CERN experience with PM magnet design and assembly inside CLIC Final Focus system R&D and with other PM based magnet assembly.

M. Modena, CERN

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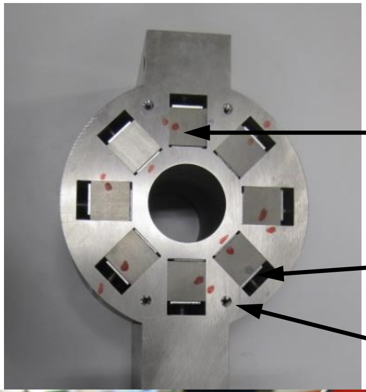
Content:

- *Some general experience of CERN in PM magnet design (information courtesy of P. Thonet)*
- *The experience within CLIC QD0 prototype*
- *The experience within CLIC SD0 prototype*

Some recent CERN experience in designing and assembling PM based magnets (courtesy P. Thonet):

- LINAC4 "iron-free" quadrupoles:

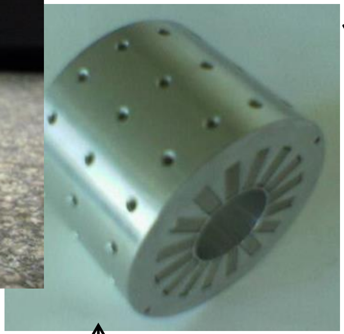


(14 units, G: 11-16T/m, different for each quad)

Permanent magnet block (Sm2Co17)

Non magnetic shims (austenitic steel 316LN)

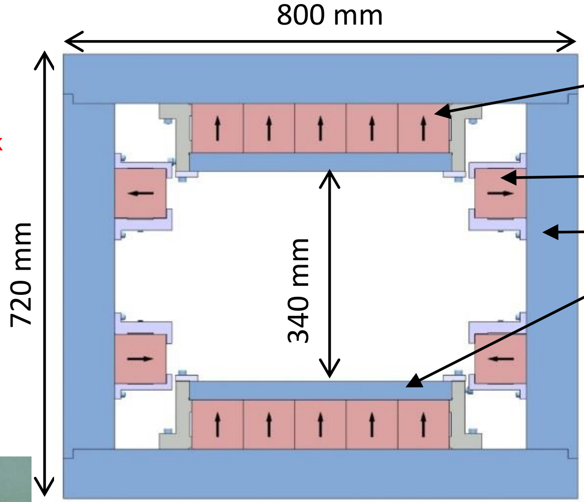
Non magnetic yoke (austenitic steel 316LN)



LINAC4 PMQS Quadrupoles (in DTL)

- *"In vacuum" functioning*
- *1.2-2.4 T integrated grad.*
- *Sm_2Co_{17}*
- *316 LN structure*

- "n-Tof" dipole: (0.25 T; 168 PM blocks !)



PM block Sm_2Co_{17}, as a flux generator

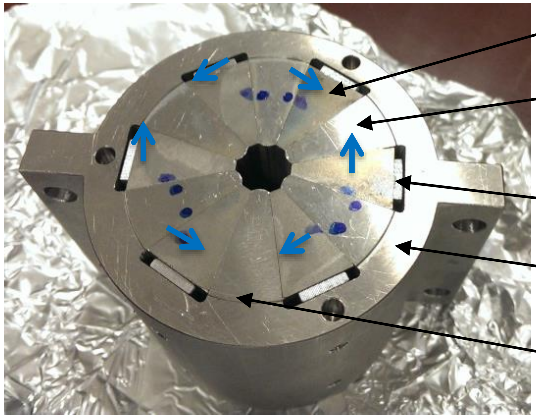
PM block to improve field quality

Return yoke low-carbon steel

Pole tip to smooth in PM block magnetization direction

- ASACUSA sextupoles (two units installed INSIDE the high vacuum spectroscopy beam line, G= 114480 T/m²)

72 mm



PM block Sm_2Co_{17}, as a flux generator.

Pole Fe-Co, to canalize magnetic flux and assure field quality.

Shim 316LN non magnetic austenitic steel but possibility to insert iron shims to adjust the sextupole field.

External yoke Titanium T40, non magnetic to hold the poles together and to guarantee the good geometry.

Vacuum brazing Gapasil filler.

Content:

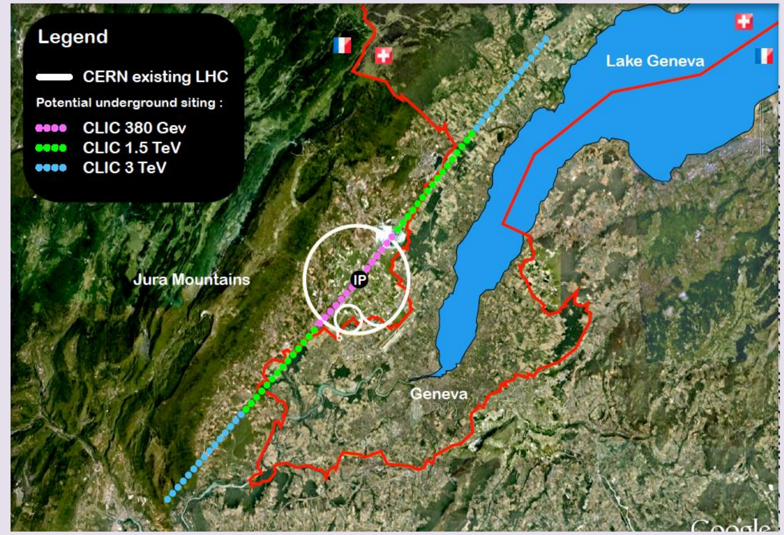
- *Some general experience of CERN in PM magnet design (information courtesy of P. Thonet)*
- *The experience within CLIC QD0 prototype*
- *The experience within CLIC SD0 prototype*

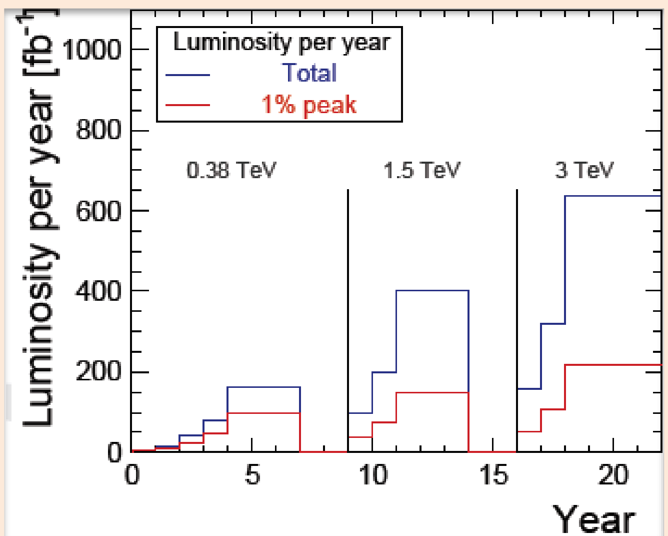
CLIC Staged Scenario:

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

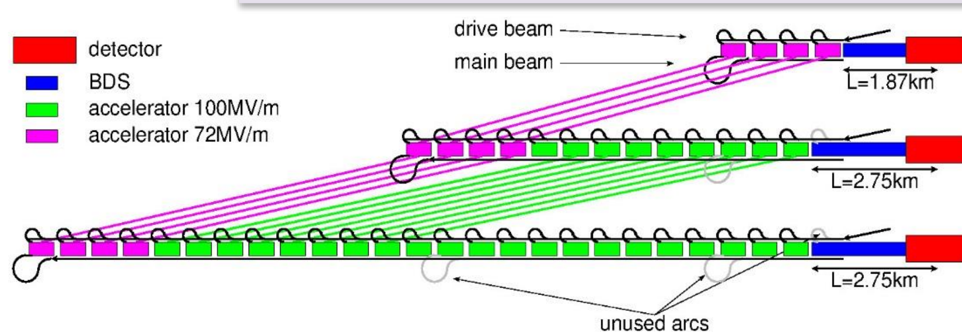
Luminosity targets from Physics Study group
Hopefully input from LHC

Central complex on Prevessin site





Luminosity evolution



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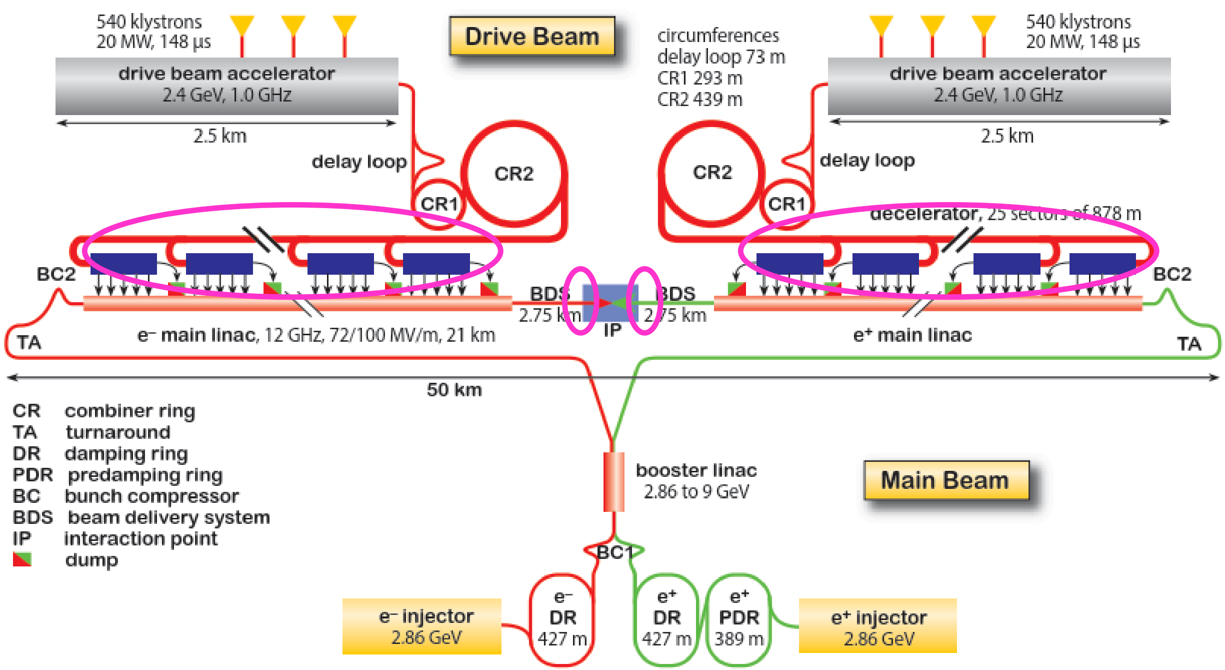
("Future Accelerator Machines", EPS 2017, D. Schulte)

all info on CLIC at: http://clic-study.web.cern.ch/

New CLIC layout at 3 TeV



- Removed 1 e$^-$-damping ring
- 50 km length instead of 48 km
- 25 sectors instead of 24 sectors, ...

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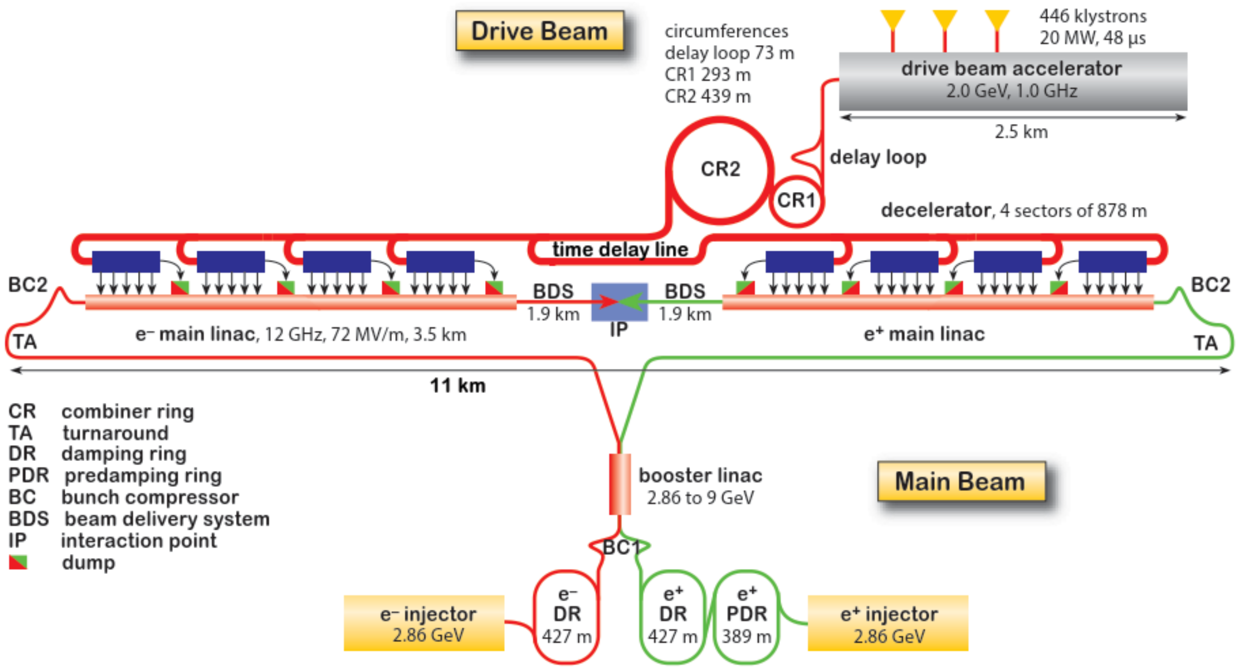
New CLIC layout at 380 GeV



- Removed 1 e^--damping ring
- 11 km length (instead of 13 km at 500 GeV)
- 4 sectors (instead of 5 sectors at 500 GeV), ...

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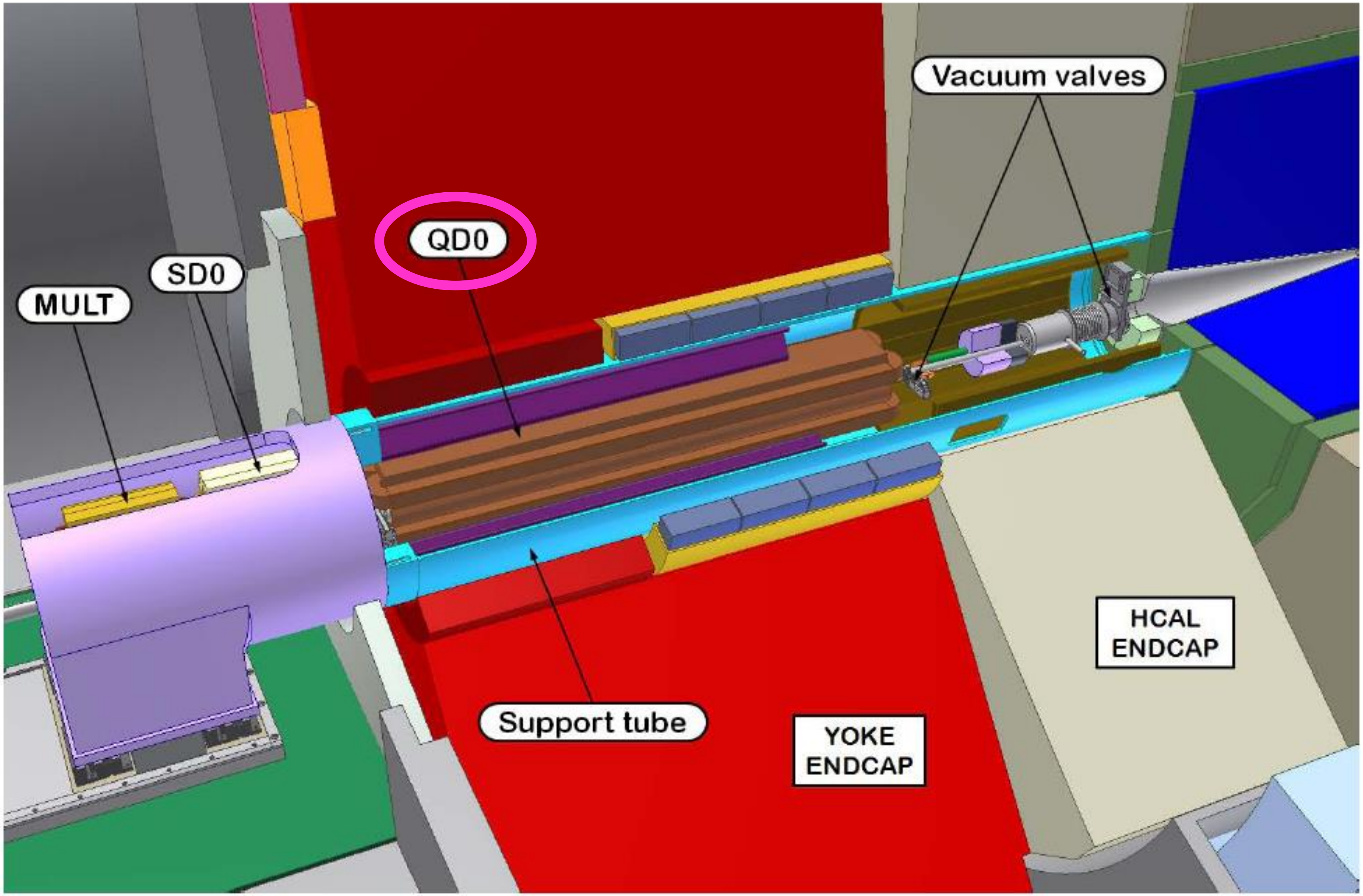
QD0 located INSIDE the Detectors (L=3.5 m layout):*



*(QD0 integration in MDI: courtesy of **H.Gerwig/N.Siegrist**)*

the main requirements for QD0:

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

QD0 study & design requirements :

To develop a high gradient quadrupole towards a required nominal gradient value of 575 T/m.

Magnet design must be compatible with:

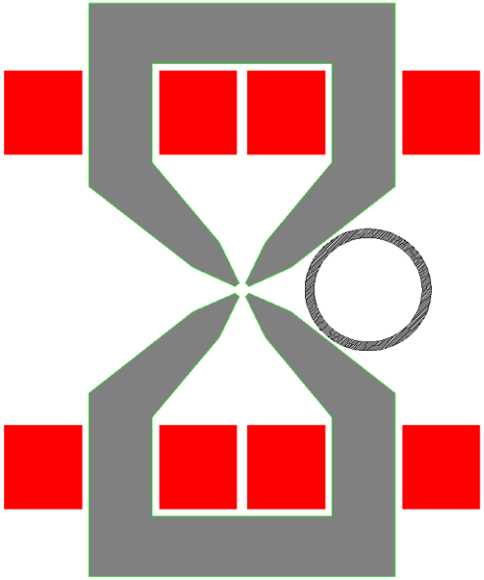
-**Active stabilization** (i.e. vibration and weight)

-Presence of the **post-collision line beam vacuum chamber** (at its closer position: 35 mm from main beam axis)

- As much as possible **compact design** (to be compatible with an L* of 3.5 m, so minimizing the solid angle subtracted to the Detector)

QD0 *evolution of prototype design*

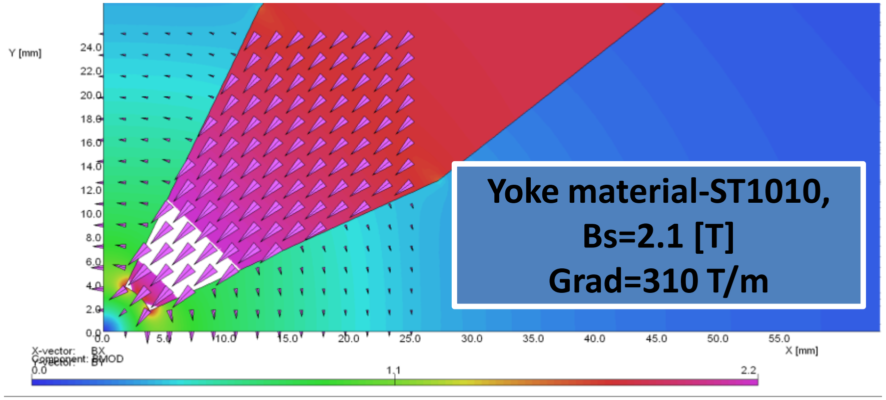
"Pure electro-magnetic" approach:



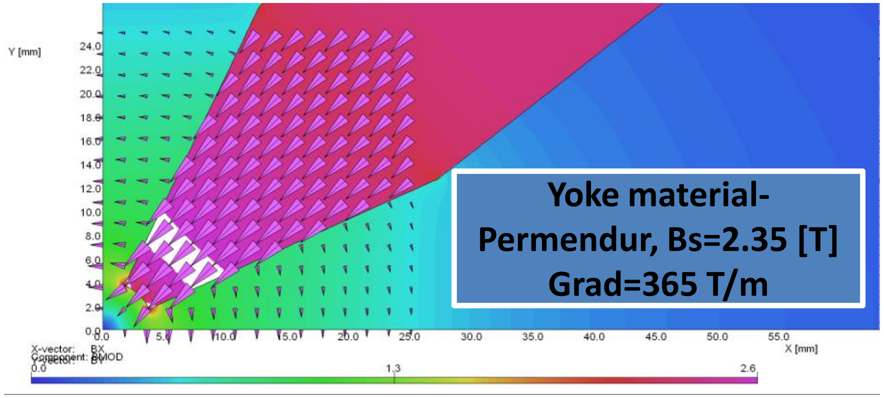
- **"8 shape" or "two leaves"** quad. design: (it permits to accommodate the post-collision beam vacuum chamber)

- **magnetic saturation** appears in the poles with both material proposed

Note: "Permendur" is a Fe-Co alloy (50%-50%) characterized by a higher magnetic flux saturation comparing to the classical low-carbon magnetic steels.



(NI= 5000 A)



(Opera 2D/3D simulations: courtesy of ***A.Vorozhtsov****)*

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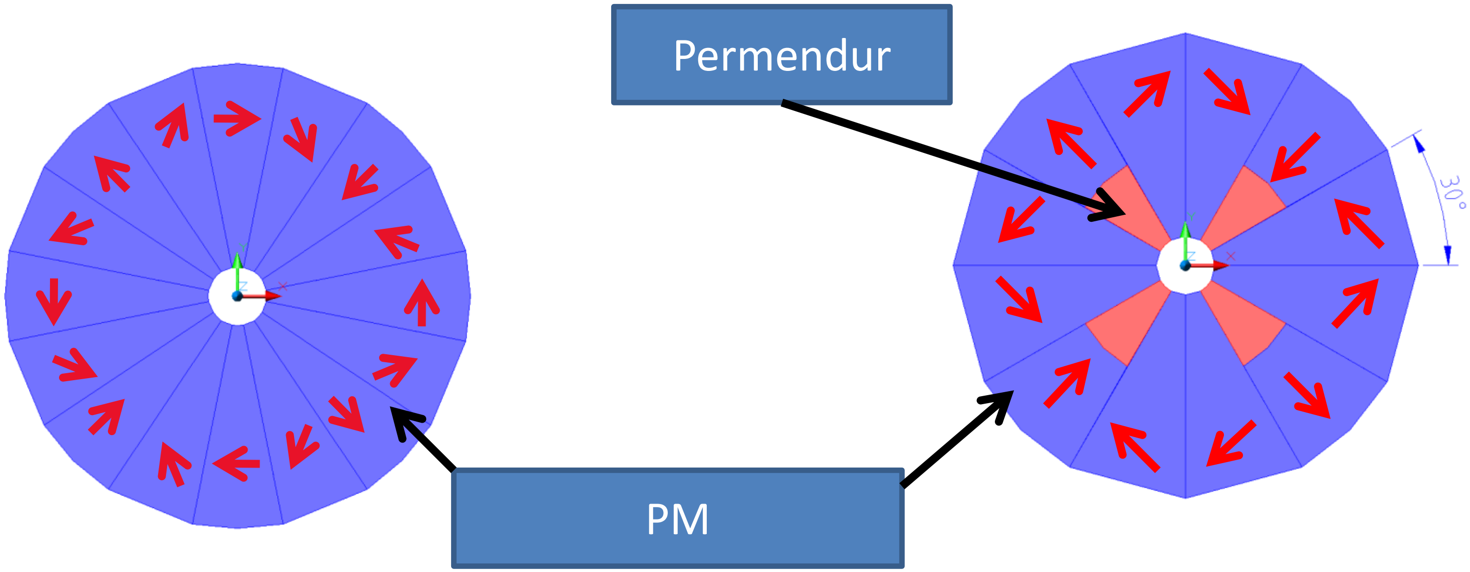
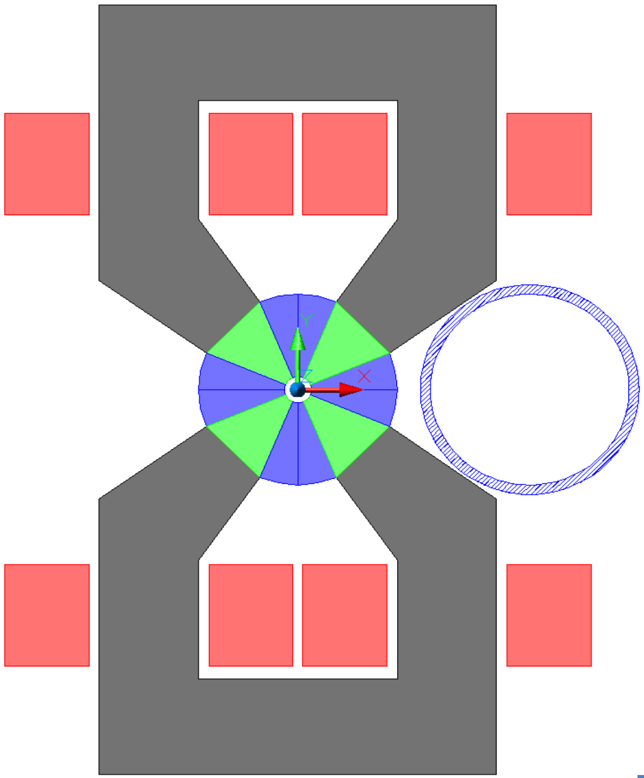
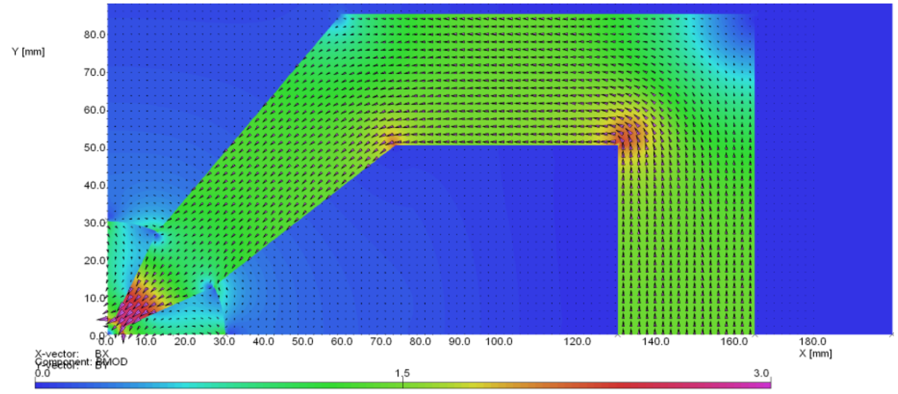
“Pure PM” approach: Halbach vs. SuperStrong:

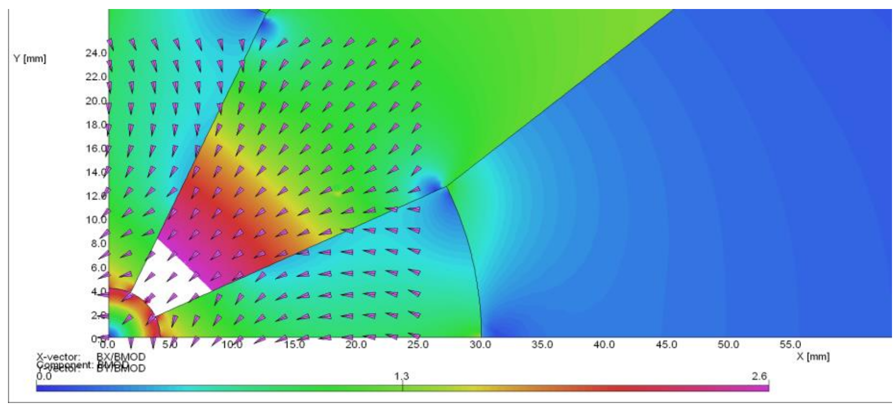


	R=3.8 [mm] (no chamber)		R=4.125 [mm]	
Material	Sm_2Co_{17}	$Nd_2Fe_{14}B$	Sm_2Co_{17}	$Nd_2Fe_{14}B$
Grad [T/m] “Halbach”	450	593	409	540
Grad [T/m] “Super Strong”	564	678	512	615

“Hybrid” design Version 1:







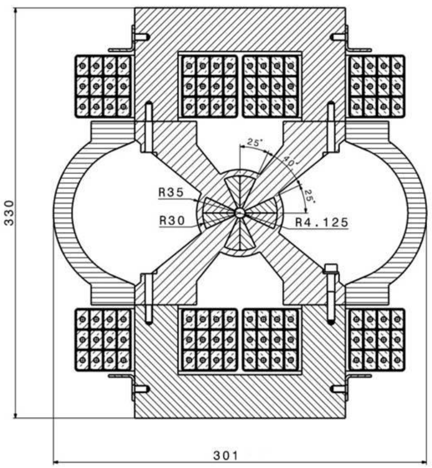
-Presence of PM wedges reduce strongly saturation in the poles

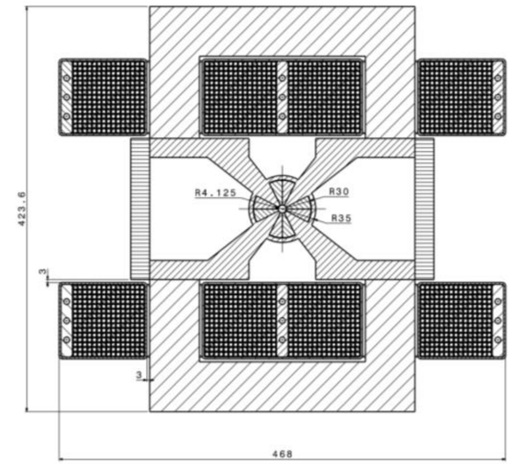
→Max Gradient increase of a factor 1.5-1.68

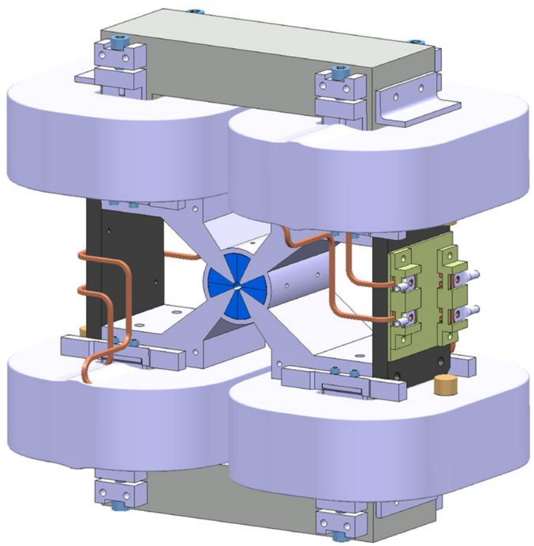
Of course, **tunability** is the other most interesting aspects of this configuration

	Iw=5000 [A]
Grad [T/m] Sm_2Co_{17}	550
Grad [T/m] $Nd_2Fe_{14}B$	615

further evolution and final prototype design:





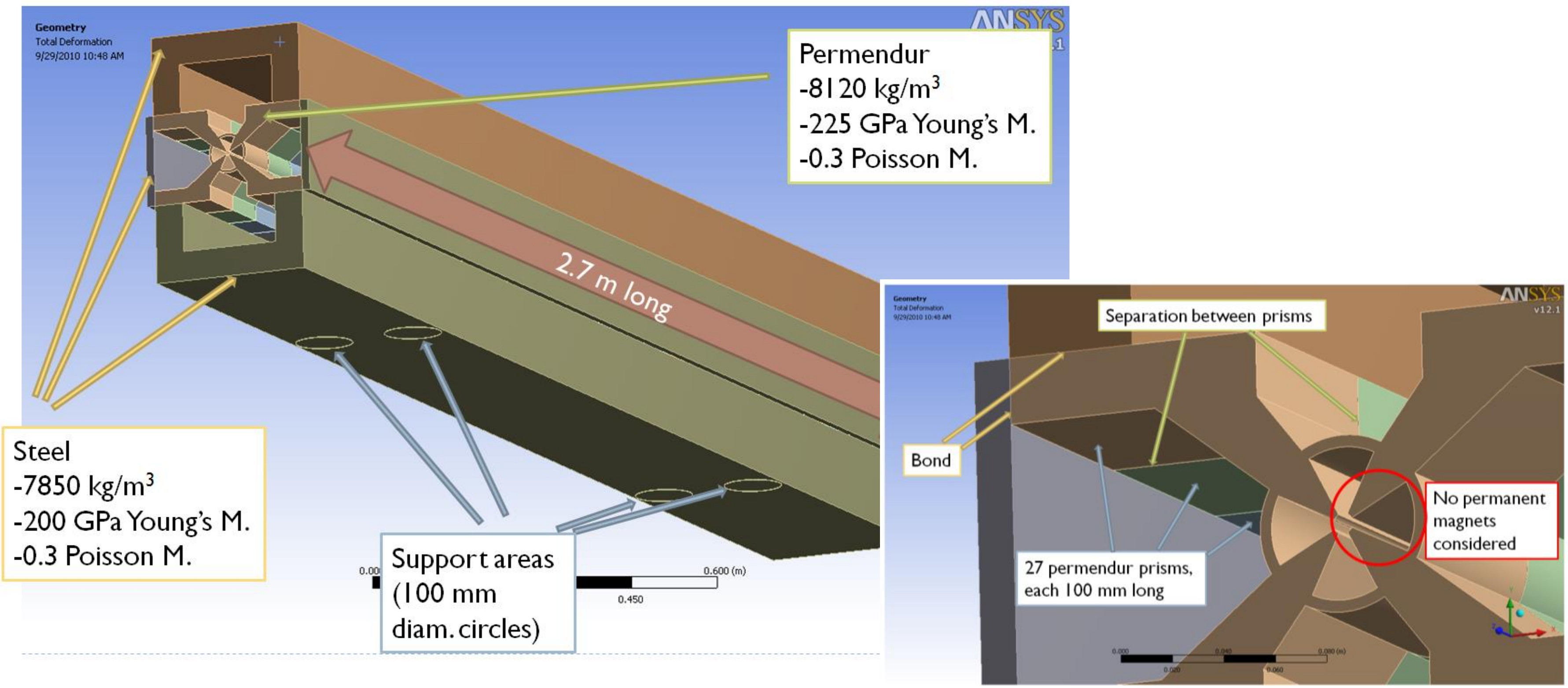


	Iw=5000 [A]
Grad [T/m] Sm_2Co_{17}	531
Grad [T/m] $Nd_2Fe_{14}B$	599

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

design toward a full size QD0: a modular structure

<u>- Extrapolation of the QD0 short prototype design to a longer (full size) magnet</u> seems in principle possible, first basic mechanical assessments were done in this direction.
- Depending by CLIC R&D evolution and priorities, we could imagine to procure in the future a longer/middle-size prototype to investigate and check the aspects link to the performances of a "modular assembly" done by a very precise assembly of several shorter QD0 modules-like elements.



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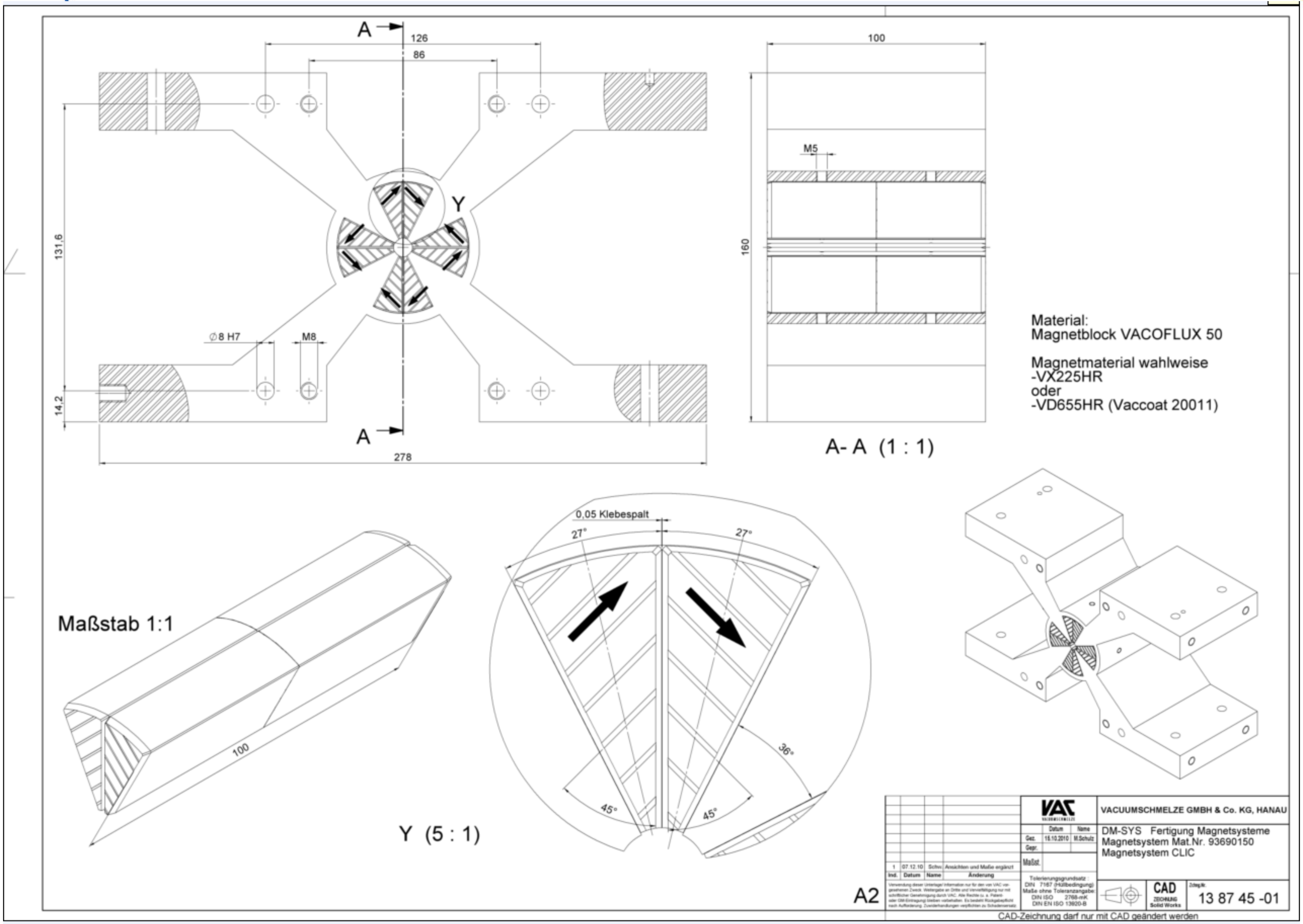
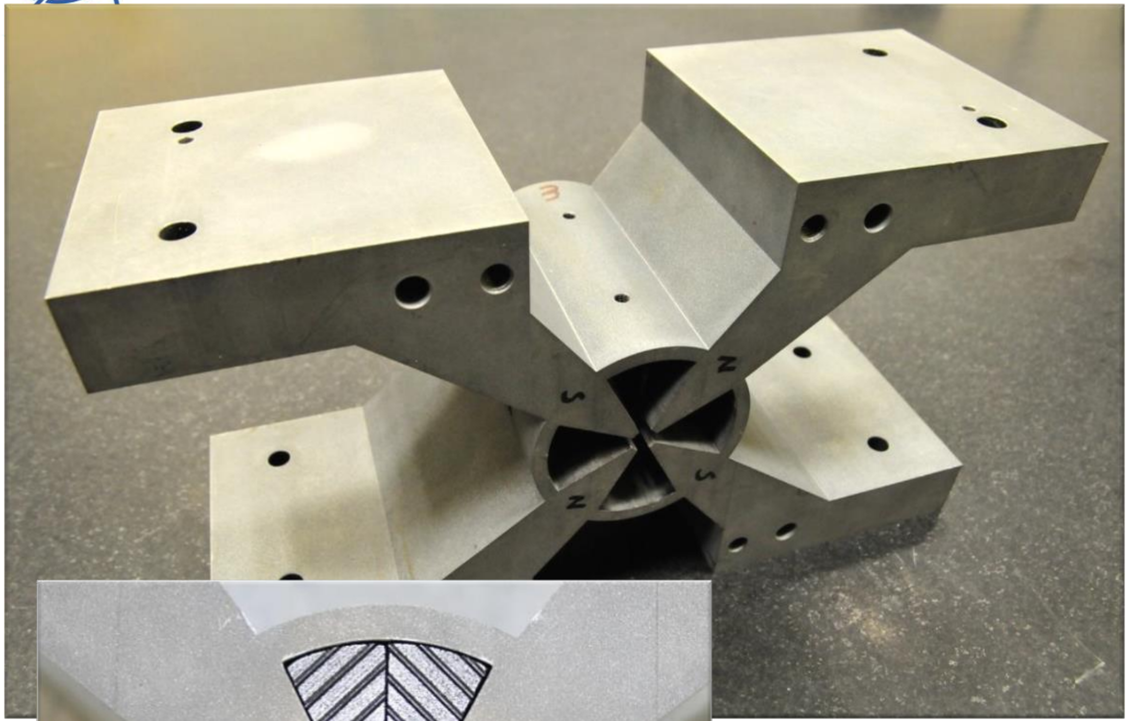
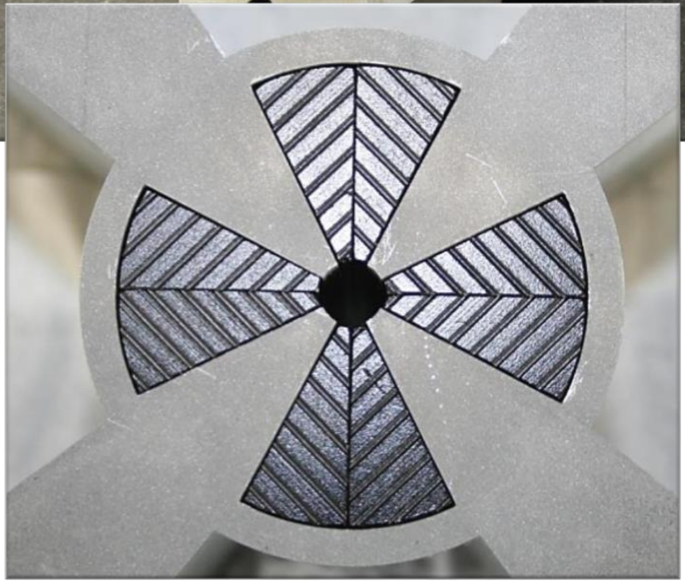
Procurement and assembly

procurement of main components:







Permendur part and PM blocks produced by Electric Discharge Machining (EDM) technique at Vacuumschmelze (D).

(Remind that each of the four PM block is in fact composed by 4 sub-blocks glued together.
A billet of Permendur was produced ad hoc in order to have the right dimensions, controlled quality and isotropy).

These components (plus the extracting/inserting tooling) were delivered in Summer 2011

reception of main components at CERN Metrology Lab:

PIECE : FOCUSING MAGNET PERMENDURE RING

CERN - METROLOGIE

No EDMS 1147865

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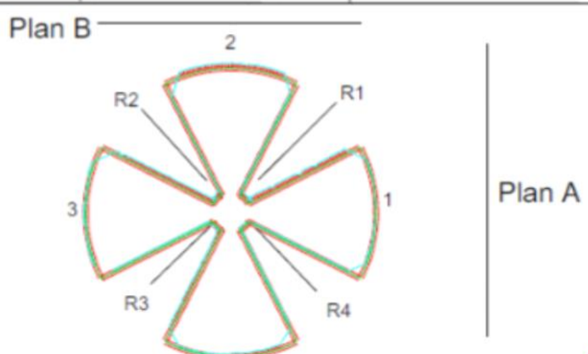
Controleur : Lilian REMANDET	Plan No : CLIMQYAA0001
Client : P. THONET	Fournisseur :
Machine : Ferranti	Piece No : Pièce 01
Temperature : 20°C ±1°C	Date : 10/06/11 15:23:46
Precision des mesures : ± 3 µm	Nom du programme : CLIMQYAA0001 FOCUSING MAGNET RING

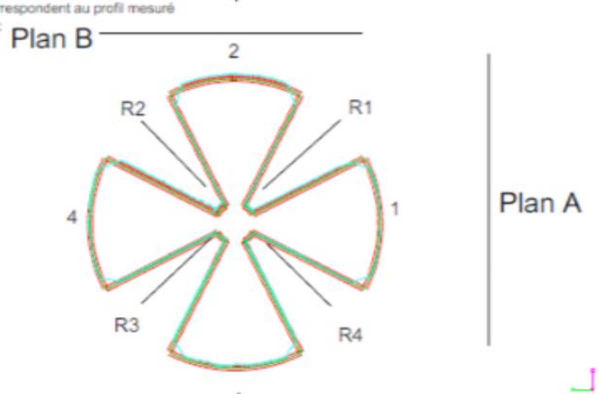
CONCLUSION CONTROLE	VISA MME	ACCEPTATION CLIENT
OK	NOM :	NOM :
X NON CONFORME	DATE :	DATE :

Vue VUE-SECTION-10MM/C



Les courbes rouges correspondent aux tolérances ±0.01
Les courbes vertes correspondent au profil théorique
Les courbes bleues correspondent au profil mesuré

Vue VUE-SECTION-90MM/C



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	Référence	Théorique	Mesuré	Tol -	Tol +	Ecart	Tendance
Mesure des références et de leurs défauts de forme associés							
PLTE-PLAN-A Planéité PLAN-A							
	PLAN	0.000	0.013		0.050	0.013	
PERP-PLAN-B/0.05/A Perpendic. PLAN-B/PLAN-A - Zone P - Nuage de points							
	PERP	0.000	0.013		0.050	0.013	
PERP-PLAN-C/0.1/A Perpendic. PLAN-C/PLAN-A - Zone P - Nuage de points							
	PERP	0.000	0.032		0.050	0.032	
PERP-PLAN-C/0.1/B Perpendic. PLAN-C/PLAN-B - Zone P - Nuage de points							
	PERP	0.000	0.023		0.050	0.023	
Mesure de la localisation 0.05 CZ / A / B du plan opposé à A							
LOCA-PLAN-OPPOSE-A/0.05/A/B Localis. PLAN-OPPOSE-A/NOMINAL - REP-ABC - Zone P - - Nuage de points							
	LOCA	0.000	0.025		0.050	0.025	
PERP-PLAN-OPPOSE-A/0.1/C Perpendic. PLAN-OPPOSE-A/PLAN-C - Zone P - Nuage de points							
	PERP	0.000	0.018		0.100	0.018	
DIST-160 Distance PLAN-OPPOSE-A - PLAN-A / REP-ABC							
	D1	160.000	160.013	-0.025	0.025	0.013	
	D2	160.000	160.000	-0.025	0.025	0.000	
Evaluation des localisations des perçages Ø5H7 coté opposé plan A Perçage Ø5H7 coté opposé plan A - référence D							
CERC-Ø5H7-OPPA-D Cercle Critère : MOINDRES CARRES (en 18 pts sur NOMINAL)							
	DIAM	5.000	4.033	0.000	0.012	-0.967	-0.967
	X	70.000	70.036	-0.050	0.050	0.036	
	Z	-252.000	-251.956	-0.050	0.050	0.044	
	E.F.		0.011			0.011	
LOCA-Ø5H7-OPPA-D Localis. CERC-Ø5H7-OPPA-D/NOMINAL - REP-ABC - Zone C - XZ - Nominal							
	LOCA	0.000	0.114		0.100	0.114	0.014
Perçage Ø5H7 coté opposé plan A - localisé par rapport à D							
CERC-Ø5H7-OPPA Cercle Critère : MOINDRES CARRES (en 18 pts sur NOMINAL)							
	DIAM	5.000	4.031	0.000	0.012	-0.969	-0.969
	X	30.000	29.886	-0.050	0.050	-0.114	-0.064
	Z	-26.000	-25.982	-0.050	0.050	0.018	
	E.F.		0.010			0.010	
LOCA-Ø5H7-OPPA Localis. CERC-Ø5H7-OPPA/NOMINAL - REP-ABC - Zone C - XZ - Nominal							
	LOCA	0.000	0.232		0.100	0.232	0.132
LOCA-Ø5H7-OPPA-0.1/D Localis. CERC-Ø5H7-OPPA/CERC-Ø5H7-OPPA-D - REP-ABC - Zone C - Cote=229.512 - N...							
	LOCA	0.000	0.002		0.100	0.002	
Evaluation des localisations des perçages Ø5H7 coté plan A Perçage Ø5H7 coté plan A - référence E							
CERC-Ø5H7-A-E Cercle Critère : MOINDRES CARRES (en 18 pts sur NOMINAL)							
	DIAM	5.000	4.034	0.000	0.012	-0.966	-0.966
	X	30.000	30.013	-0.050	0.050	0.013	
	Z	-252.000	-252.002	-0.050	0.050	-0.002	
	E.F.		0.026			0.026	
LOCA-Ø5H7-OPPA-E Localis. CERC-Ø5H7-A-E/NOMINAL - REP-ABC - Zone C - XZ - Nominal							
	LOCA	0.000	0.026		0.100	0.026	
Perçage Ø5H7 coté plan A - localisé par rapport à D							
CERC-Ø5H7-A Cercle Critère : MOINDRES CARRES (en 18 pts sur NOMINAL)							
	DIAM	5.000	4.031	0.000	0.012	-0.969	-0.969
	X	70.000	70.134	-0.050	0.050	0.134	0.084
	Z	-26.000	-26.037	-0.050	0.050	-0.037	
	E.F.		0.017			0.017	

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first (partial) magnetic measurements:

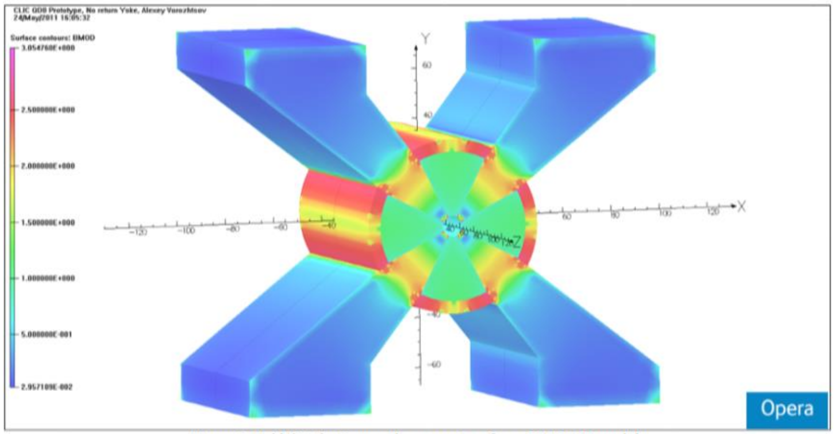
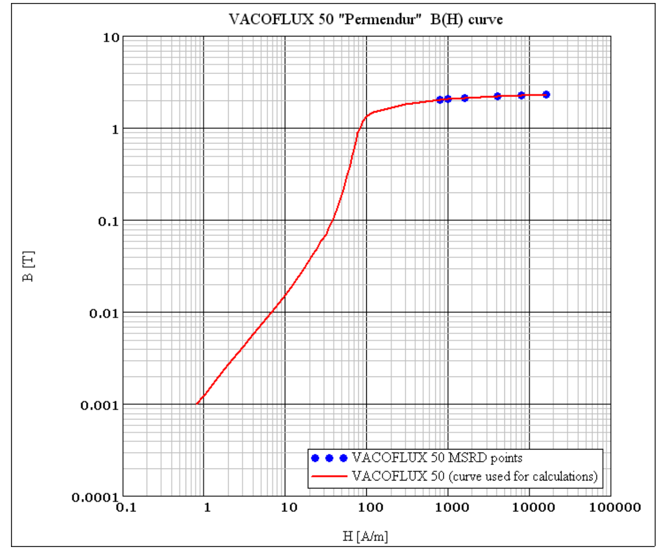
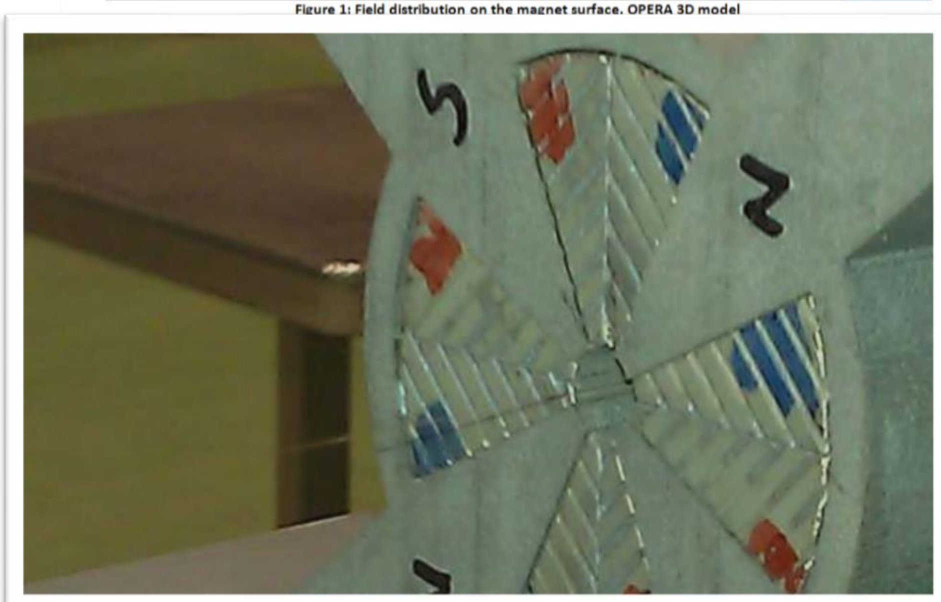

Structure: Only central part (P.M. blocks, Permendur structure) of the QD0 prototype was modeled as shown in Figure 1.

Figure 1: Field distribution on the magnet surface. OPERA 3D model





PM material type	Integrated gradient ∫Gdl [T]	
	MSRD	Calculated
VACOMAX 225HR (Sm_2Co_{17})	15.4	15.6
VACODYM 655HR ($Nd_2Fe_{14}B$)	20.3	21.2

*(magnetic measurements: courtesy of **C.Petrone and J. Garcia**)*

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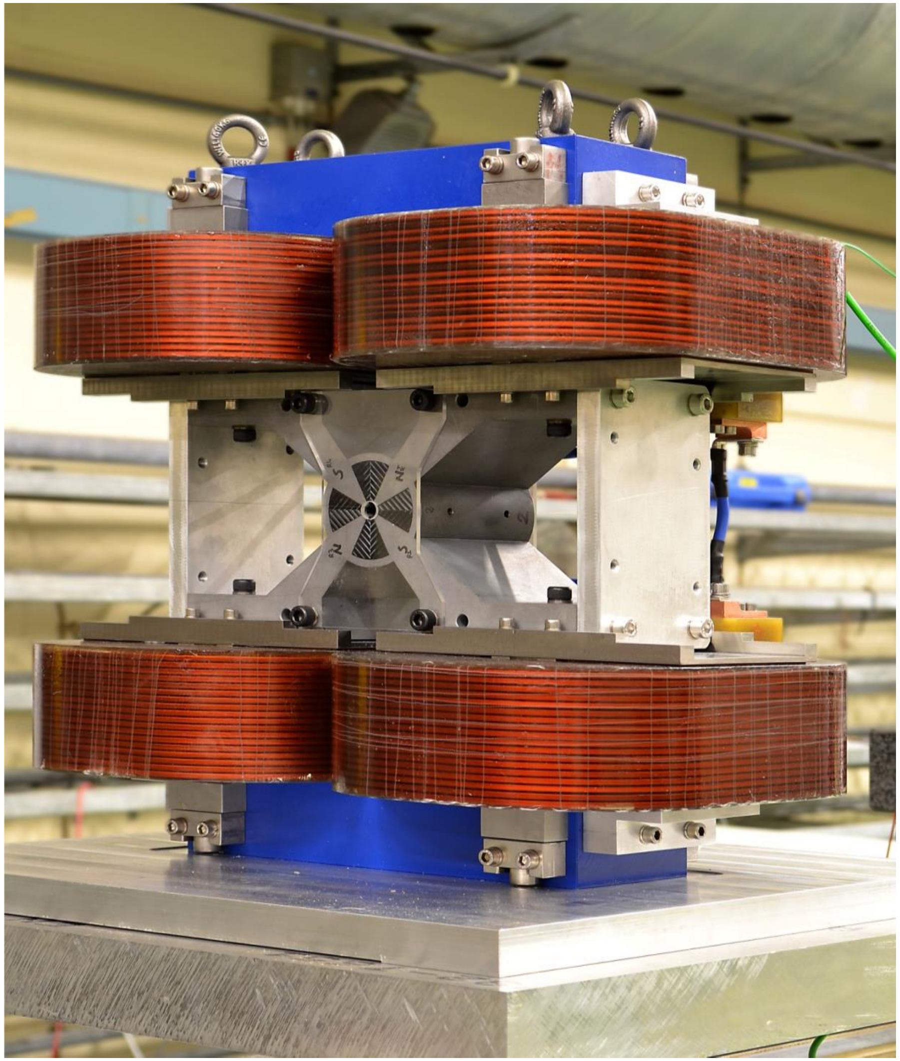
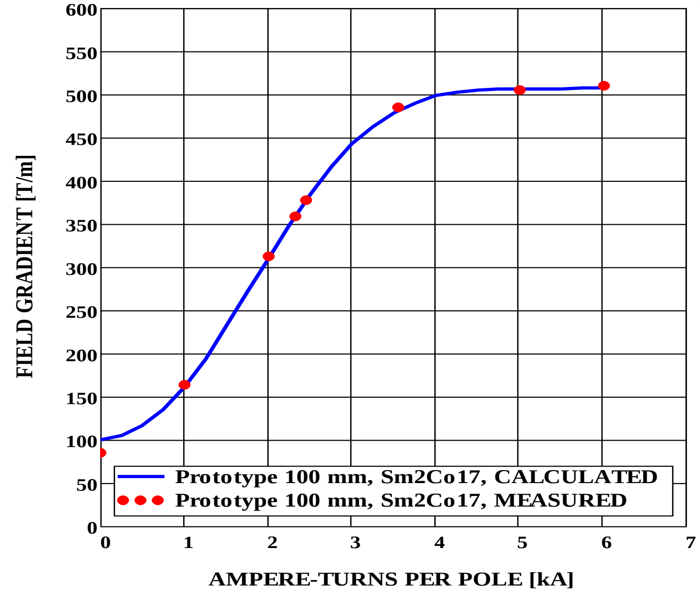
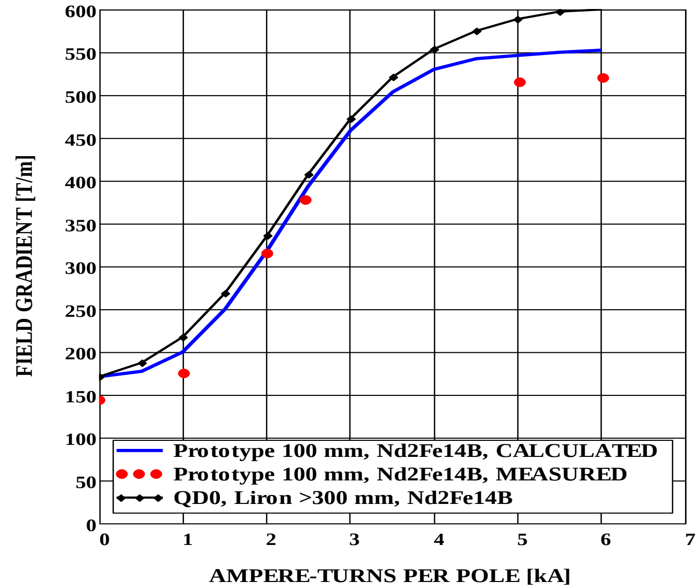
final assembly of the magnet and magnetic measurements:



*(magnet assembly: courtesy of : **C. Lopez and P. Thonet**)*





(magnetic measurements: magnetic strength modulus)

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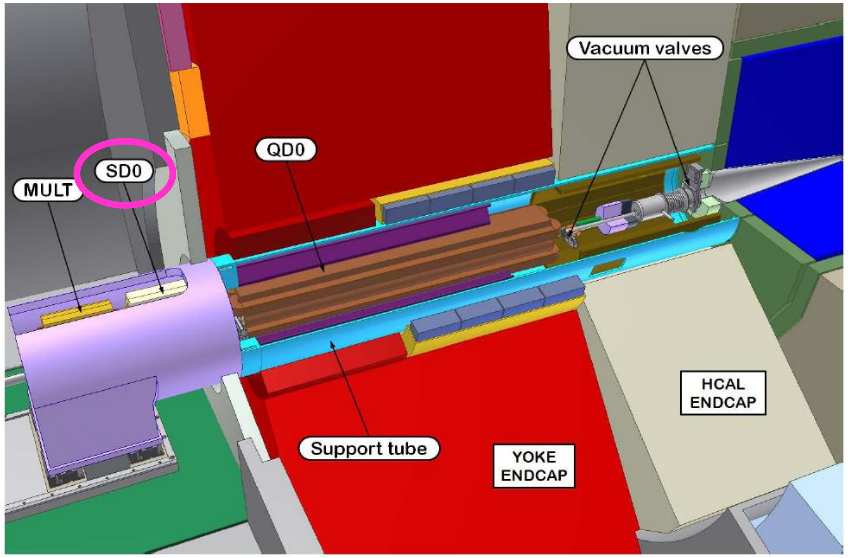
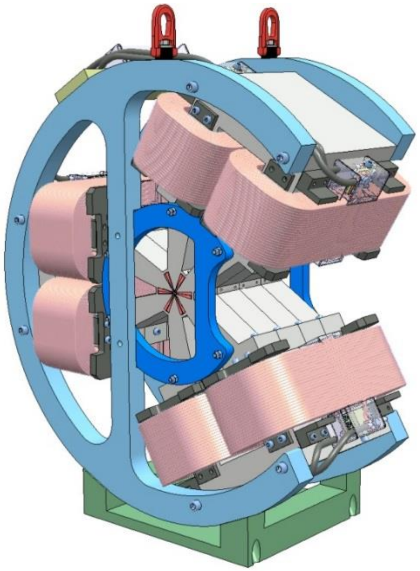
- *The experience within CLIC SD0 prototype*

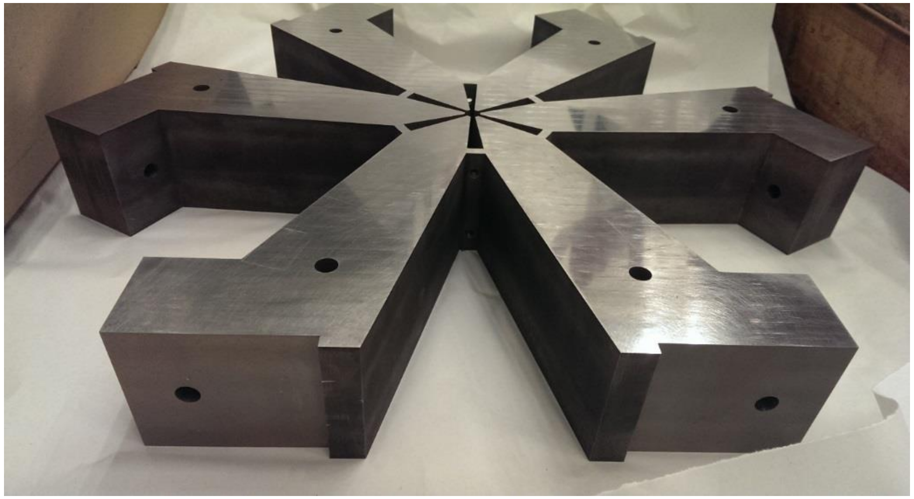
The CLIC Final Focus the Sextupole SD0 prototype:



Key aspects:

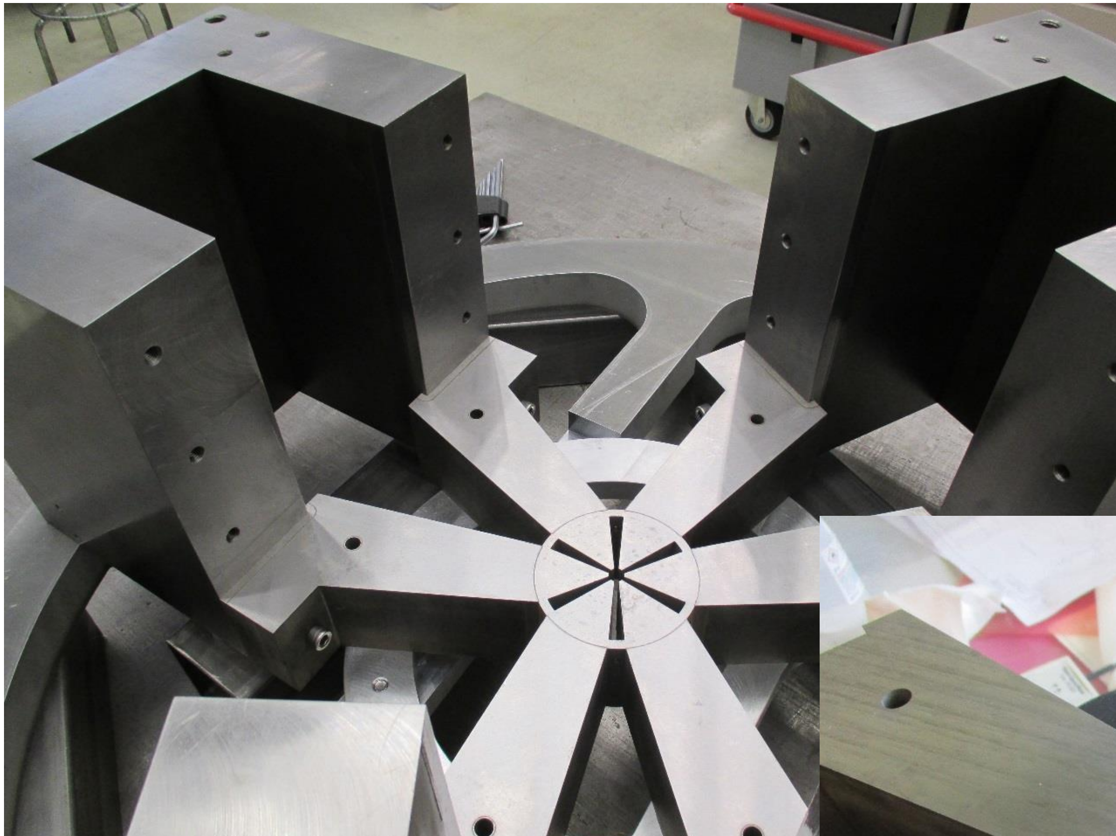
- Manufacturing (precision) of each Permendur sector, PM block, etc.
- Sorting of PM blocks
- Assembly of the sectors (magnetic forces between blocks, fragility of PM blocks,…)
- Magnetic Measurements (an ad-hoc coils will be developed by a PACMAN PhD student).
- Fiducialisation and alignment





Parameter	Value
Inner radius	4.3 mm
Nom. Sext. Gradient	219403 T/m^2
Magnetic Length	0.248 m

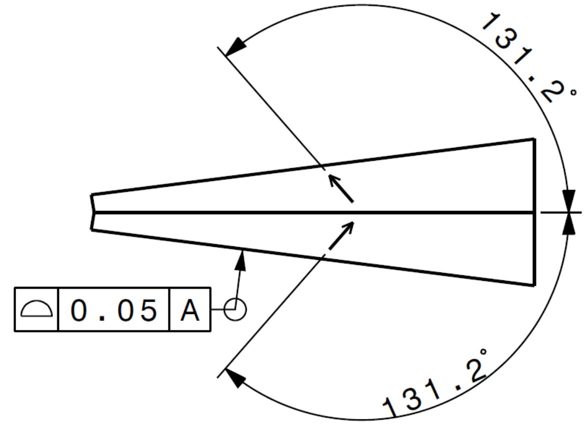
The CLIC Final Focus the Sextupole SD0 prototype:



…now in assembly phase…

Field quality tuning: SD0

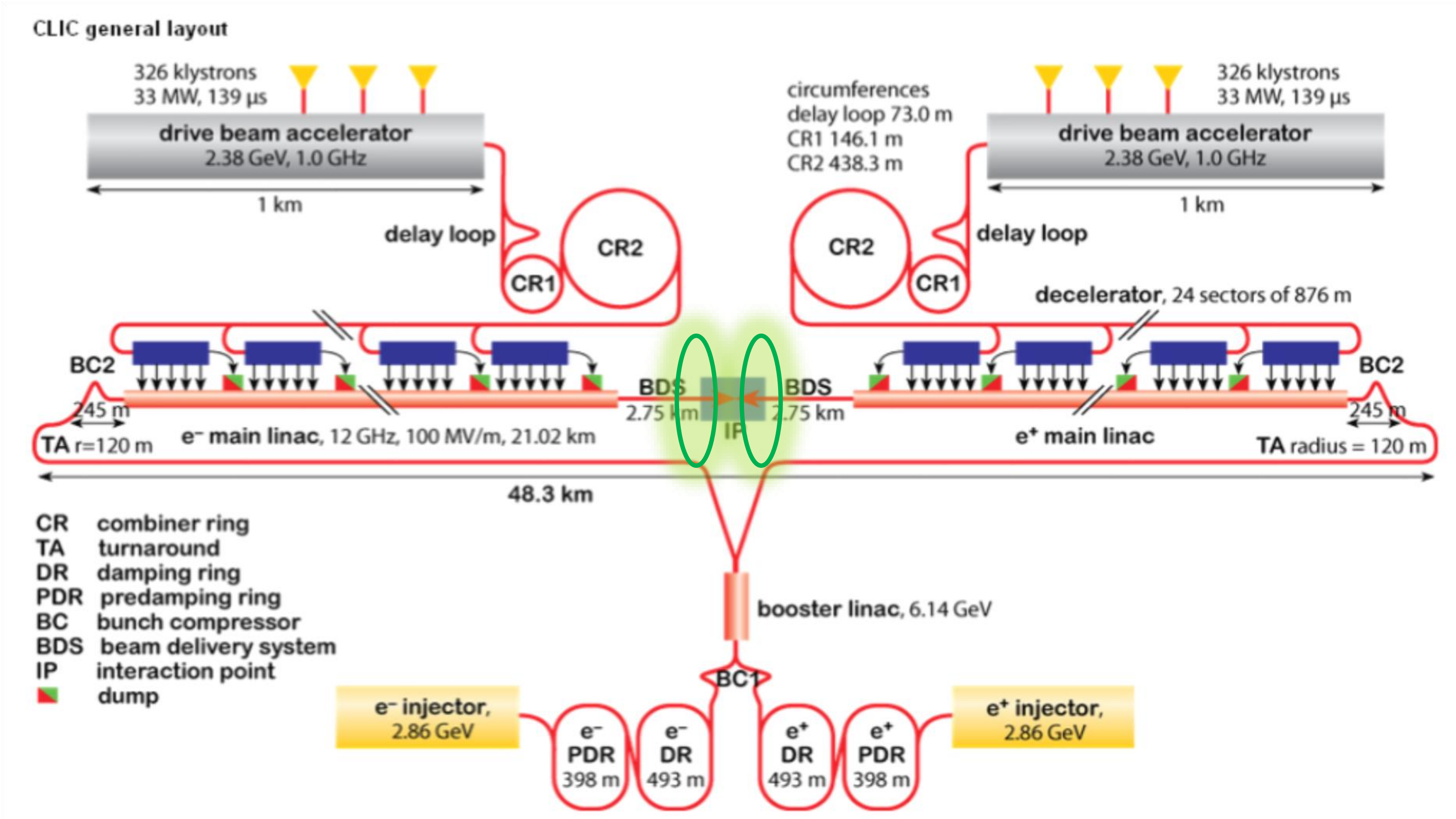
A sensitivity study of the the field quality versus error in the magnetization angle was also initiated:
The table below shows the appearance of undesiderable multipole components when an error of 1 degree in the magnetization angle appears in ONE block.
(NOTE: this case is much worse than the case where the same error appear in 6 symmetrically positioned blocks)



	bn				an		
N (b)	**60°**	**360°**	**1° error in only one block**	**N (a)**	**60°**	**360°**	**1° error in only one block**
1	0.00	-0.05	-8.05	**1**	0.00	-0.15	9.40
2	0.00	-0.01	-3.34	**2**	0.00	-0.01	6.48
3	10000.00	10000.00	10000.00	**3**	0.00	-0.01	4.01
4	0.00	0.00	-0.46	**4**	0.00	0.01	2.42
5	0.00	0.00	-0.17	**5**	0.00	0.01	1.48
6	0.01	0.00	0.57	**6**	0.00	0.00	1.37
7	0.00	0.00	0.34	**7**	0.00	0.00	0.96
8	0.00	0.00	0.31	**8**	0.00	0.00	0.55
9	-0.01	-0.05	0.20	**9**	0.00	0.00	0.30
10	0.00	0.00	0.18	**10**	0.00	0.00	0.16
11	0.00	0.00	0.13	**11**	0.00	0.00	0.08
12	0.01	0.00	0.06	**12**	0.00	0.00	0.01
13	0.00	0.00	0.04	**13**	0.00	0.00	-0.01
14	0.00	0.00	0.02	**14**	0.00	0.00	-0.01
15	0.10	0.09	0.10	**15**	0.00	0.00	-0.01

…Extra slides

QD0(s) in the CLIC layout:



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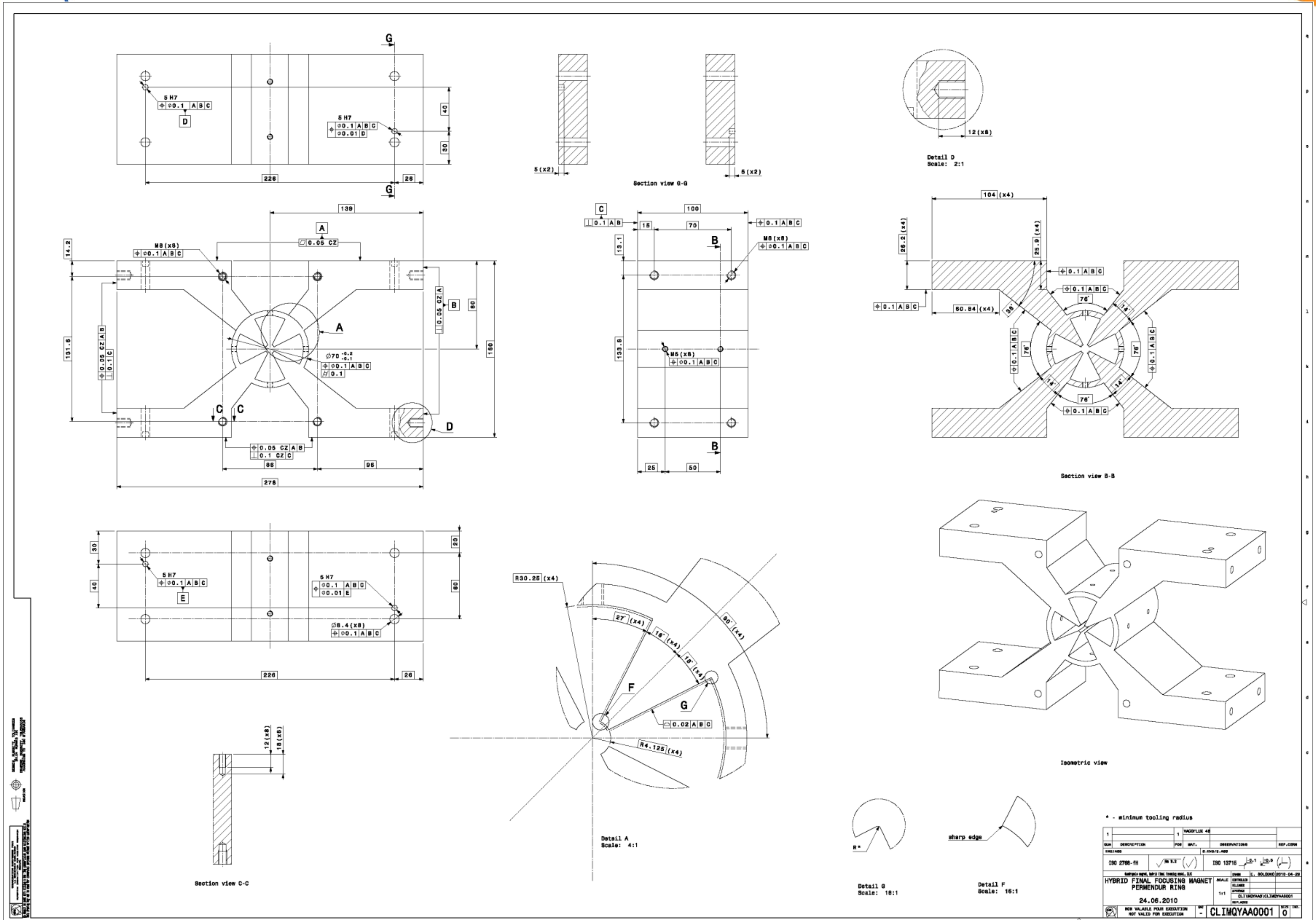
procurement of main components: launched in Spring 2010



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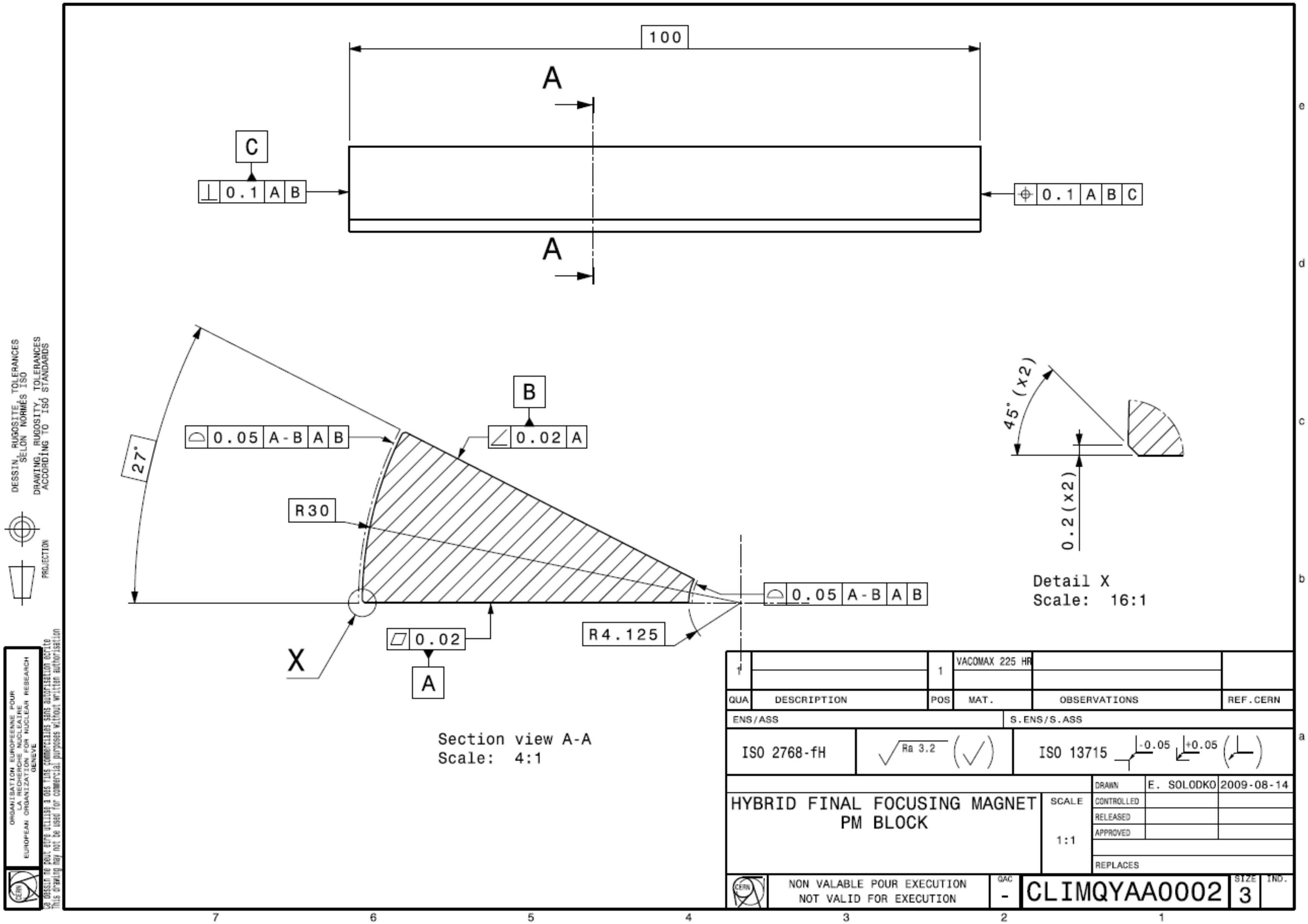
procurement of main components:



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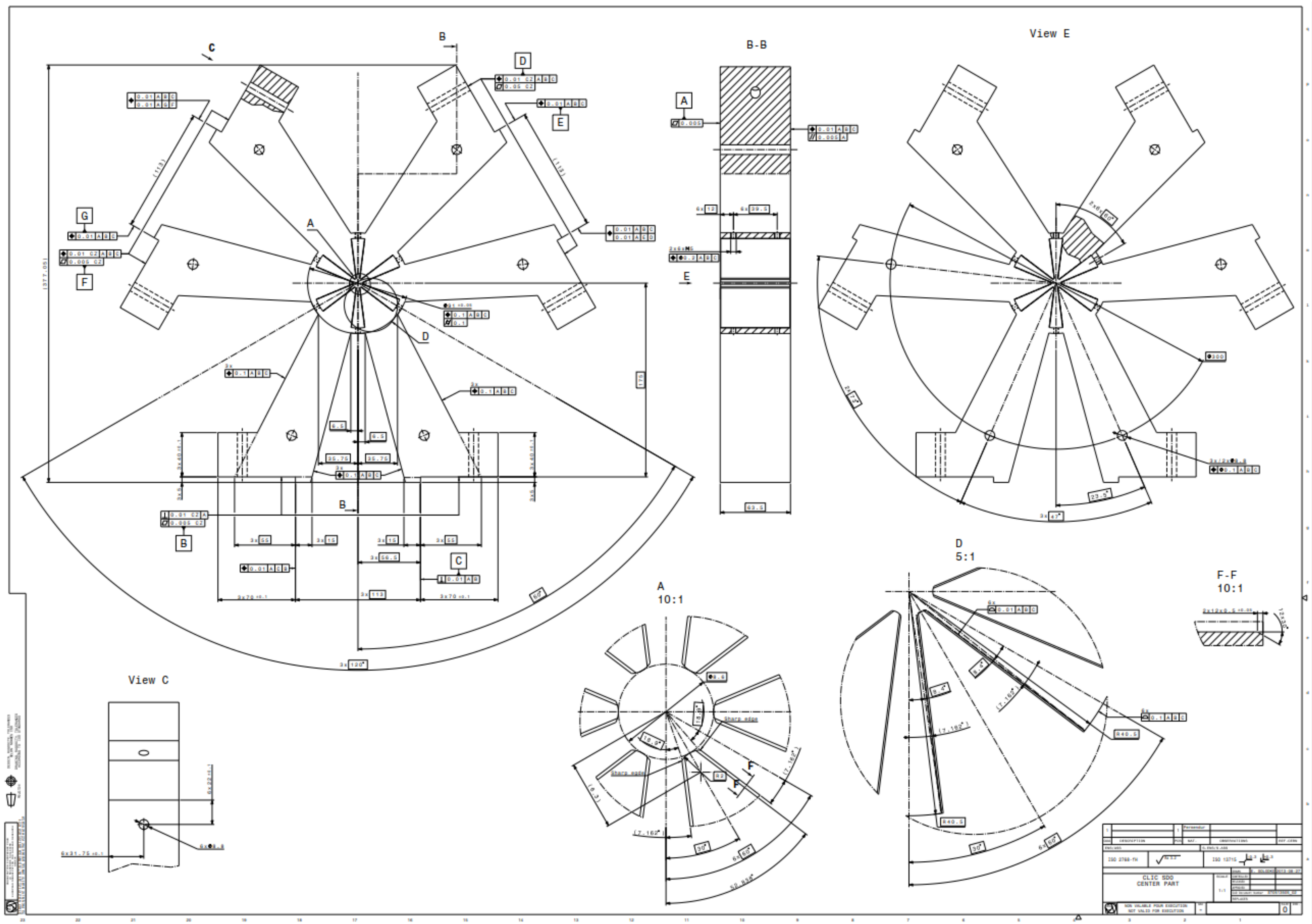
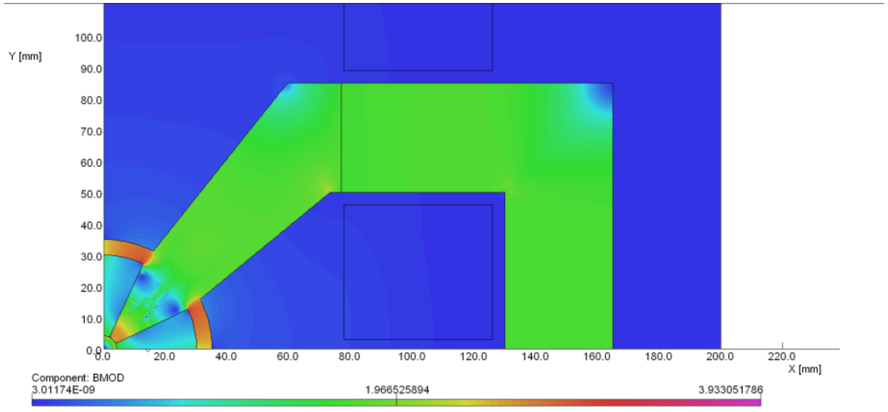
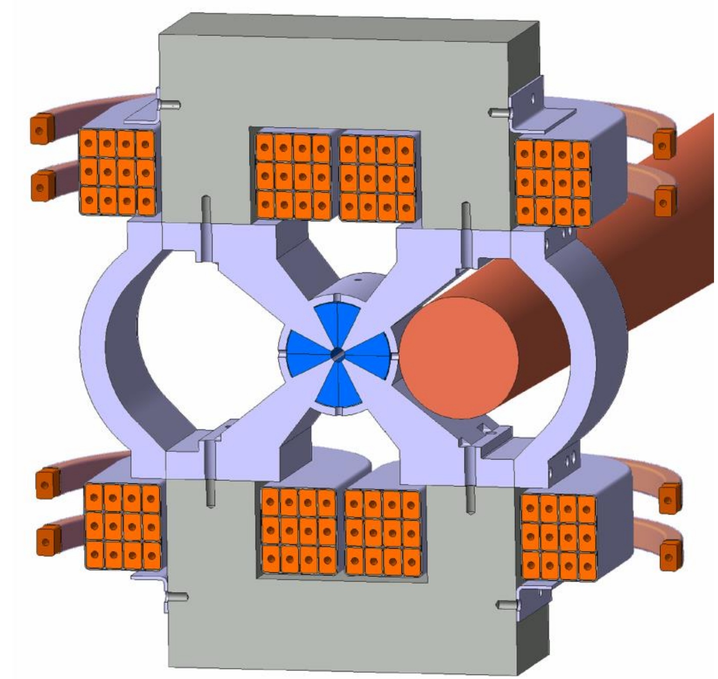

View E
B-B
View C
A
10:1
D
5:1
F-F
10:1
CLIC SDO
CENTER PART

“Hybrid” design Version 2 :



	Iw=5000 [A]
Grad [T/m] Sm_2Co_{17}	531
Grad [T/m] $Nd_2Fe_{14}B$	599



(2D/3D Drawings: courtesy of ***E. Solodko****)*

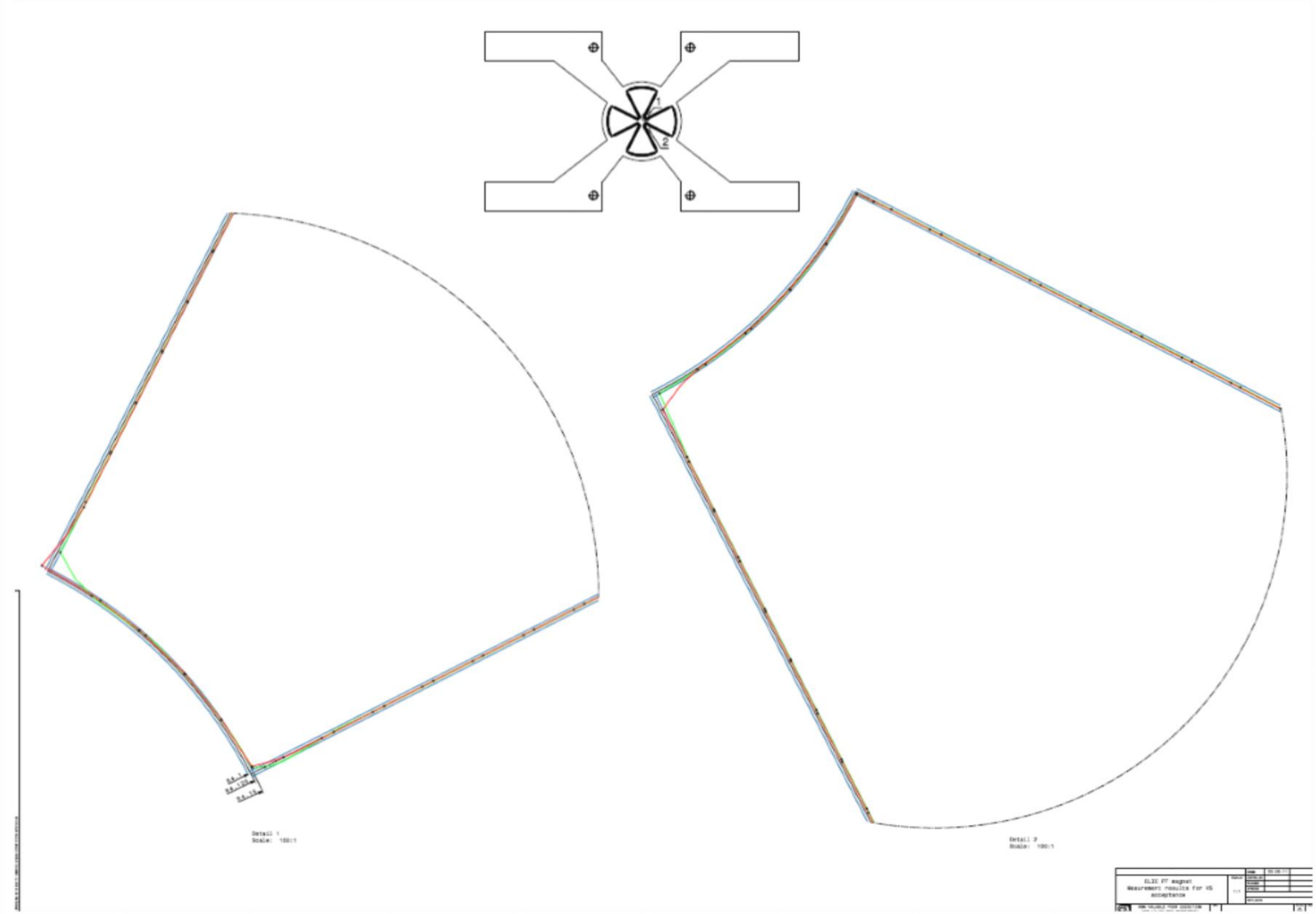
- The presence of the “ring” decrease slightly the Gradient (by 15-20 T/m) but it assure a very stiff assembly of the four poles and a precise housing for the PM blocks.

- EM Coils design would permit wide operation conditions: at 0 current Gradients will be respectively: ~ 145 and ~175 T/m.

(Note how in this Version 2 it was still planned to have water cooled coils, this was finally modify in order to improve the stabilization aspects.

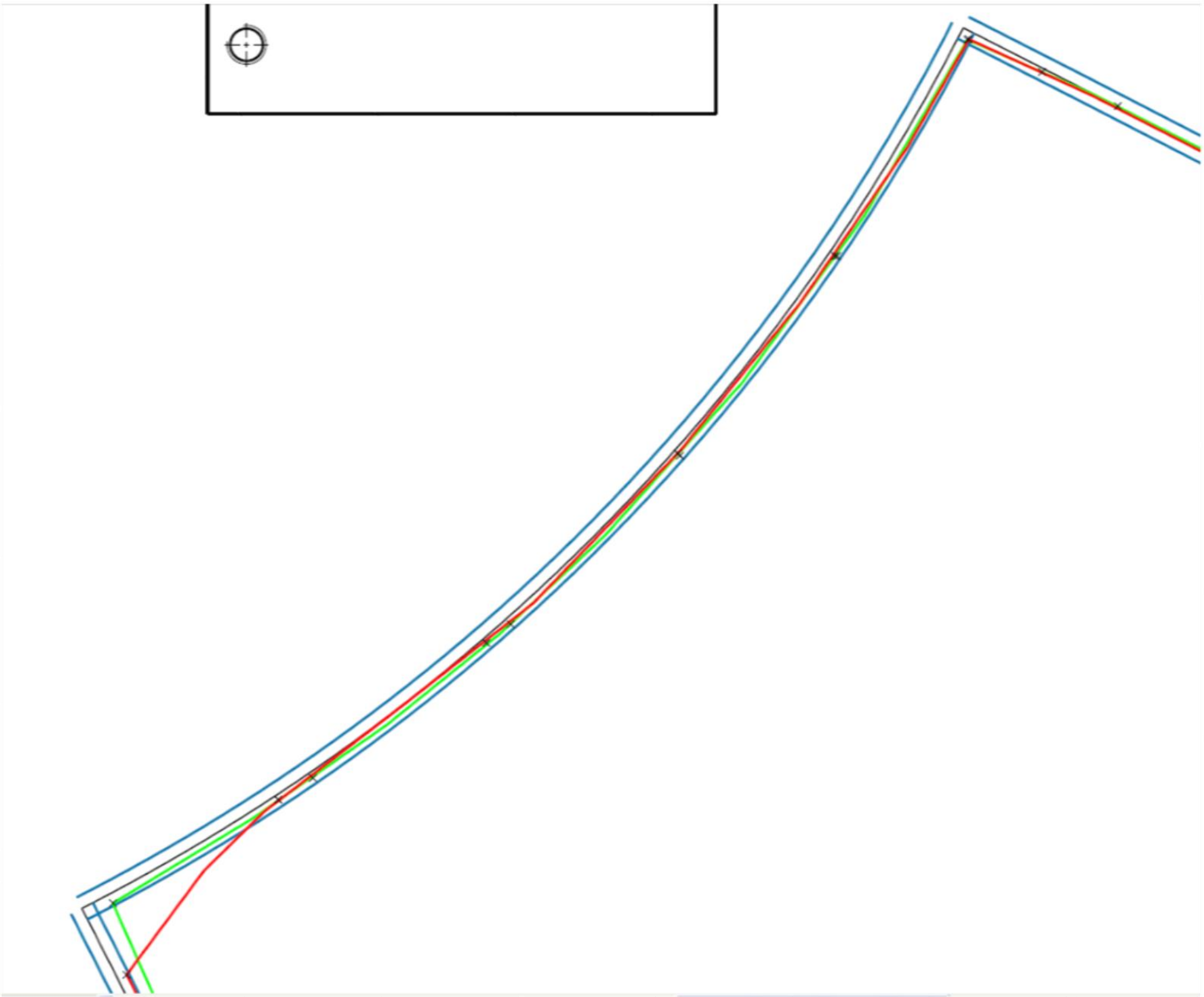
TE/MSC

reception of main components:



"CERN-Vacuumschmelze Meeting" 21 Nov. 2017, M. Modena CERN

reception of main components:



reception of main components at Metrology Lab:

MÉTROLOGIE EN-MME-MM

CERTIFICAT DE CONTRÔLE

CONCLUSION CONTRÔLE		VISA MME	ACCEPTATION CLIENT
X	OK	Nom :	Nom :
	Non conforme	Date :	Date :

NUMERO DE PLAN: ...
DESIGNATION: **PM BLOCK REAL**
NOMBRE DE PIECES: 4+4
N° EDMS: 114865

REQUERANT: **THONET**
CONTROLEUR: J.P

COTES DU PLAN	repère pièce	1/2	3/4	5/6
	matière: Samarium Cobalt			
100.04		99.130	99.110	99.100
		99.140	99.170	99.140
position de mesure/ axe de symétrie de face A et B		section extrémité C		
R30.19 -25°		30.132	30.132	30.087
-12.5°		30.076	30.132	30.100
-2°		30.067	30.126	30.086
2°		30.048	30.113	30.047
12.5°		30.040	30.117	30.054
25°		30.046	30.116	30.057
R4.355 -12.5°		4.239	4.308	4.285
12.5°		4.241	4.291	4.222
54°		53.82°	53.93°	53.97°
		section extrémité D		
R30.19 -25°		30.044	30.066	30.131
-12.5°		30.047	30.068	30.110
-2°		30.029	30.068	30.116
2°		30.063	30.112	30.063
12.5°		30.073	30.112	30.071
25°		30.060	30.108	30.054
R4.355 -12.5°		4.243	4.225	4.300
12.5°		4.255	4.295	4.254
54°		53.94°	53.93°	53.94°

DATE	OBSERVATIONS
28.06.2011	CONTRÔLE CONVENTIONNEL
APPROUVE PAR	
A.CHERIF	

Température : 20 °C | Moyens utilisés (incertitude de mesure estimée) : | Unités de mesure : mm
projecteur de profil: ± 0.005[mm] ; Comparateur digital : ± 0.012[mm];