FUTURE
CIRCULAR
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The FCC-ee Final Focus quadrupole prototype

M. Koratzinos

12/6/2024

Massachusetts
Institute of
Technology

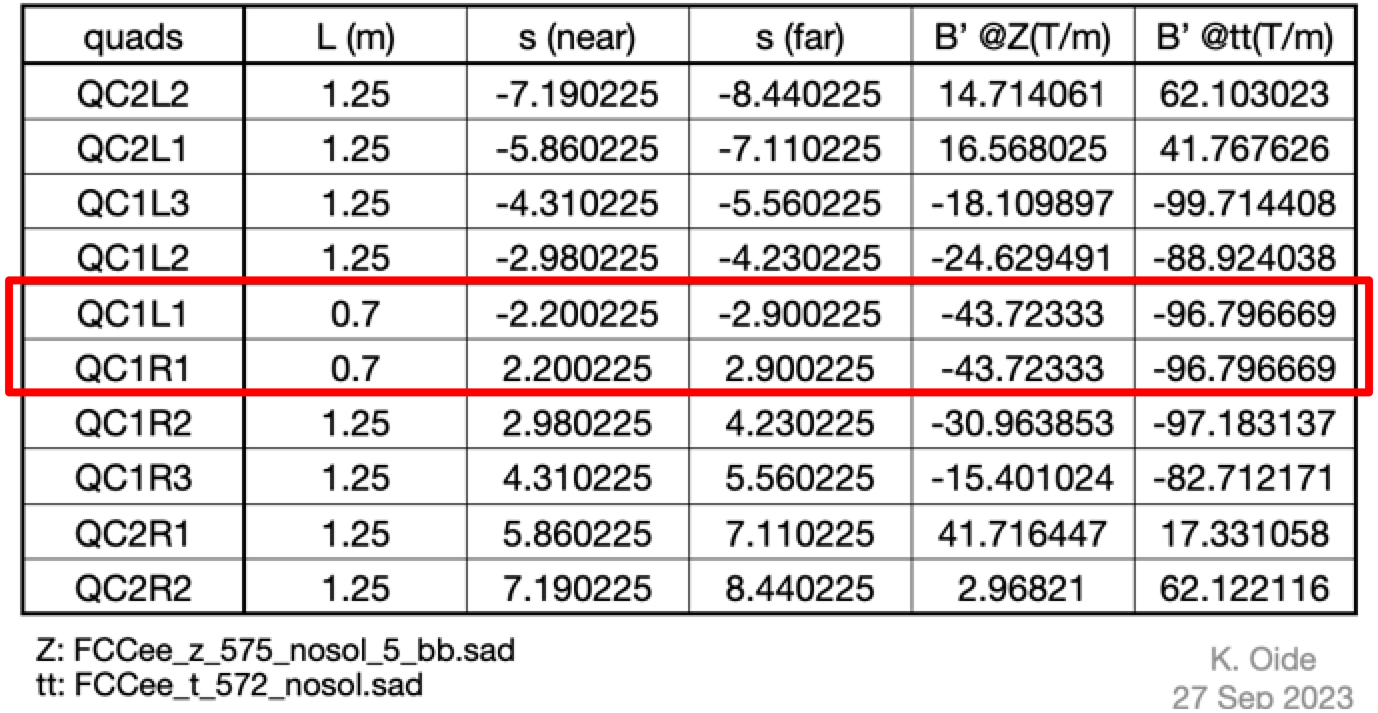
PAUL SCHERRER INSTITUT

Acknowledgements

- For the design: Glyn Kirby, Jeroen van Nugteren (author of Field)
- Manufacturing: the CERN main workshop, Karol Scibor
- Bits and pieces: the B927 boys, Pierre-Antoine Contat, Jacky Mazet
- Winding and assembly: Herman ten Kate’s team in B180, Tim Mulder
- Special tools manufacturing: the CMS workshop in P5, Maf Alidra
- Warm testing: the B311 boys Carlo Petrone, Melvin Liebsch, Dmitry Akhmedyanov, Stefano Sorti
- Impregnation: Michael Daly, Colin Müller, Jaap Kosse, Daniel Barna
- SM18 cold testing: Gerard Willering, Jerome Feuvrier, Adrien Thabuis
- This work would not have been possible without the support of many people. I would like to especially thank Austin Ball, Katsunobu Oide, Frank Zimmermann, Guenther Dissertori, Michael Benedikt

The final focus system of FCC

- Three quadrupoles in a cryostat inside the detector (QC1)
- Two more (QC2) outside the detector
- QC1L1, closest to the IP, is the toughest challenge
  - Distance at tip from the other beam is 66mm
  - Distance at the other tip is 87mm
- There are packaging and integration issues – very little space!



quads	L (m)	s (near)	s (far)	B' @Z(T/m)	B' @tt(T/m)
QC2L2	1.25	-7.190225	-8.440225	14.714061	62.103023
QC2L1	1.25	-5.860225	-7.110225	16.568025	41.767626
QC1L3	1.25	-4.310225	-5.560225	-18.109897	-99.714408
QC1L2	1.25	-2.980225	-4.230225	-24.629491	-88.924038
QC1L1	0.7	-2.200225	-2.900225	-43.72333	-96.796669
QC1R1	0.7	2.200225	2.900225	-43.72333	-96.796669
QC1R2	1.25	2.980225	4.230225	-30.963853	-97.183137
QC1R3	1.25	4.310225	5.560225	-15.401024	-82.712171
QC2R1	1.25	5.860225	7.110225	41.716447	17.331058
QC2R2	1.25	7.190225	8.440225	2.96821	62.122116

Z: FCCee_z_575_nosol_5_bb.sad
tt: FCCee_t_572_nosol.sad

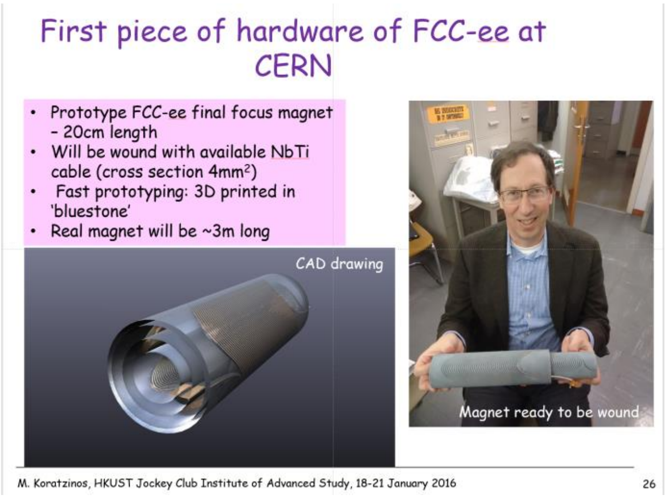
K. Oide
27 Sep 2023

QC1L1

- The quad closest to the IP (and closest to its neighbour)
- Length 700mm
- Strength 100T/m
- Inner diameter of the beam pipe: 30mm
- A CCT prototype was constructed in 2019
  - Length 420mm
  - Aperture 40mm
  - Strength 100T/m
  - Conductor: NbTi (8X0.825mm LHC strand)
  - Temperature: 1.9K (superfluid He)

FF quad prototype over the years in conferences

2016



First piece of hardware of FCC-ee at CERN

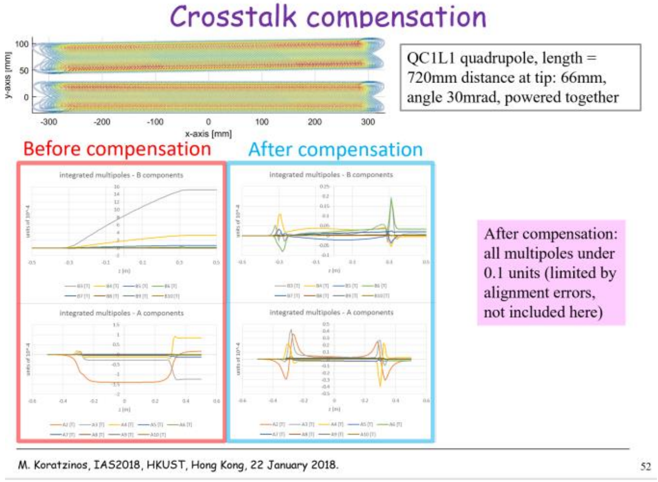
- Prototype FCC-ee final focus magnet – 20cm length
- Will be wound with available NbTi cable (cross section 4mm^2)
- Fast prototyping: 3D printed in 'bluestone'
- Real magnet will be ~3m long

CAD drawing

Magnet ready to be wound

M. Koratzinos, HKUST Jockey Club Institute of Advanced Study, 18-21 January 2016 26

2018



Crosstalk compensation

QC1L1 quadrupole, length = 720mm distance at tip: 66mm, angle 30mrad, powered together

Before compensation

After compensation

After compensation: all multipoles under 0.1 units (limited by alignment errors, not included here)

M. Koratzinos, IAS2018, HKUST, Hong Kong, 22 January 2018. 52

2019

Prototype fully machined and anodized

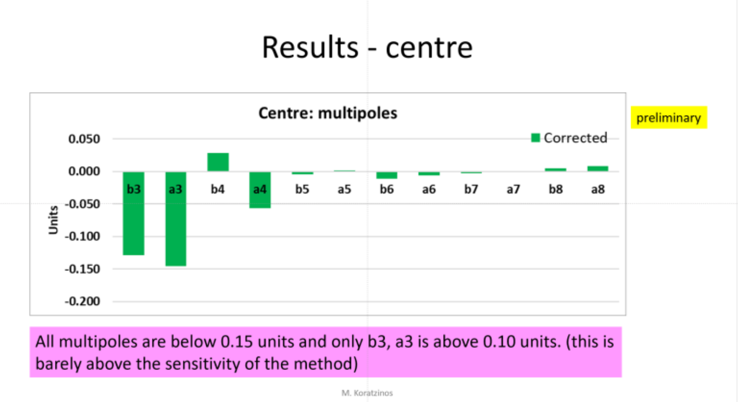
M. Koratzinos, FCC-ee MDI, IAS HKUST 2019 31

2020

Winding process

M. Koratzinos, IAS 2020

2021



Results - centre

All multipoles are below 0.15 units and only b3, a3 is above 0.10 units. (this is barely above the sensitivity of the method)

M. Koratzinos

Progress has been reported every year: interesting to see the project from the concept stage to fruition

How to eliminate crosstalk?

- Using iron to shield the two apertures gives significant field imperfections (close to 50 units @10mm)
- Non-linearities are ~4 units
- Using a different method to correct for the fringe fields of adjacent magnets seems preferable
- This is the approach of FCC.
- We are using a CCT quadrupole which has offending multipoles removed by design.
- This is an iron-free design with the added benefit of having no non-linearities.

The FCC-ee CDR solution

- Use CCT technology and NbTi conductor
- CCT was used as it can eliminate crosstalk
- NbTi was used as it was proven technology at the time
- To get the 100T/m gradient needed, we need to operate at 1.9K (superfluid helium)

The FF quad prototype

- A final focus quad prototype was built in 2019 and tested at warm.
- The prototype was impregnated with wax at PSI (August 2023)
- During October 2023 it was tested at CERN’s SM18 facility at 1.9K and 4.5K

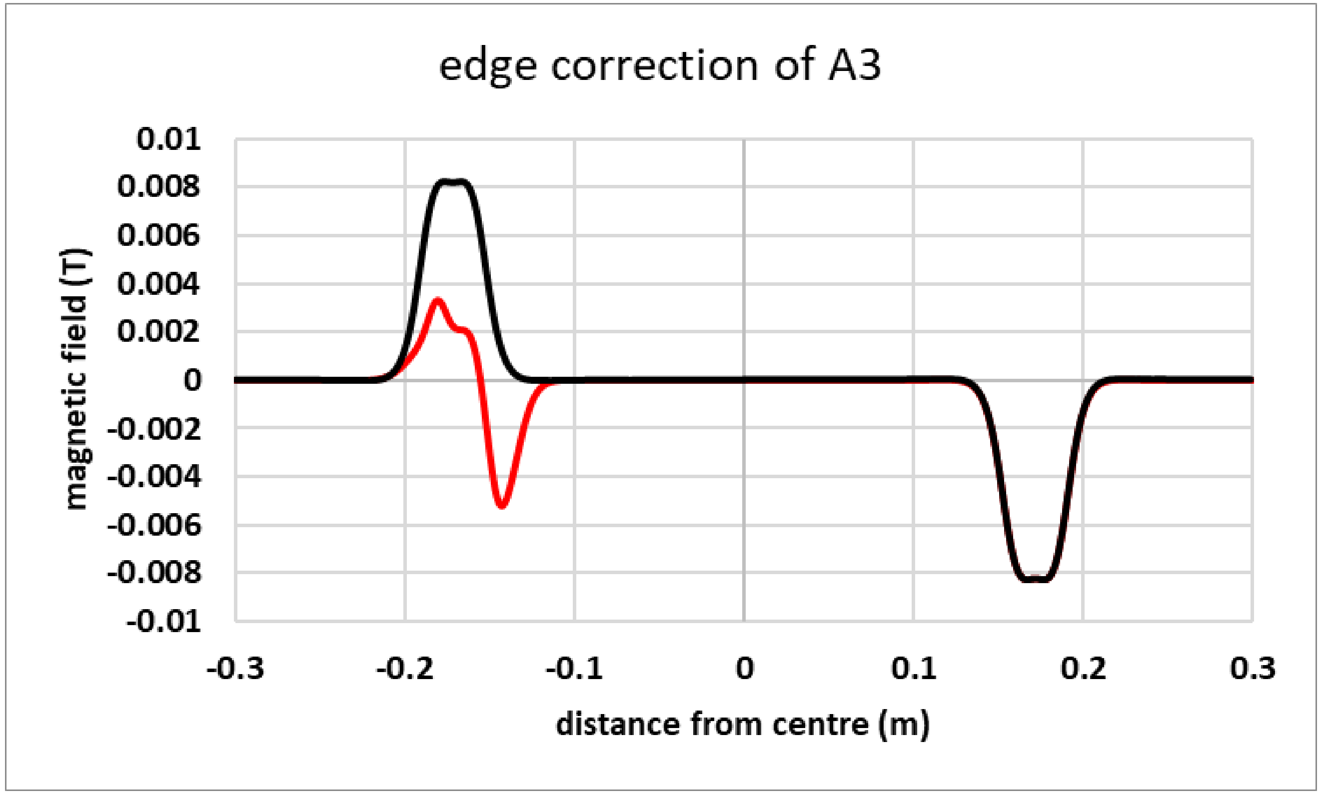
Design

- Was done in-house using the FIELD suite of programs
- Mechanical design done in Autodesk Inventor

Local edge correction

- By design, a CCT magnet has all integral multipoles vanish (with the exception of the main one).
- However, the skew (A) components of the magnetic field compensate only because they have opposite signs at the entry and exit of the magnet.
- QC1L1 sits in an area of rapidly-changing optics functions: the change of beam size between the entry and exit of the magnet is a factor of ~2. ➔ a local correction is preferable
- **The mathematics of local edge correction are identical to crosstalk compensation**

Example: correction of A3 component, one side only. In red: corrected; in black: uncorrected



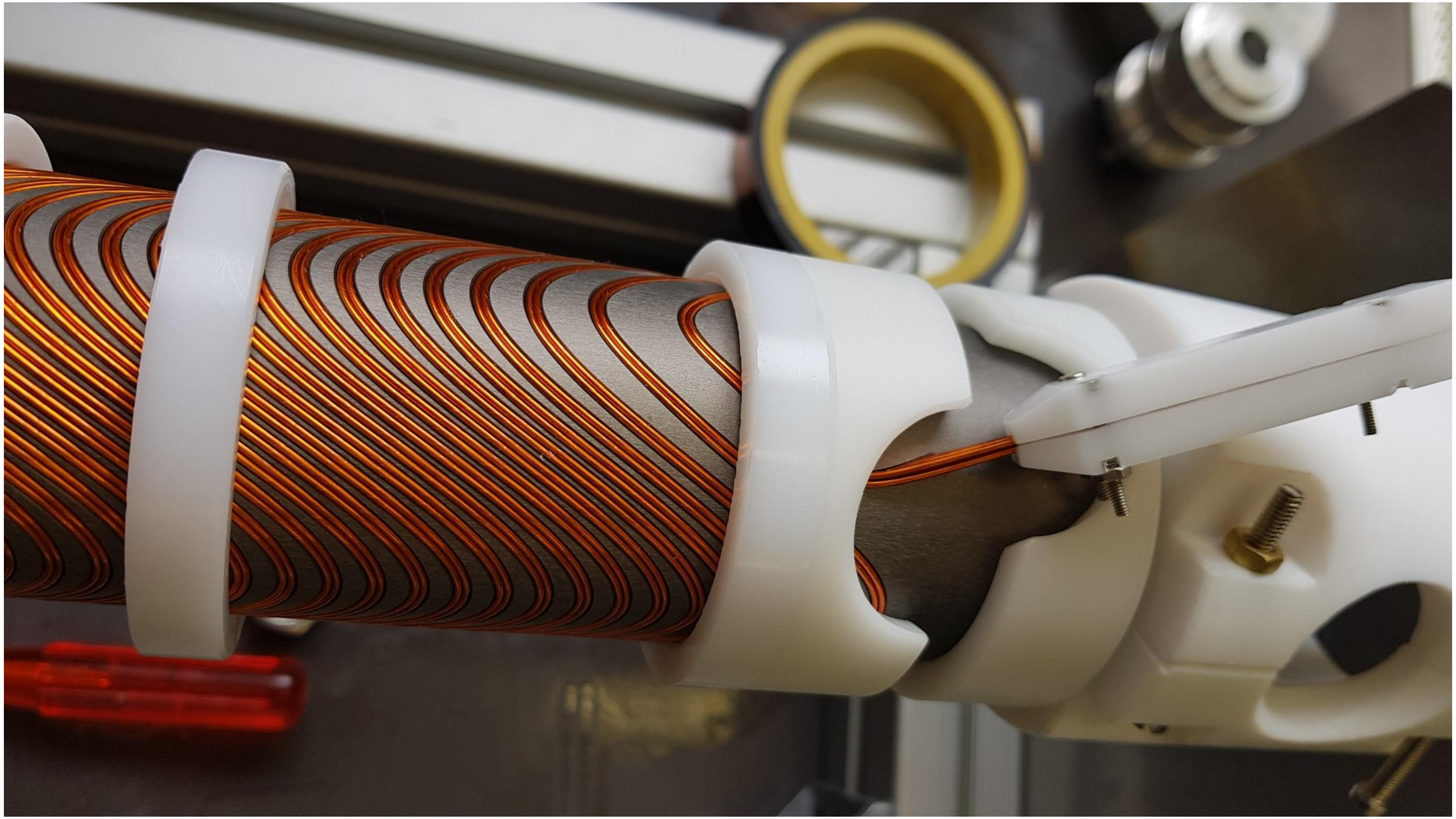
M. Koratzinos et al.1709.08444 [physics.acc-ph]

Manufacturing

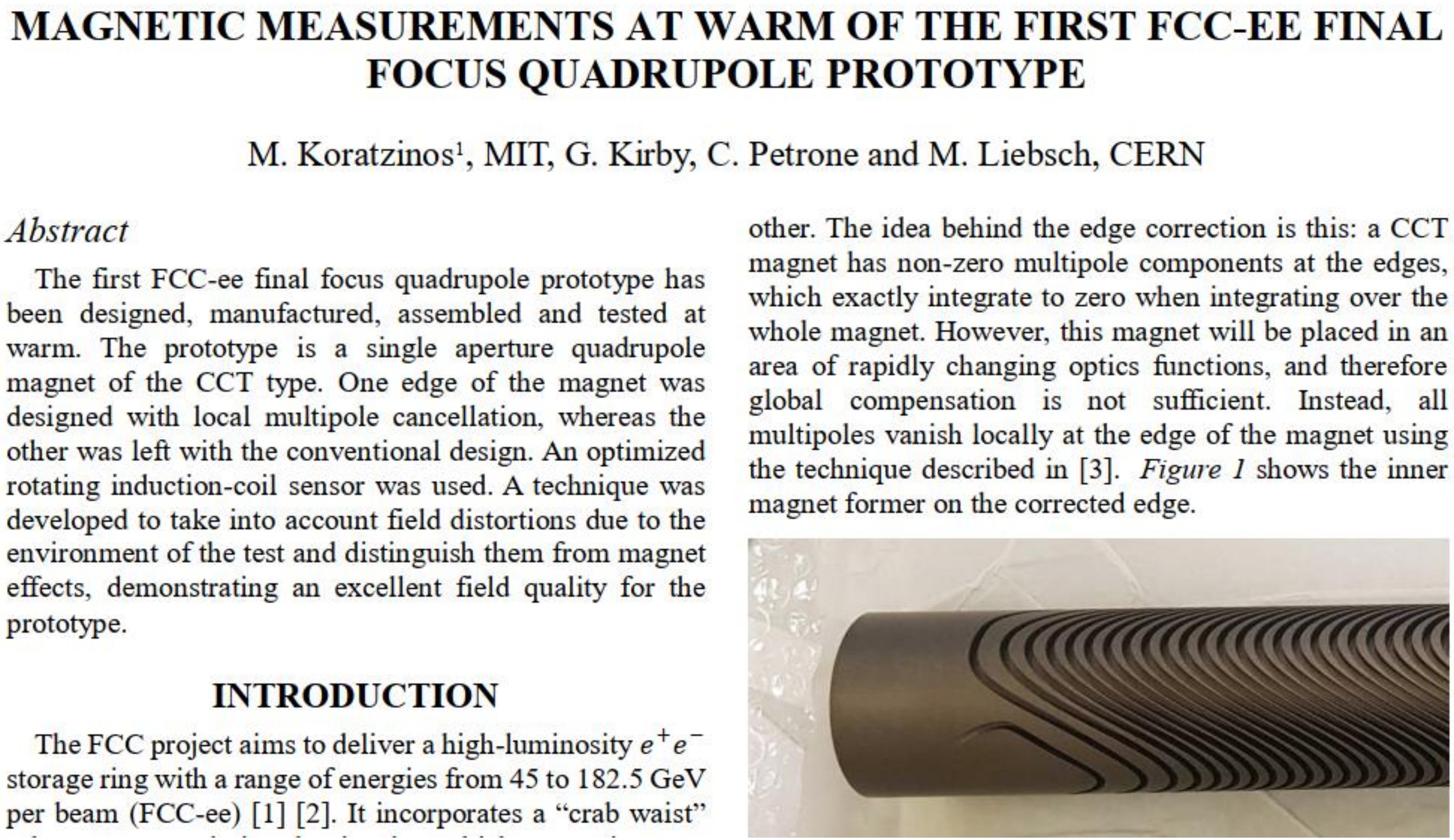
- Was done at the main CERN workshop. Material: Aluminium 6082-T6, hard-anodized

winding

Done in-house using standard LHC 0.825 NbTi strand



IPAC21 paper – measurements at warm



MAGNETIC MEASUREMENTS AT WARM OF THE FIRST FCC-EE FINAL FOCUS QUADRUPOLE PROTOTYPE

M. Koratzinos[1], MIT, G. Kirby, C. Petrone and M. Liebsch, CERN

Abstract

The first FCC-ee final focus quadrupole prototype has been designed, manufactured, assembled and tested at warm. The prototype is a single aperture quadrupole magnet of the CCT type. One edge of the magnet was designed with local multipole cancellation, whereas the other was left with the conventional design. An optimized rotating induction-coil sensor was used. A technique was developed to take into account field distortions due to the environment of the test and distinguish them from magnet effects, demonstrating an excellent field quality for the prototype.

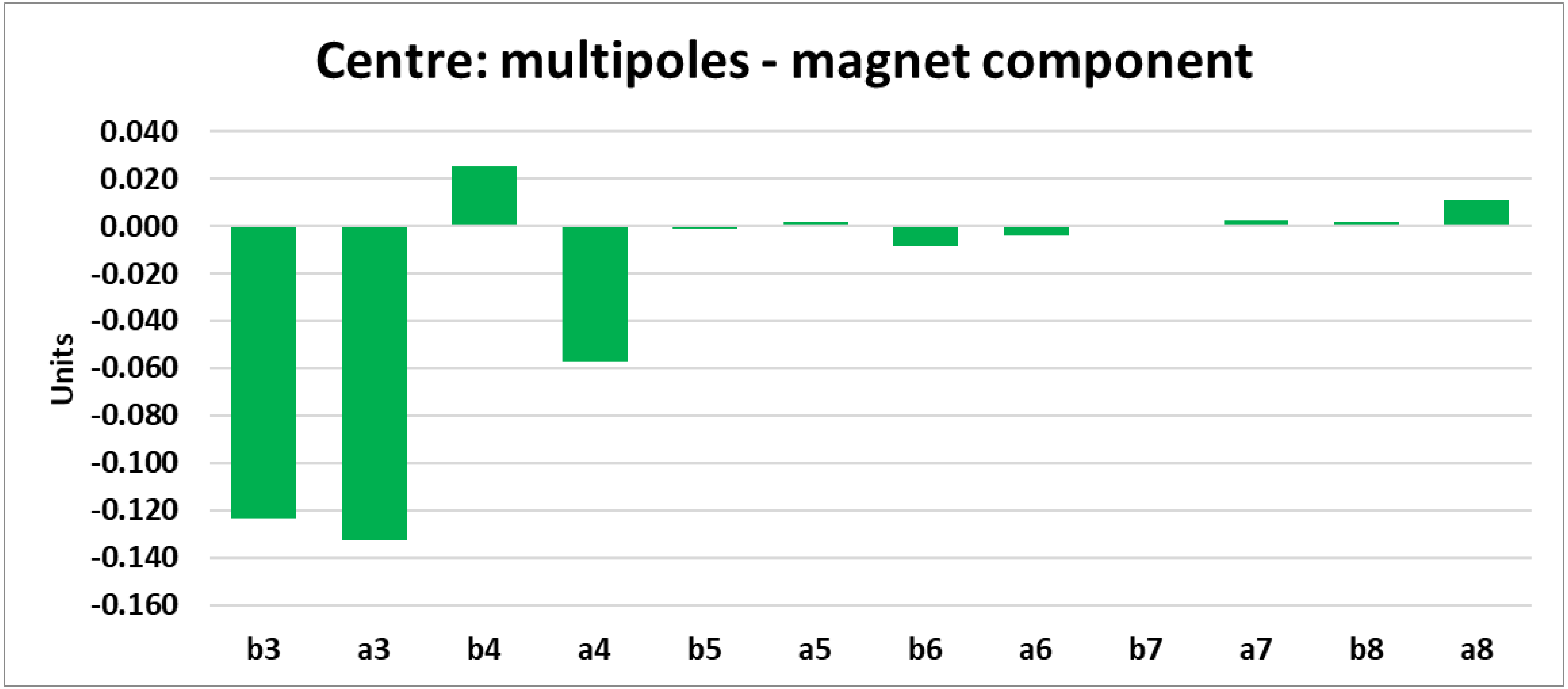
INTRODUCTION

The FCC project aims to deliver a high-luminosity e^+e^- storage ring with a range of energies from 45 to 182.5 GeV per beam (FCC-ee) [1] [2]. It incorporates a "crab waist"

other. The idea behind the edge correction is this: a CCT magnet has non-zero multipole components at the edges, which exactly integrate to zero when integrating over the whole magnet. However, this magnet will be placed in an area of rapidly changing optics functions, and therefore global compensation is not sufficient. Instead, all multipoles vanish locally at the edge of the magnet using the technique described in [3]. *Figure 1* shows the inner magnet former on the corrected edge.

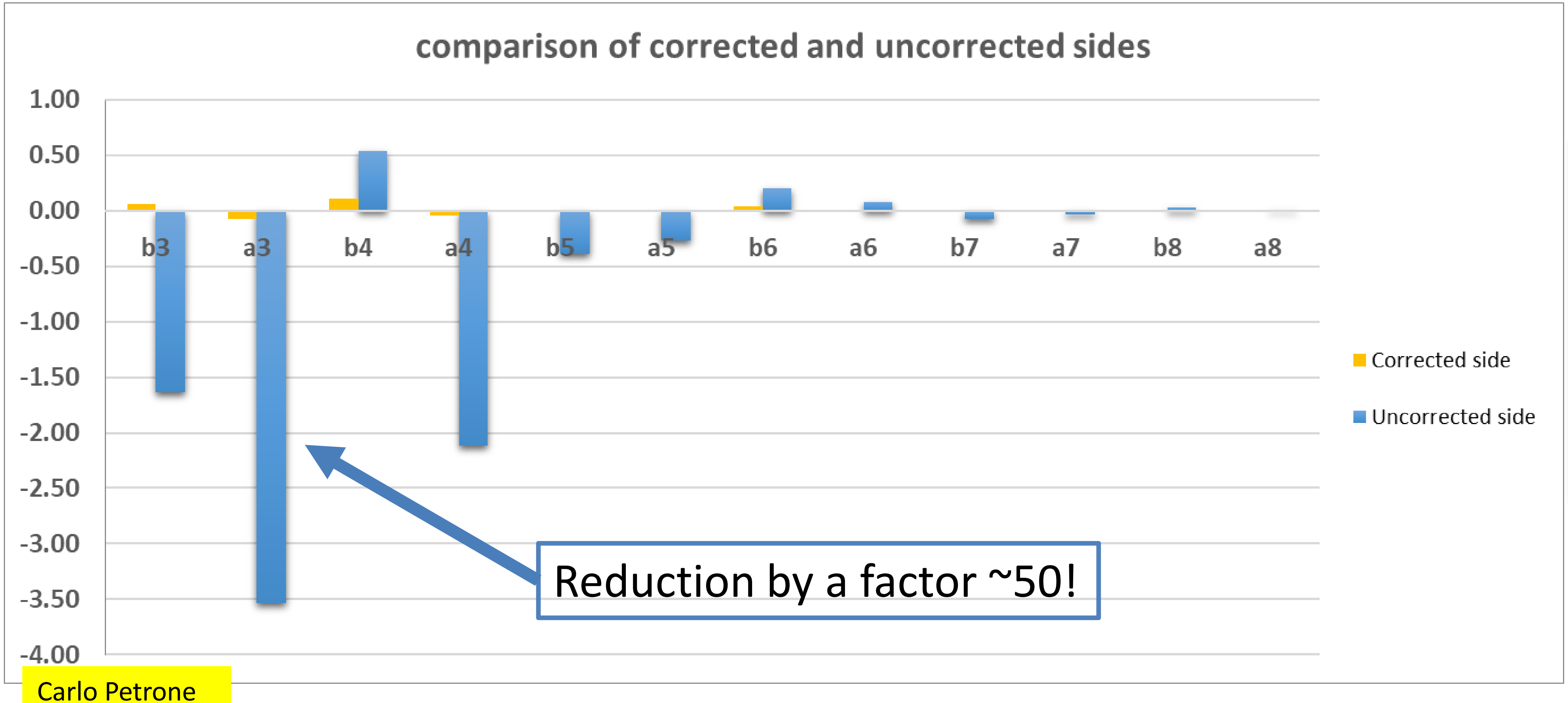
arXiv:2105.13230 **[physics.acc-ph]**

Results - centre



All multipoles are below 0.15 units and only b3, a3 is above 0.10 units. (this is barely above the sensitivity of the method)

Field quality at the edge, comparison



Reduction by a factor ~50!

Carlo Petrone

Corrected side has edge effects that are 0.1 units or less

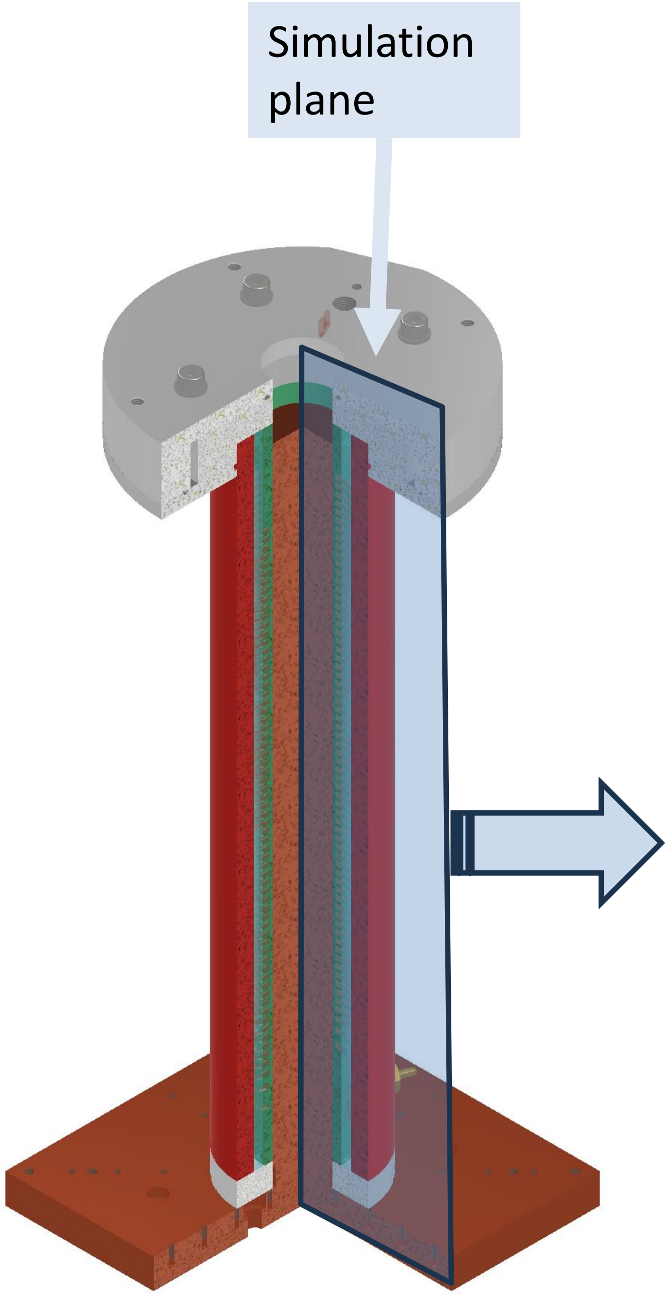
For both plots, the normalization is to the full length of QC1L1 (1200mm)

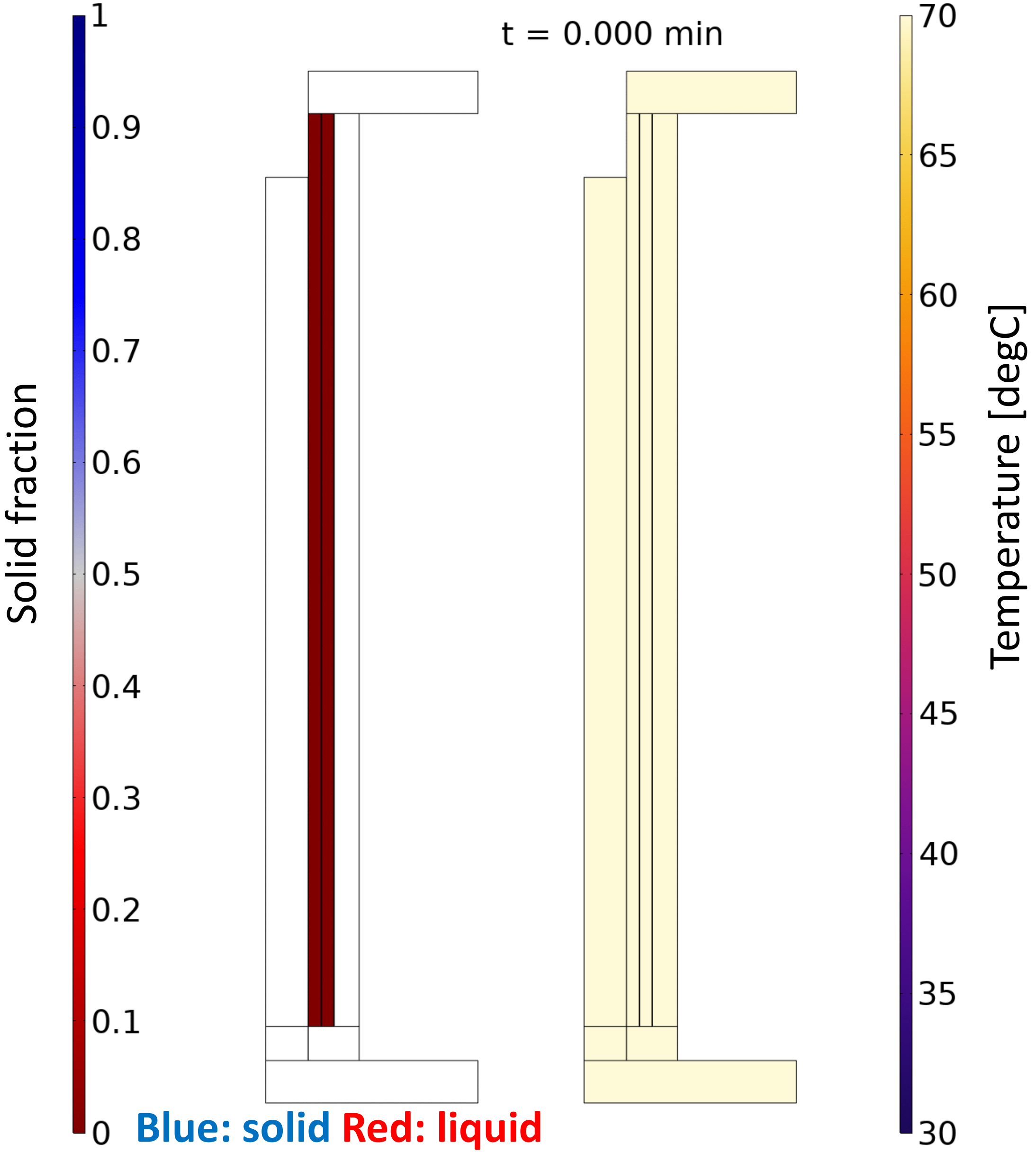
Edge correction really works!

Impregnation

- Wax was chosen for its (expected) performance during quench training
- Wax contracts by 15% when it crystalizes creating voids if no measure is taken
- Voids can be avoided if crystallization occurs in a controlled manner (inner to outer and bottom to top)
- Using the experience gathered by different experts on wax impregnation, a new method was tried: The magnet was impregnated and cooled in a controlled manner at PSI

Simulation





Blue: solid **Red: liquid**

Crystallization range
[51.5,54.5] Celsius

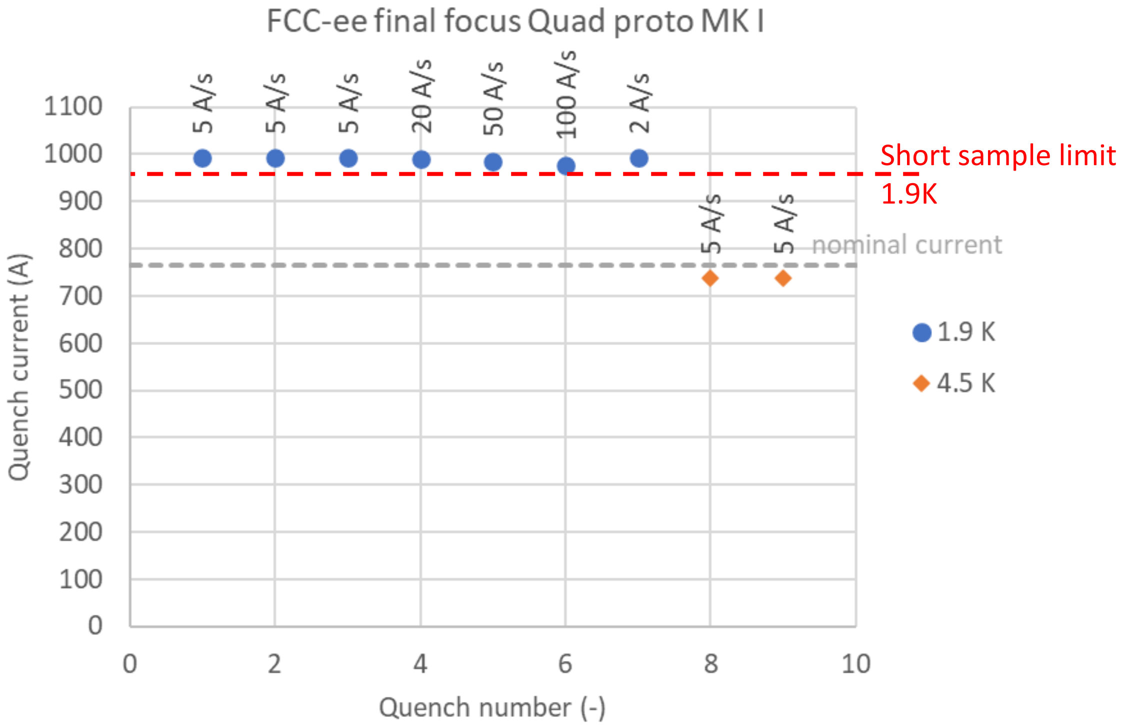
Jaap Kosse


Testing at cold at SM18 (CERN)

The test at SM18

- Cryostat supporting 1.9K superfluid helium
- Training campaign
- Measurement of splice resistance
- Measurement of quenchback
- Measurement of RRR

SM18 Test results Oct 27-31 - Training

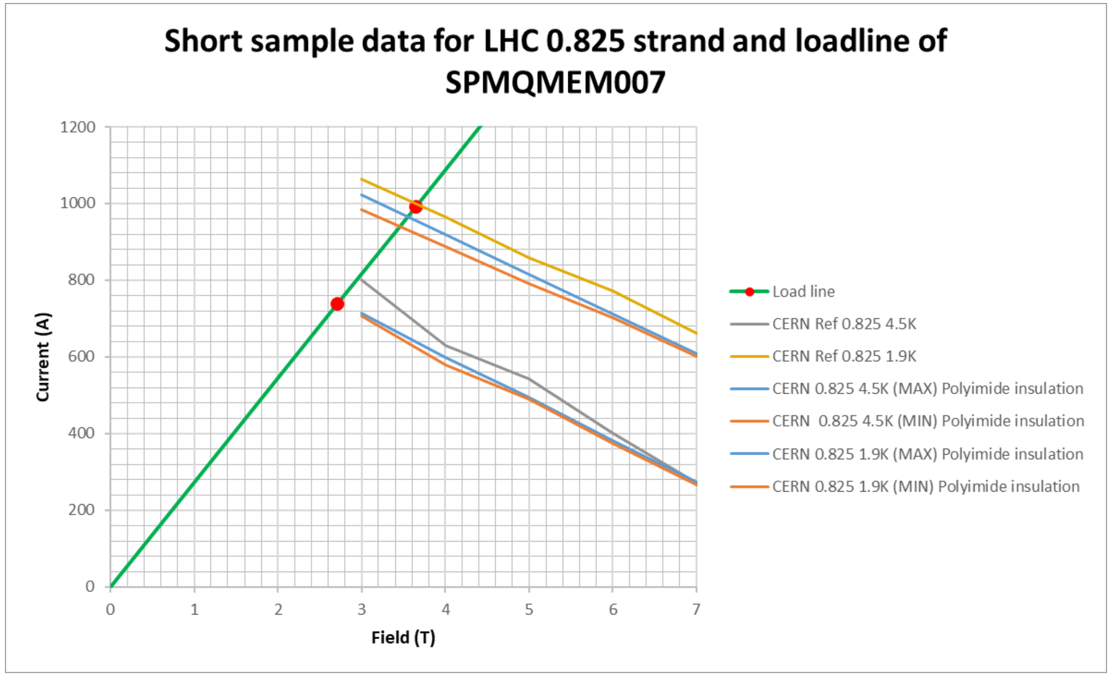


No training quenches were seen up to short sample limit

No degradation was seen for quenches at short sample limit

1.9 K: reached 991 A, peak field on conductor is 3.65 T

4.5 K: reached 738 A, peak field on conductor is 2.71 T



Gradients achieved:

- (Nominal): 100T/m
- Maximum at 1.9K: 130T/m
- Maximum at 4.5T: 96T/m

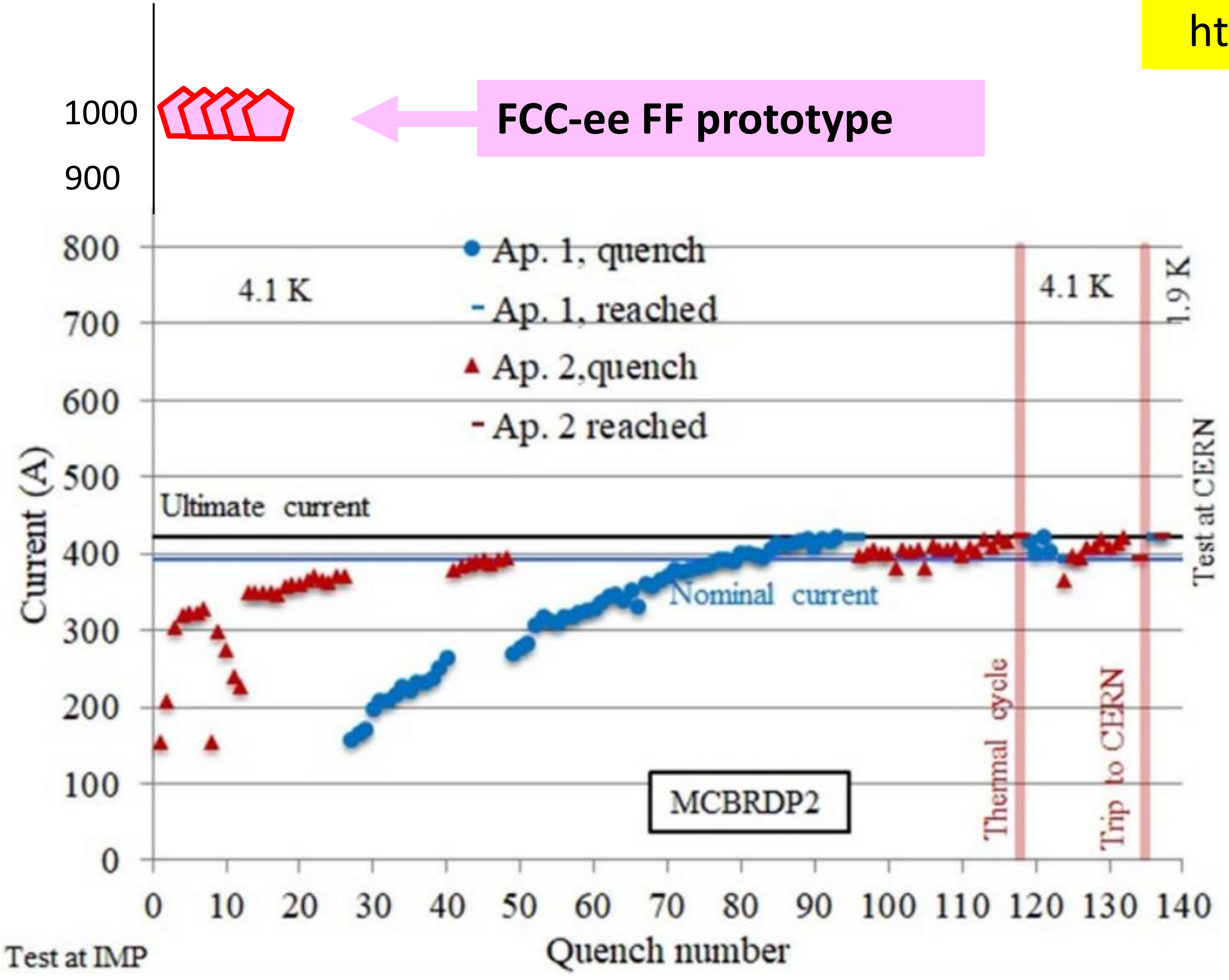
#	T(K)	RR (A/s)	Iquench(A)	Quench location
1	1.9	5	992	Coil 2
2	1.9	5	992	Coil 2
3	1.9	5	992	Coil 2
4	1.9	20	991	Coil 2
5	1.9	50	985	Coil 2
6	1.9	100	977	Coil 2
7	1.9	2	992	Coil 2
8	4.5	5	738	Coil 1
9	4.5	5	737	Coil 1

Test report EDMS https://edms.cern.ch/document/2976492/1

Gerard Willering, Jerome Feuvrier for TE-MSC-TM

Comparison to similar projects

https://iopscience.iop.org/article/10.1088/1361-6668/abdba4/pdf



FCC-ee FF prototype

But note that the MCBRD is a larger magnet!

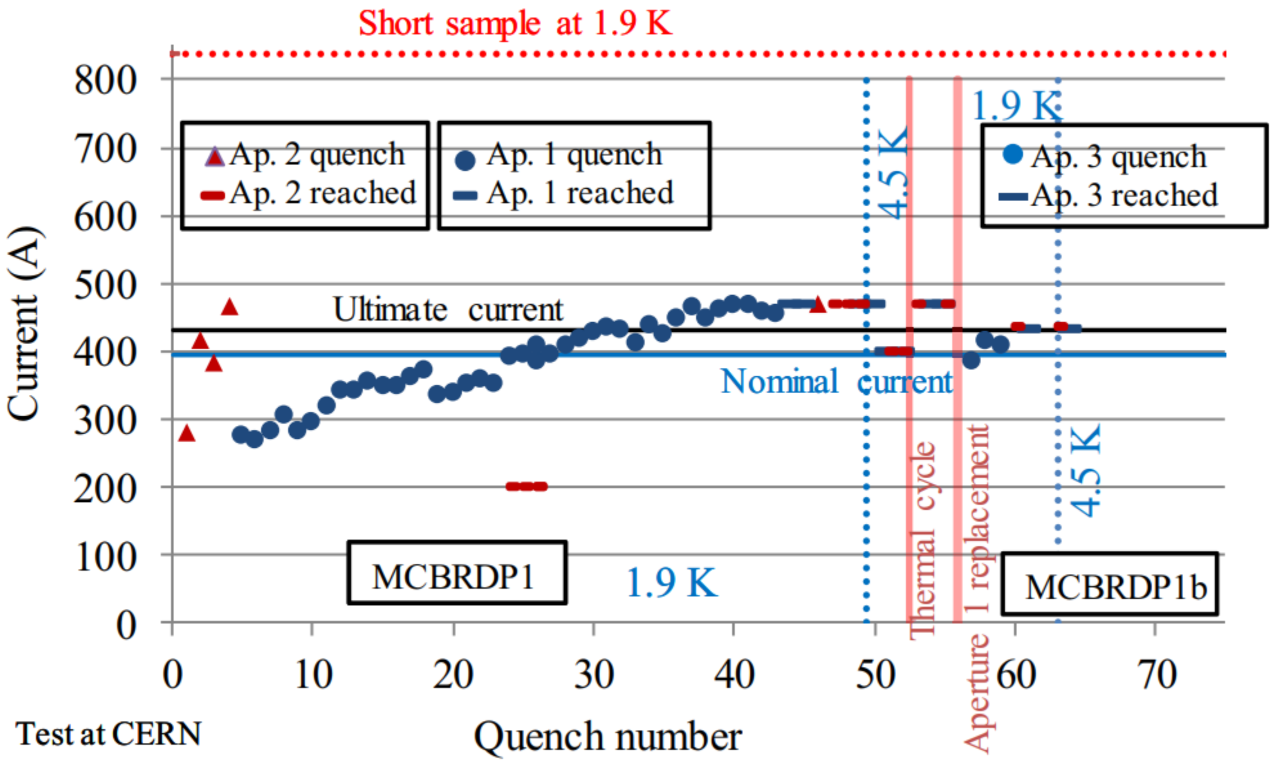


Figure 57. Training performance of D2 corrector first prototype.

Figure 56. Training performance of D2 corrector first prototype.

Chinese-made MCBRD HiLumi dipole corrector

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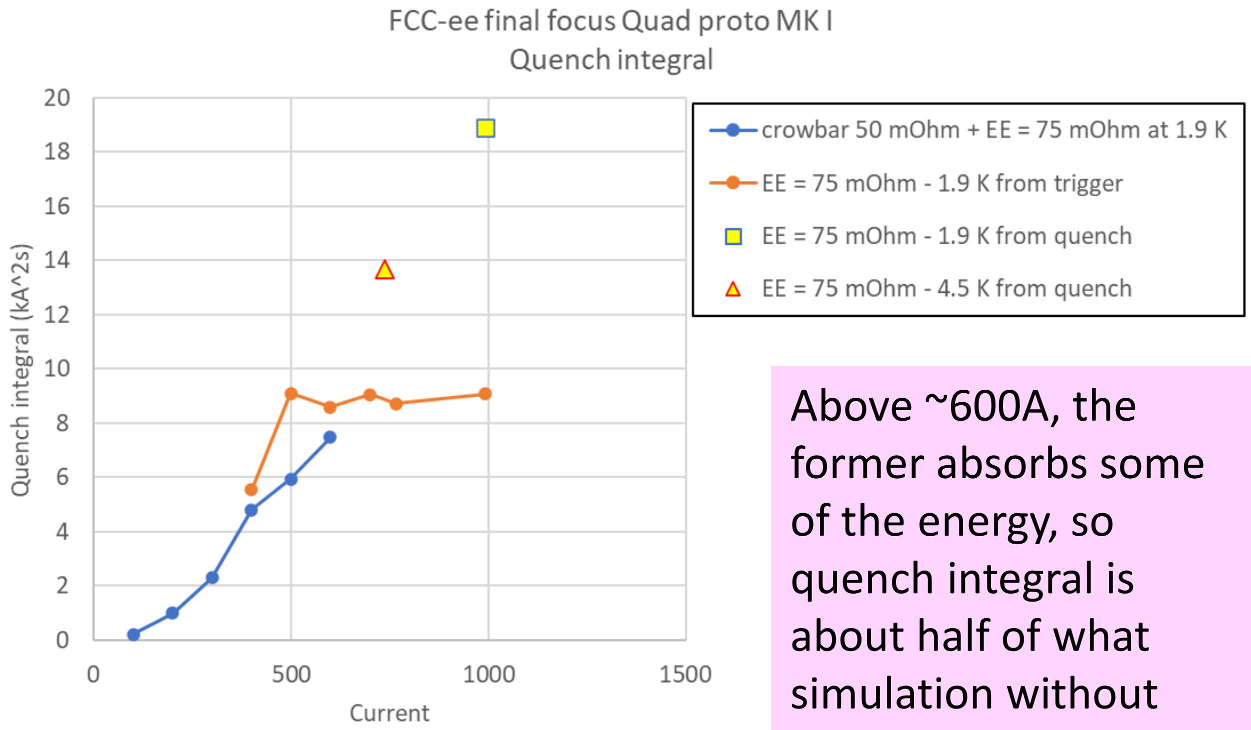
CERN-made MCBRD HiLumi dipole corrector

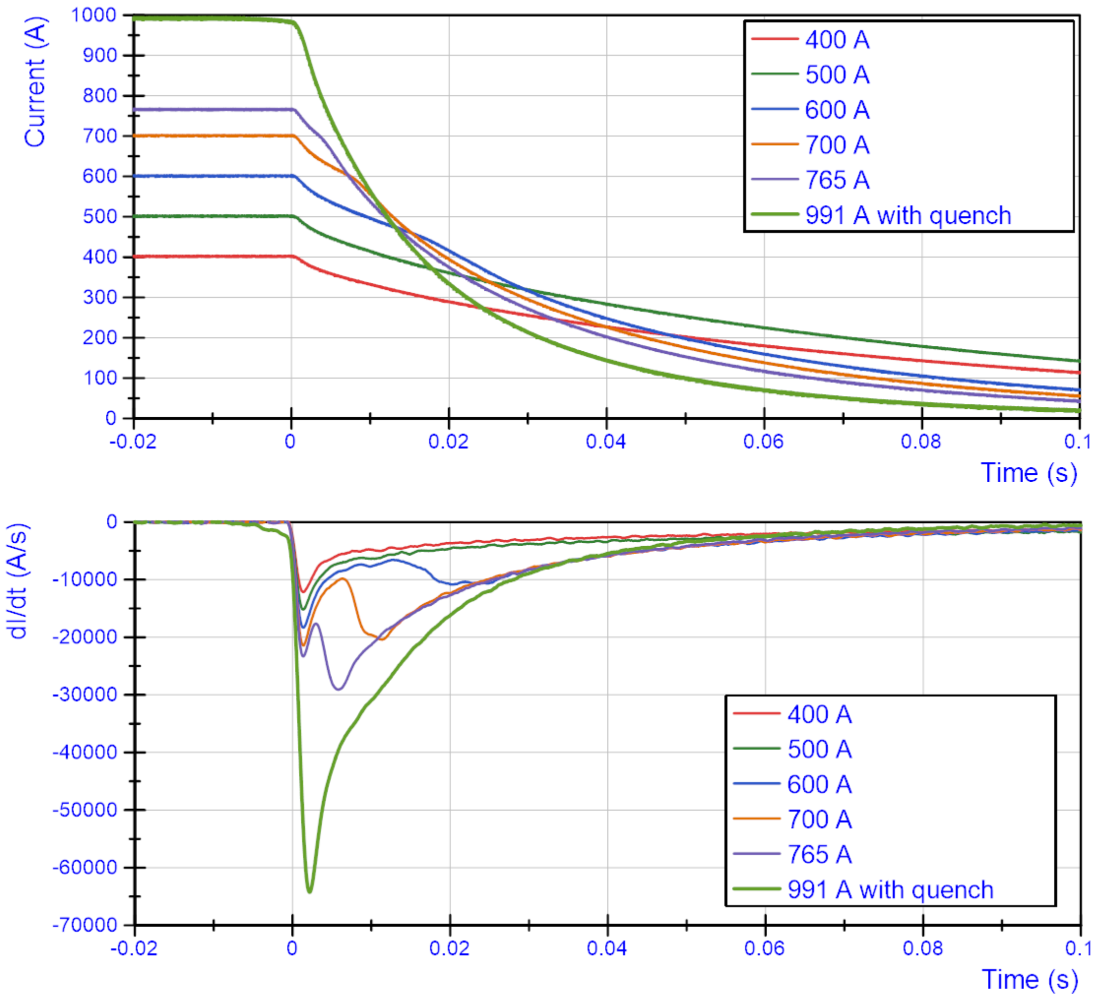
Quench integral and Quenchback



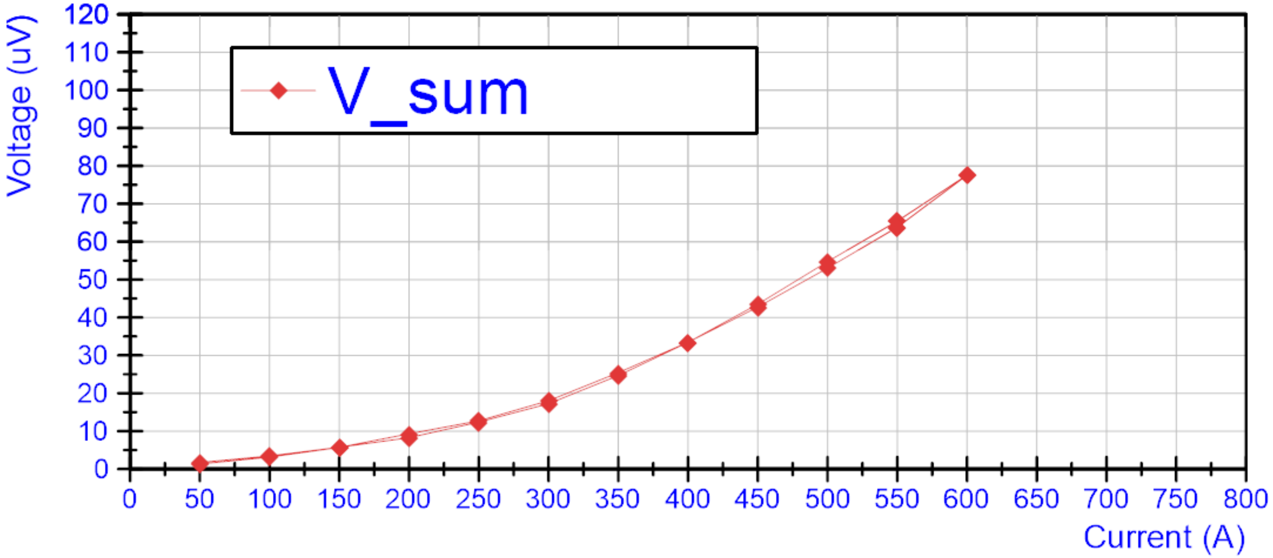
Above ~600A, the former absorbs some of the energy, so quench integral is about half of what simulation without former predicts

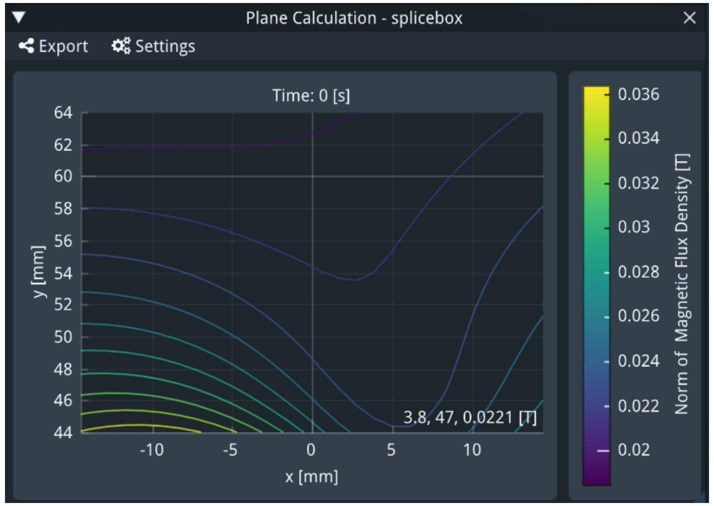
Effects to take into account:

- Quench back starts between 400 and 500 A with 50 mOhm crowbar + 75 mOhm EE.
- Quench back starts between 500 and 600 A for 75 mOhm EE.
- The contribution of the former becomes more important at higher dI/dt. This could explain why the curve is flat above 500 A.

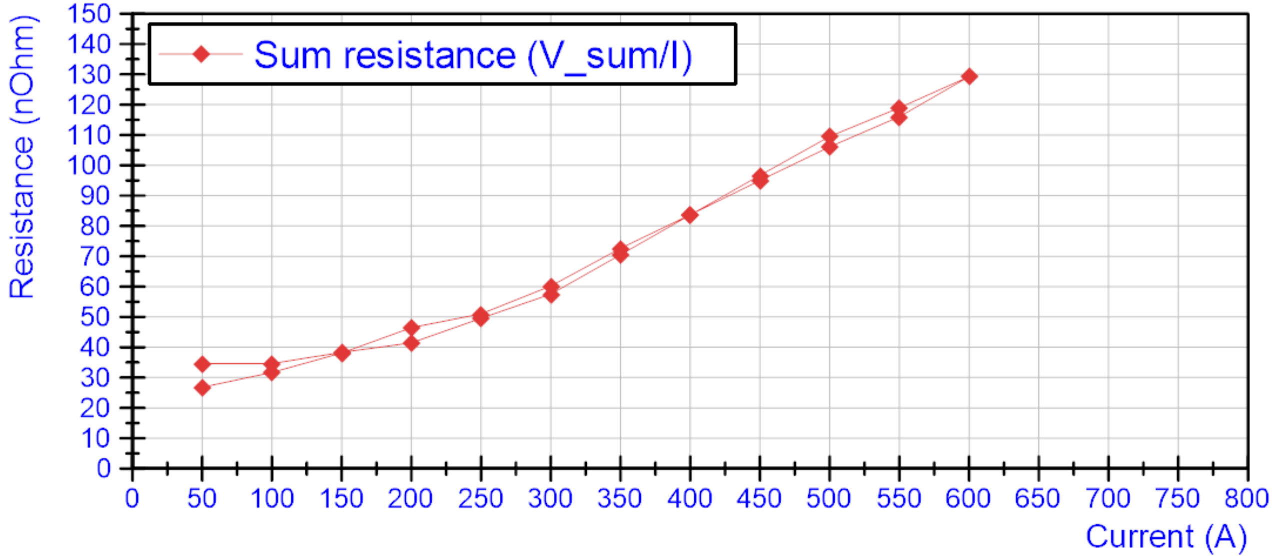


Splice resistance





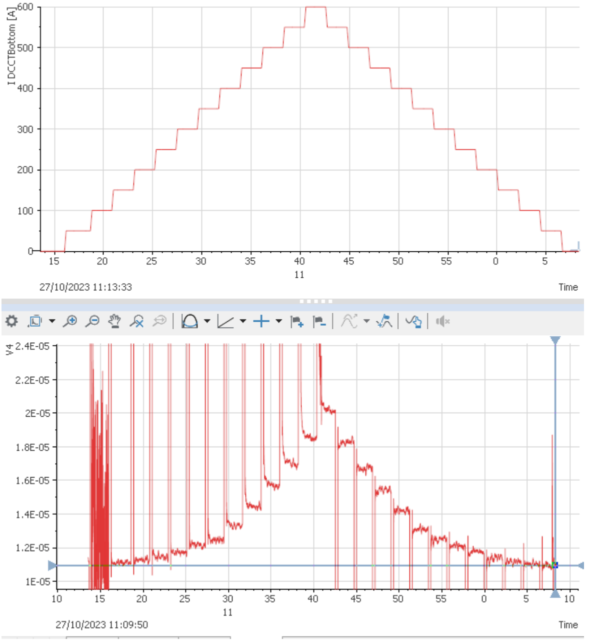
Field at the splice box – around 30mT



nos

Non-linear behaviour due to solder becoming superconducting at lower currents

Example raw data for V4 with non-linear voltage build up

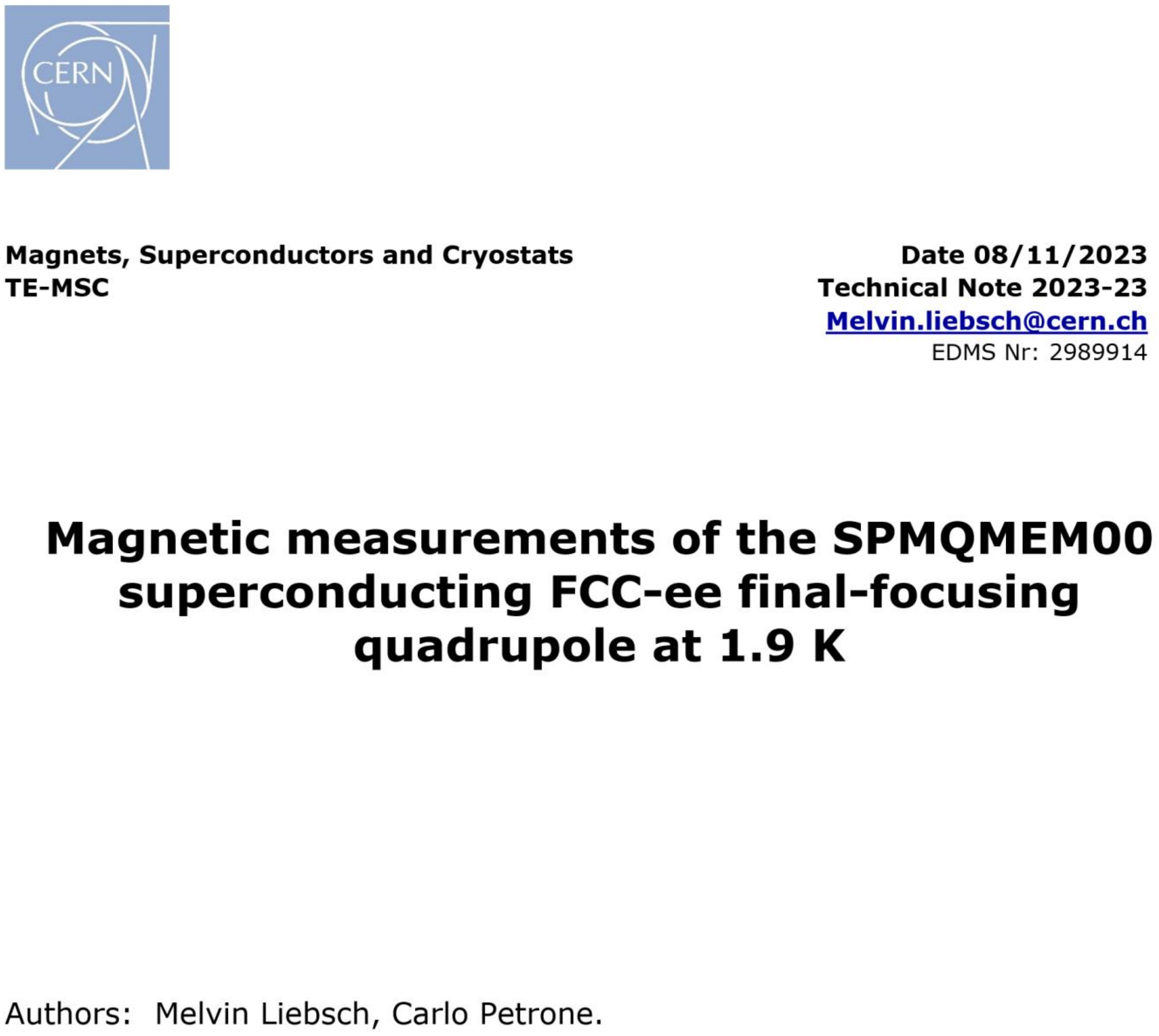


RRR of copper stabilizer

- Measured resistance at 10K and 293K
- RRR around 200

Coil	R_10 K (mOhm)	R_293K (mOhm)	RRR
V1	10.1	2160	214
V2	9.92	2080	210
V3	9.78	2040	209
V4	9.74	2040	209
V5	9.5	2040	215
V6	9.36	2020	216
V7	9.34	1980	212
V8	9.44	2020	214

Field measurements



Magnets, Superconductors and Cryostats
TE-MSC

Date 08/11/2023
Technical Note 2023-23
Melvin.liebsch@cern.ch
EDMS Nr: 2989914

Magnetic measurements of the SPMQMEM00 superconducting FCC-ee final-focusing quadrupole at 1.9 K

Authors: Melvin Liebsch, Carlo Petrone.

More info (data) can be found in EDMS:

https://edms.cern.ch/document/2989914/1

Rotating coil in five sections (three in magnetic field)

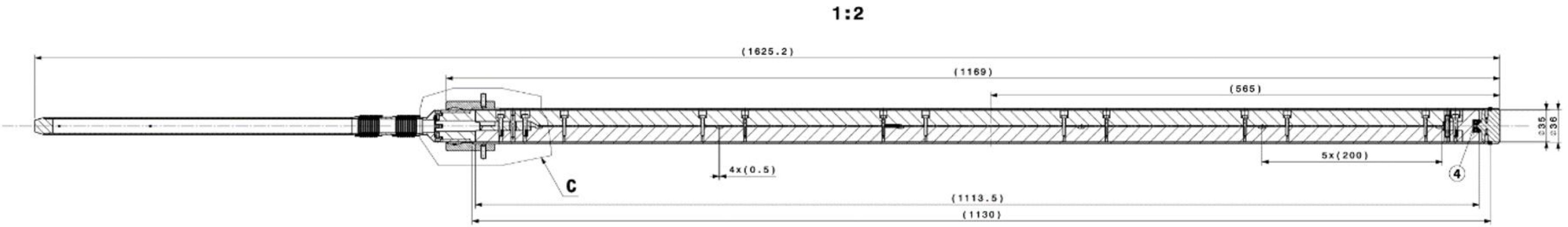


Figure 2: The measurement shaft LHCMMWEC0504.

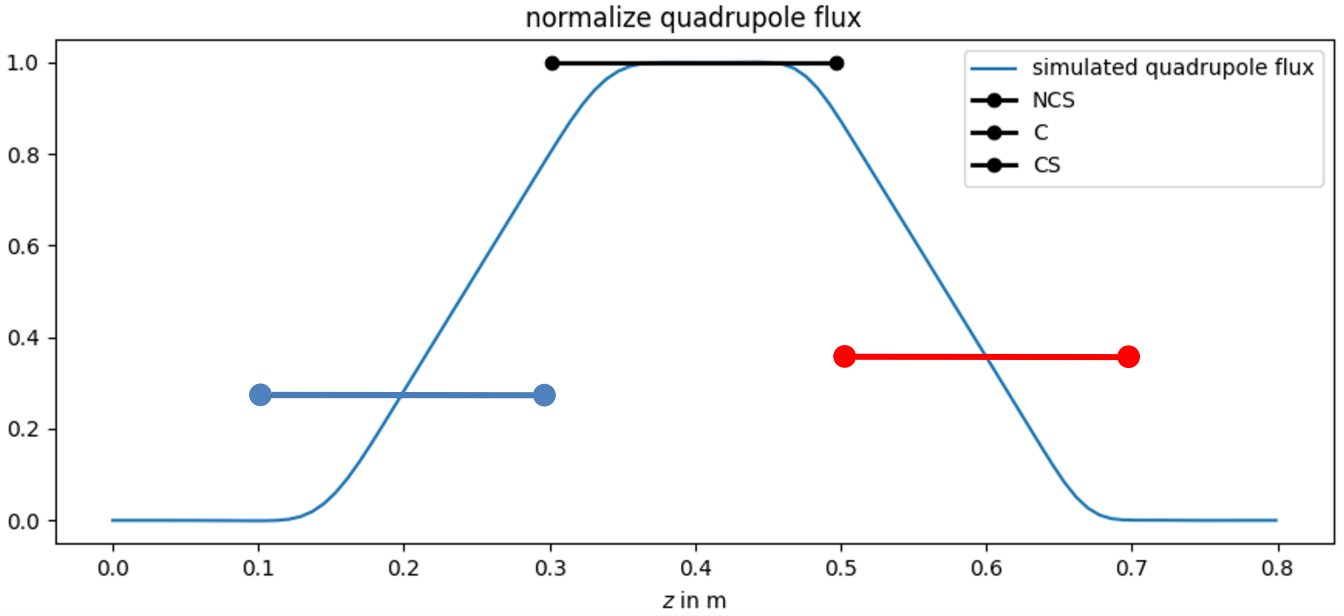


Figure 4: Sensor positions with respect to the numerical field simulation.

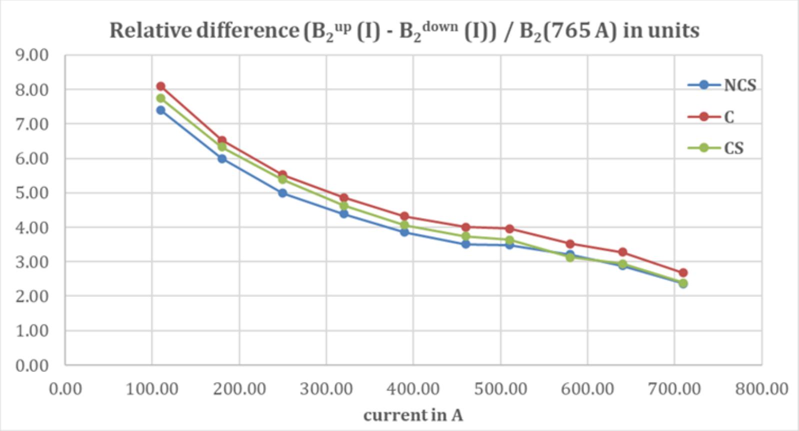
- Three relevant sections:
- C – Centre
- CS – Connection side (the uncocorrected one)
- NCS – Non-connection side - corrected

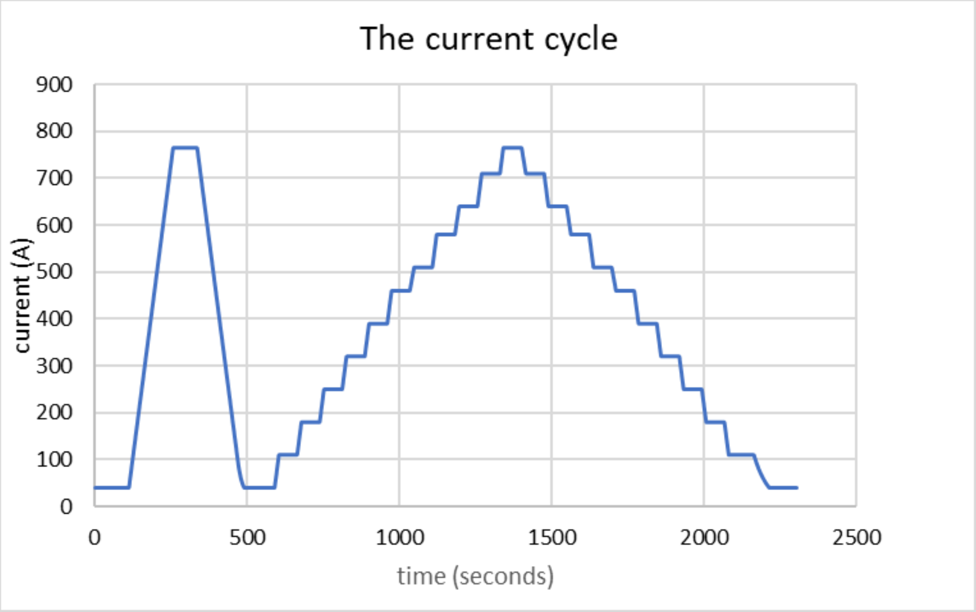
Transfer function

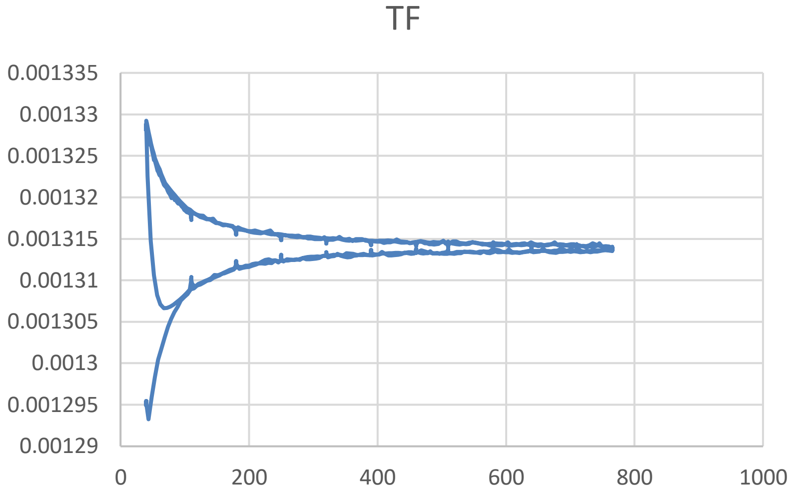
The measured and simulated quadrupole fields at 10 mm and 765 A

	Measured (T)	Simulated (T)	difference
corrected	0.27700	.27698	-7.10^{-5}
Center	1.00503	1.00506	3.10^{-5}
uncorrected	0.35926	0.35928	6.10^{-5}

- Exhibits quite a bit of hysteresis, although there is no iron
- During ramping, this comes from eddy currents in the aluminium former
- During flat tops, presumably we get persistent currents in the superconductor







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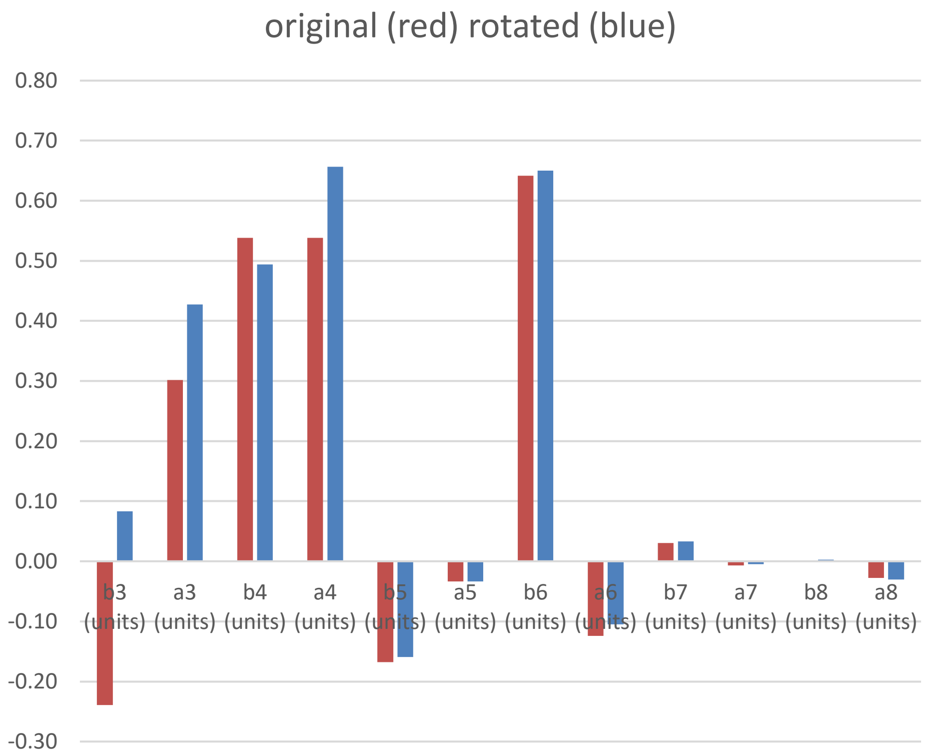
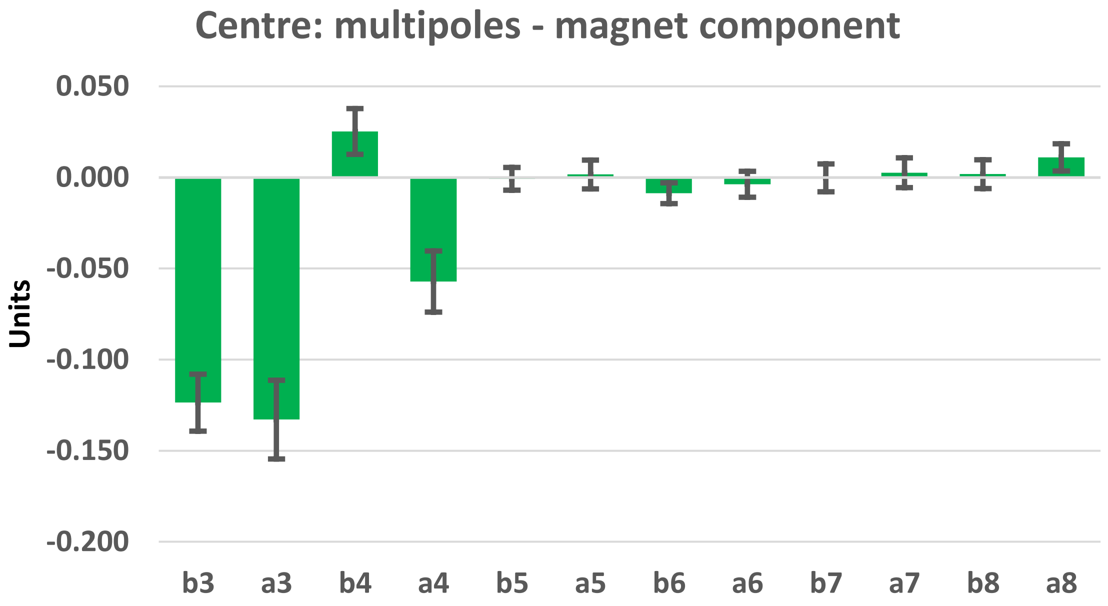
Field quality – the story before

Mysterious ‘environment’ component extracted after repeating warm measurement with a 42 degree tilt of the magnet

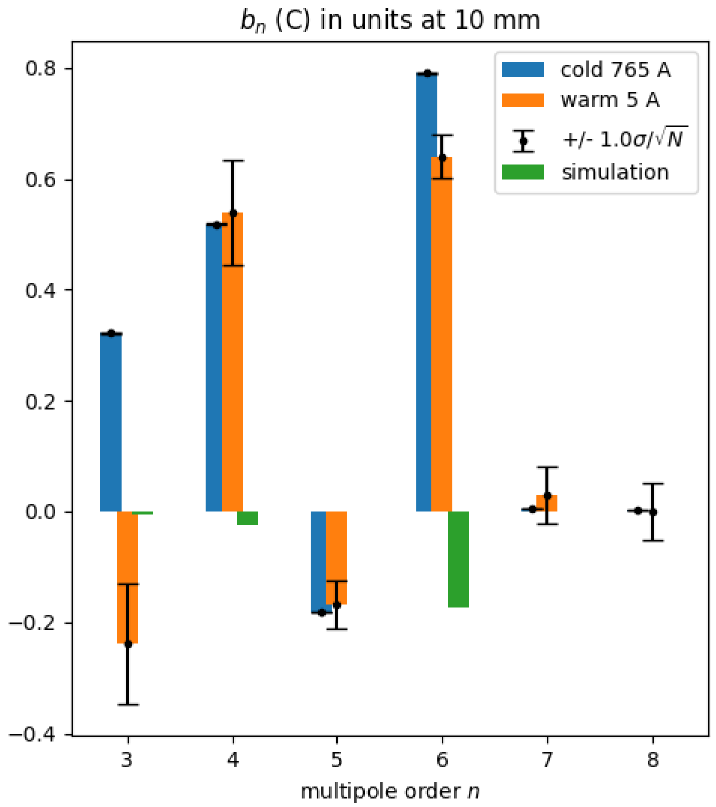
Measurement at warm

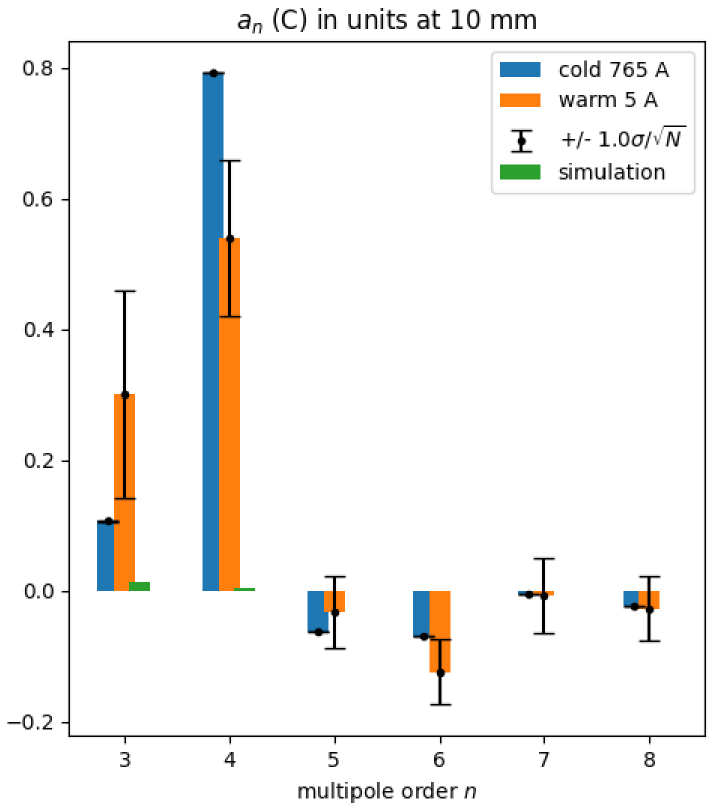




Field quality - cold

- <1unit for all multipoles
- We did not do the same trick during cold measurements
- We did not measure at 4.5K, only at 1.9K
- The 'warm' measurements below come from the unrotated data





THE FIRST SUPERCONDUCTING FINAL FOCUS QUADRUPOLE PROTOTYPE OF THE FCC-ee STUDY

A. Thabuis, M. Koratzinos, G. Kirby, M. Liebsch, C. Petrone
European Organization for Nuclear Research (CERN), Geneva, Switzerland

https://arxiv.org/abs/2405.20105

There is still some tension between the warm and cold measurements (up to ~0.5 units)
The cold measurements did not have the benefit of the second rotated measurement.

Measured field quality table at cold

Units of 10^{-4} at a reference radius of 10mm (2/3 aperture)

n	Center section	Non-corrected section	Corrected section	Extrapolated total
b_3	0.19	-7.02	0.12	0.31
b_4	0.31	3.02	0.59	0.87
b_5	-0.11	-1.60	-0.05	-0.16
b_6	0.48	0.90	0.21	0.68
b_7	0.01	-0.32	-0.01	0.00
b_8	0.00	0.14	0.00	0.00
a_3	0.07	-12.56	-0.14	-0.06
a_4	0.48	-8.19	-0.25	0.24
a_5	-0.04	-0.90	0.03	-0.01
a_6	-0.04	0.39	-0.02	-0.06
a_7	-0.01	-0.20	0.00	0.00
a_8	-0.01	0.08	-0.01	-0.02

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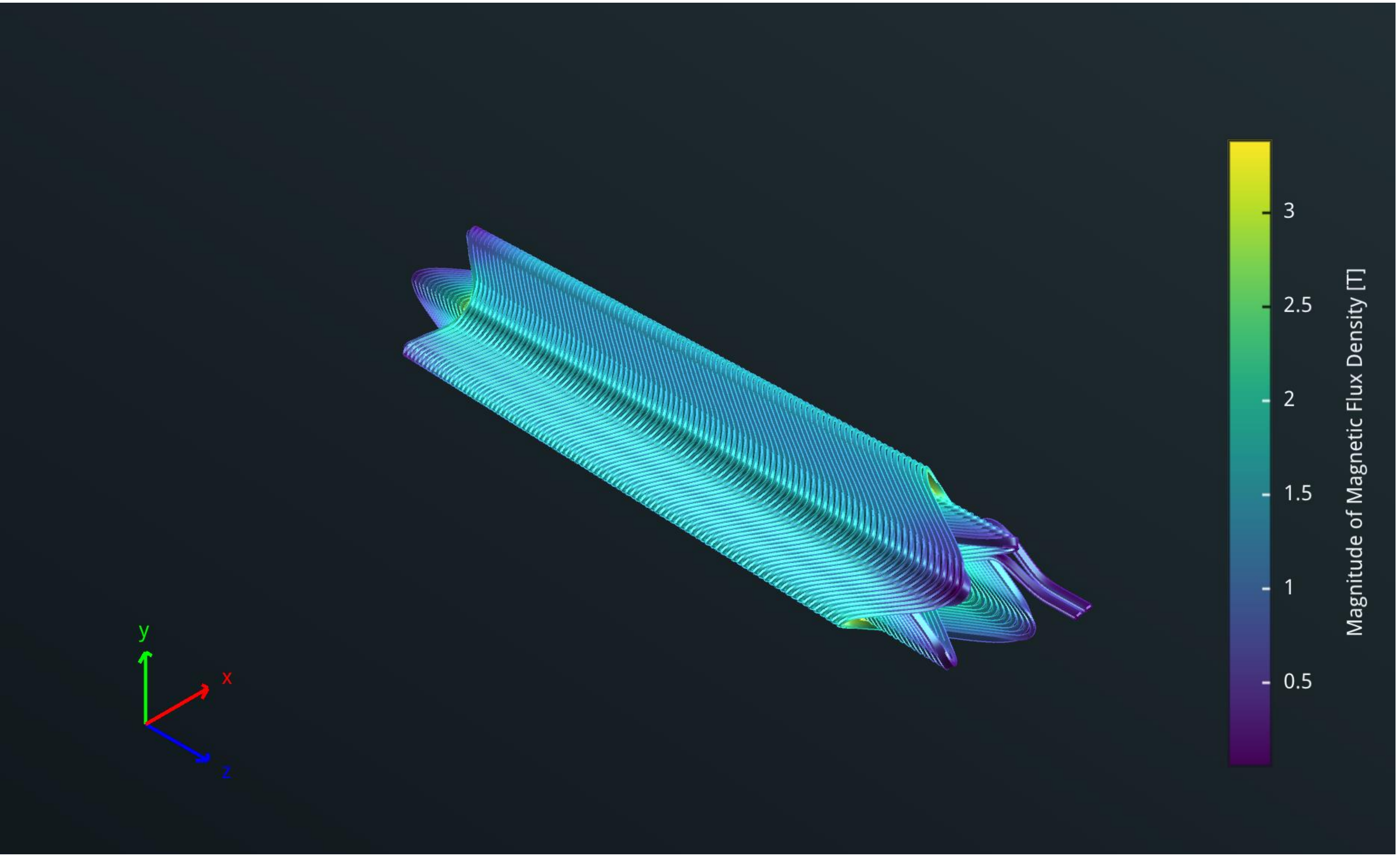
Multipole field errors in units of 10^{-4} normalized to the full prototype (magnetic length 332mm). Last column extrapolates to the full length QC1L1 (magnetic length 700mm) by using 2.83 center sections and twice the corrected section

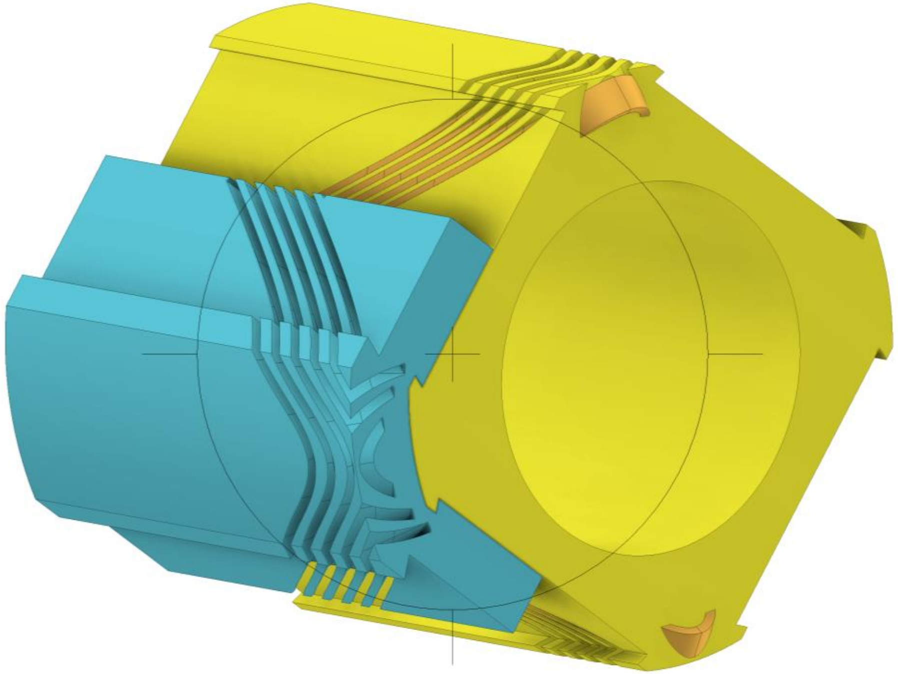
Upgrade to HTS

- Changing the technology from NbTi to HTS would mean that we can operate at 30K instead of 2K.
- BUT, HTS comes in form of tapes, not trivial to design a quadrupole with crosstalk compensation.
- I am happy to report that I think I have solved all these technical problems.
- LAPP is interested in collaborating for building a prototype (and water-cooled beampipe) – see ‘extra slides’ below

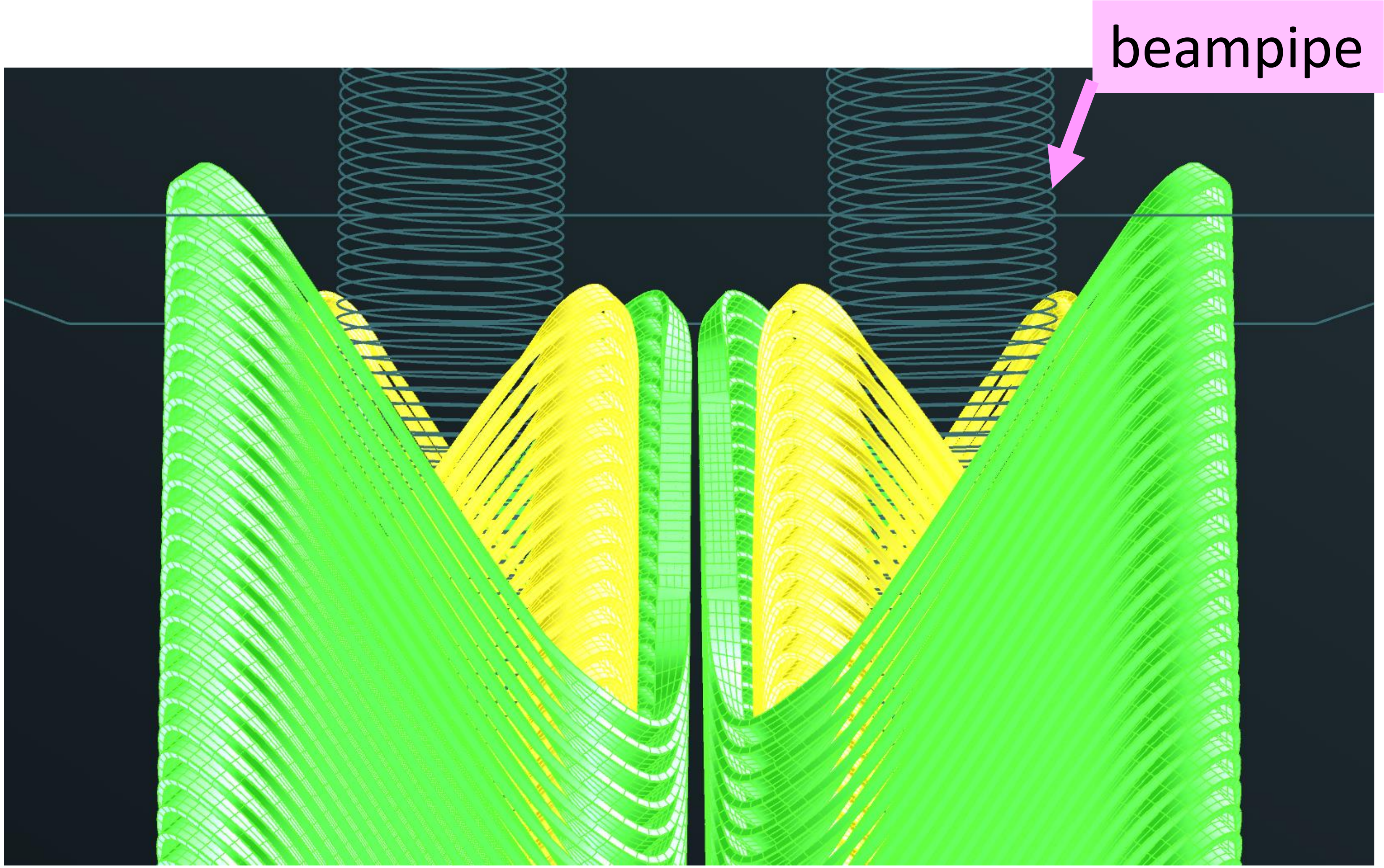
Magnetic and mechanical design of single aperture prototype



Similar in size to NbTi prototype

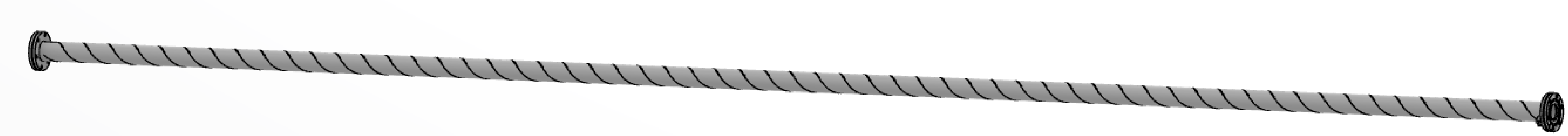


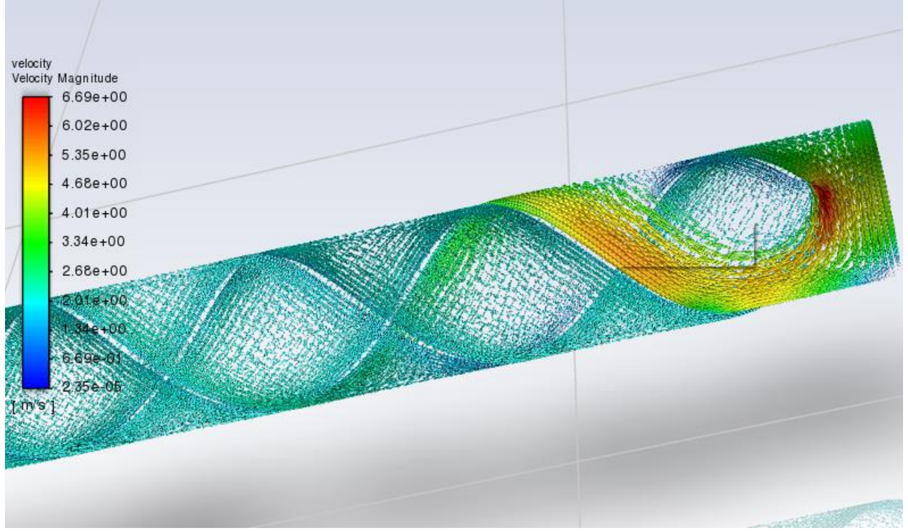
Detail at 2200mm from the IP

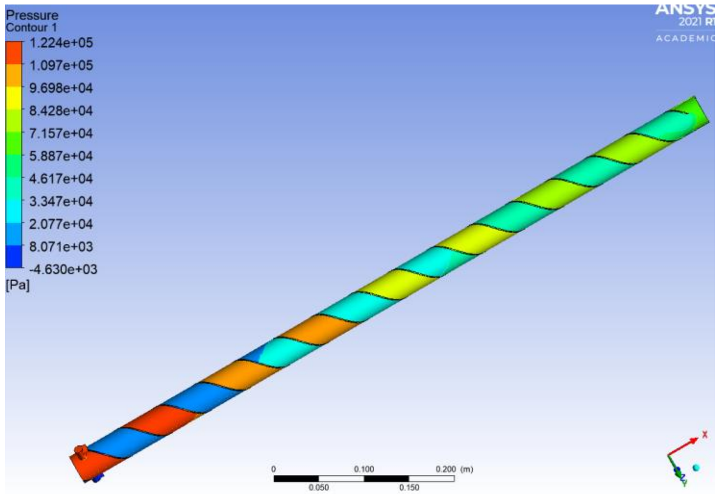

beampipe

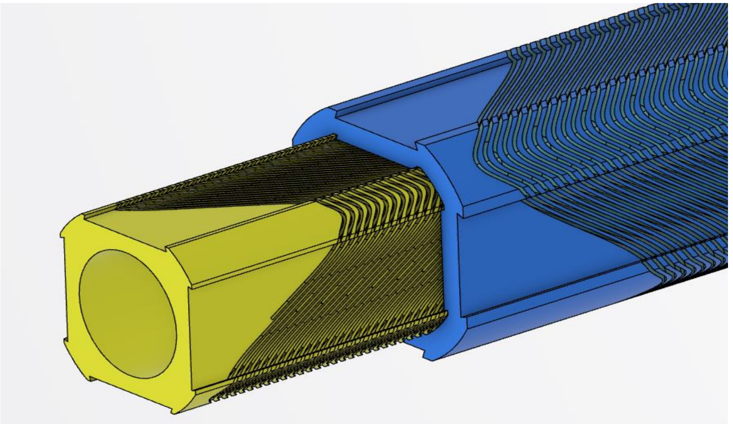
Work started at LAPP!

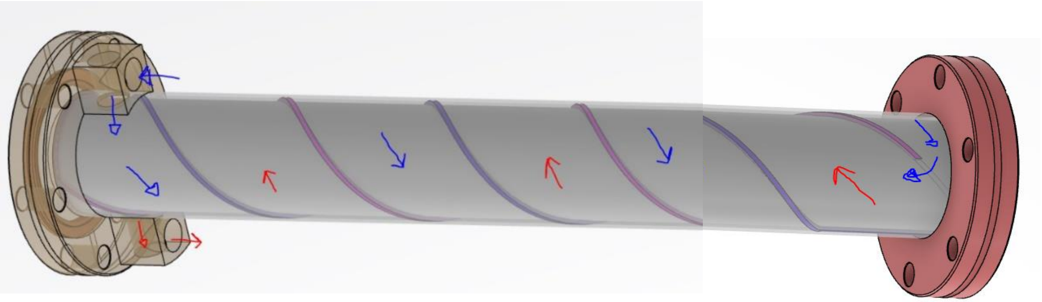
- See slides in the ‘extra slides’ section

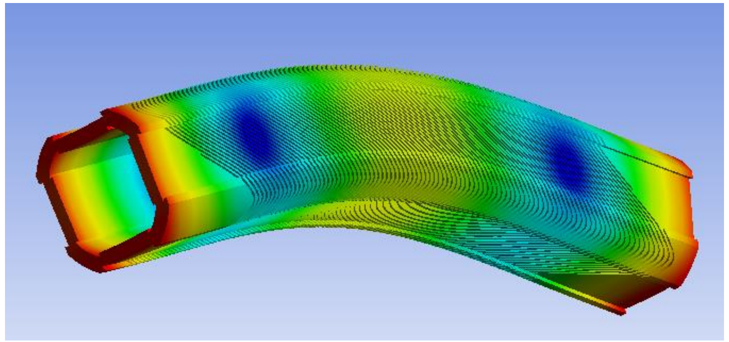










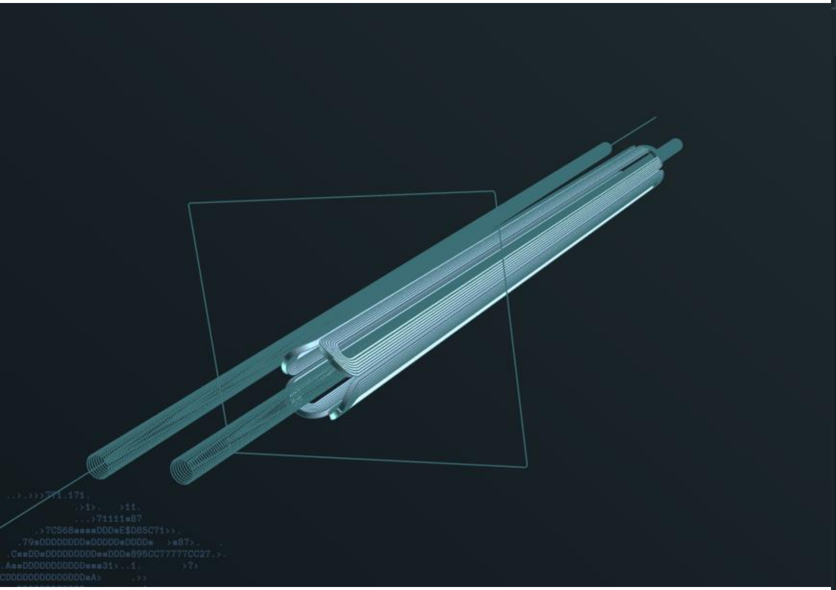


Conclusions

- The first FCC-ee FF quad prototype has been designed, build, wound, impregnated, tested at warm and finally tested at cold with excellent results.
- The choice of CCT iron-free technology seems justified.
- Making the FF quads of FCC using HTS tape conductors now appears possible.
- This will give sizable advantages and a proposal to build a prototype has been put forward.

EXTRA SLIDES

Single cosine-theta quad



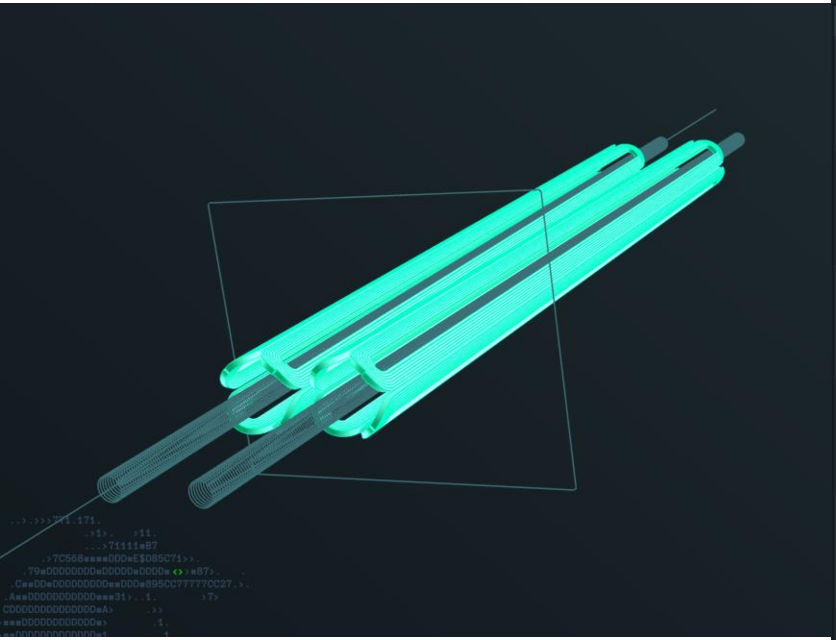
harmonics given at a reference radius of: 7.500 [mm]

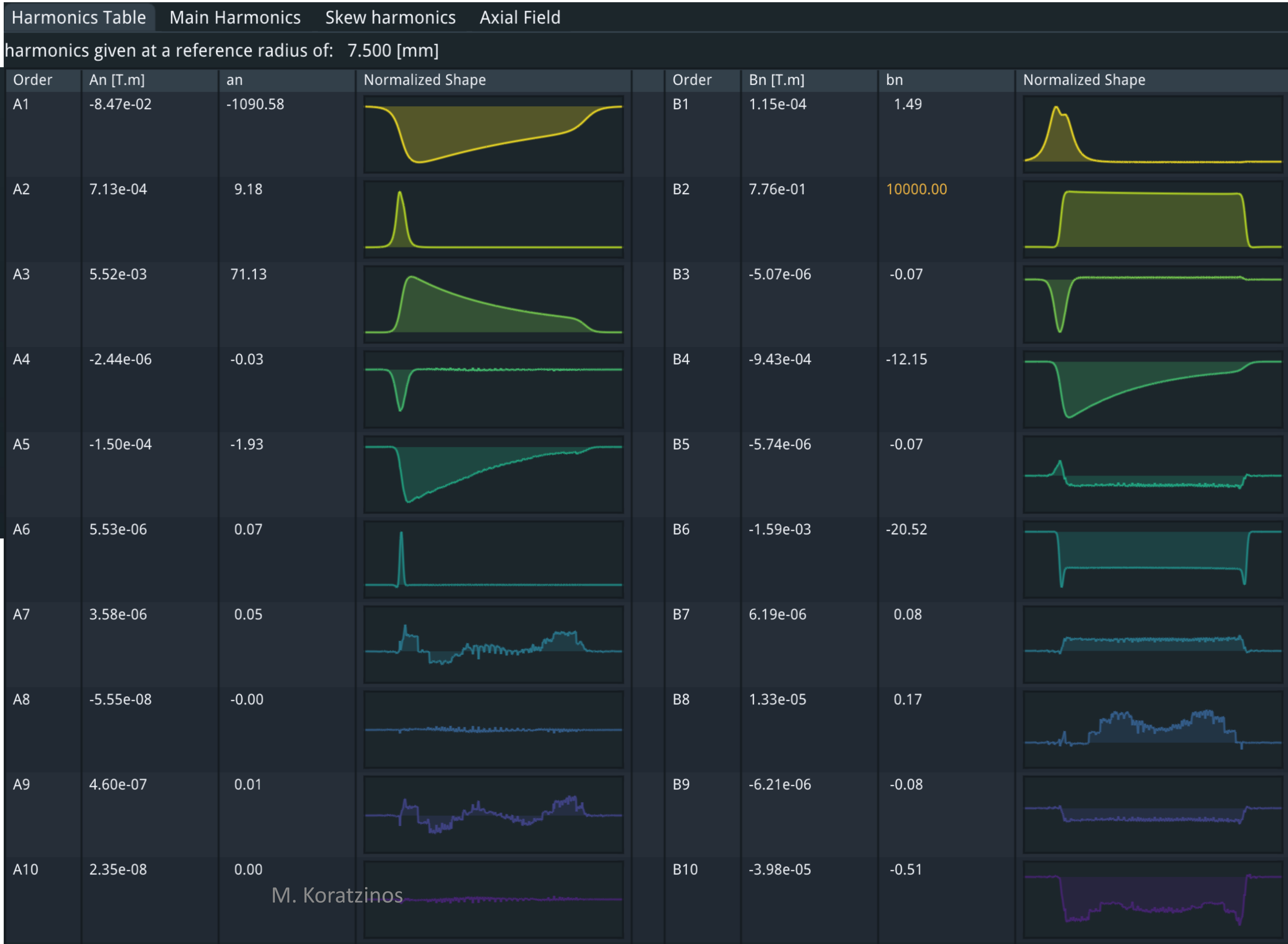
Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	-9.82e-07	-0.01		B1	-6.16e-06	-0.08	
A2	6.67e-04	8.90		B2	7.50e-01	10000.00	
A3	7.85e-07	0.01		B3	6.17e-06	0.08	
A4	1.53e-08	0.00		B4	1.91e-05	0.26	
A5	8.77e-07	0.01		B5	-6.17e-06	-0.08	
A6	5.37e-06	0.07		B6	-1.61e-03	-21.52	
A7	6.43e-07	0.01		B7	6.17e-06	0.08	
A8	1.48e-08	0.00		B8	1.48e-05	0.20	
A9	1.82e-07	0.00		B9	-6.17e-06	-0.08	
A10	-4.32e-08	-0.00		B10	-3.86e-05	-0.51	

M. Koratzinos

@7.5mm reference radius!
(FCC-ee reference radius: 10mm)

Double quad no iron





harmonics given at a reference radius of: 7.500 [mm]

Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	-8.47e-02	-1090.58		B1	1.15e-04	1.49	
A2	7.13e-04	9.18		B2	7.76e-01	10000.00	
A3	5.52e-03	71.13		B3	-5.07e-06	-0.07	
A4	-2.44e-06	-0.03		B4	-9.43e-04	-12.15	
A5	-1.50e-04	-1.93		B5	-5.74e-06	-0.07	
A6	5.53e-06	0.07		B6	-1.59e-03	-20.52	
A7	3.58e-06	0.05		B7	6.19e-06	0.08	
A8	-5.55e-08	-0.00		B8	1.33e-05	0.17	
A9	4.60e-07	0.01		B9	-6.21e-06	-0.08	
A10	2.35e-08	0.00		B10	-3.98e-05	-0.51	

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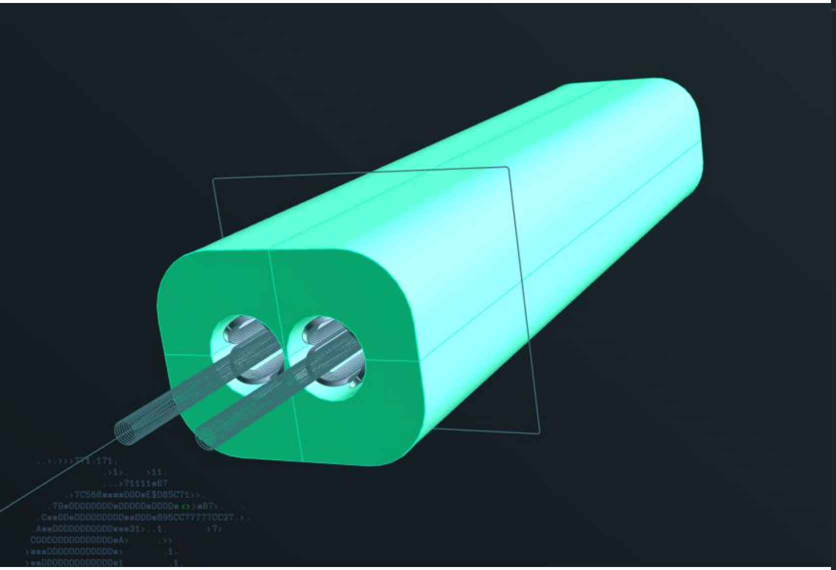
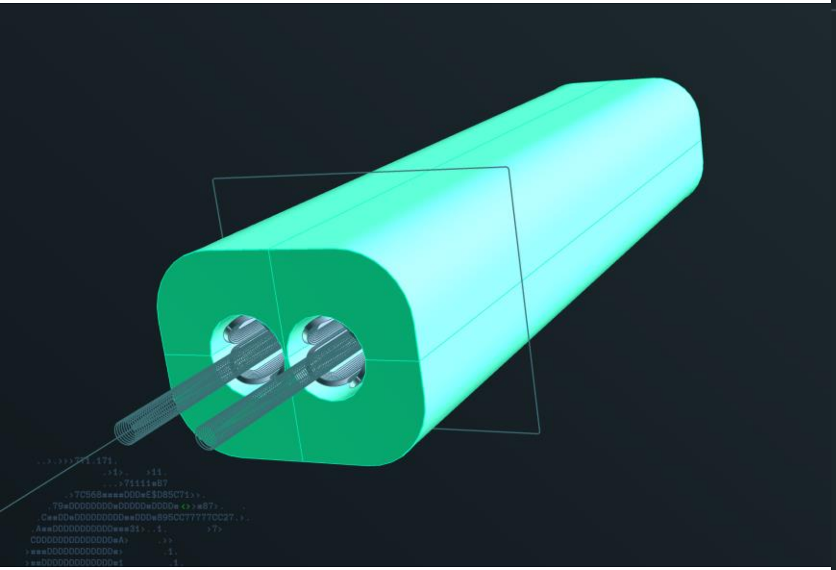
Double quad plus iron



harmonics given at a reference radius of: 7.500 [mm]

Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	-1.52e-02	-154.02		B1	3.70e-05	0.37	
A2	7.19e-04	7.27		B2	9.90e-01	10000.00	
A3	1.60e-03	16.15		B3	-1.54e-05	-0.16	
A4	-7.56e-06	-0.08		B4	-2.17e-04	-2.19	
A5	-4.89e-05	-0.49		B5	-6.06e-06	-0.06	
A6	5.46e-06	0.06		B6	-1.56e-03	-15.76	
A7	1.38e-06	0.01		B7	6.32e-06	0.06	
A8	2.32e-08	0.00		B8	1.30e-05	0.13	
A9	8.31e-07	0.01		B9	-6.24e-06	-0.06	
A10	-5.44e-08	-0.00		B10	-3.99e-05	-0.40	

Double quad with iron, half strength



harmonics given at a reference radius of: 7.500 [mm]

Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	-7.35e-03	-142.50		B1	3.08e-05	0.60	
A2	3.51e-04	6.81		B2	5.16e-01	10000.00	
A3	7.12e-04	13.80		B3	-1.52e-05	-0.29	
A4	-5.92e-08	-0.00		B4	-9.94e-05	-1.93	
A5	-8.91e-07	-0.02		B5	-2.97e-06	-0.06	
A6	2.76e-06	0.05		B6	-8.34e-04	-16.16	
A7	-5.83e-07	-0.01		B7	3.15e-06	0.06	
A8	-9.80e-09	-0.00		B8	6.50e-06	0.13	
A9	4.33e-07	0.01		B9	-3.11e-06	-0.06	
A10	-1.66e-08	-0.00		B10	-1.99e-05	-0.39	

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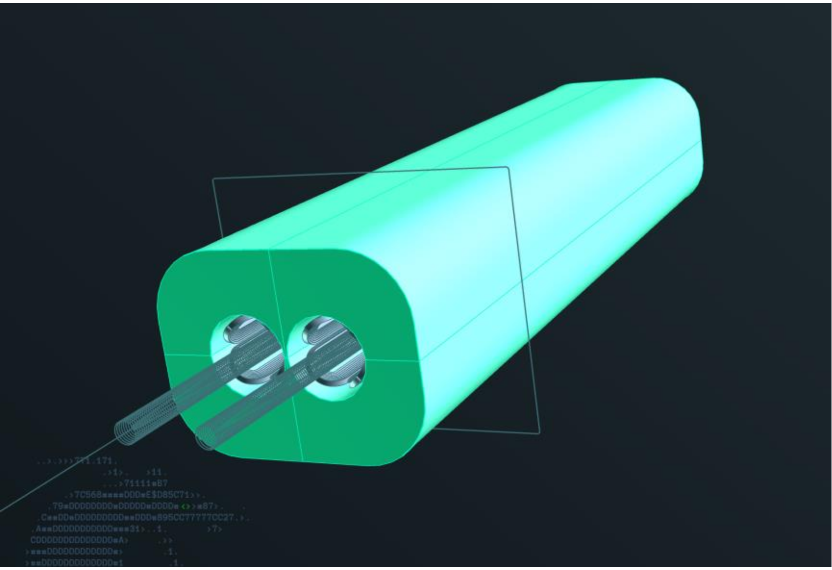
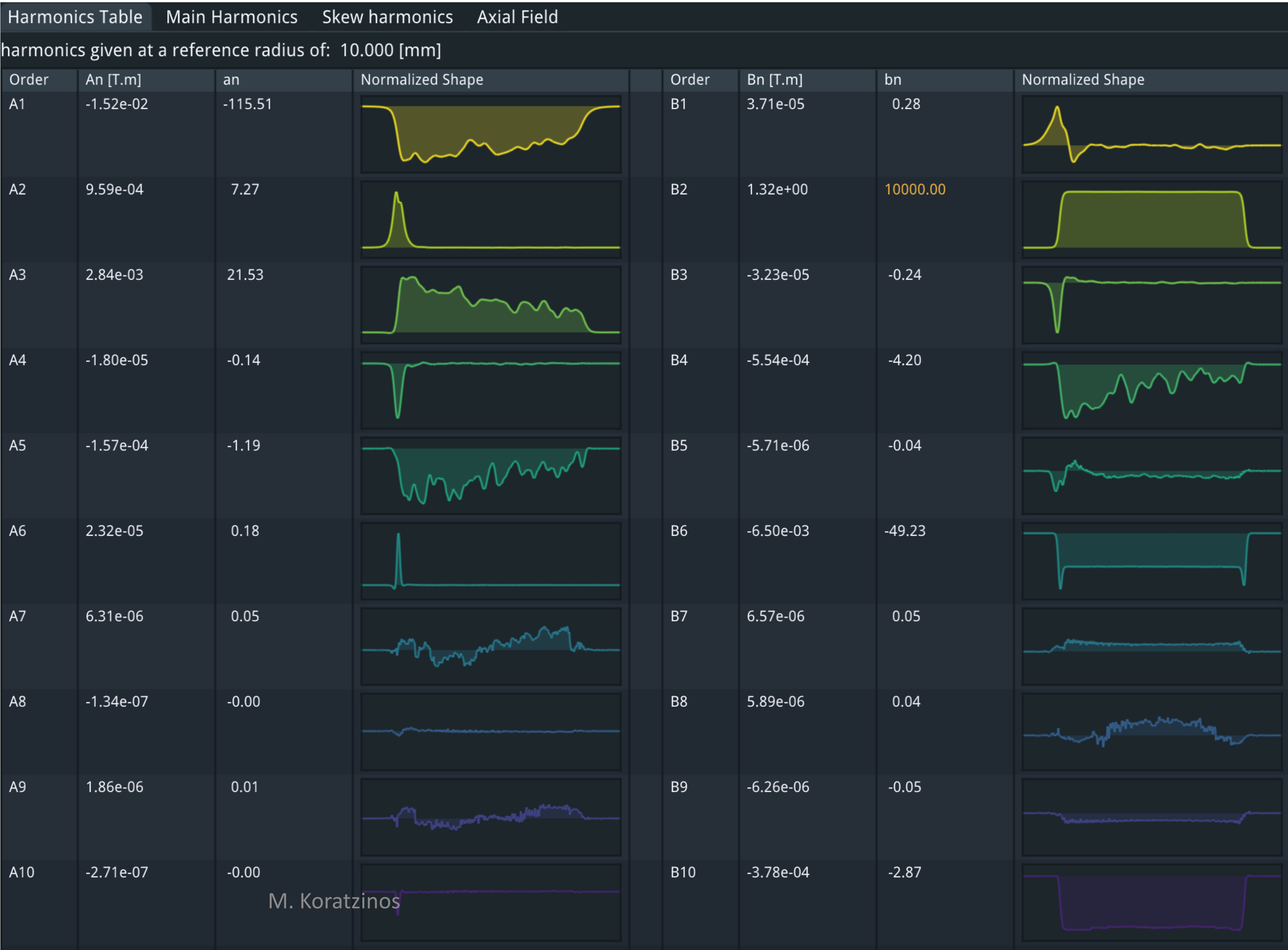
Non-linearity from half to full strength:
A1:12 units
A3: 2 units

(Double quad, iron, 10mm reference radius)





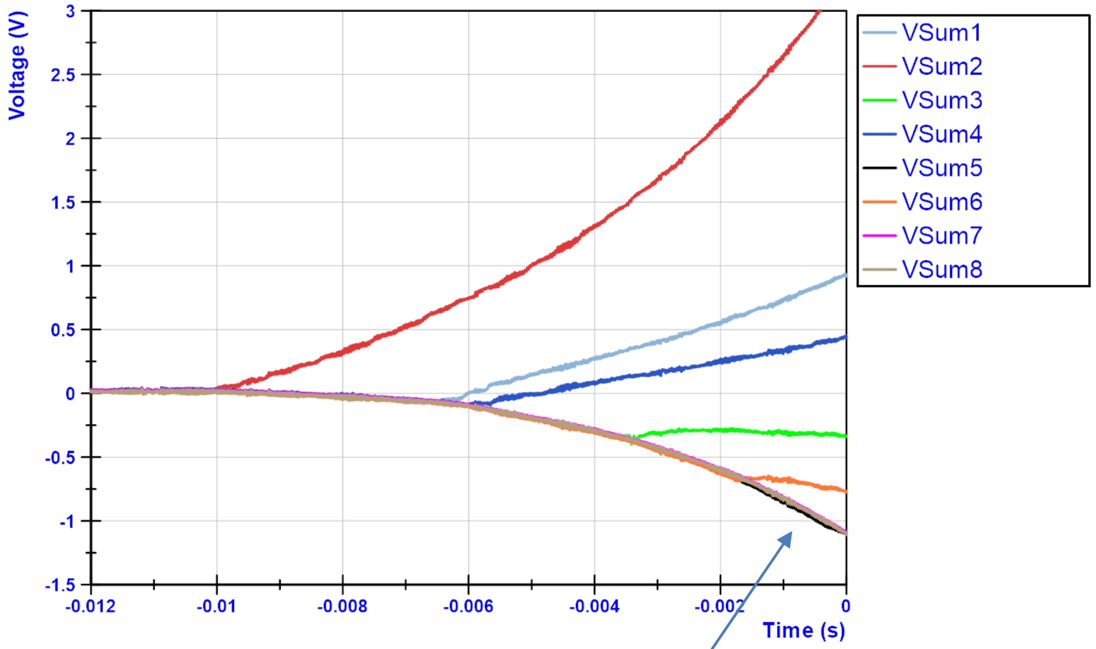
harmonics given at a reference radius of: 10.000 [mm]

Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	-1.52e-02	-115.51		B1	3.71e-05	0.28	
A2	9.59e-04	7.27		B2	1.32e+00	10000.00	
A3	2.84e-03	21.53		B3	-3.23e-05	-0.24	
A4	-1.80e-05	-0.14		B4	-5.54e-04	-4.20	
A5	-1.57e-04	-1.19		B5	-5.71e-06	-0.04	
A6	2.32e-05	0.18		B6	-6.50e-03	-49.23	
A7	6.31e-06	0.05		B7	6.57e-06	0.05	
A8	-1.34e-07	-0.00		B8	5.89e-06	0.04	
A9	1.86e-06	0.01		B9	-6.26e-06	-0.05	
A10	-2.71e-07	-0.00		B10	-3.78e-04	-2.87	

M. Koratzinos

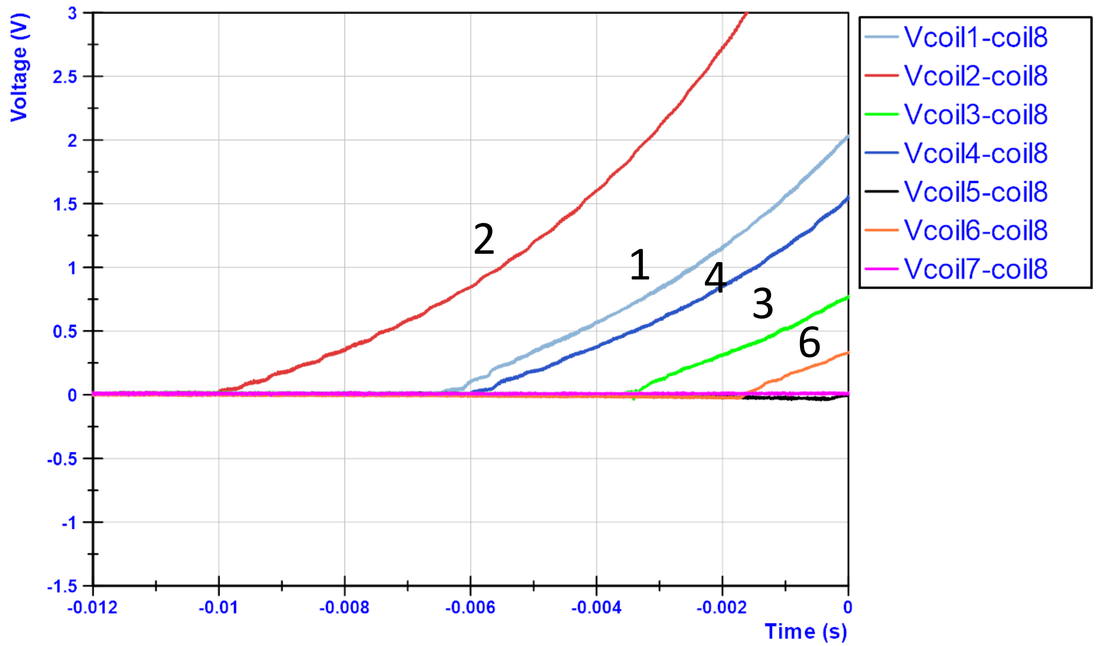
Multipoles larger than 1 unit:
A3: 22 units
A5: 1 unit
B4: 4 units
B6: 49 units
B10: 3 units

Quench analysis at short sample limit, 1.9 K at 991 A.



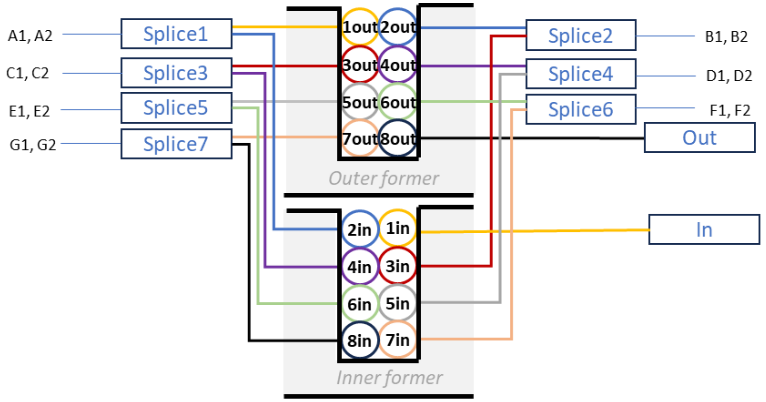
Measured voltage per coil

SPMQMEM000-00000007__O202310311658_a003(0)



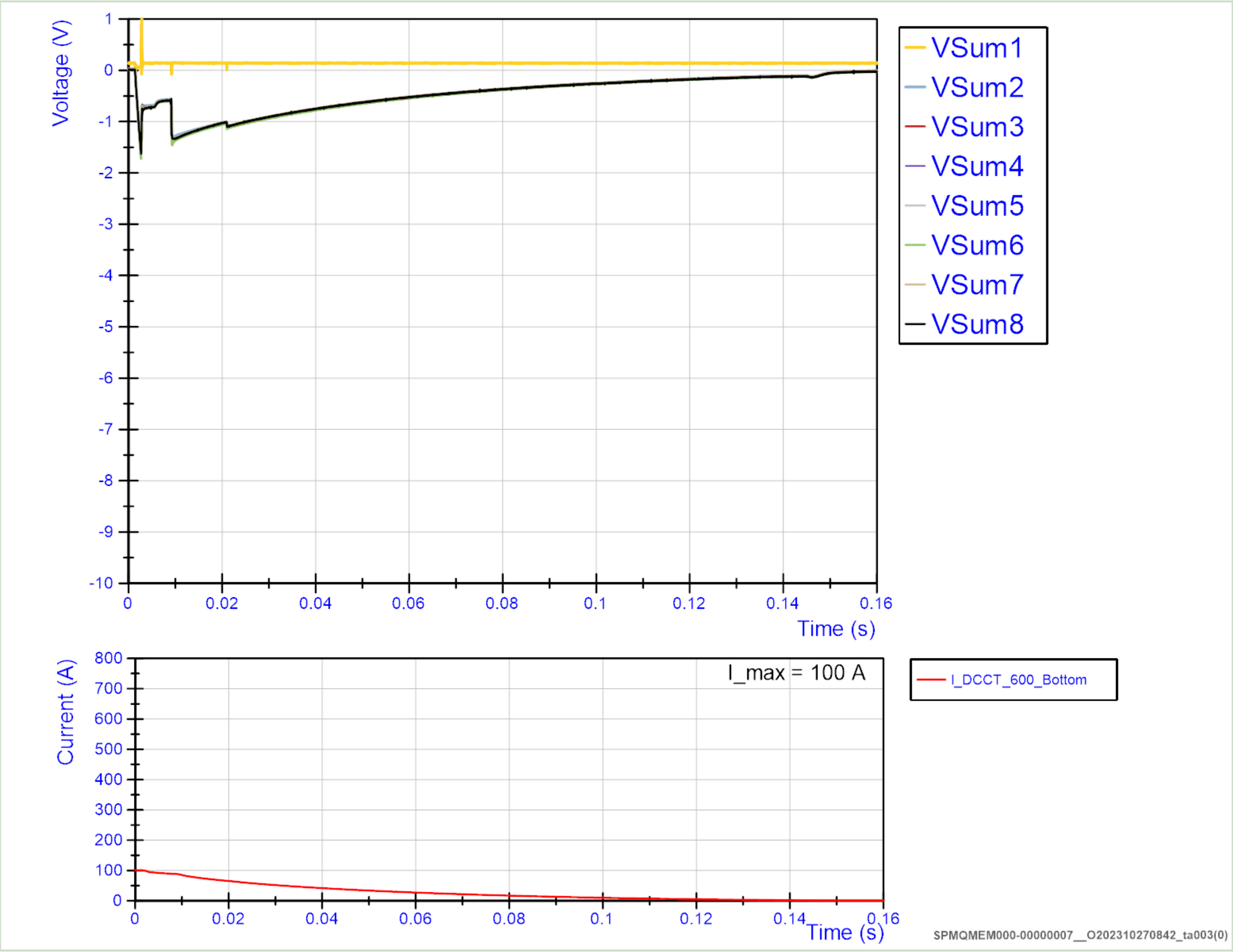
Assuming coil 8 is not yet quenched and only has inductive voltage, this calculation shows the resistive voltage of each coil.

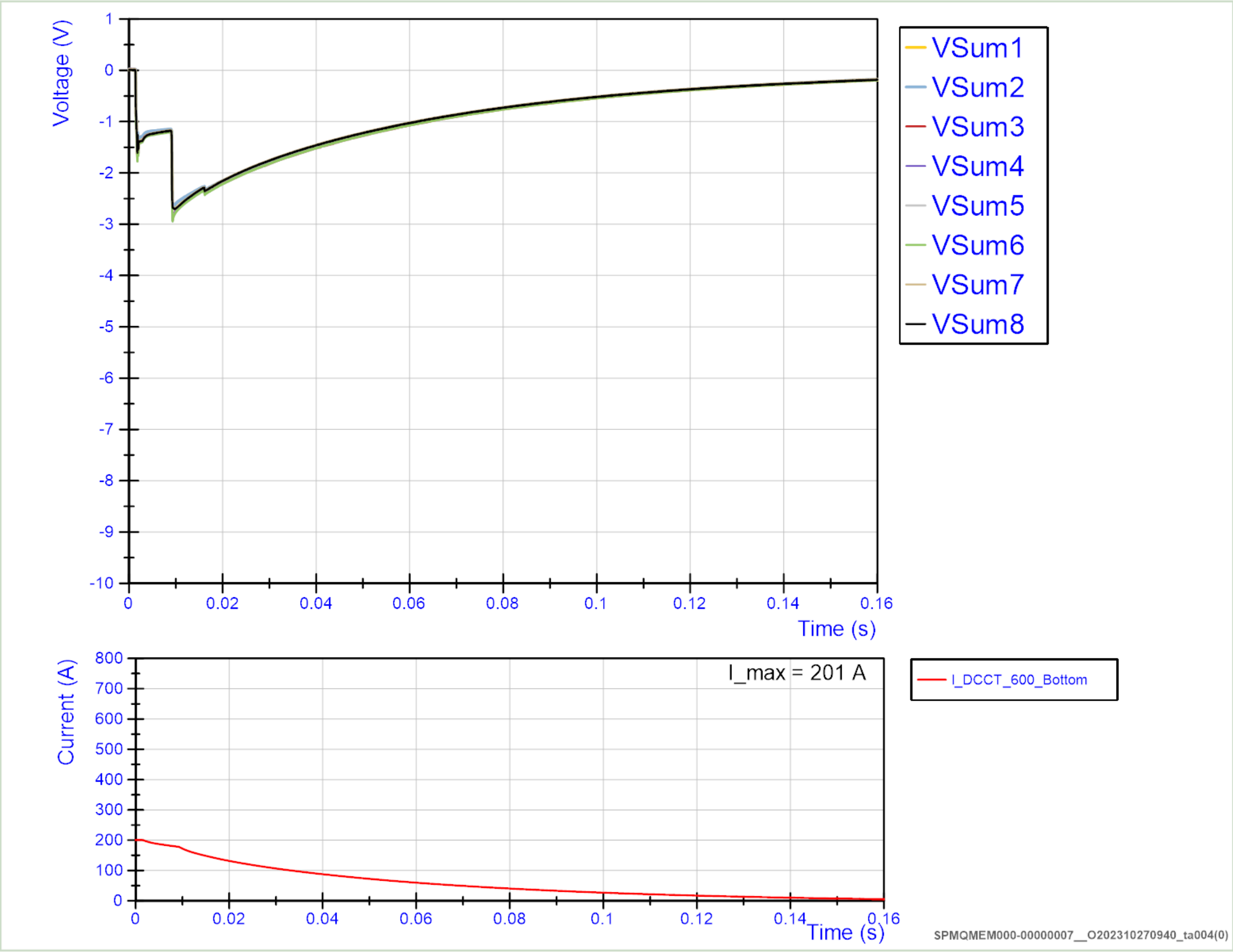
SPMQMEM000-00000007__O202310311658_a003(0)



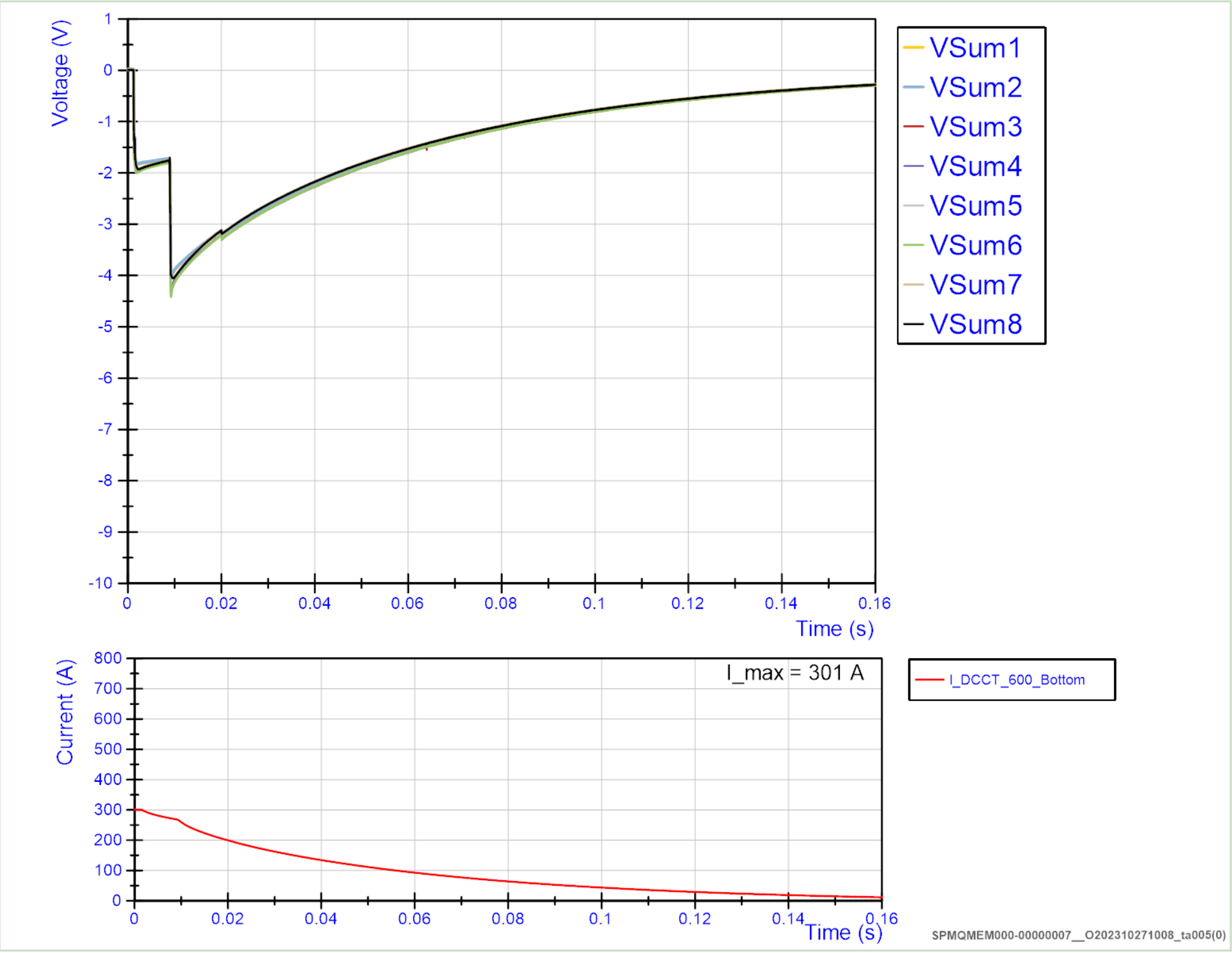
Negative (inductive) component due to dI/dt

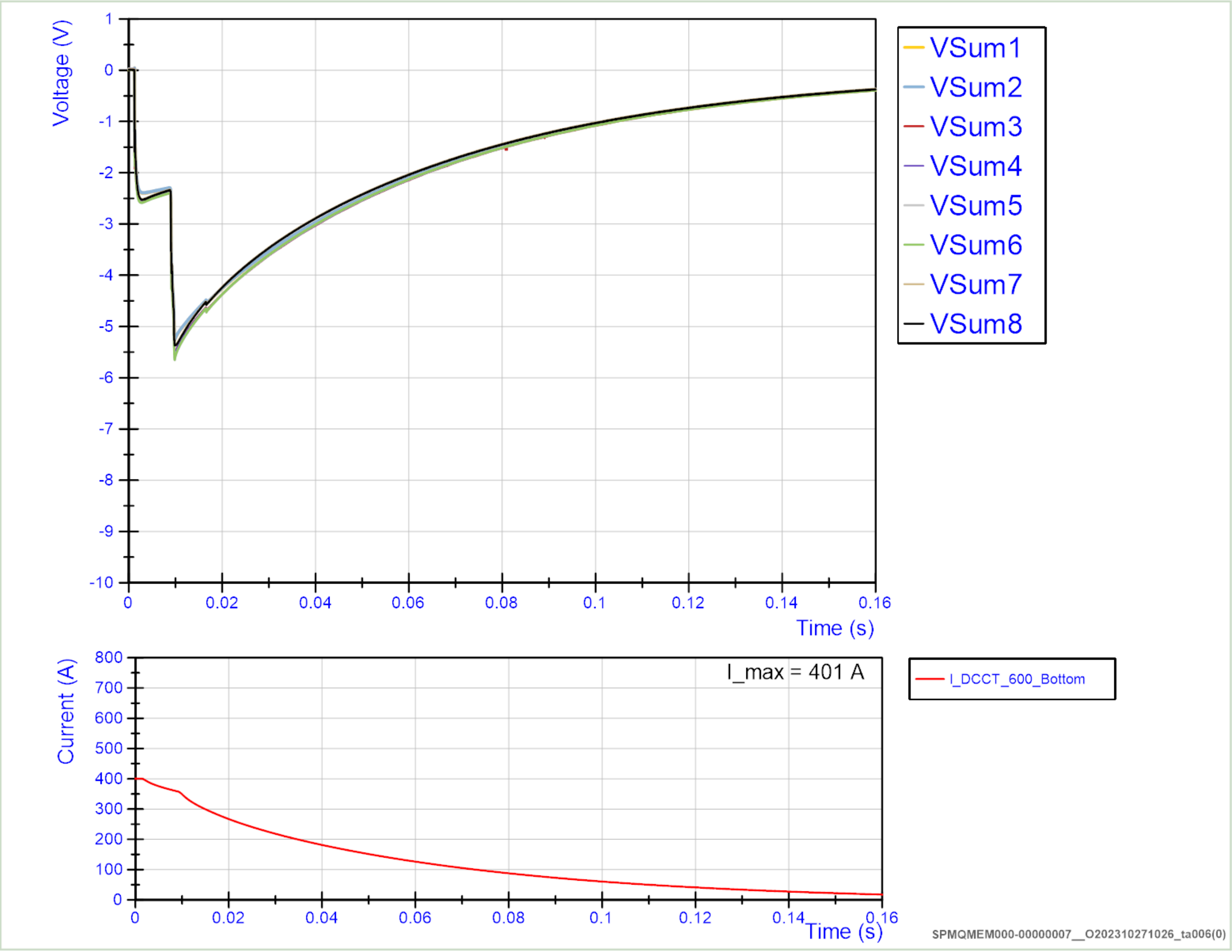
Quenchback studies from 100 A and 200 A
Using 50 Ohm crowbar + 75 Ohm EE



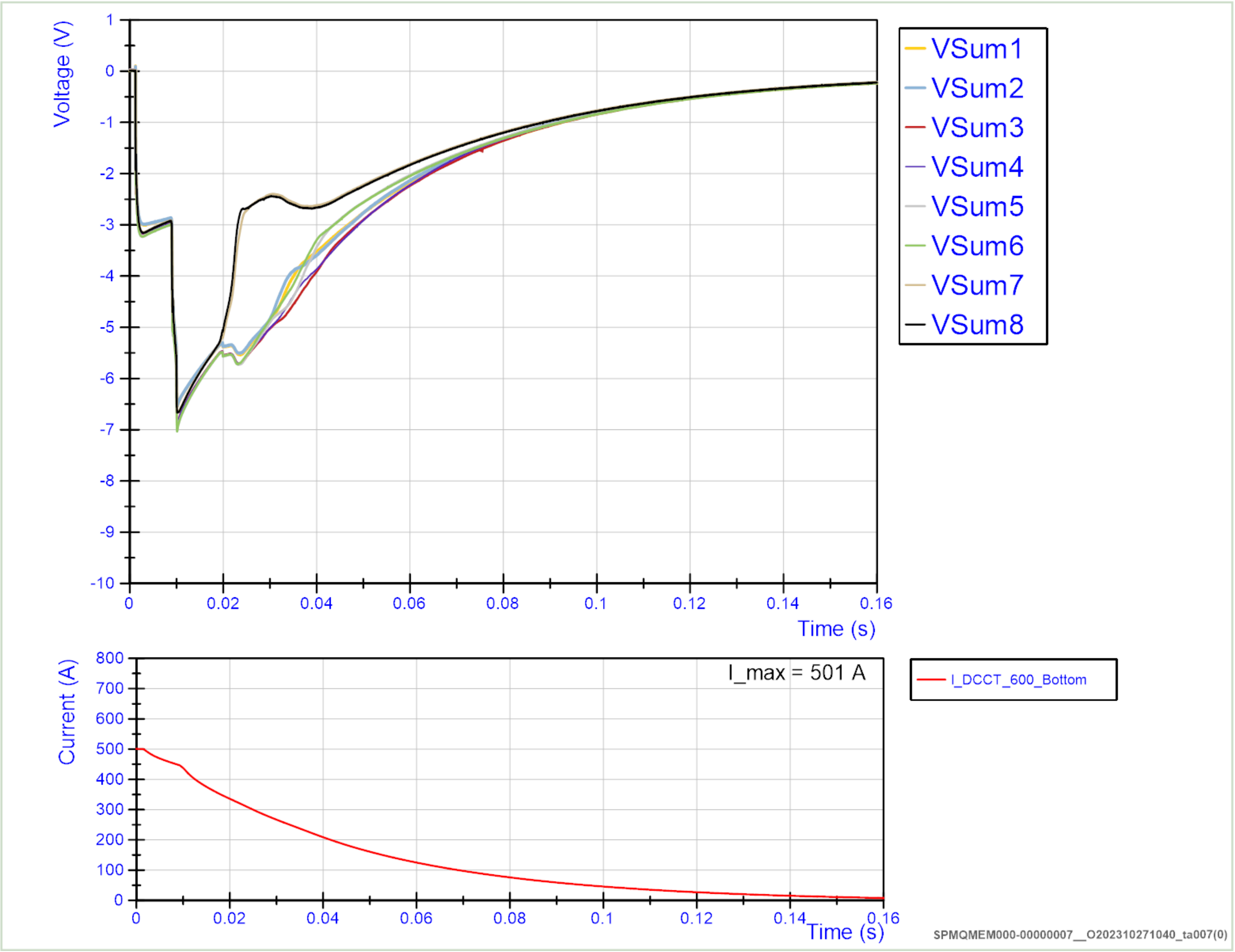


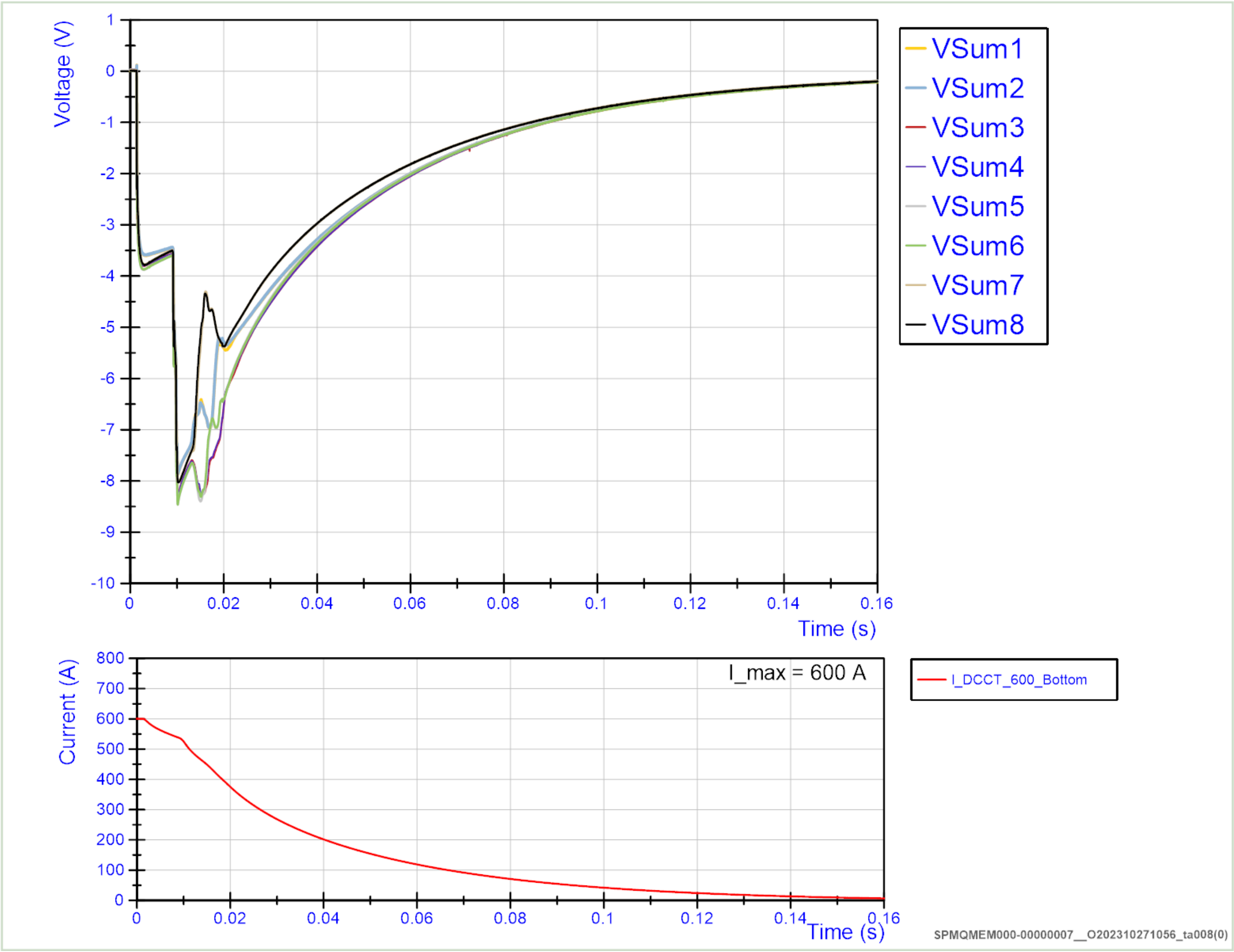
Quenchback studies from 300 A and 400 A
Using 50 Ohm crowbar + 75 Ohm EE



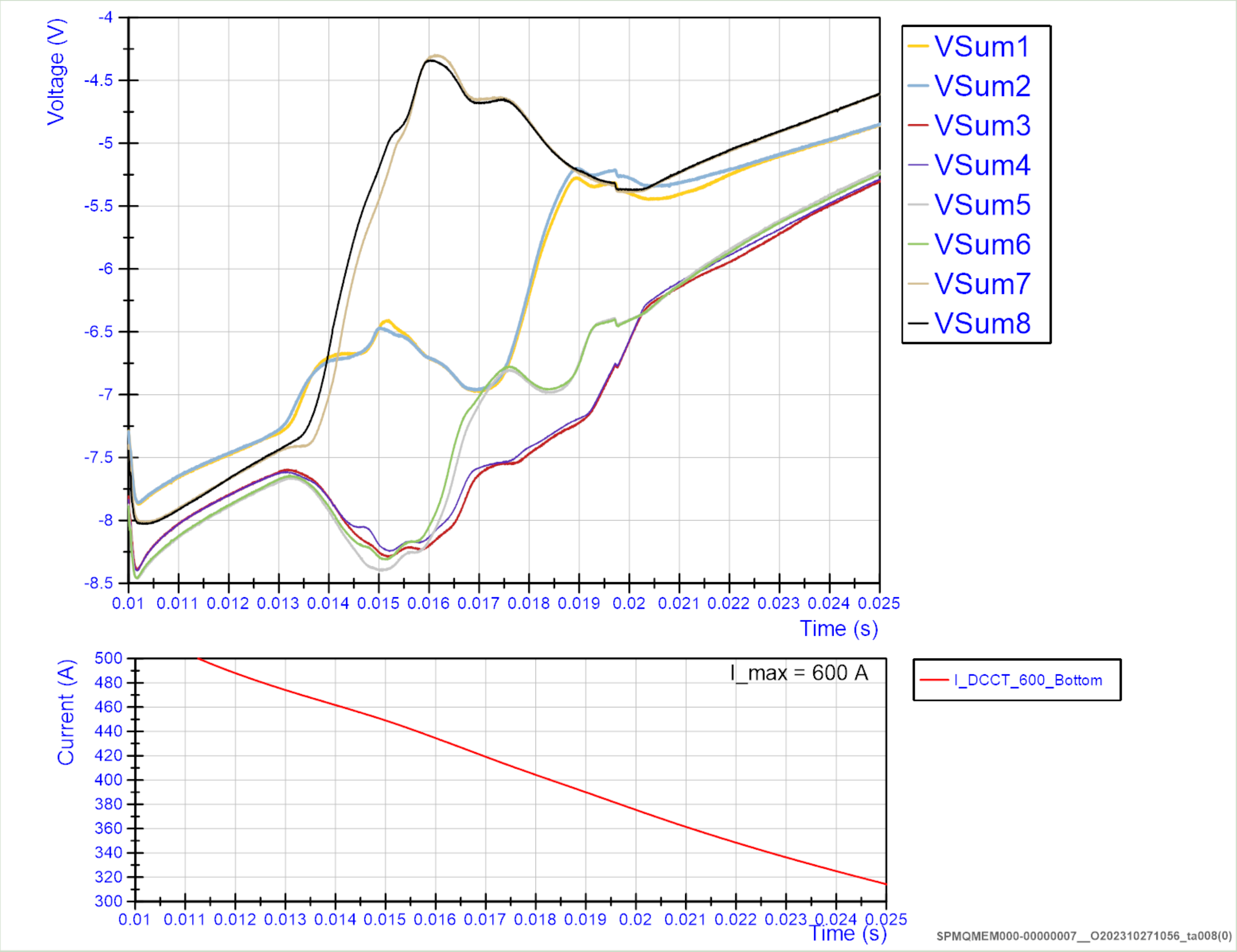


Quenchback studies from 500 A and 600 A
Using 50 Ohm crowbar + 75 Ohm EE





Quenchback studies from 600 A – Zoomed in
Using 50 Ohm crowbar + 75 Ohm EE



Dynamic effects a3/b3

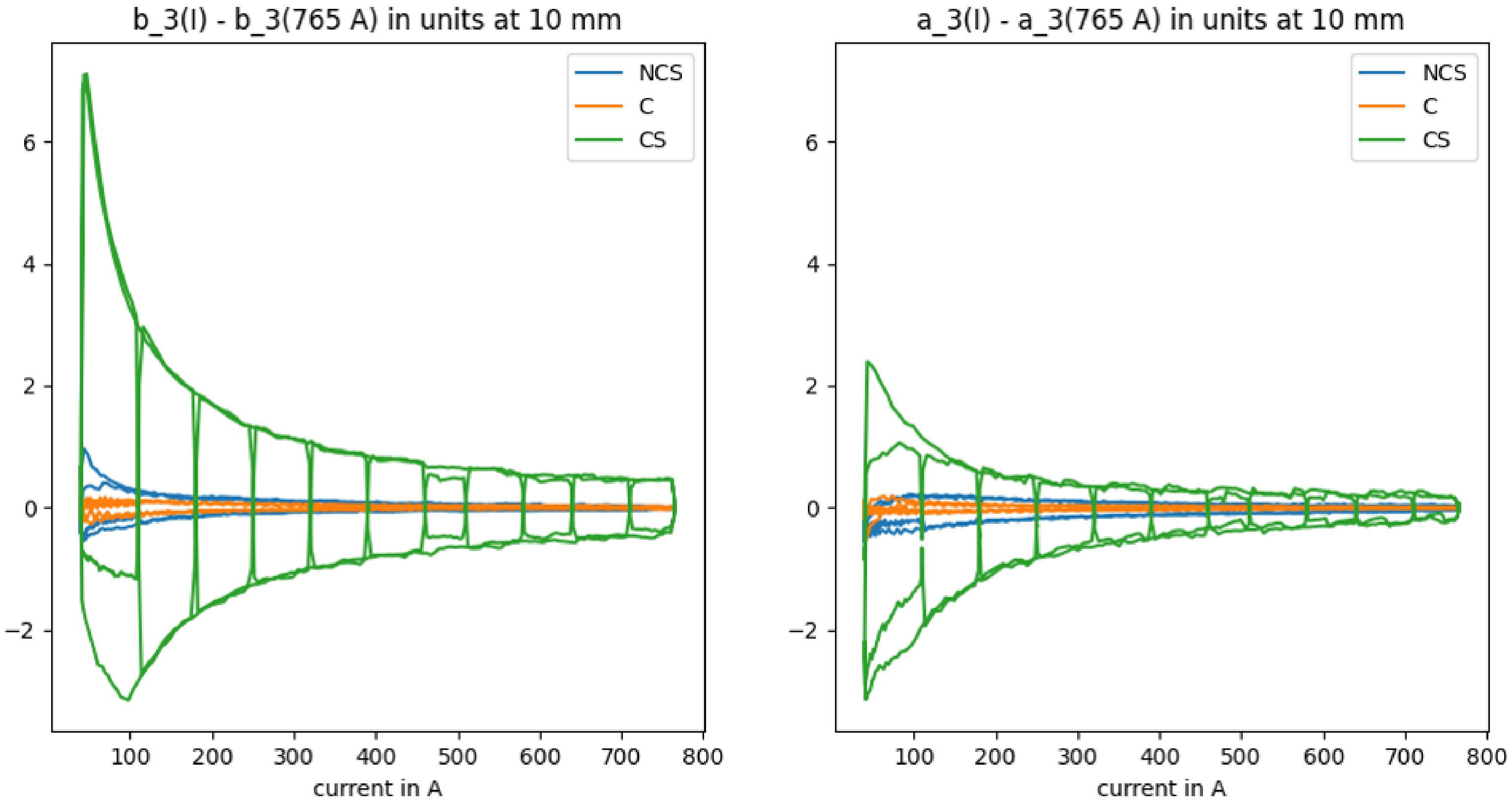


Figure 9: Dynamic effects in the sextupole field.

Dynamic effects a4/b4

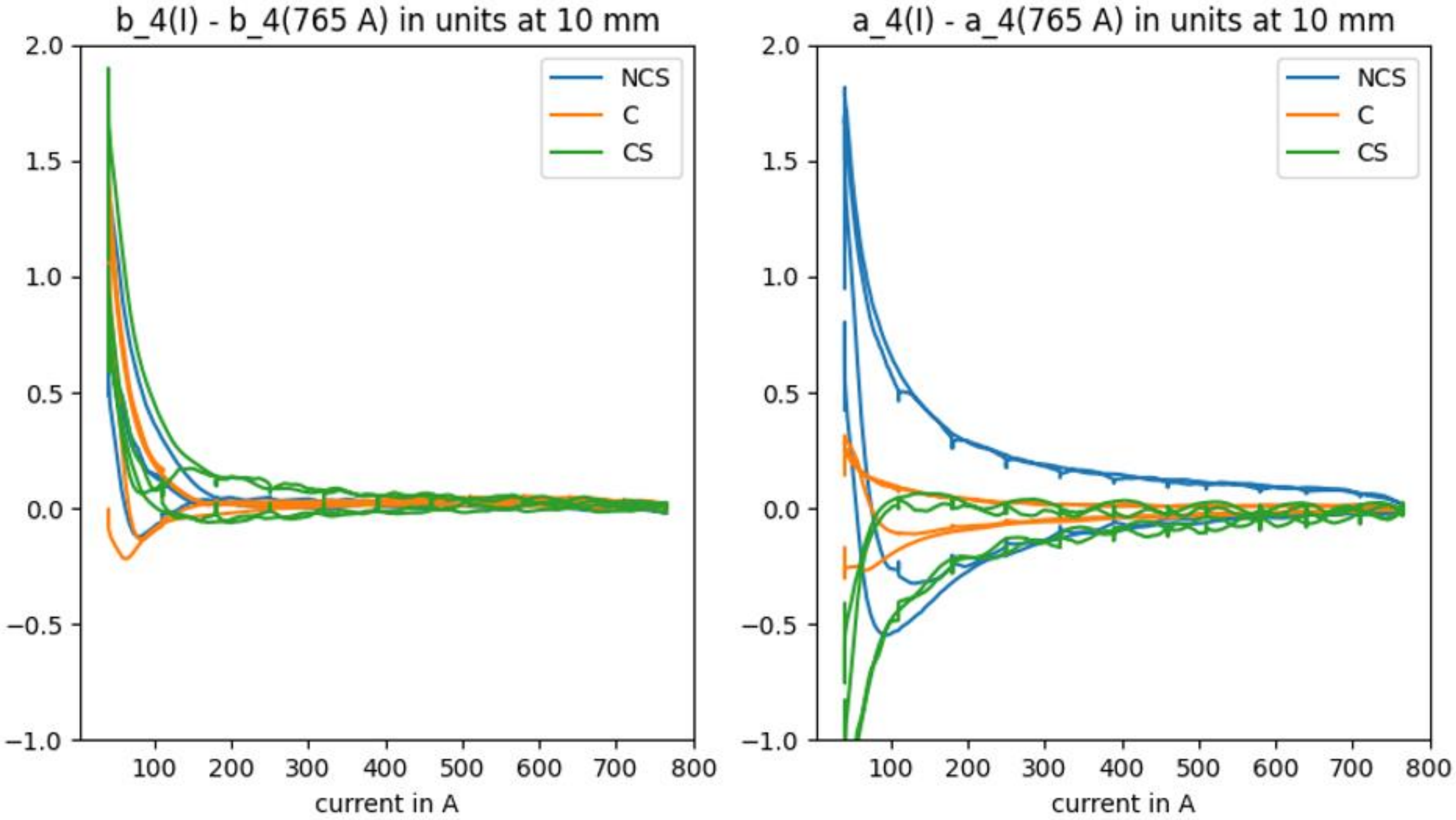


Figure 10: Dynamic effects in the octupole field.

Dynamic effects a6/b6

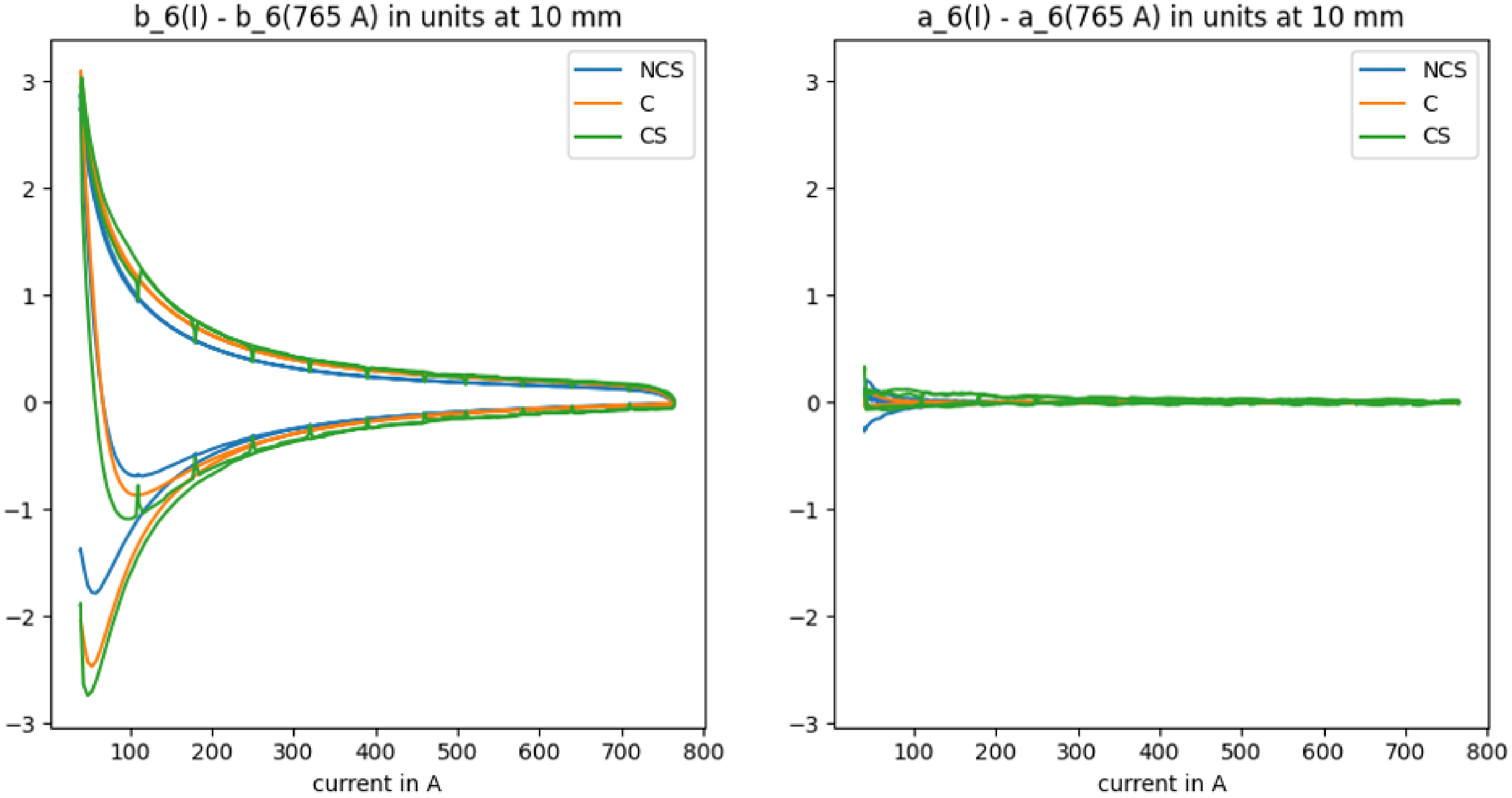


Figure 11: Dynamic effects in the 12-pole field.

Comparison with warm measurement

- At warm we used a more elaborate technique to measure the field quality at the centre of the magnet, by taking two independent measurements where we left the measuring system untouched and rotated the magnet only.
- The results obtained from these two measurements enabled us to subtract any contribution from any field distorting environmental effects.
- The final numbers for the field quality of the magnet at warm was better than at cold
- The sides contribution, where we did not use the same trick, were similar to the cold measurements.

Crosstalk compensation e+ beam

harmonics given at a reference radius of: 10.000 [mm]

Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	-3.39e-05	-0.49		B1	3.44e-05	0.50	
A2	4.38e-05	0.63		B2	6.95e-01	10000.00	
A3	-4.47e-05	-0.64		B3	-5.26e-06	-0.08	
A4	2.52e-05	0.36		B4	-4.56e-05	-0.66	
A5	3.44e-06	0.05		B5	-9.05e-06	-0.13	
A6	-1.07e-06	-0.02		B6	3.89e-05	0.56	
A7	2.25e-06	0.03		B7	-4.74e-05	-0.68	
A8	4.80e-07	0.01		B8	-2.13e-05	-0.31	
A9	1.33e-06	0.02		B9	-6.11e-07	-0.01	

M. Koratzinos

All multipoles below 10^{-4}. I stopped the optimization when I reached this level, but further improvement is possible and easy, up to the manufacturing tolerances (10^{-5}??).

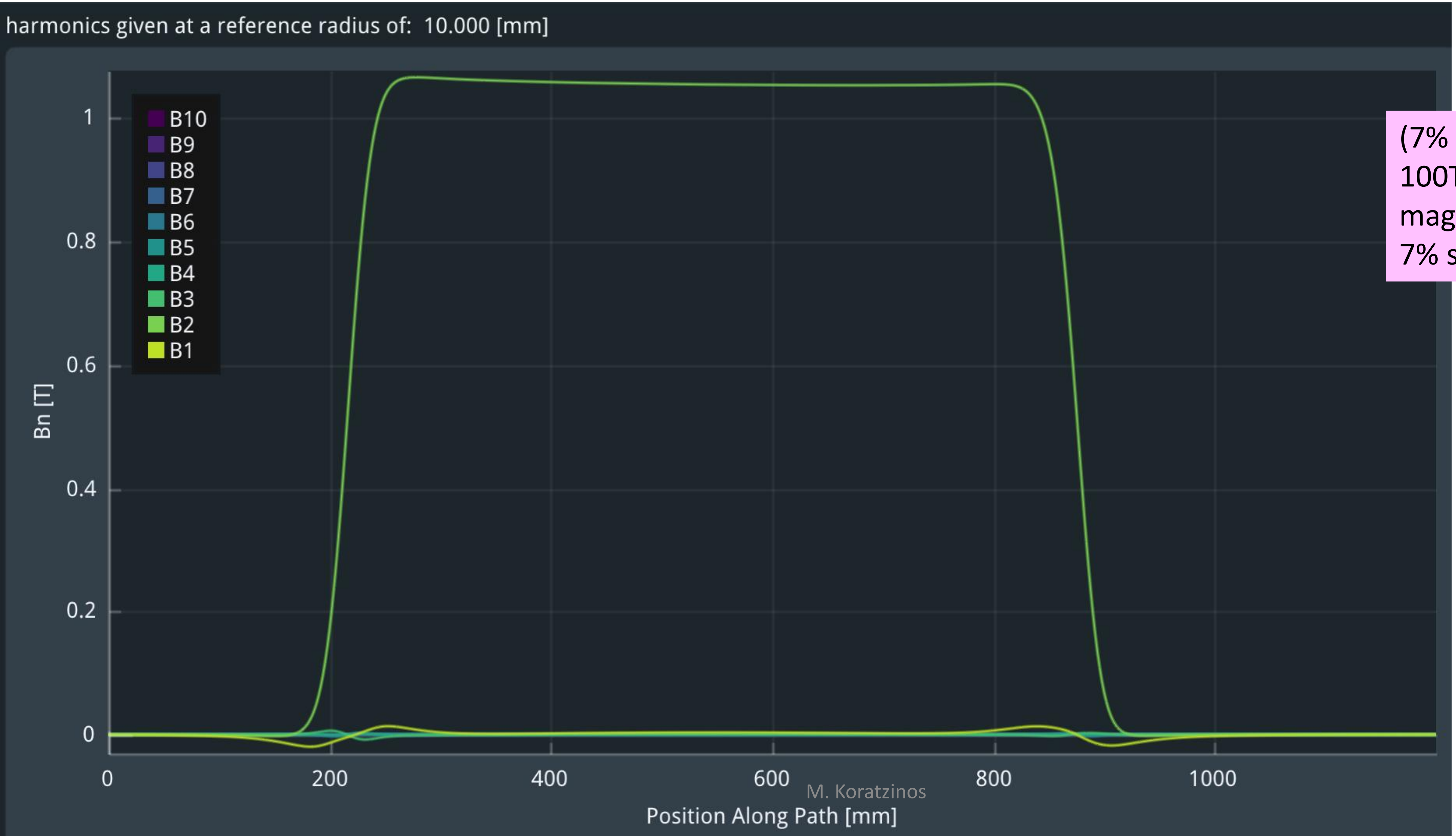
Crosstalk compensation e- beam

harmonics given at a reference radius of: 10.000 [mm]

Order	An [T.m]	an	Normalized Shape		Order	Bn [T.m]	bn	Normalized Shape
A1	-3.39e-05	-0.49			B1	-3.44e-05	-0.50	
A2	-4.38e-05	-0.63			B2	6.95e-01	10000.00	
A3	-4.47e-05	-0.64			B3	5.26e-06	0.08	
A4	-2.52e-05	-0.36			B4	-4.56e-05	-0.66	
A5	3.44e-06	0.05			B5	9.05e-06	0.13	
A6	1.07e-06	0.02			B6	3.89e-05	0.56	
A7	2.25e-06	0.03			B7	4.74e-05	0.68	
A8	-4.80e-07	-0.01			B8	-2.13e-05	-0.31	
A9	1.33e-06	0.02			B9	6.11e-07	0.01	
A10	-3.78e-08	-0.00			B10	-8.33e-06	-0.12	

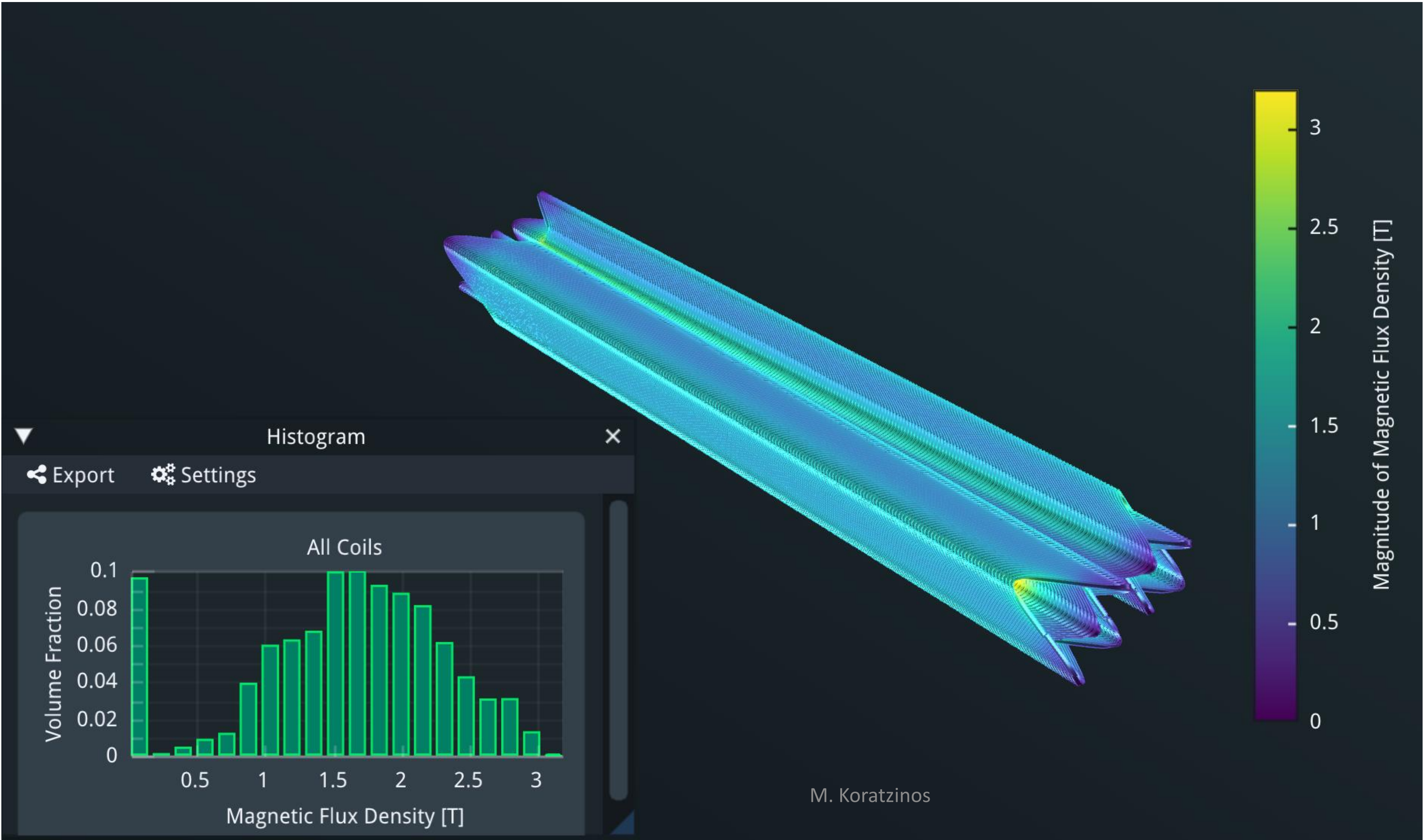
(System is symmetric)

Field gradient


harmonics given at a reference radius of: 10.000 [mm]

(7% higher than 100T/m since the magnetic length is 7% smaller)

Magnetic field for 100T/m gradient



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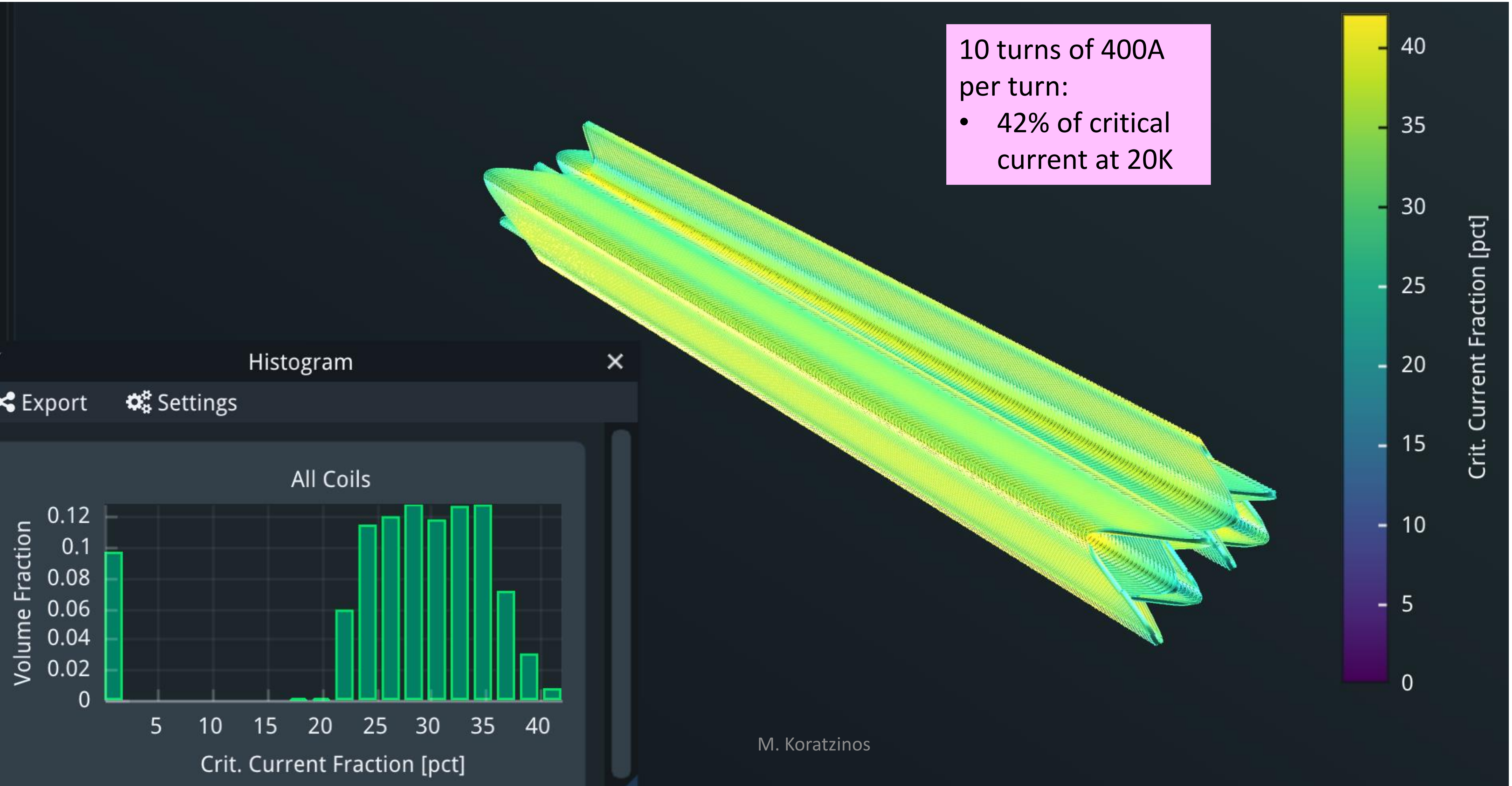
Critical current



10 turns of 400A per turn:

- 42% of critical current at 20K

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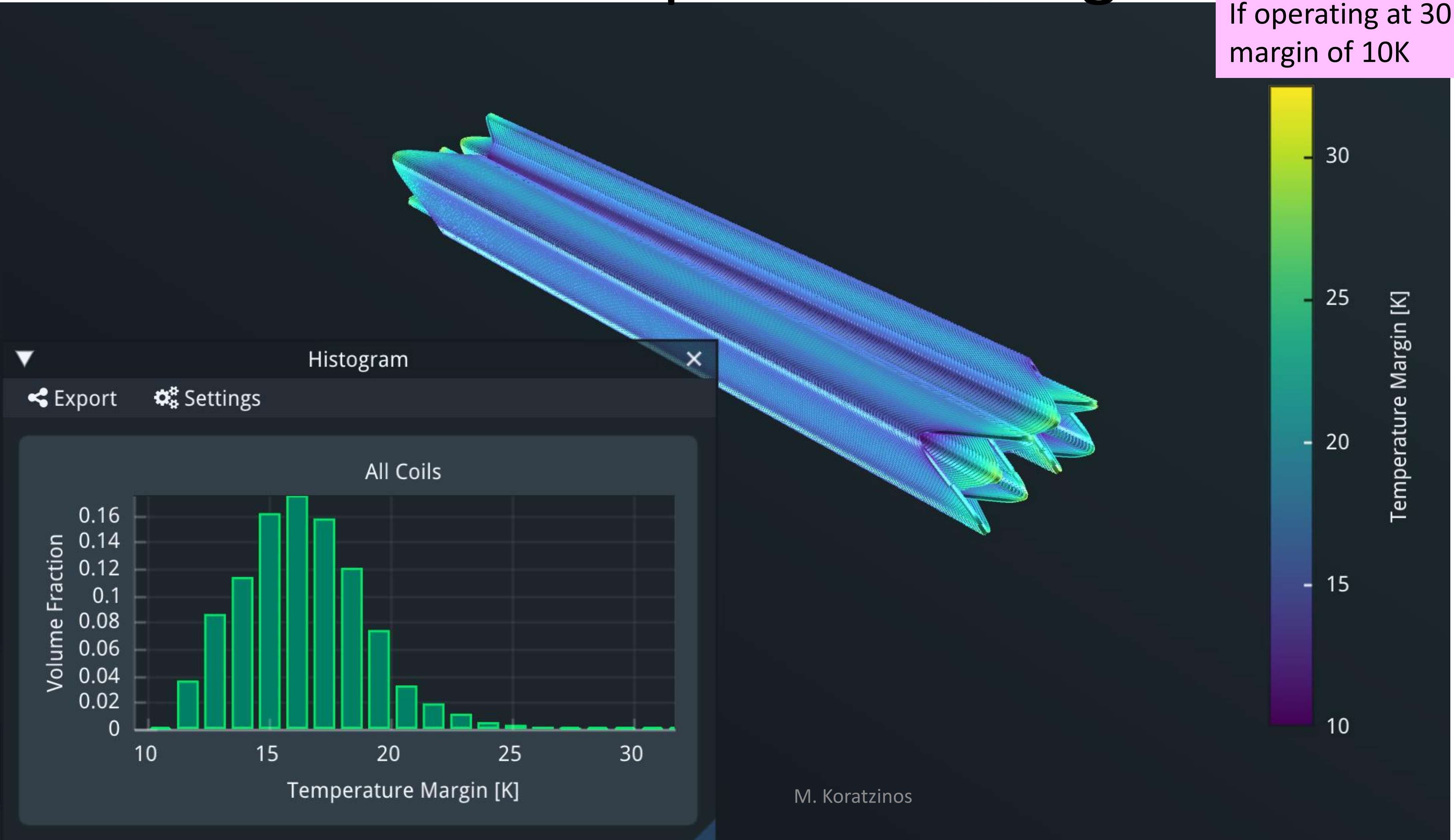
Temperature margin

If operating at 30K we have a margin of 10K



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Parasitic currents

- A potential problem of HTS tapes is parasitic currents when running well below the critical current that could introduce multipole errors
- The real answer of how important these are will be given when we measure the HTS arc sextupole, currently under manufacture for the FCCee-HTS4 project.
- Simulations show that the problem for the HTS4 sextupole is well below 1 unit of 10^{-4}
- Need to measure!

CERN – LAPP COLLABORATION

FCC QUADRUPOLE AND BEAM PIPE : DESIGN AND FABRICATION

Michael Koraztinos[1], Adrien Thabuis[1], Laurent Brunetti[2], Matthieu Marchand[2]

23.04.2024

[1] CERN
[2] LAPP

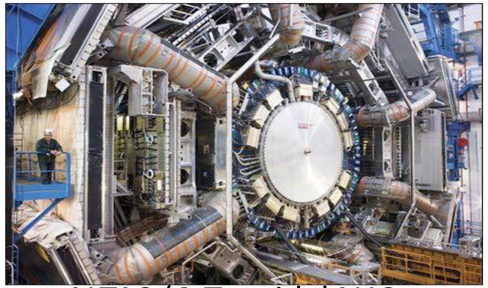
Laboratoire d'Annecy de Physique des Particules (LAPP) – Fundamental Research in Annecy

- Created in 1976, the **LAPP** is a laboratory of the **CNRS** French National Institute for Nuclear and Particle Physics (**IN2P3**) and **USMB.**
- **Particle and Astroparticle physics,** a combination of the experimental investigations of the two infinities, from the largest-scale structures in the observable Universe to the most fundamental particles.
- A theory Laboratory (LAPth) and different research fields working on several fundamental physic experiments all around the world.

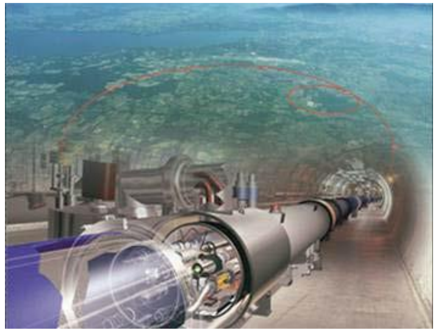
CTA (Cherenkov telescope Array)

VIRGO (Michelson Interferometer for gravitational waves)

DUNE (Deep Underground neutrino Experiment

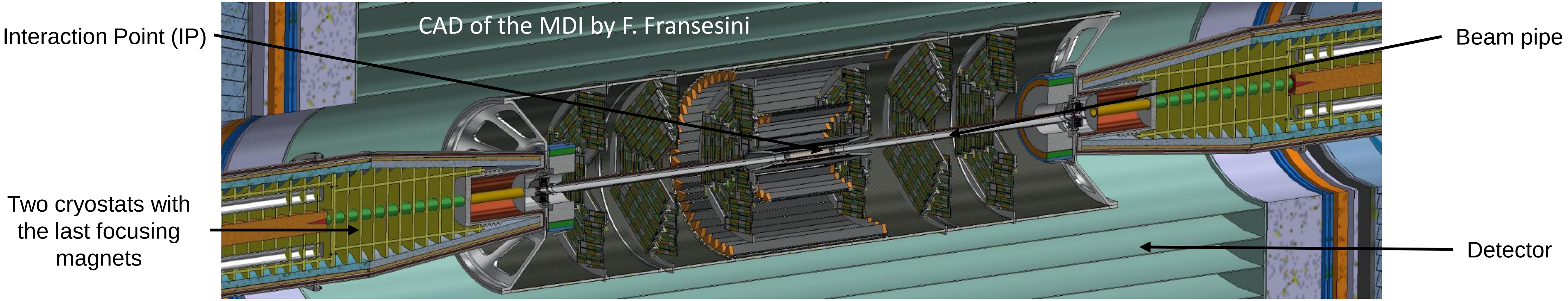


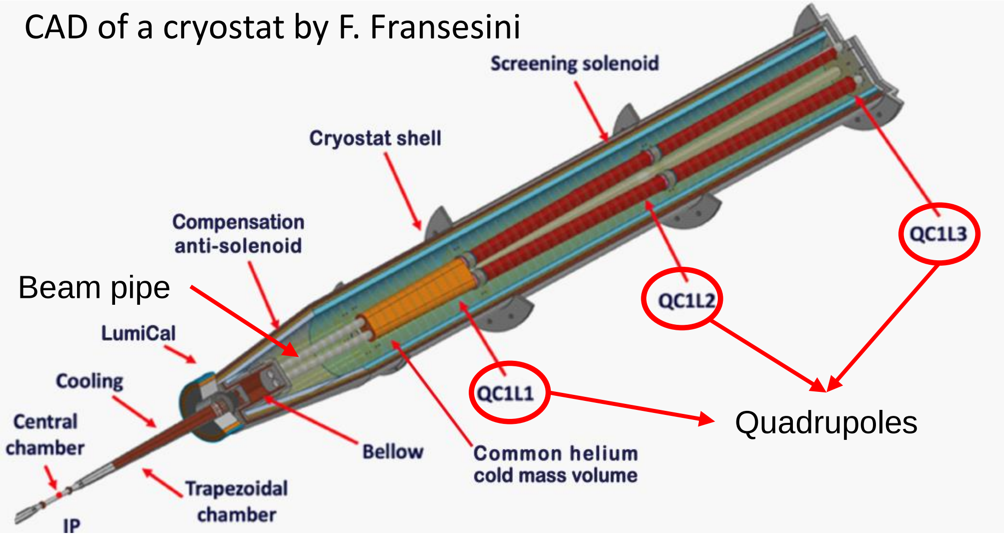
ALTAS (**A** **T**oroidal **L**HC Apparatu**S** **–** particles detector for LHC)



FCC (Future Circular Collider)

The Machine Detector Interface (MDI) – A key area in the FCC


CAD of the MDI by F. Fransesini


CAD of a cryostat by F. Fransesini

- The MDI, the area at the interface between the accelerator and the detector and near the Interaction Point (IP), where the particles collide.

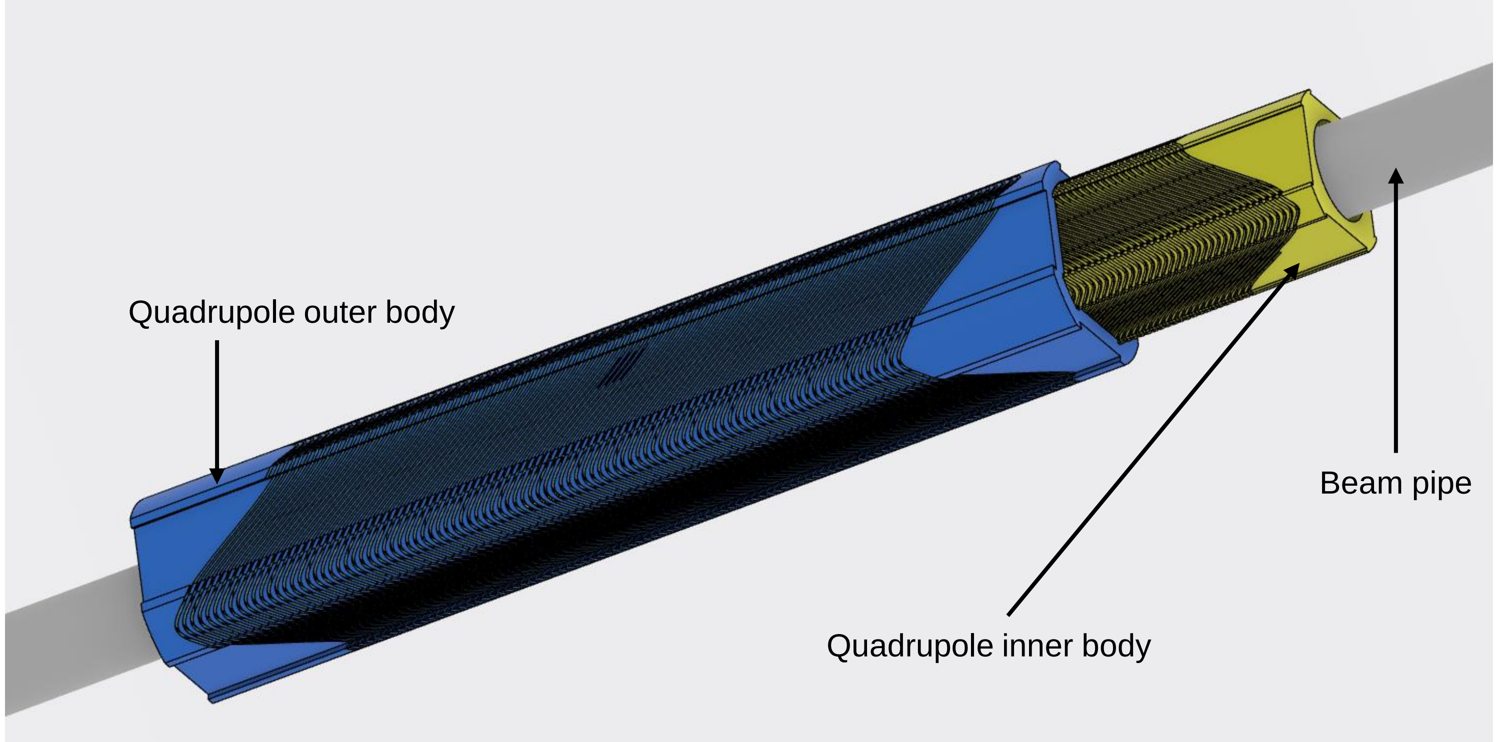
- It’s composed of two cryostats, where a succession of quadrupoles, supra-conductor magnets, “focalizes” the particle beam.

- To focalize the particle beams is to ensure the maximum of collision between the particles in a closed environment, the beam pipe.

- The beam pipe is a tube passing through the quadrupoles and containing the particle beam.

CERN – LAPP Collaboration – The Project

- The CERN – LAPP collaboration project aims to design and fabricate a prototype for the quadrupole (priority) and the beam pipe.
- The objective is to find a partner(s) to help us fabricate the prototypes, along with all the related technical challenges.
- Once the prototypes are built, we can start the trials.
- Presentation of the two pieces :
  - Function and Design
  - Technical specifications
  - Fabricability challenge



The Quadrupole (1/4) – A Supra-conductor Magnet

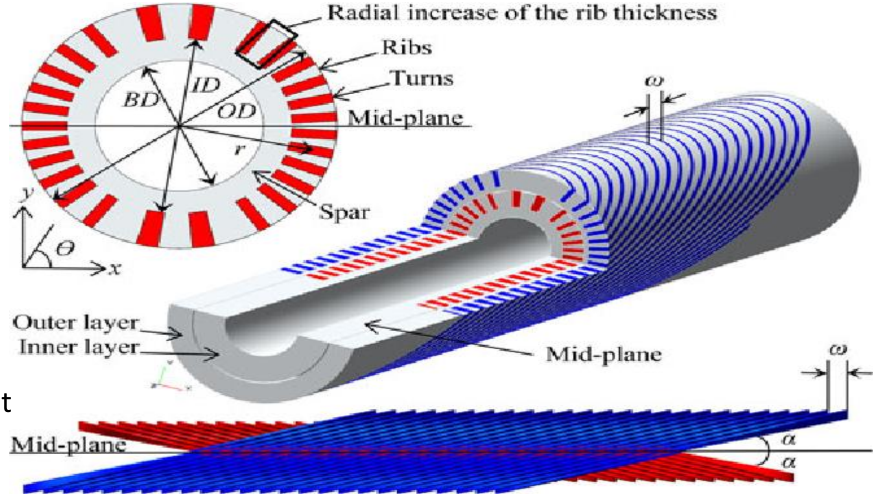
Supra-conductor ribbon used in a CCT magnet

- A supra-conductor magnet, a magnet with a supra conductor coil material , emitting a magnetic field without any loss of energy (no electric resistance). It needs to be in a cold environment to function, near absolute zero (2° Kelvin).

- The quadrupole is a HTS and CCT supra-conductor magnet.

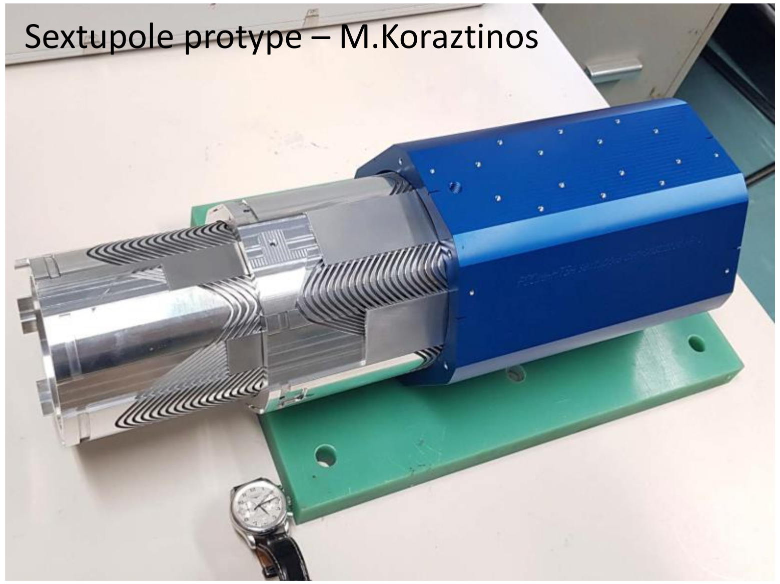
- HTS = supra conductor coil functioning at higher temperature (>30° Kelvin)

- CCT = a magnet design using two opposed and canted solenoid fields. The HTS coil is nested inside titled grooves, in each layer



Example of a 2-layer CCT magnet
layout with rectangular cable
L. Garcia Fajardo

The Quadrupole (2/4) – The Design

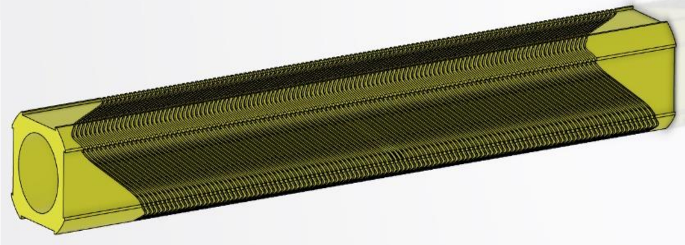


Sextupole protype – M.Koraztinos

- The CERN already prototyped and tested a sextupole, another kind a magnet in the FCC.
- The tests were very promising, the next step is to prototype the quadrupole.
- The magnet design starting point is the magnetic field. A magnetic simulation enables to know the shape the coil has to take for the magnet to meet the physic specifications.
- The magnet body is designed around this coil shape according to the technical specifications.

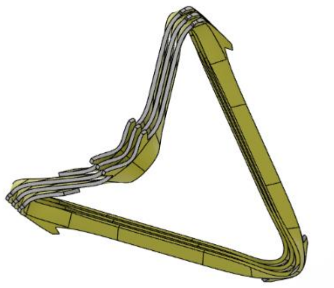
Magnetic representation of the quadrupole -M Koratzinos

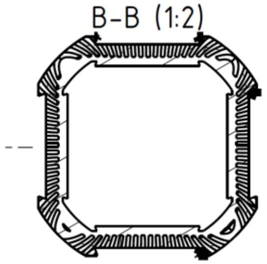
The Quadrupole (3/4) – The Technical Specifications



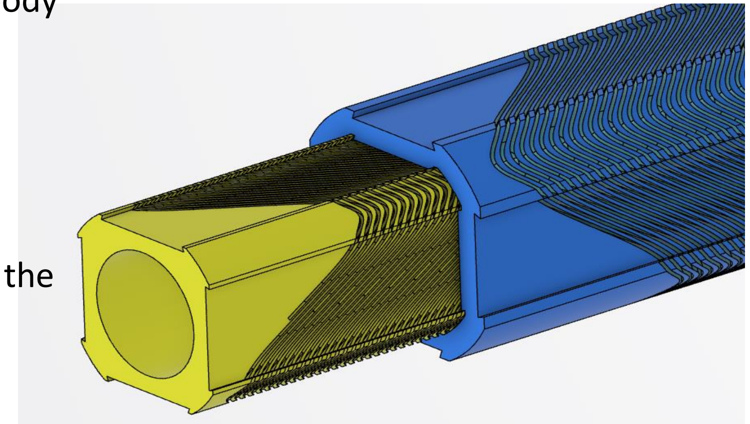
- Main characteristics
  - Two body parts to cancel solenoid fields => the inner body (yellow) nested in the outer one (blue)
  - Aluminum => non magnetic
  - Shape => square (4 sides) with rounded extremities , cylinder shape inside the inner body

- Dimensions
  - Length => 400mm prototype and 600mm final piece
  - Inner cylinder => 40mm diameter
  - Inner body maximal diameter => 65mm
  - Outer body maximal diameter => 84mm





- Groove
  - Single canted groove on each body => nest of the supra-conductor ribbon
  - 0,9mm wide (constant), 4 to 8mm deep, 1.8 spacing
  - +/-60° tilt in relation to the axe's body



- Assembling
  - Pin system to stop the translation between the bodies
  - A 0,3mm space between the two bodies => no contact
  - Surface finish => sufficient to respect the space between the two bodies + not damaging the coil inside the groove
  - Tolerance => see drawings

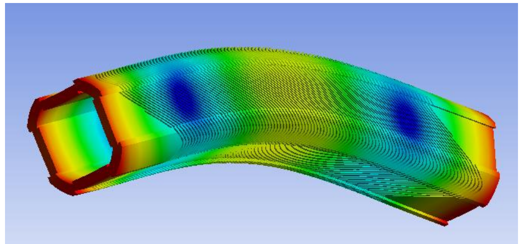
The Quadrupole (4/4) – The Fabrication Challenge

- The complex design make the fabrication of this piece complicated. A test has already been made in CERN. The surface finish was not ideal and the machining timing was very long.

- Fabrication process
  - 3D fusion impression of both bodies
  - 5 axes CNC machining for surface finish correction

- Fabrication challenges
  - Not a lot of 3D and CNC machine with a 600mm capacity
  - May need to fabricate 200mm section of the magnet and assembled them together => alignment complications for the groove and rigidity
  - The very thin width of the magnet (between the bottom of the groove and the internal wall of the bodies) => deformation and tearing during the machining
  - 600mm inner body first mode of deformation (cantilever): 244Hz
  - 600mm outer body first mode of deformation (cantilever): 134Hz

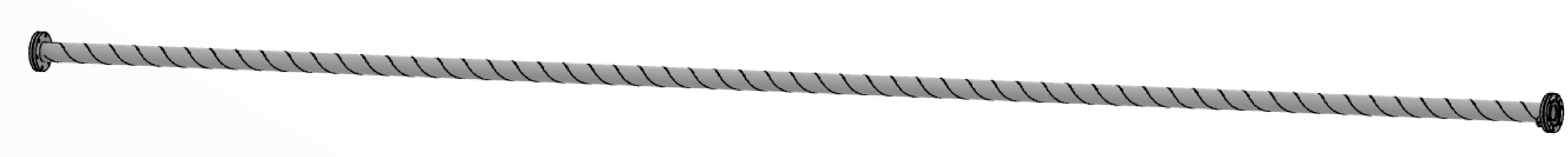
Machined Quadrupole-M Koratzinos

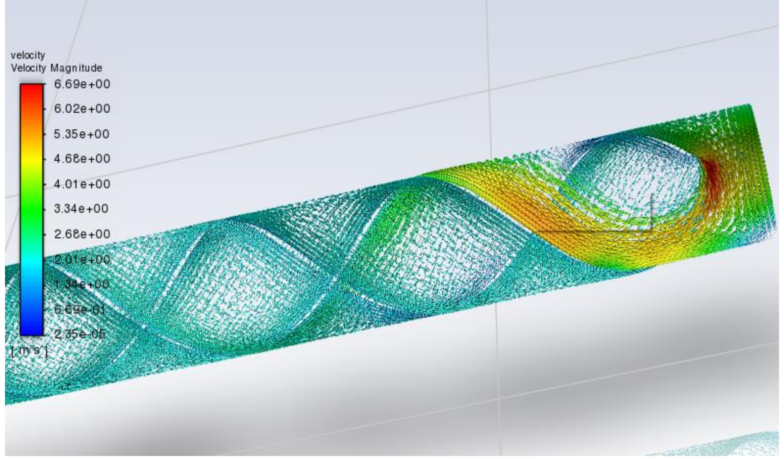


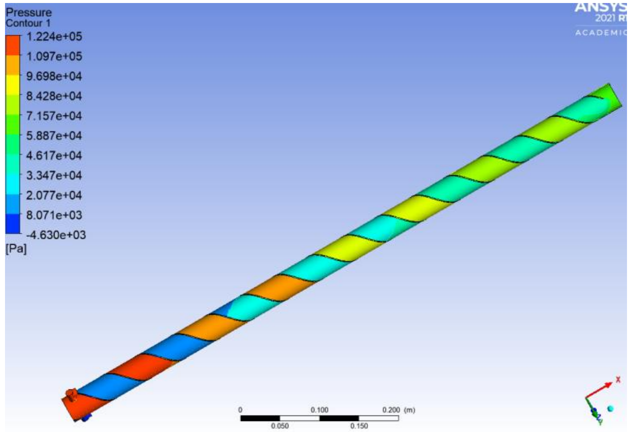
The Beam Pipe (1/3) – A high vacuum-sealed tube

- The beam pipe, a tube where the particle beam passes through, is a vacuum tube.

- The beam pipe inside the cryostat passes trough the quadrupoles, and need to be cool down due to the heat radiation of the beam.



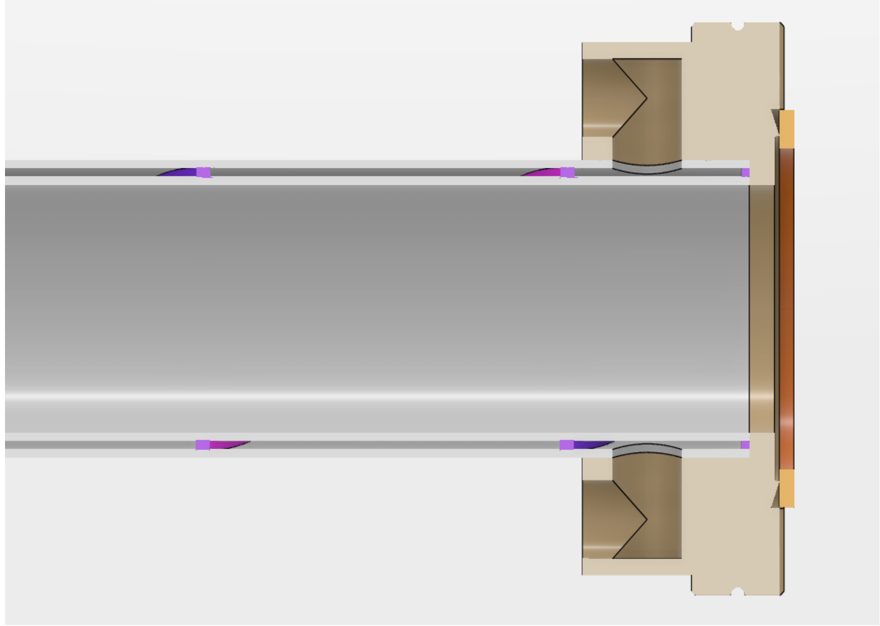




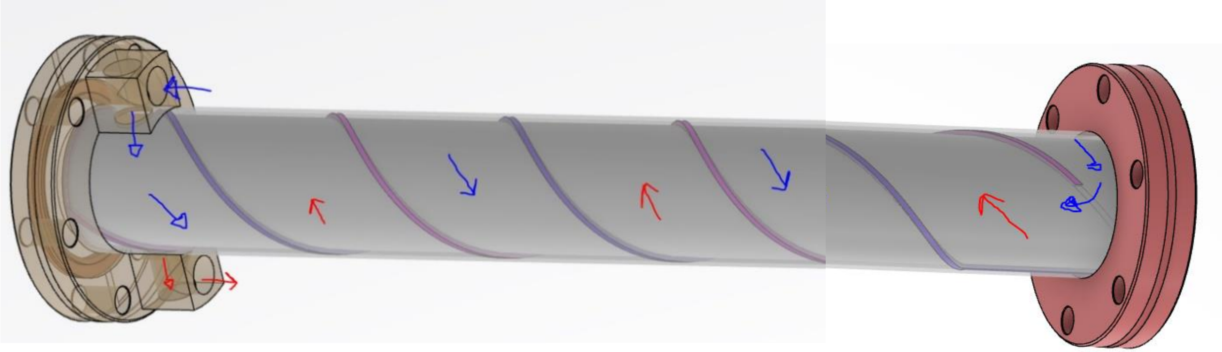
- The tube has an inner structure in spiral which allow a fluid flow to cool down the tube walls.

- The design is at its premises. It will evolve according the future structural, vibrational and fluidic studies, as well with the physics specifications if needed.

The Beam Pipe (2/3) – The Technical Specifications



- Main characteristics
  - A hollow wall tube with a double structure helix inside the wall pipe => heat transfer to cool the tube down
  - Fluid => water
  - Vacuum => inside a 10e-10Pa ultra-vacuum, outside a 10e-4 primary vacuum
  - Inox or aluminum => compromise between fabricability process and rigidity
  - Airtight and leakproof
  - Congestion in the cryostat force us to place the enter and exit of the flow at the same extremity
  - Two flanges at each extremity to connect the tube to the other section of the beam pipe outside of the cryostat



- Dimension
  - Length => 3 meters
  - Inter diameter => 30mm
  - Outside diameter => 36mm
  - Wall thickness => 1mm
  - Spiral => 1mm thick, 2mm wide
  - Flanges => 70mm diameter, 12.7mm thick, 1/8 inches tapping for hydraulics connectors, welded to the tube
  - Surface finish and tolerances => sufficient to not disrupt to fluw

- Data => 0,1MPa water pressure ; 1m/s fluid velocity ; 100W/m to dissipate
- Adapt the design to reduce turbulences and wall shear stress

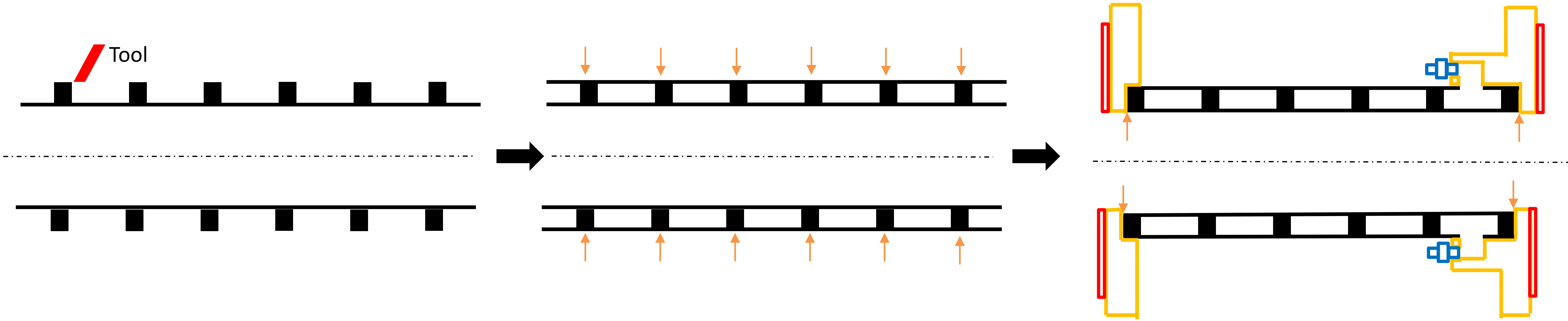
at the enter, exist and return flow

The Beam Pipe (3/3) – The Fabrication Challenge

- The complex design make the fabrication of this piece complicated. The shape and the length of the piece make it impossible to fabricate it in one continue block

- Fabrication process
  - Several section welded together
  - 2mm thick pipe, machined to create the spiral structure
  - The machined tube is slide into another 1mm tube, and then welded together via electron beam
  - The flanges are welded to the tube by electron beam or FSW

- Fabrication challenges
  - Thickness of the pipe wall => deformation and tearing during machining
  - Length => find machines capable to welded 3 meters of tube
  - A solution could be the 3D impression of the section before the welding



The helices section (black square) are machined on the 2mm thick

The superior pipe is welded (green arrows) to the first pipe at the exact position of the helices.

The flanges (yellow) are welded to the beam pipe, as well as the hydraulic connectors (blue) and the copper joints (red) are added.