Status of BDS (QD0 and SD0) and PCL magnet studies for CLiC

M. Modena CERN

Acknowledgments:

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ECFA LC2013
European Linear Collider Workshop

27-31 May 2013, Hamburg

Outline:

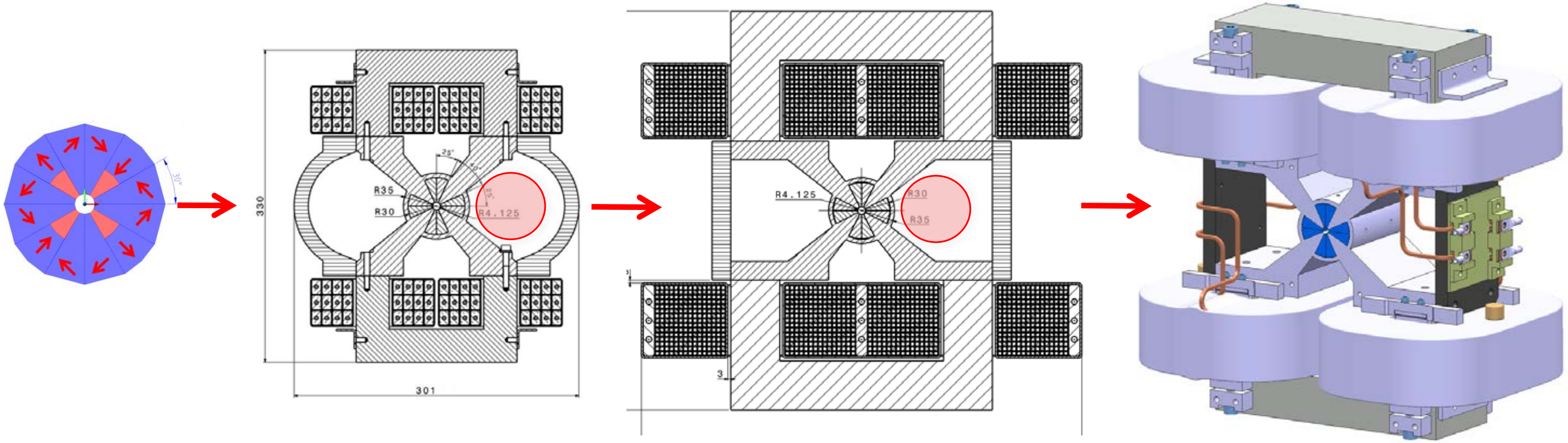
1) CLiC QD0 status

2) CLiC SD0 Status

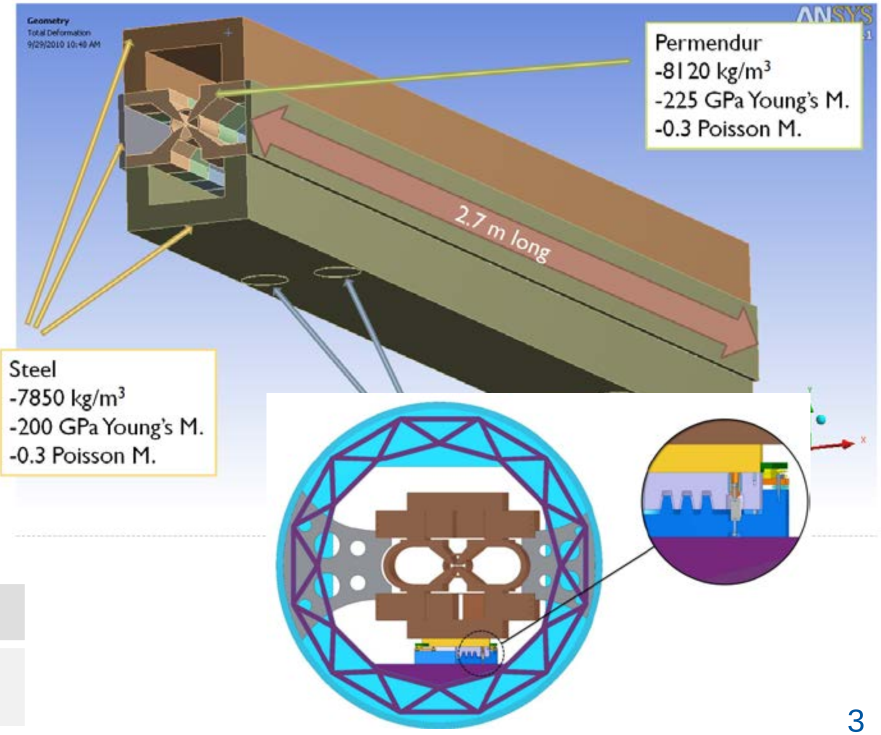
4) Post Collision Line design status

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

CLiC QD0 design in one slide

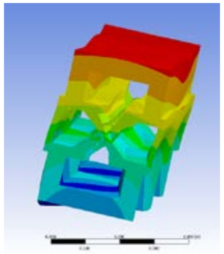


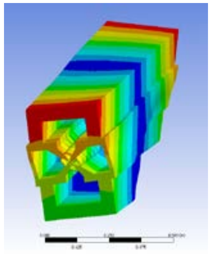
CLIC QD0 Main Parameters		100mm prototype	Real magnet 2.7m
Yoke			
Yoke length	[m]	0.1	2.7
Coil			
Conductor size	[mm]	4×4	4×4
Number of turns per coil		18×18=324	18×18=324
Average turn length	[m]	0.586	5.786
Total conductor length/magnet	[m]	0.586×324×4=760	5.786×324×4=7500
Total conductor mass/magnet	[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



Permendur
-8120 kg/m^3
-225 GPa Young's M.
-0.3 Poisson M.

Steel
-7850 kg/m^3
-200 GPa Young's M.
-0.3 Poisson M.

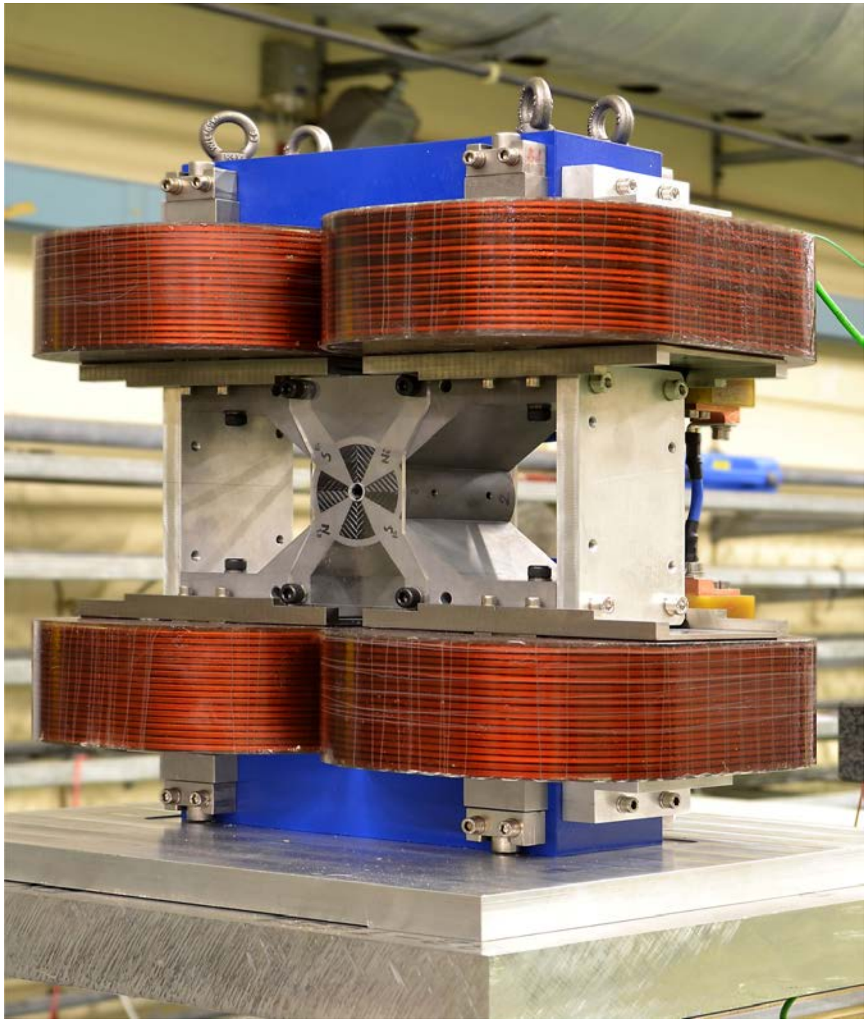




Mode	1st	2nd	3rd	4th
Freq [Hz]	190	260	310	366

CLiC QD0 Status

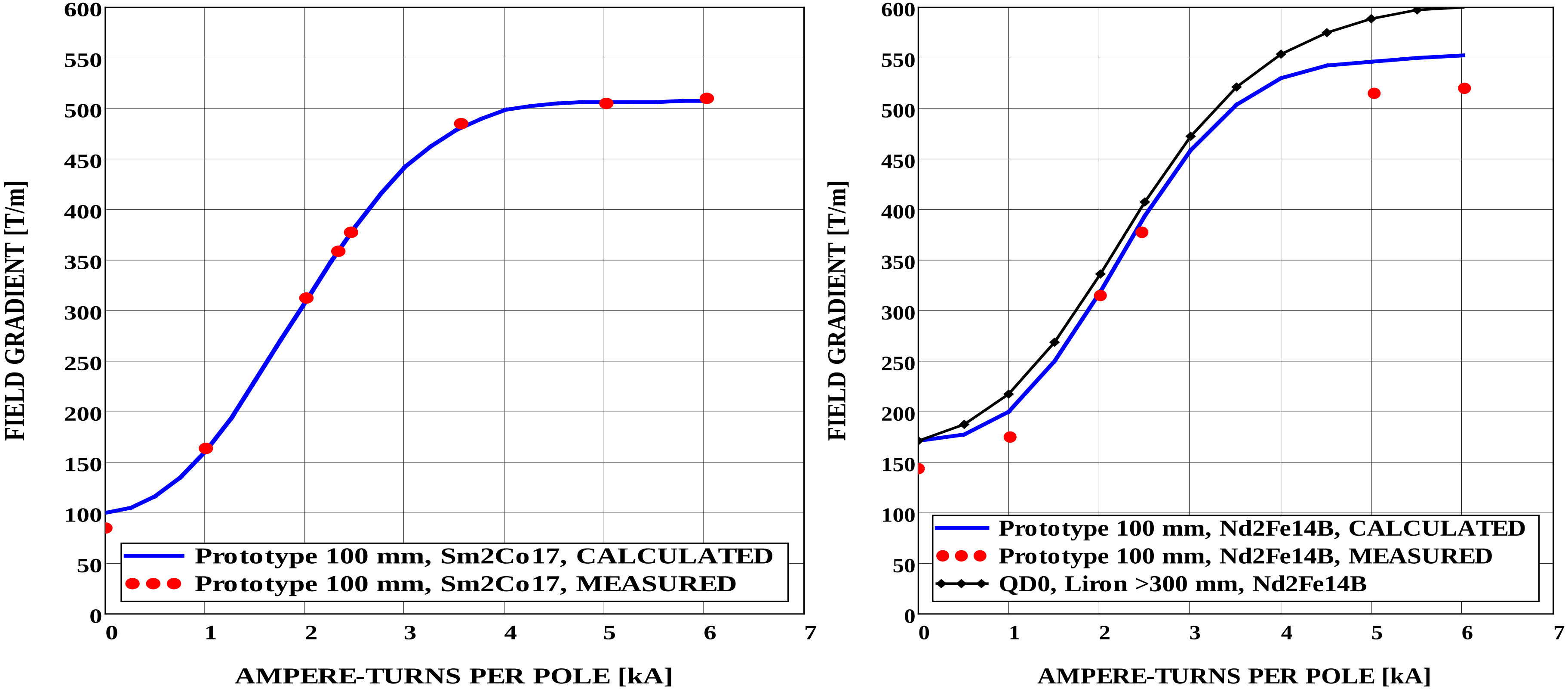
- A **short QD0 prototype** (for CLiC 3TeV layout) **was built** at CERN in 2010-2011.
- **Objective**: validate the Hybrid Magnet design proposed:
  PM blocks - Permendur core structure - coils for tunability (low current density).
- **Two** campaign of measurements were done in 2012 in two different configuration:
  - in January 2012: the QD0 equipped with **$Nd_2Fe_{14}B$** blocks
  - in August 2012: the QD0 equipped with **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%

CLiC QD0 Status

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

  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 <u>quality (magnetization module and/or direction) </u>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 .

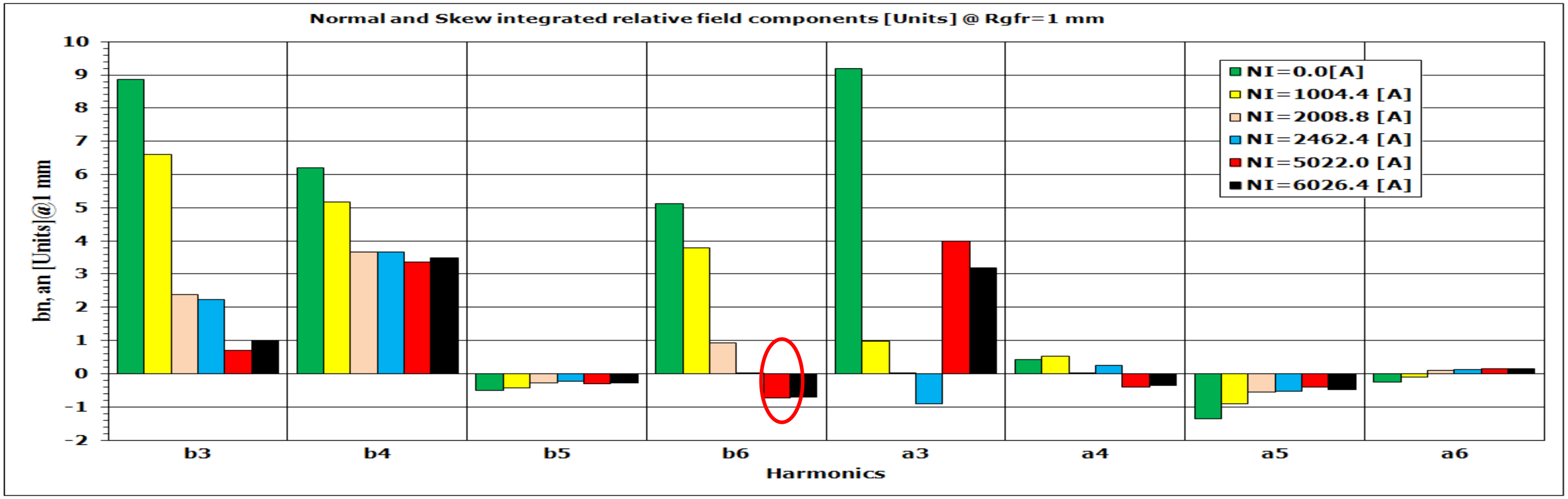
Helmholtz coil

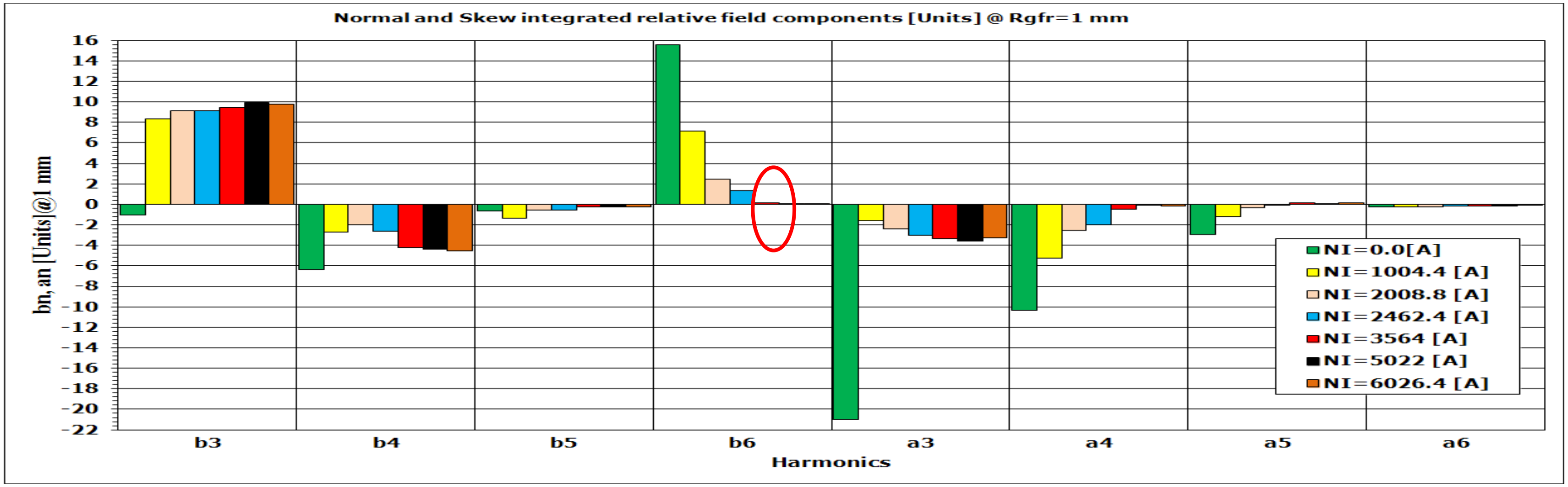
3D Helmholtz coil

CLiC QD0 Status

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" mutipole is b6: at NI=5000A we compute b6=1.4 units (NdFeB) and b6=0.7 units (SmCo).





Outline:

1) CLiC QD0 status
2) CLiC SD0 Status
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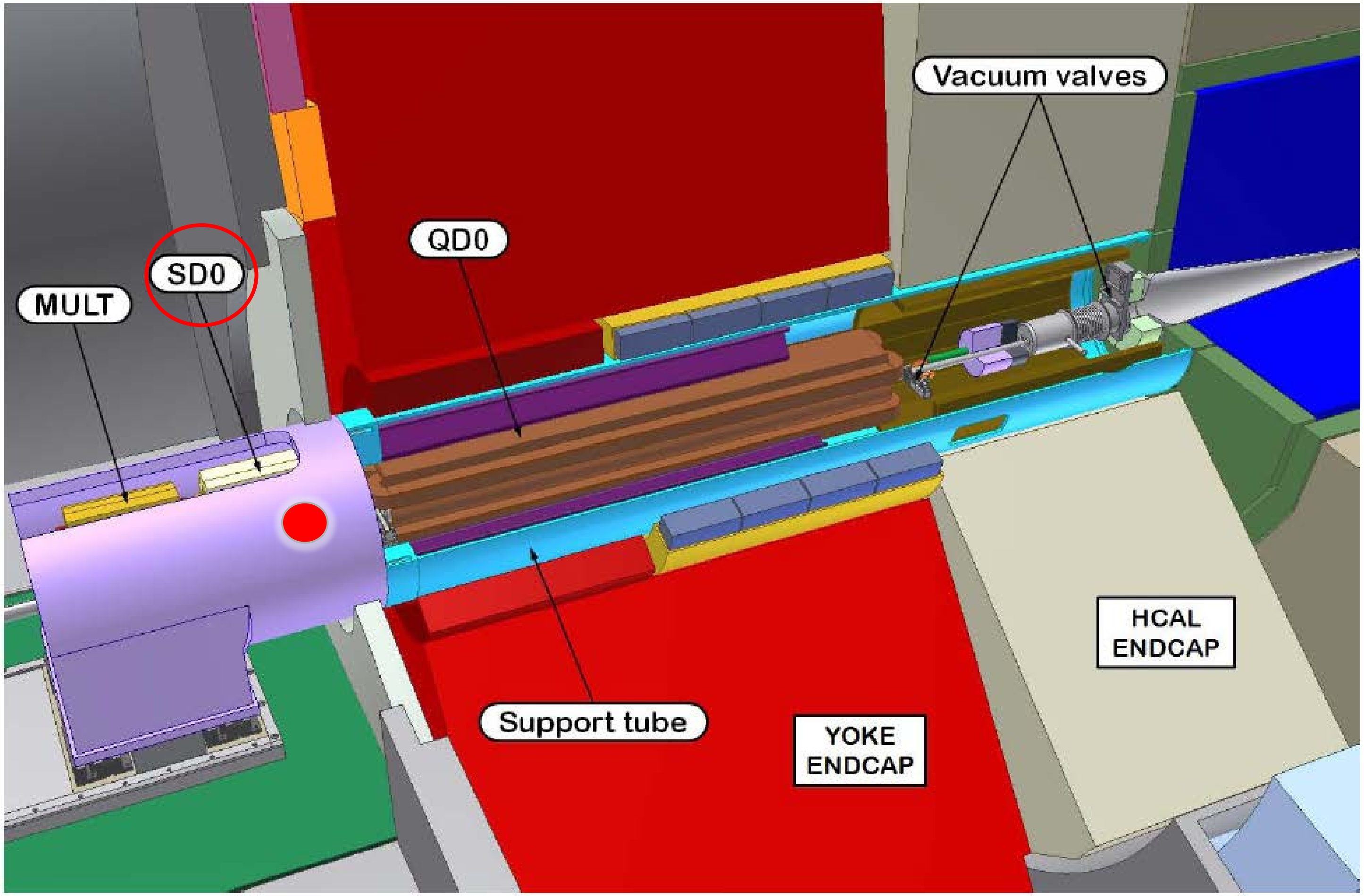
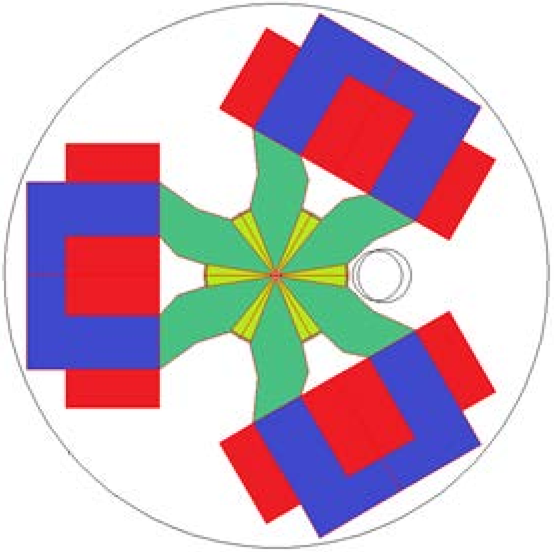
CLiC SD0 Status

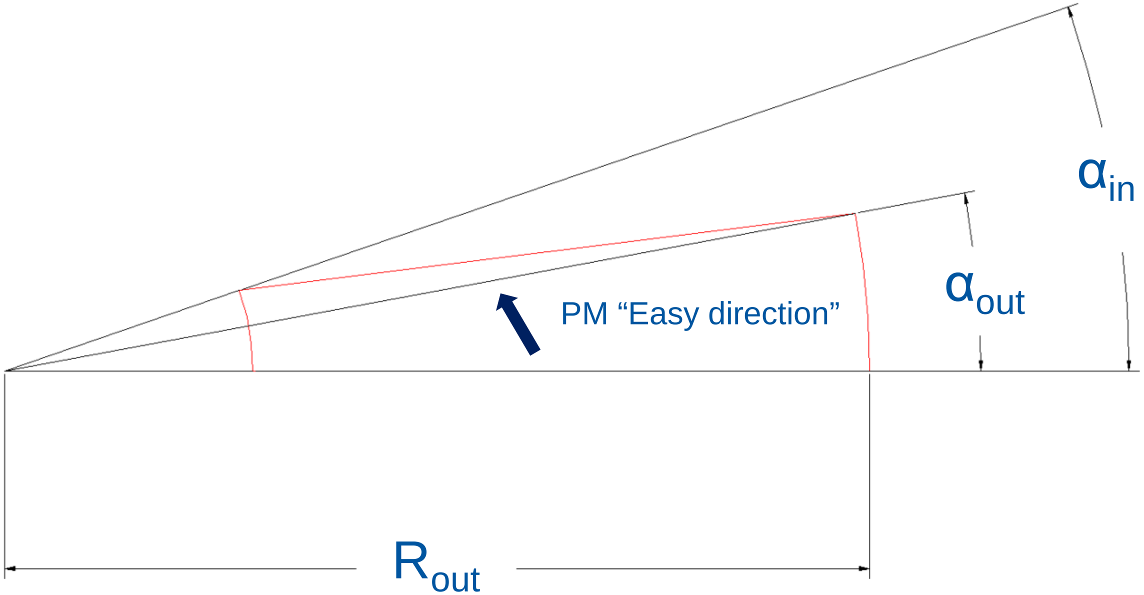
- **SDO** can be also considered a BDS critical magnet as it is requested with the stronger as possible gradient.
- It is the last magnet of the BDS placed on the tunnel, just at the border with the experimental Hall
- Being much shorter and not placed inside the Detector, the magnet has less tight geometric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

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





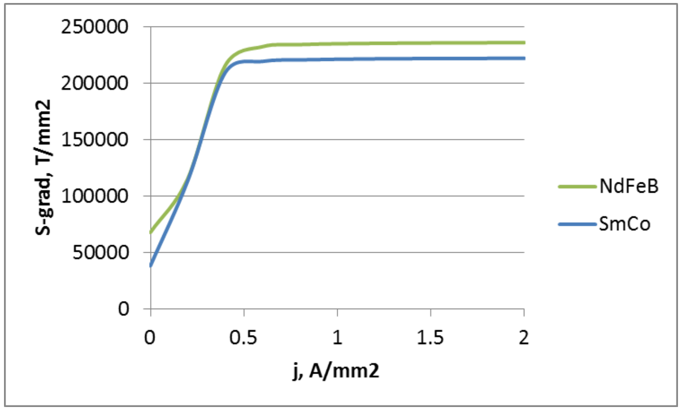
SD0 conceptual layout



PM block analysed parameters

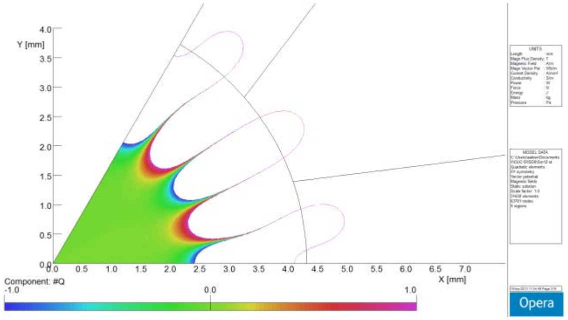
Optimization process provides these values : $\alpha_{in} = 18.9°$ $\alpha_{out} = 8.4°$ $R_{out} = 40$ mm

	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

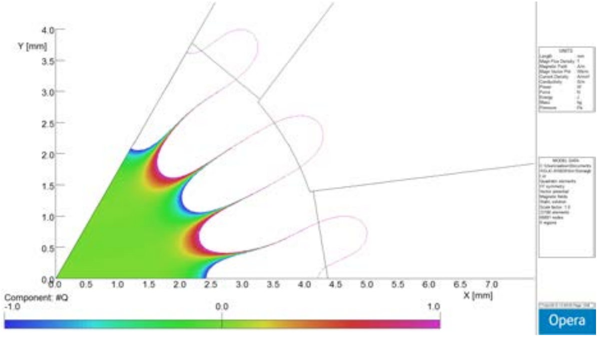


Magnet powering curve

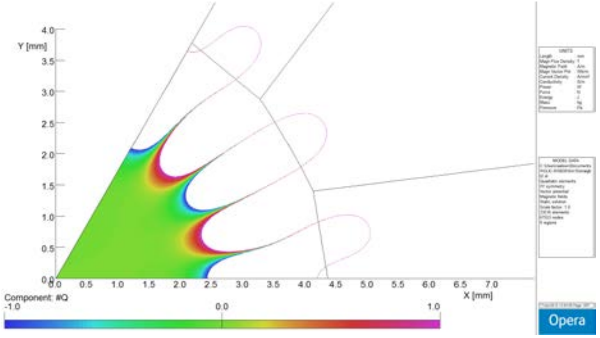
CLiC SD0 Status



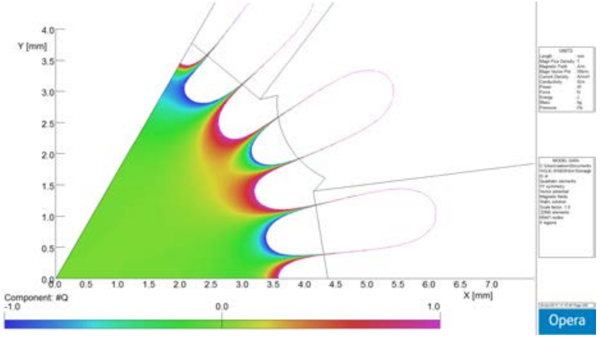
Opt.1 S-grad 222 020 T/m²



Opt.3 S-grad 221 247 T/m²

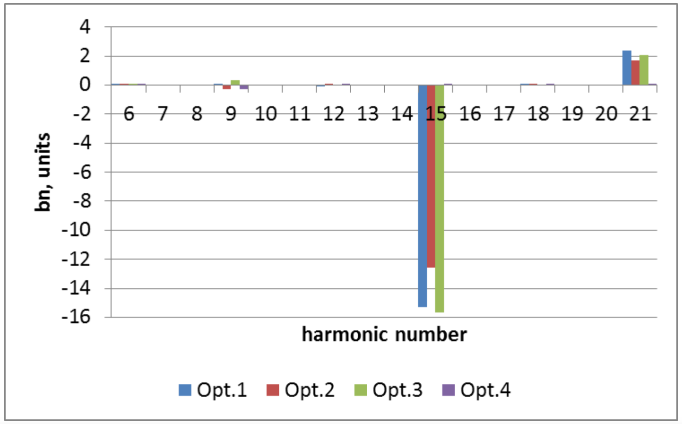


Opt.2 S-grad 220 349 T/m²

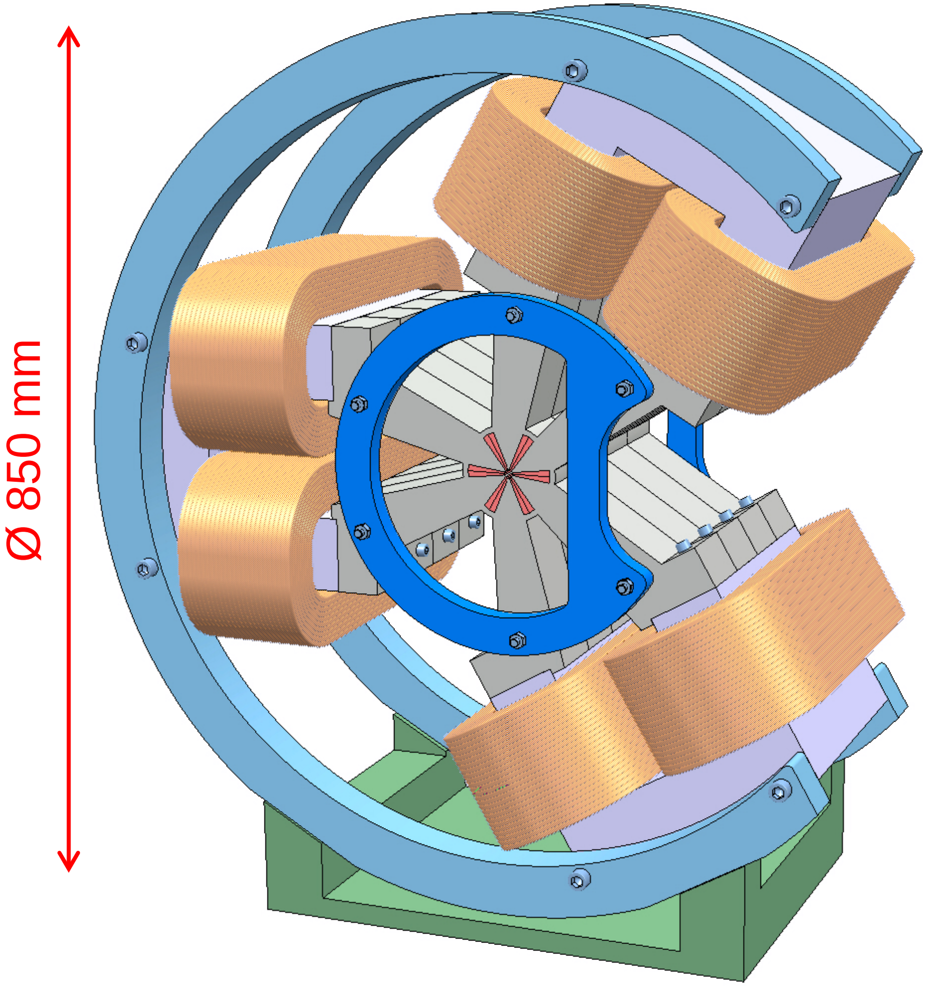


Opt.4 S-grad 215 785 T/m²

	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



CLiC SD0 Status



- ***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 onthe Accelerator Tunnel border.

- **Prototype key aspects:**
  - The proposed design should permit us to investigate the very precise assembly of several (4 or 5) longitudinal sections, each equipped with PM.
  - Manufacturing (with highest precision) of each Permendur sector, PM insert, “C” shape return yokes
  - Measuring, Assembly and sorting of PM blocks
  - Assembly of the sectors (magnetic forces between blocks impact? PM blocks are very fragile!)
  - Magnetic measurements
  - Final alignment

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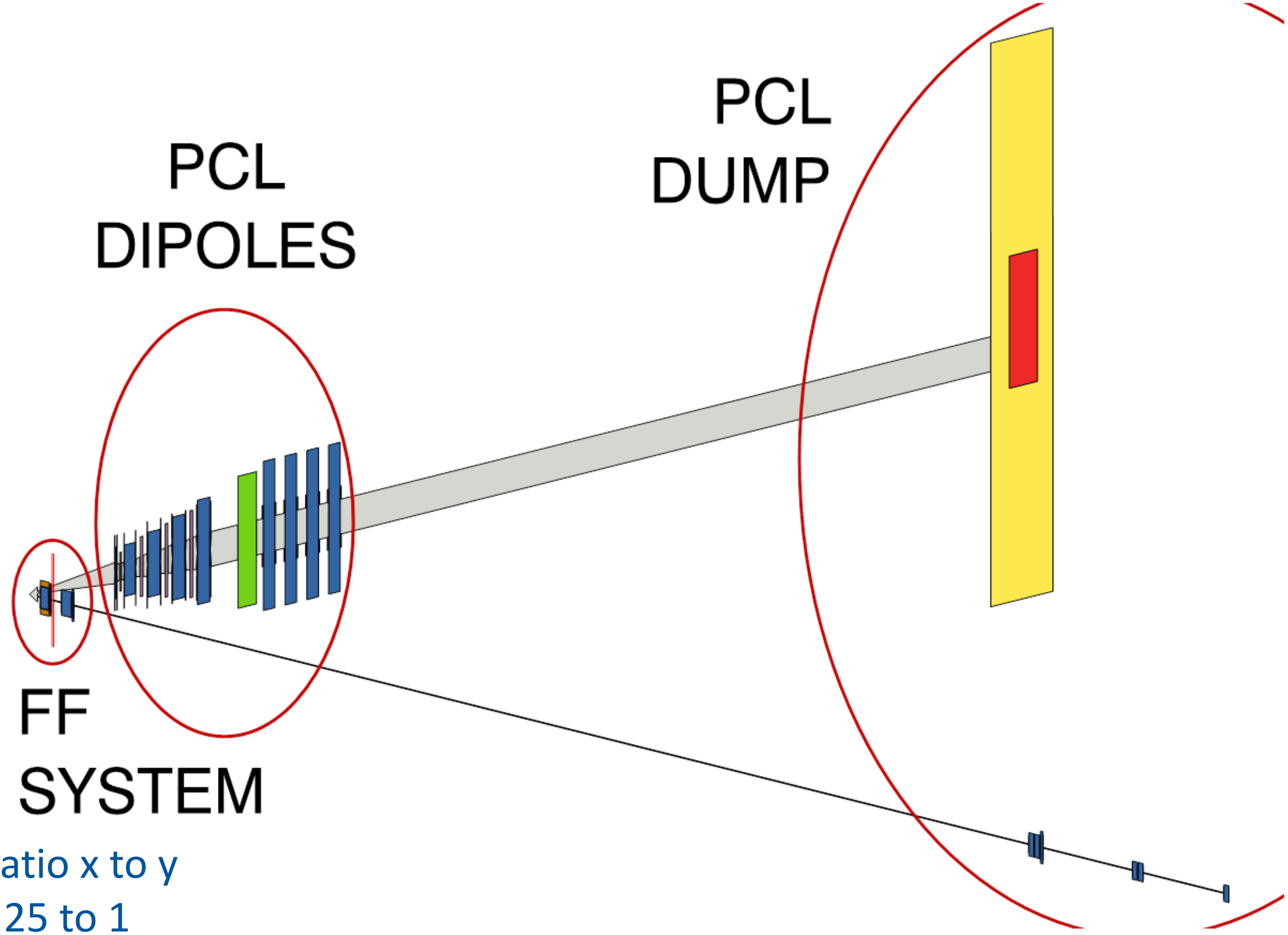
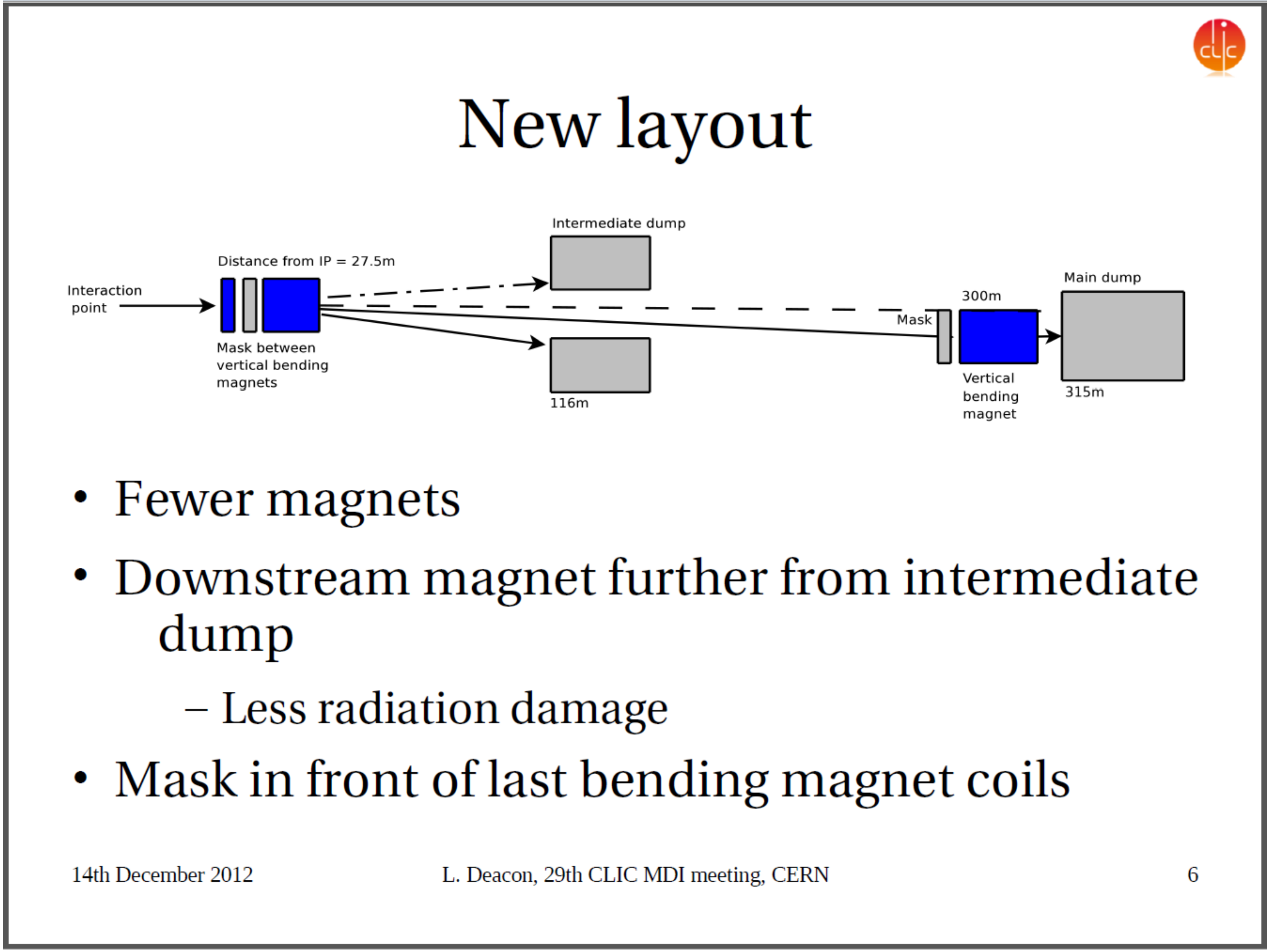
Areas under investigation



Aspect ratio x to y
is set as 25 to 1

A. Bartalesi 14/12/2012

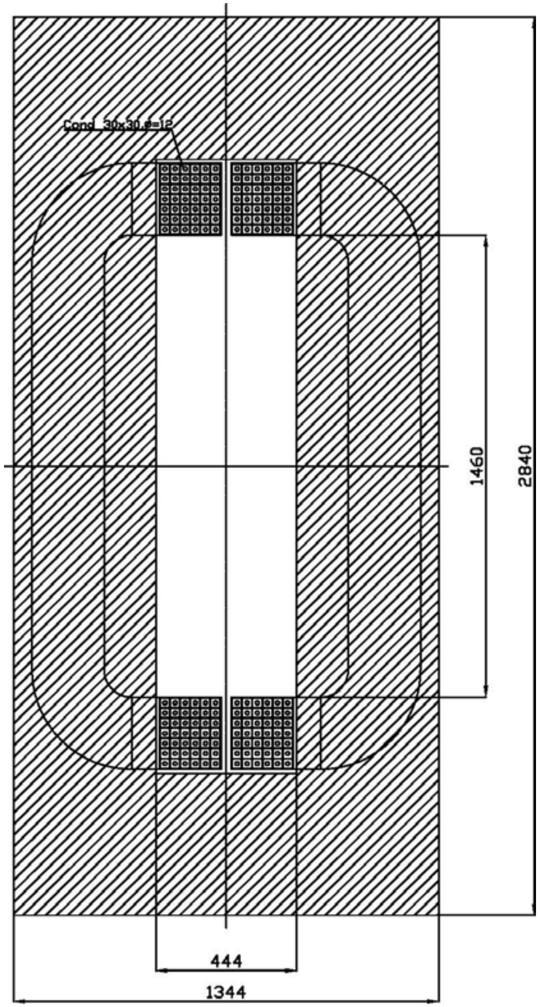


New layout

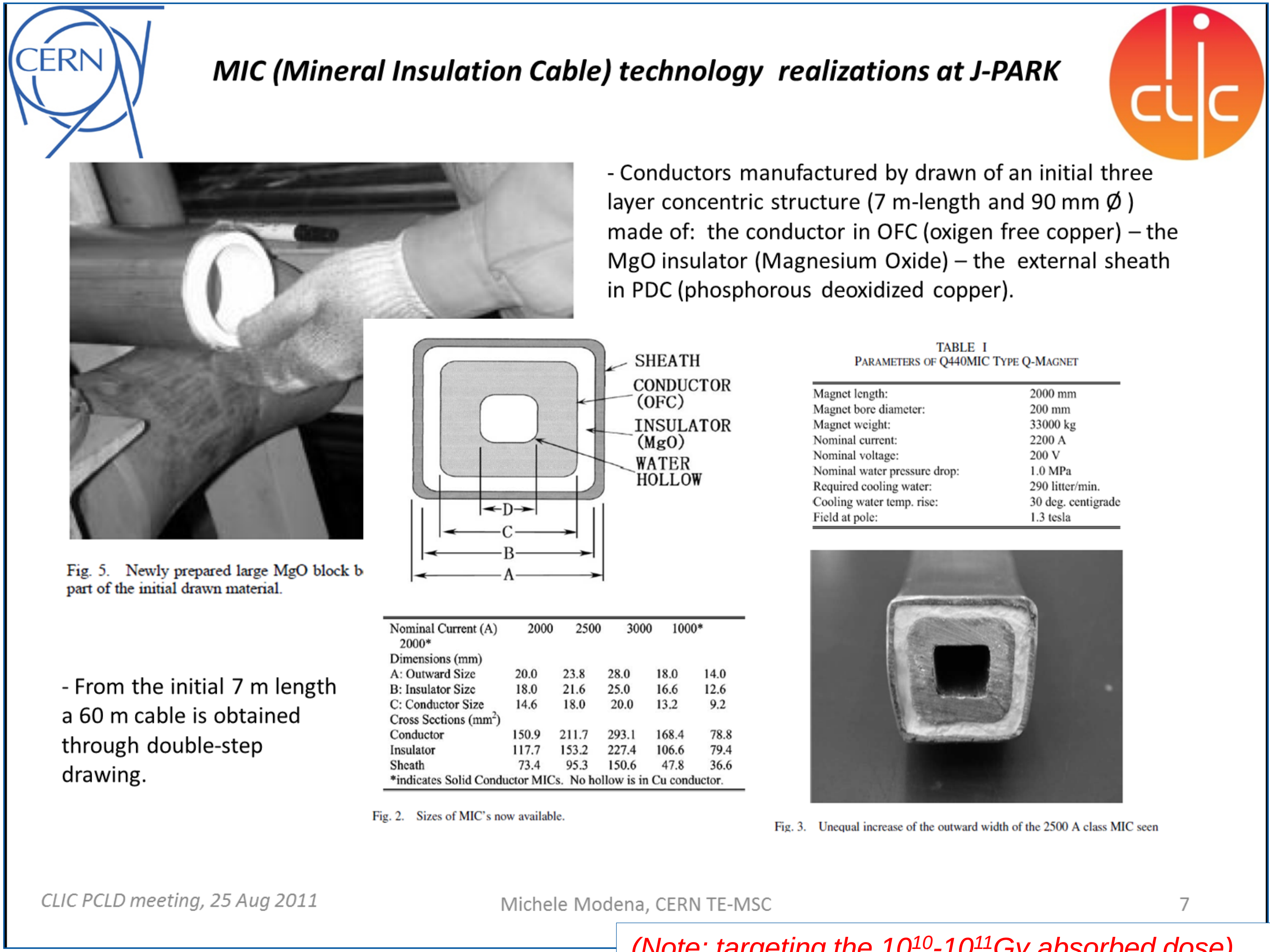
- Fewer magnets
- Downstream magnet further from intermediate dump
  - Less radiation damage
- Mask in front of last bending magnet coils

14th December 2012 L. Deacon, 29th CLIC MDI meeting, CERN 6

Post Collision Line design status



Parameters	UNITS	
Magnet type, name		Dipole Mag4
Full aperture (Horizontal)	[mm]	444
Effective length	[mm]	4000
Strength	[T]	0.8
YOKE		
Yoke length	[mm]	3750
Yoke cross section area	[m^2]	2.96
Yoke mass	[kg]	87’227
COIL		
Conductor type	“Luvata”[ID number- 8200]	30[mm]×30[mm], Ø=12[mm]
Number of turns per coil		42
Number of pancakes per coil		6
Total conductor mass	[kg]	6341
Electrical parameters		
Current	[A]	3542
Current density	[A/mm^2]	4.5
Total resistance	[mOhm]	21.6
Total inductance	[mH]	127.5
Voltage	[V]	76.5
Power	[kW]	271
COOLING		
Cooling circuits per magnet		12
Cooling flow per circuit	[l/min]	16.1
Temperature rise	[K]	20



MIC (Mineral Insulation Cable) technology realizations at J-PARK

- Conductors manufactured by drawn of an initial three layer concentric structure (7 m-length and 90 mm Ø) made of: the conductor in OFC (oxigen free copper) – the MgO insulator (Magnesium Oxide) – the external sheath in PDC (phosphorous deoxidized copper).

Fig. 5. Newly prepared large MgO block b
part of the initial drawn material.

- From the initial 7 m length a 60 m cable is obtained through double-step drawing.

TABLE I
PARAMETERS OF Q440MIC TYPE Q-MAGNET

Magnet length:	2000 mm
Magnet bore diameter:	200 mm
Magnet weight:	33000 kg
Nominal current:	2200 A
Nominal voltage:	200 V
Nominal water pressure drop:	1.0 MPa
Required cooling water:	290 litter/min.
Cooling water temp. rise:	30 deg. centigrade
Field at pole:	1.3 tesla

Nominal Current (A)	2000	2500	3000	1000*	2000*
Dimensions (mm)					
A: Outward Size	20.0	23.8	28.0	18.0	14.0
B: Insulator Size	18.0	21.6	25.0	16.6	12.6
C: Conductor Size	14.6	18.0	20.0	13.2	9.2
Cross Sections (mm^2)					
Conductor	150.9	211.7	293.1	168.4	78.8
Insulator	117.7	153.2	227.4	106.6	79.4
Sheath	73.4	95.3	150.6	47.8	36.6

*indicates Solid Conductor MICs. No hollow is in Cu conductor.

Fig. 2. Sizes of MIC's now available.

Fig. 3. Unequal increase of the outward width of the 2500 A class MIC seen

CLIC PCLD meeting, 25 Aug 2011 Michele Modena, CERN TE-MSC 7

(Note: targeting the 10^{10}-10^{11}Gy absorbed dose)

Post Collision Line design status

Studies for a possible “low consumption” alternative design initiated.

Key aspects:

- To provide a “low consumption” design
- RELIABILITY is the key word for these magnets: they are very big, placed in a dumping tunnel, in a high radioactive region and interventions must be MINIMIZED.
- The magnets could be subjected to high doses of radiation (new simulation on-going)→impact on coils.

Basic assumptions are the following:

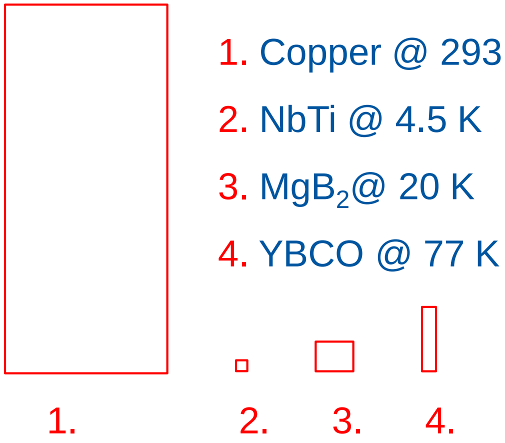
- The simpler (and economic) cryogenic solution is to take advantage of the cryo coolants available at the IP (Detector Solenoid). They will be at 4.5 K (LHe for the solenoid) or at 40-60 K (thermal shields). Distance from the PCL magnets is 35-100m (depending by the PCL versions considered).
- In these condition the cryogenic system will consist in the cryogenic transfer line and the valve boxes for feeding the magnet coils. Other solution (cryocooler) can be also considered.
- For the magnet COILS, several possibility can be evaluated:
  - “Classic SC” solution (i.e. NbTi)
  - HTS (High Temperature Superconductor) (i.e. MgB_2,YBCO, etc.)

Each solution has advantages and disadvantages, we will try to identify them and to provide some guidelines.

An “active” coil cross-section comparison for some different SC solutions is shown on the right

Other aspect to be considered:

- Complexity/cost of the coil winding
- Complexity/cost of cryostats
- Operation
- Stability and radiation resistance



1. Copper @ 293 K
2. NbTi @ 4.5 K
3. MgB_2@ 20 K
4. YBCO @ 77 K

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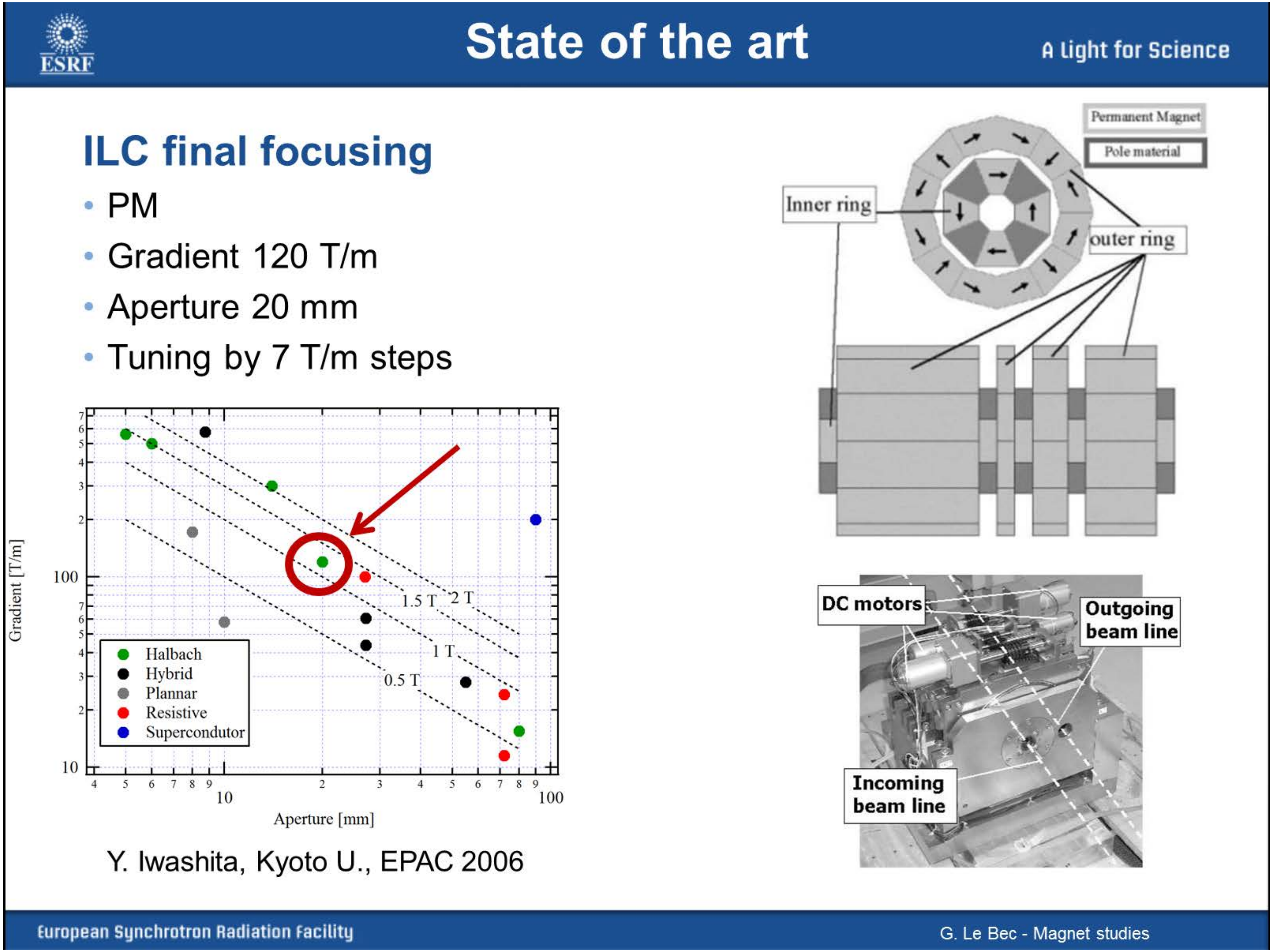
A hybrid QD0 for ILC ?



State of the art

A light for Science

ILC final focusing

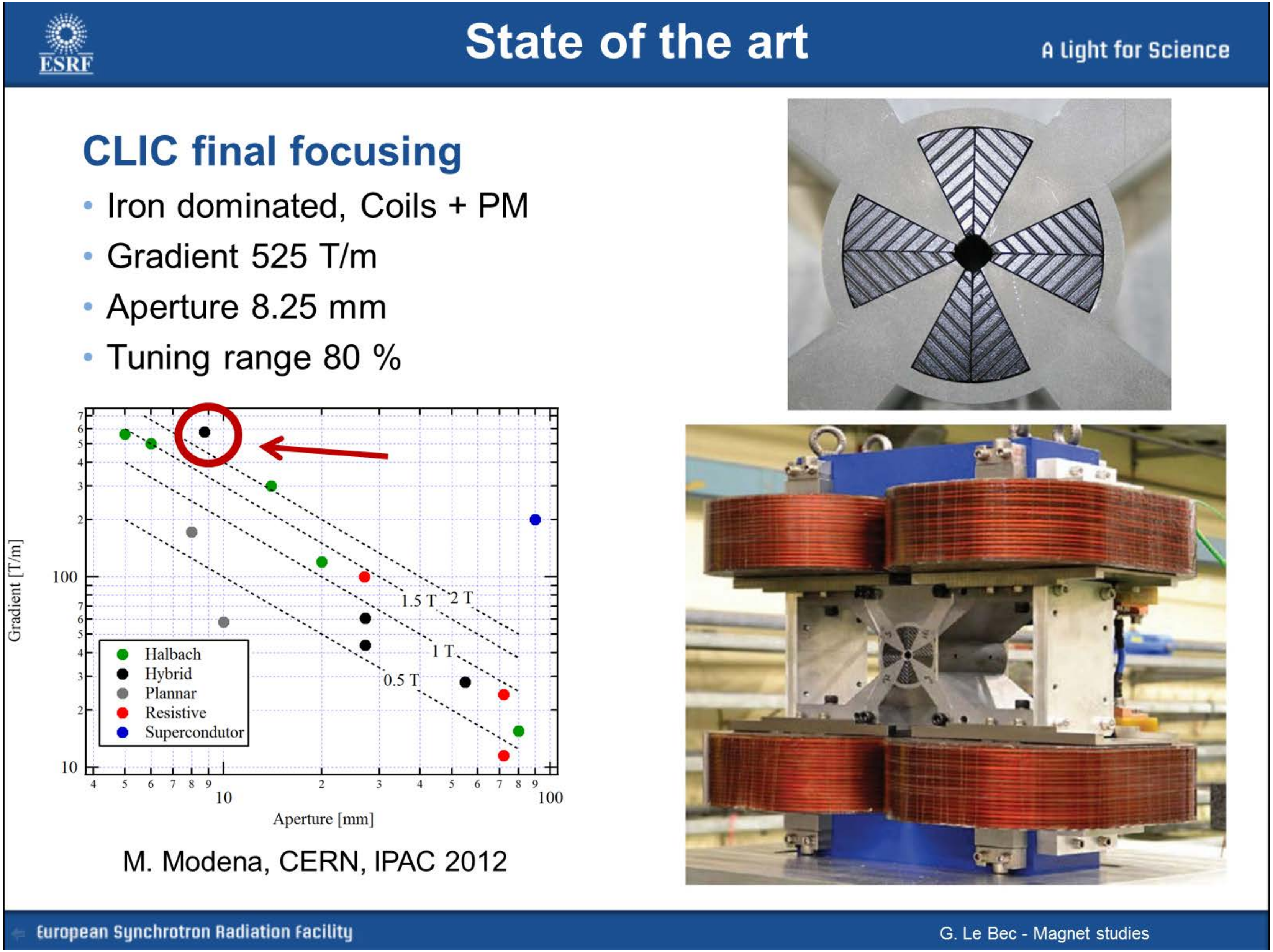
- PM
- Gradient 120 T/m
- Aperture 20 mm
- Tuning by 7 T/m steps

Y. Iwashita, Kyoto U., EPAC 2006

European Synchrotron Radiation Facility

G. Le Bec - Magnet studies

A hybrid QD0 for ILC ?



State of the art

A light for Science

CLIC final focusing

- Iron dominated, Coils + PM
- Gradient 525 T/m
- Aperture 8.25 mm
- Tuning range 80 %

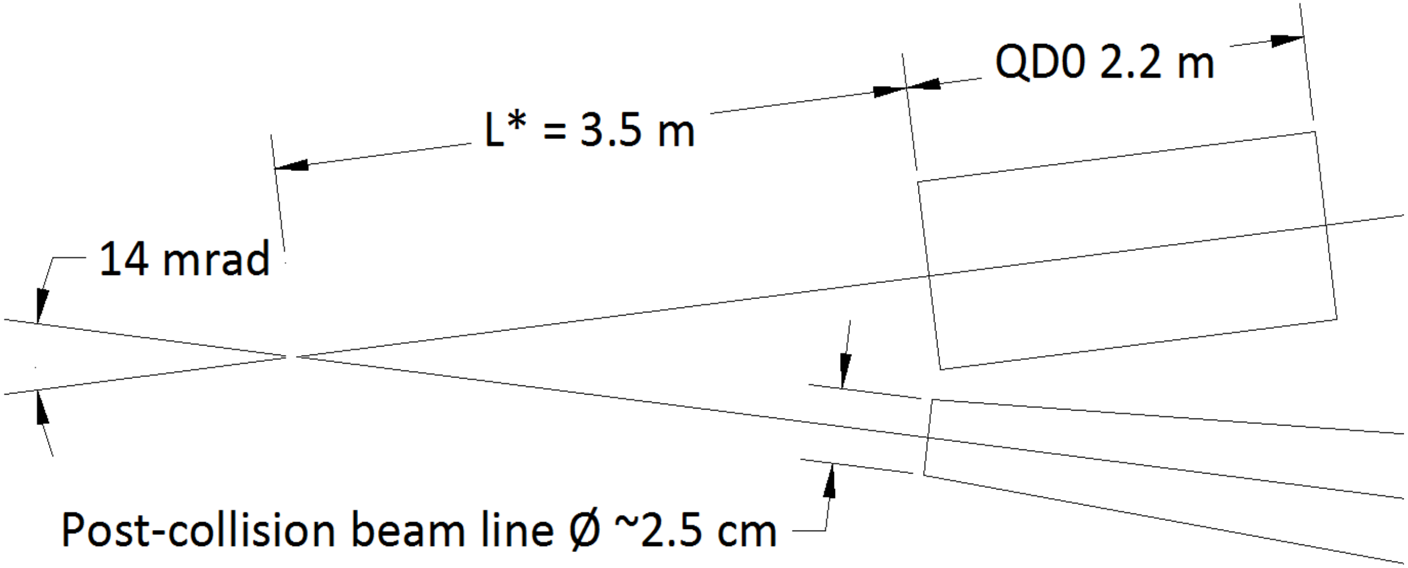
M. Modena, CERN, IPAC 2012

European Synchrotron Radiation Facility

G. Le Bec - Magnet studies

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

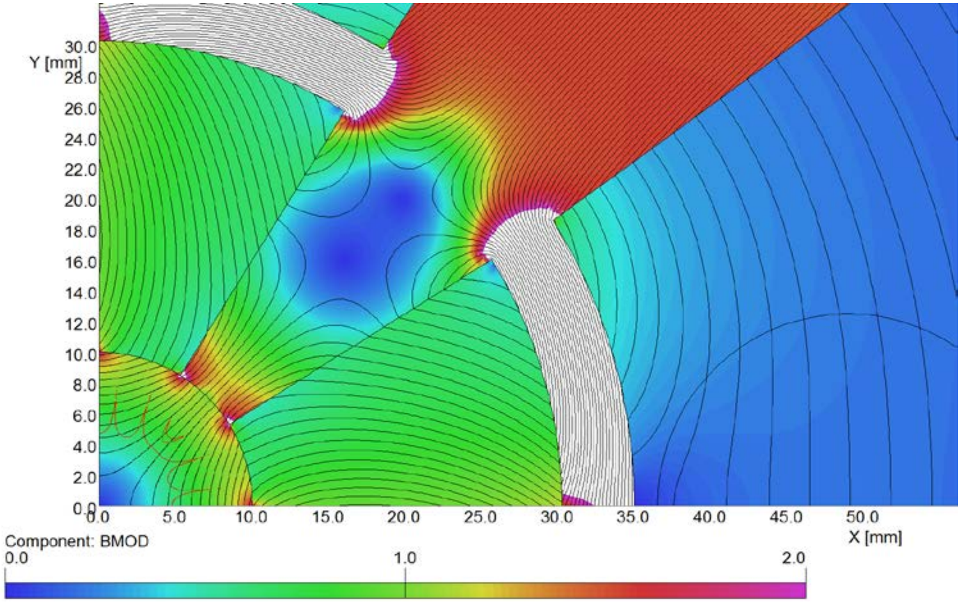
- Crossing angle: 14 mrad
- L* = 3.5 m
- QD0 full aperture: 2 cm
- QD0 total length: 2.2 m
- QD0 gradient: 124 T/m
- Post Collision Line vacuum pipe radius at 3.5 m: ~ 12.5 mm

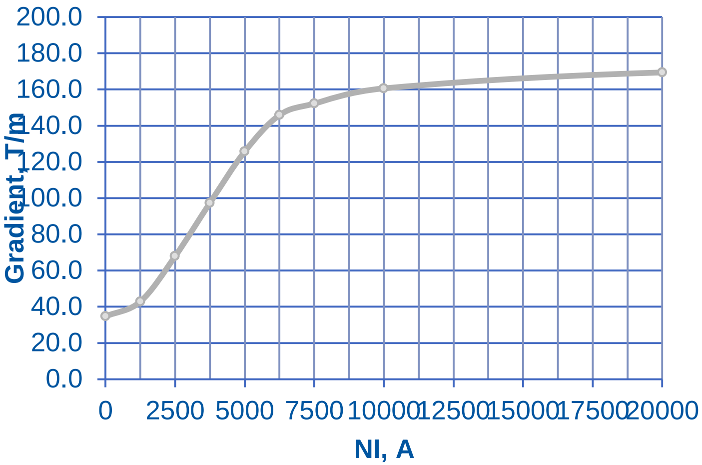


A hybrid QD0 for ILC ?

We have tried to "scale" our QD0 design taking into account the geometric condition but also starting an optimization of the main parameter toward a wider field quality range for the asked tunability.

*(thanks to **A. Aloev** for the fast and efficient following of the FEA calculation!).*





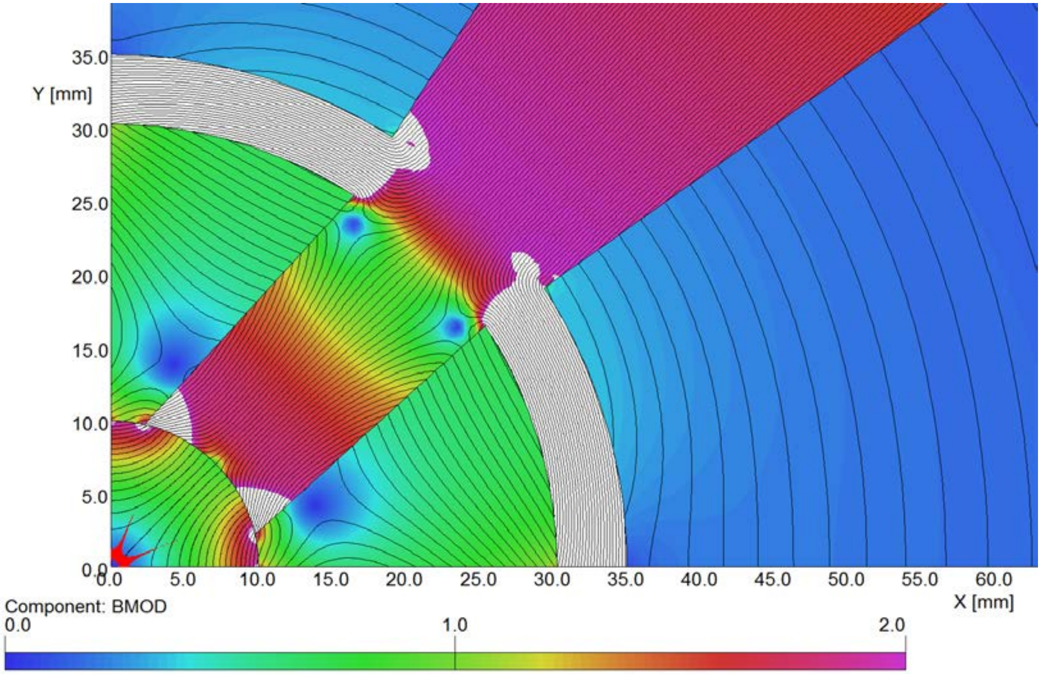
"red line" inside the aperture: area where ΔG/G ≤1 units (good field region)

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		0.1978	0.1510	0.0769	0.0386	0.0215	0.0173	0.0173	0.0182	0.0201	0.0217
b14		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		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)

A hybrid QD0 for ILC ?

In this slide the MAXIMUM GRADIENT configuration (~ 142 T/m)
Poles are wider, saturation appear in some areas, field quality is deeply affected
(even in these IDEAL CALCULATION To not forget!)

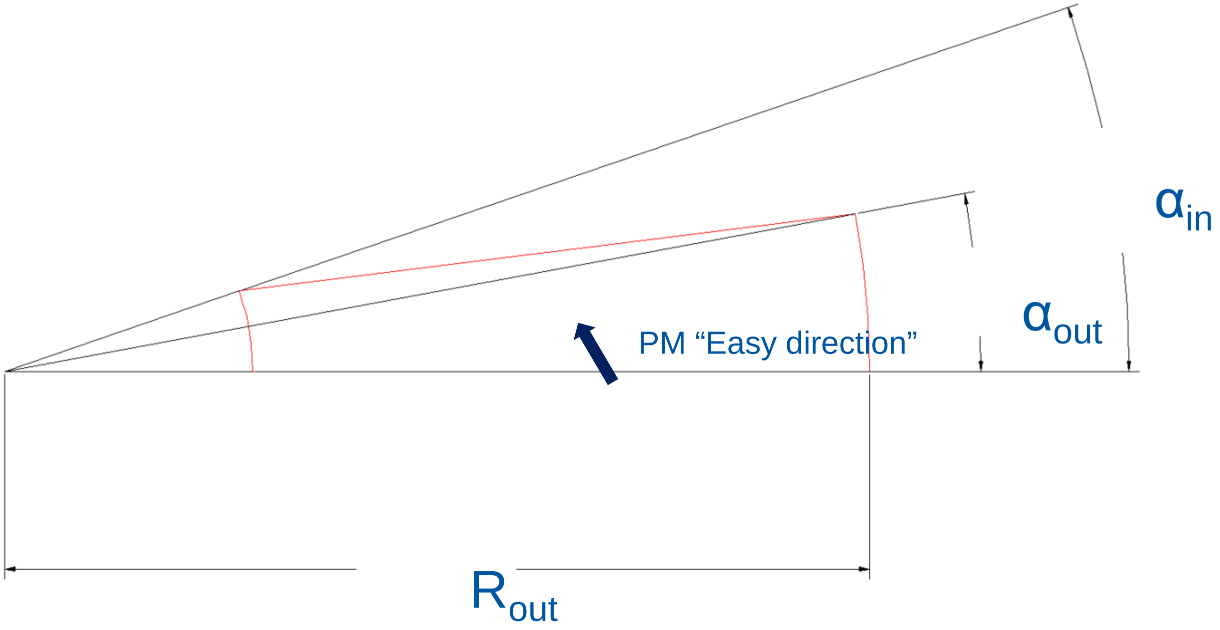


"red line" inside the aperture: area where ΔG/G ≤1 units (good field region)

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

A hybrid QD0 for ILC ?

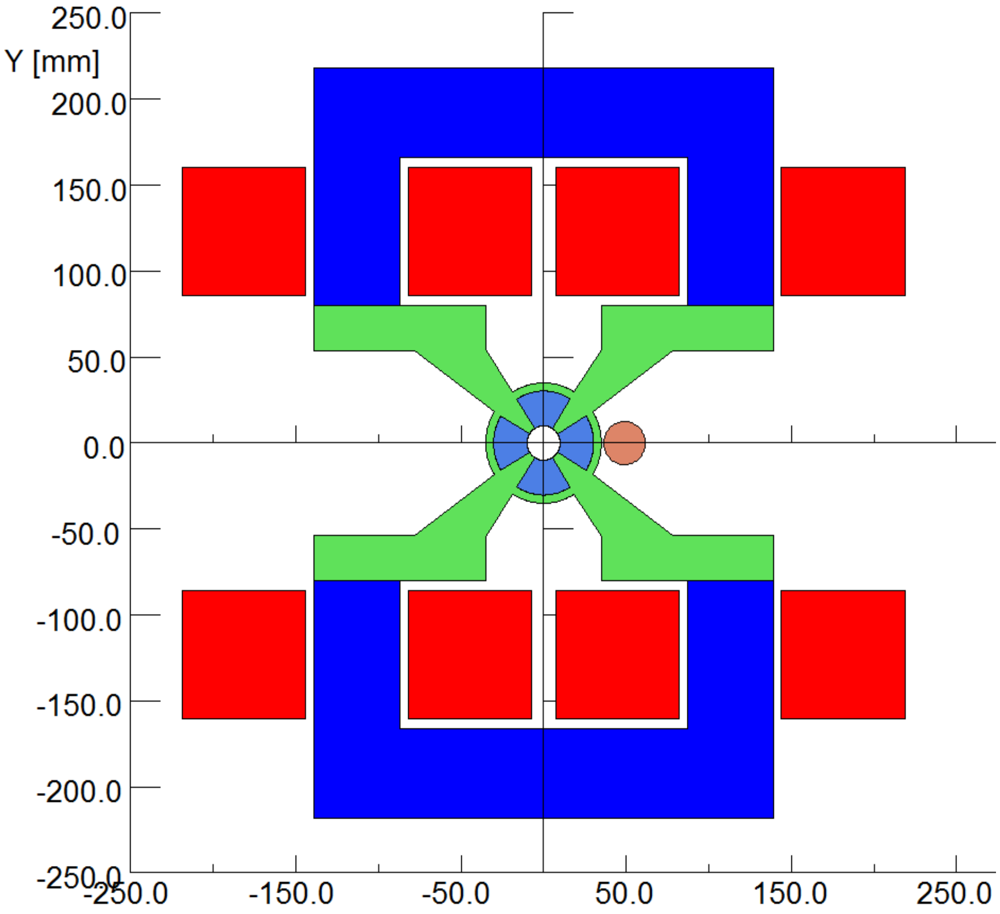
Examples of the optimization done on 3 parameters (α_{in}, α_{out}, ↑$_{easy\ dir}$) (R out=30 mm).
The sets of values that maximize field quality are 32° for both α_{in}, α_{out}, and 55 ° for the easy dir. (1st Table)



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 hybrid QD0 for ILC ?



A basic sketch for the hybrid QD0 adapted to the ILC parameters:
- Coils are sized to a current density of J ~ 0.9 A/mm
- Overall dimension are in the range of 500 x 500 mm.

Conclusions:

- **QD0:**
- \- About the short prototype performances with NdFeB blocks we are waiting the magnetic measurement (Helmholtz system) to investigate the PM blocks quality. Depending from results we could eventually purchase new sets of PM blocks.
- \- Depending from CERN-TE magn. meas. resources we could envisage other MM targeting field quality in function of: magnet working point, PM blocks quality and sorting, etc.
- \- Others QD0 key aspects are now moved on SD0 design and procurement.

- **SD0:**
- \- Conceptual design is advancing.
- \- Compare to the QD0, more investigation and optimization towards field quality are now on-going. *(NOTE: this is also due to improving interactions with Beam Physic Team (R. Tomas Garcia and Y. Levinsen) that provide us more details on FF magnets requirements in terms of acceptable multipoles. This is a critical aspect for our R&D).*

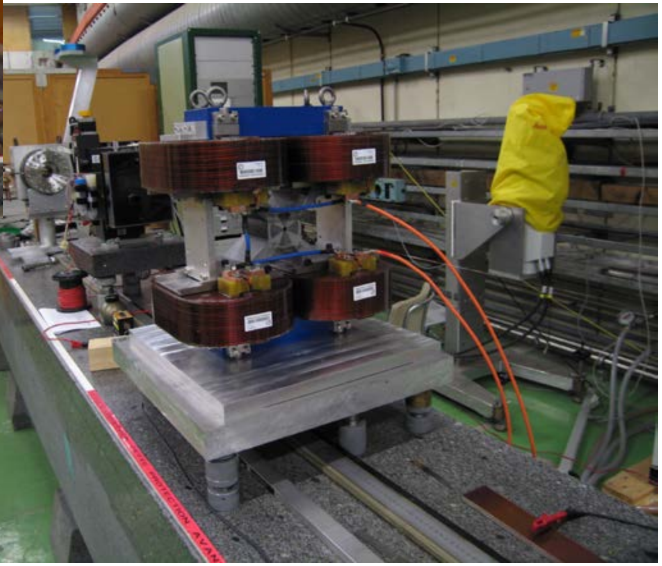
- **Post Collision Line magnets:**
- \- Waiting the official approval of the new baseline, we are advancing with studies for possible alternative dipoles design targeting: low consumption, reliability, resistance to radiation.

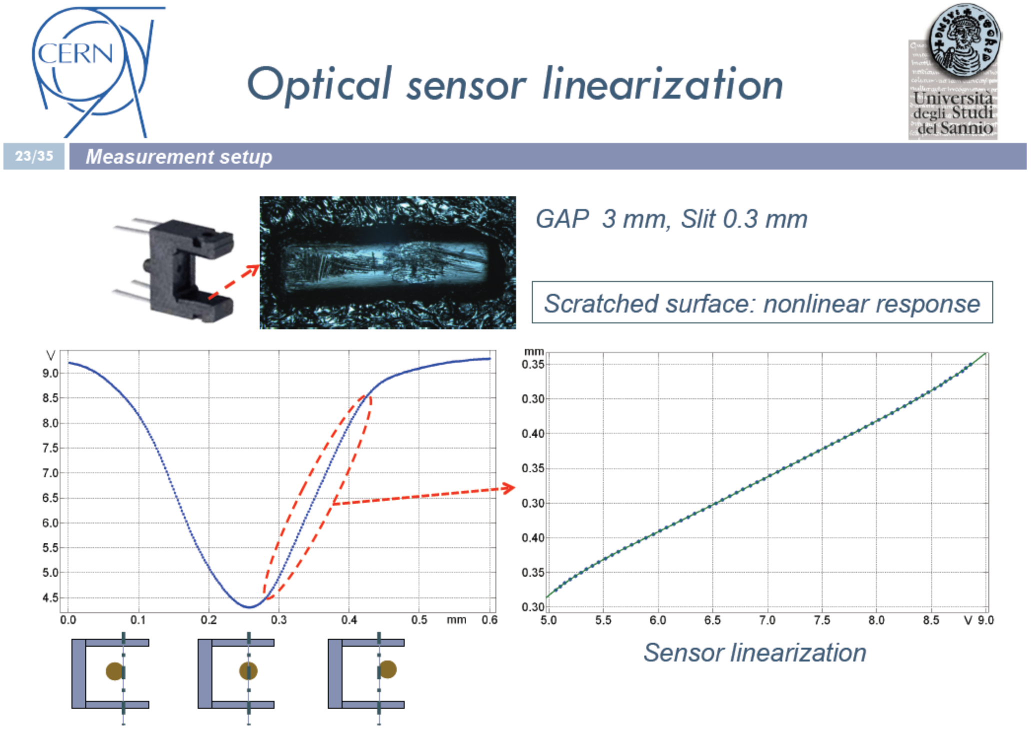
- **Hybrid QDO for ILC:**
- \- A basic magnetic design (our design scaled to ILC geometric and strength parameters) was presented. Achievable field quality aspects were also take into account showing a possible optimization of some critical design parameters.

- ***Thanks***

Extra slides

The “Single Stretched Wire”, “Vibrating Wire” and “oscillating wire” MM Systems





Optical sensor linearization

Università degli Studi del Sannio

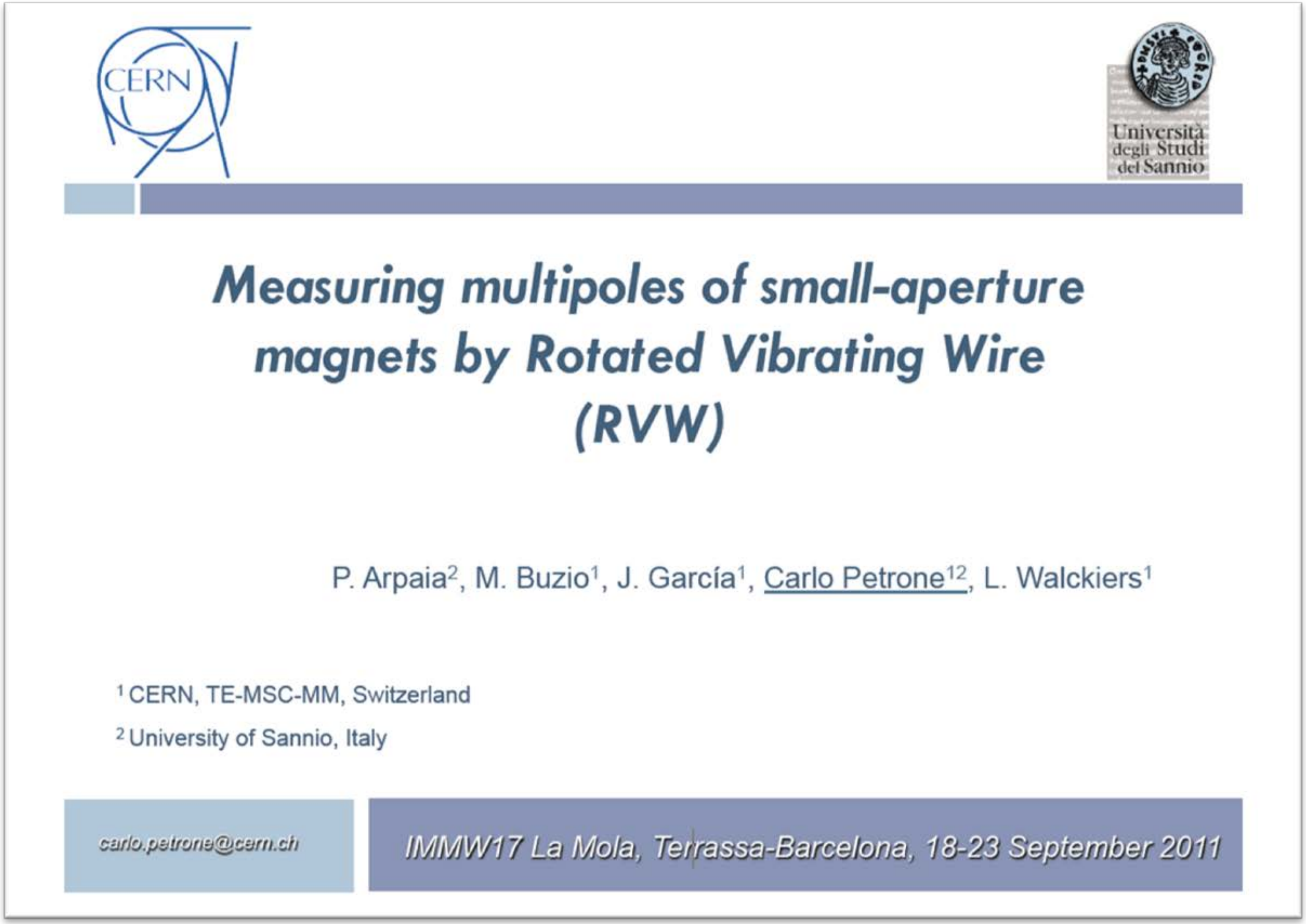
23/35 **Measurement setup**

GAP 3 mm, Slit 0.3 mm

Scratched surface: nonlinear response

Sensor linearization

The "Rotated Vibrating Wire" MM System: ***some basic concepts taken from a recent presentation at IMMW17 ("17th International Magnetic Measurement Workshop")***



Measuring multipoles of small-aperture magnets by Rotated Vibrating Wire (RVW)

P. Arpaia[2], M. Buzio[1], J. García[1], Carlo Petrone[12], L. Walckiers[1]

[1] CERN, TE-MSC-MM, Switzerland

[2] University of Sannio, Italy

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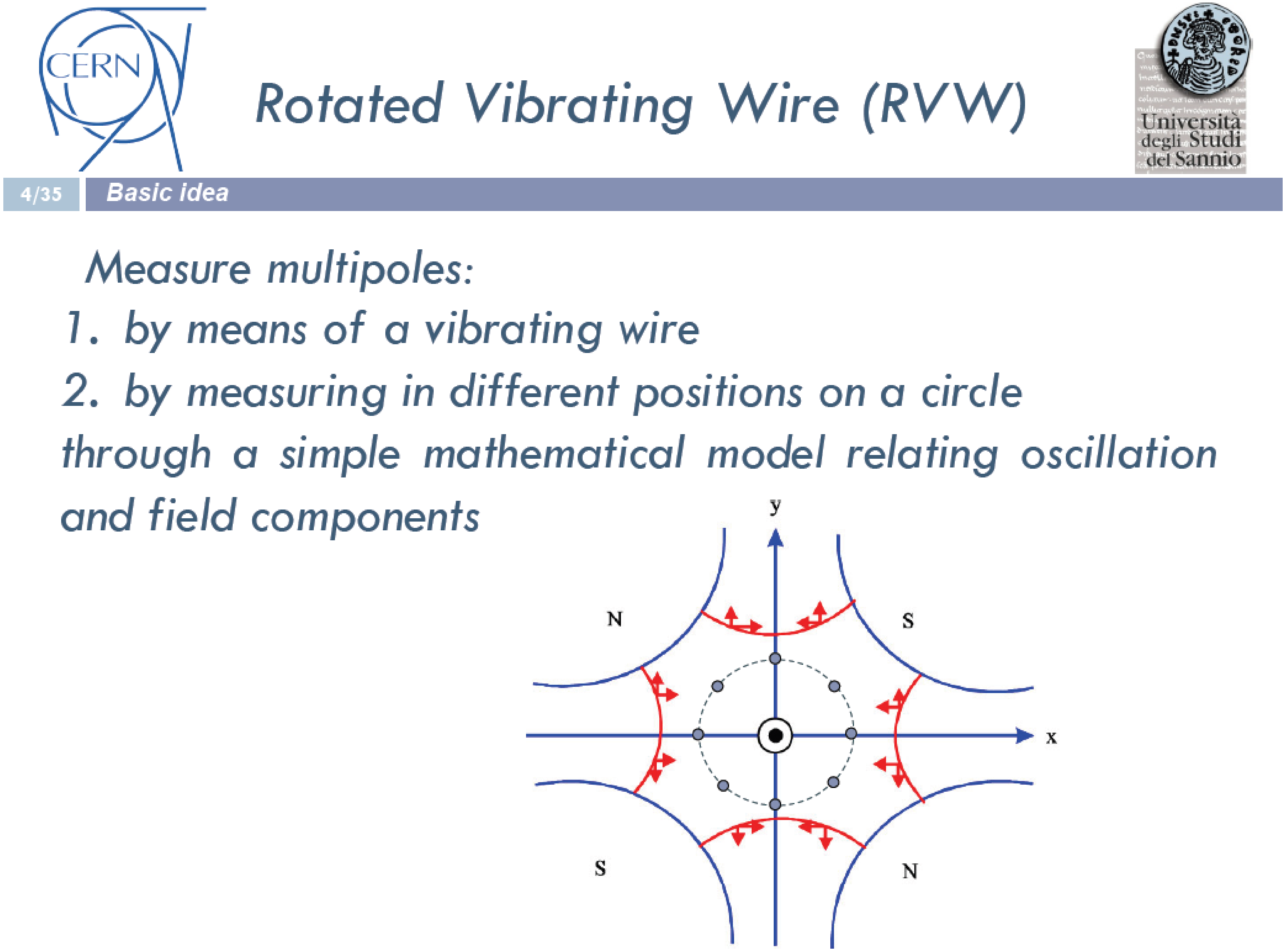
IMMW17 La Mola, Terrassa-Barcelona, 18-23 September 2011

The “Rotated Vibrating Wire” MM System



Rotated Vibrating Wire (RVW)

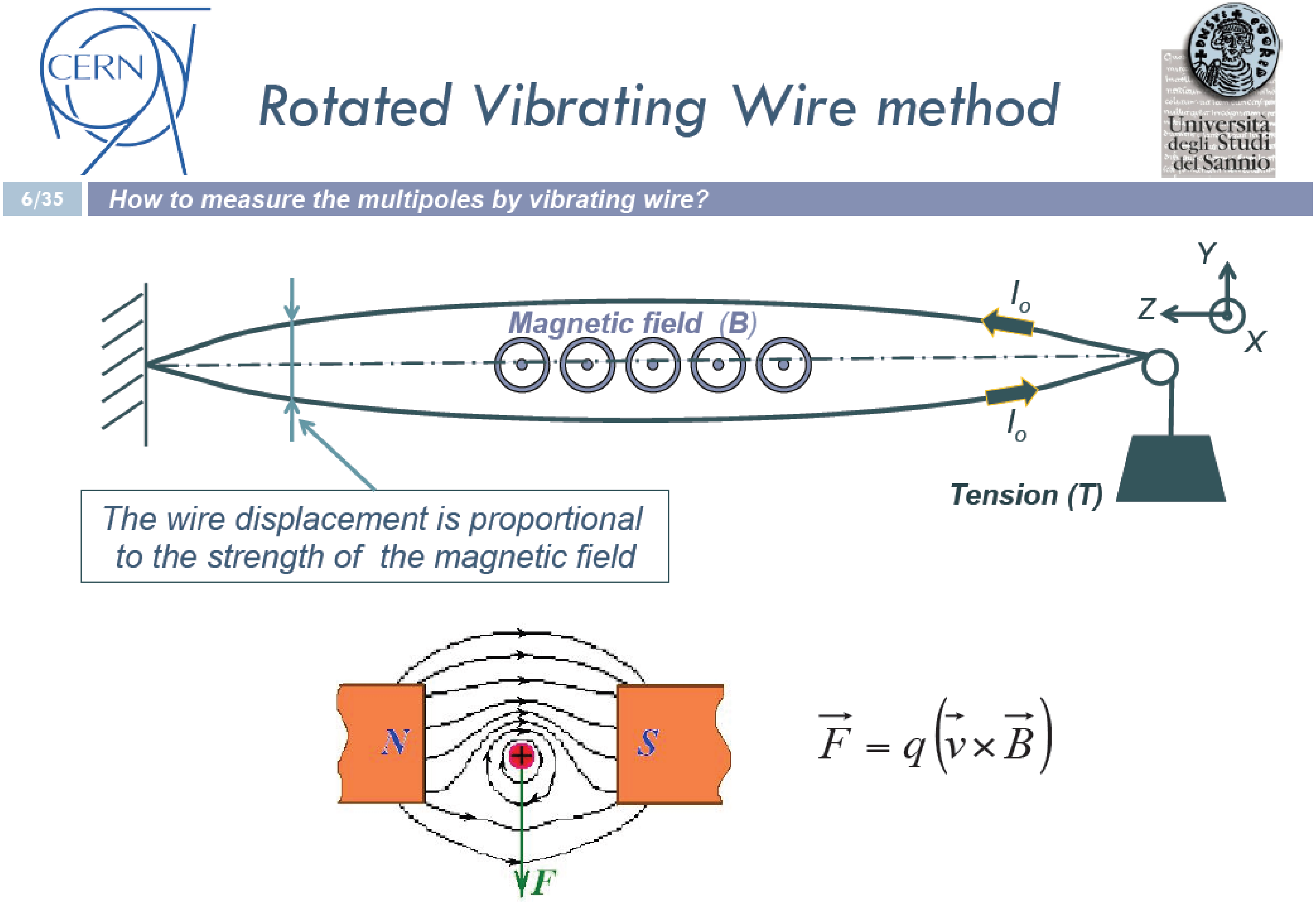
4/35 **Basic idea**

Measure multipoles:

1. by means of a vibrating wire
2. by measuring in different positions on a circle

through a simple mathematical model relating oscillation and field components

The “Rotated Vibrating Wire” MM System



Rotated Vibrating Wire method

6/35

How to measure the multipoles by vibrating wire?

The wire displacement is proportional to the strength of the magnetic field

$$\vec{F} = q\left(\vec{v} \times \vec{B}\right)$$

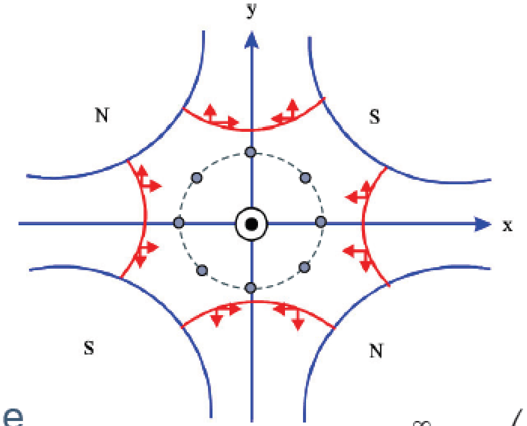
The “Rotated Vibrating Wire” MM System

Rotated Vibrating Wire method

9/35 **Mathematical model**

The wire displacement components are proportional to the magnetic field components

$$A_x \propto B_y \qquad A_y \propto B_x$$



The amplitude **A** can be represented in the complex plane as the magnetic field:

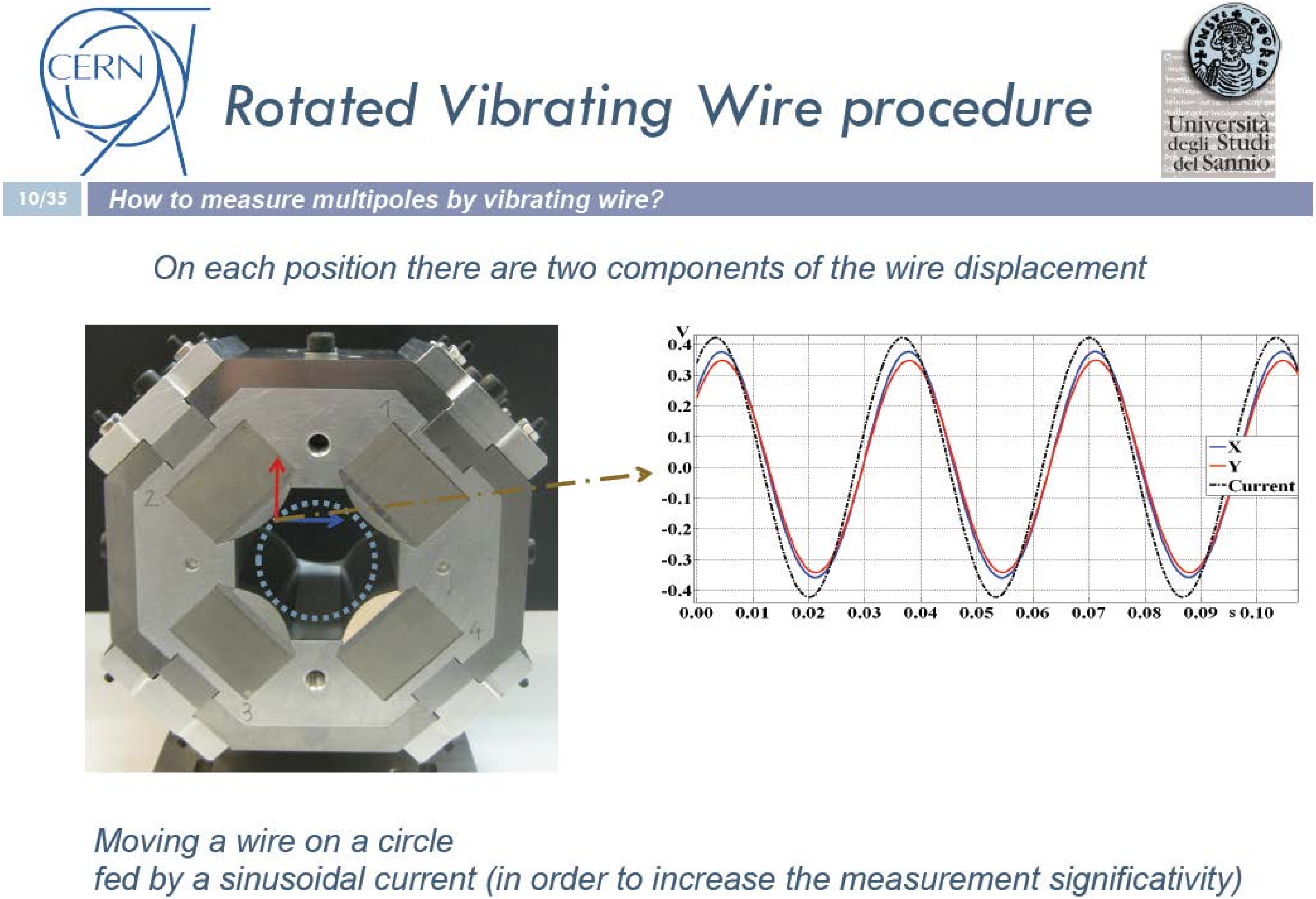
$$\mathbf{A}(z) = A_x + iA_y = \sum_{n=1}^{\infty} \mathbf{V}_n \left(\frac{\mathbf{z}}{R_{ref}}\right)^{n-1}$$

R_{ref} :reference radius

The relative multipoles, scaled on the main component in units, are:

$$\mathbf{V}_n = P_n + iQ_n \rightarrow \mathbf{c}_n = 10^4 \frac{\mathbf{V}_n}{P_{main}} = 10^4 \left(\frac{P_n}{P_{main}} + i\frac{Q_n}{P_{main}}\right) = \boxed{b_n + ia_n}$$

The “Rotated Vibrating Wire” MM System



Rotated Vibrating Wire procedure

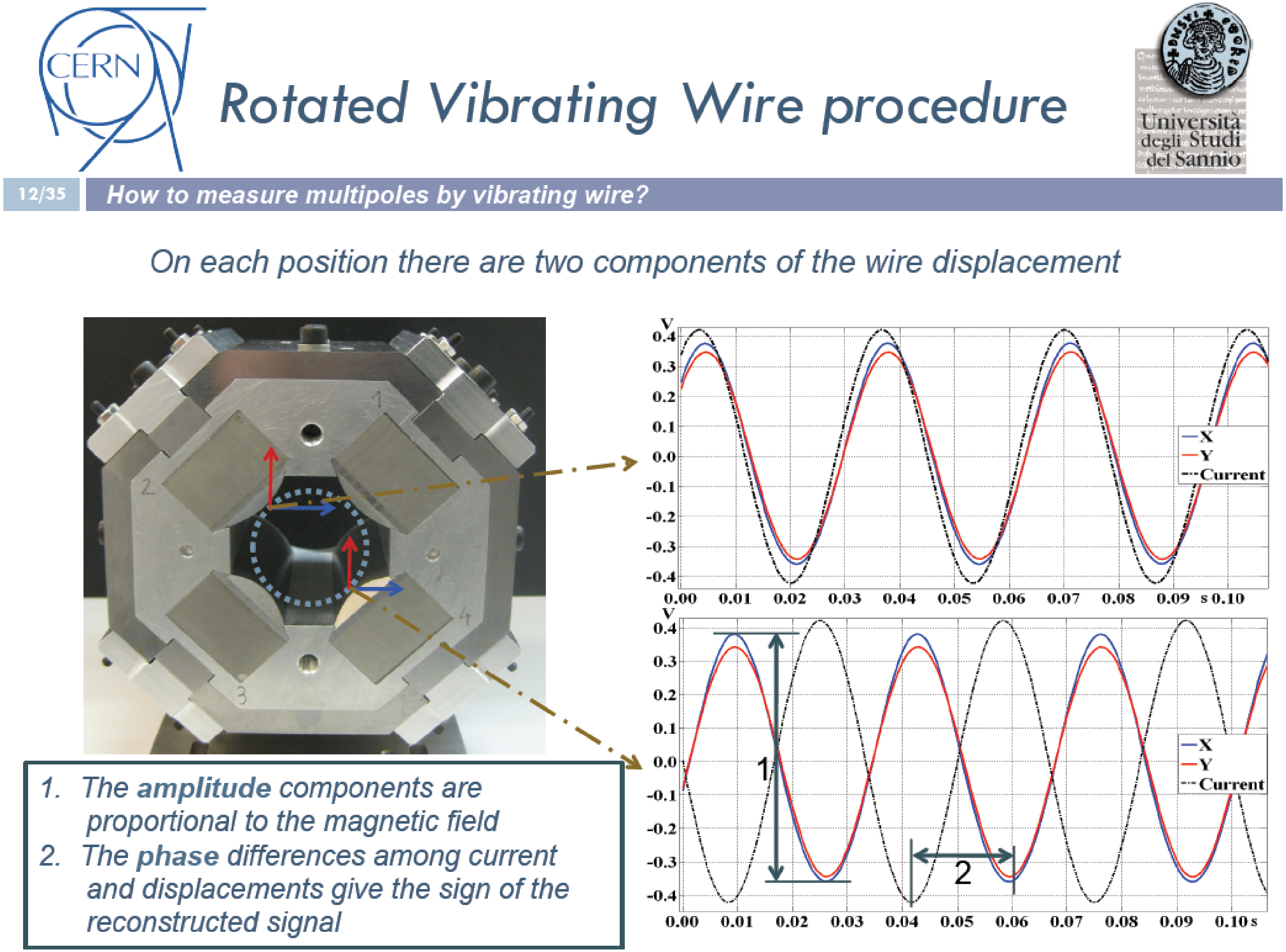
10/35

How to measure multipoles by vibrating wire?

On each position there are two components of the wire displacement

Moving a wire on a circle
fed by a sinusoidal current (in order to increase the measurement significativity)

The “Rotated Vibrating Wire” MM System



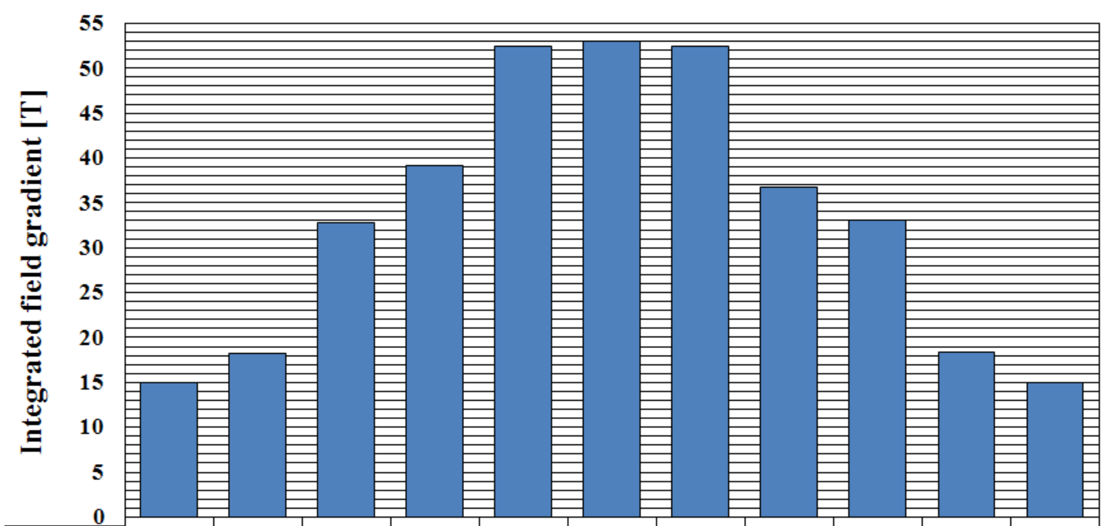
Rotated Vibrating Wire procedure

12/35 ***How to measure multipoles by vibrating wire?***

On each position there are two components of the wire displacement

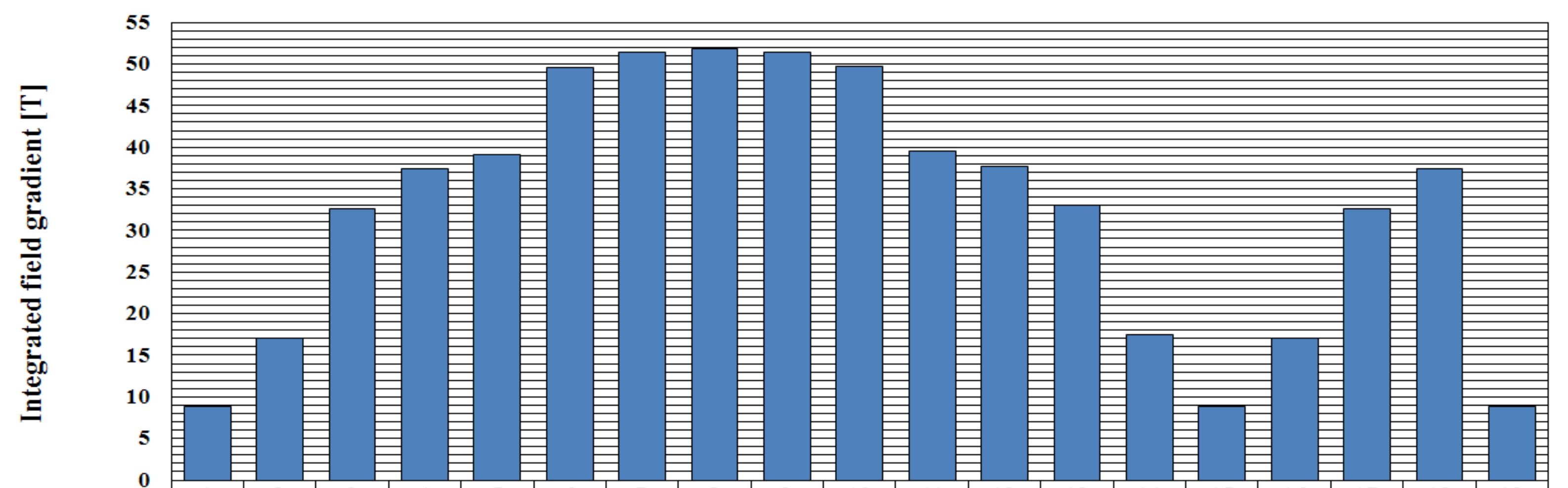
1. *The **amplitude** components are proportional to the magnetic field*
2. *The **phase** differences among current and displacements give the sign of the reconstructed signal*

CLiC QD0 Status

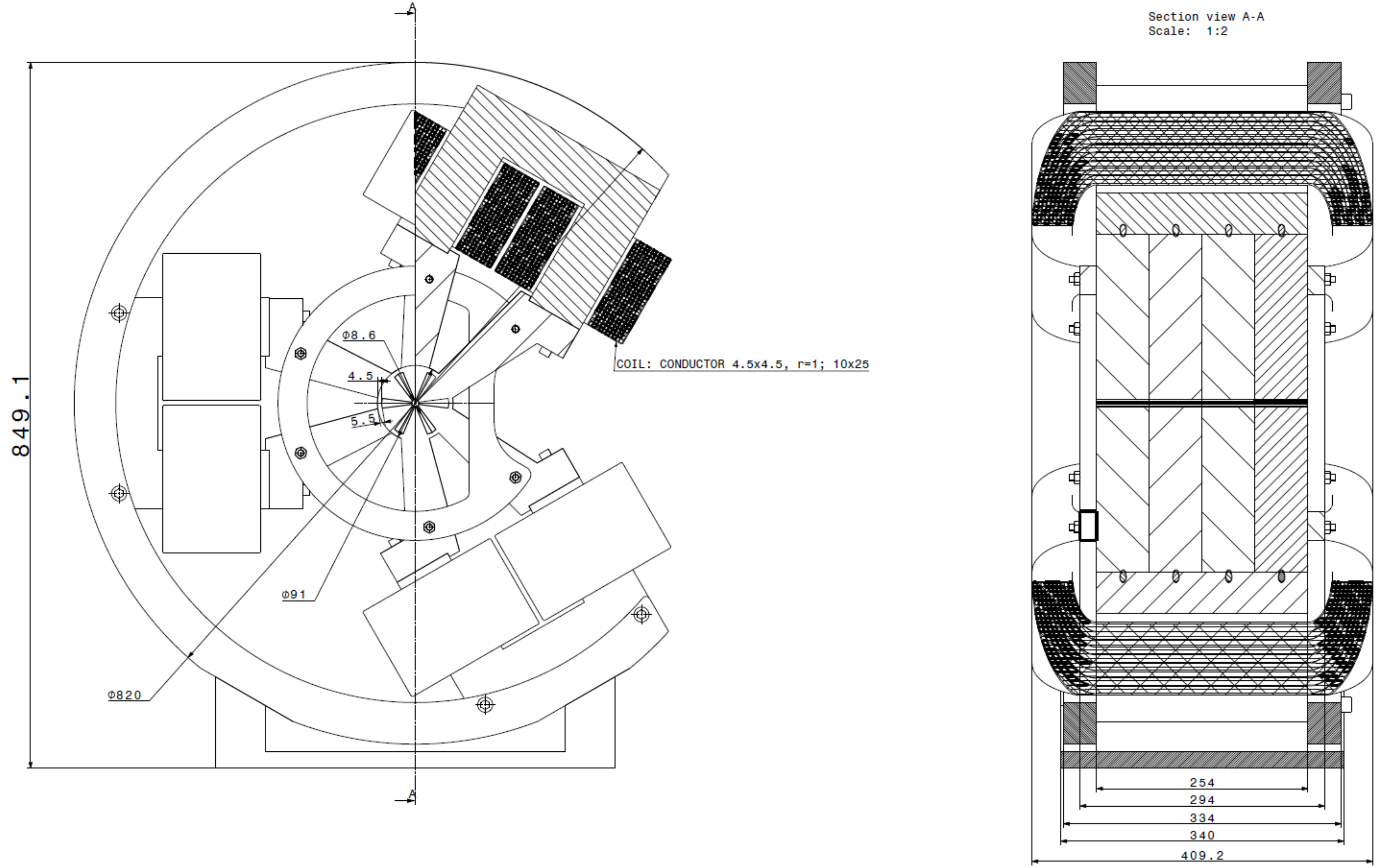


N of meas	1	2	3	4	5	6	7	8	9	10	11
GL [T]	14.971	18.283	32.773	39.095	52.494	52.956	52.501	36.790	33.001	18.432	14.913
NI [A]	0.0	1004.4	2008.8	2462.4	5022.0	6026.4	5022.0	2268.0	2008.8	1004.4	0.0

The curves below shows the INTEGRATED GRADIENT measured versus the QD0 powering (total coils current NI) for both QD0 configurations; upper graph for $Nd_2Fe_{14}B$, lower graph for Sm_2Co_{17}. No demagnetization nor hysteresis effects (very interesting point) are visible (same gradient for same current all along the cycles).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
GL [T]	8.900	17.050	32.600	37.350	39.150	49.550	51.450	51.900	51.450	49.650	39.500	37.700	33.000	17.400	8.900	17.050	32.600	37.400	8.900
NI [A]	0.0	1004.4	2008.8	2332.8	2462.4	3564.0	5022.0	6026.4	5022.0	3564.0	2462.4	2332.8	2008.8	1004.4	0.0	1004.4	2008.8	2332.8	0.0


A
849.1
Φ8.6
4.5
5.5
Φ91
Φ820
COIL: CONDUCTOR 4.5x4.5, r=1; 10x25
A
Section view A-A
Scale: 1:2
254
294
334
340
409.2