IAS Program on High Energy Physics (HEP 2024)

SC Final Focus quadrupoles

M. Koratzinos

23/1/2024

FUTURE CIRCULAR COLLIDER

CERN

A tale of two projects

CEPC and FCC-ee are the two circular collider future flagship projects with a lot in common and very few differences!

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

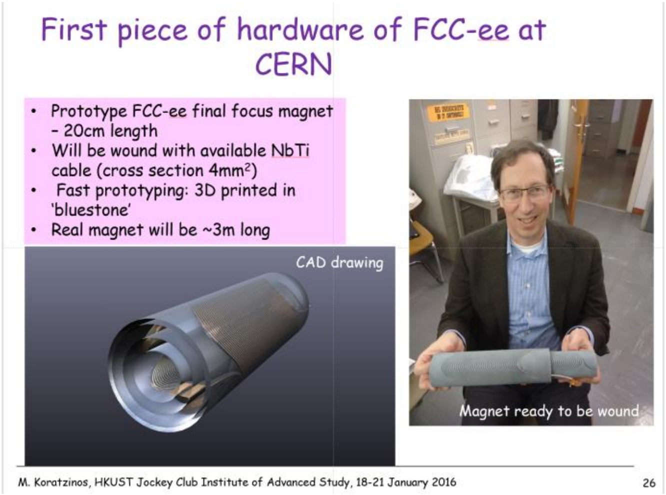
K. Oide
27 Sep 2023

QC1L1

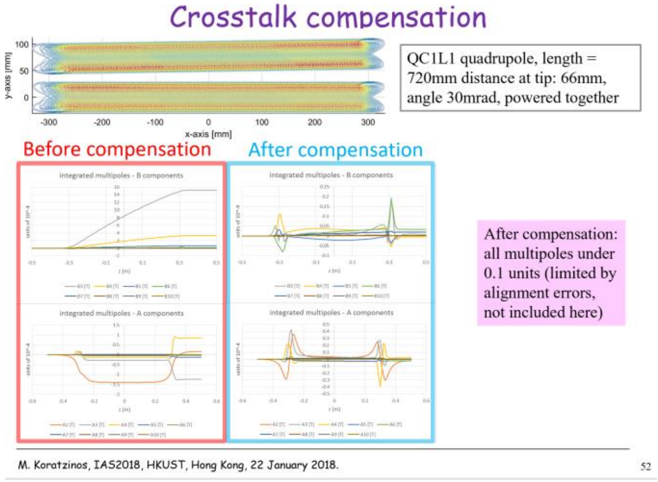
- The quad closest to the IP (and closest to its neighbour)
- Length 700mm
- Strength 100T/m
- Inner diameter of the beam pipe: 30mm
- A CCT prototype was constructed in 2019
  - Length 420mm
  - Aperture 40mm
  - Strength 100T/m
  - Conductor: NbTi (8X0.825mm LHC strand)
  - Temperature: 1.9K (superfluid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

Final Focus quads in IAS conferences

2016



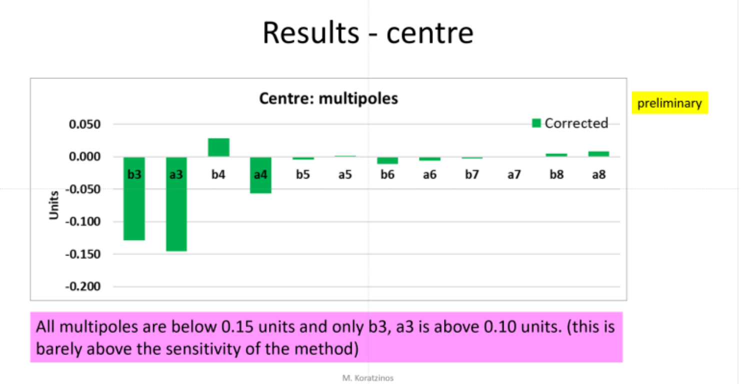
2018



2019

2020

2021

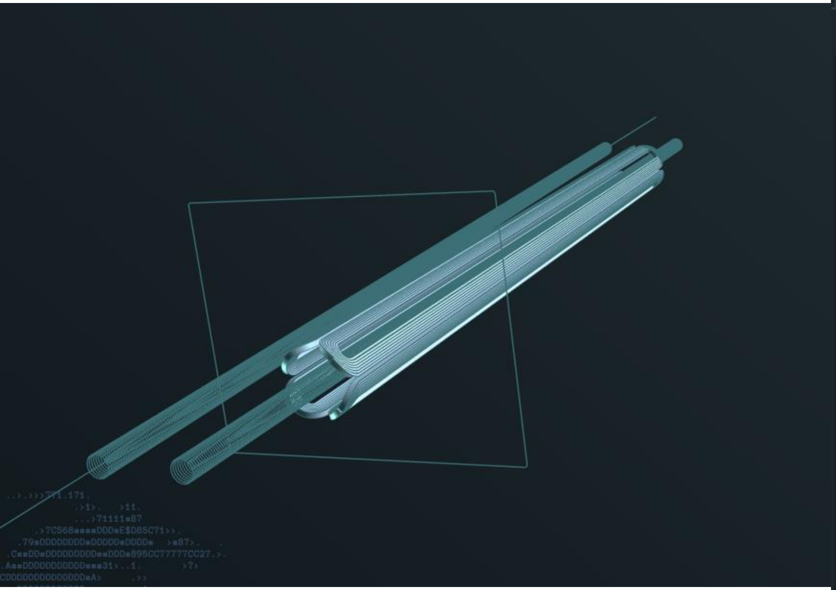


Progress has been reported every year: interesting to see the project from the concept stage to fruition

How to eliminate crosstalk?

- Especially for QC1L1, there is very little space between the e+ and e- quadrupoles.
- One possible strategy would be to use iron to shield one quad from the other
- Is this good enough?
- [In this talk I will be talking about “units”. A unit is a multipole that has a magnitude of 1/10,000 of the main multipole (quadrupole in our case)
- The briefing we were given by the Optics people is that we should limit ourselves to imperfections of less than 1 unit.
- These multipoles are measured at a specific reference radius, traditionally taken to be 2/3 of the aperture. FCC uses 10mm CEPC 7.5mm]

Single cosine-theta quad



Harmonics Table | Main Harmonics | Skew harmonics | Axial Field

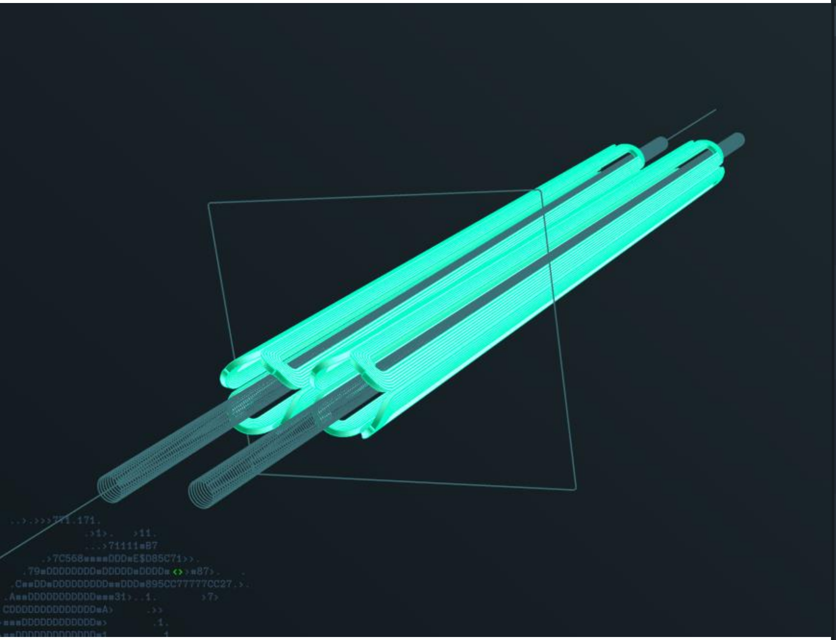
harmonics given at a reference radius of: 7.500 [mm]

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	

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

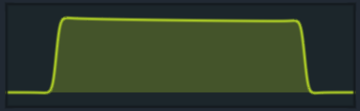
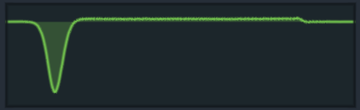
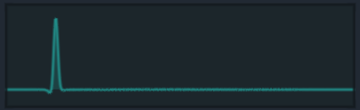
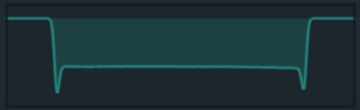
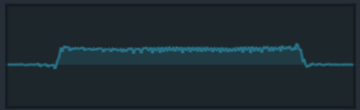
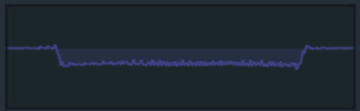
M. Koratzinos

Double quad no iron



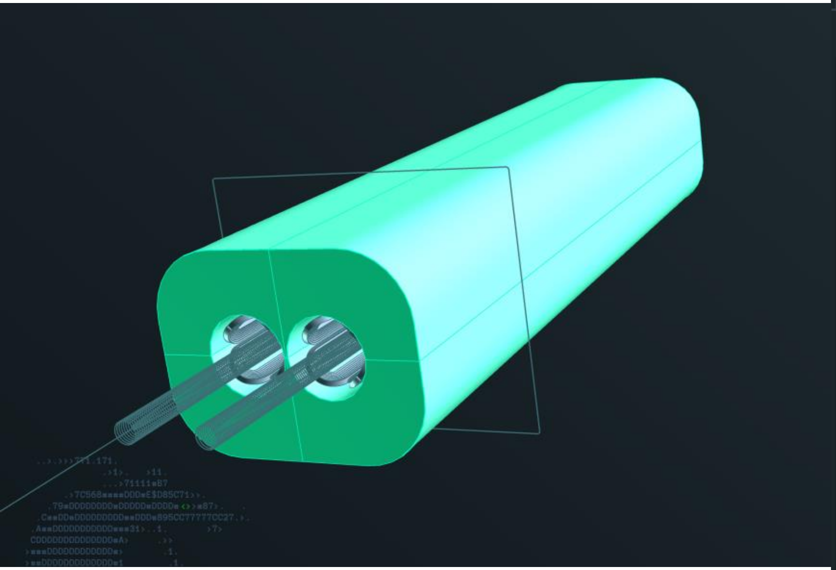
Harmonics Table | Main Harmonics | Skew harmonics | Axial Field

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	

M. Koratzinos

Double quad plus iron



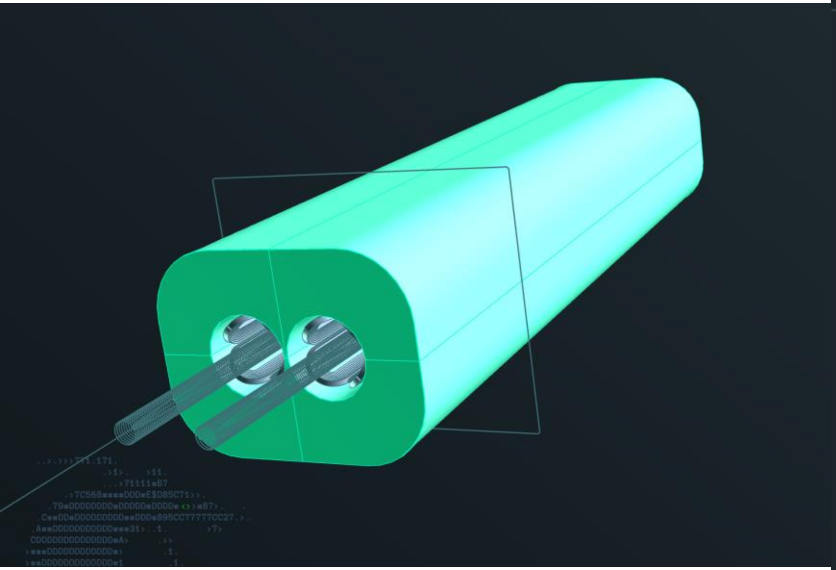
Harmonics Table | Main Harmonics | Skew harmonics | Axial Field

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	

M. Koratzinos

Double quad with iron, half strength

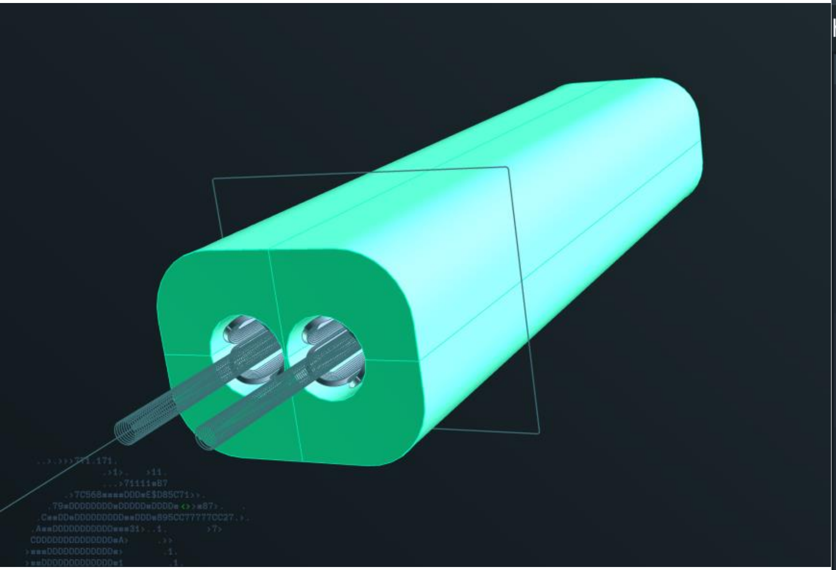


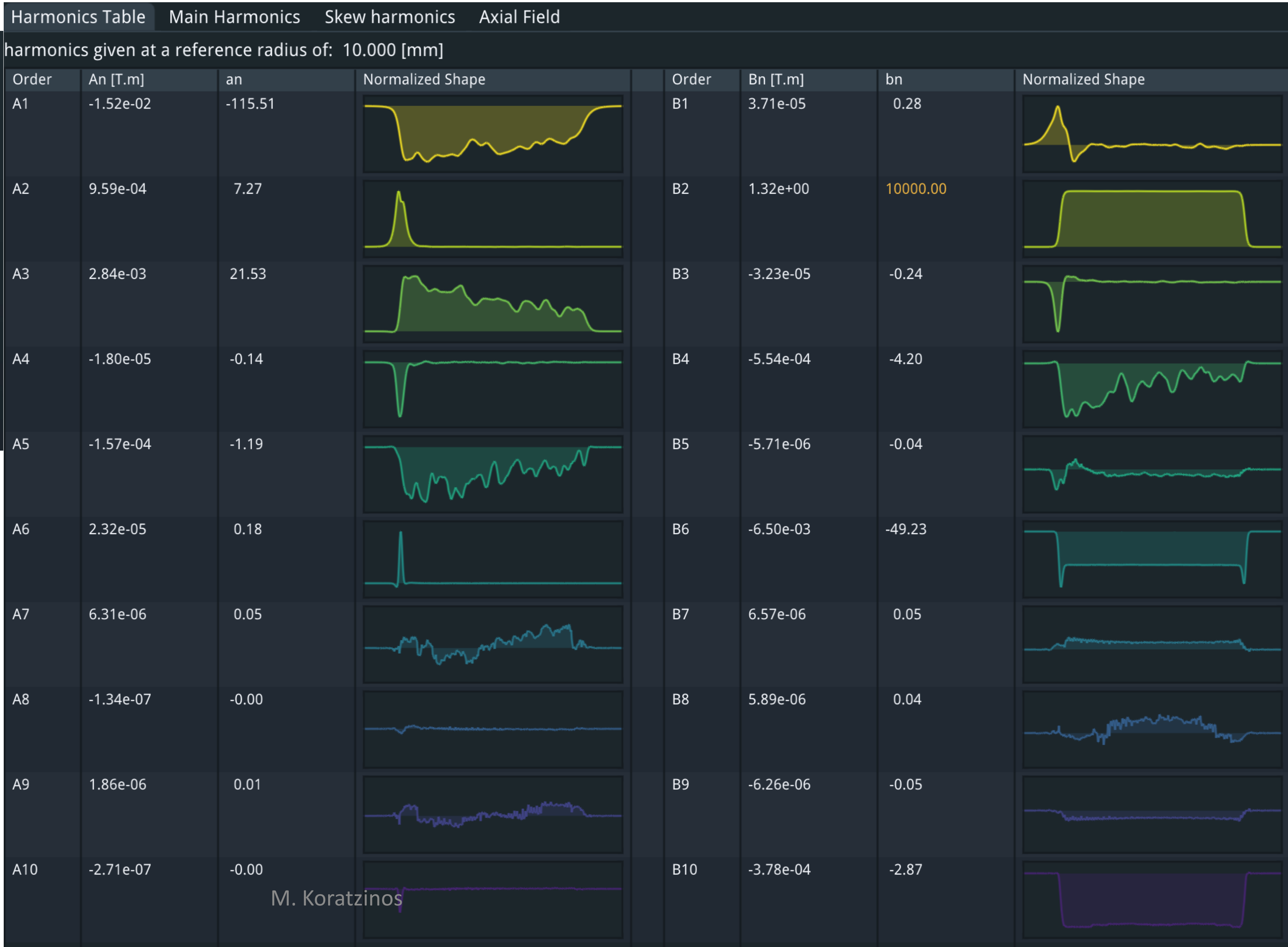
Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	-7.35e-03	-142.50		B1	3.08e-05	0.60	
A2	3.51e-04	6.81		B2	5.16e-01	10000.00	
A3	7.12e-04	13.80		B3	-1.52e-05	-0.29	
A4	-5.92e-08	-0.00		B4	-9.94e-05	-1.93	
A5	-8.91e-07	-0.02		B5	-2.97e-06	-0.06	
A6	2.76e-06	0.05		B6	-8.34e-04	-16.16	
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	

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

M. Koratzinos

(Double quad, iron, 10mm reference radius)





Harmonics Table | Main Harmonics | Skew harmonics | Axial Field

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	

Multipoles larger than 1 unit:
A3: 22 units
A5: 1 unit
B4: 4 units

Iron vs non-iron

- Using iron to shield the two apertures gives significant field imperfections (larger than 10 units @7.5mm)
- Non-linearities are ~2 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

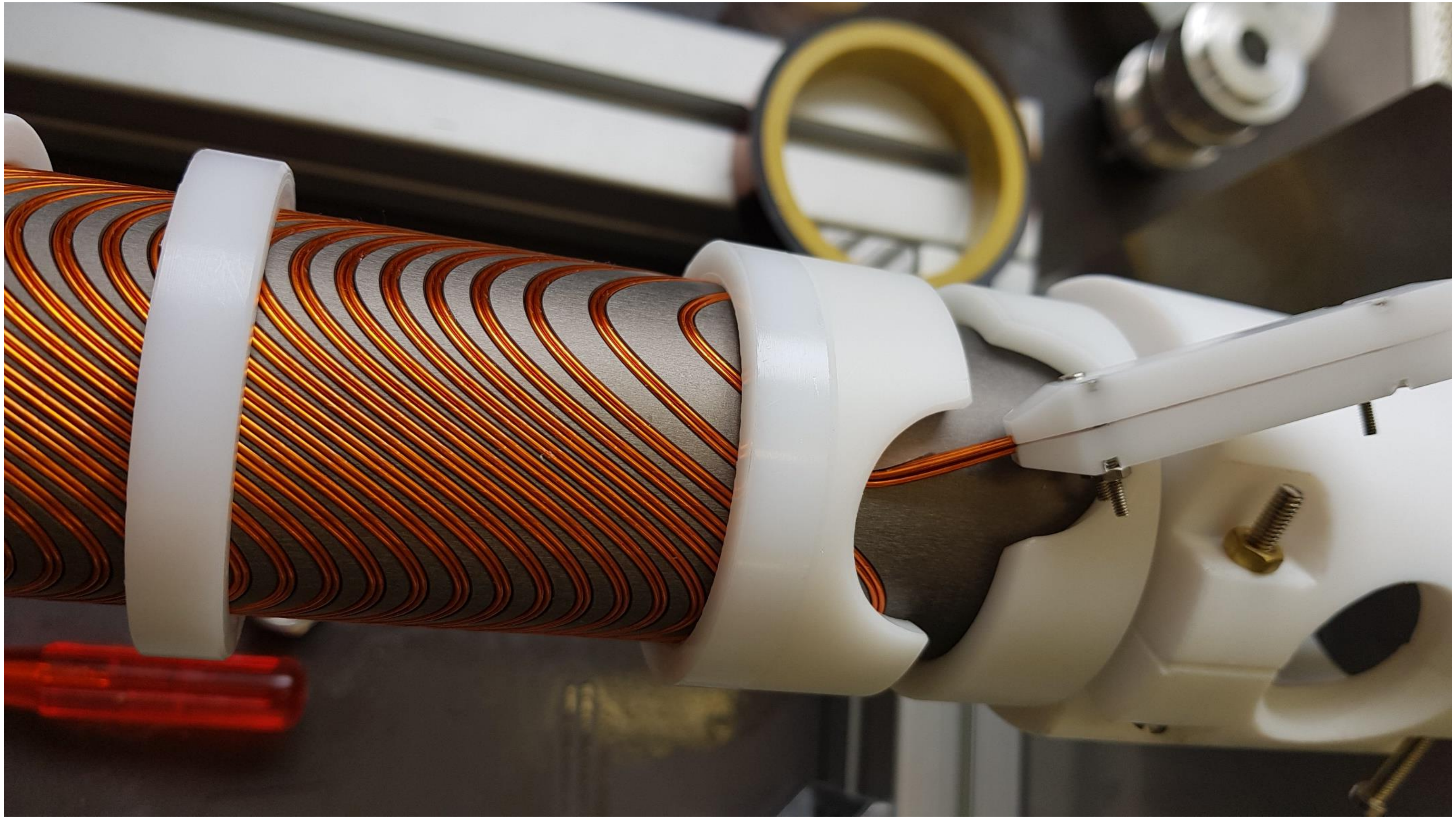
- Was done in-house using the FIELD suite of programs
- Mechanical design done in Autodesk Inventor

Manufacturing

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

winding

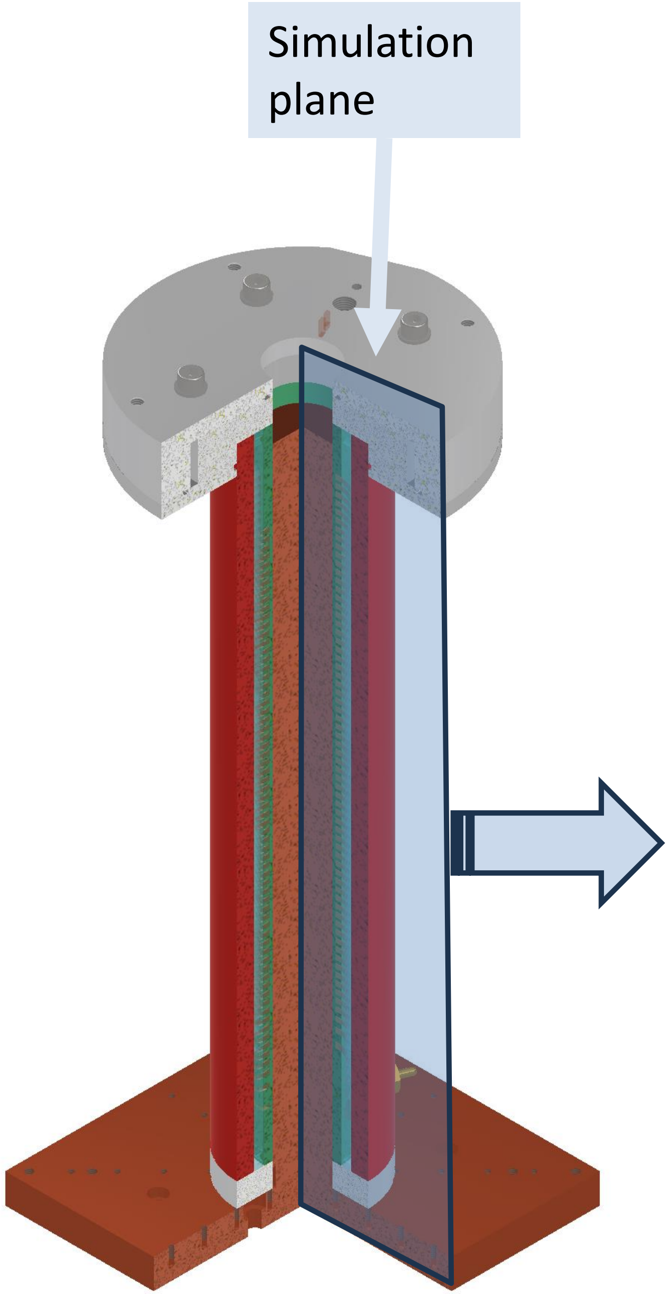
Done in-house using standard LHC 0.825 NbTi strand

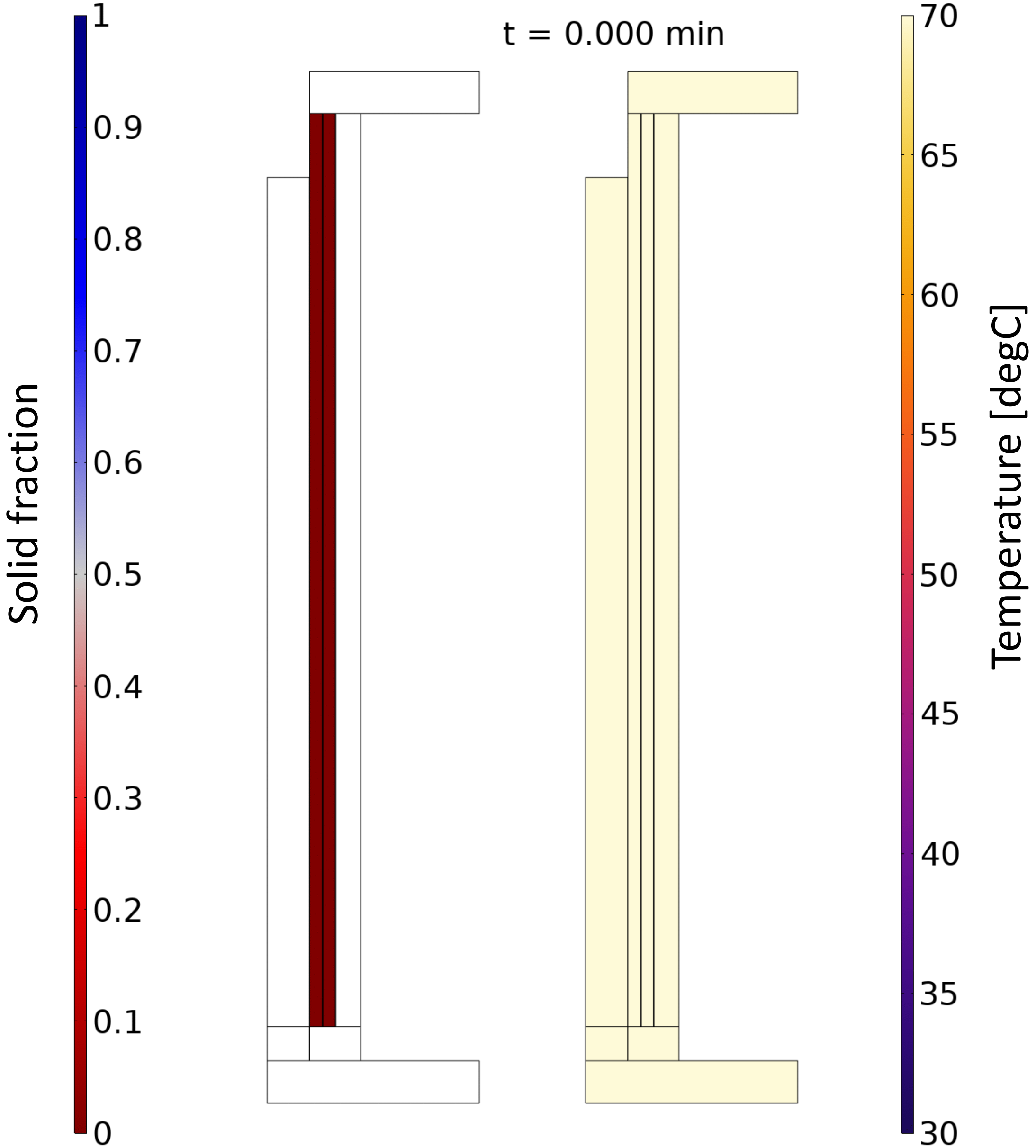


Impregnation

- 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





Crystallization range
[51.5,54.5] Celsius

Jaap Kosse

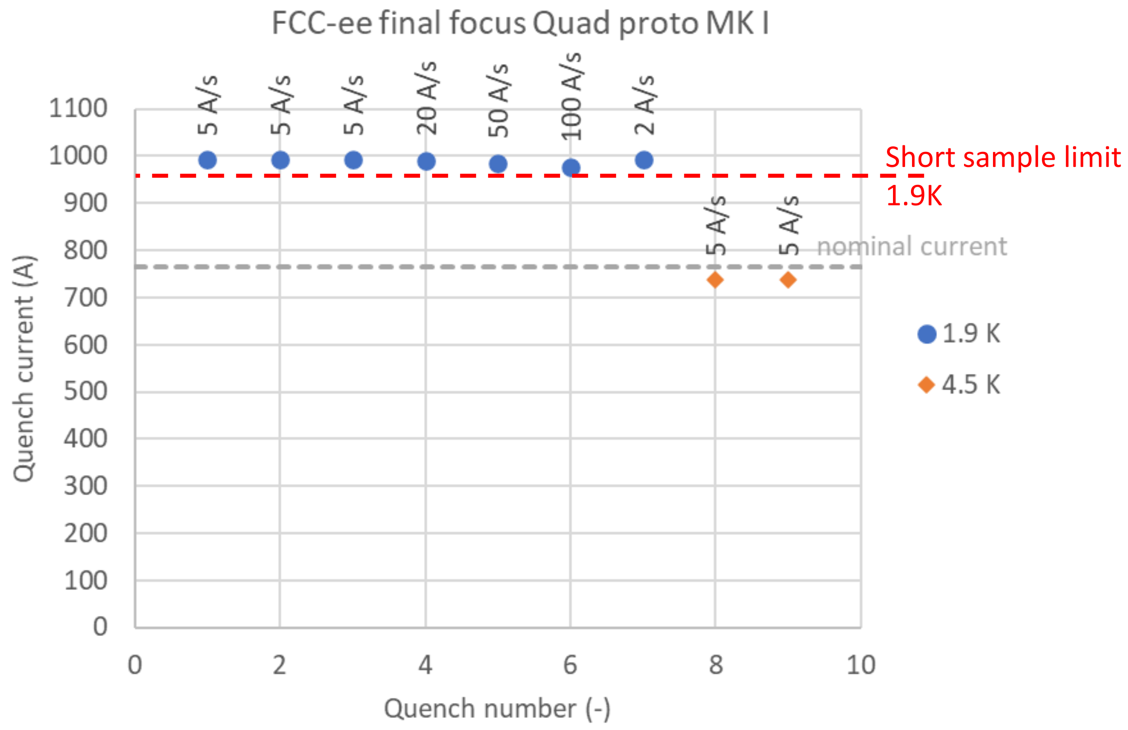
The test at SM18

- 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

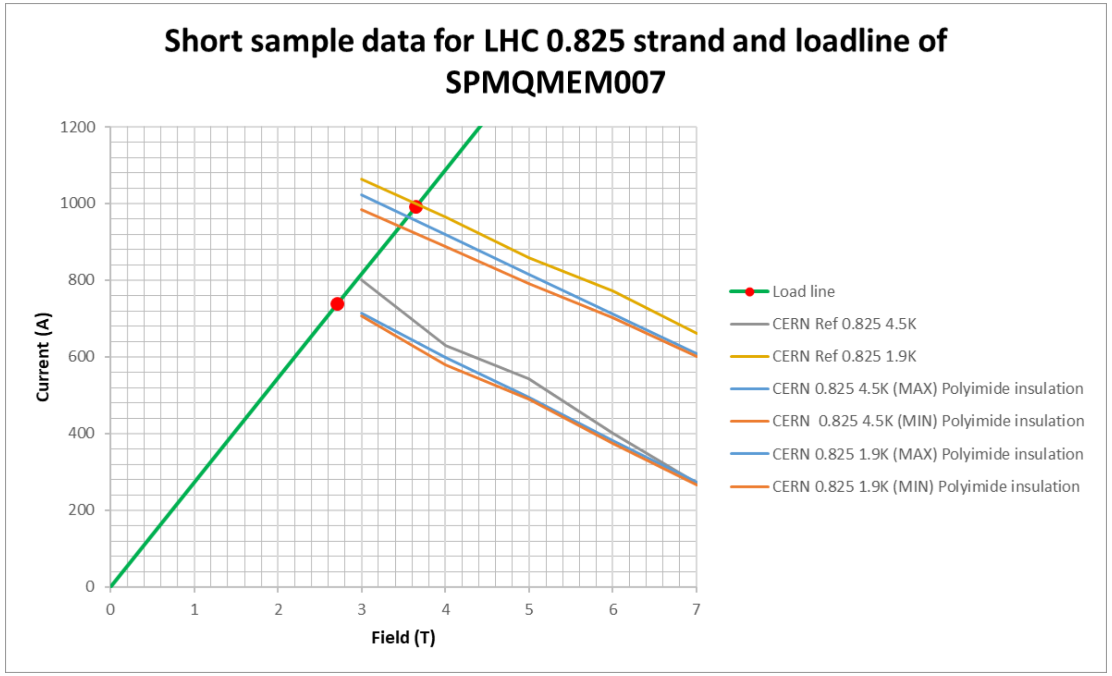
1.9 K: reached 991 A, peak field on conductor is 3.65 T
4.5 K: reached 738 A, peak field on conductor is 2.71 T



Gradients:

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

M. Koratzinos



Comparison to similar projects

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

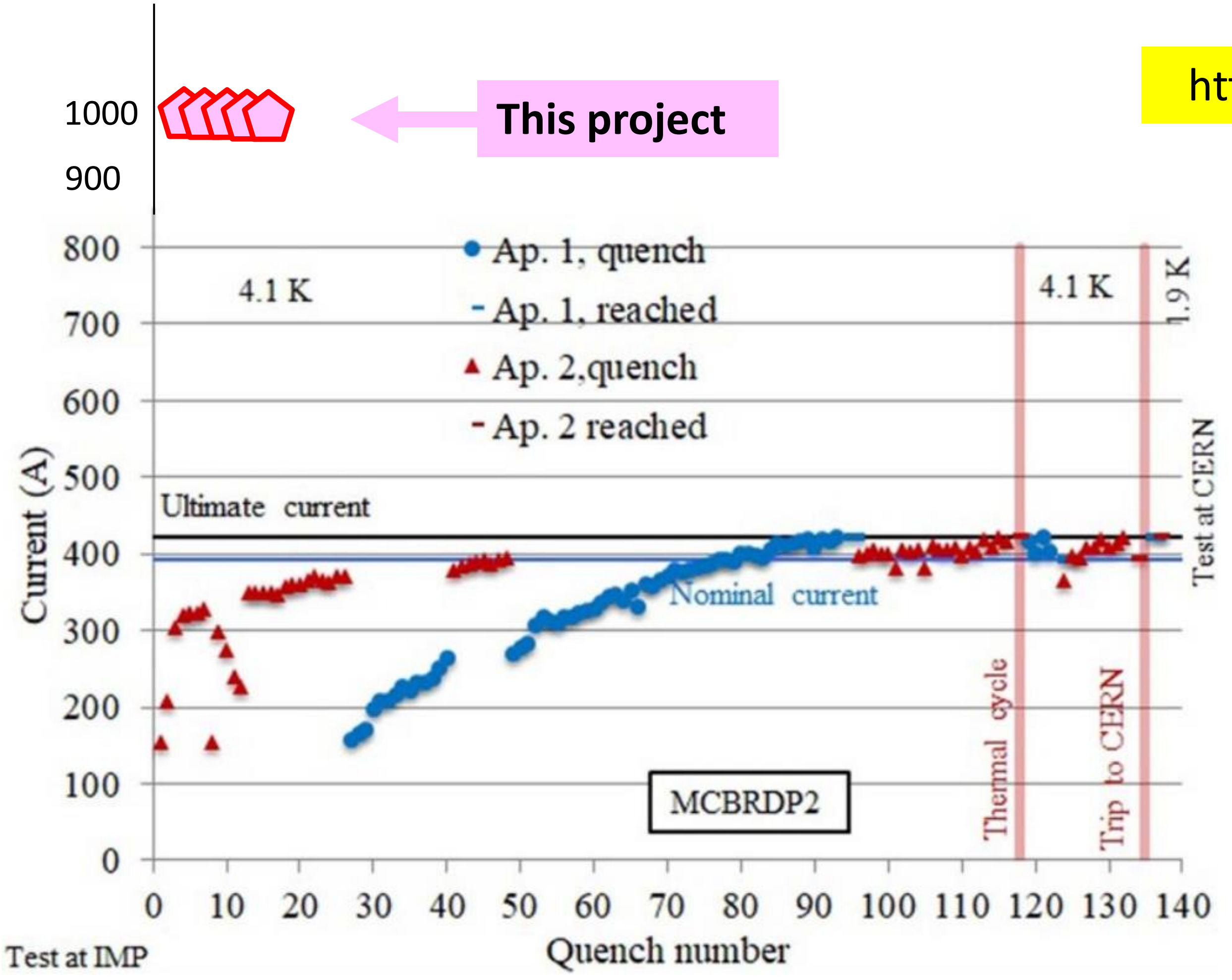


Figure 57. Training performance of D2 corrector first prototype.

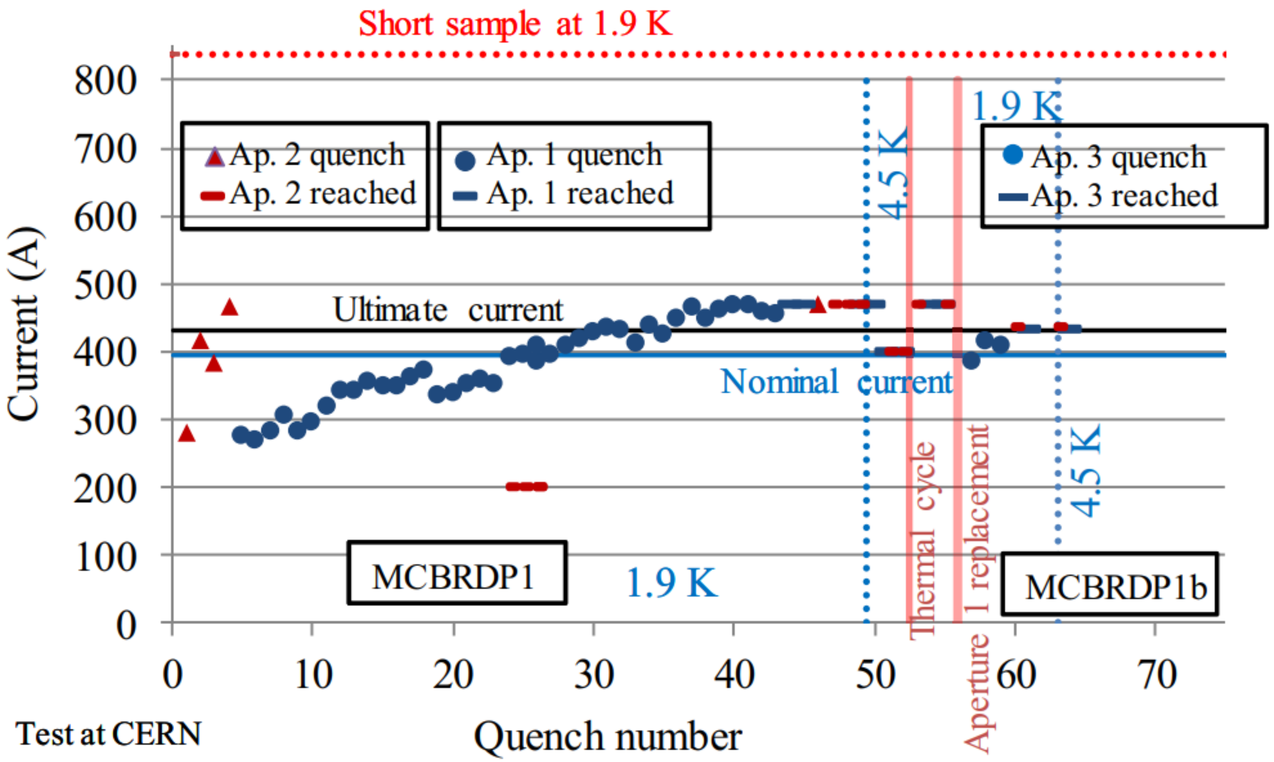
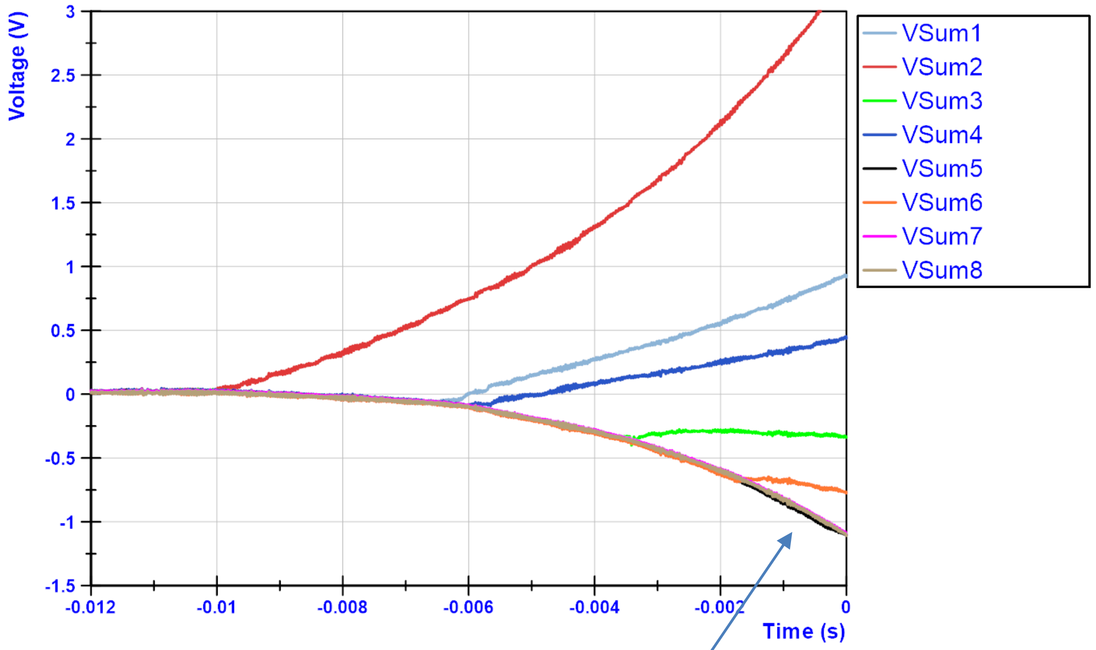


Figure 56. Training performance of D2 corrector first prototype.

Chinese-made MCBRD HiLumi dipole corrector

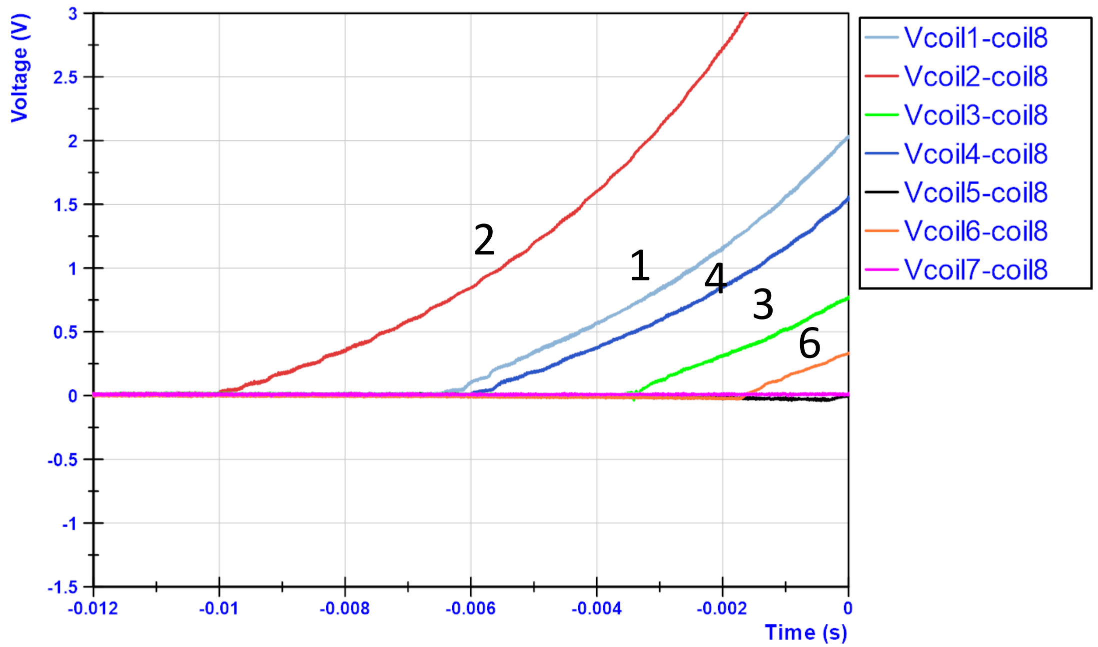
CERN-made MCBRD HiLumi dipole corrector

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



Measured voltage per coil

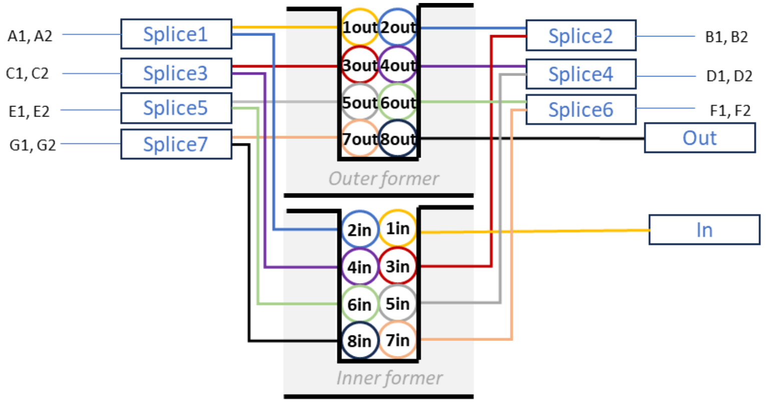
SPMQMEM000-00000007__O202310311658_a003(0)



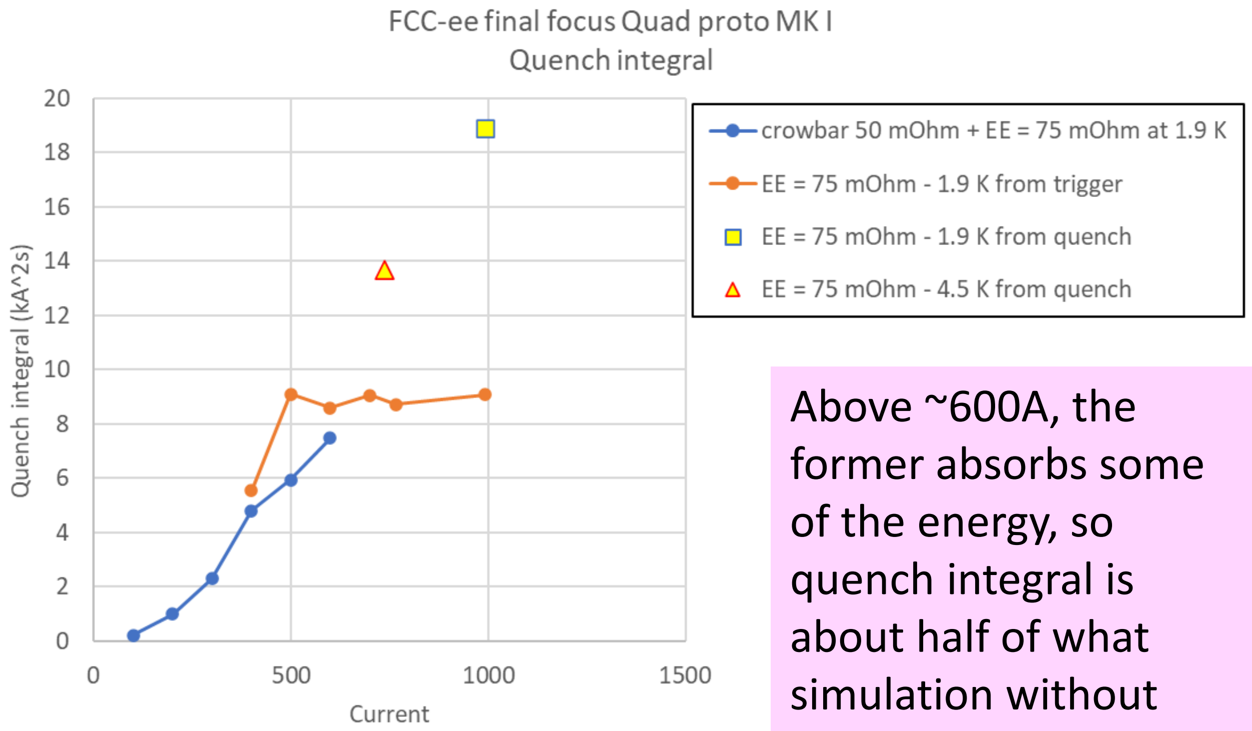
Assuming coil 8 is not yet quenched and only has inductive voltage, this calculation shows the resistive voltage of each coil.

SPMQMEM000-00000007__O202310311658_a003(0)

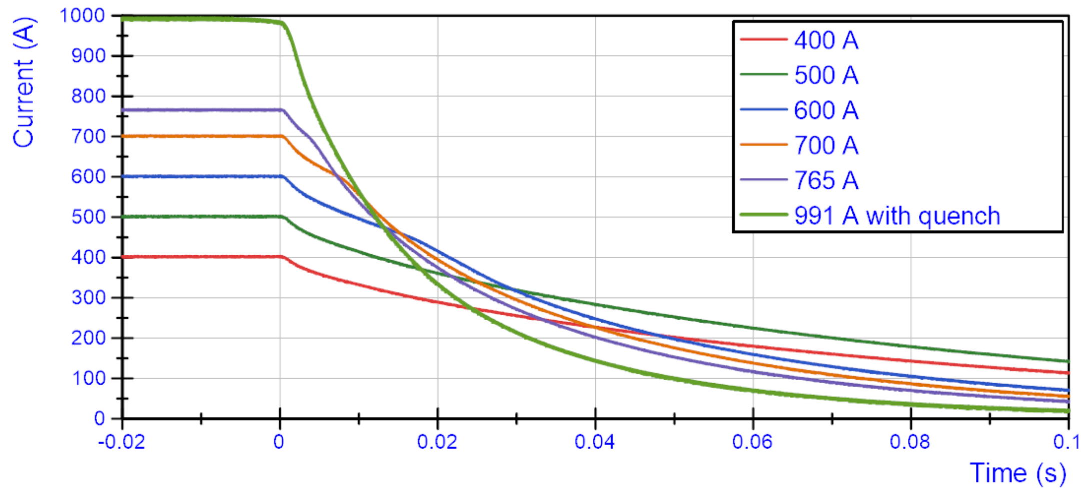
Negative (inductive) component due to dI/dt

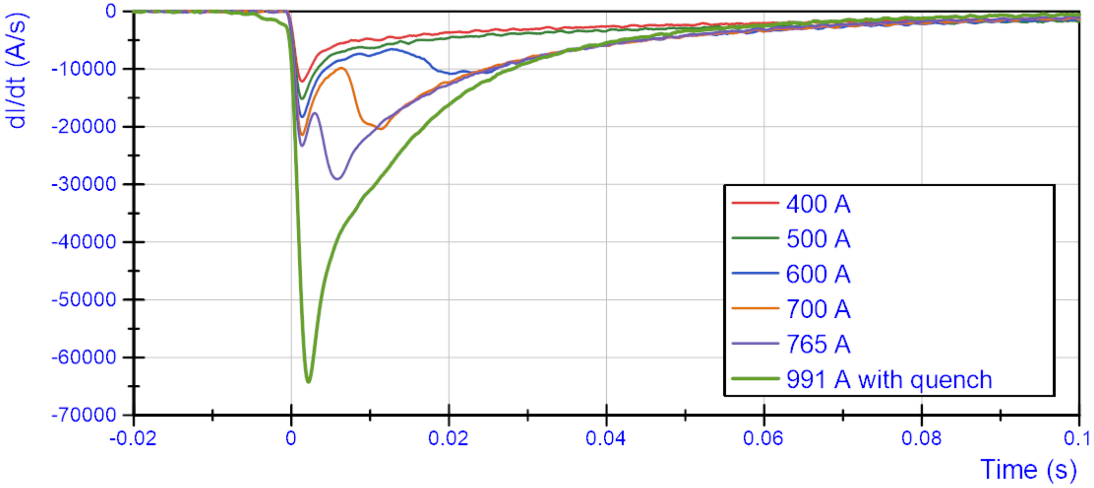


Quench integral and Quenchback



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





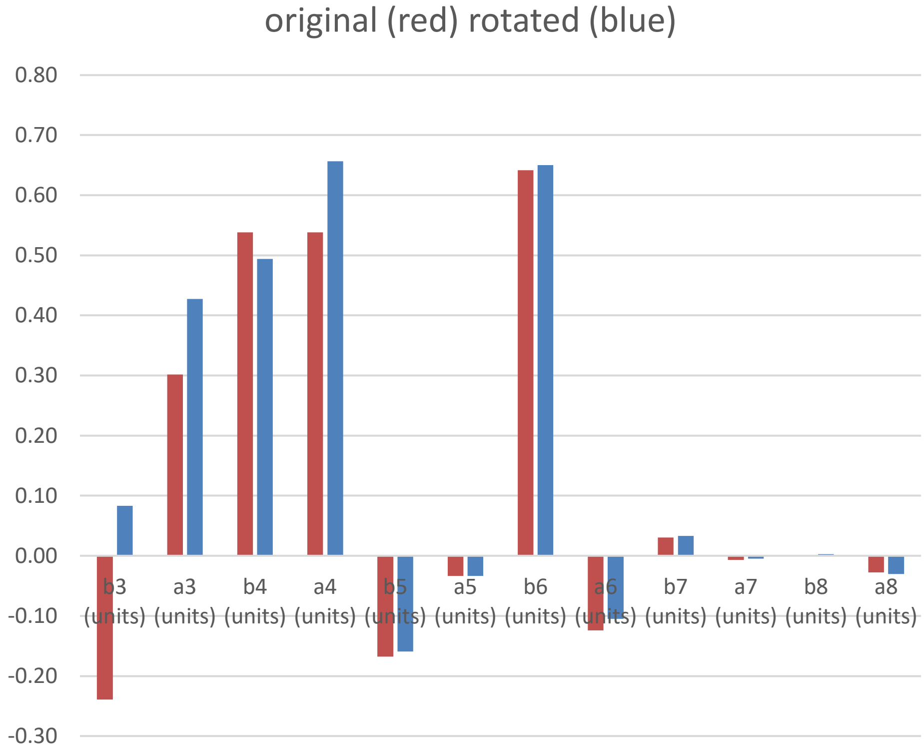
Effects to take into account:

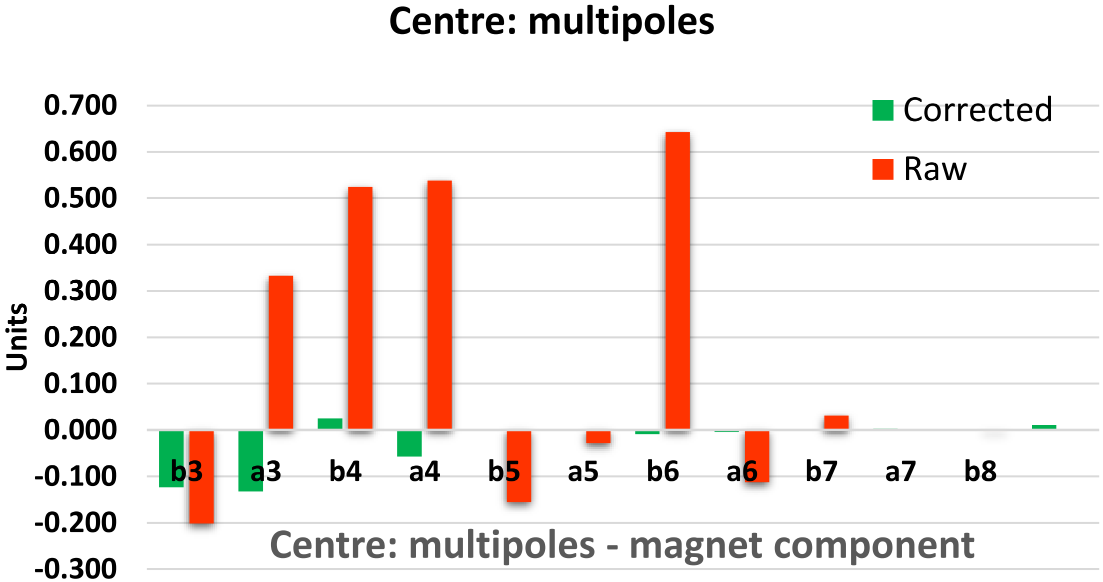
- Quench back starts between 400 and 500 A with 50 mOhm crowbar + 75 mOhm EE.
- Quench back starts between 500 and 600 A for 75 mOhm EE.
- The contribution of the former becomes more important at higher dI/dt. This could explain why the curve is flat above 500 A.

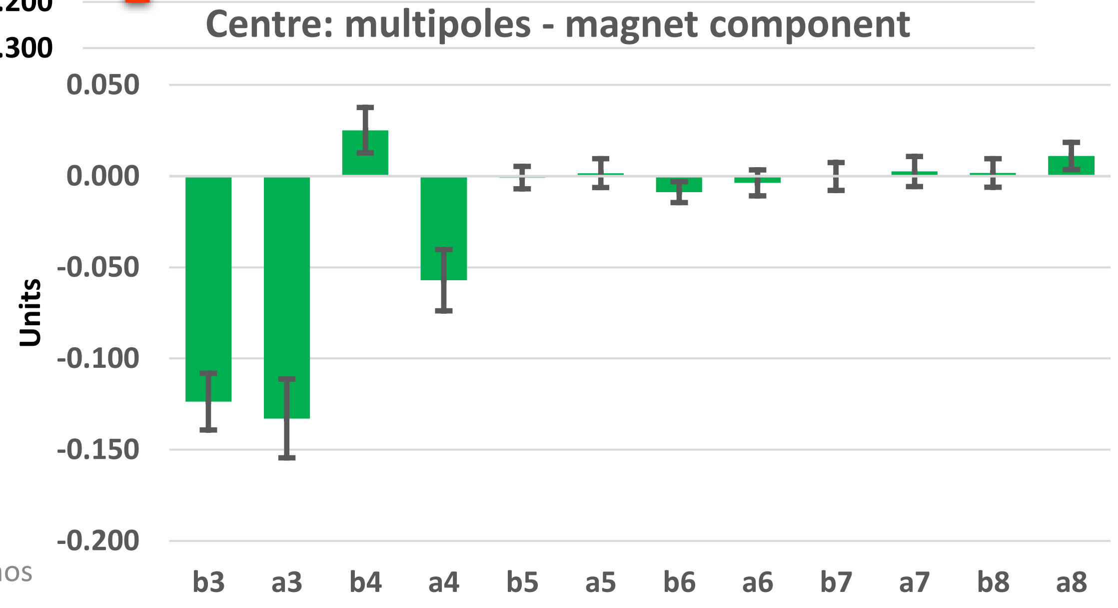
M. Koratzinos

Field quality – measurements at warm

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



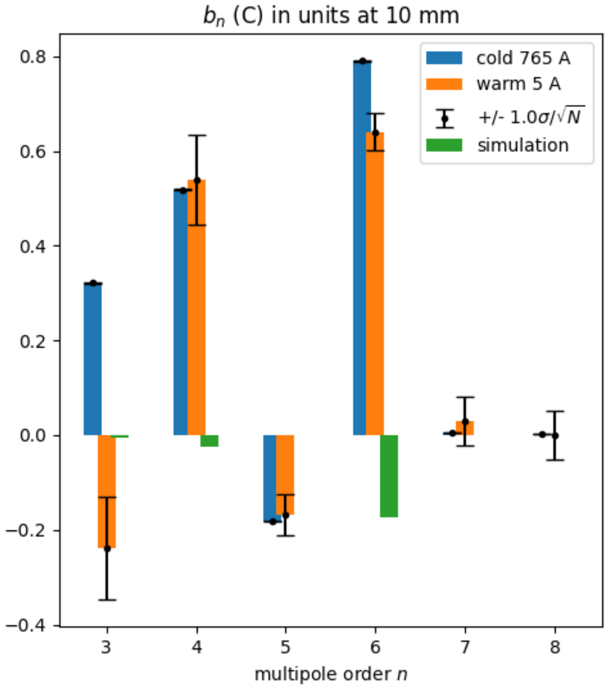


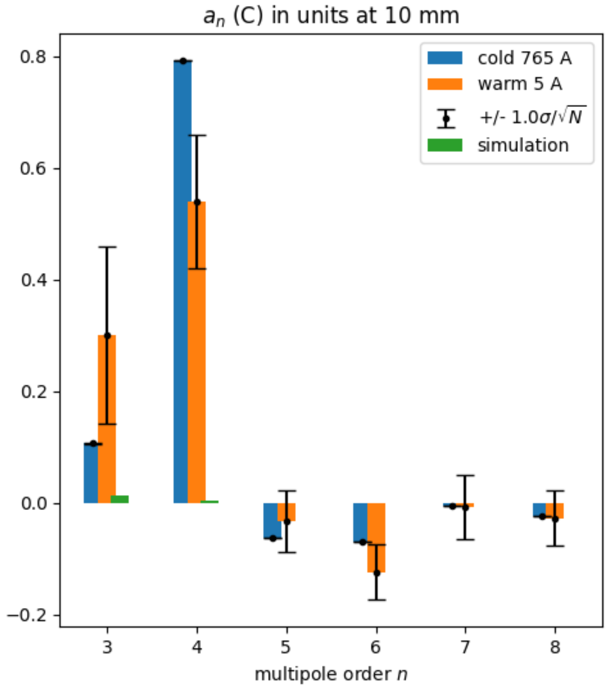


M. Koratzinos

Field quality - cold

- Work under way, but already <1unit for all multipoles
- We did not do the same trick during cold measurements
- The ‘warm’ measurements below come from the unrotated data





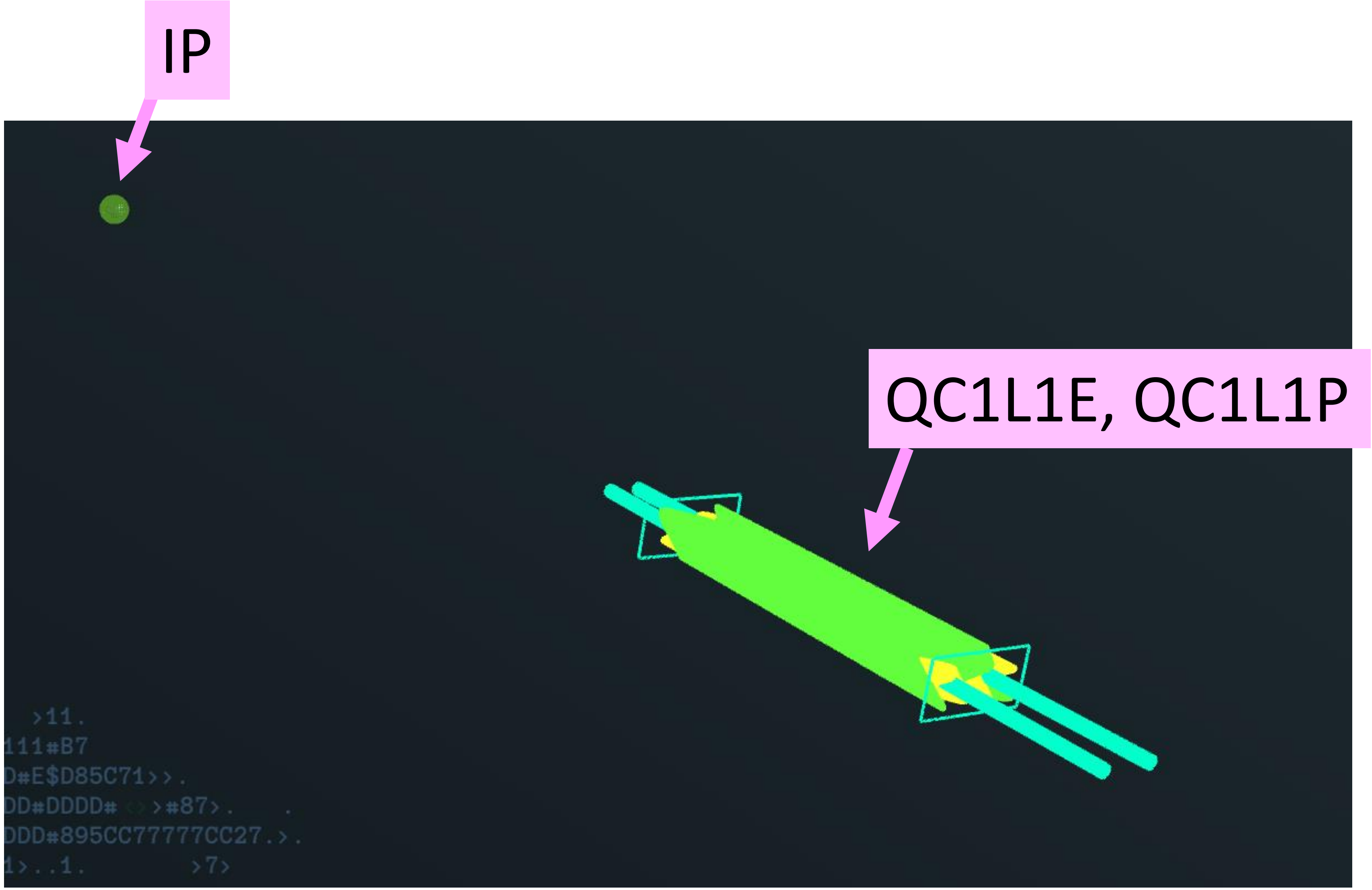
Next steps

- Last remaining question is the radiation resistance of wax.
- The plan would be to irradiate and re-measure.
- I have requested for this irradiation to be done at Dafne in Frascati.

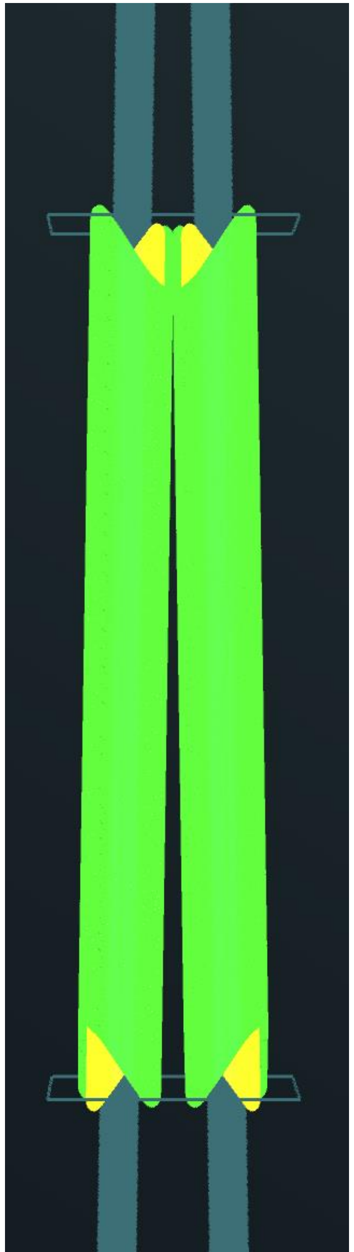
Upgrade to HTS

- 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.
- Earlier attempts resulted in large B6 (dodecapole) component which needed a dedicated corrector…
- I am happy to report that I think I have solved all these technical problems.

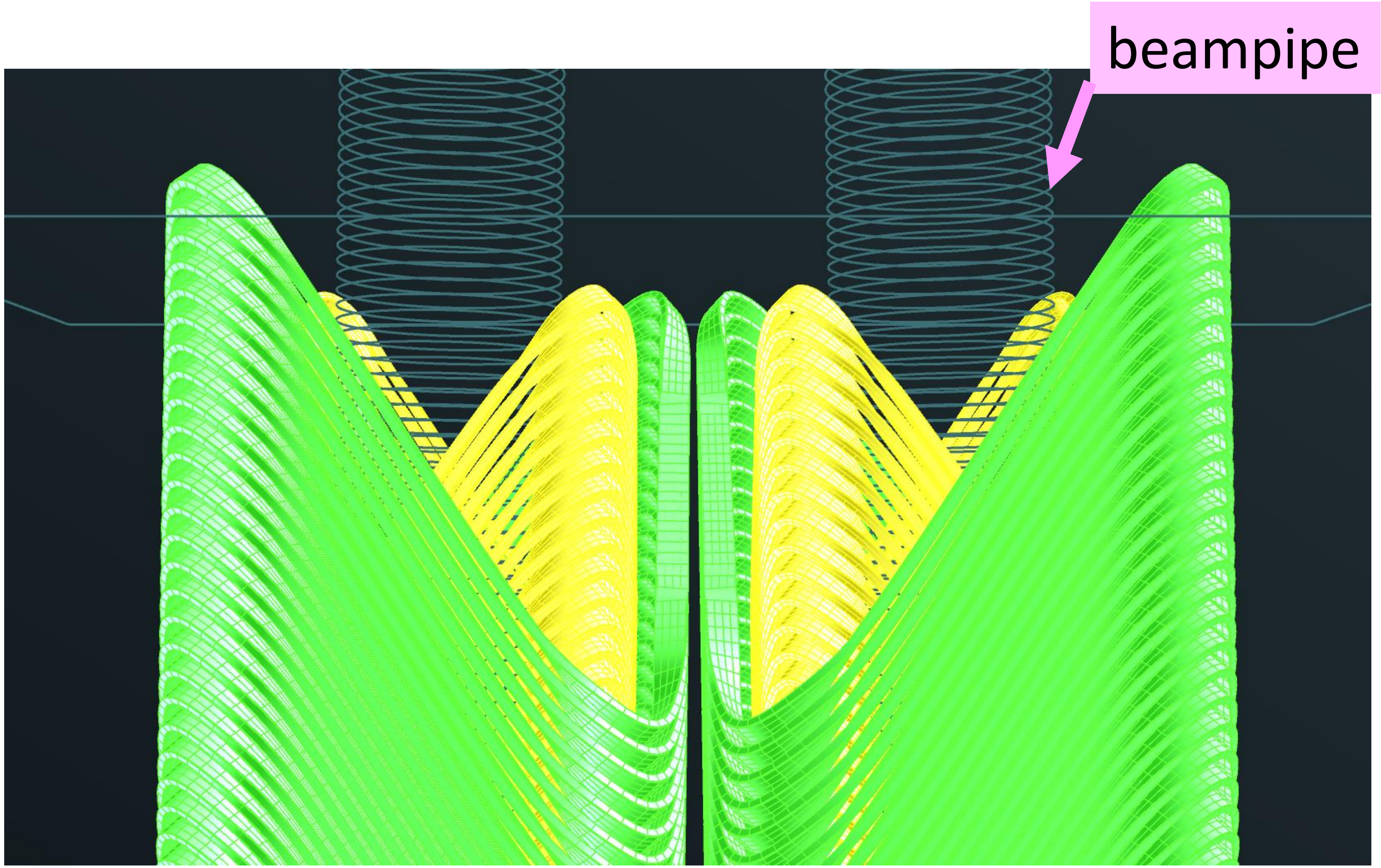
The new HTS design



View from the top



Detail at 2200mm from the IP



Crosstalk compensation e+ beam

Harmonics Calculation - Harmonics electron beam

Export

Harmonics Table | Main Harmonics | Skew harmonics | Axial Field

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 Calculation - Harmonics positron beam

Export

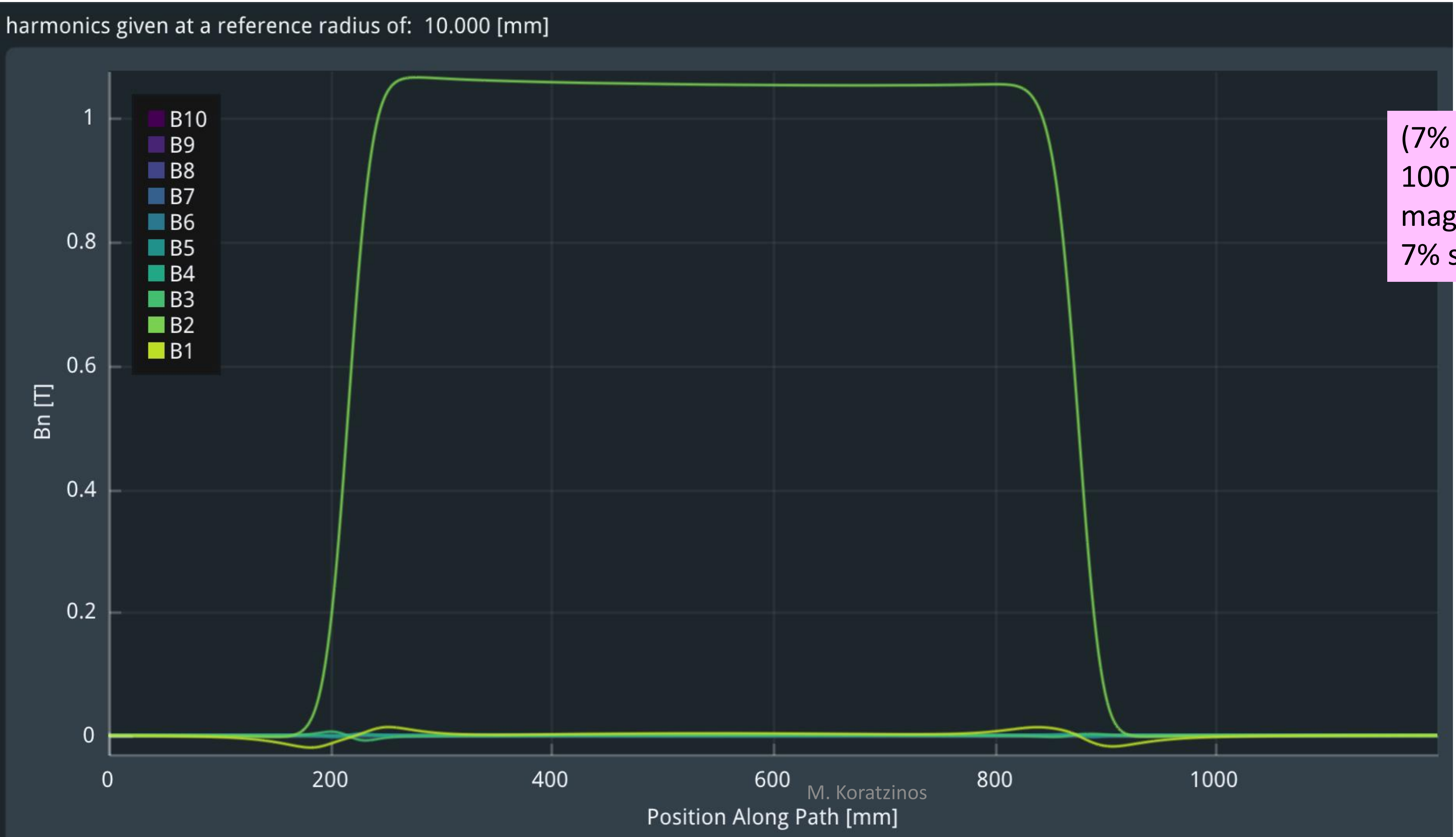
Harmonics Table | Main Harmonics | Skew harmonics | Axial Field

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	

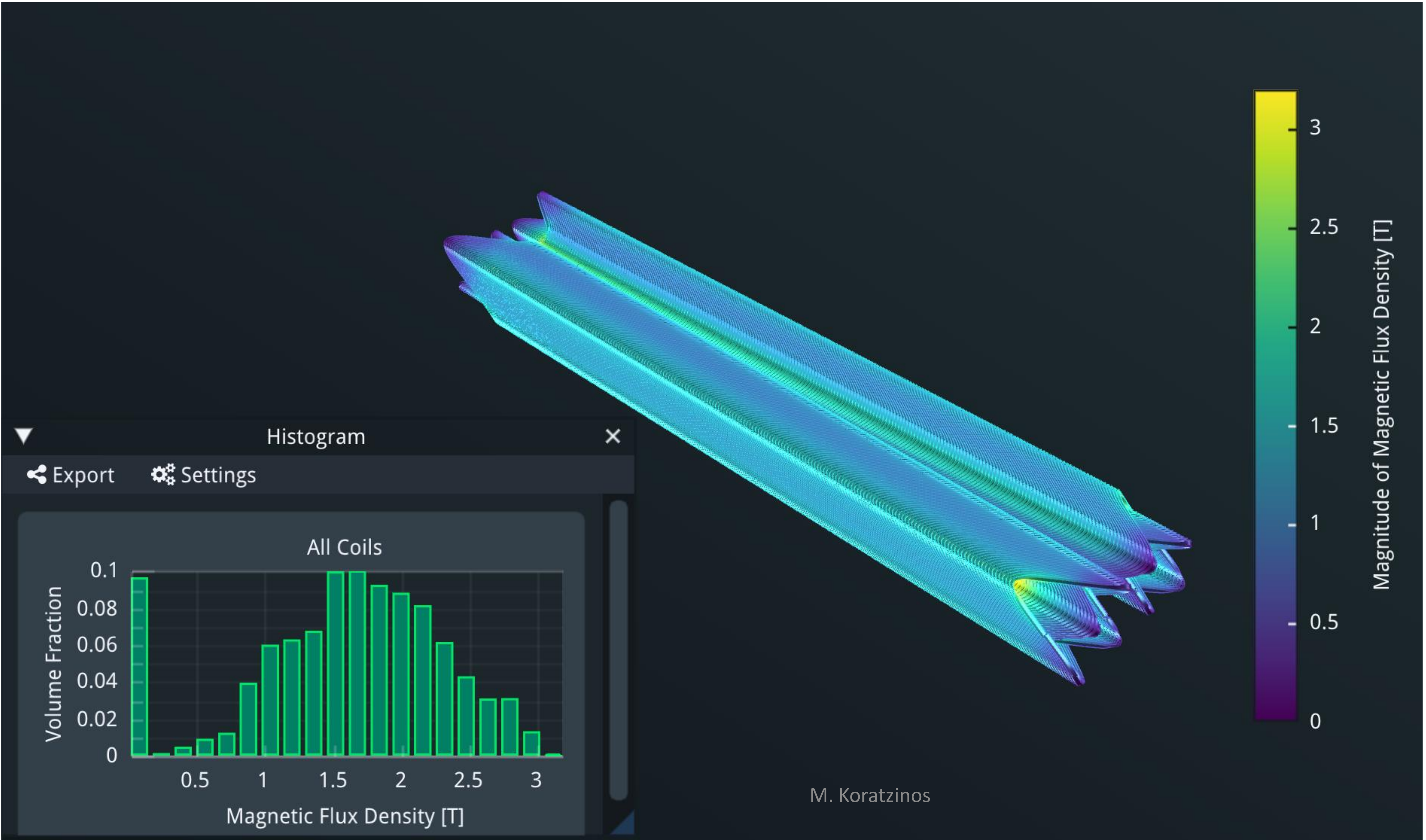
(System is symmetric)

Field gradient



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

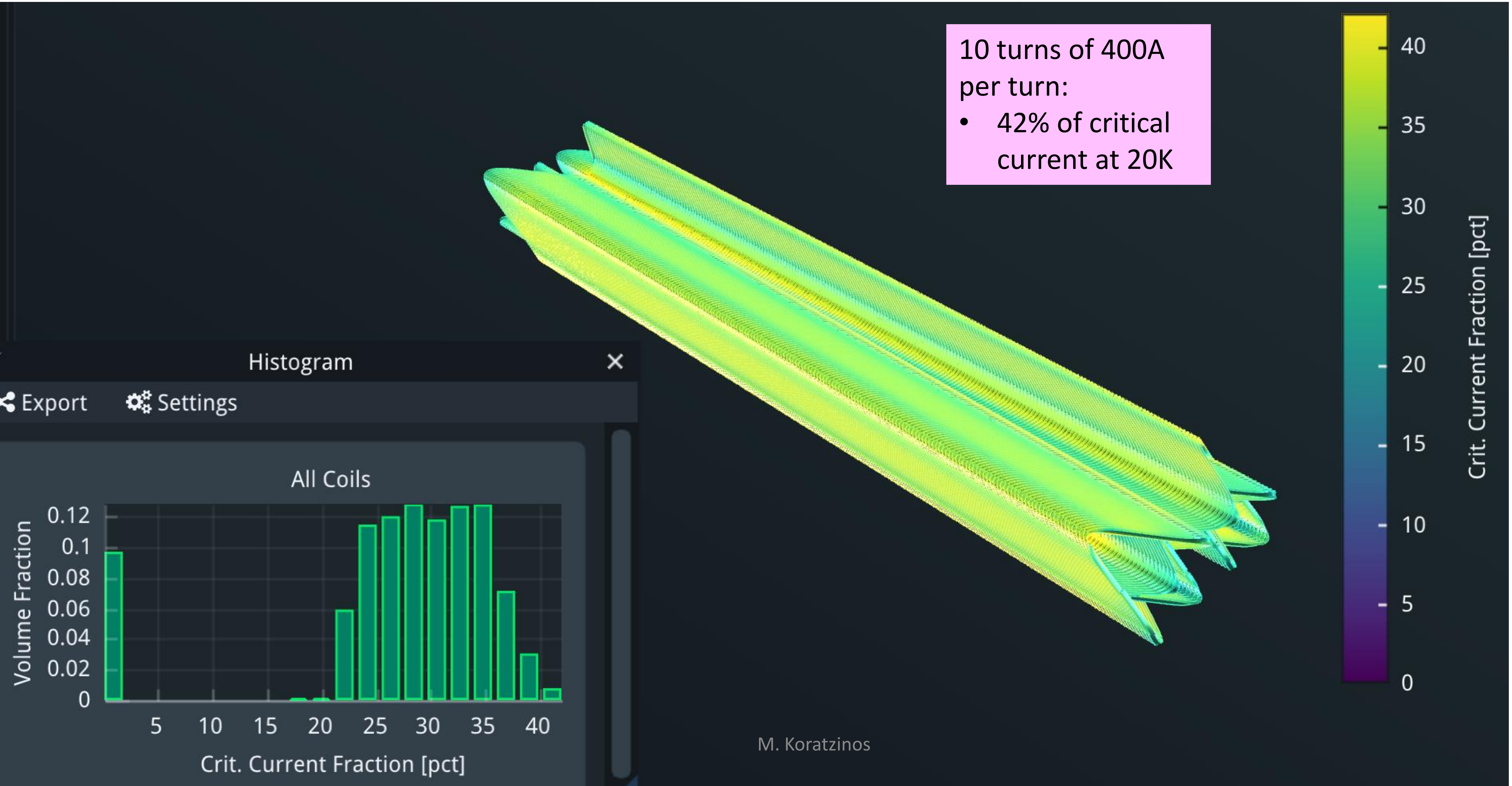
Magnetic field for 100T/m gradient



Critical current

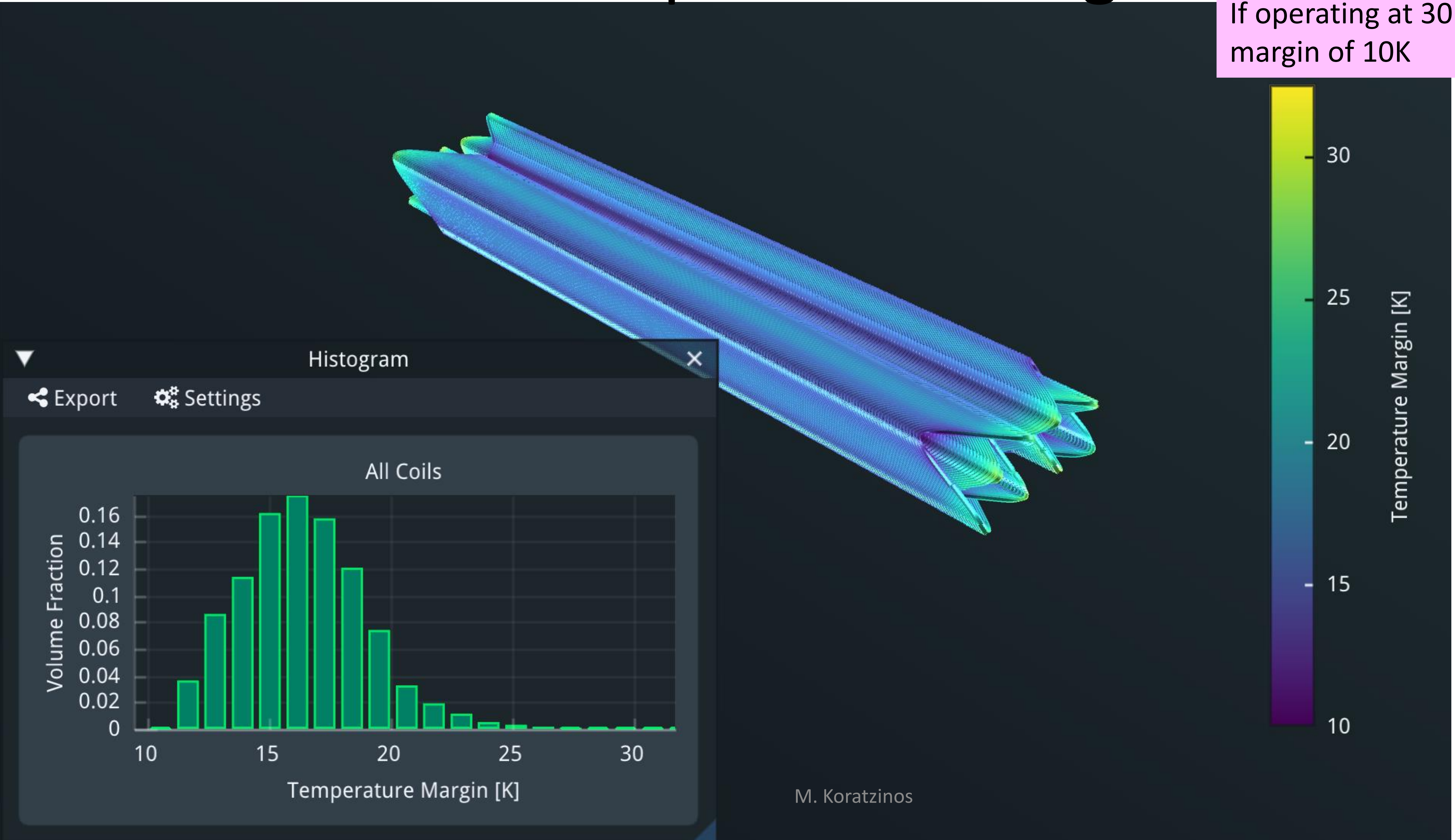
10 turns of 400A per turn:

- 42% of critical current at 20K

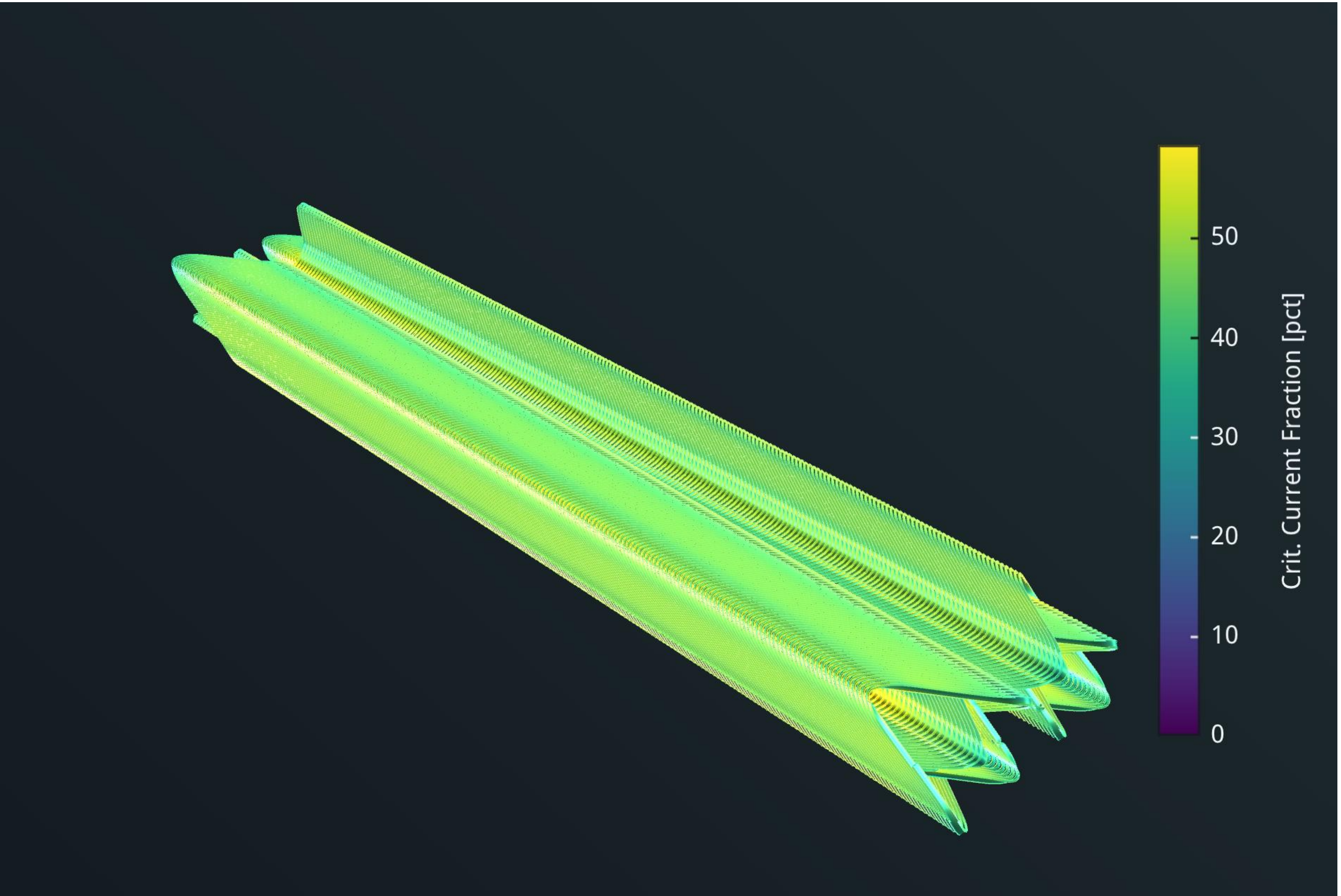


Temperature margin

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



Running at 1.9K

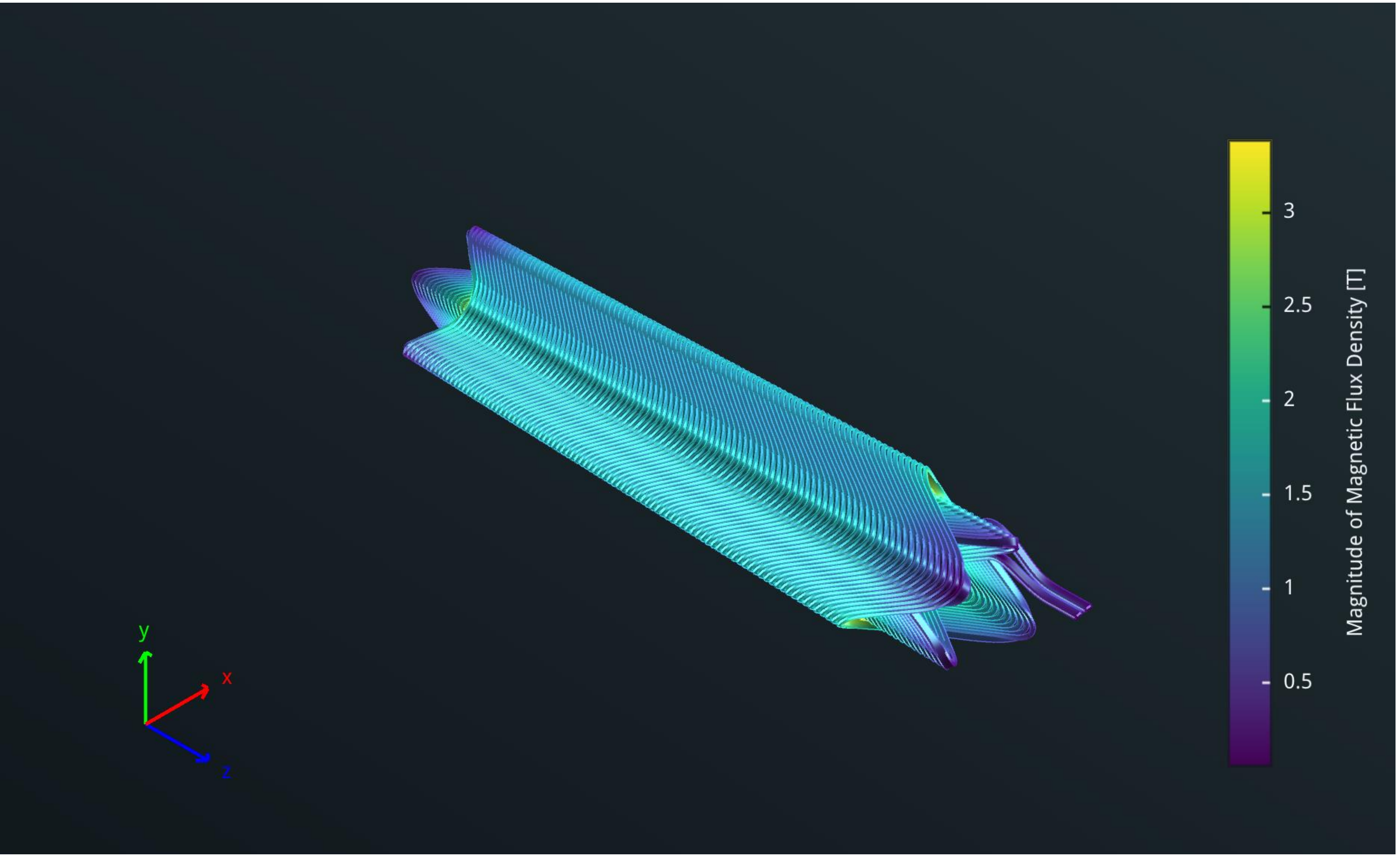


- Number of turns reduced to 4 (from 10) and current increased to 1000A
- Critical current fraction ~60%

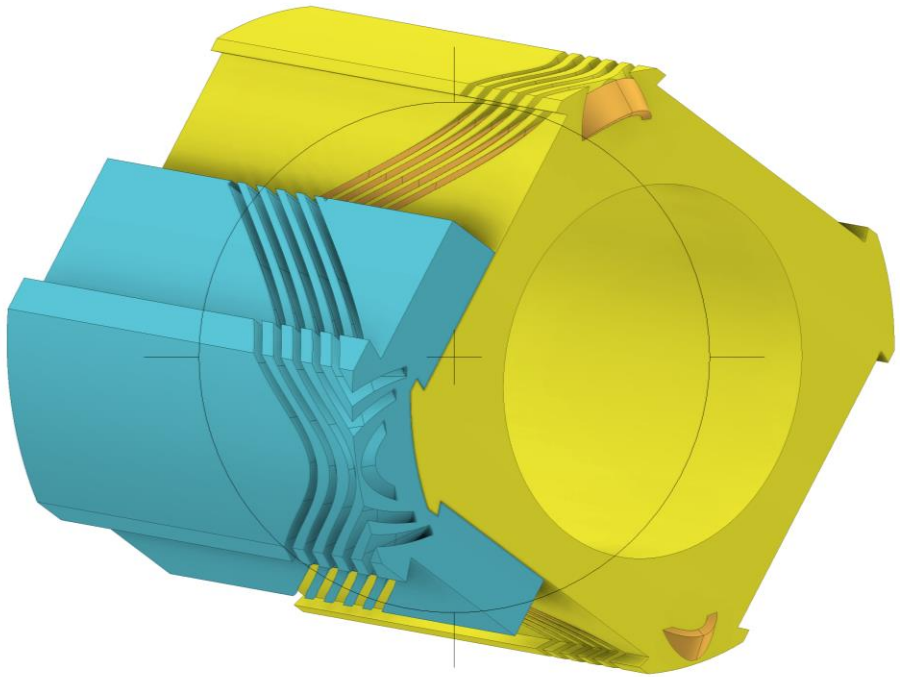
Parasitic currents

- 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!

Magnetic and mechanical design of single aperture prototype



Similar in size to NbTi prototype



Conclusions

- The first FCC-ee FF quad prototype was 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.

THANK YOU

GO, FCC!


SHARK
(F.C.C.)
BRIDGESTONE
Honda France
SHOWA
ECO PLAN
NGK
SPARK PLUGS
RK