Investigations on LHC polarities

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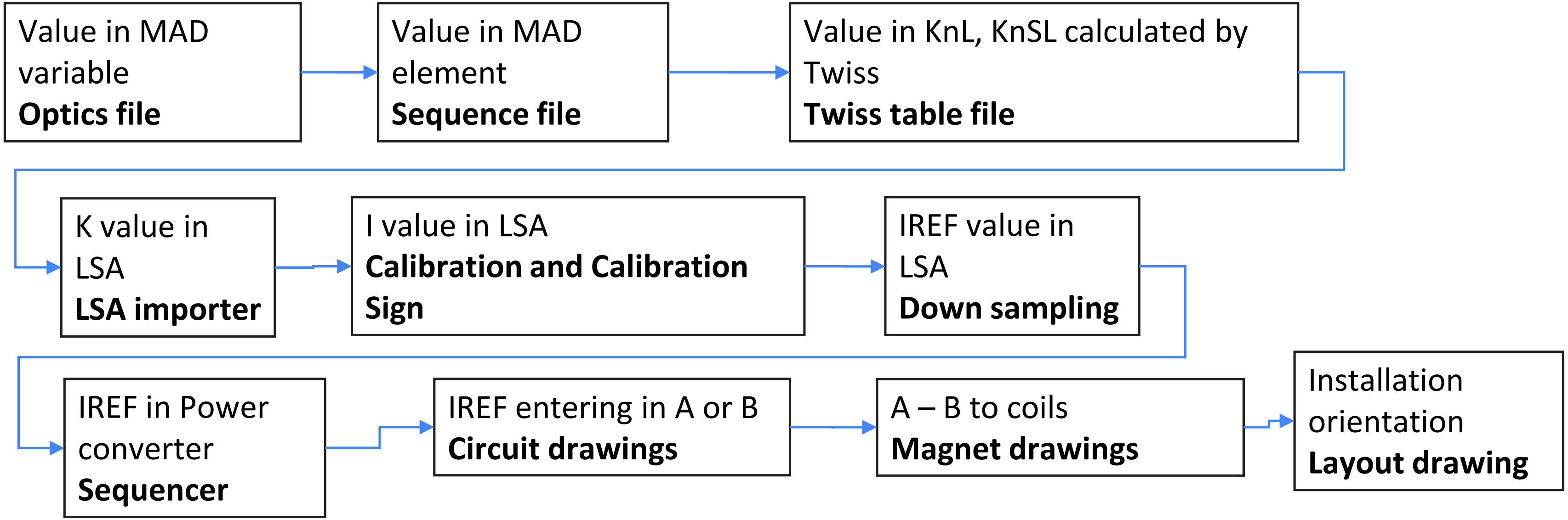
Thanks to H. Prin, S. Russenschuk, M. Kappinen, P. Orlandi, R. Tomas, J. Wenninger, M. Hostettler, E. MacLean, T. Persson

Motivation of the talk: decide polarities of the HL-LHC magnets, understand polarity observation with beam.

From MAD-x variables to fields



Beam observations *Rogelio, Ewen, Tobias, OMC team*

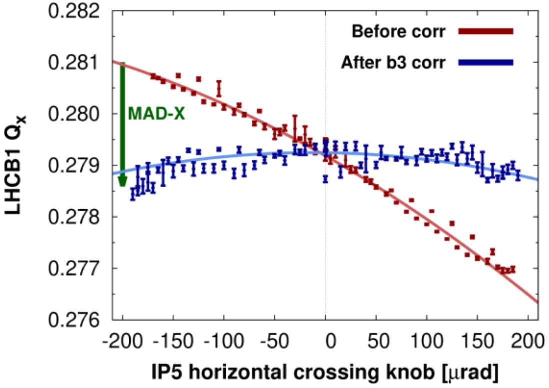
Confirmed by years of experience:

- **Normal multipole Correct**
- **Skew multipoles Reversed**

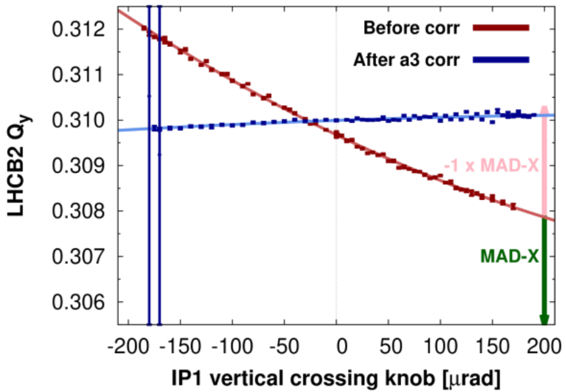
Type	Location	Polarity	Location	Polarity
MOF	A12 B1	Correct	A12 B2	Correct
MOF	A23 B1	Correct	A23 B2	Correct
MOF	A34 B1	Correct	A34 B2	Correct
MOF	A45 B1	Correct	A45 B2	Correct
MOF	A56 B1	Correct	A56 B2	Correct
MOF	A67 B1	Correct	A67 B2	Correct
MOF	A78 B1	Correct	A78 B2	Correct
MOF	A81 B1	Correct	A81 B2	Correct
MOD	A12 B1	Correct	A12 B2	Correct
MOD	A23 B1	Correct	A23 B2	Correct
MOD	A34 B1	Correct	A34 B2	Correct
MOD	A45 B1	Correct	A45 B2	Correct
MOD	A56 B1	Correct	A56 B2	Correct
MOD	A67 B1	Correct	A67 B2	Correct
MOD	A78 B1	Correct	A78 B2	Correct
MOD	A81 B1	Correct	A81 B2	Correct
MCO	A12 B1	–	A12 B2	–
MCO	A23 B1	–	A23 B2	–
MCO	A34 B1	Correct	A34 B2	Correct
MCO	A45 B1	Correct	A45 B2	Correct
MCO	A56 B1	Correct	A56 B2	Correct
MCO	A67 B1	Correct	A67 B2	Correct
MCO	A78 B1	Correct	A78 B2	–
MCO	A81 B1	Correct	A81 B2	–
MSS	A12 B1	Reversed	A12 B2	Reversed
MSS	A23 B1	–	A23 B2	Reversed
MSS	A34 B1	Reversed	A34 B2	Reversed
MSS	A45 B1	–	A45 B2	Reversed
MSS	A56 B1	–	A56 B2	Reversed
MSS	A67 B1	–	A67 B2	Reversed
MSS	A78 B1	–	A78 B2	–
MSS	A81 B1	–	A81 B2	–
MCSSX	L1	Reversed	R1	Reversed
~~MCSX~~	~~L5~~	~~Reversed~~	~~R5~~	~~Reversed~~
MQS	All	Reversed	All	Reversed
MQSX	All	Reversed	All	Reversed
KTQX2	All	Reversed	All	Reversed

https://cds.cern.ch/record/1667590/files/CERN-ACC-NOTE-2014-0012.pdf

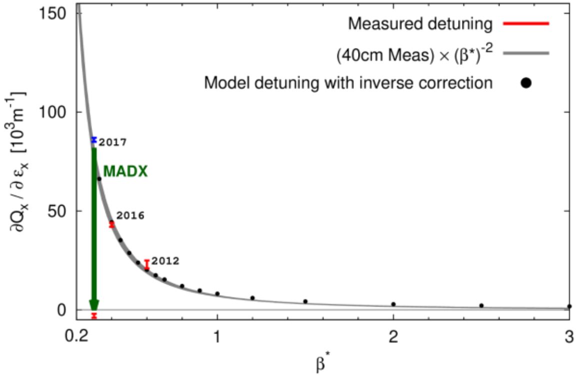
MCSX response matches mad



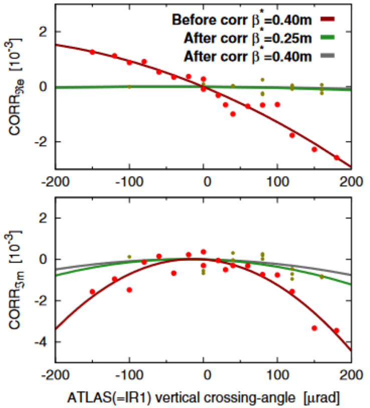
MCSSX response swapped vs mad



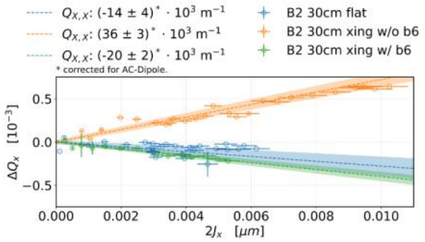
MCOX response matches mad



A4 corrections (assuming reversed response to madx) worked well



MCTX response matches mad



Polarity conventions

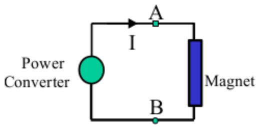
Official polarity convention: LHC-DC-ES-0001 Magnet polarity convention https://edms.cern.ch/document/90041/3.2

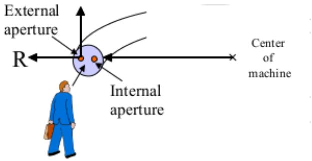
Rules: set of rules does not follow the conventions of the beam optics program MAD or the conventions for magnetic field computations and measurements. Rules:

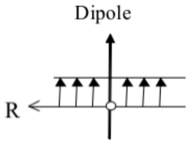
1) Terminals are labelled 'A' and 'B', magnet built without knowing how it will be installed.

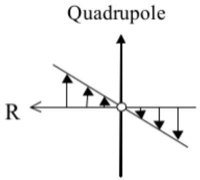
2) Positive normal multipole has the field point upwards and increase along the outward pointing machine radius with current entering into A. Skew multipole is a positive multipole turned clockwise.

3) Each magnet has a normal installation direction (typically connection side upstream to Beam1) and if installed differently, the warm circuit will take this into account.

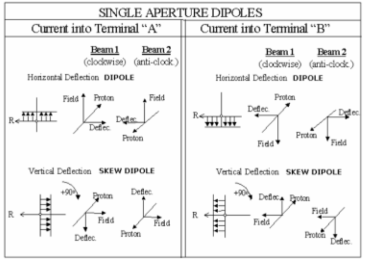


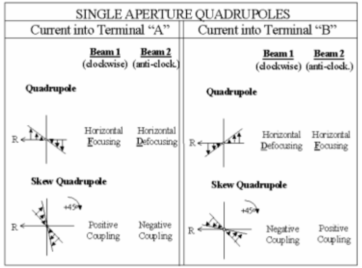


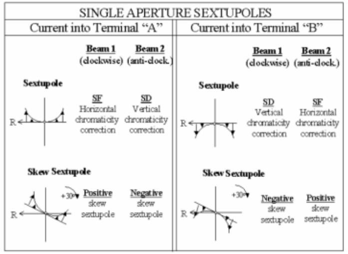


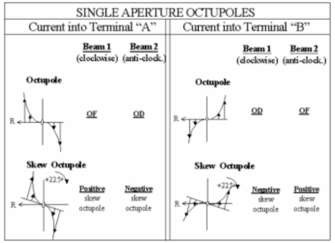


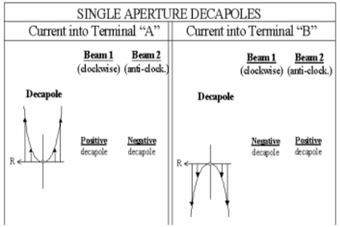
Polarities LHC-DC-ES-0001 rev 3.2

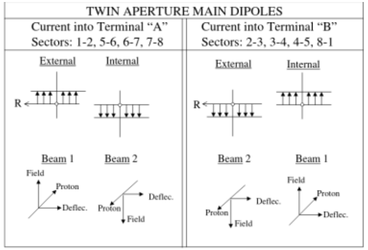


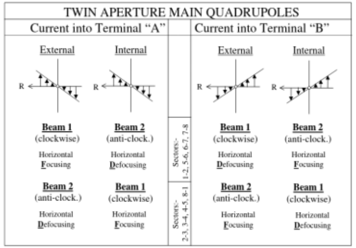


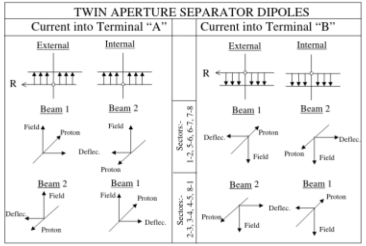


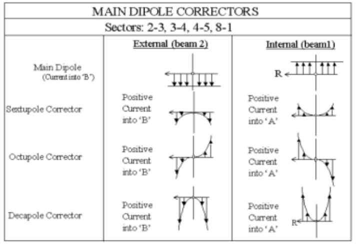


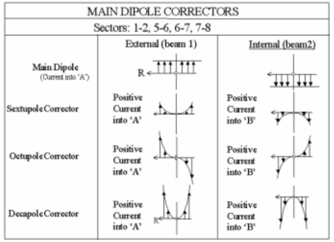






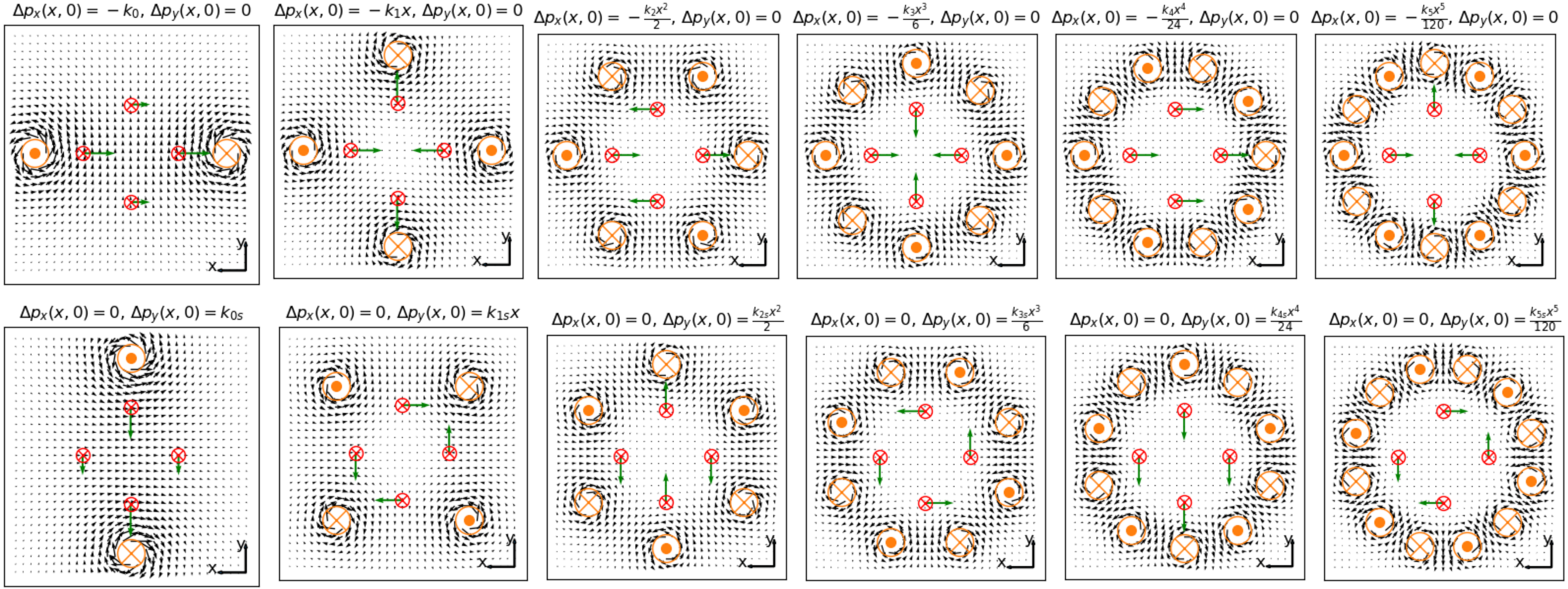






Polarity conventions

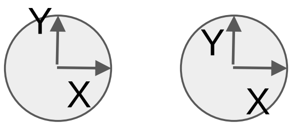
- Official polarity convention: LHC-DC-ES-0001 Magnet polarity convention https://edms.cern.ch/document/90041/3.2
- Positive normal multipoles By(x>0,y=0)>0 that is $k_n>0$ using MAD-X conventions
- Positive skew multipoles Bx(x>0,y=0)<0 (positive normal multipole rotated clock-wise) that is $k_{ns}<0$ MAD-X conventions



Magnetic measurement conventions

Connection side

V1 V2



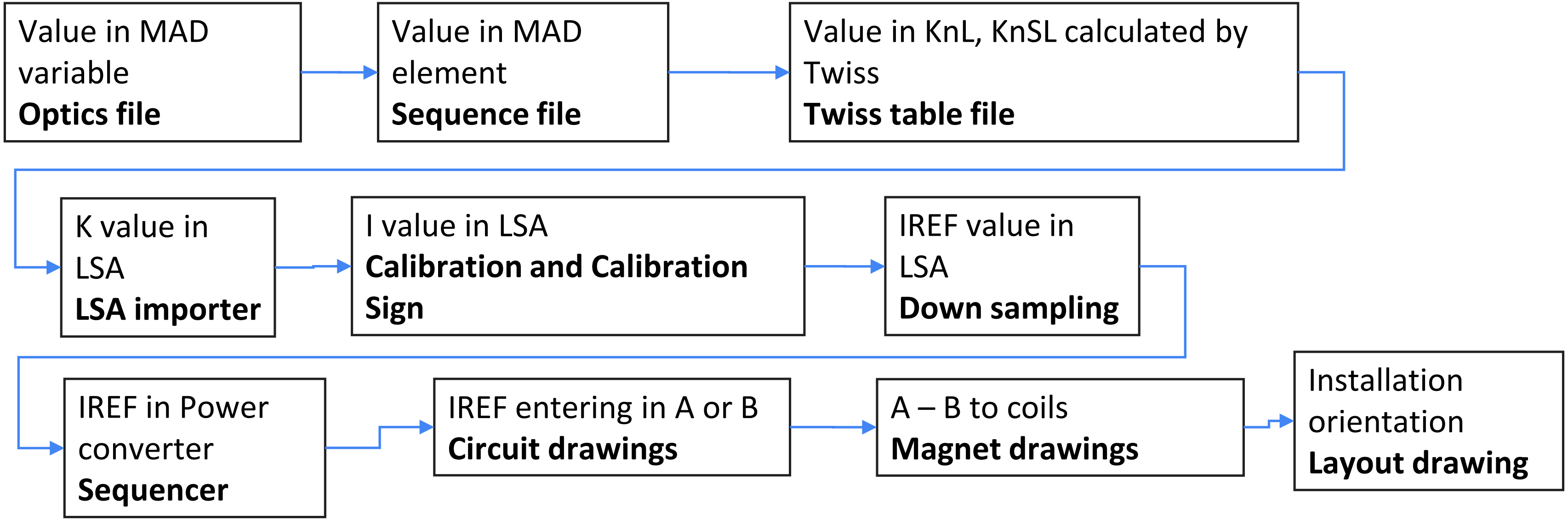
$$B_y + iB_x = \sum_{n=1} \frac{B_n + iA_n}{r_0^{n-1}} (x+iy)^{n-1}$$
$$= B_N \sum_{n=N} \frac{b_n + ia_n}{r_0^{n-1}} (x+iy)^{n-1}.$$

Since X points to the inside of the machine

	B_{even}>0	B_{odd}>0	A_{even}>0	A_{odd}>0
Polarity	Positive	Negative	Negative	Positive

A magnet is normal if Beam 1 enters from the connection side
A magnet is inverted if Beam 1 enters from the non connection side.

From MAD-x variables to fields



MAD Conventions

	S/RBEND	HKICKER	VKICKER	MULTIPOLE (normal)	MULTIPOLE (skew)
Attribute=1	ANGLE	KICK	KICK	KNL	KSL
Bx(x=1,y=0)	0	0	1	0	1/n!
By(x=1,y=0)	1	-1	0	1/n!	0
Δpx*	-1	1	0	-1/n!	0
Δpy*	0	0	1	0	1/n!
Polarity	Positive	Negative	Positive	Positive	Negative

Positive KSn produces negative skew multipoles.
In MAD-X sequence magnet are mostly specified with variables through positive signs, except:
Defocus. Triplets, some D1-4, 3/7 def quads, Beam 2 magnets to keep conventions.

Sequence has also a polarity flag not used in calculation, but should be used to obtain the correct sign of the current.
(see also LSA Calibration sign)

* excluding change of references

$$p_x \leftarrow p_x - \chi L \cdot \Re\left[\sum_{n=0} \frac{1}{n!}(k_n + i\hat{k}_n)(x+iy)^n\right]$$

$$p_y \leftarrow p_y + \chi L \cdot \Im\left[\sum_{n=0} \frac{1}{n!}(k_n + i\hat{k}_n)(x+iy)^n\right]$$

```
MQXA.1R1,       K1 := kqx.r1+ktqx1.r1, polarity=+1;
MCBXV.2R1,      KICK := acbxv2.r1, polarity=+1;
MQSX.3R1,       K1S := kqsx3.r1, polarity=-1;
MQXB.B2R1,      K1 := -kqx.r1-ktqx2.r1, polarity=-1;
MCSX.3R1,       KNL := {0, 0, kcsx3.r1*l.MCSX, 0, 0, 0}, polarity=+1;
MCOSX.3R1,      KSL := {0, 0, 0, kcosx3.r1*l.MCOSX}, polarity=-1;
MCOX.3R1,       KNL := {0, 0, 0, kcox3.r1*l.MCOX}, polarity=+1;
MBXW.A4R1,      ANGLE := -ad1.lr1, K0 := -kd1.lr1, polarity=-1;
MQY.4R1.B1,     K1 := kq4.r1b1, polarity=-1;
MQML.5R1.B1,    K1 := kq5.r1b1, polarity=+1;
MQS.23R1.B1,    K1S := kqs.r1b1, polarity=-1;
```

MAD to LSA

Strength are taken from KnL,KSnL from Twiss tables (LSA Code here)

LSA has calibration curves from B -> I or BL -> I and every circuit (logical device) has a CalibrationSign which can flip the sign of the calibration curve (LSA Code, DeviceService.findLogicalHardware()).

LSA has also a flag PolaritySwitch (ALICE / LHCb spectrometers) whether the PC has a physical polarity switch that can change dynamically.

Exception: the RQTL7.R3 has a B1/B2 inversion, there the Beam 1 logical is connected to the Beam 2 power converter.

NB. The K value and calibration sign is attached to a circuit, but not to a magnet. Some circuits power magnets with opposite polarities, such as RQX, RD1.LR. In those cases, a specific magnet is taken as reference.

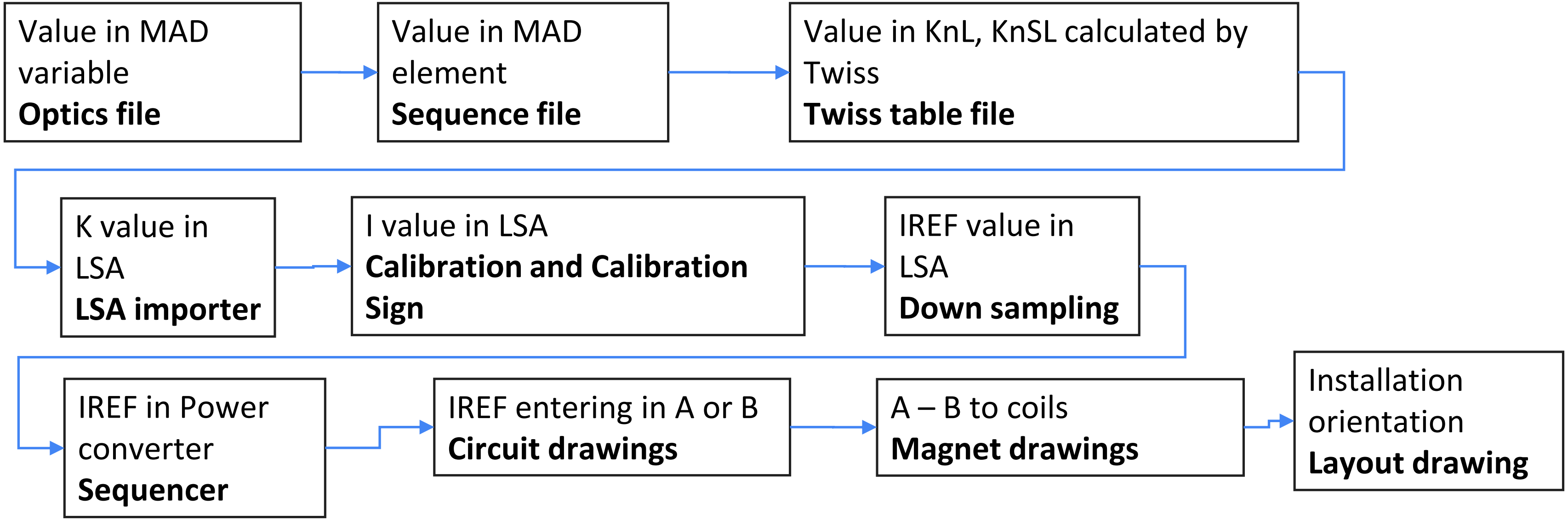
LSA CalibrationSign -> sign(K in circuit/I)

MAD Polarity -> Sign(K in Twiss/I)

LSA Calibration sign

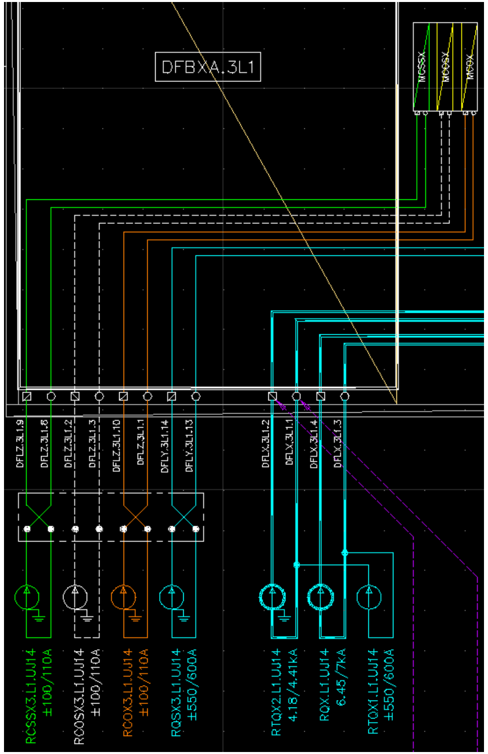
Circuits	Reason	Calibration Sign	MAD Polarity	MAD var Def	Expected
RB.A12 RB.A23 RB.A81	?	-1	+1	1	No
RCBXH3.L8	Non conformity not followed-up	-1	+1	1	
RBAWV.R2 RBLWH.R8 RBXWSH.L8 RBXWTV.L2	?				
MBAW.1R2	?	+1	-1		
RD1.L2 RD1.L8 RD1.LR1	D1 By<0	-1	-1	-1	Yes
RD1.LR5	?	+1	-1	-1	No
RD2.L1 RD2.L5 RD2.R2 RD2.R8	D2 By<0	-1	-1		Yes
RD2.L2		+1	-1		No
RD3.L4 RD3.R4 RD34.LR7	D34 By<0 ?				
RMSD.LR6B1 RMSD.LR6B2 RMSI.L2B1	?				
RQ4.L1B2 RQ4.L2B1 RQ4.L5B2 RQ4.L6B1…… RQD.A12 RQD.A23…. RQTD.A12B1 RQTD.A12B2…	Defoc. Quads	-1	-1	+1	Yes
RQX.L1 RQX.L5 RTQX1.L1 … RQX.R2 RQX.R8 RTQX1.R2…	Defoc. Q3, trim adds	-1	-1	+1	Yes
RQX.L8 RQX.R5 RTQX1.L8….	Foc. Q3, trim adds	-1	1	+1	No
ROD.A12B1 ROD.A12B2…	Defoc. Octupole	-1	-1	+1	Yes
RSD1.A12B1 RSD1.A12B2 ….	Defoc. Sextupole	-1	-1	+1	Yes
RQS.A12B1 …	Skew Quad	+1	-1	+1	No
RSS.A12B1 ..	Skew Sext	+1	-1	+1	No

From MAD-x variables to fields

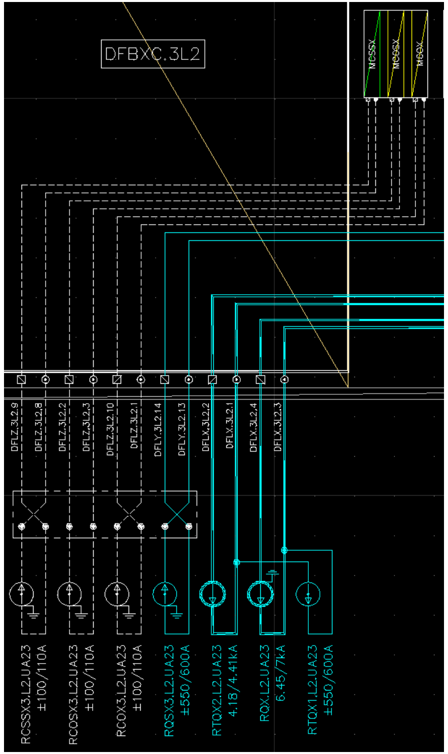


Circuit drawing Triplet

□ A
○ B



https://edms.cern.ch/document/202016/AJ



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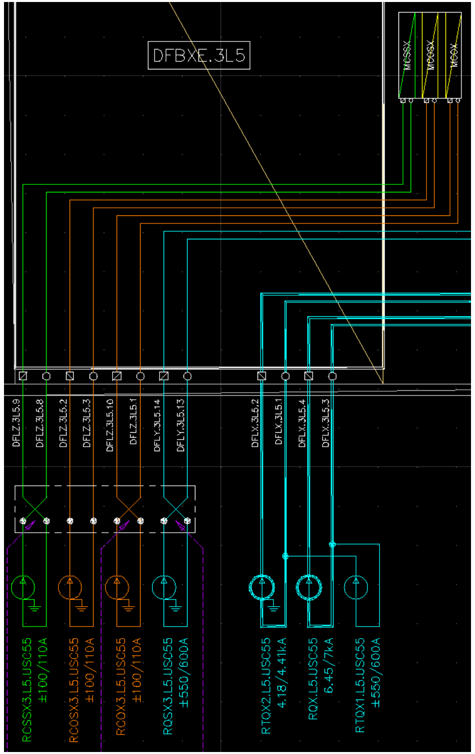


https://edms.cern.ch/document/201995/AI

Source	Source Pole	Target	Target Pole
DCYQ.3L1.12		MCOX.3L1	A
MCOX.3L1	A	DCYQ.3L1.11	

Not clear why MCOX enters in B, while it declared A in LDB.

ELQA test reports triplets

	Magnet Order	Magnetic Field Orientation	Polarity	d(Main harmonic)/dI [mT/A]
Expected Values	1	Normal	Positive	6.0909
Expected Values	1	Skew	Positive	5.9273
Expected Values	2	Skew	Negative	2.4727
Expected Values	3	Normal	Positive	0.1500
Expected Values	3	Skew	Positive	1.0890
Expected Values	4	Normal	Negative	0.4530
Expected Values	4	Skew	Negative	0.4750
Expected Values	6	Normal	Negative	0.1288

https://edms.cern.ch/ui/file/686210/1/PolarityCheck_LQXC-03.pdf

Not clear why ELQA test expected a negative B4

https://edms.cern.ch/project/CERN-0000073301 many non conformity reports. Some typical non-conformity:

Wrong polarity of the circuit RCOX3.R2 powered via the DFBXD.R2 due to a turn of the corrector magnet assembly inside the Q3R2 cold mass. Inversion of the labels at the level of the patch panel is required.

Wrong polarity of the circuit RQSX3.R5 powered via the DFBXF.R5 due to a cross of the bus-bars inside the DFBXF helium enclosure.
Inversion of the labels at the level of the patch panel is required.

All RQSX3, RCSSX3, RCOX3 had wrong polarity that was corrected.

Test bench	181
Test Operator	PG
Date	9/1/2005
Mouse Unit	5
Cryomagnet assembly	Q3-CORRS-001
Magnet name	MCOX
Magnet type	Octupole
Aperture	1
Insertion side	Upstream
Longitudinal position [mm]	300.00
N. of data points/turn	64
Positive current lead	B4A(+) B4B(-)

Test Results:

	Magnet Order	Magnetic Field Orientation	Polarity	d(Main harmonic)/dI [mT/A]
Measured Values	4	Normal	Positive	0.4459
Expected Values	4	Normal	Negative	0.4530

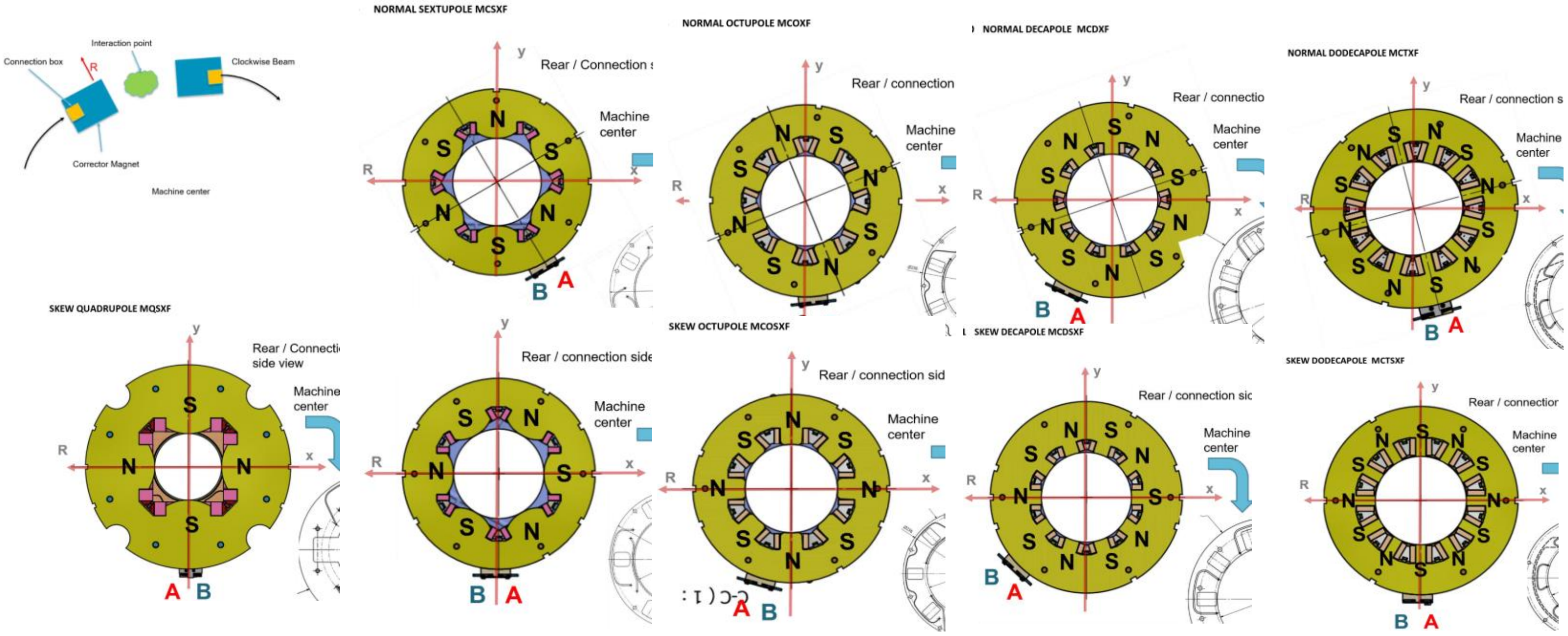
Run	Time	I [A]	Mouse tilt angle init. [degree]	Mouse tilt angle fin. [degree]	Bmain harmonic [mT @ 17 mm]	A main harmonic [mT @ 17 mm]
1	3:27 PM	-0.50	-0.110	-0.155	-0.2237	0.0196
2	3:28 PM	0.50	-0.148	-0.180	0.2222	-0.0200

TEST NOT PASSED

Summary

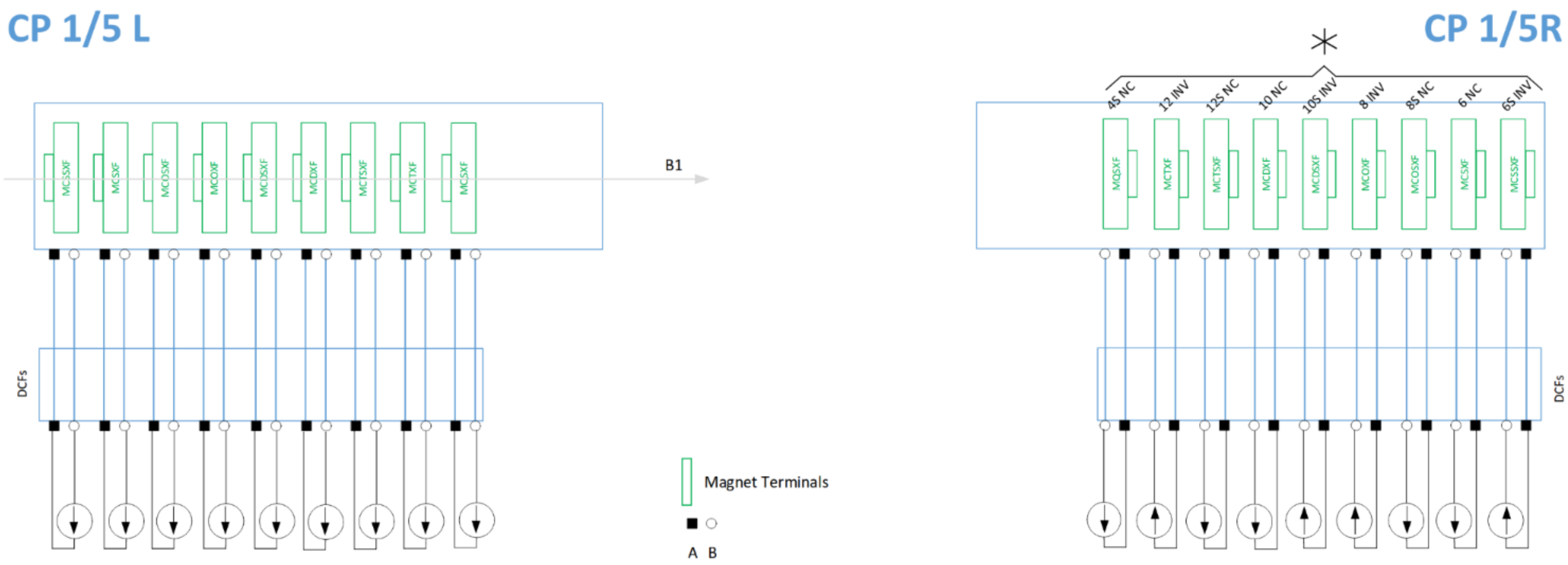
	Left									Right								
	MQ	MC	MC	MC	MC	MC	MC	MC	MC	MQ	MC	MC	MC	MC	MC	MC	MC	MC
	SX	SX	SSX	OX	OSX	DX	DSX	TX	TSX	SX	SX	SSX	OX	OSX	DX	DSX	TX	TSX
Multipole	a2	b3	a3	b4	a4	b5	A5	b6	a6	a2	b3	a3	b4	a4	b5	a5	b6	a6
Entering	B	A	B	B	A			A		B	A	A	A	A			B	
Turned	N	N	N	N	N			N		Y	Y	Y	Y	Y			Y	
ELQA exp.	-1	1	1	-1	-1			-1		-1	1	1	-1	-1			-1	
Polarity (90041)	1	1	-1	1	1			1		-1	1	-1	1	-1			1	
MAD-X (SEQ)	-1	1	-1	1	-1			1		-1	1	-1	1	-1			1	
ABP Beam	R	OK	R	OK	R			OK		R	OK	R	OK	R			OK	

HO Multipoles HL-LHC



https://edms.cern.ch/document/2269414/1.1

HL-LHC polarity proposal



References

Russenschuck, "Checking the Polarity of Superconducting Multipole LHC Magnets", https://cds.cern.ch/record/970340/files/lhc-project-report-869.pdf, LHC Project Report 869
Russenschuck, "LHC Magnet Polarities", https://cds.cern.ch/record/986617/files/cham-xiv-4_02.pdf

R. Tomas et al. "Magnet polarity checks in the LHC" https://cds.cern.ch/record/1667590/files/CERN-ACC-NOTE-2014-0012.pdf

LHCLSD1_0003 Orlandi plots https://edms.cern.ch/document/202016/AJ

LHC-DC-ES-0001 Magnet polarity convention https://edms.cern.ch/document/90041/3.2

HL-LHC HO correctors https://edms.cern.ch/document/2269414/1.1

CP LHC https://edms.cern.ch/file/211122/AC/lhcmqsxa0001-vAC.plt