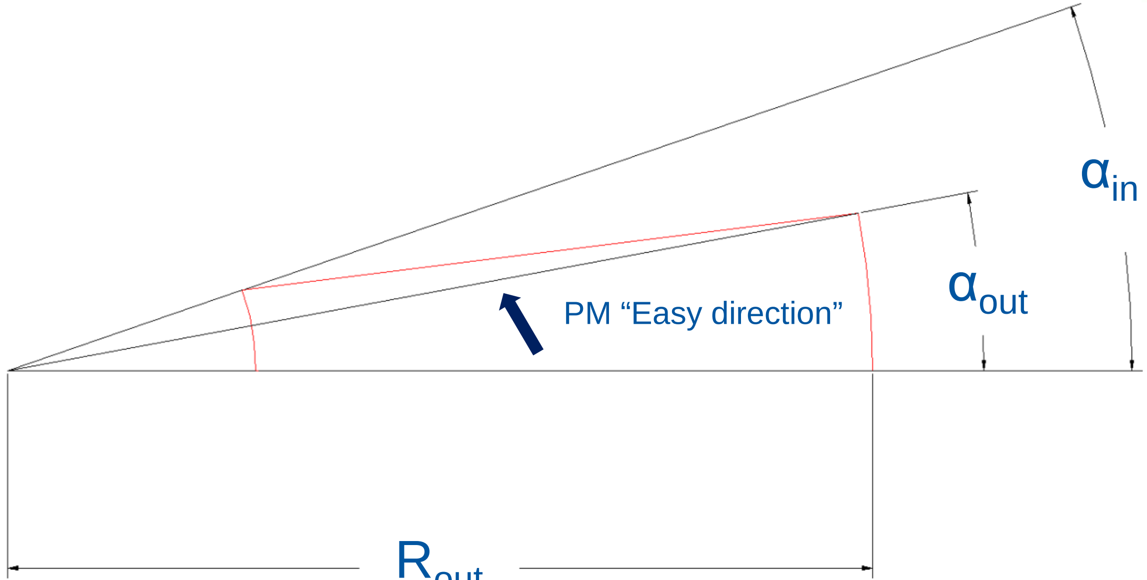
- ***Main requirements & boundary conditions:***
  - Tunability of ~ -20 %
  - Minimized vibrations (magnet should be actively stabilized)
  - Integration with the Post Collision vacuum pipe needed.

- Compactness is less critical respect to QD0. Magnet is placed outside the Detector at the accelerator tunnel border.

- **Prototype key aspects:**
  - The proposed design should permit to investigate the very precise longitudinal assembly of four sections, each equipped with PM blocks.
  - Manufacturing (with highest precision) of each Permendur sector, and PM blocks.
  - Measuring, sorting, insertion/extraction of PM blocks (very fragile!).
  - Assembly of the sectors (magnetic forces between blocks will play a role?) on the “C shaped” return yokes.
  - Magnetic measurements.
  - Final alignment.



SD0 conceptual layout

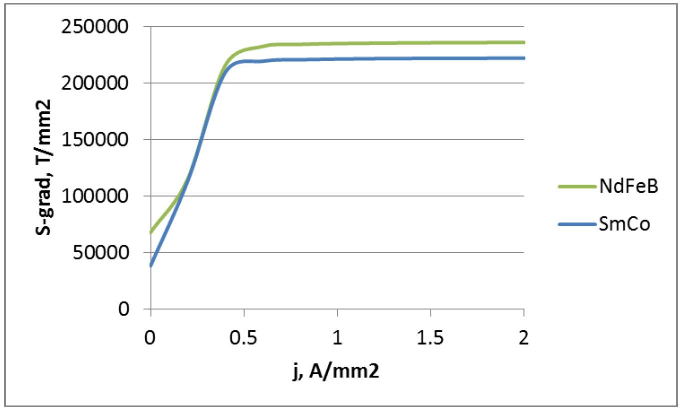


PM block analysed parameters

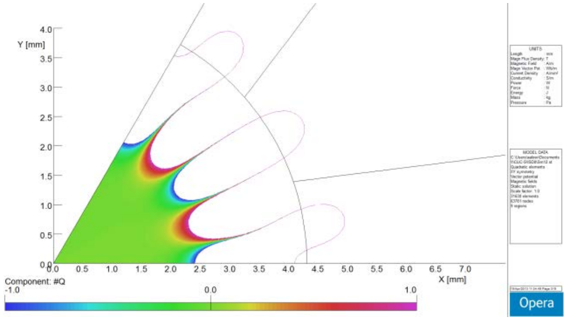
Optimization process provides these values : α_{in} = 18.9° α_{out} = 8.4 ° R_{out} = 40 mm

	NdFeB	SmCo
R_{out} mm	*S-gradient, T/m²*	
20	217 271	200 368
40	234 438	220 891
70	235 926	222 188
90	236 000	222 188

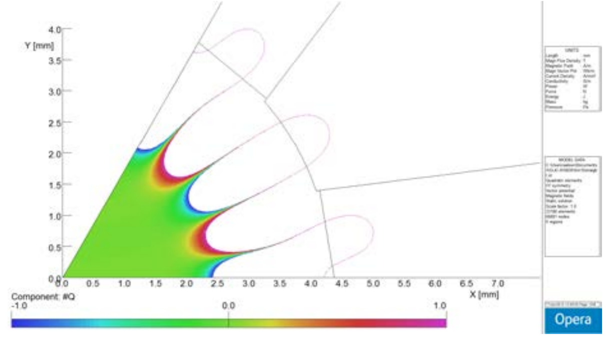
Magnet powering curve



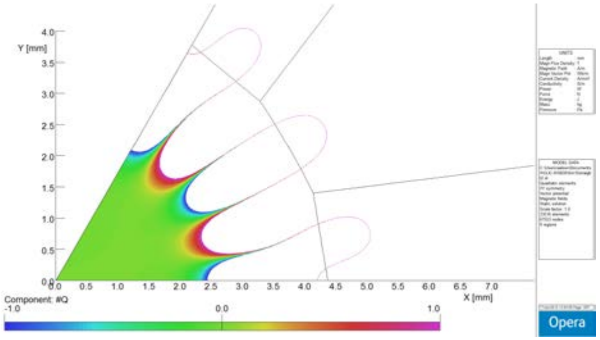
(Computation: courtesy A. Aloev)



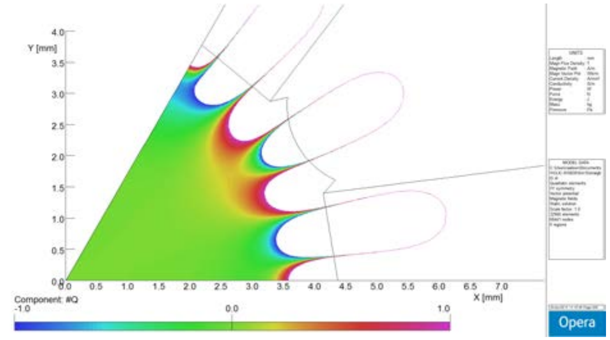
Opt.1 S-grad 222 020 T/m²



Opt.3 S-grad 221 247 T/m²

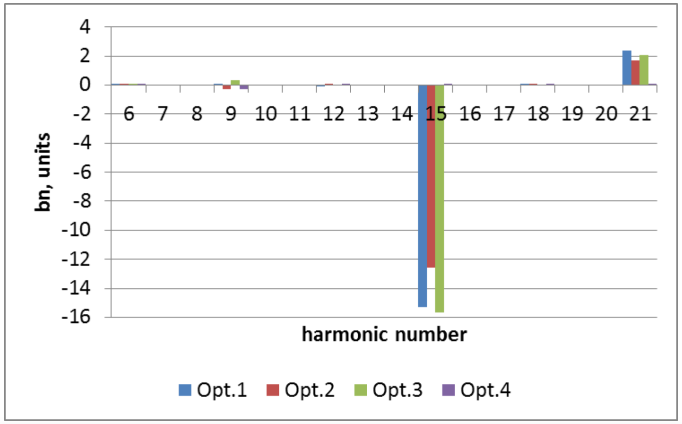


Opt.2 S-grad 220 349 T/m²



Opt.4 S-grad 215 785 T/m²

	b6	b9	b12	b15	b18	b21
	units					
Opt.1	0.097462	0.039891	-0.08626	-15.3198	0.010636	2.390928
Opt.2	0.023376	-0.25272	0.037967	-12.5842	0.05568	1.663802
Opt.3	0.011564	0.32237	-0.00902	-15.6347	-0.06368	2.075975
Opt.4	0.008644	-0.25438	0.04409	0.000104	0.046933	0.037846



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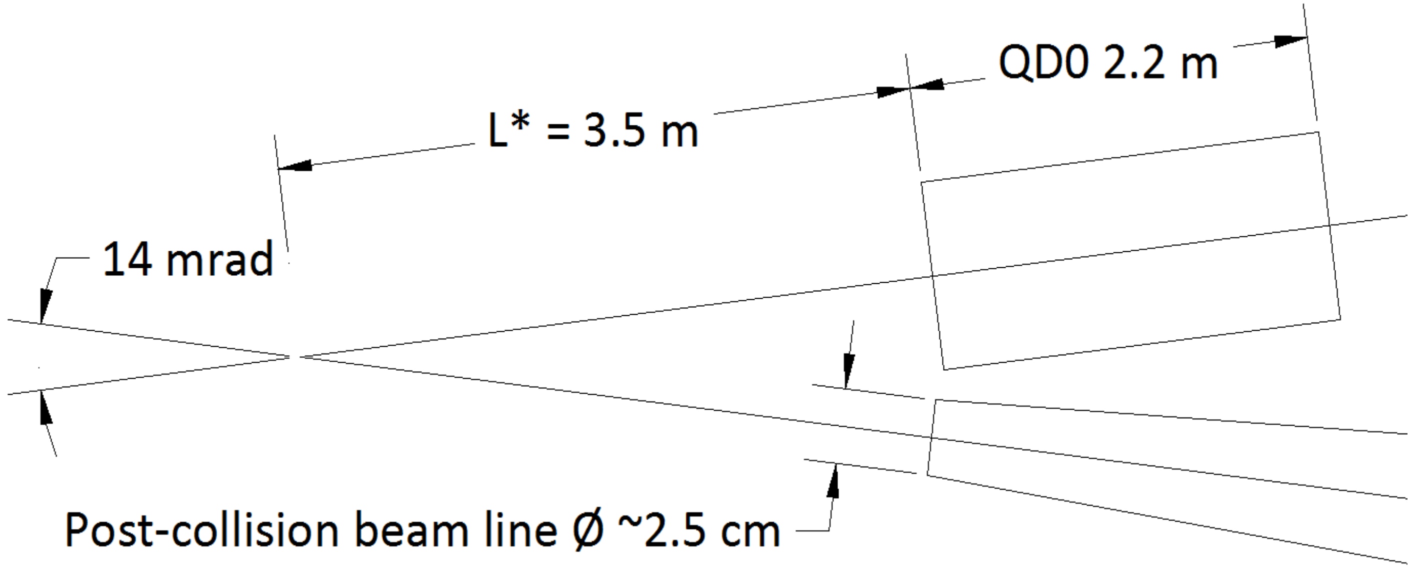
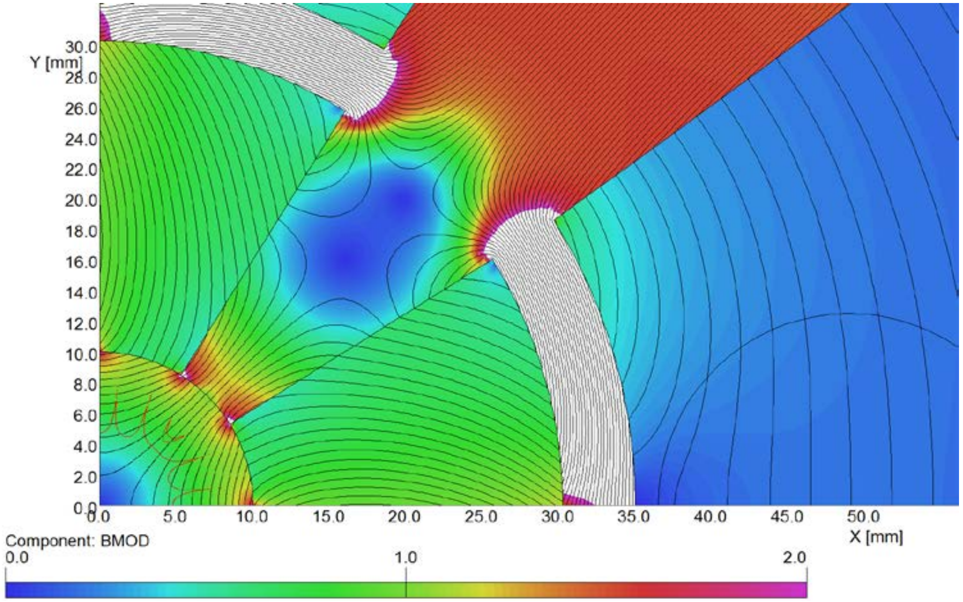
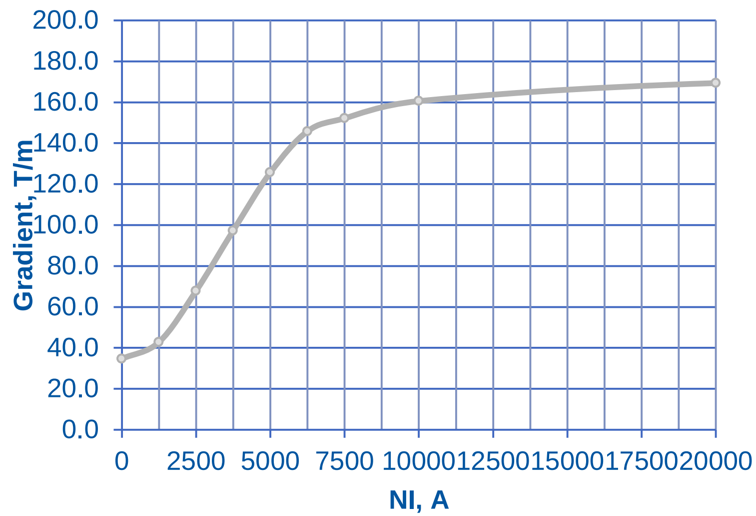
Basic ILC QD0 parameters *(from R. Tomas Garcia: private communication of 8 May 2013):*

- Crossing angle: 14 mrad
- L* = 3.5 m
- QD0 full aperture: 2 cm
- QD0 total length: 2.2 m
- QD0 gradient: 124 T/m
- Post Collision Line vacuum pipe radius at 3.5 m: ~ 12.5 mm



We have tried to "scale" our CLIC QD0 design taking into account the ILC layout and geometric conditions but also starting an optimization of the main parameter toward a wider field quality range for the demanded tunability.





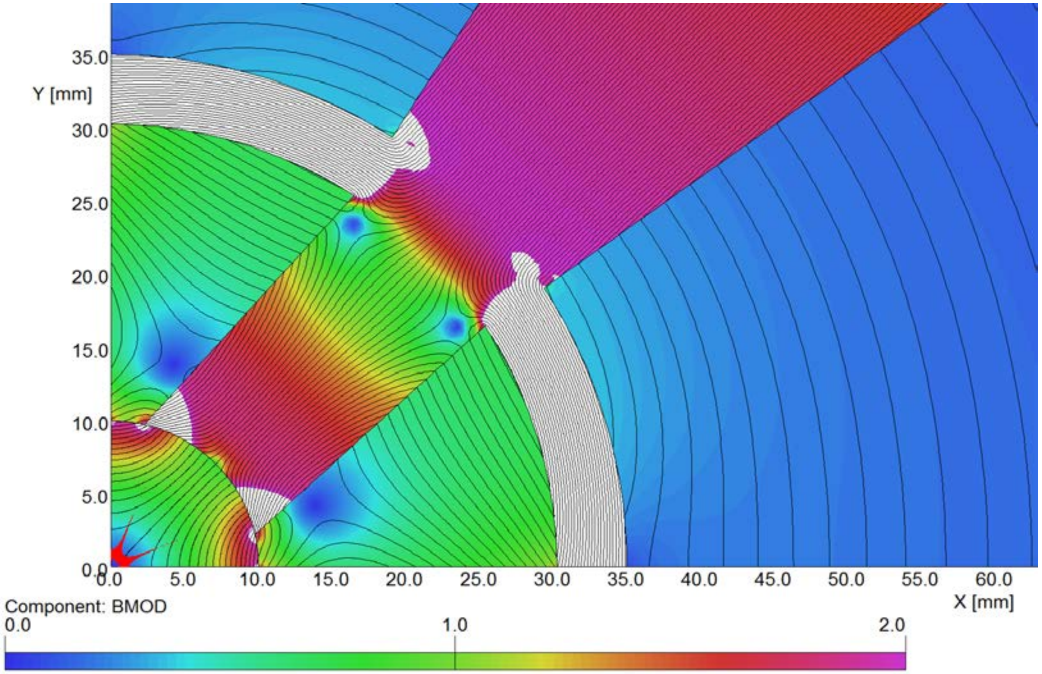
"red line" inside the aperture: area where ΔG/G ≤1 unit (good field region)

NI	A	0	1250	2500	3750	5000	6250	7500	10000	20000	40000
Gradient	**T/m**	**34.7**	**42.8**	**67.8**	**97.3**	**125.7**	**145.8**	**152.2**	**160.6**	**169.4**	**174.9**
b6	units	61.2472	45.2059	19.9428	6.8605	-0.0183	-3.3895	-4.2944	-5.3982	-6.4427	-7.0075
b10	units	0.1978	0.1510	0.0769	0.0386	0.0215	0.0173	0.0173	0.0182	0.0201	0.0217
b14	units	0.000192	4.51E-04	8.62E-04	1.07E-03	1.16E-03	1.16E-03	0.001148	0.001123	0.001086	0.001056
b18	units	0.003501	2.58E-03	1.14E-03	3.89E-04	-4.59E-06	-1.98E-04	-0.00025	-0.00031	-0.00037	-0.0004

Main multipoles estimated at r = 3 mm; 5000 NI is the nominal working point (125 T/m)

(Computation: courtesy A. Aloev)

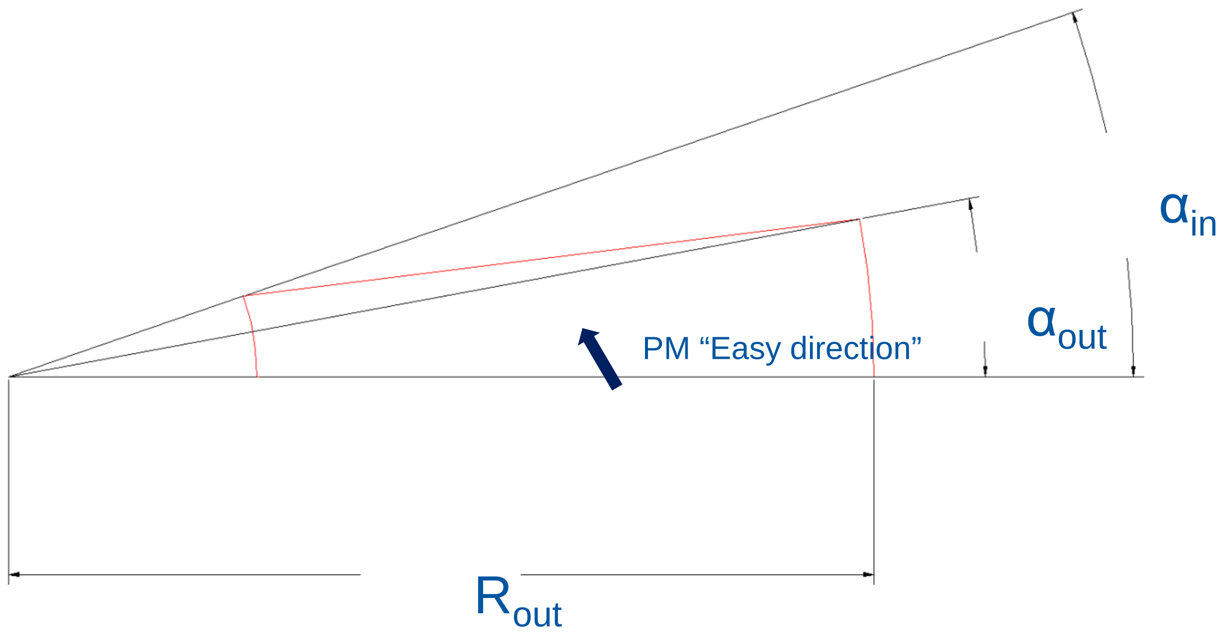
This slide shows a configuration for a MAXIMUM GRADIENT (~ 142 T/m);
Poles are wider, saturation appear in some areas, field quality is deeply affected (even in these IDEAL calculation (to be not forget!)



"red line" inside the aperture: area where ΔG/G ≤1 unit (good field region)

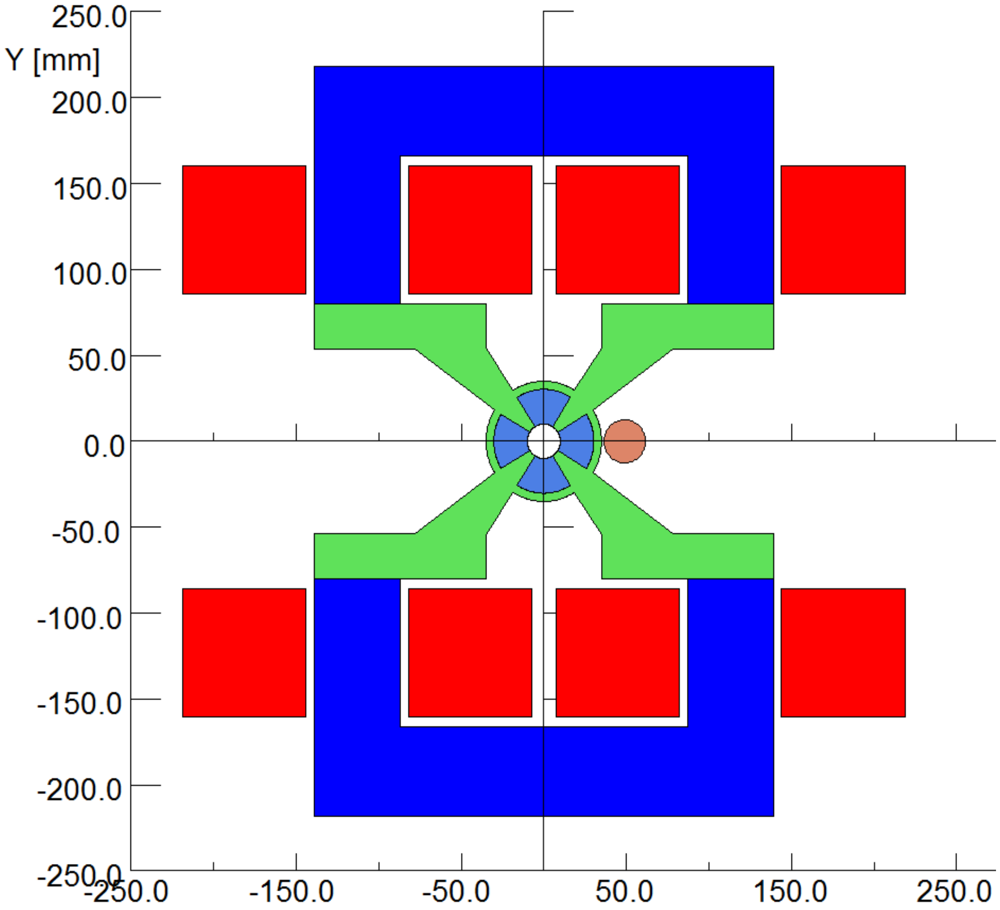
NI	A	1250	2500	3750	5000	6250	40000
Gradient	T/m	**44.14719**	**75.58737**	**111.0874**	**142.2917**	**155.2365**	**171.4439**
b6	units	58.93988	54.76554	48.30059	40.41387	36.75506	32.13193
b10		0.216246	0.14742	0.072838	0.023252	0.013356	0.011051
b14		0.001752	1.04E-03	0.000633	6.08E-04	6.24E-04	5.96E-04
b18		0.000583	5.37E-04	0.000473	3.95E-04	3.59E-04	3.13E-04

Examples of the optimization done on 3 parameters (α_{in}, α_{out}, $\uparrow_{easy\ dir}$) (R out=30 mm).
The sets of values that maximize field quality are 32° for both α_{in}, α_{out}, and 55 ° for the easy dir. (1st Table)



outer angle	inner angle	easy direction	Gradient, T/m	b6, units	b10, units	b14, units	b18, units	abs(b6)
32	32	55	-125.6883919	-0.018011928	0.021495857	0.001156133	-5.42639E-06	0.018011928
14	33	37	-109.7656866	0.035278019	0.020945055	0.000970438	-1.71047E-06	0.035278019
28	28	32	-128.8464878	-0.069765144	-0.102218168	0.001223987	7.28026E-06	0.069765144

outer angle	inner angle	easy direction	Gradient, T/m	b6, units	b10, units	b14, units	b18, units
33	13	32	-142.2927103	40.41430891	0.020803327	0.001981567	-0.000987569
33	13	34	-142.2817507	40.80280099	0.024709188	0.002024723	-0.000996354
33	12	30	-142.2787609	41.64605989	0.039128861	-0.002075543	0.000436098



A basic sketch of the hybrid QD0 adapted to the ILC parameters:
- Coils are sized for a current density J of ~0.9 A/mm
- Overall cross-section dimensions should be inside 500 x 500 mm.

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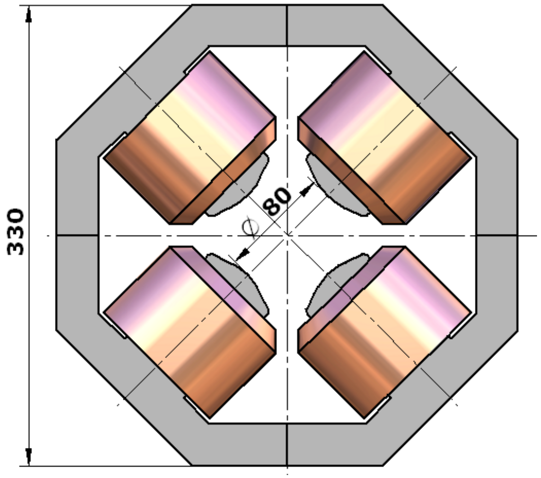
Requirements for QF1 and QD0 *

*H. Garcia, E. Marin. R. Tomas. “ATF2 QD0FF and QF1FF specifications”, CERN, 26/07/2011.

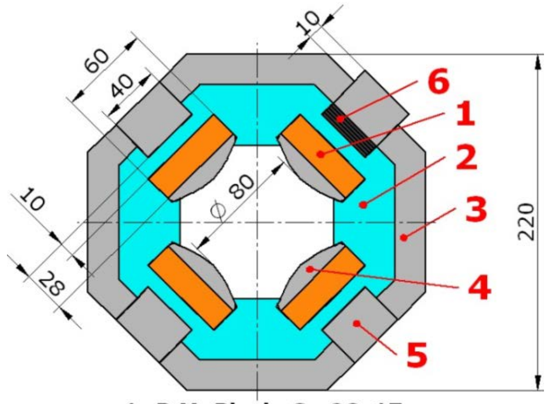
Magnet Name	**QF1FF**	**QD0FF**	**Units**
Gradient Nom. / Ultra low	6.772 / 6.791	12.45 / 12.46	T/m
Magnetic length	475		mm
Nom. Integrated gradient	3.226	5.919	T
Tuning range	±5		%
Aperture radius	> 35		mm
Good Field Region radius	20		mm
Constrains	Top half of the magnet has to be dismountable		
Field quality requirements			
Harmonic №:	Skew an=An/B2	Normal bn=Bn/B2	
3	0.124	0.748	units@r_{GFR}
4	0.344	4.12	units@r_{GFR}
5	0.665	2.76	units@r_{GFR}
6	1.57	9.82	units@r_{GFR}

Magnet design options

1) EM quadrupole:

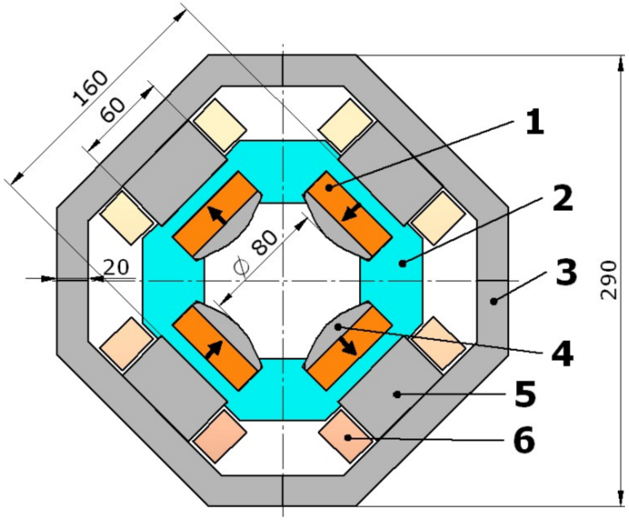


2) PMQ



1- P.M. Block, Sm_2Co_{17}
2- Aluminium core
3- Return Yoke, AISI 1010
4- Pole Tip, AISI 1010
5- Tuning block, AISI 1010
6- Spacers, Stainless steel

3) Hybrid (based on PMQ)



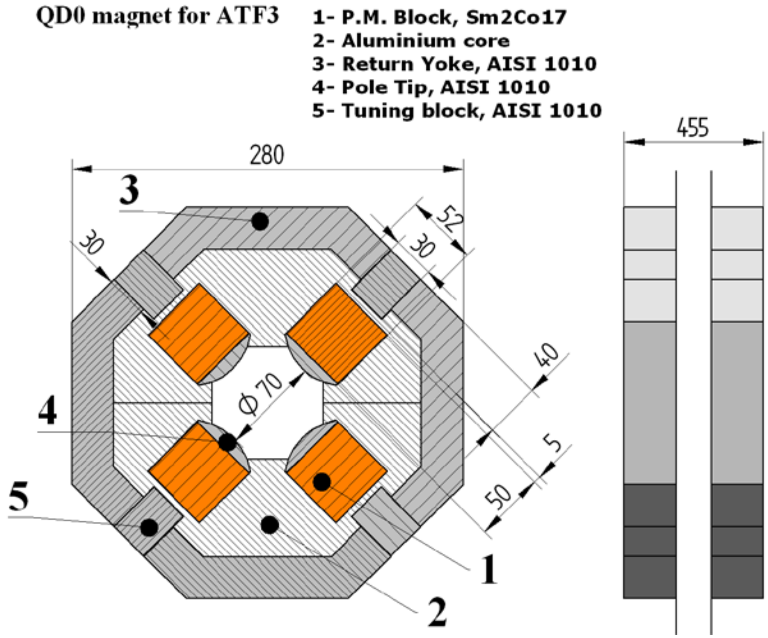
The PMQ solution looks preferable in respect of the EMQ due to the following reasons:

- Compactness.
- No vibration of the magnet induced by an active water cooling system.
- No risk of problems/failures in the power supplies (increases reliability).
- Maintenance of cooling system, power supplies coils is not required.
- Set to zero operational costs related to electrical energy and cooling systems.
- PMQ can be assembled from one or two pieces, while for the EMQ option four pieces yoke structure seems necessary.
- The proposed PMQ design has an ability to suppress the possible higher order multipole errors performed by the tuning blocks, while for the EMQ and the hybrid cases an additional trim coils and four independent power supplies are needed.

The Hybrid solution looks preferable if gradient tuning is required frequently and during operation:

- Coils could be water cooling free but this depends by the working parameters (aperture and gradient needed) and by eventual limitations in dimensions and weight.

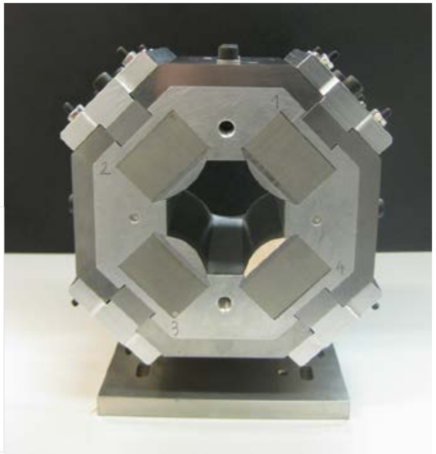
QD0 PMQ: Permanent Quadrupole Magnet (PMQ) with adjustable strength



1. P.M. blocks -as a flux generators
2. Aluminum ring (made in a 2 pieces: only 3 degree of freedom) -as a support structure, p.m. blocks and pole nose will be mechanically clamped by this ring.
4. Pole tip made of soft iron material- to smooth the effects of possible differences, among the p.m., in terms of easy axis orientation.
5. Tuning blocks (movable mechanically at 10 mm (max), independently per pole) - to compensate the possible p.m. inequalities, to set the field gradient (max at 12.5% from the nominal value), to suppress the sextupole field components b3,a3
6. Spacers the exact position of the block will be regulated by the non-magnetic spacers of different thickness.

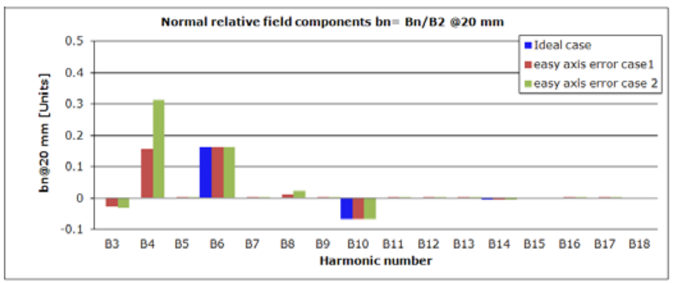
	QD0
Aperture radius	35 mm
Magnet length	475 mm
Yoke height ×width × length	280 mm × 280 mm × 455 mm
Magnet weight	165.3 kg
Effective length	473.1 mm
Nom. field gradient at Z=0 mm	12.5 T/m
Nom. Integrated field gradient	5.91 T
Tuning range	7%

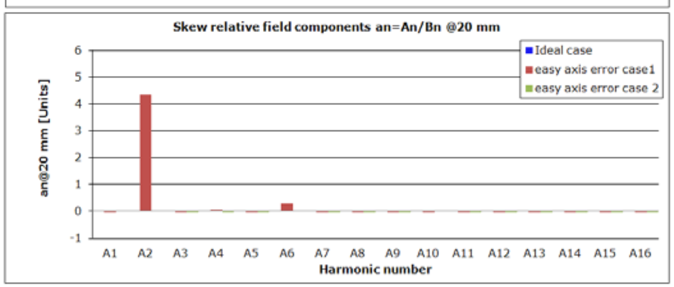
Ex. a smaller prototype built for LINAC4:
Aperture: 45 mm
Gradient: 16 T/m



Field quality aspects:

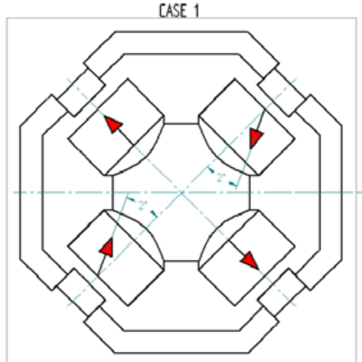
2. P.M. easy axis orientation errors:
The effects of possible permanent blocks inequalities due to the easy axis orientation errors were computed by introducing an angular deviation from the nominal value in the range of ± 2^0, representing an upper limit according to the permanent magnet blocks manufacturer



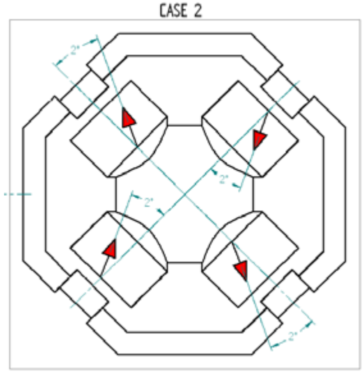


(Computation: courtesy A. Vorozhtsov)

CASE 1

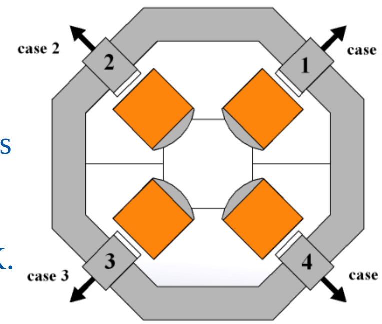


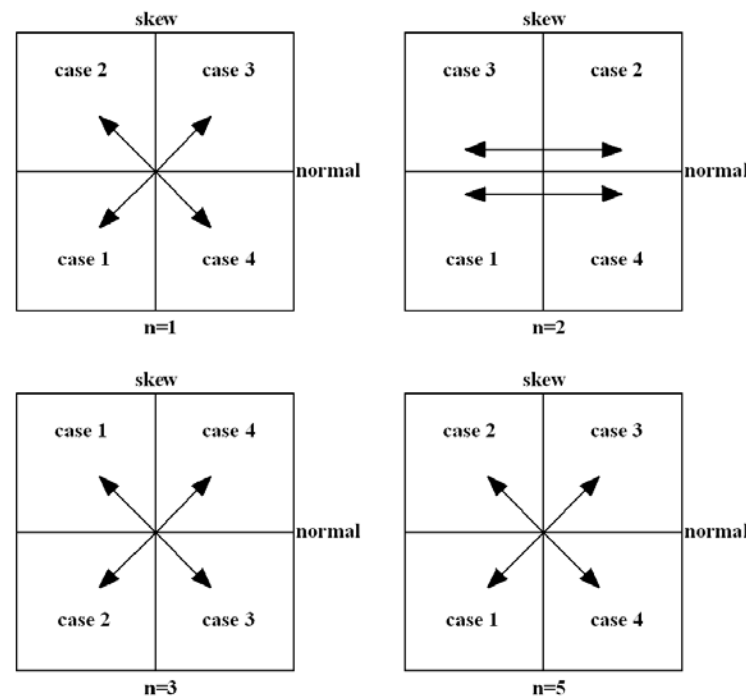
CASE 2



1. Field components suppression: field components can be suppressed by tuning of magnetic reluctance on each individual pole performed by radial offset of the tuning blocks (at 45^0, 135^0, 225^0, and 315^0) .

Vectors of field components in normal-skew phase plane, generated by tuning blocks for the four cases (K. Halbach**):





** K. Halbach "First order perturbation effects in iron-dominated two-dimensional symmetrical multipoles", 1969

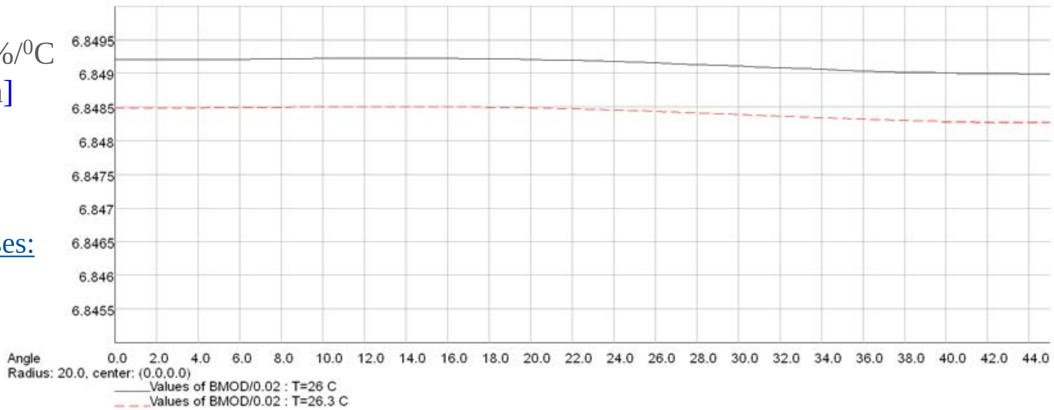
Magnet stability (Temperature dependence)

Temperature at installation site estimated at T=26 ^{0}C, Temperature variation : $\Delta T = 0.3\ ^0C$

Permanent magnet material :Sm2Co17 RECOMA® 30S

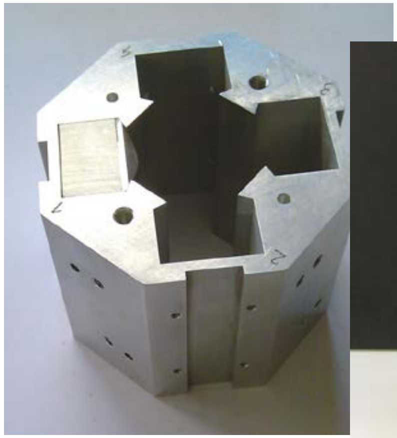
- Reversible temperature coefficient of Br = -0.035%/^{0}C
- Br=1.12 [Tesla] @ 20^{0}C => Δ Br ≈ 1.2×10^{-4} [Tesla]

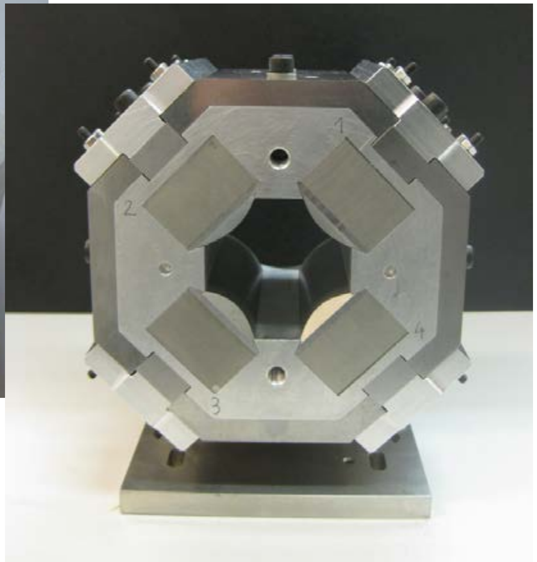
Field gradient QF1 for two simulation cases:
1) T=26 ^{0}C
2) T=26.3 ^{0}C



An experimental work was done last year at CERN on this subject:
CERN, TE-MSC Internal Note 2012-17 EDMS Nr: 1240879:

A. Bartalesi, R. Chritin, M. Modena: «Experimental Test to determine the Magnet Reversible Temperature Coefficient for a Permanent Magnet Quadrupole».





The main conclusions of the work were:

1. A "magnet reversible temperature coefficient" is determined for the PM quadrupole and estimated as −0.041 % per °C

2. The phenomenon is linear and there are no hysteresis effects on the ferromagnetic elements of the magnet. This is probably due to the relatively small range of temperature investigated (from 20 to 30 °C), which lead to very small changes in gradient.

Outline:

1) CLIC QD0 status

2) CLIC SD0 Status

4) A hybrid QD0 for ILC ? (basic conceptual design)

5) Upgrade of QD0 for ATF

6) OCTUPOLES for ATF

We were recently contacted for a possible contribution to future ATF program with 2 octupole magnets, (R.Tomas Garcia: private communication on 22 July 2013).

The required field quality is not yet fully defined, magnets is asked to be “very good” from that point of view and field quality will be specified at a 20 mm radius.

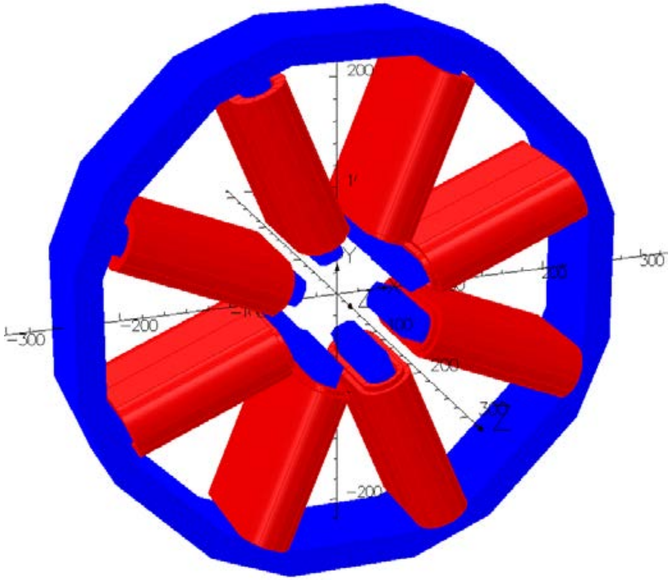
PARAMETER	*UNITS*	*VALUE*
Nominal Gradient,	**T/m^3**	**5284**
Required tunability	**%**	**-75, +20**
Integrated gradient	**T/m^2**	**560**
Aperture radius	**mm**	**50**
Iron length	**m**	**0.100**
Magnetic length	**m**	**0.106**
Coil number of turns		**61**
Conductor size	**mm x mm**	**5 x 5**
Ampere-turns	**A**	**1200**
Current	**A**	**19.7**
Resistance (per coil)	**mΩ**	**14**
Conductor length (per coil)	**m**	**19.9**
Conductor mass (per coil)	**kg**	**4.5**
Yoke mass	**kg**	**56**
Total mass	**kg**	**92**

With these information it was possible to define a conceptual magnetic design, taking into account the following aspects:

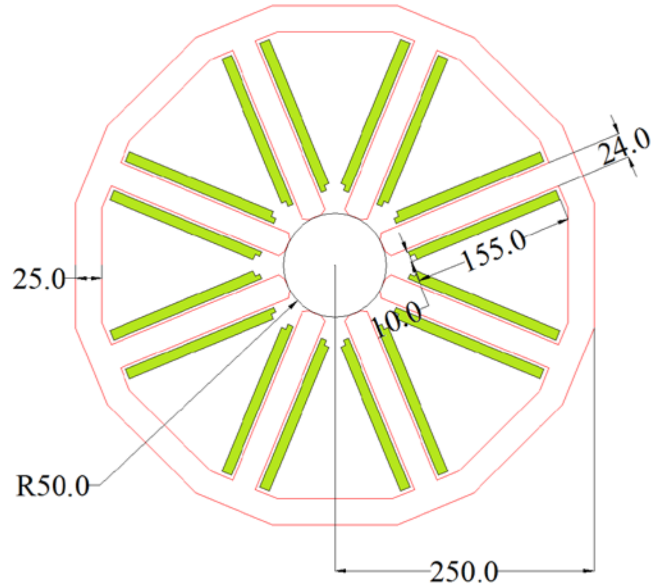
- To get the best field quality we intend to limit the yokes part to a minimum (possibly two half-yokes)
- The magnet aperture will be relatively big for the following reasons:

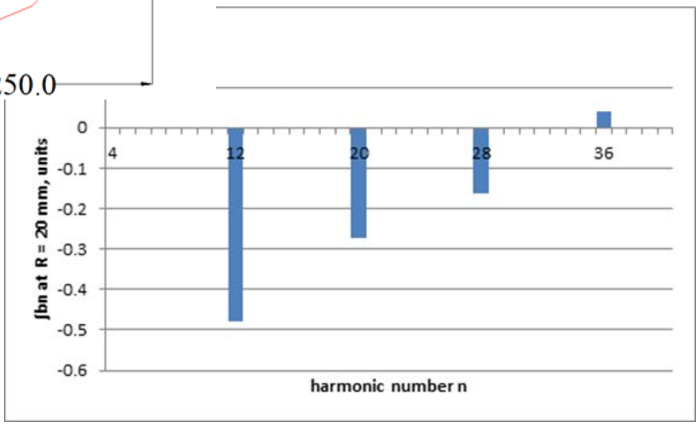
a. To avoid working with too low saturation (at -75% working point)
b. To be able to insert the coils in only two half-yokes
c. To improve the field quality at 20 mm radius.

- The outer radius is big in order to utilize coils with low current density.



(Computation: courtesy A. Aloev)





The achievable field quality should be excellent (less of 1 unit for permitted harmonics computed).

Similarly to QD0/SD0 magnet, we plan to procure the main components and do at CERN the coils and the final assembly.

A cost estimation is also on-going.

Conclusions

- **CLIC QD0:**
- \- Prototype procured in 2011-12 shows very good results from the point of view of magnet design concept and performances (SmCo).
- \- An open point is with the quality of one set of PM blocks (NdFeB). We just take the decision to procure a "turn key" Helmholtz coil system (1D) to quickly investigate the blocks.
- \- Others QD0 design key aspects (longitudinal assembly of modules, sorting of PM blocks, etc.) will be now investigate with the SD0 design and procurement.

- **CLIC SD0:**
- \- Procurement decided; we are now finalizing the mechanical design.
- \- In comparison to the QD0, more investigation and optimization towards field quality are on-going (this is also due to improving interactions with and advancement of beam physic Team studies: (Rogelio et al.).

- **Hybrid QDO for ILC?:**
- \- A conceptual magnetic design (CLIC QD0 design scaled to ILC geometric and strength parameters) was done. Achievable field quality aspects were also taken into account showing possible optimization of design parameters. We are available and very interested to go on with this design, eventually procuring a short prototype if this considered interesting by the ILC/CLIC community.

- **QD0 and Octupoles procurement for ATF:**
- \- Conceptual magnetic design available for both magnets. QD0 performance and tuning method under evaluation (tightly linked with magnet parameters as the acceptable minimum aperture).
- \- Even in this case we are waiting comments and further definition of requirements from the ATF community, and we are very interested to go on with design and procurement.

Thanks