HL-LHC
IR Higher Order Corrector Magnets Conceptual Design & Construction Activity

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Presented by Giovanni Volpini

V 20 11 b

KEK, 20 November 2014

outline

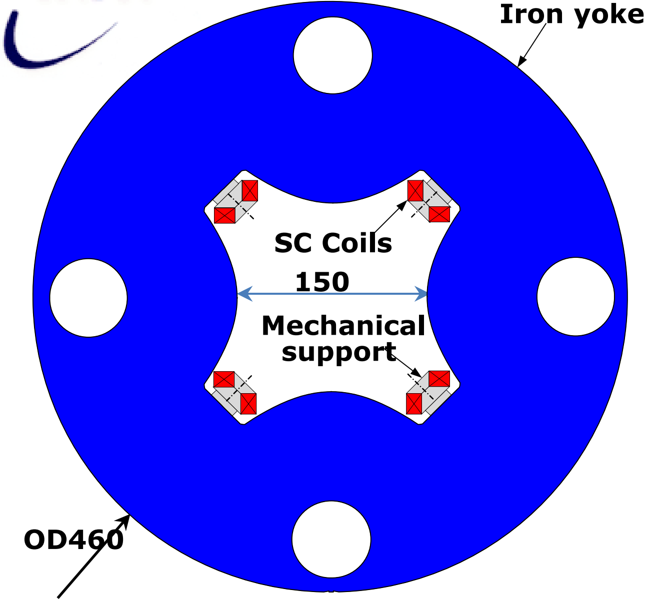
1. 2D & 3D electromagnetic design

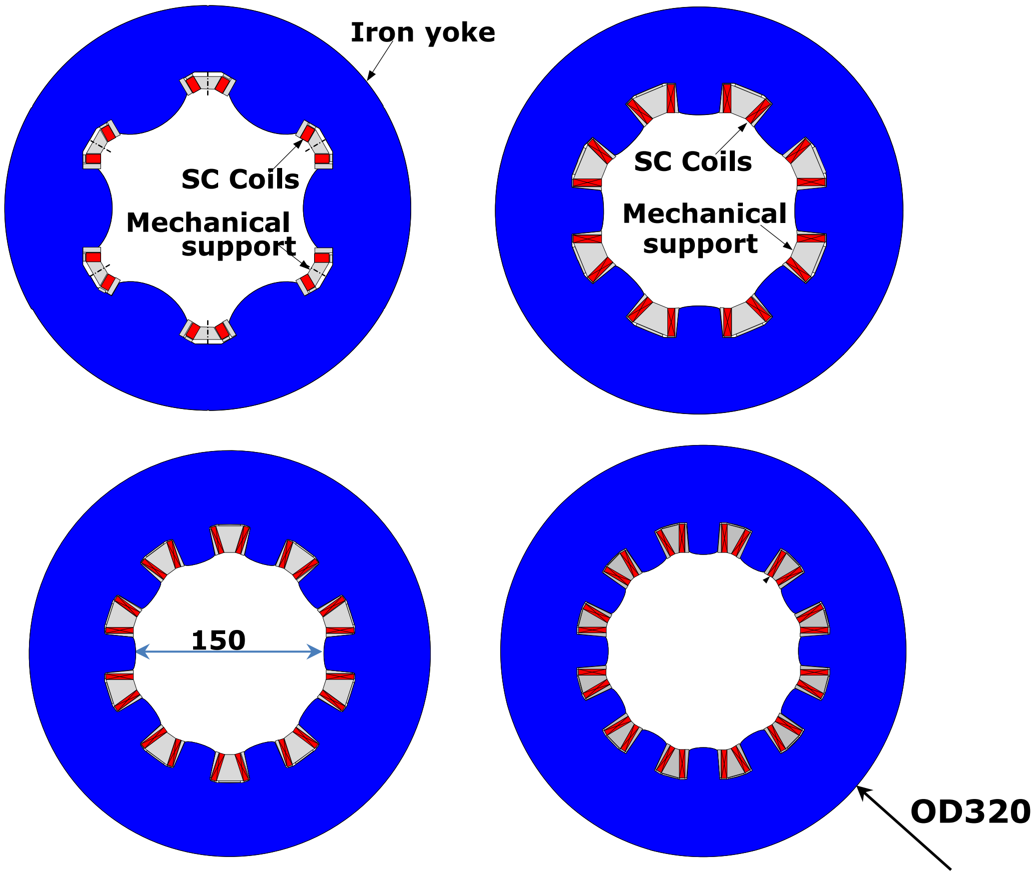
2. magnet coupling

3. magnet construction &
   technological developments

4. organization, next steps, conclusion

Corrector magnet inventory





From 6-pole to 12-pole magnets exist in both normal and skew form (the latter is shown)

The superferric design was chosen for ease of construction, compact shape, modularity, following the good performance of earlier corrector prototype magnets developed by Ciemat (Spain).

LHC vs. HL-LHC corrector magnet comparison chart

		LHC						HL-LHC					
Order	Type			Aperture	Stored energy	Operating Current	Inductance	Aperture	Stored energy	Operating Current	Integrated field at r=50 mm	Magnetic Length	Differential Inductance @ Iop
				mm	[J]	[A]	[mH]	[mm]	[kJ]	[A]	[T.m]	[m]	[H]
2	S	MQSX		70	2,116	550	14	150	24.57	182	1.00	0.807	1.247
3	N	MCSX	MCSTX	70	39	100	4.7	150	1.28	132	0.06	0.111	0.118
3	S	MCSSX	MCSOX	70	6	50	7.8	150	1.28	132	0.06	0.111	0.118
4	N	MCOX		70	16	100	4.4	150	1.41	120	0.04	0.087	0.152
4	S	MCOSX		70	22	100	3.2	150	1.41	120	0.04	0.087	0.152
5	N							150	1.39	139	0.03	0.095	0.107
5	S							150	1.39	139	0.03	0.095	0.107
6	N	MCTX	MCSTX	70	94	80	29.2	150	4.35	167	0.086	0.430	0.229
6	S							150	0.92	163	0.017	0.089	0.052

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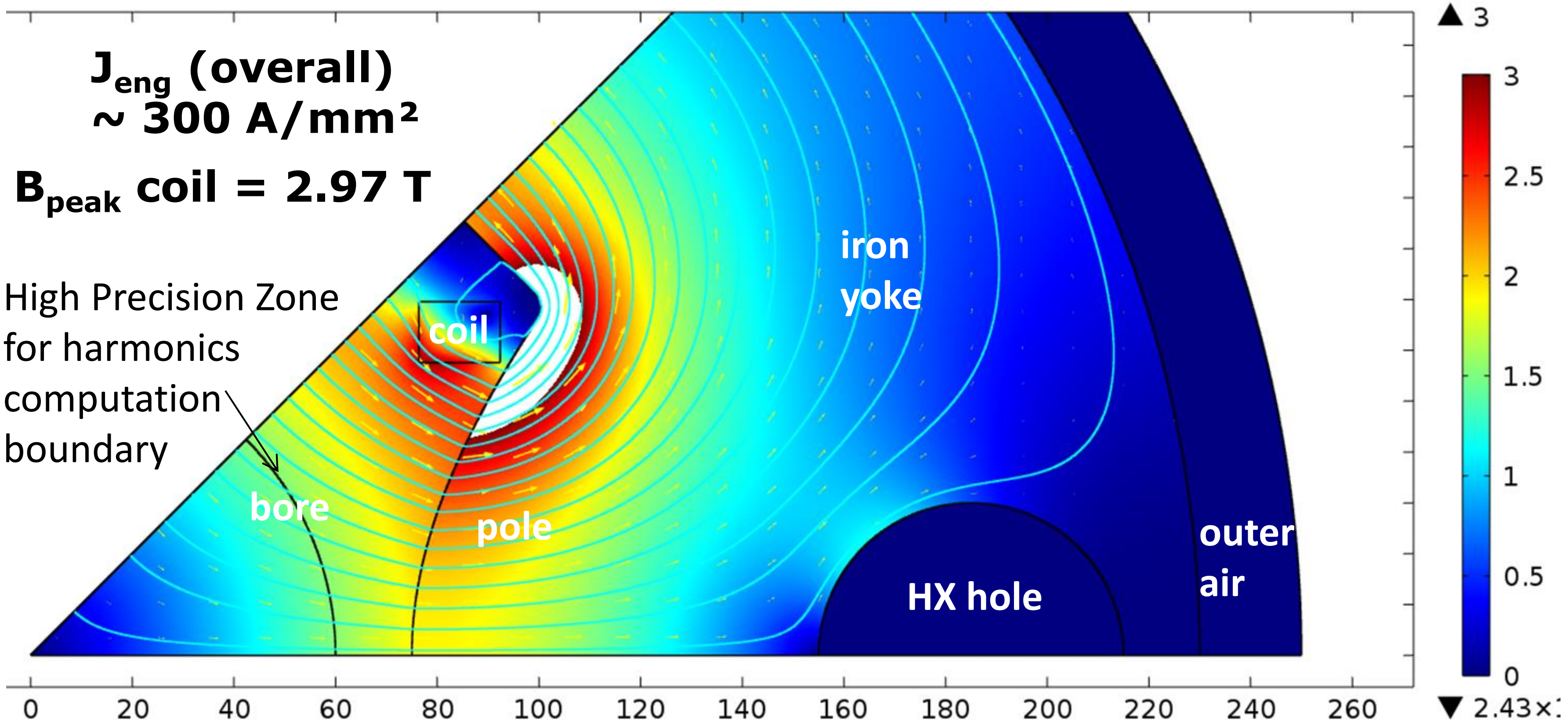
Quadrupole 2D cross section

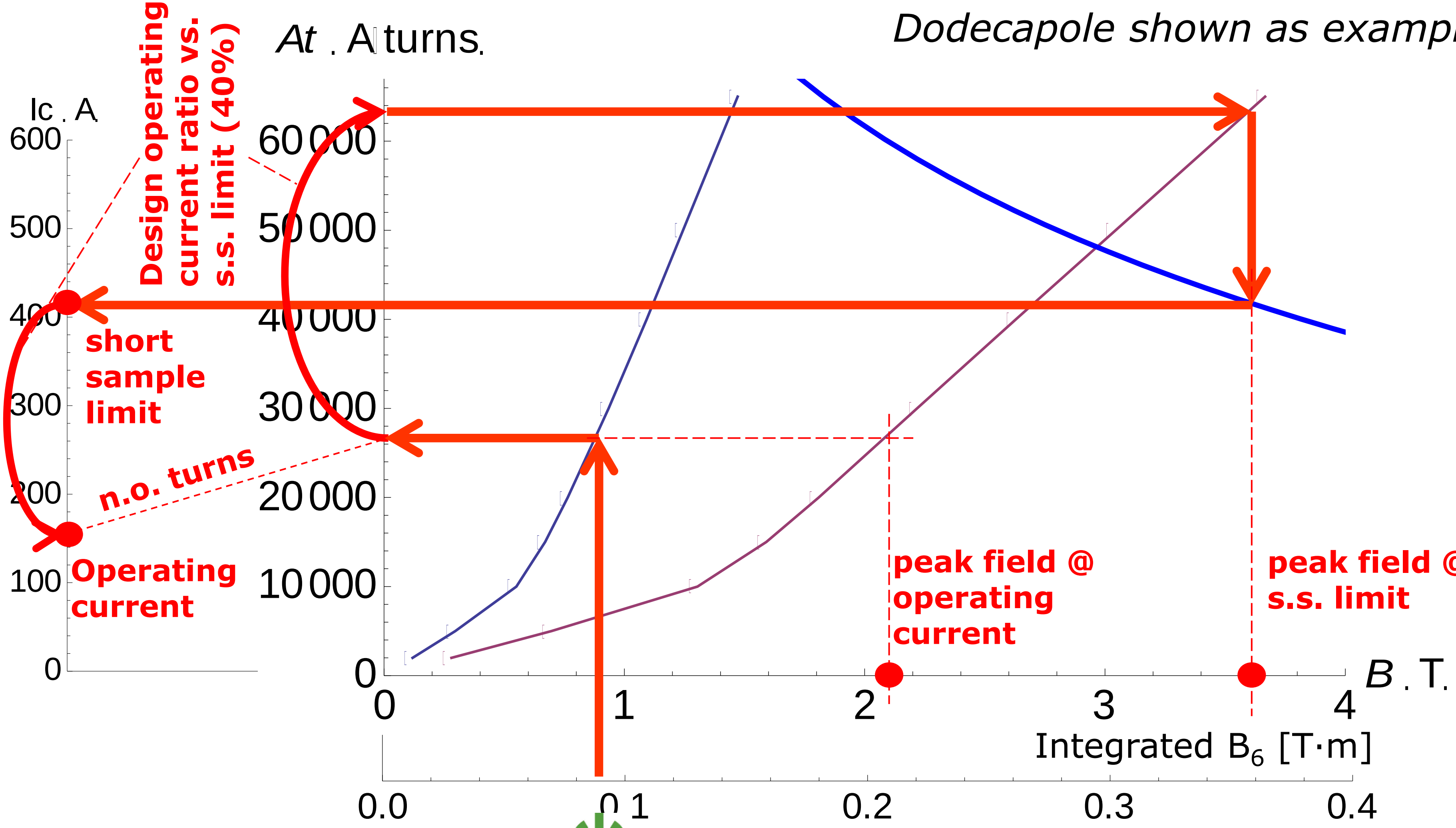
Yoke radius = 230 mm



HX bore D 60 mm @ r = 185 mm

Load line & optimization procedure

Dodecapole shown as example



Design operating current ratio vs. s.s. limit (40%)

short sample limit

n.o. turns

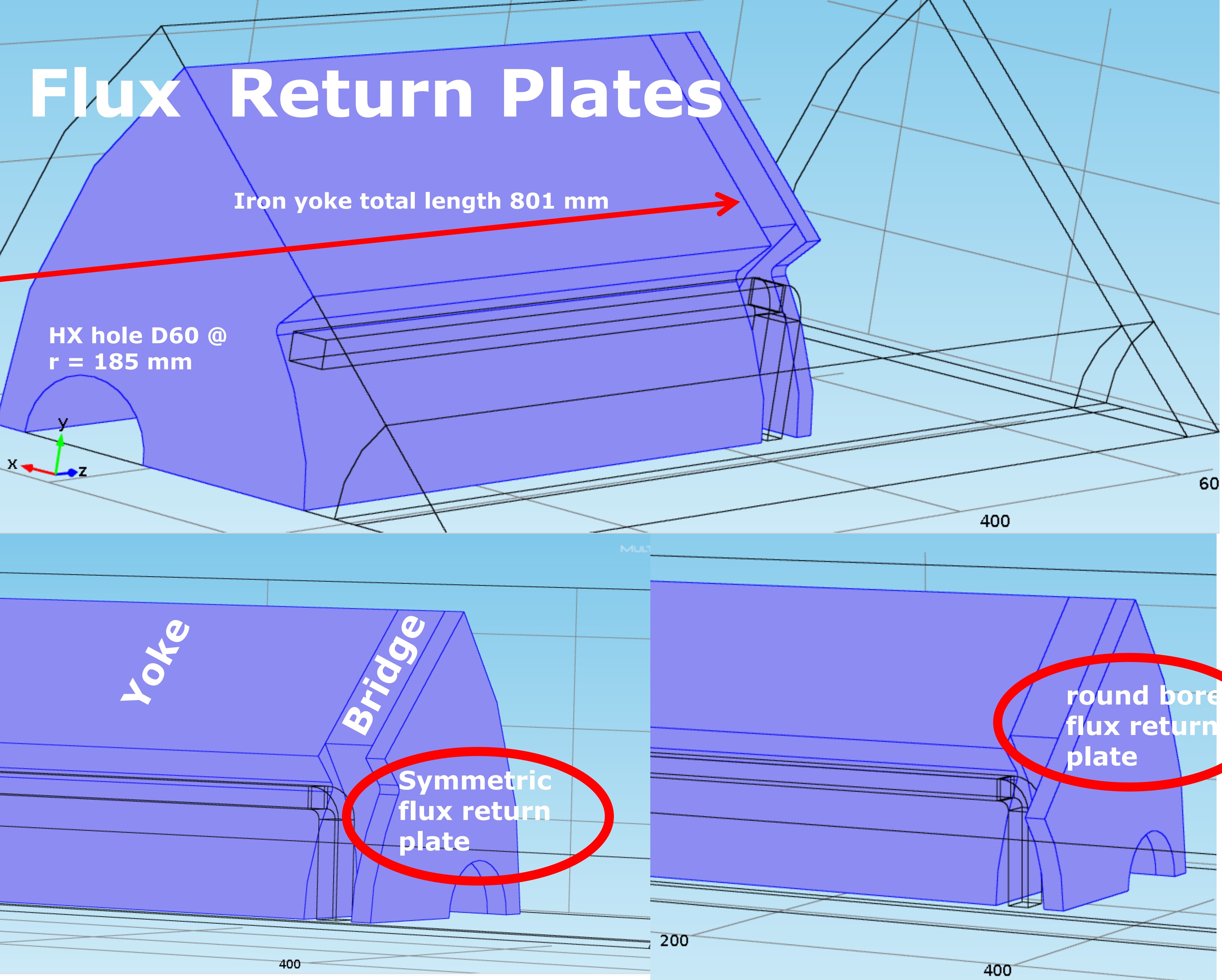
Operating current

peak field @ operating current

peak field @ s.s. limit

Design integrated strength 0.086 T·m

Flux Return Plates



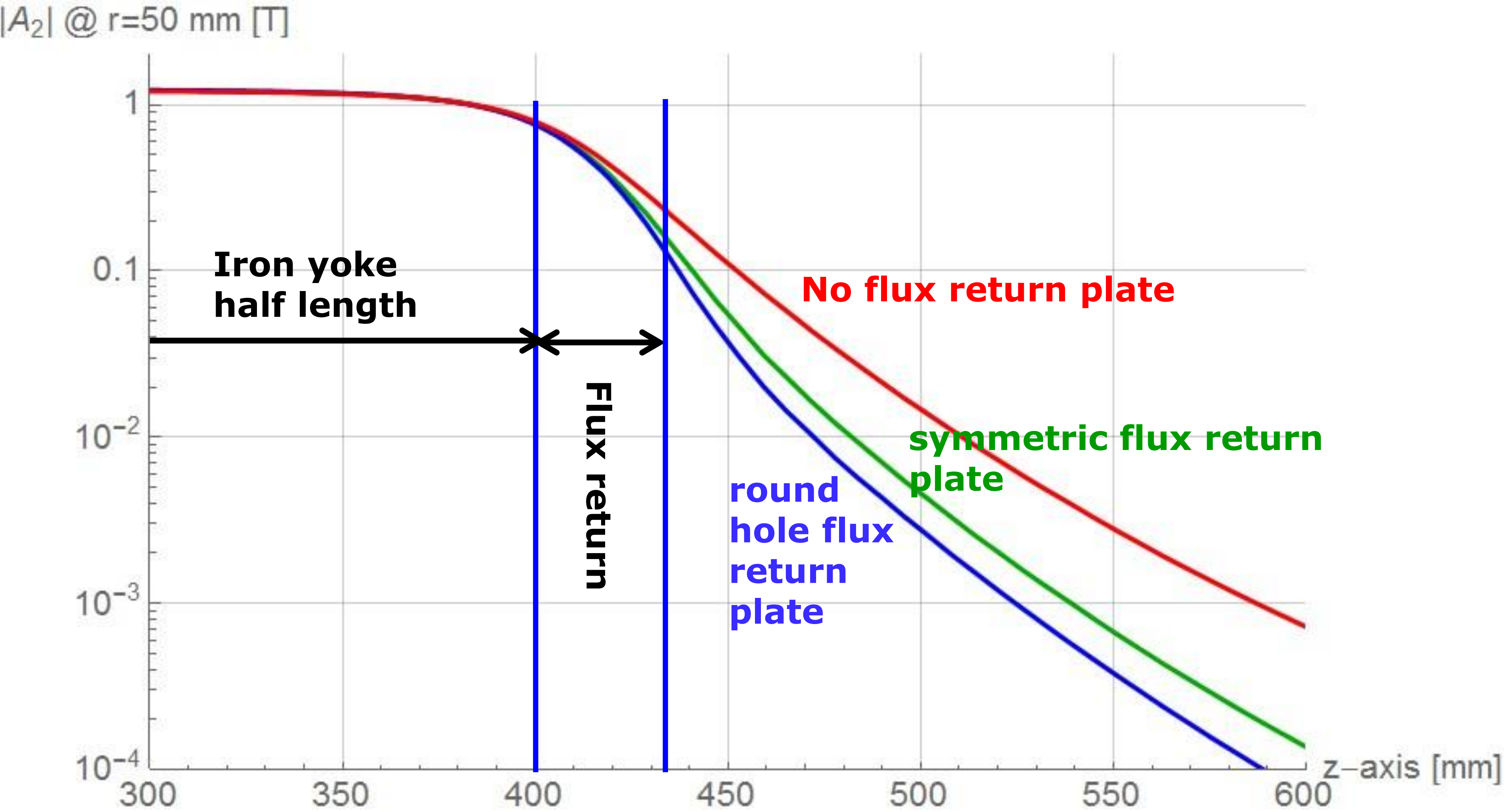
Iron yoke total length 801 mm

HX hole D60 @
r = 185 mm

Symmetric
flux return
plate

round bore
flux return
plate

Stray Field



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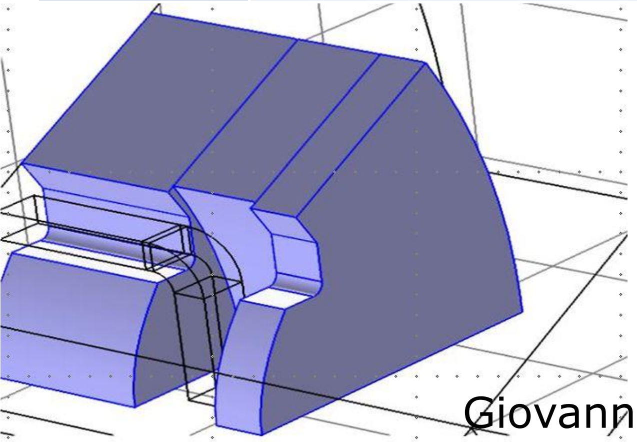
A Comparison of Codes

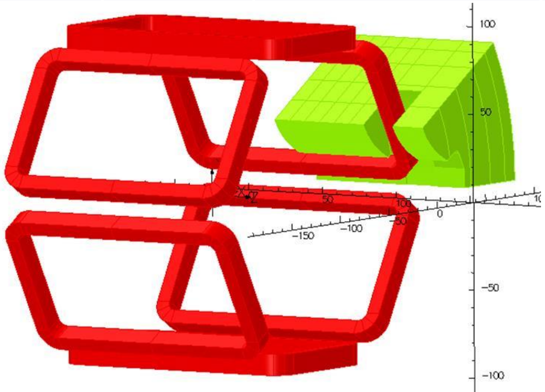
Use different codes to simulate the same sextupole, to cross-check & validate the results:

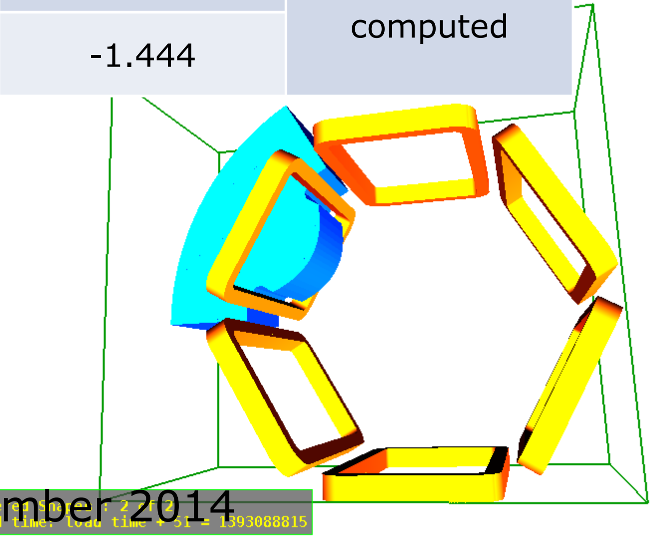
- **COMSOL + Mathematica for harmonic analysis**
- **OPERA** (2D and 3D models developed by ***Alejandro Sanz-Ull, CERN-TE-MSC***)
- **Roxie**

2D computations: agreement within few parts/10^4 on fields; ~ 1/10 of unit on relevant harmonics.

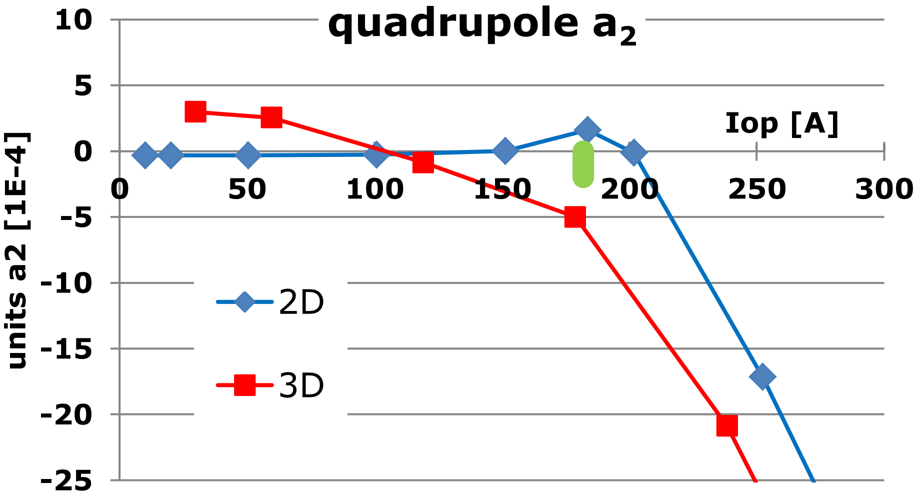
3D computations			**COMSOL™**	**OPERA™**	**Roxie**
No FRY	Integrated B_3 @ r = 50 mm	T·m	-0.0758	-0.0759	-0.0756
	b_9	10^{-4}	-21.50	-21.57	-22.5
With FRY	Integrated B_3 @ r = 50 mm	T·m	-0.0686	-0.0688	not computed
	b_9	10^{-4}	-1.494	-1.444	

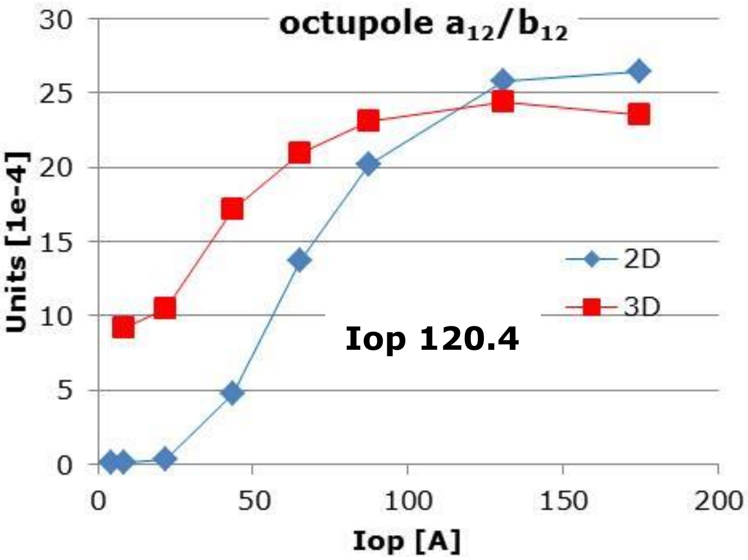


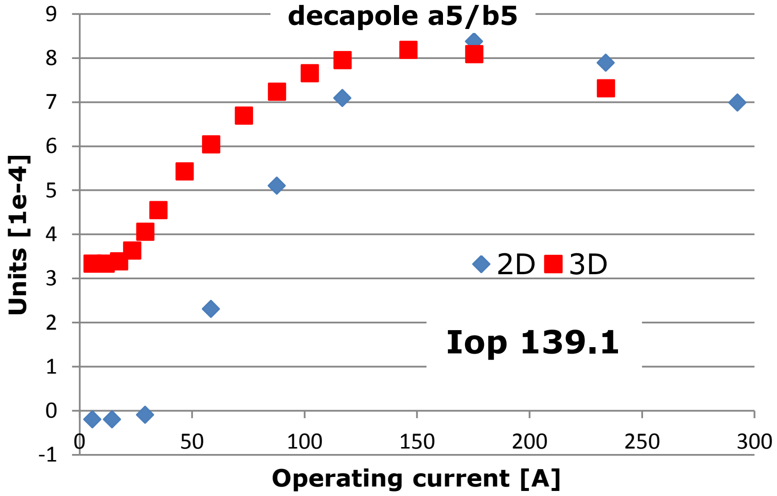


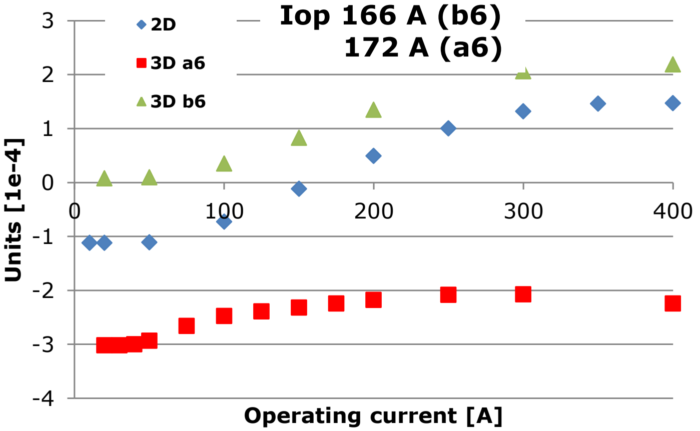


Harmonics vs. operating current



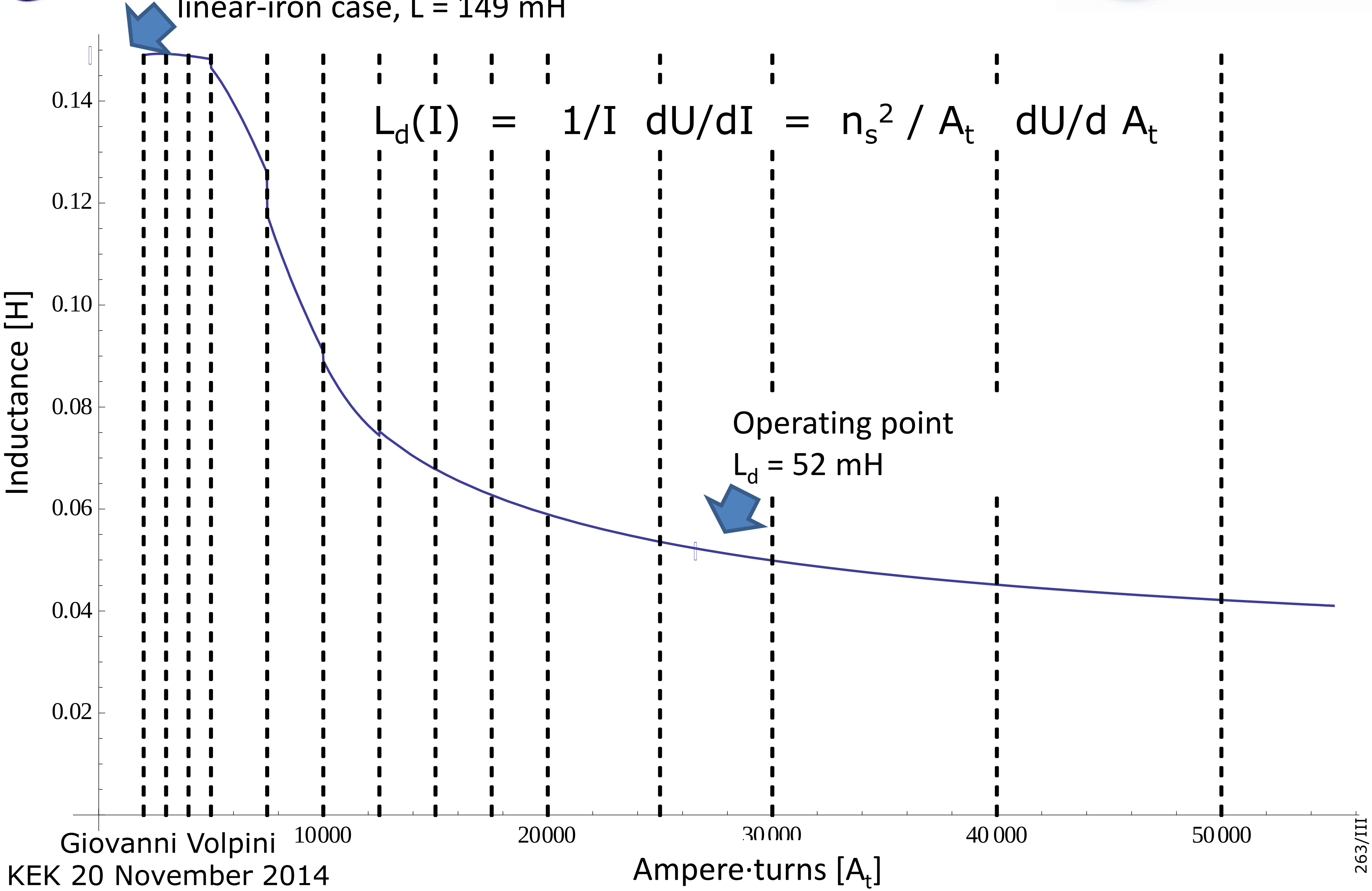






Differential Inductance, a_6

«zero-current» inductance, from linear-iron case, L = 149 mH



$$L_d(I) = 1/I \;\; dU/dI = n_s^2 / A_t \;\; dU/d\,A_t$$

Operating point
L_d = 52 mH

1. 2D & 3D electromagnetic design

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Problem statement

Coupling: electromagnetic cross-talk and forces acting between adjacent corrector magnets.

A full (2π) model has been developed since in the most general case no symmetry exists. One magnet is powered, with real iron and the second one (coupled) is described through its iron yoke, assuming linear iron. Loose boundary conditions and the «mixture» of different problems (high field, current driven on one side, and «quasi magnetostatic» on the other), led to convergence problem and doubtful solutions.

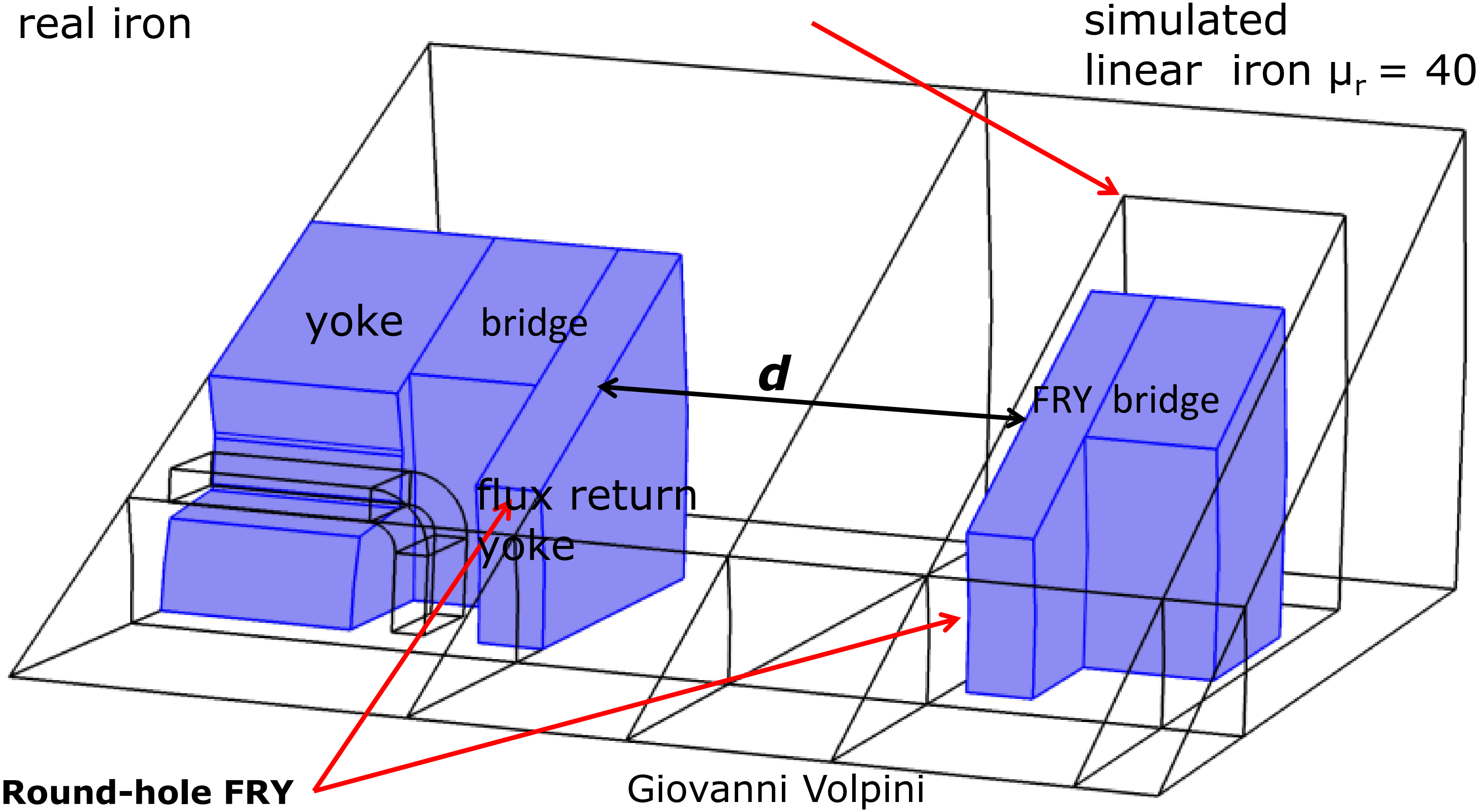
A **simplified model** has therefore been introduced, **leaving out the iron yoke and considering only the flux return yoke and the bridge of second magnet.** This increases the symmetry of the problem (only π /n is now required), reducing computation time/increasing the accuracy, at the price of a somewhat less accurate description of the second magnet.

We have considered two cases: **quadrupole** and **octupole**

Model

source magnet:
current
yoke+bridge+FRY
real iron

coupled magnet:
no current
only FRY + bridge simulated
linear iron $\mu_r = 4000$



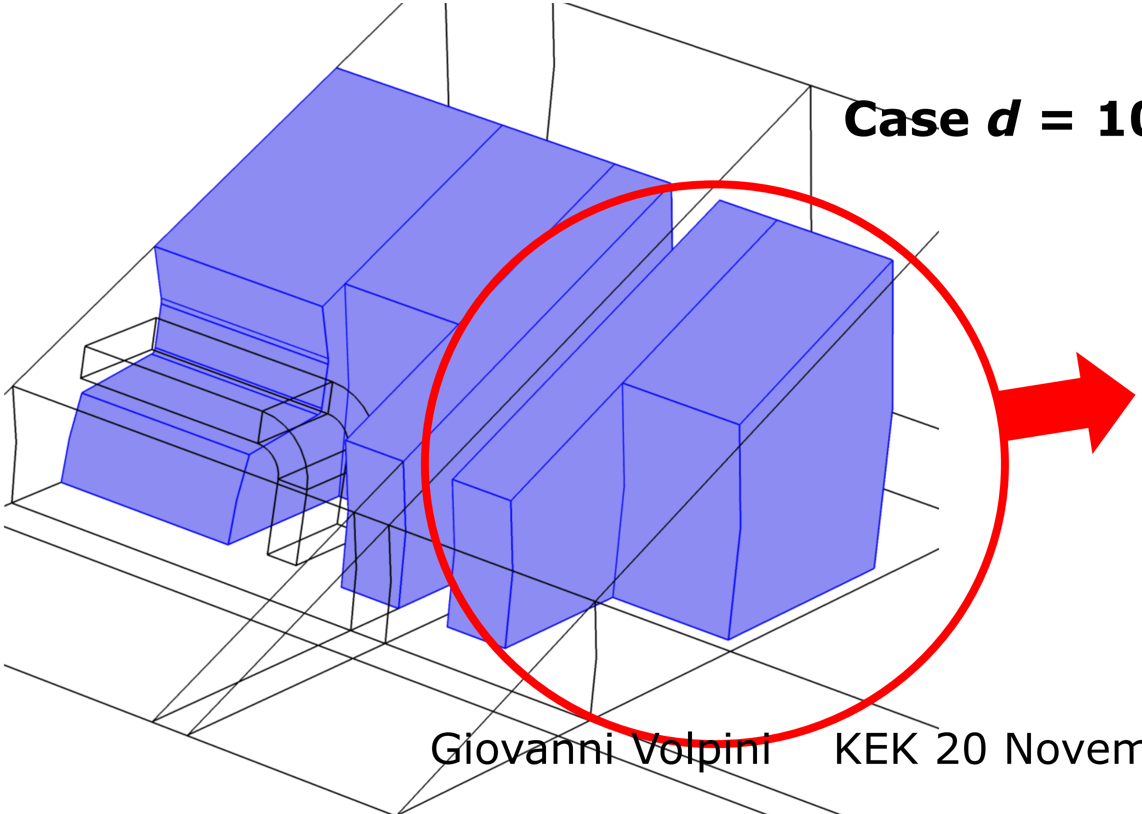
Box for Maxwell e.m. stress tensor calculation

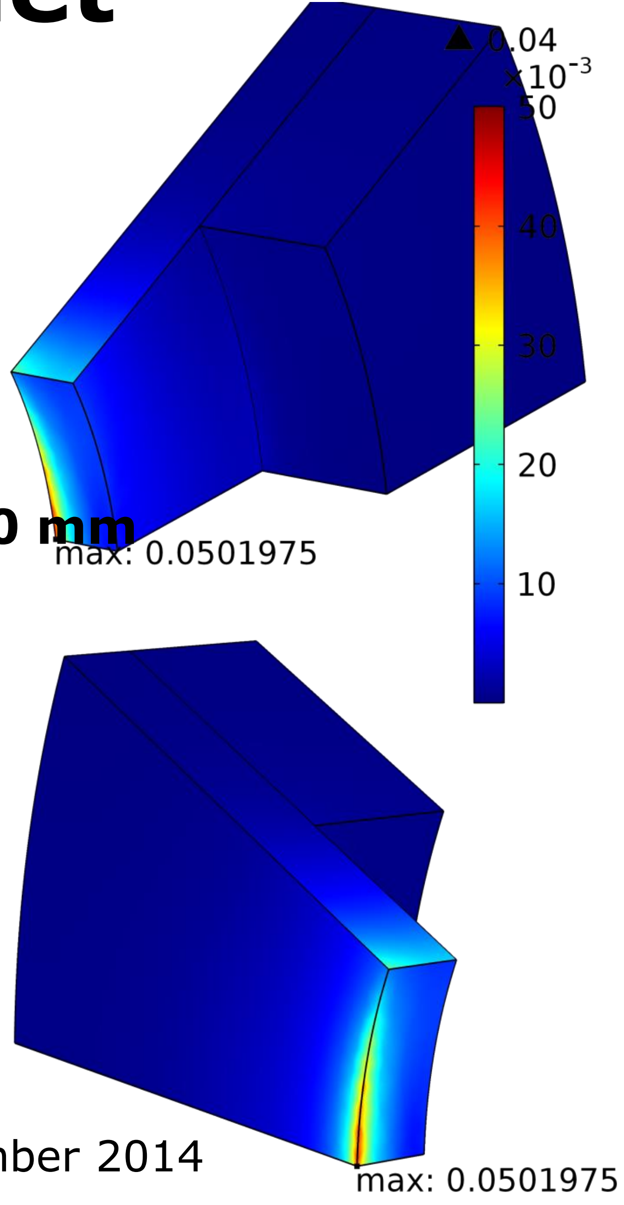
Round-hole FRY

Cross-talk in the coupled magnet

The magnetic induction in the FRY of the coupled magnet is mostly concentrated close to the bore, and is extremely small in the bridge connecting the FRY to the yoke (the latter is not modelized)

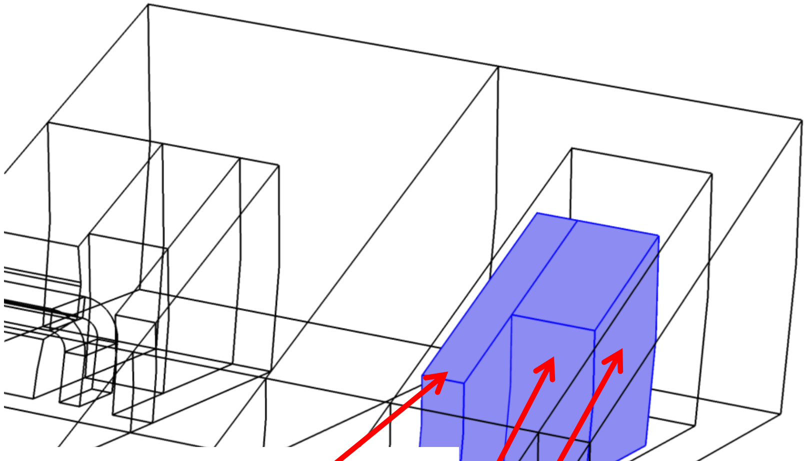
Case *d* = 10 mm

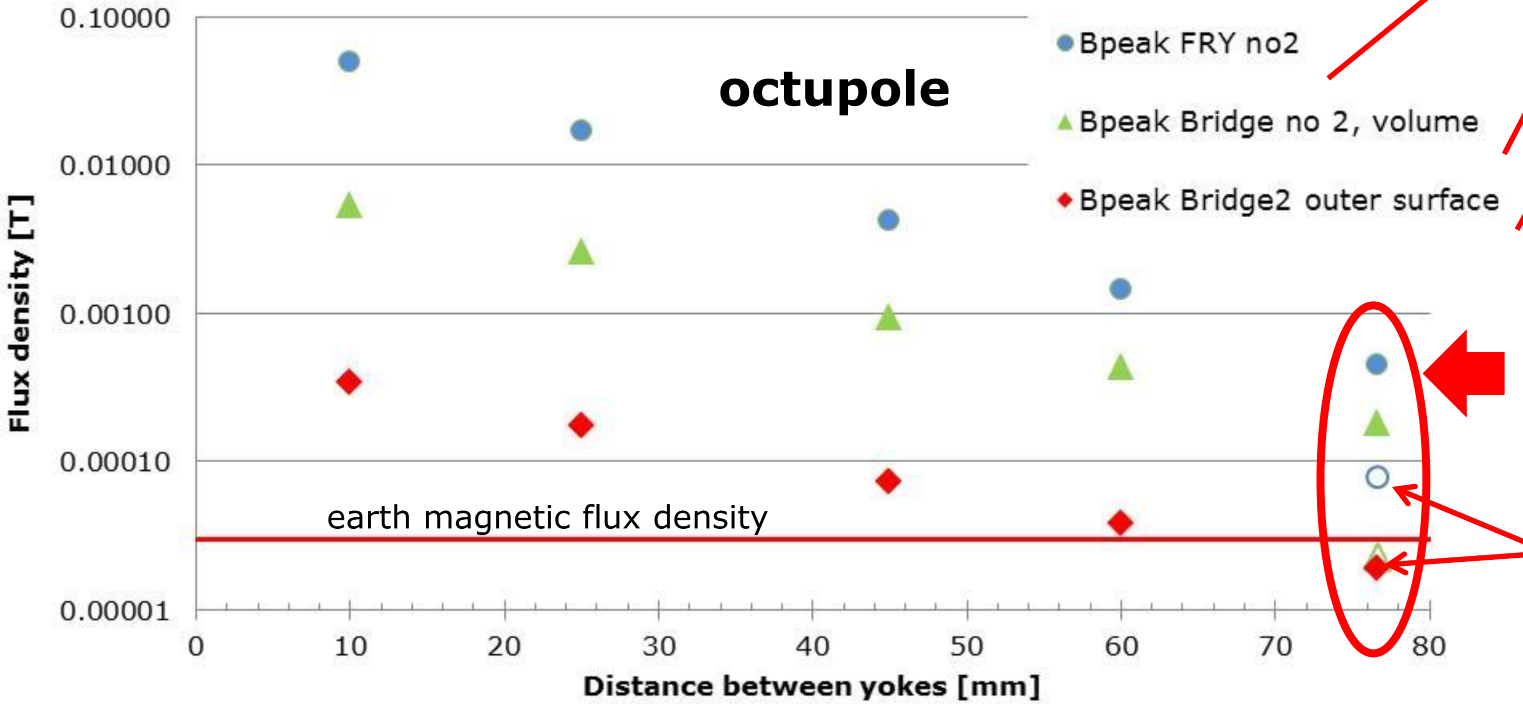




B in the coupled magnet as a function of the separation: octupole

Flux density in the coupled magnet FRY and bridge decreases exponentially with increasing separation between magnets. We can assume that the value in the yoke is even smaller, leading to a negligible excitation of the magnet.

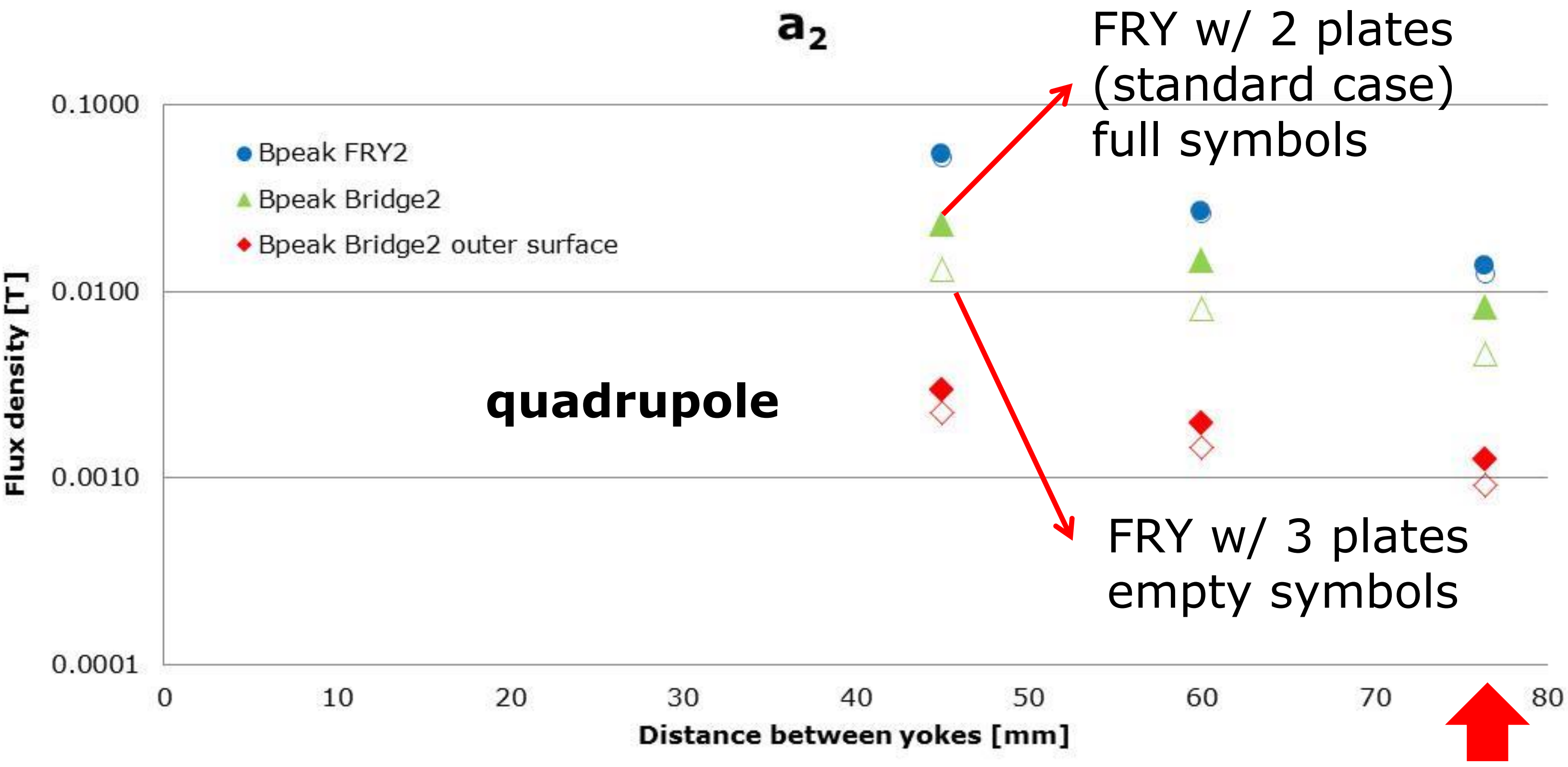




Nominal separation between iron yokes: 76.44 mm

Cross check: Iron replaced w/ air in the second magnet

B in the coupled magnet as a function of the separation: quadrupole



FRY w/ 2 plates
(standard case)
full symbols

FRY w/ 3 plates
empty symbols

Nominal separation
between iron
yokes:
76.44 mm

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Forces between magnets I

Computation of the force between iron yokes turned out to be harder than expected.
Following methods were exploited:

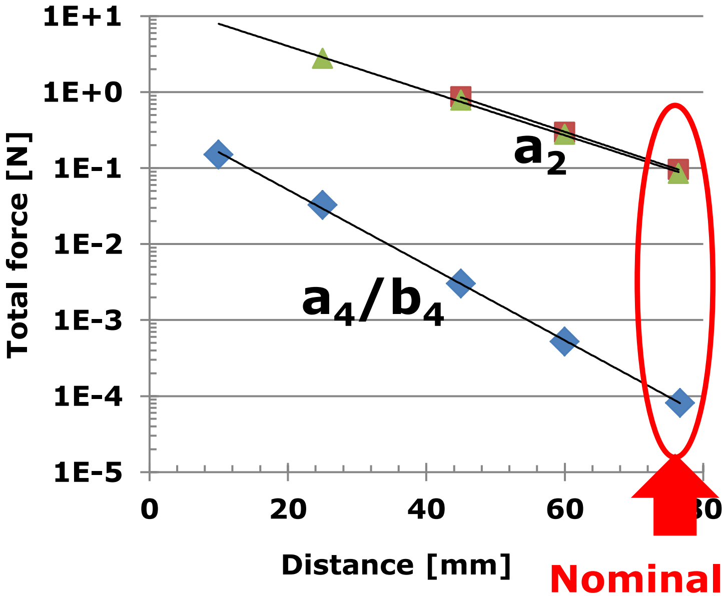
1 Integration of the Maxwell stress tensor (MST) on the surface of an air volume sourrounding the iron. In this case, we are interested in the net (external) force, so we neglected the surface on the ϱ-z planes;

2 An internal feature of COMSOL, which is based also on the Maxwell stress tensor;

3 Virtual work principle.

1 was computed considering a surface in air encompassing the iron of the second magnet;
Despite we do not know precisely how **2** works (COMSOL documentation explains that MST is integrated on the relevant surface, but it is unclear how this is precisely accomplished, since some components of **B** and **H** are not continuous across the iron surface), **the results of 2 agree with 1 to within ±3%.**
3 requires in our case knowledge of the energy with ppm (or ppb!) accuracy, which is unrealistic. **Still it can be used to set an upper bound on the forces.**

Forces between magnets II



Attractive force decreases exponentially, the higher orders the faster.

$F(z) = F(0)\, e^{-(z/\lambda)}$

$\lambda \approx 33$ mm (quadrupole)

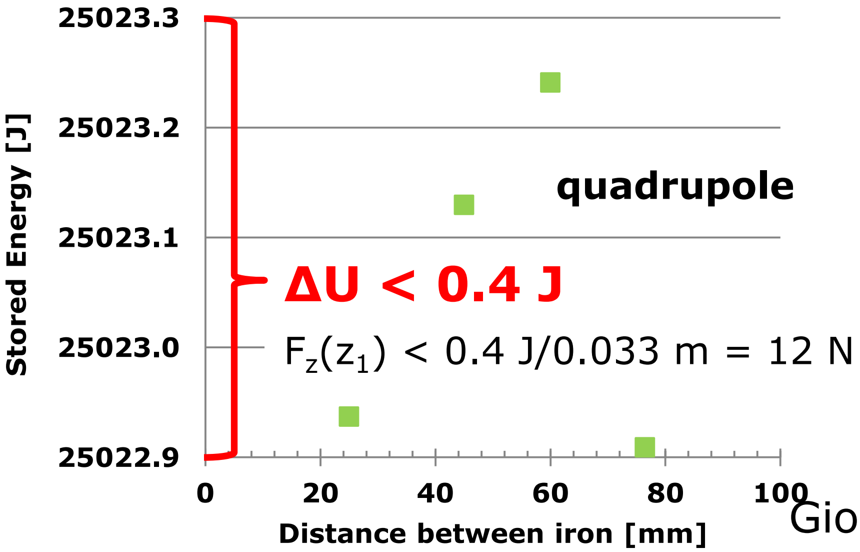
$\lambda \approx 20$ mm (octupole)

If ΔU is an upper bound for the stored energy variation changing the separation by $\Delta z = z_2 - z_1$, an upper bound for the attractive force is given by

$F(z_1) < \Delta U / \lambda \quad ; \quad \lambda < \Delta z$

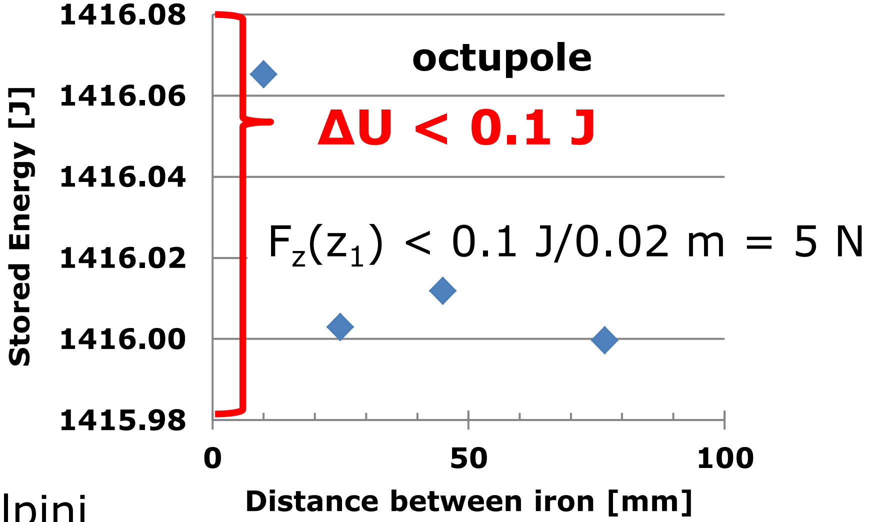
$F(z_1) < \Delta U / \Delta z \quad ; \quad \lambda > \Delta z$

Nominal separation between iron yokes: 76.44 mm



$\Delta U < 0.4$ J

$F_z(z_1) < 0.4$ J/0.033 m = 12 N



$\Delta U < 0.1$ J

$F_z(z_1) < 0.1$ J/0.02 m = 5 N

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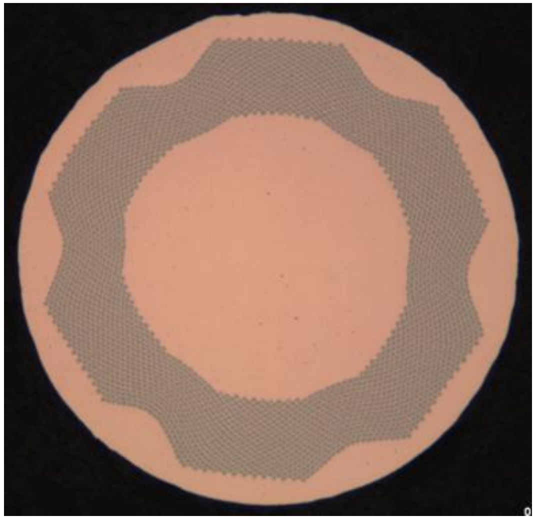
SC wire

- *Small wire (low operating current), but not too small (must be easy to handle, insulation should not reduce too much the J_e)*

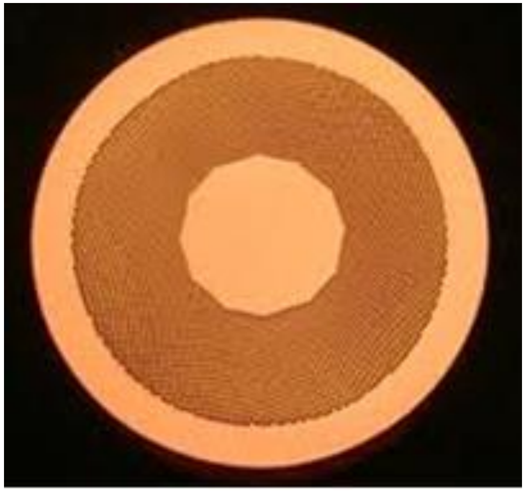
- *High Cu content (again, low operating current, 4-pole protection)*

- *Off the shelf product: small amount required (10's of kg)*

- *Small filament: not a strict requirement, but these magnets are designed to operate in the whole range 0-I_{max}*



Bruker-EAS
NbTi for Fusion application
Fine filaments ITER PF wire
Wire type 2
Cu:NbTi ≈ 2.30
Number of filaments 3282
Filament diameter≈ 8 μm @ 0.73 mm
Two wire diameters: 0.5 and 0.7 mm
S2-glass insulation,
1 km batch of 0.5mm delivered
Waiting for the delivery of 8 km + 8 km

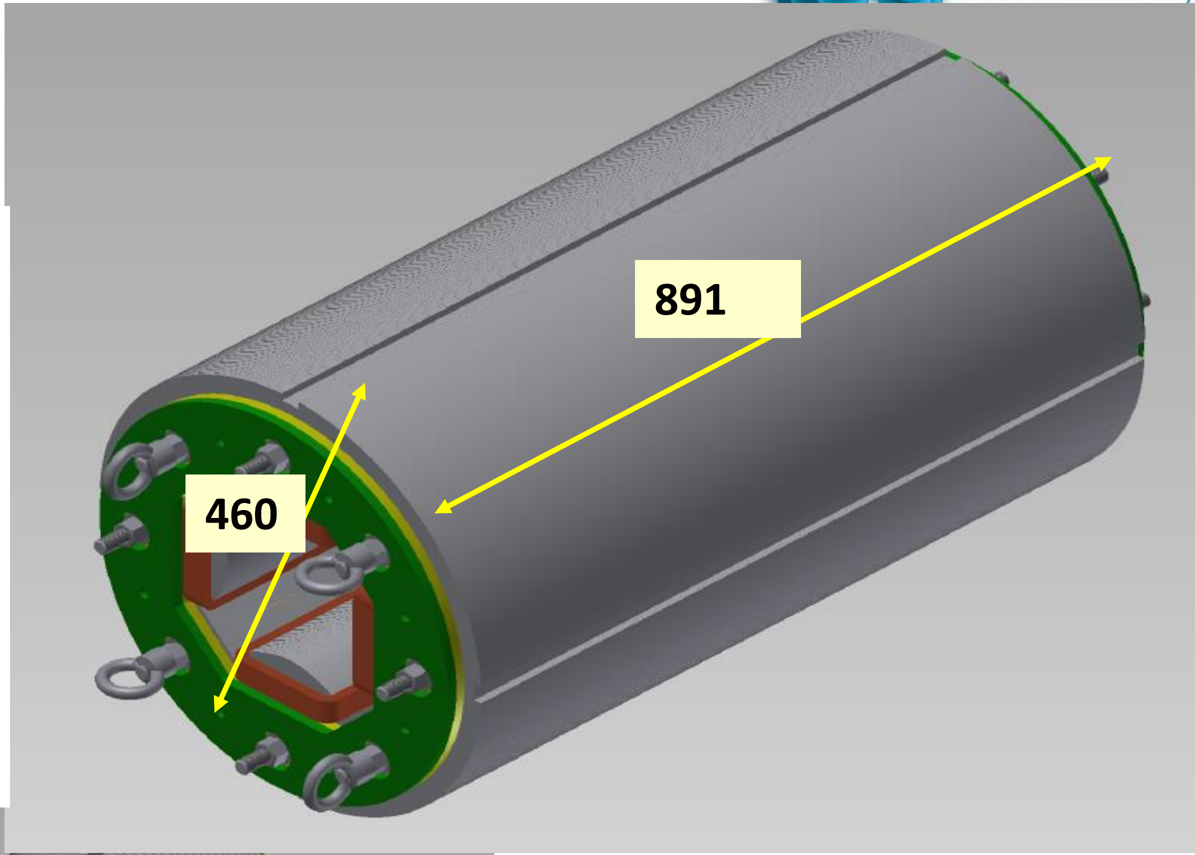


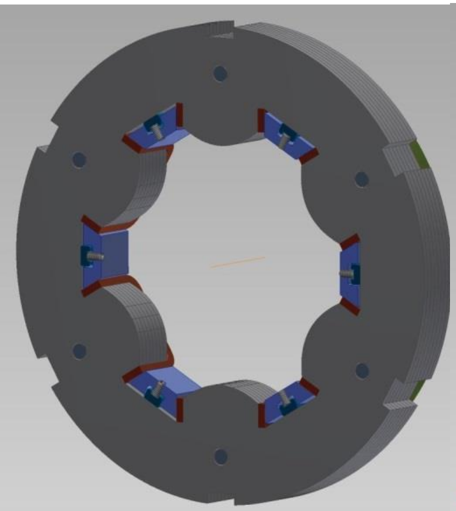
Luvata Pori
OK3900
Cu:NbTi ≈ 2.00
Number of filaments 3900
wire diameter 0.575 mm
Filament diameter≈ 5.3 μm
Bare wire
20 km delivered

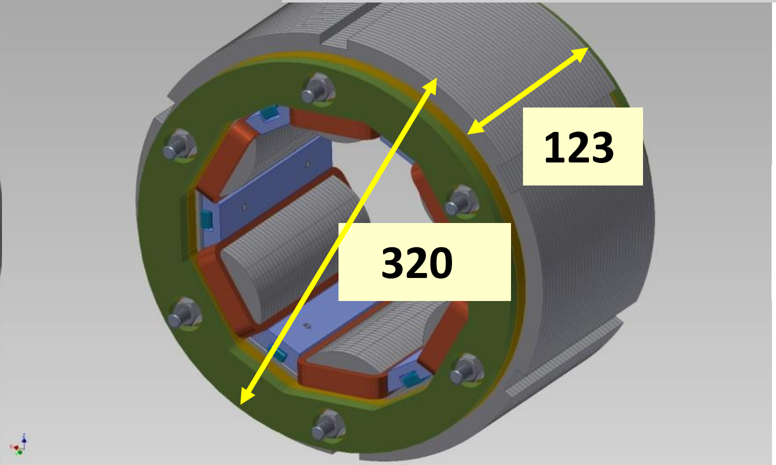
Design

Yoke laminations machined by laser cut
followed by EDM (final accuracy 1/100 mm) on the relevant surfaces: poles, coil slots, alignment slots.

5.8 mm thick iron laminations, supplied by CERN







Sextupole preliminary desig

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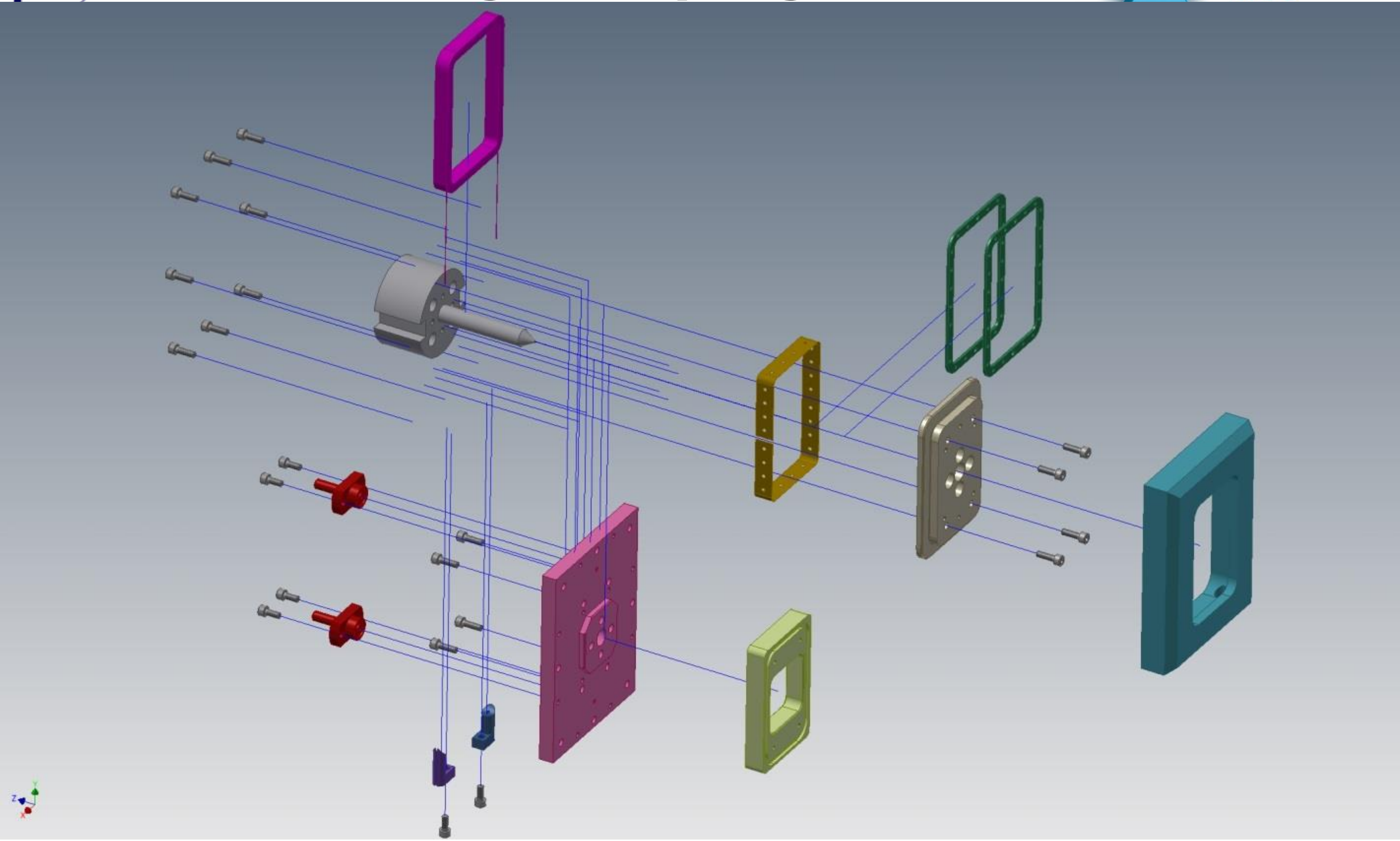
Tool for winding & impregnation



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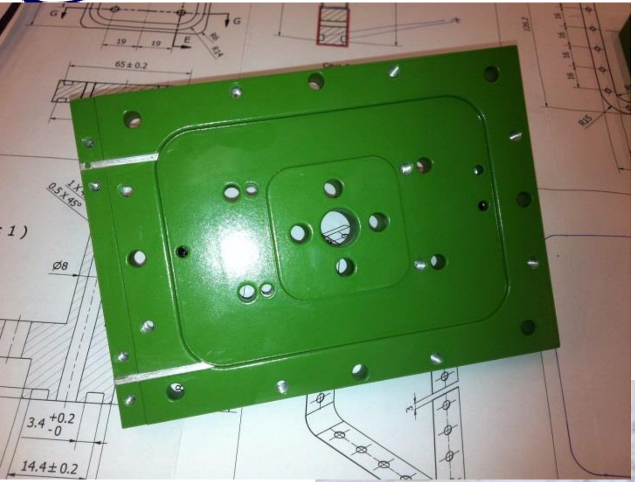
Coil tooling



Insulation scheme:

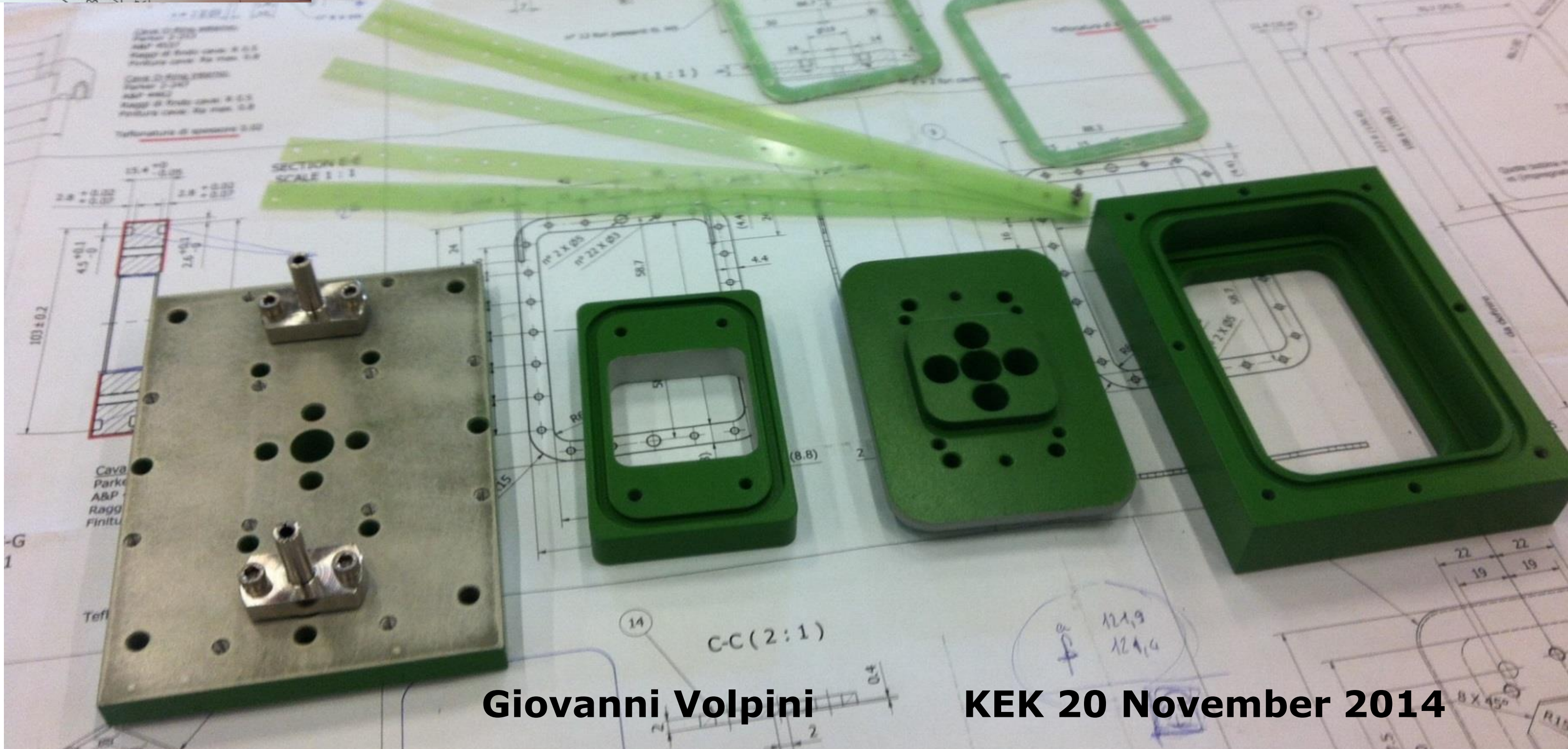
-wire w/ S2 glass 0.14 mm thick (on dia)

-ground insulation:

G11, 2 mm thick plates on both sides of the coil, include the wire exits

G11 thin, flexible layer on the inner wall of the coil;

S2 tape on the outer wall



winding and impregnation

Winding machine:

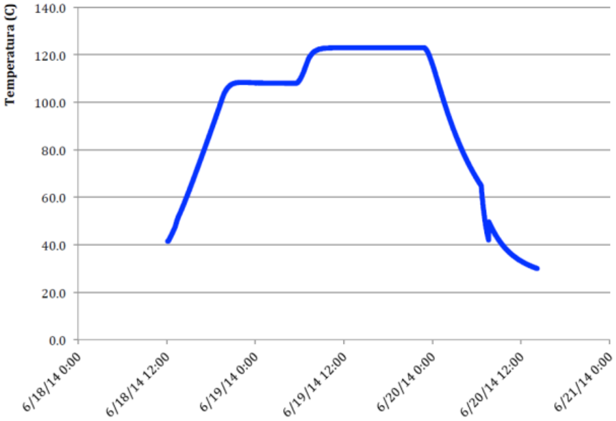
Commercial winding machine;

Home-developed braking system, electrical synchronous motor controlled by a variable frequency inverter regulating the wire tensioning between 1 and 20 kg ;

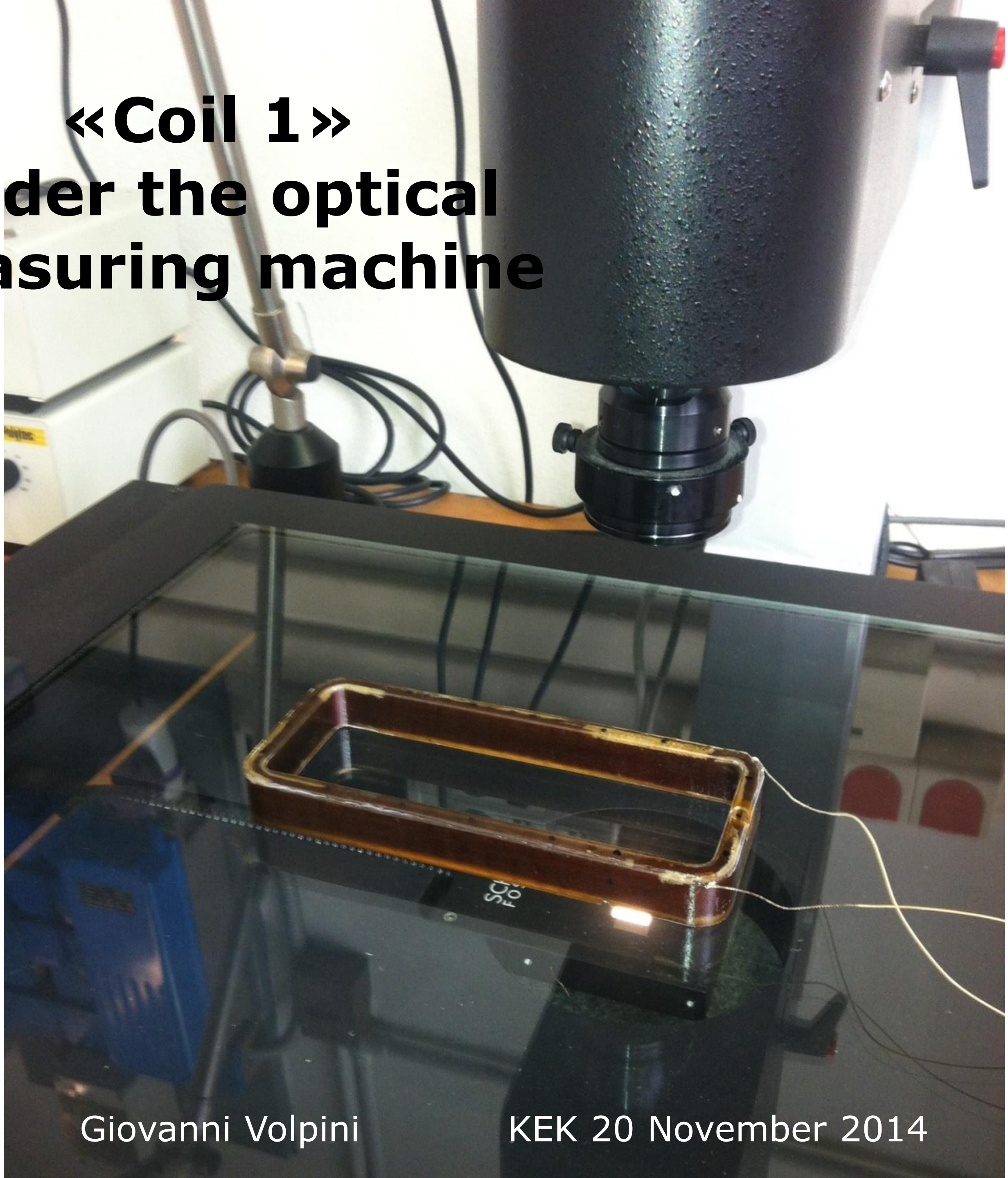
Oven

CTD 101 K resin system

Temperature monitored with a PT100 on the mould, in agreement within +/- 1°C wrt the set temperature (in stationary conditions)



«Coil 1» under the optical measuring machine

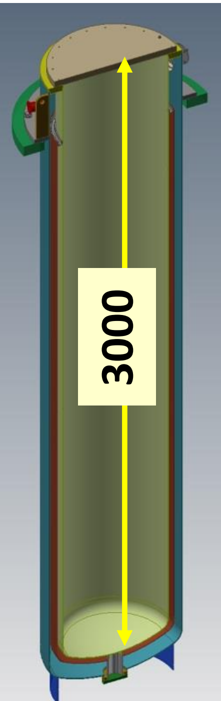


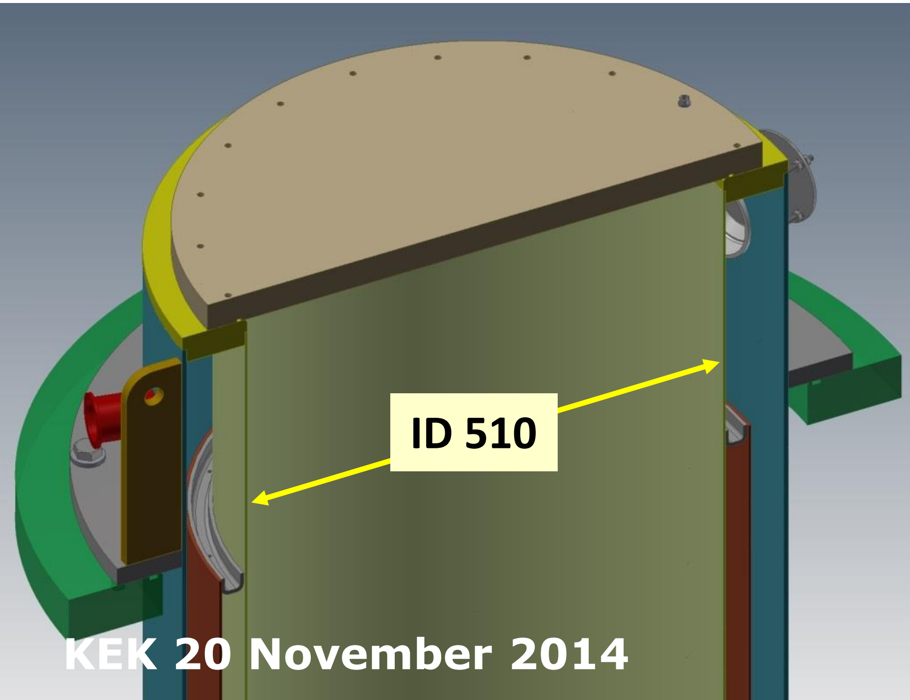
Test station

The LASA magnet test station will be used for the magnet cold test. An existing cryostat will be used for the test of sextupole to skew dodecapole.

Fast and slow data acquisition are now being adapted for the new test. A new QDS is now being built.

A new cryostat, to be fit inside the exsisting magnet test station at LASA, has been designed to test 4-pole. This allows to use the exsisting services (current, LHe feed and GHe recovery, signal, etc.)





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MAGIX &
INFN participation to HL-LHC

MAGIX		
WP1	CORRAL	Design, construction and test of the five prototypes of the corrector magnets for the HL interaction regions of HiLUMI
WP2	PADS	2D & 3D engineering design of the D2 magnets
WP3	SCOW-2G	Development of HTS coil for application to detectors and accelerators
WP4	SAFFO	Low-loss SC development for application to AC magnets

MAGIX is a INFN-funded research project, (GrV, «Call») whose goal is to develop superconducting technologies for application to future accelerator magnets.
It includes four WP's, two of which are relevant to HL-LHC
2014-2017, 1 M€ + personnel funds (all WP's)

CERN-INFN Collaboration Agreement

Approved by the INFN Board of Directors & signed by INFN President on June 2014; signed by CERN DG on July 17th.
CERN endorses MAGIX WP1 & WP2 deliverables and milestones, contributing with 527 k€

A

Done in two copies in the English language on:

Date: 25 GIU. 2014

Instituto Nazionale di Fisica Nucleare (INFN)

Prof. Fernando Ferroni
President

Date: 17 JUIL. 2014

The European Organisation for Nuclear Research (CERN)

Prof. Rolf-Dieter Heuer
Director-General

T. Lagrange
Head of Finance, Procurement and Knowledge Transfer Department

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B

INFN already involved in FP7-HiLumi (**UE-HILUMI**, GrV)
WP2 beam dynamics, LNF
WP3 magnets, MI-LASA
WP6 cold powering, MI-LASA

High Luminosity LHC

Next Steps

Sextupole

Residual magnetization at I=0 and impact on the harmonics	~Feb 15
Executive design	Jan 15

Sextupole Construction & test

Cryostat for the sextupole test commissioned	Jan 15
QDS and slow and fast data acquisition adapted	Feb 15
Order to workshop for mechanical components manufacture	Feb 15
Sextupole assembled	May 15
Sextupole tested	June 15

Other design

Executive design octupole to dodecapole	Nov 15
MgB_2 quadrupole design completed.	Dec 15

Conclusion

Conceptual design from quadrupole to dodecapole concluded

Attractive forces between nearby magnets << 1 newton; cross-talk negligible

Executive design of the sextupole started

Superconducting wire delivery to be completed soon

Winding & impregnation tests in progress

Test preparation in progress, in view of the sextupole test in 2015 *thank you for your attention!*

Spare

Corrector Magnet Summary Table I

General								**SC wire**				
Name	Order	No of magnets for series	No of spare magnets	Aperture	Int strenght at radius = 50 mm	Iron outer radius	Loadline margin	Ic @ 4.2K 5T	Bare wire diameter	Cu/non Cu	Jc NbTi current density	Wire insulated diameter
				mm	T·m	mm		A	mm	-	A/mm²	mm
MCQSX	2	4	2	150	1.00	230	60%	350	0.7	2.3	3001.2	0.84
MCSX	3	4	1	150	0.06	160	60%	179	0.5	2.3	3008.4	0.64
MCSSX	3	4	1	150	0.06	160	60%	179	0.5	2.3	3008.4	0.64
MCOX	4	4	1	150	0.04	160	60%	179	0.5	2.3	3008.4	0.64
MCOSX	4	4	1	150	0.04	160	60%	179	0.5	2.3	3008.4	0.64
MCDX	5	4	1	150	0.03	160	60%	179	0.5	2.3	3008.4	0.64
MCDSX	5	4	1	150	0.03	160	60%	179	0.5	2.3	3008.4	0.64
MCTX	6	4	2	150	0.086	160	60%	179	0.5	2.3	3008.4	0.64
MCTSX	6	4	2	150	0.017	160	60%	179	0.5	2.3	3008.4	0.64
		36	**12**									
		48										

Corrector Magnet Summary Table II

General			Operational Values											
Name	Order	Aturns	Number of turn: design value	Iop	Coil Peak Field @ Iop	3D magnetic length	(Iper)gradient	Overall current density	Overall current density: official value	Stored energy	Stored energy per unit length	Differential inductance @ Iop	Linear Inductance @ 0 A
		Aturns	-	A	T	m	T/m^(n-1)	A/mm²	A/mm²	kJ	kJ/m	H	H
MCQSX	2	57,674	320	182.0	2.97	0.807	25	303.3	303	24.57	30.44	1.247	1.608
MCSX	3	28,193	214	131.6	2.33	0.111	11	353.0	350	1.28	11.61	0.118	0.179
MCSSX	3	28,193	214	131.6	2.33	0.111	11	353.0	350	1.28	11.61	0.118	0.179
MCOX	4	41,396	344	120.4	2.41	0.087	3,688	313.7	320	1.41	16.30	0.152	0.391
MCOSX	4	41,396	344	120.4	2.41	0.087	2,766	313.7	320	1.41	16.30	0.152	0.391
MCDX	5	35,672	256	139.1	2.34	0.095	50,623	359.7	360	1.39	14.69	0.107	0.301
MCDSX	5	35,672	256	139.1	2.34	0.095	50,623	359.7	360	1.39	14.69	0.107	0.301
MCTX	6	25,497	154	166.8	2.04	0.430	640,141	259.4	350	4.35	10.11	0.229	0.600
MCTSX	6	26,984	**172**	156.9	2.01	0.089	612,604	283.6	350	0.92	10.40	0.052	0.149

Corrector Magnet Summary Table III

General			Geometry details								
Name	Order	Aturns	Coil cross section nominal	overall wire length for 1 coil	Max voltage rating to ground	External magnet diameter (iron yoke OD)	Weight: CS value	Coil Physical length	Yoke length	Overall iron length	Mechanical length end plate to e.p.
		Aturns	mm²	m	V	mm	kg	mm	mm	mm	mm
MCQSX	2	57,674	192	604.5	300	460	1000	840.8	800.8	871.5	890.5
MCSX	3	28,193	79.8	79.4	300	320	80	123.4	94.2	164.9	183.9
MCSSX	3	28,193	79.8	79.4	300	320	80	123.4	94.2	164.9	183.9
MCOX	4	41,396	132	88.1	300	320	70	98.7	70.7	141.3	160.4
MCOSX	4	41,396	132	88.1	300	320	70	98.7	70.7	141.3	160.4
MCDX	5	35,672	99	67.0	300	320	75	107.4	82.4	153.1	172.2
MCDSX	5	35,672	99	67.0	300	320	75	107.4	82.4	153.1	172.2
MCTX	6	25,497	99	144.1	300	320	250	449.0	424.0	494.6	513.7
MCTSX	6	26,984	99	41.5	300	320	75	101.5	76.5	147.2	166.3

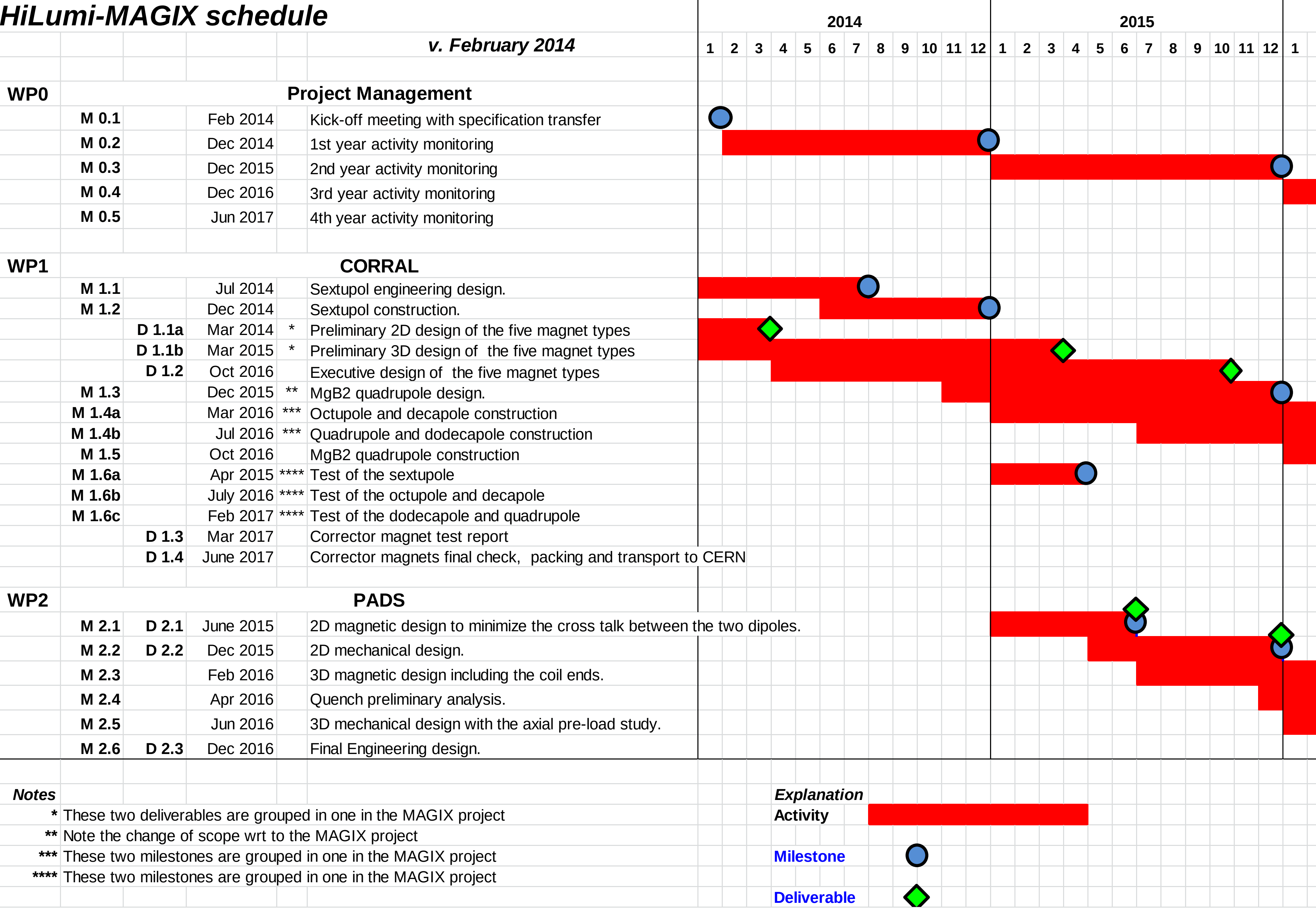
Corrector Magnet Summary Table IV

General		Protection						Forces							Wire needed	
Name	Order	Dump Resistor	τ = L/R	Safety factor (current ratio)	"MIITs" exponential discharge	Wire MIITs	Discharge/Wire	Force: x component	Force: y component	Force: z component	Specific force: x-component	Specific force: y-component	Specific force: x-component from 2D model	Specific force: y-component from 2D model	Total wire required D0.7	Total wire required D0.5
		Ω	s	-	A²·s	A²·s	-	N	N	N	N/m	N/m	N/m	N/m	m	m
MCQSX	2	1.648	0.976	110%	19,549	19,473	100.4%	41,538	47,777	4,038	51,472	59,203	52,113	58,025	14,508	
MCSX	3	2.279	0.078	110%	821	5,069	16.2%	2,915	1,497	630	26,343	13,529				2,383
MCSSX	3	2.279	0.078	110%	821	5,069	16.2%	2,915	1,497	630	26,343	13,529				2,383
MCOX	4	2.492	0.157	110%	1,376	5,069	27.1%	2,504	2,018	912	28,866	23,260				3,523
MCOSX	4	2.492	0.157	110%	1,376	5,069	27.1%	2,504	2,018	912	28,866	23,260				3,523
MCDX	5	2.157	0.139	110%	1,632	5,069	32.2%	2,184	1,839	602	23,038	19,399				3,350
MCDSX	5	2.157	0.139	110%	1,632	5,069	32.2%	2,184	1,839	602	23,038	19,399				3,350
MCTX	6	1.799	0.334	110%	5,612	5,069	110.7%	6,879	4,485	296	16,000	10,432				10,377
MCTSX	6	1.838	0.081	110%	1,309	5,069	25.8%	1,386	1,125	330	15,608	12,668				2,986

Total for series + spares: 45 + 51 kg
procured for prototypes: 38 kg

HiLumi-MAGIX schedule

v. February 2014



WP0				**Project Management**
M 0.1		Feb 2014		Kick-off meeting with specification transfer
M 0.2		Dec 2014		1st year activity monitoring
M 0.3		Dec 2015		2nd year activity monitoring
M 0.4		Dec 2016		3rd year activity monitoring
M 0.5		Jun 2017		4th year activity monitoring
WP1				**CORRAL**
M 1.1		Jul 2014		Sextupol engineering design.
M 1.2		Dec 2014		Sextupol construction.
	D 1.1a	Mar 2014	*	Preliminary 2D design of the five magnet types
	D 1.1b	Mar 2015	*	Preliminary 3D design of the five magnet types
	D 1.2	Oct 2016		Executive design of the five magnet types
M 1.3		Dec 2015	**	MgB2 quadrupole design.
M 1.4a		Mar 2016	***	Octupole and decapole construction
M 1.4b		Jul 2016	***	Quadrupole and dodecapole construction
M 1.5		Oct 2016		MgB2 quadrupole construction
M 1.6a		Apr 2015	****	Test of the sextupole
M 1.6b		July 2016	****	Test of the octupole and decapole
M 1.6c		Feb 2017	****	Test of the dodecapole and quadrupole
	D 1.3	Mar 2017		Corrector magnet test report
	D 1.4	June 2017		Corrector magnets final check, packing and transport to CERN
WP2				**PADS**
M 2.1	**D 2.1**	June 2015		2D magnetic design to minimize the cross talk between the two dipoles.
M 2.2	**D 2.2**	Dec 2015		2D mechanical design.
M 2.3		Feb 2016		3D magnetic design including the coil ends.
M 2.4		Apr 2016		Quench preliminary analysis.
M 2.5		Jun 2016		3D mechanical design with the axial pre-load study.
M 2.6	**D 2.3**	Dec 2016		Final Engineering design.

Notes

* These two deliverables are grouped in one in the MAGIX project
** Note the change of scope wrt to the MAGIX project
*** These two milestones are grouped in one in the MAGIX project
**** These two milestones are grouped in one in the MAGIX project

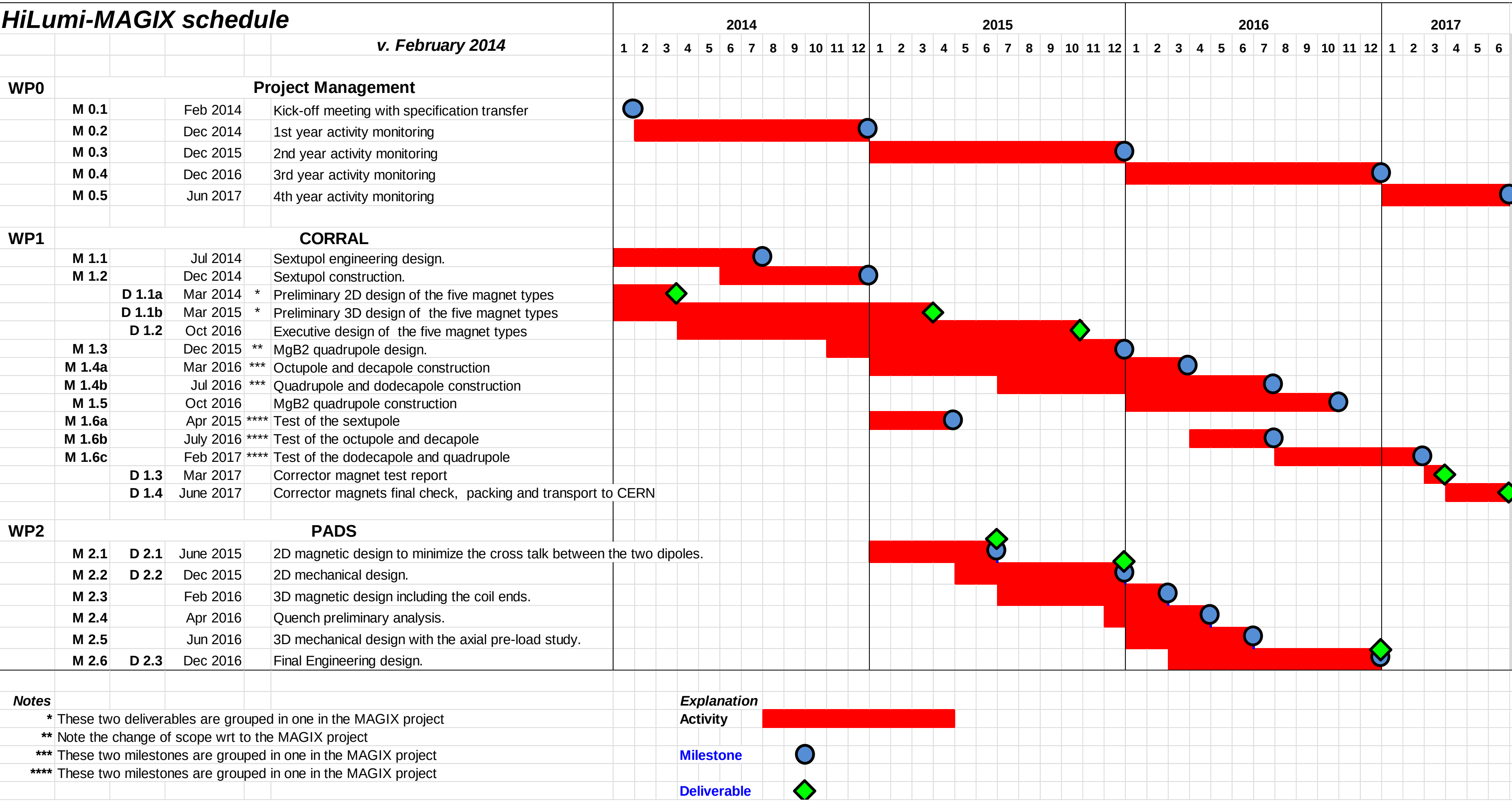
Explanation

Activity 🟥
Milestone ●
Deliverable ◆

INFN-CERN Agreement approved by INFN board of directors in June '14, to be signed by INFN President

HiLumi-MAGIX schedule

v. February 2014



WP0					**Project Management**
	M 0.1		Feb 2014		Kick-off meeting with specification transfer
	M 0.2		Dec 2014		1st year activity monitoring
	M 0.3		Dec 2015		2nd year activity monitoring
	M 0.4		Dec 2016		3rd year activity monitoring
	M 0.5		Jun 2017		4th year activity monitoring
WP1					**CORRAL**
	M 1.1		Jul 2014		Sextupol engineering design.
	M 1.2		Dec 2014		Sextupol construction.
		D 1.1a	Mar 2014	*	Preliminary 2D design of the five magnet types
		D 1.1b	Mar 2015	*	Preliminary 3D design of the five magnet types
		D 1.2	Oct 2016		Executive design of the five magnet types
	M 1.3		Dec 2015	**	MgB2 quadrupole design.
	M 1.4a		Mar 2016	***	Octupole and decapole construction
	M 1.4b		Jul 2016	***	Quadrupole and dodecapole construction
	M 1.5		Oct 2016		MgB2 quadrupole construction
	M 1.6a		Apr 2015	****	Test of the sextupole
	M 1.6b		July 2016	****	Test of the octupole and decapole
	M 1.6c		Feb 2017	****	Test of the dodecapole and quadrupole
		D 1.3	Mar 2017		Corrector magnet test report
		D 1.4	June 2017		Corrector magnets final check, packing and transport to CERN
WP2					**PADS**
	M 2.1	**D 2.1**	June 2015		2D magnetic design to minimize the cross talk between the two dipoles.
	M 2.2	**D 2.2**	Dec 2015		2D mechanical design.
	M 2.3		Feb 2016		3D magnetic design including the coil ends.
	M 2.4		Apr 2016		Quench preliminary analysis.
	M 2.5		Jun 2016		3D mechanical design with the axial pre-load study.
	M 2.6	**D 2.3**	Dec 2016		Final Engineering design.

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Explanation

Activity 🟥

Milestone ●

Deliverable ◆

Milestones and Deliverables

Milestones

M 1.1	**Sextupole engineering design completed.**	**July 2014**
M 1.2	**Sextupole construction completed.**	**December 2014**
M 1.3	**MgB2 quadrupole design completed.**	**December 2015**
M 1.4.a	Octupole and decapole construction completed.	March 2016
M 1.4.b	Quadrupole and dodecapole construction completed.	July 2016
M 1.5	MgB2 quadrupole construction completed	October 2016
M 1.6.a	**Sextupole test**	**April 2015**
M 1.6.b	Octupole and decapole test.	July 2016
M 1.6.c	Quadrupole and dodecapole test.	February 2017

Deliverables

D 1.1a	**Preliminary 2D design of the five magnets, from quadrupole to dodecapole**	**March 2014**	✓
D 1.1b	**Preliminary 3D design of the five magnets, from quadrupole to dodecapole.**	**March 2015**	✓
D 1.2	**Executive design of the five magnets, from quadrupole to dodecapole.**	**October 2015**	
D 1.3	Test report (…) with the tests results performed on the corrector magnets	March 2017	
D 1.4	Magnet Corrector magnet prototypes for all the five types, cold tested and qualified.	June 2017	

It does not include:

the warm and cold magnetic characterization (harmonic analysis);
the cryostat and its mechanical connections;
the mechanical and electrical interconnections between the magnets themselves and the rest of the machine;
the realization of the series, composed of a total of 48 magnets of various types.