UNIVERSITÀ DEGLI STUDI DI MILANO
FACOLTÀ DI SCIENZE E TECNOLOGIE

Quench Localization in Superconducting Magnets using the Harmonic Field Analysis Method

Samuele Mariotto

on behalf of INFN LASA
Superconducting Magnet Group
Milan, Italy

Structure

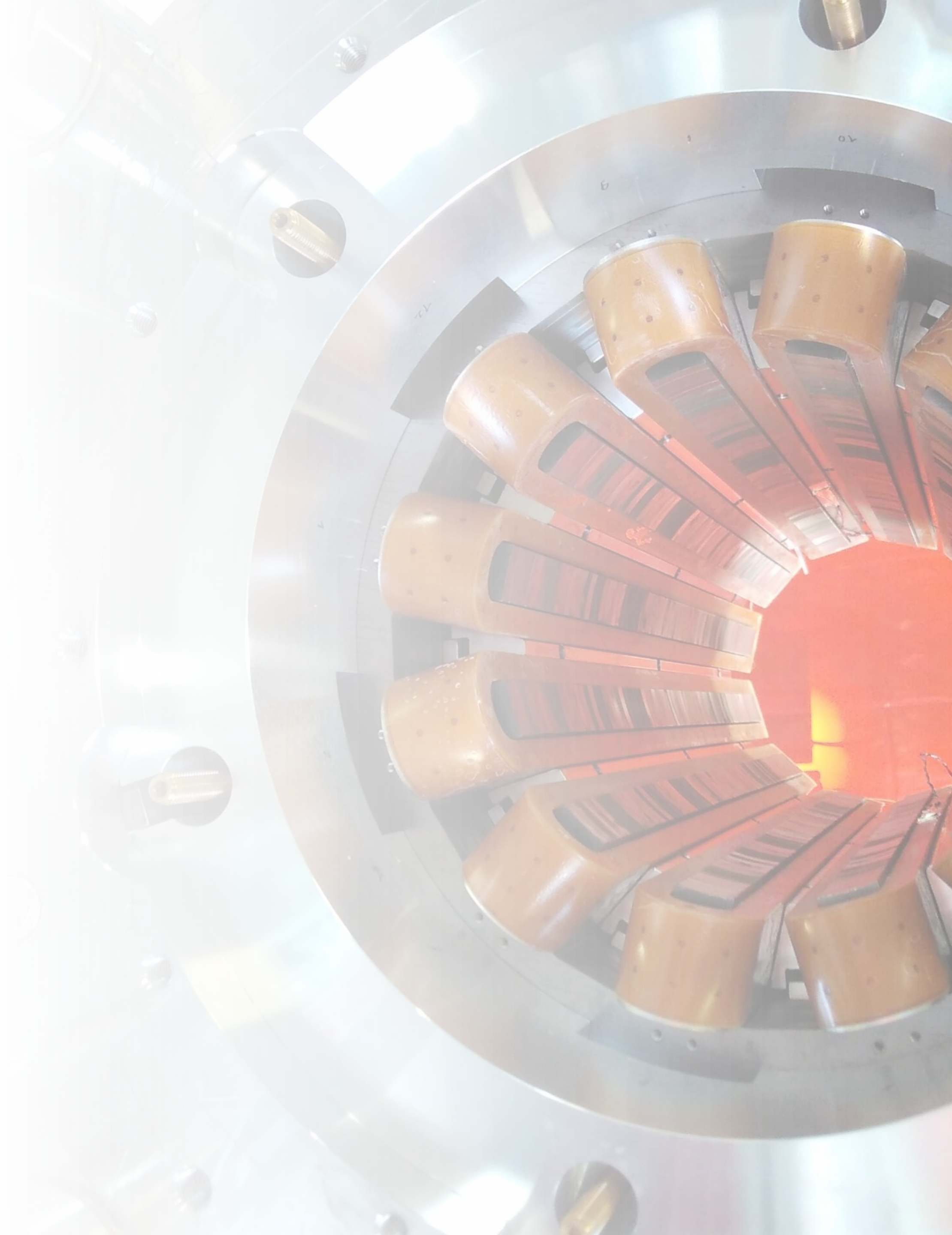
1. The HL-LHC High Order Corrector Magnets

2. Theoretical Model of magnetic analysis for Quench localization

3. Experimental Quench Reconstructions

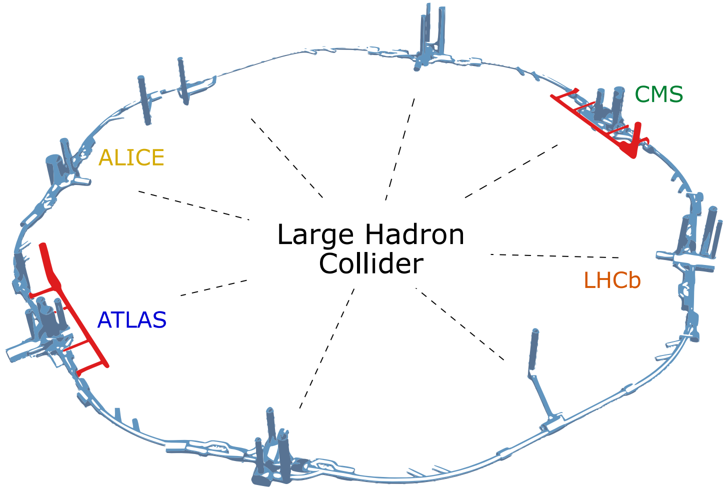
4. Case of Multi-coil Quench

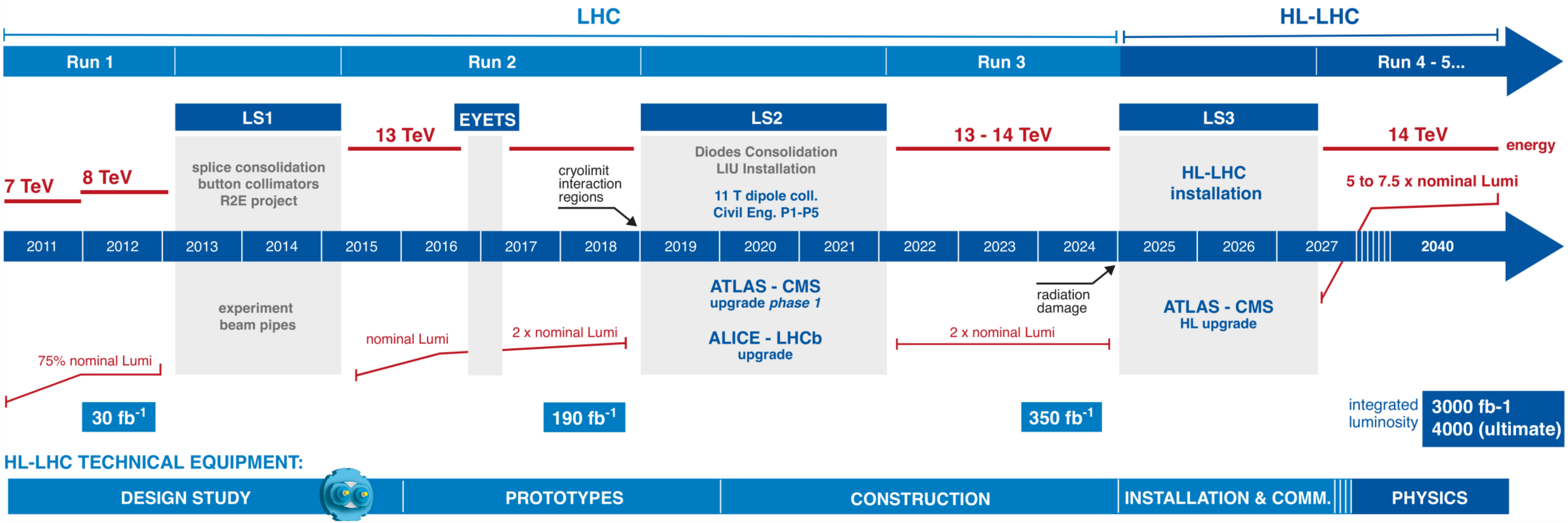
5. Conclusion



High Luminosity Project

LHC - integrated luminosity 300 fb^{-1} by 2023
HL LHC - upgrade interacting regions 2025/27
3000 fb^{-1} integrated luminosity by 2040





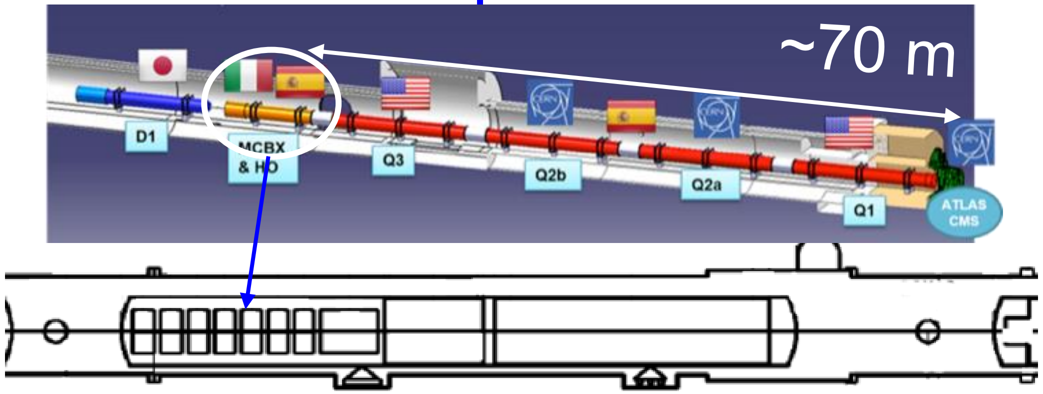
High Order Corrector Magnets

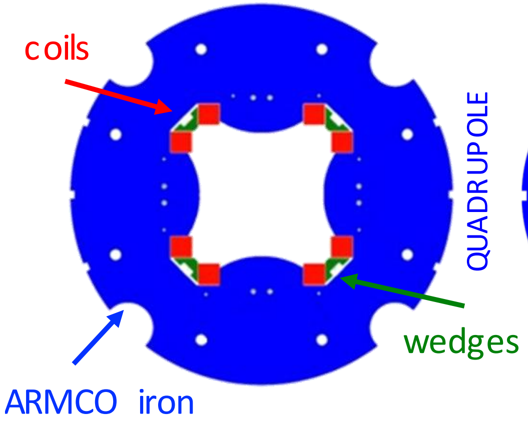
In kind contribution CERN-INFN (2014-2019)

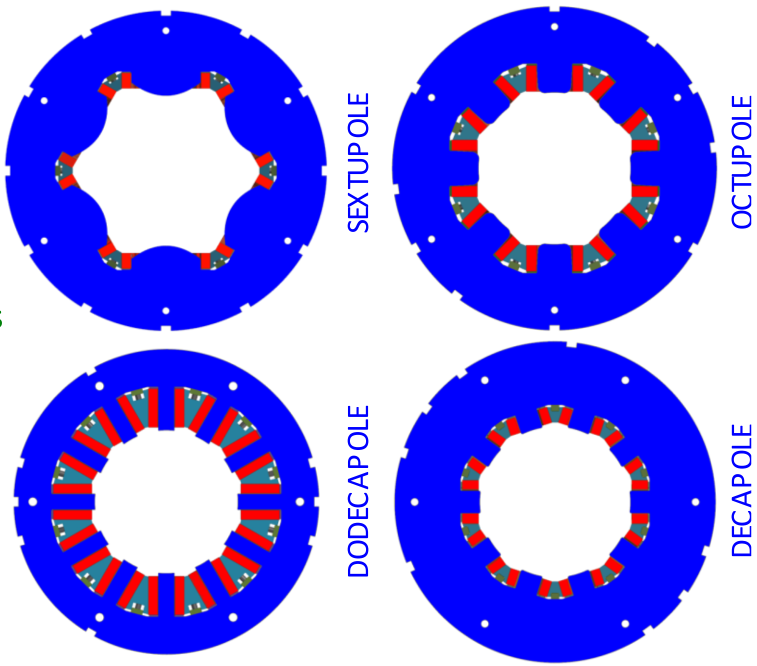
- 5 types of NbTi superferric corrector magnets:
- Quadrupole, Sextupole, Octupole, Decapole and Dodecapole

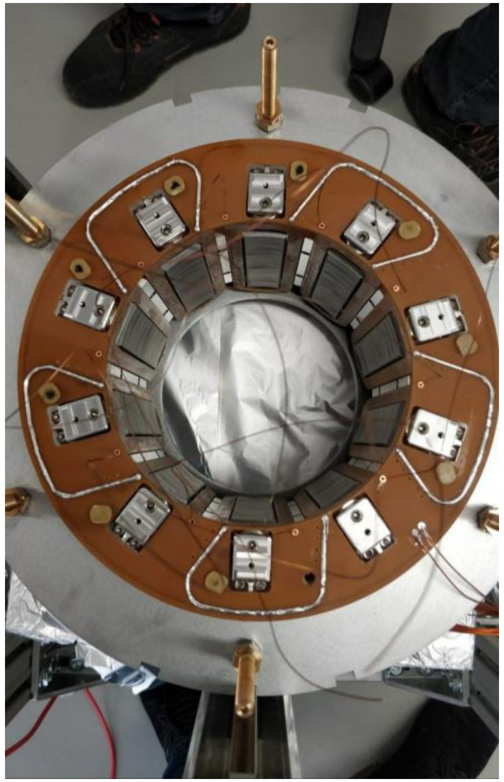
Agreement CERN and INFN-LASA (2019-2022)

- Construction of all the 54 magnets for the installation in HL-LHC

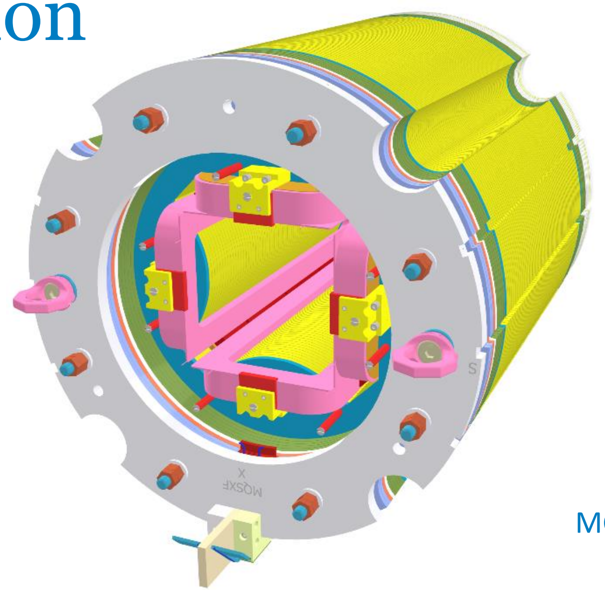


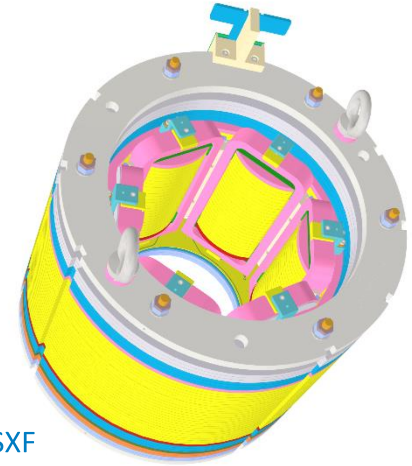






Design and Quench Protection





Superferric design

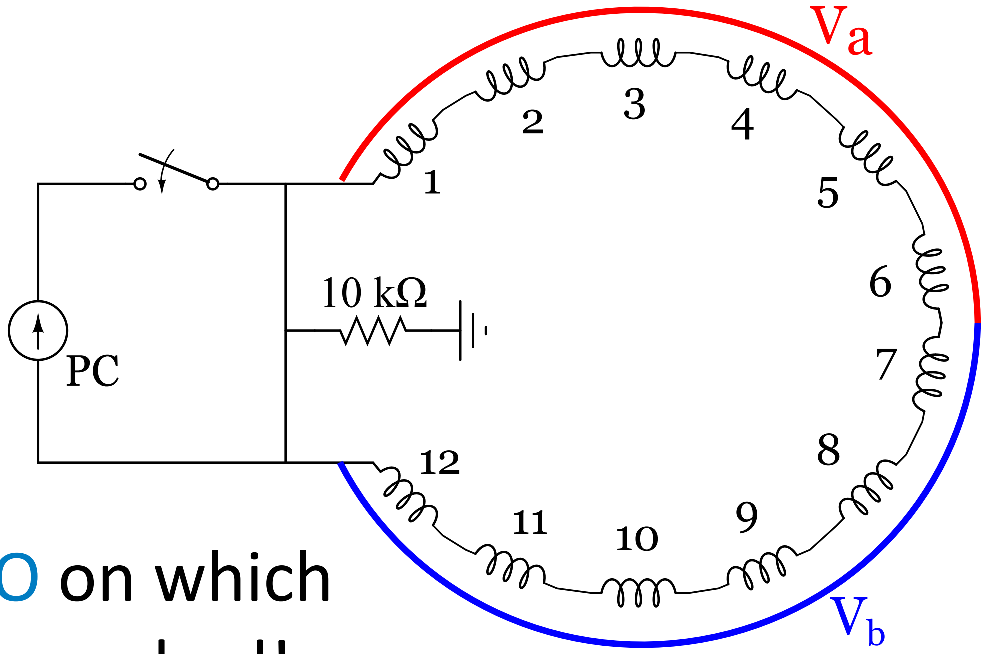
- Compact and modular
- Strong contribution of the iron poles
- Field quality influenced by the shape of the poles

NbTi superconding coils

- Racetrack
- Insulation by S2 glass reinforced material

MAGNETS PARAMETERS

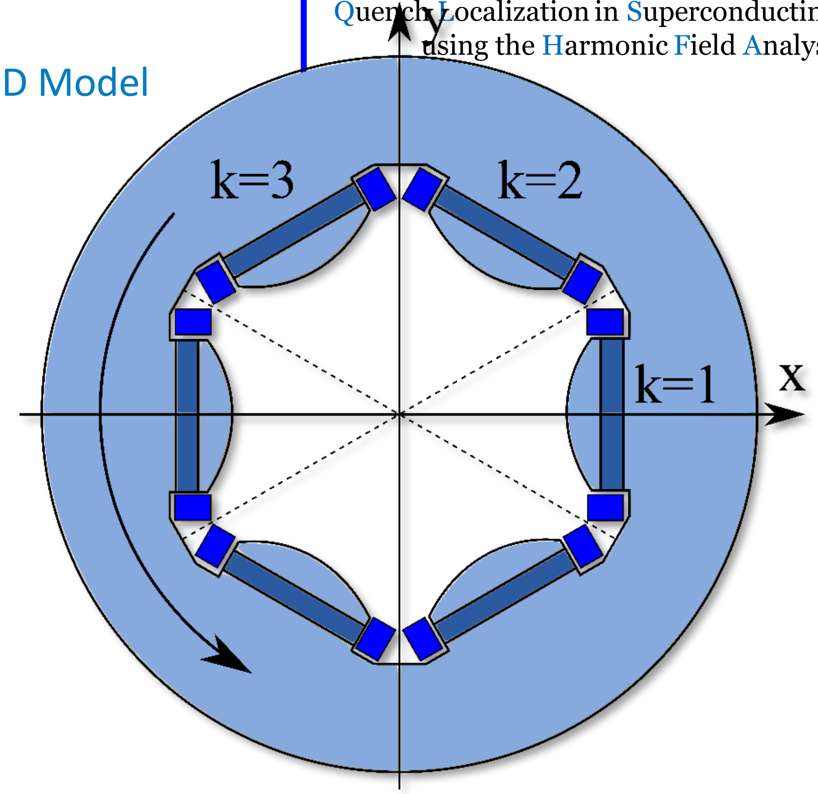
	MQSXF	MCSXF	MCOXF	MCDXF	MCTXF	MCSTXF
Order	2	3	4	5	6	6
Integrated Strength [Tm]	0.700	0.095	0.069	0.037	0.086	0.017
Coil Length [mm]	457	192	172	172	498	123
Magnet Length [mm]	614	254	233	233	575	200
Magnetic Length [mm]	401	168	145	145	469	99
Gradient [T/m^{n-1}]	34.8	224	3680	40480	585600	550400
Strand Diameter [mm]	0.7	0.5	0.5	0.5	0.5	0.5
Insulation Thickness [mm]	0.07	0.07	0.07	0.07	0.07	0.07
Nturns/Pole	754	288	372	228	432	432
Coil Peak Field [T]	3.6	2.23	2.09	1.63	1.57	1.5
Nominal Current [A]	174	99	102	92	85	84
Loadline	44%	31%	31%	26%	27%	27%
L_{diff} @ I_{nom} [mH]	1530	213	220	120	805	177
Stored Energy [kJ]	30.8	1.72	1.55	0.67	3.6	0.73



No INFO on which Coil Quenched!

New Idea

Uniform 2D Model



Assumptions

- Only Single Coil quench observed during prototype construction phase
  No quench propagation to all the magnet coils
- Quenched coils will not have residual magnetization
- The all coil volume is not magnetized after the quench

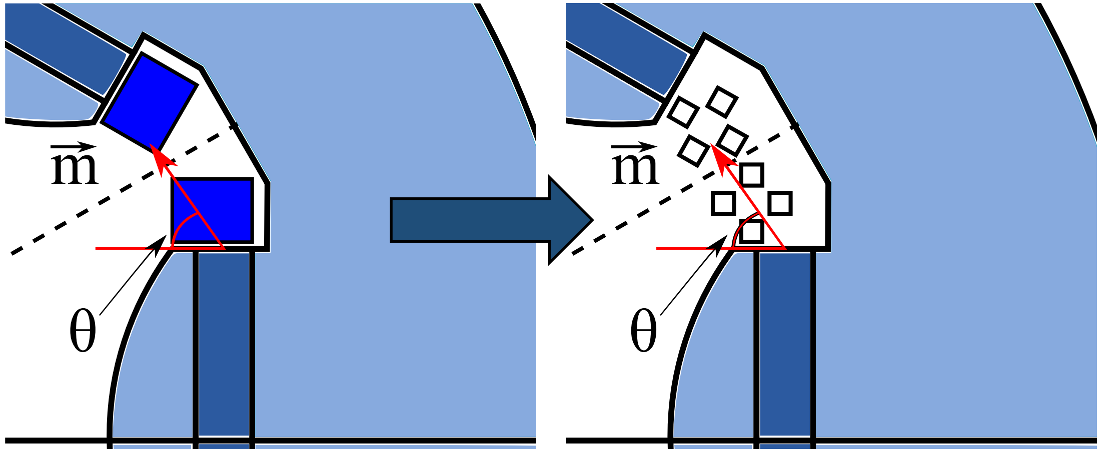
Kim-Anderson model parameters

Parameter	J_0	B_0	A_0	A_1
Unit	A/mm^2	T	A/mm^2	A/Tmm^2
Value	2.92E+04	0.1203	5.97E+03	-7.0E+02

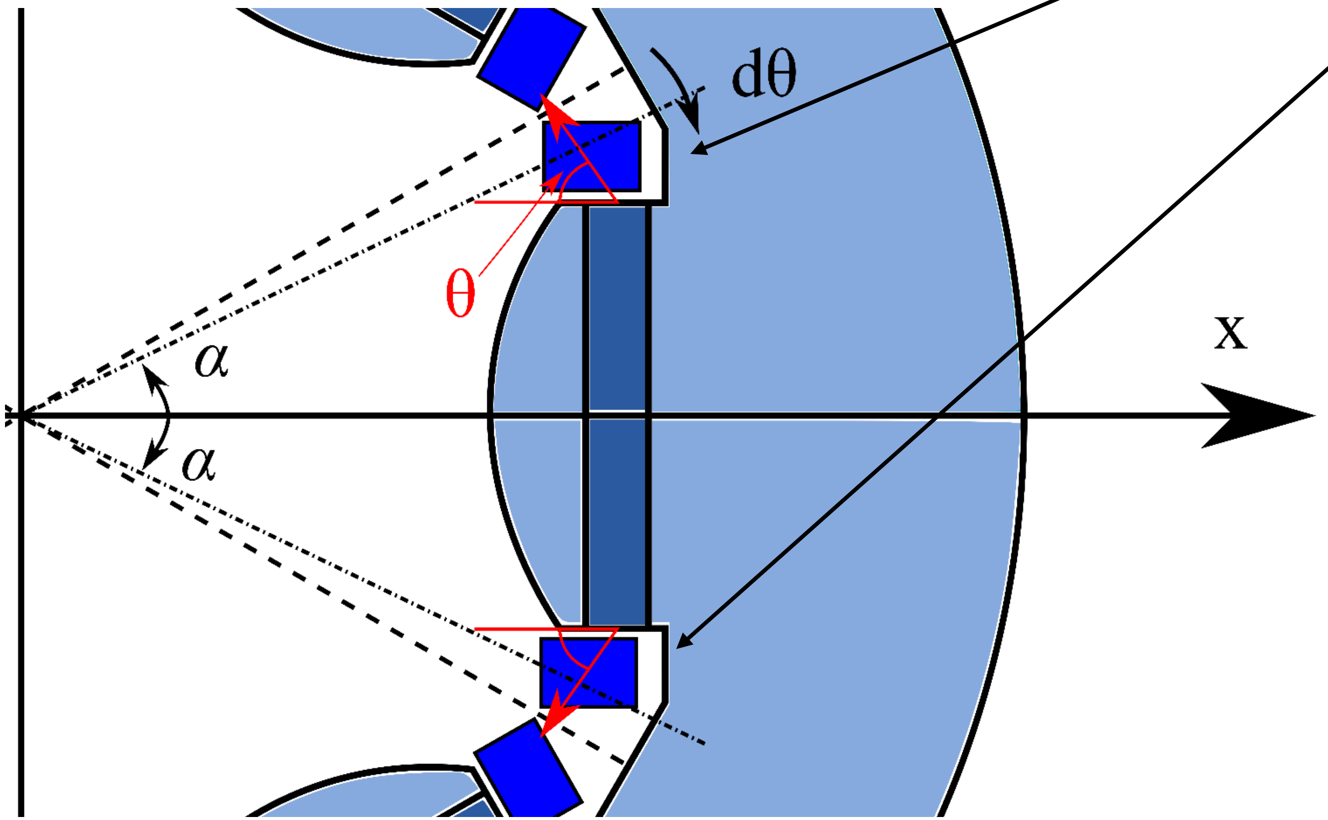
$$M = \frac{2}{3\pi} J_c D_s \frac{\lambda^{\frac{3}{2}}}{\sqrt{N_f}} \lambda_c \qquad J_c(B) = \frac{J_0 B_0}{B + B_0} + A_0 + A_1 \cdot B$$

Single Superconducting coil cross section contribution

$$C_n = \frac{i\mu_0 n}{2\pi} \int d\sigma \left[\frac{J_1 idy}{w^{n+1}} - \frac{J_2 dx}{w^{n+1}} \right] = -\frac{\mu_0 n}{2\pi L_z} \left[\frac{m_x + i m_y}{w^{n+1}} \right]$$



Analytical Model



Direct calculation of the Harmonic Coefficients

$$C_n^1 = -\frac{\mu_0 n}{2\pi L_z}\left[\frac{m_1}{w_1^{n+1}}\right] = -\frac{\mu_0 n}{2\pi L_z}\left[\frac{m_1}{\rho^{n+1}}\right] e^{-i(n+1)\alpha}$$

$$C_n^2 = -\frac{\mu_0 n}{2\pi L_z}\left[\frac{m_2}{w_2^{n+1}}\right] = -\frac{\mu_0 n}{2\pi L_z}\left[\frac{m_2}{\rho^{n+1}}\right] e^{i(n+1)\alpha}$$

- Transformation to calculate the different coils contribution

$$m_1 \rightarrow m_1' = m_1\,(-1)^{k-1}\, e^{i(k-1)\frac{\pi}{b}}$$

$$m_2 \rightarrow m_2' = m_2\,(-1)^{k-1}\, e^{i(k-1)\frac{\pi}{b}}$$

- Each magnetic dipole moment is rotated and inverted in the direction to account for the opposite polarities

Single k_{th}-Coil Contribution

$$C_n(k) = \frac{-\mu_0 n m}{2\pi L_z \rho^{n+1}} \cos[\theta - (n+1)\alpha]\, e^{-i\frac{n-b}{b}(k-1)\pi}$$

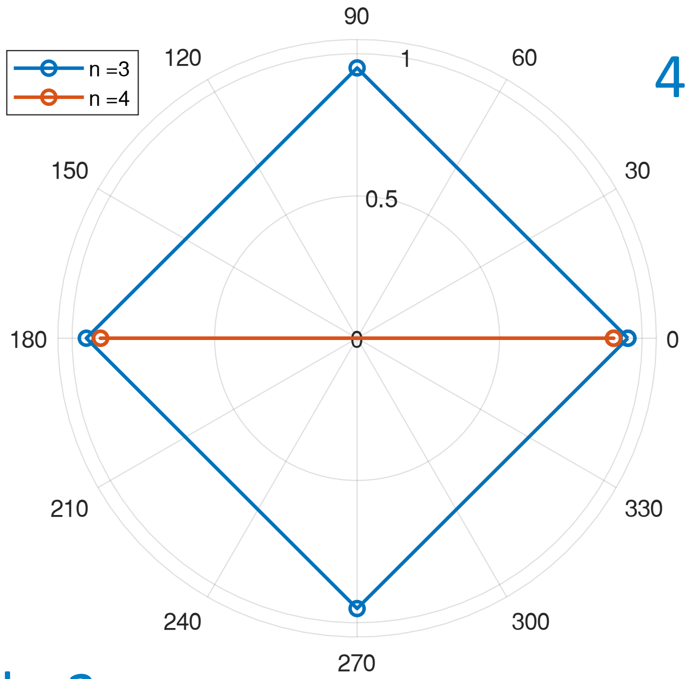
FINAL Harmonic Content

$$C_n^j = \sum_{k=1}^{2b} C_n(k) - C_n(j)$$

S. Mariotto and M. Sorbi. “*Quench position reconstruction through harmonic field analysis in superconducting magnets*”. Superconductor Science and Technology, 35(1):015006, nov 2021.

Field Harmonics Phase

4P



b=2

n	k=1	k=2	k=3	k=4
1	0	$\frac{3}{2}\pi$	π	$\frac{\pi}{2}$
3	0	$\frac{\pi}{2}$	π	$\frac{3}{2}\pi$
4	0	π	0	π

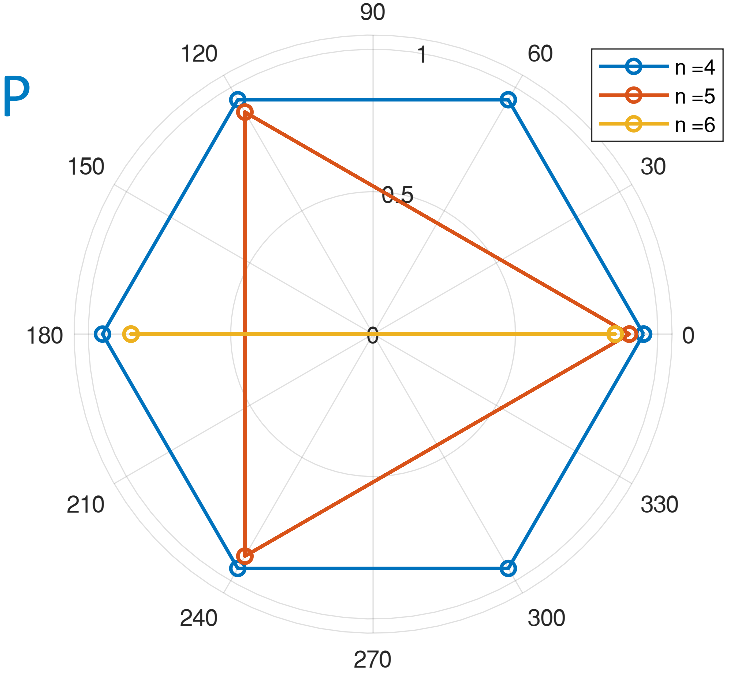
Possible Harmonic Phases

$$\Theta(C_n(k)) = \frac{n-b}{b}(k-1)\pi$$

Best Harmonic
For Unique Reconstruction

$$n = b \pm 1$$

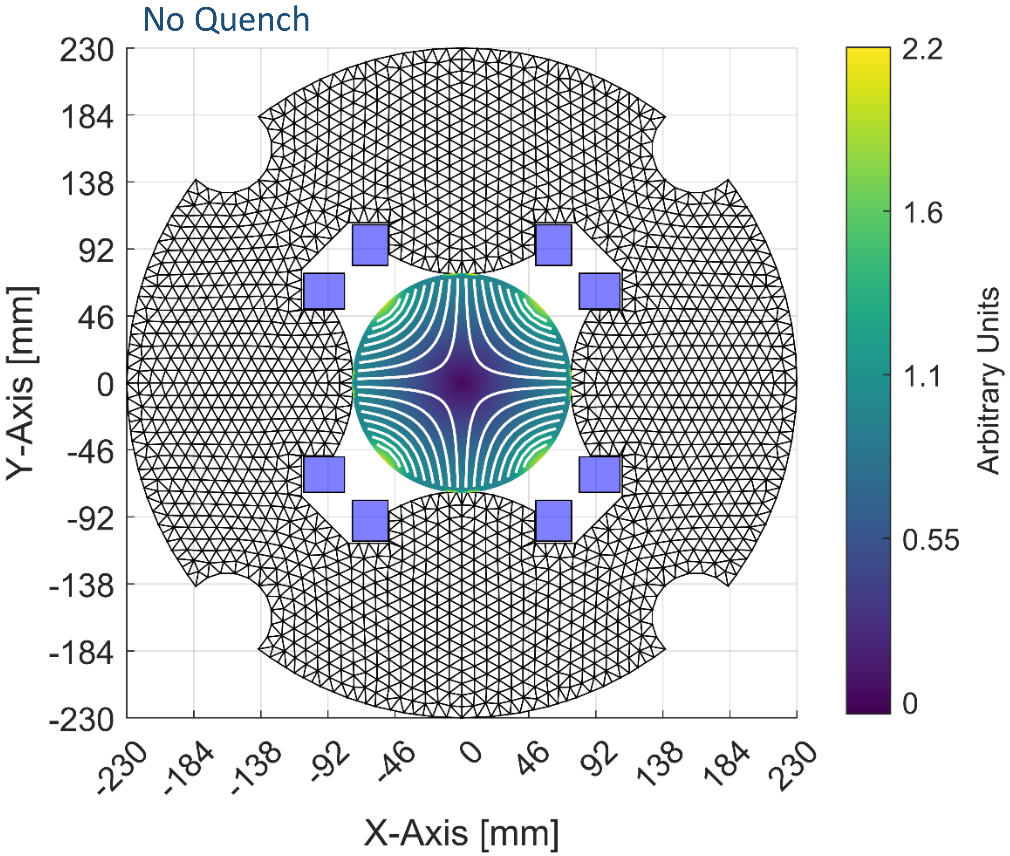
6P

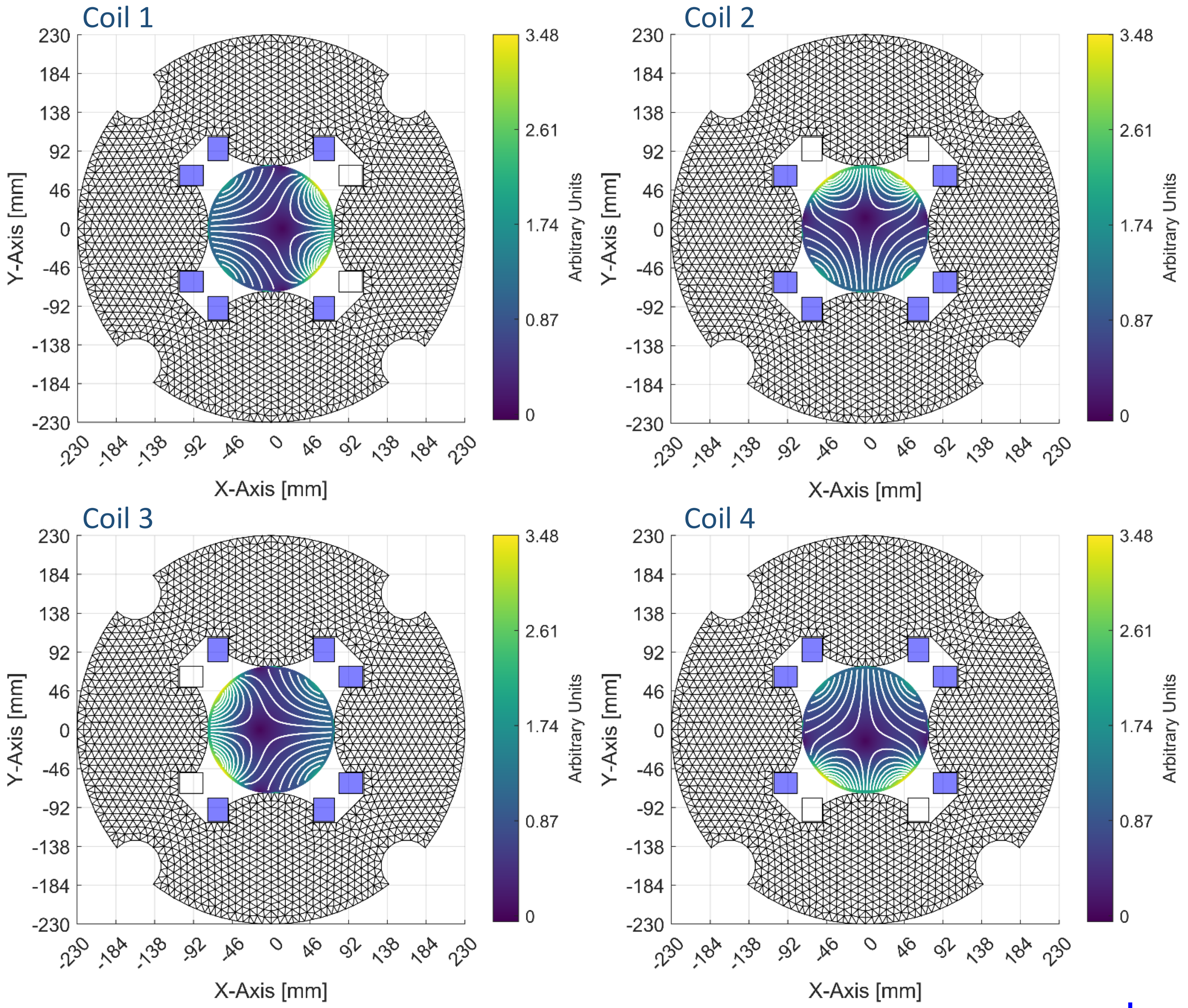


b=3

n	k=1	k=2	k=3	k=4	k=5	k=6
2	0	$\frac{5}{3}\pi$	$\frac{4}{3}\pi$	π	$\frac{2}{3}\pi$	$\frac{\pi}{3}$
4	0	$\frac{\pi}{3}$	$\frac{2}{3}\pi$	π	$\frac{4}{3}\pi$	$\frac{5}{3}\pi$
5	0	$\frac{2}{3}\pi$	$\frac{4}{3}\pi$	0	$\frac{2}{3}\pi$	$\frac{4}{3}\pi$
6	0	π	0	π	0	π

Not Allowed Harmonics





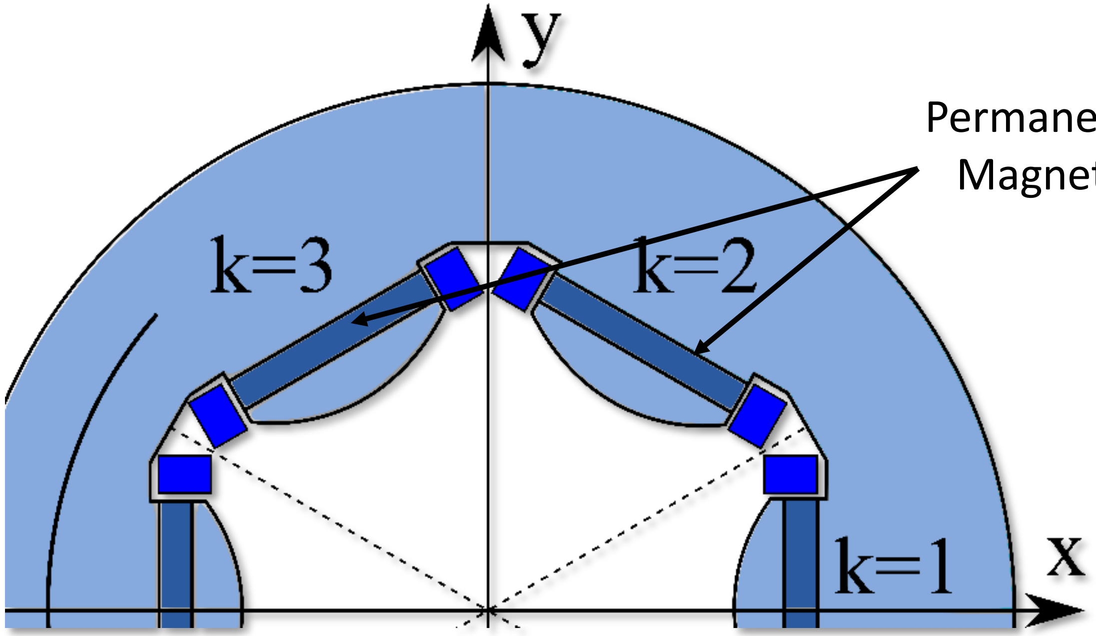
4P Allowed Harmonics (No Quench) = C_2, C_6, C_{10}

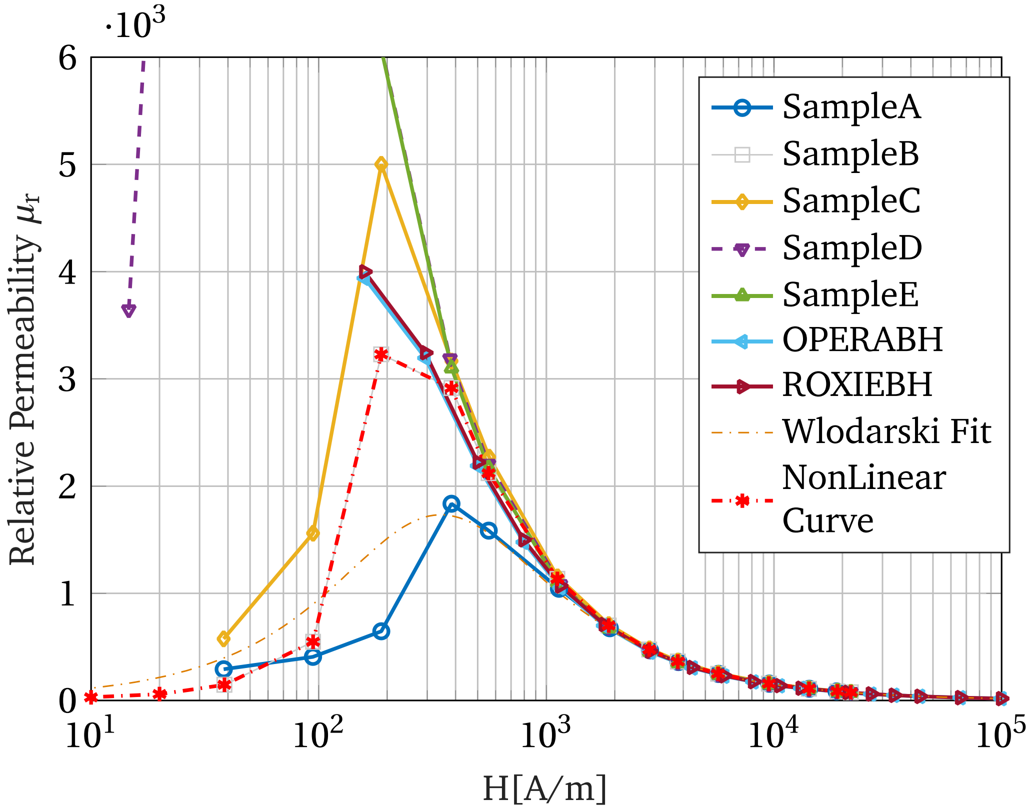
With Quenched Coil = C_1, C_3, C_4, C_5, C_7

FEM Model

5 different OPERA 2D Models

- No consideration of 3D coil end shape
- ARMCO Iron BH Curve
- Imposed permanent magnet strenght based on MQSXFP1c measured data to reproduce the residual magnetization iron





RESULTS:

- Negligible iron effect on the not allowed harmonic orders

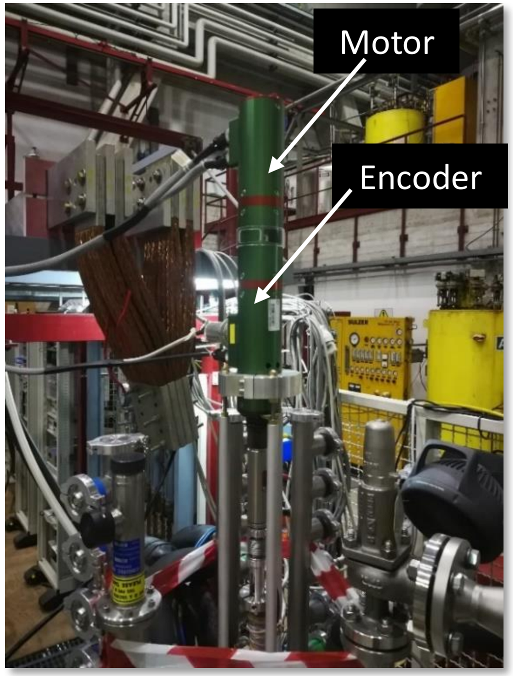
Magnetic Measurement Test Station

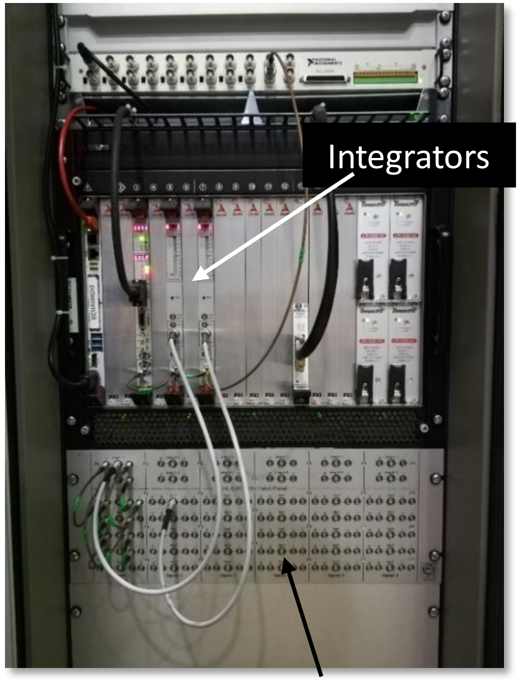
Collaboration CERN-INFN LASA

- Rotating Coil Design
- FFMM framework for the analysis of the signal
- Mechanical integration with cryogenic vertical test station at LASA

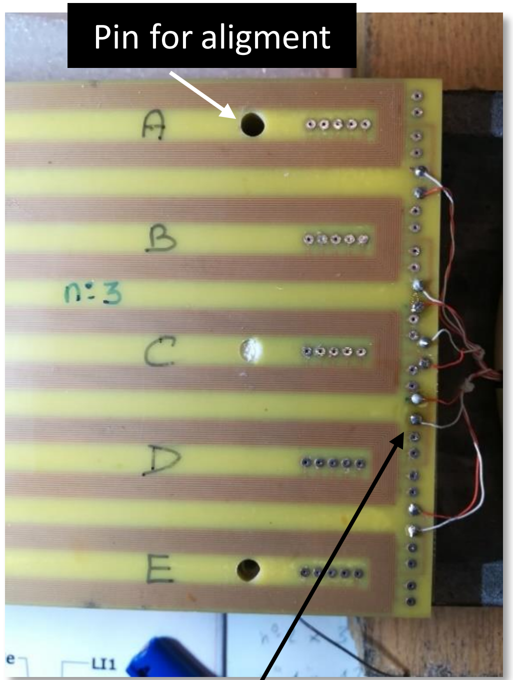
Rotating Coil Structure

- G10 T-beam Support
- 5 Slots
- R_{ref} = 50 mm
- PCB lenght: 0.356 m

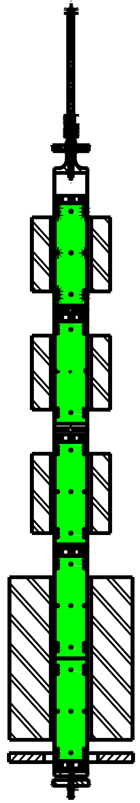




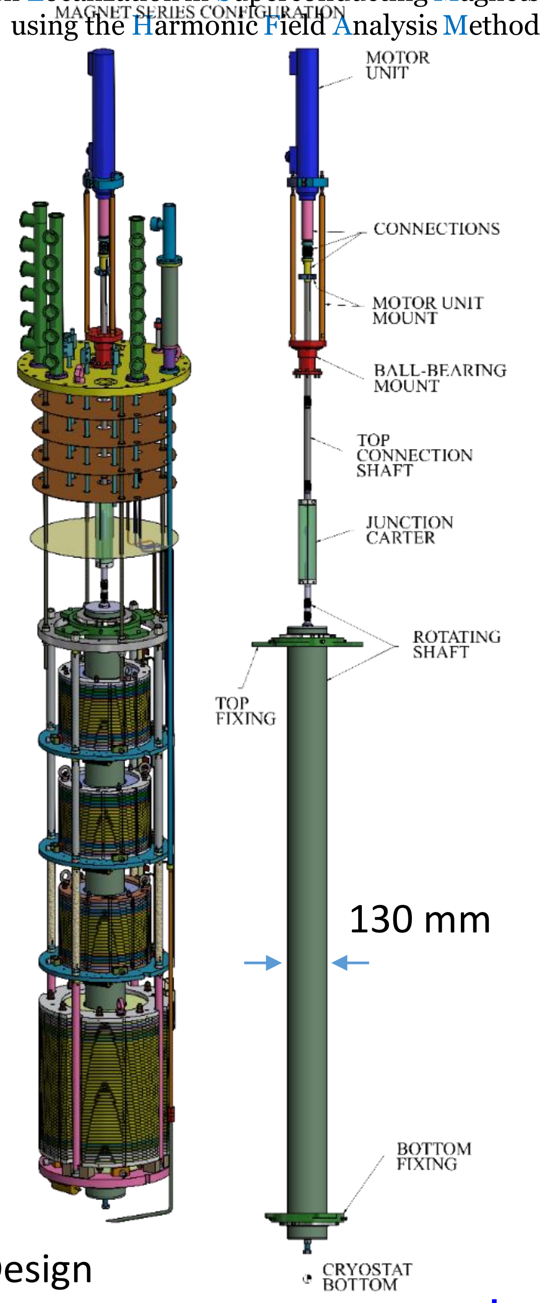
Connections



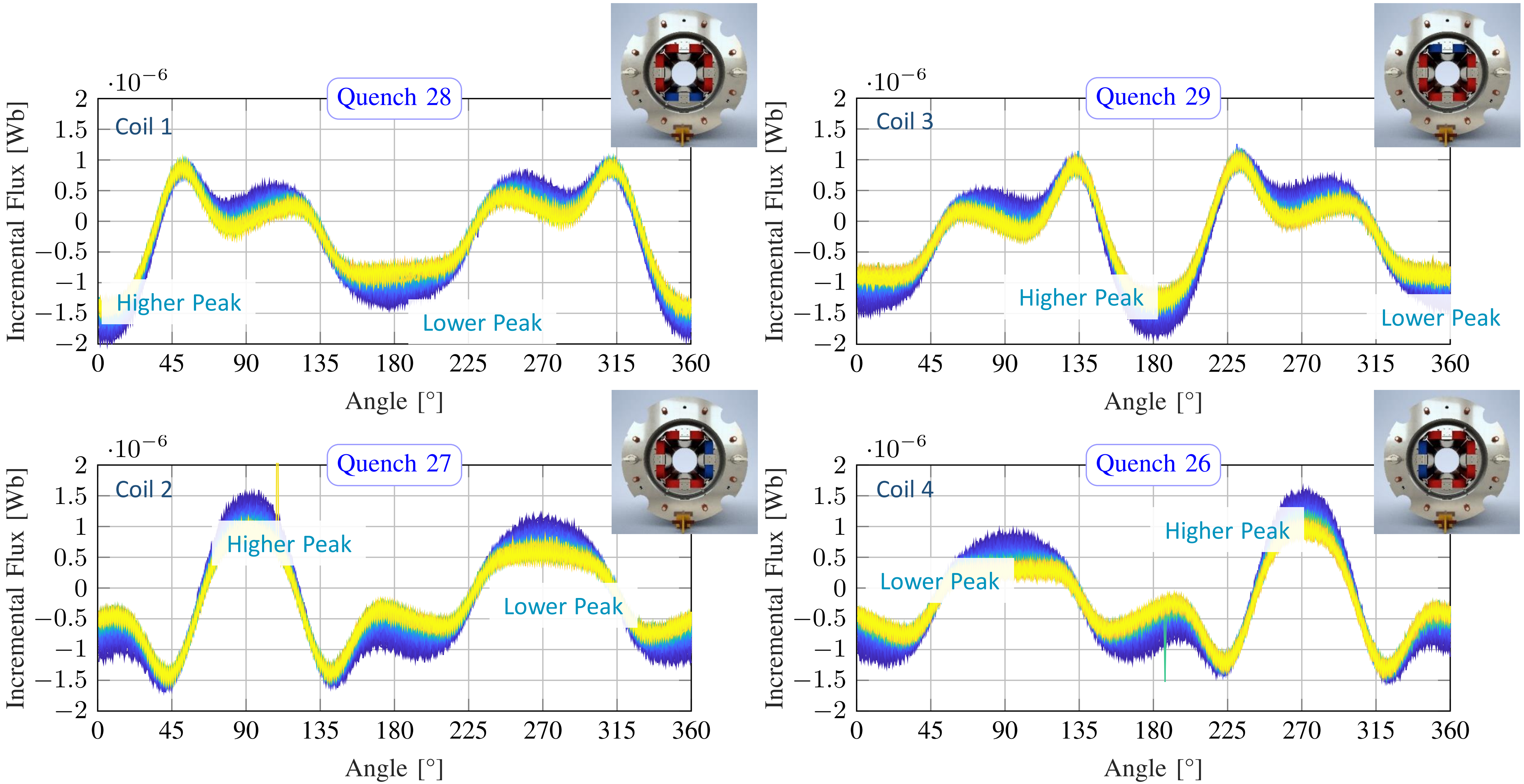
Connections

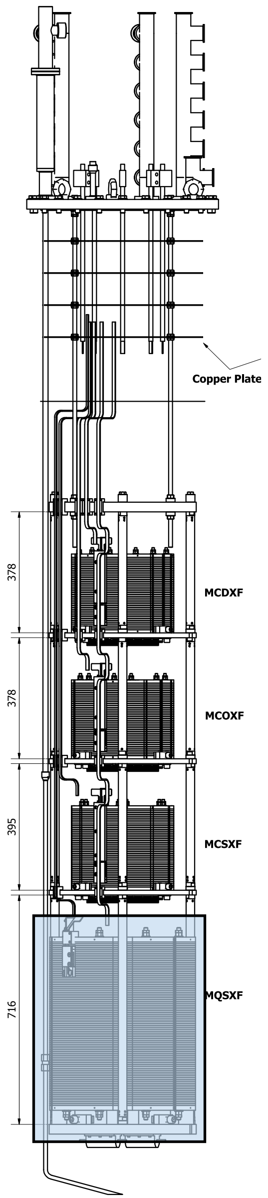


AD-HOC Design



Raw Signal Example MQSXF1





Analysis Results

6P

MCSXF05 Powering Test

Quench N	Current [A]	C_4 Meas. ϕ [°]	De. Std. [°]	Sim. ϕ [°]	N Coil	VA/VB QDS	VA/VB MM
1	113.5	32.1	5.5	30	3	Va	Va ✓

8P

MCOXF07 Powering Test

Quench N	Current [A]	C_5 Meas. ϕ [°]	De. Std. [°]	Sim. ϕ [°]	N Coil	VA/VB QDS	VA/VB MM
1	79	280.4	10.76	292.5	6	Va	Va ✓
2	97	335.0	4.56	337.5	5	Va	Va ✓

12PS

MCTSXF1 Powering Test

Quench N	Current [A]	C_7 Meas. ϕ [°]	De. Std. [°]	Sim. ϕ [°]	N Coil	VA/VB QDS	VA/VB MM
1	81	284.6	9.33	285	6	Va	Va ✓

12PN

MCTXF3 Powering Test

Quench N	Current [A]	C_7 Meas. ϕ [°]	De. Std. [°]	Sim. ϕ [°]	N Coil	VA/VB QDS	VA/VB MM
1	97	126.8	2.30	120	1	Vb	Vb ✓
2	97	182.7	2.40	180	5	Vb	Vb ✓
3	83	142.2	12.30	150	6 and 8	Va/Vb	Vb ✓

4P

MQSXF2 Powering Test

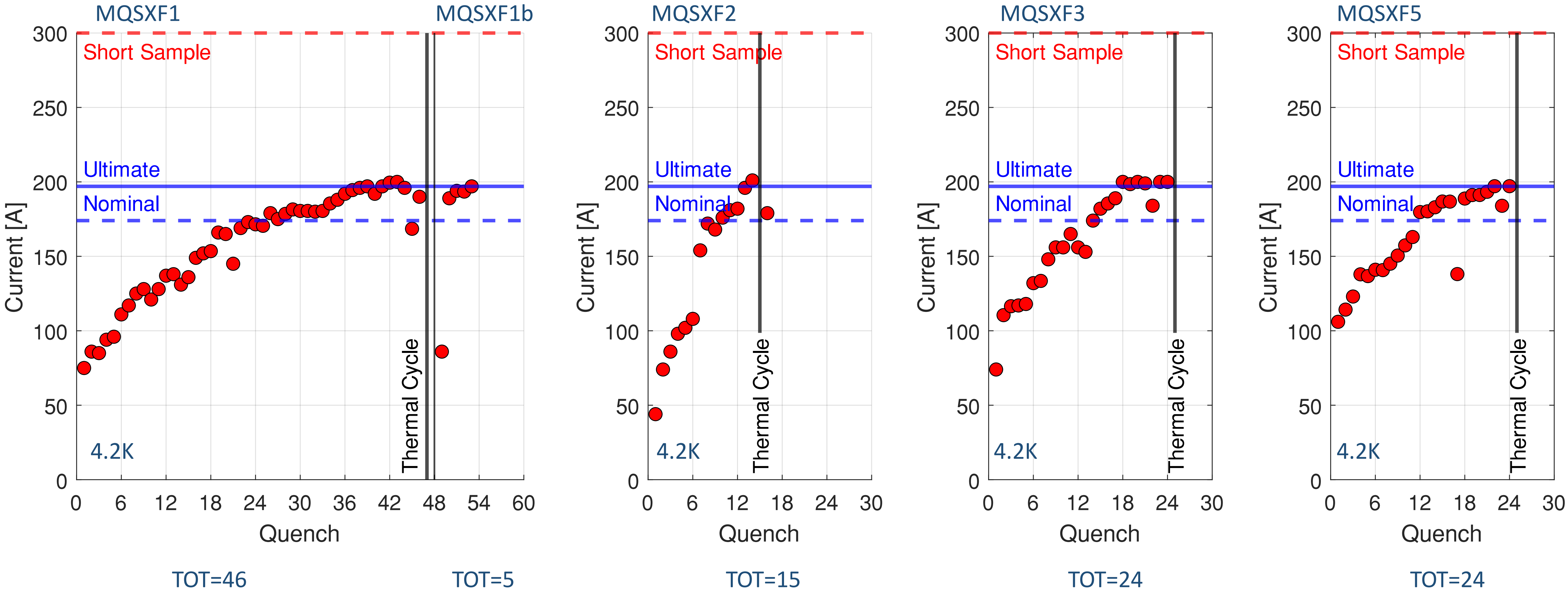
Quench N	Current [A]	C_3 Meas. ϕ [°]	De. Std. [°]	Sim. ϕ [°]	N Coil	VA/VB QDS	VA/VB MM
1	44	88.8	1.6	90	1	Vb	Vb ✓
2	74	90.5	0.7	90	1	Vb	Vb ✓
3	86	353.3	0.7	360	2	Va	Va ✓
4	98	269.7	0.7	270	3	Va	Va ✓
5	102	226.4	0.8	225	3 and 4	Va	Va/Vb ✓
6	108	88.7	0.7	90	1	Vb	Vb ✓
7	154	87.2	0.8	90	1	Vb	Vb ✓
8	172	353	0.9	360	2	Va	Va ✓
9	168	185.3	1	180	4	Vb	Vb ✓
10	176	42.5	0.6	45	1 and 2	Vb	Va/Vb ✓
11	181	185.4	0.9	180	4	Vb	Vb ✓
12	182	185.3	1	180	4	Vb	Vb ✓
13	196	28.4	7.1	?	All	Vb	Va/Vb
14	201	352.8	1	360	2	Va	Va ✓
15	179	89.8	1.4	90	1	Vb	Vb ✓

- All magnet types have been characterized at least in one cryogenic test at LASA
- 150 Quench Analyzed (P = $1/2^{150} \approx 10^{-46}$)
  114 Quench (76% of Total)
  Occured in the 4 Tested Skew 4P

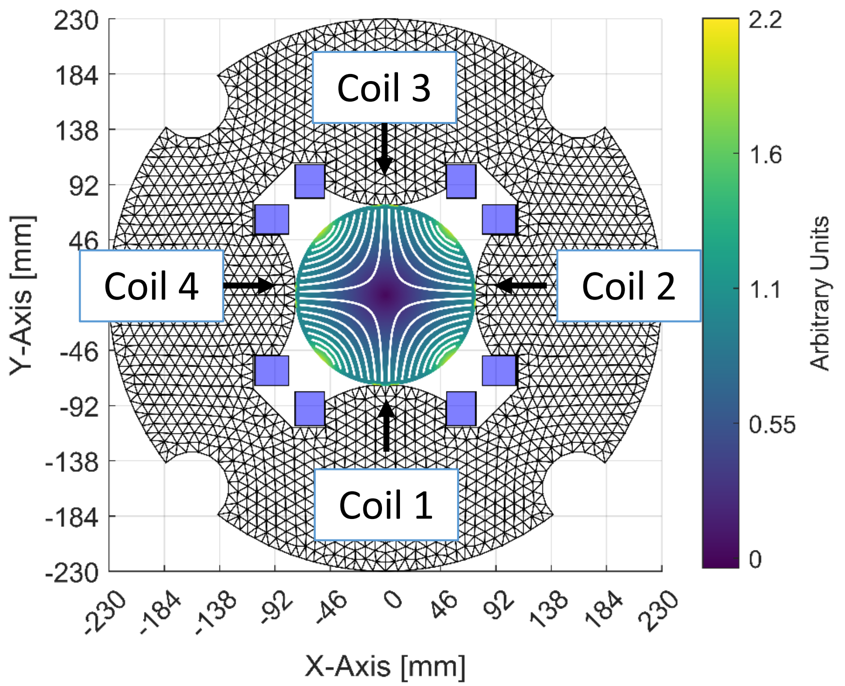
S. Mariotto *et al*. "*Quench Localization in the High Order Corrector Magnets using the Harmonic Field Method*". Accepted by IEEE Transaction on Applied Superconductivity, 2022.

MQSXF1 Case Study

Why so many Quench in MQSXF1??? How many of them are MULTIPLE-COILS quench?



MQSXF1 Case Study

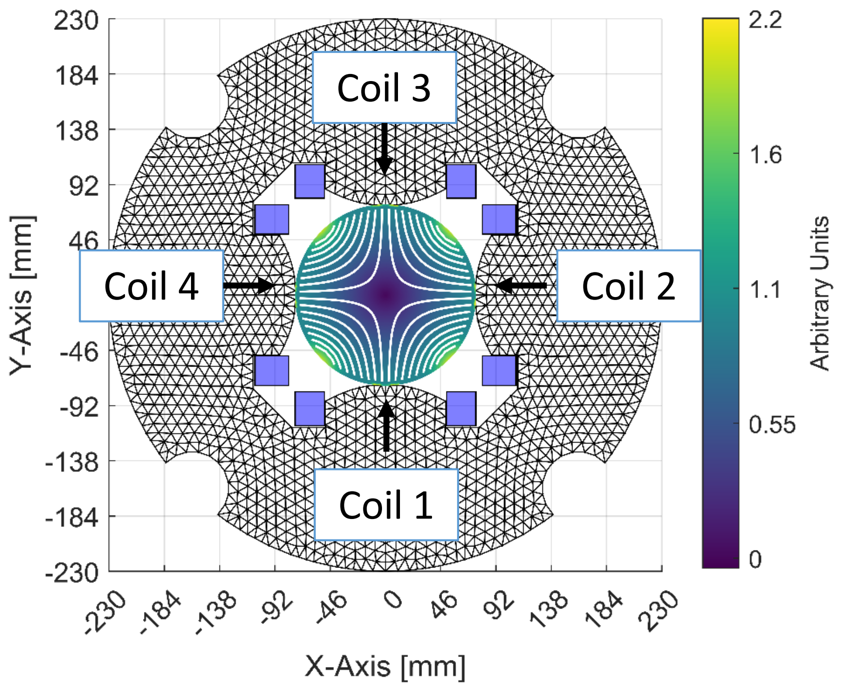


Quench N	Current [A]	C_3 Meas. ϕ [°]	De. Std. [°]	Sim. ϕ [°]	N Coil	VA/VB QDS	VA/VB MM
1	75	179.1	0.82	180	4	Vb	Vb ✓
2	86	358.4	0.66	360	2	Va	Va ✓
3	85	266.6	0.99	270	3	Va	Va ✓
4	94	180.2	1.05	180	4	Vb	Vb ✓
5	96	180.4	0.96	180	4	Vb	Vb ✓
6	111	267	1.25	270	3	Va	Va ✓
7	117	43.6	0.78	45	1 and 2	Va	Va-Vb ✓
8	125	267	1.21	270	3	Va	Va ✓
9	128	180.2	0.93	180	4	Vb	Vb ✓
10	121	180.3	0.99	180	4	Vb	Vb ✓
11	128	357.3	1.07	360	2	Va	Va ✓
12	137	358.1	1.08	360	2	Va	Va ✓
13	138	313.2	1.06	315	2 and 3	Va	Va ✓
14	131	358.4	0.77	360	2	Va	Va ✓
15	136	92.5	1.4	90	1	Vb	Vb ✓
16	149	312.4	0.78	315	2 and 3	Va	Va ✓
17	152	179.1	0.92	180	4	Vb	Vb ✓
18	153.5	45.5	0.93	45	1 and 2	Vb	Va-Vb ✓
19	166	134.7	7.2	135	1 and 3	Vb	Va-Vb ✓
20	165	91.6	0.82	90	1	Vb	Vb ✓
21	145	92.3	1.31	90	1	Vb	Vb ✓
22	169	265.9	1.59	270	3	Va	Va ✓
23	173	357.6	0.83	360	2	Va	Va ✓

Quench in Opposite Coils

Continue in the next slide.....

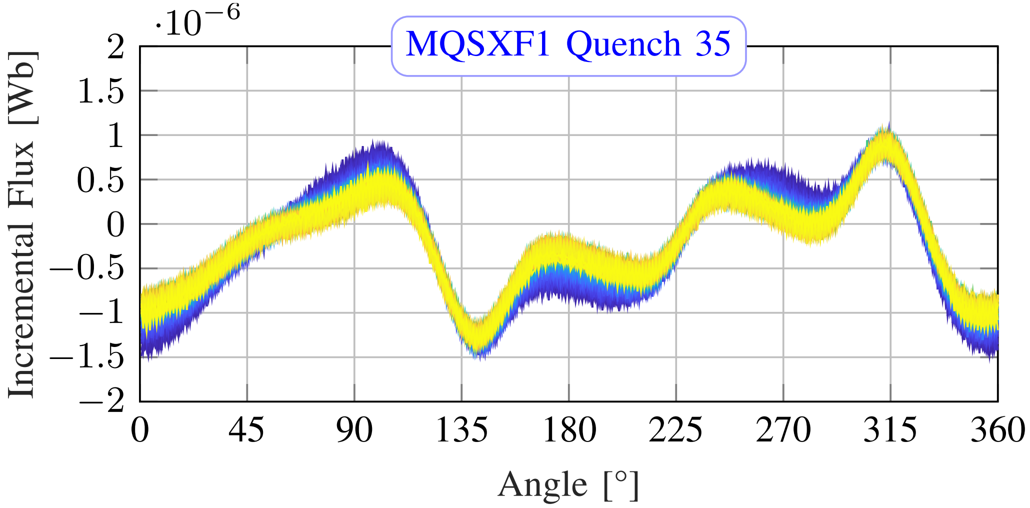
MQSXF1 Case Study

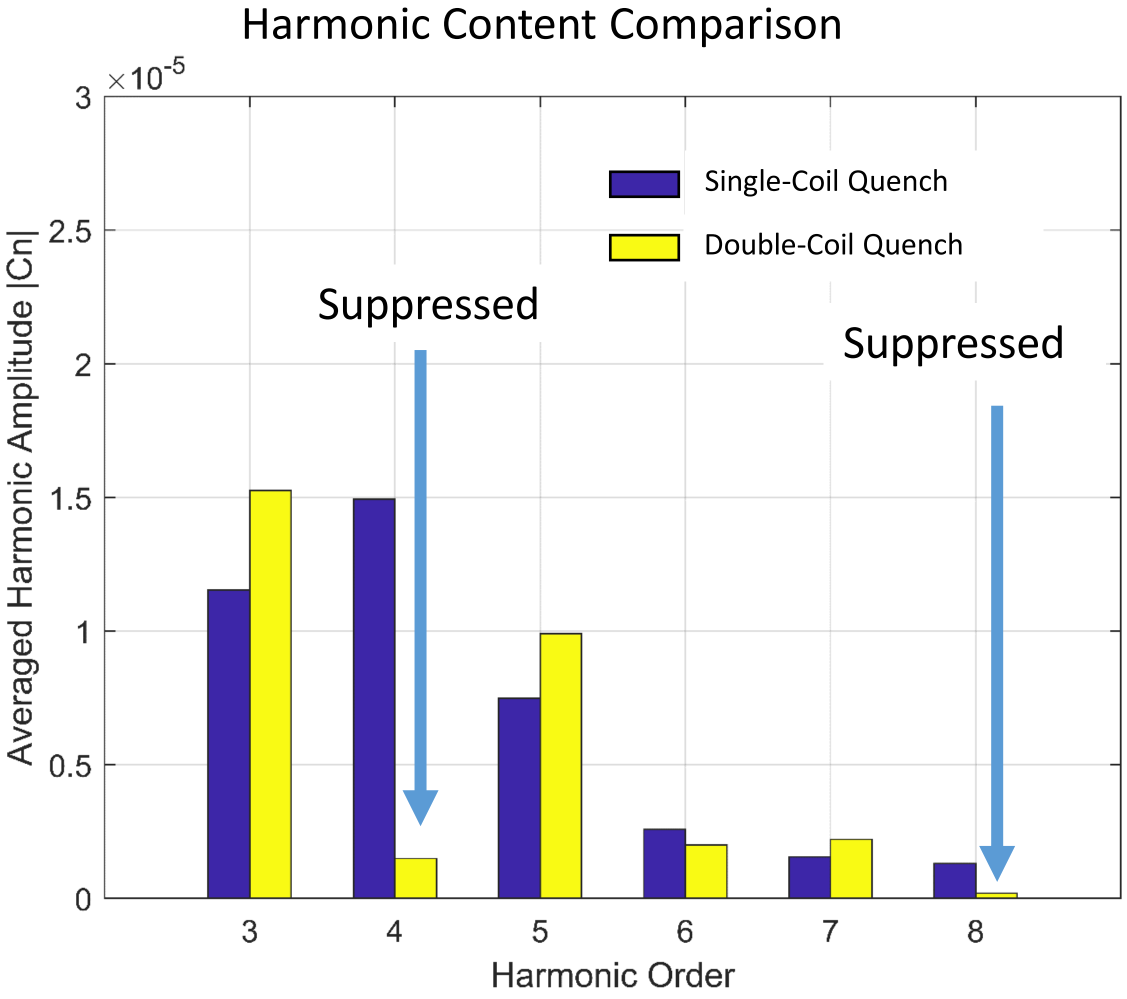


Quench N	Current [A]	C_3 Meas. ϕ [°]	De. Std. [°]	Sim. ϕ [°]	N Coil	VA/VB QDS	VA/VB
24	171.5	357.6	0.96	360	2	Va	Va ✓
25	170.5	357.7	1	360	2	Va	Va ✓
26	179	179.1	1.08	180	4	Vb	Vb ✓
27	175	357.3	1.26	360	2	Va	Va ✓
28	178.5	92.3	1.95	90	1	Vb	Vb ✓
29	181.5	265.1	1.15	270	3	Va	Va ✓
30	180.5	265	1.07	270	3	Va	Va ✓
31	180.5	264.8	1.34	270	3	Va	Va ✓
32	180	178.8	1.3	180	4	Vb	Vb ✓
33	180.5	92.3	1.41	90	1	Vb	Vb ✓
34	185.5	356.7	0.93	360	2	Va	Va ✓
35	188	46.3	0.84	45	1 and 2	Vb	Va-Vb ✓
36	192	229.8	10.29	?	All	Vb	Va-Vb
37	194.5	307.8	0.87	315	2 and 3	Va	Va ✓
38	196	39.1	57.85	?	All	Vb	Va-Vb
39	197	45.3	0.97	45	1 and 2	Vb	Va-Vb ✓
40	192	318.1	1.45	315	2 and 3	Va	Va ✓
41	197	296.4	19.6	?	All	Va	Va-Vb
42	199.5	315.1	1.21	315	2 and 3	Va	Va ✓
43	200	307.9	1.32	315	2 and 3	Va	Va ✓
44	196	308.1	1.23	315	2 and 3	Va	Va ✓
45	168.5	265.4	1.05	270	3	Va	Va ✓
46	190	264	1.35	270	3	Va	Va ✓

- More multi-coil quench at high current values
  Higher current decay rate

Multi-Coil Quench – 2 adjacent Coils





New Harmonic Content:

$$C_n^{j,j+1} = \left|C_n^j\right|\left(e^{-i\frac{n-b}{b}(j-1)\pi} + e^{-i\frac{n-b}{b}j\pi}\right)$$

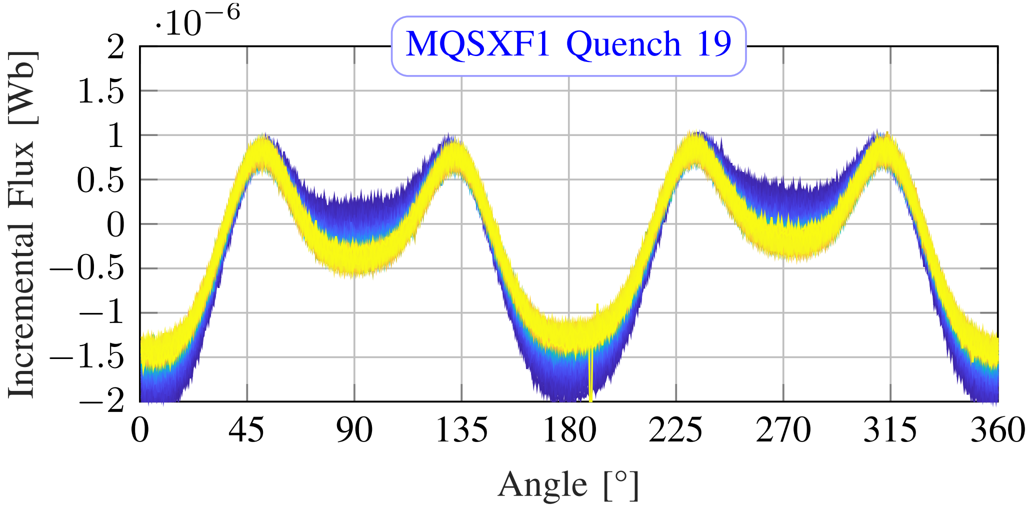
With Some algebra:

$$C_n^{j,j+1} = 2\left|C_n^j\right| e^{-i\frac{n-b}{b}(j-\frac{1}{2})\pi}\cos\left(\frac{n-b}{b}\frac{\pi}{2}\right)$$

$$cos\left(\frac{n-b}{b}\frac{\pi}{2}\right) = 0 \longrightarrow n = 2b(1 \pm l) \quad \text{with} \quad l = 0,1,2\ldots$$

If $b = 2 \quad n = 4, 8\ldots$

Multi-Coil Quench – 2 Opposite Coils



Harmonic Content:

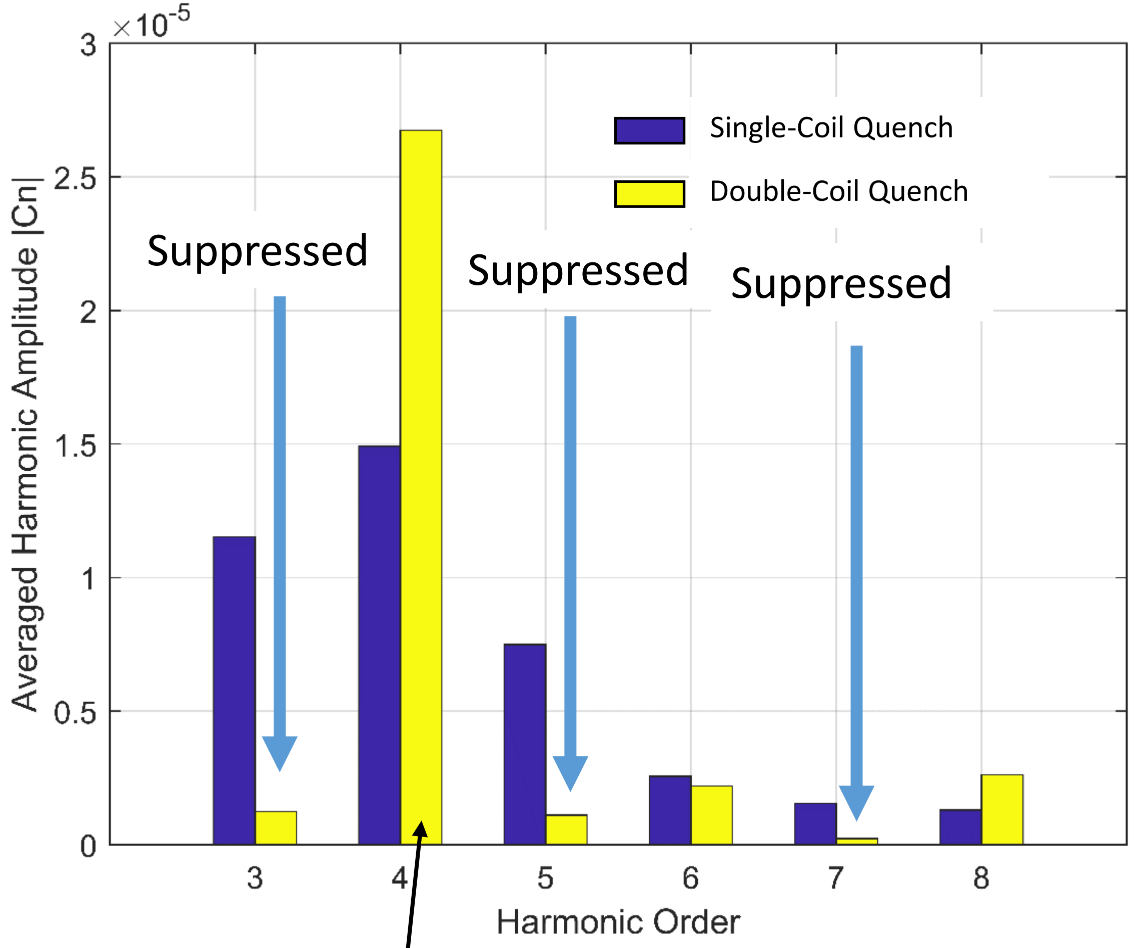
$$C_n^{j,j+b} = \left|C_n^j\right|\left(e^{-i\frac{n-b}{b}(j-1)\pi} + e^{-i\frac{n-b}{b}(j-1+b)\pi}\right)$$

With Some algebra:

$$C_n^{j,j+b} = 2\left|C_n^j\right| e^{-i\frac{n-b}{b}(j-1+\frac{b}{2})\pi} cos\left(\frac{n-b}{2}\pi\right)$$

$$cos\left(\frac{n-b}{2}\pi\right) = 0 \longrightarrow n = b+1\pm 2l \quad \text{with} \quad l = 0,1,2...$$

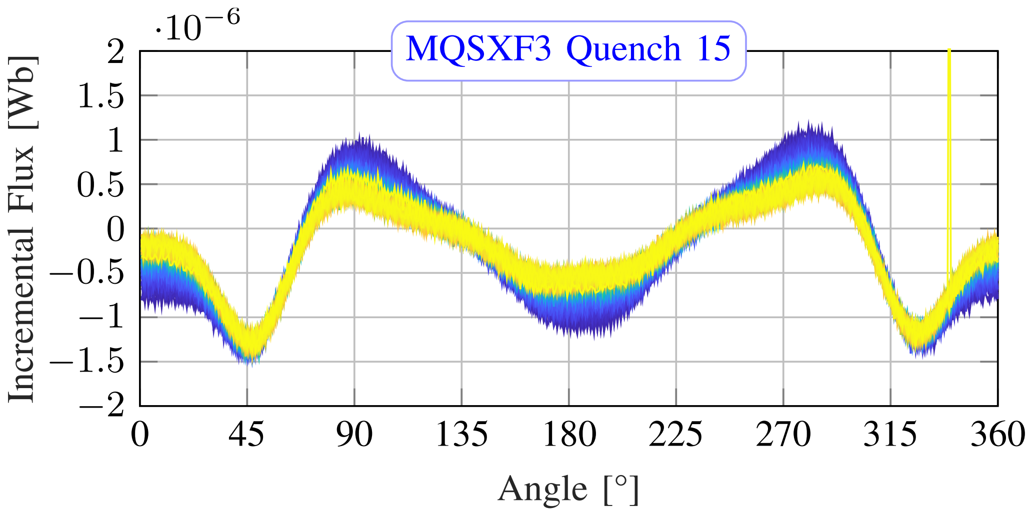
Harmonic Content Comparison

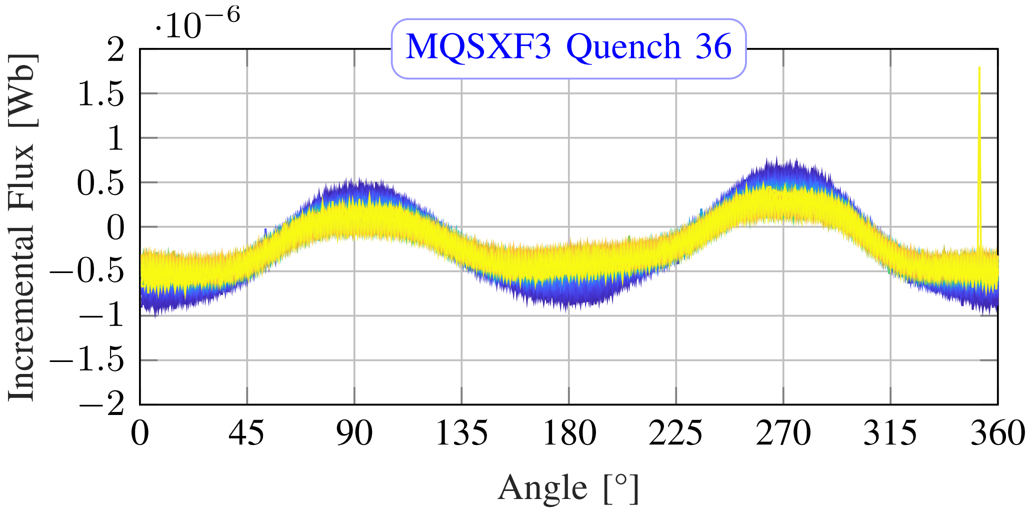


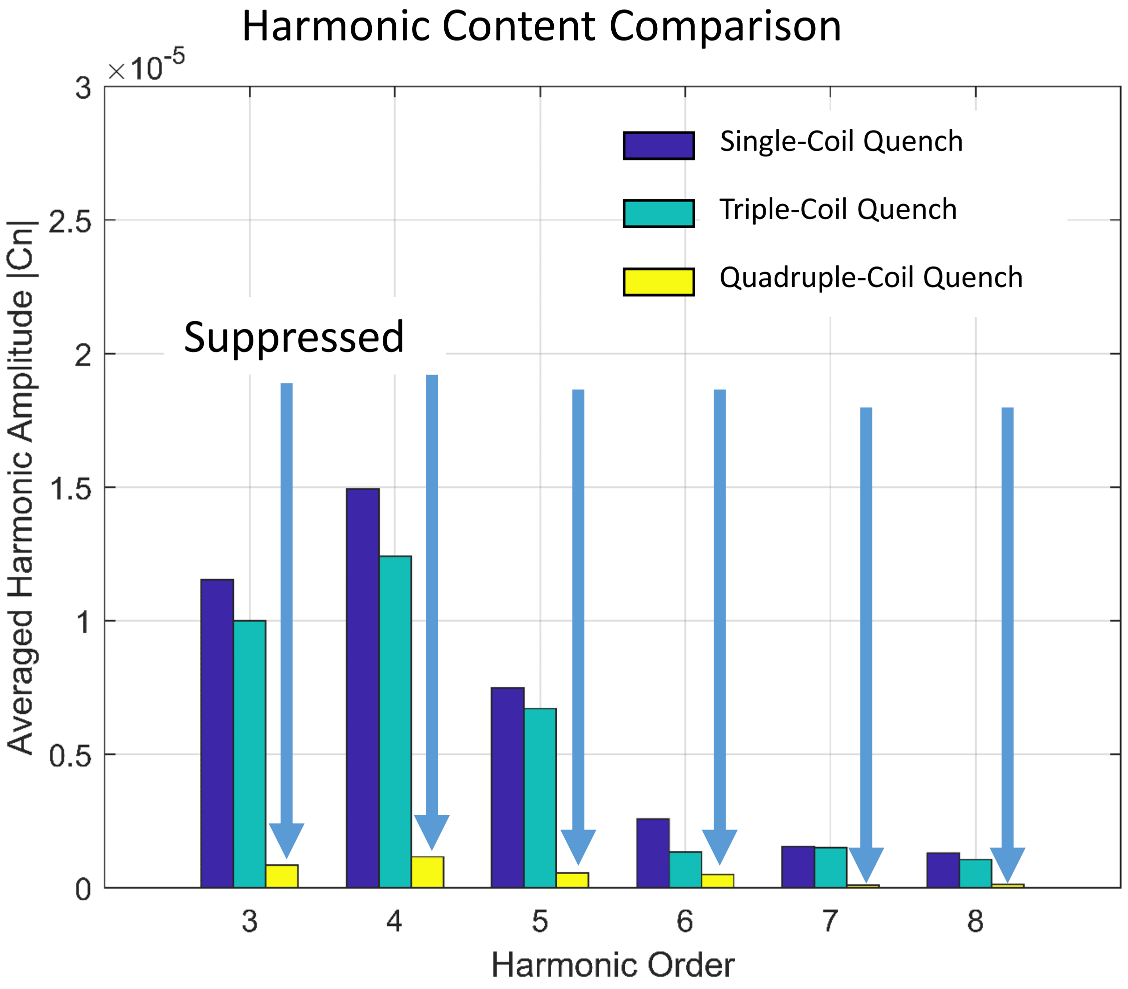
$$2\left|cos\left(\frac{4-2}{2}\pi\right)\right| = 2$$

Amplification

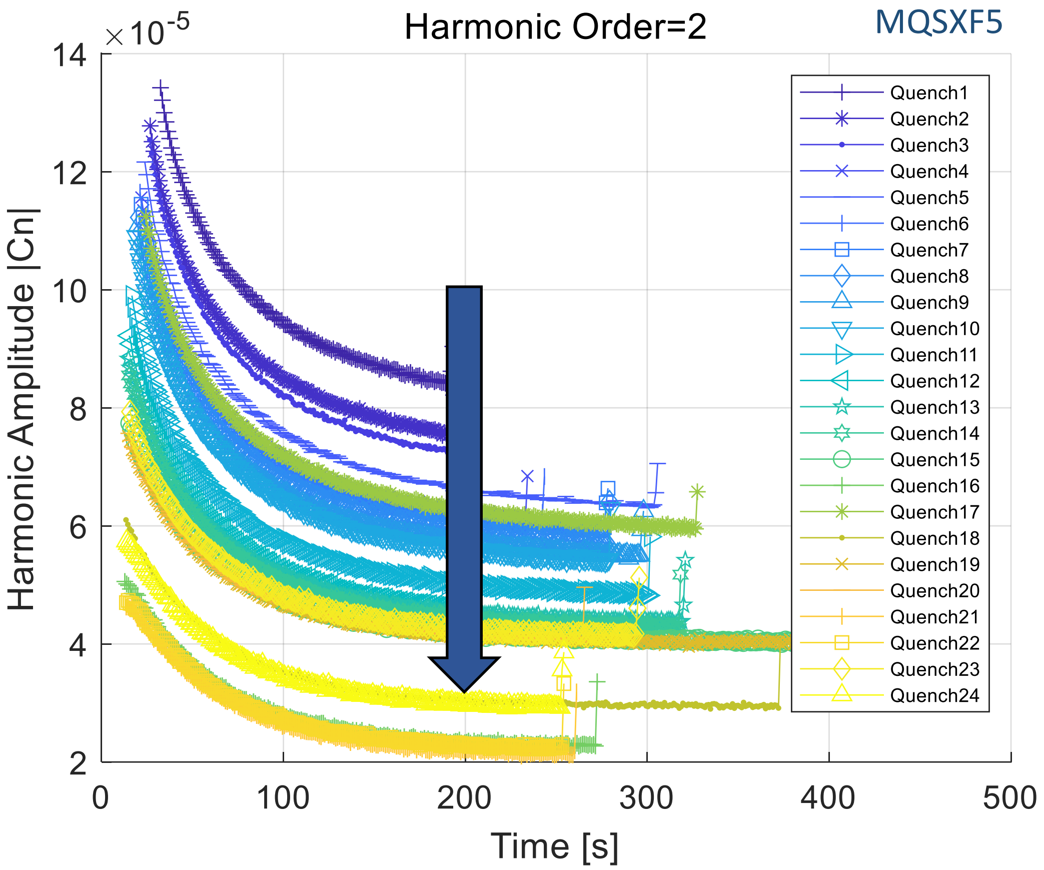
Multi-Coil Quench – 3 and 4Coils

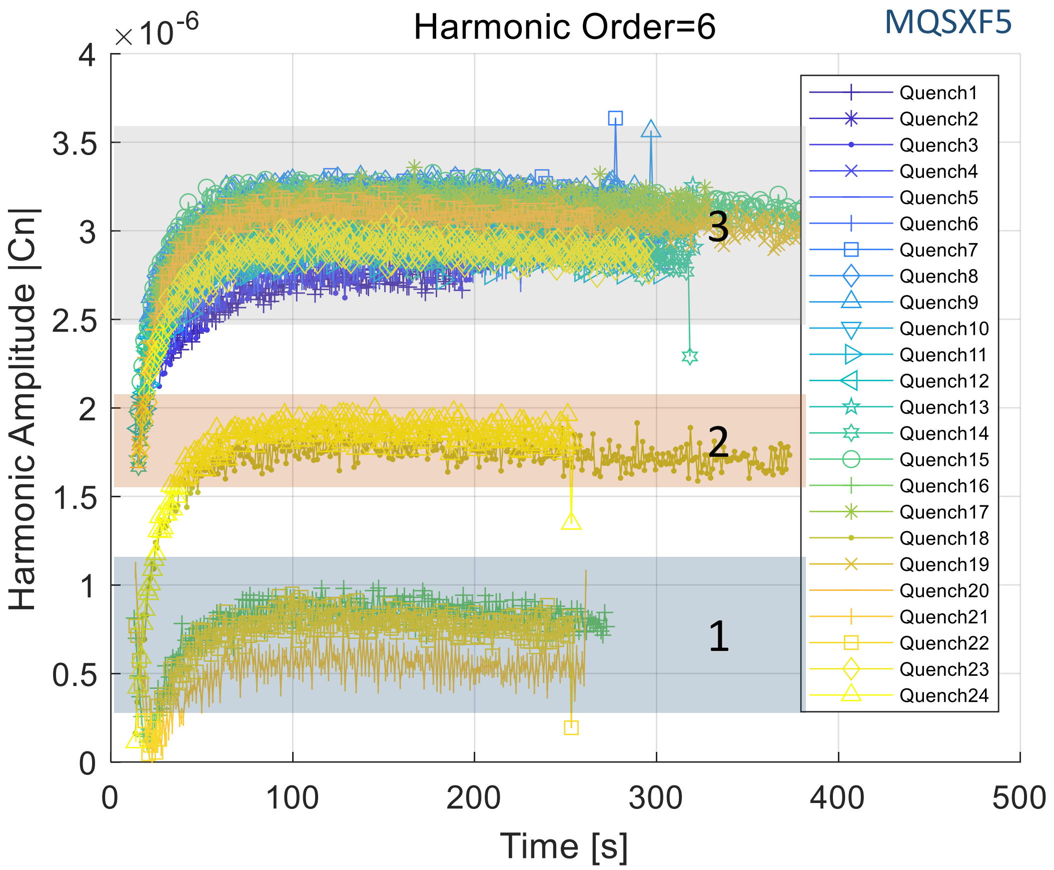






Time Dependance

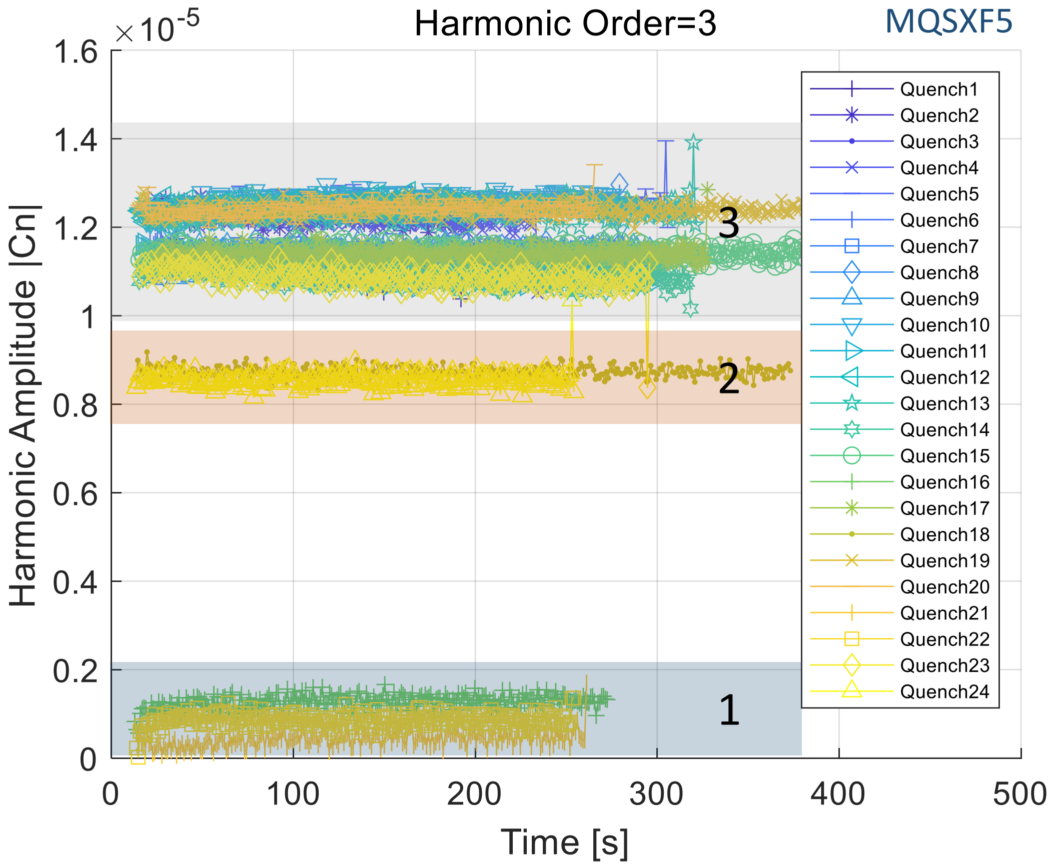


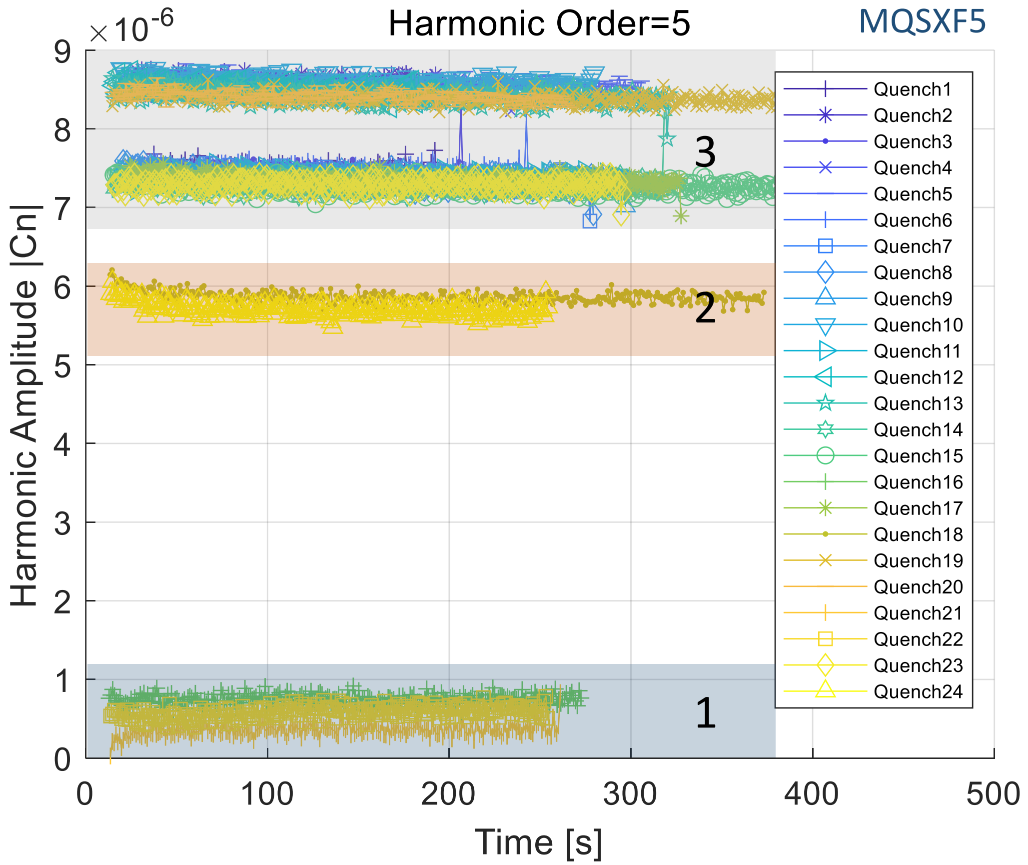


- Main allowed harmonics depends from time after quench event
  - Time Constant: order of 100 seconds!!!
  - Iron Magnetization Relaxation
    (Current decay rate dependenance)

- Three Main Regions of Amplitude
  1. All Quenched Coils
  2. Three Quenched Coils
  3. One Quenched Coil

Time Dependance





- Three Main Regions of Amplitude
  1. All Quenched Coils
  2. Three Quenched Coils
  3. One Quenched Coil

- Not-allowed harmonics DO NOT depend from time after the quench event

Conclusions

1. Developed an innovative method for quench localization
   - Based on magnetic measurent of the harmonic content produced by the residual superconductor magnetization after the quench event
2. Both analytical and FEM model are able to reconstruct exactly the quenched coil
   - Unique Reconstruction using phase of the $n = b \pm 1$ harmonic field component
3. All 150 Quench Events analyzed and reconstructed
   - Very good agreement between QDS Va/Vb signal and magnetic measurement
4. Improved diagnostic system for magnet performances during series production phase
5. Experimental evidence of multi-coil quench in the skew quadrupole training
   - Developed model is able to reconstruct these events too
   - Evidence of allowed harmonics time dependance due iron residual magnetization relaxation

INFN LASA

UNIVERSITÀ DEGLI STUDI DI MILANO
FACOLTÀ DI SCIENZE E TECNOLOGIE

HiLumi HL-LHC PROJECT

Thank you for the Attention

LASA TEAM

F. Broggi, E. De Matteis, S. Mariotto, A. Paccalini, A. Palmisano, A. Pasini, D. Pedrini, A. Leone, M. Prioli, L. Rossi, M. Sorbi, S. Sorti, M. Statera, M. Todero, C. Uva, R. Valente