STCF 超级陶粲装置 Super Tau-Charm Facility

Development of the CCT superconducting magnets for the STCF interaction region

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Contents

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- Design of STCF DQ0 CCT Magnet
- A Novel CCT Design
- Conclusion

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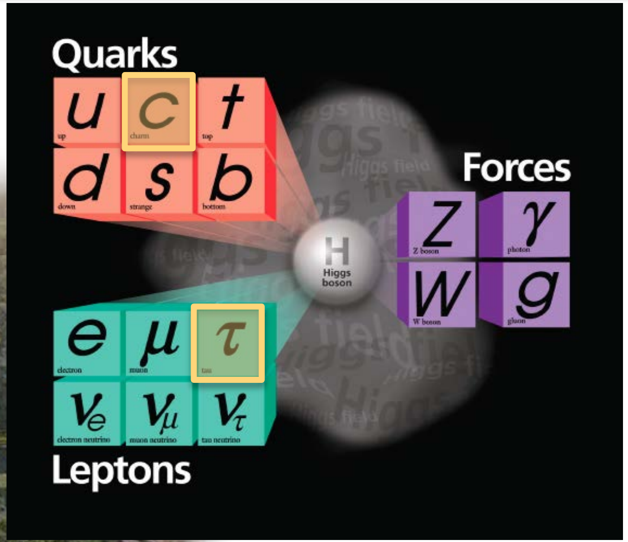
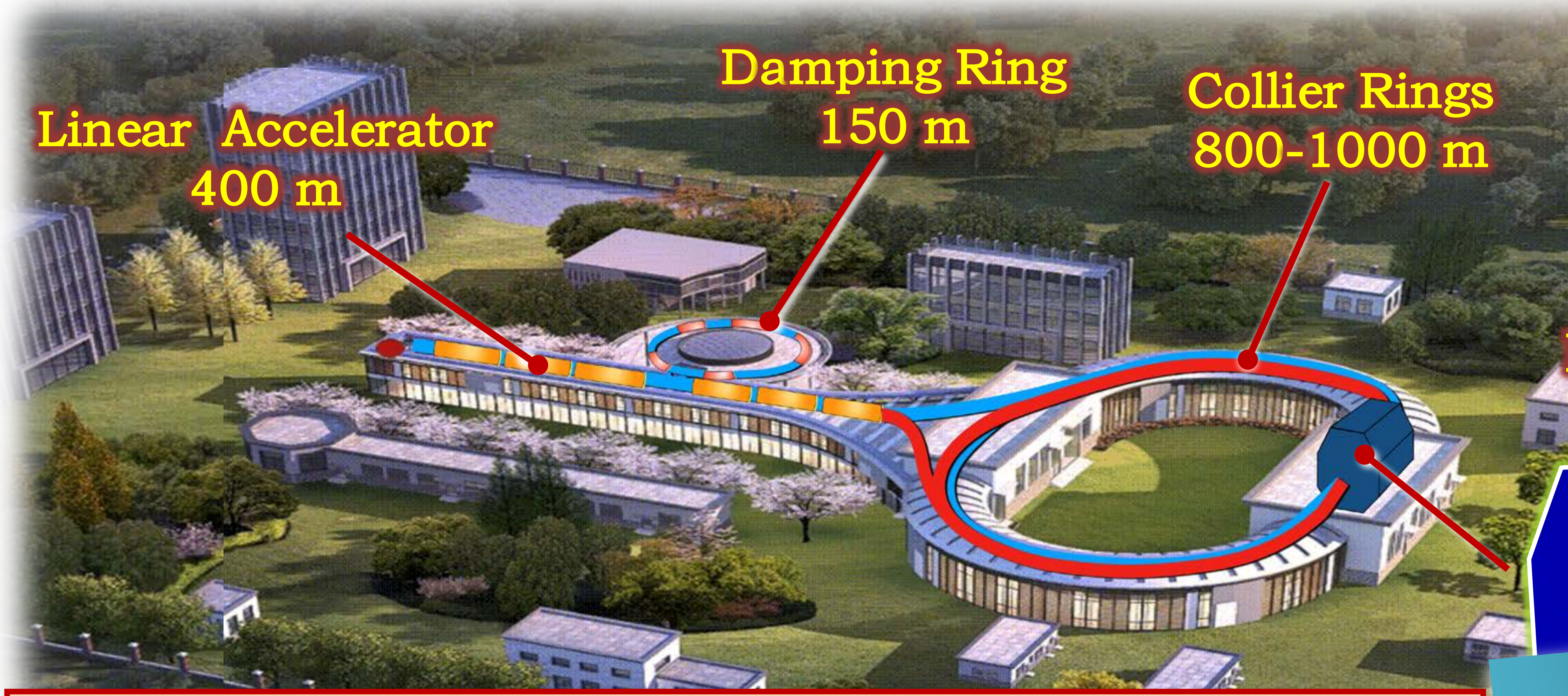
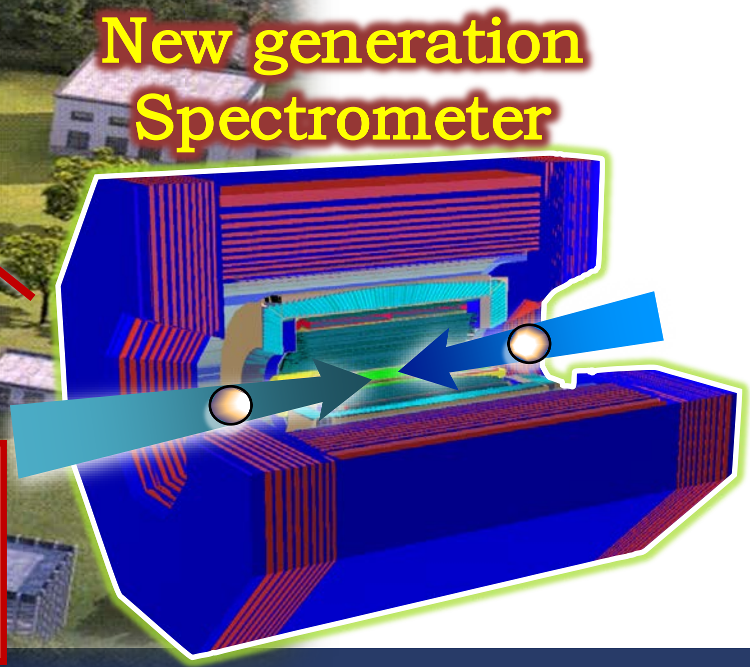
Super Tau Charm Facility (STCF)

A factory producing massive tau lepton and hadrons, to unravel the mystery of how quarks form matter and the symmetries of fundamental interactions



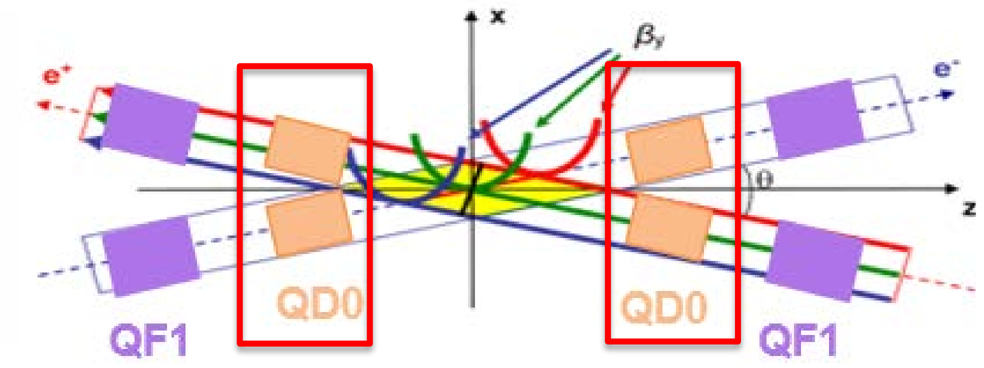


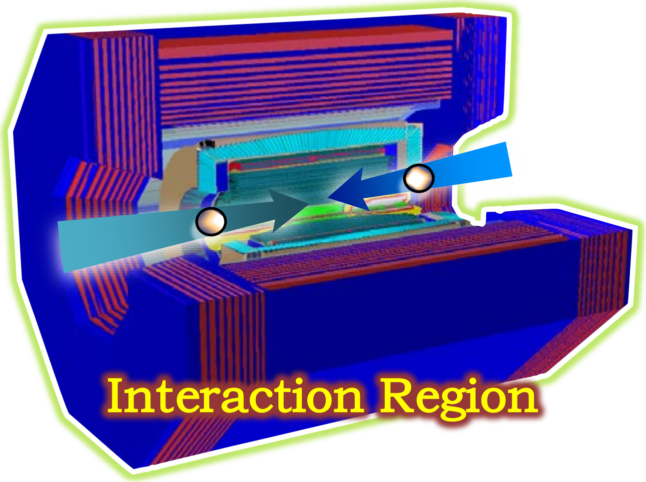


- E_{cm}= 2-7 GeV, $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1}
- Potential for upgrade to increase luminosity and realize polarized beam
- Site: 1 km^2, Hefei's suburban "Future Big Science City"

Interaction Region SC Quadrupoles

- The QD0 is the nearest magnet from IP. It needs 50 gradient with all the harmonics ≤ 2×10^{-4}.

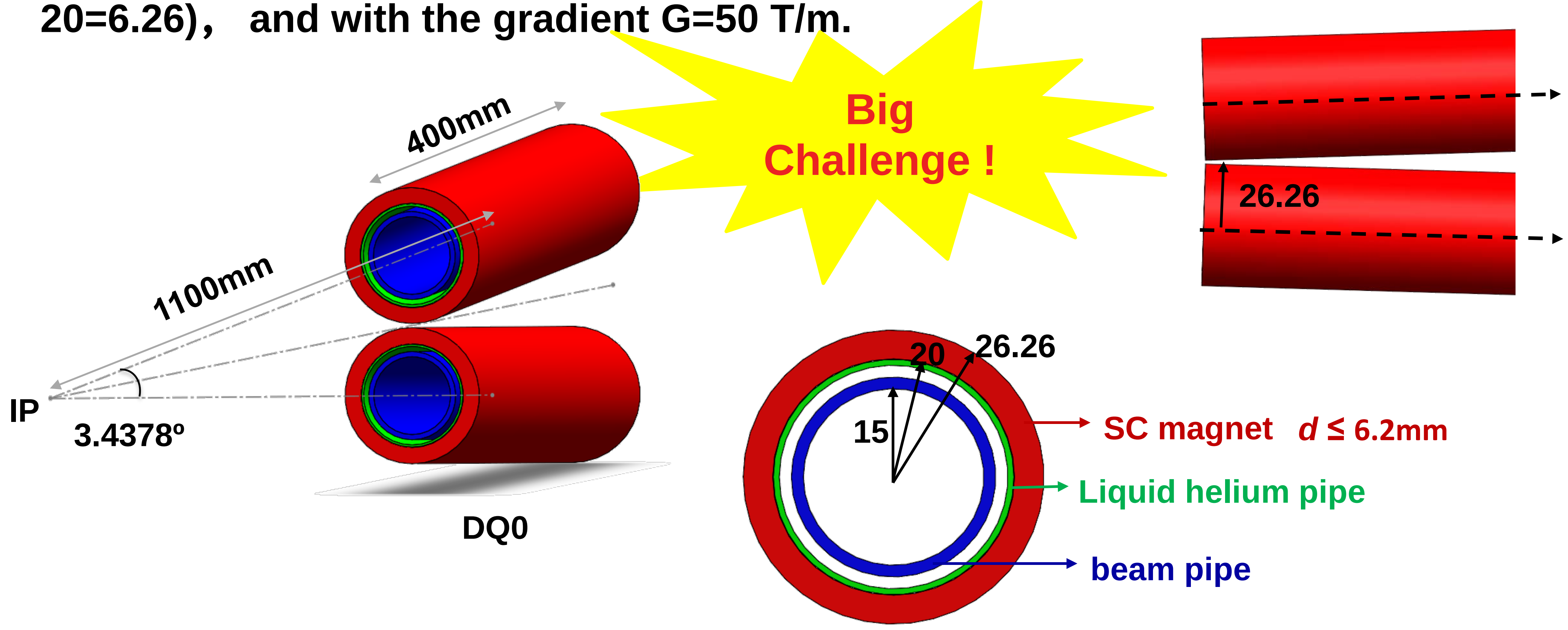




Coil	R_{ref}, (mm)	Gradient (T/m)	Effective length (mm)	High harmonics	Crosstalk (Gauss)
QD0	10	50	400	≤0.2 ‰	30
QF1	15	40	300	≤0.2 ‰	30

Interaction Region DQ0 Magnet

- In the interaction region, the beam angle is 60 mrad (<3.44º), so the usable radius space of DQ0 quadrupole and corrector magnet is d ≤ 6.2 mm (26.26-20=6.26), and with the gradient G=50 T/m.

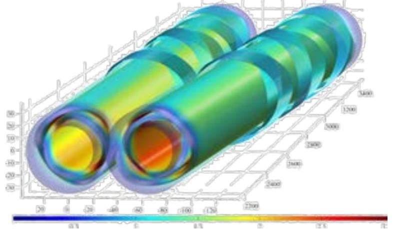
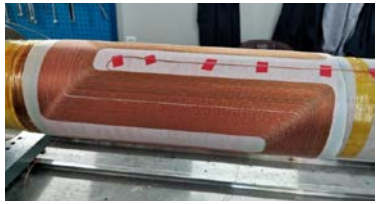
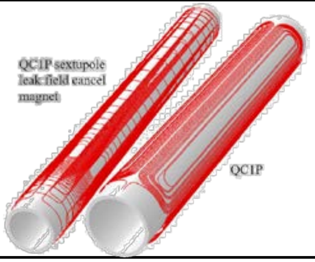
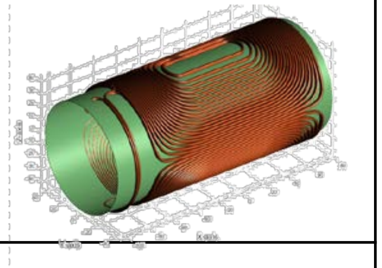


Contents

- Background
- **Design of STCF DQ0 CCT Magnet**
- A Novel CCT Design
- Conclusion

CCT Magnet Advantages

- The inner and outer radius of IR magnet DQ0 is only 20 mm and 26.26 mm. The bending radius at of the CCT coil is relatively larger, so the CCT type is selected.

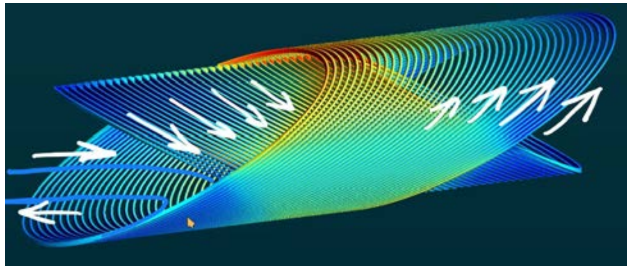
Structures	CCT coil	Serpentine coil	Cos2θ coil	DCT coil
				
advantages	• Good magnetic field quality • No accumulation stress • Relatively large bending radius at the end coil	• Compact structure • Minimal space occupied	• High magnetic field utilization • Minimal space occupied	• Good magnetic field quality • Low cold mass
disadvantages	• Long coil end • Low magnetic field utilization	• Small bending radius • Winding complicate	• Small bending radius • Multi-layer nesting • Complex mechanical structure	• Small bending radius • Low magnetic field utilization

CCT Coil

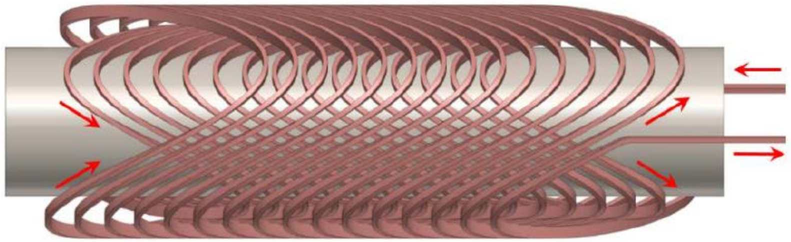
☐ CCT (Canted Cosine Theta) Magnet

- ✓ In 1970, the CCT structure was first proposed by D.I. Meyer and R. Flasck of the University of Michigan in America.
- ✓ Until 2003, the CCT coil was first made by R.B. Meiinke of the Advanced Magnet Laboratory (AML) in America.
- ✓ CCT coil is composed of two layers of canted solenoid coils with opposite skew angles.
- ✓ CCT winding patch

$$x = r\cos\theta$$
$$y = r\sin\theta$$
$$z = \frac{r\,sin\,n\theta}{n\times tan\,\alpha} + \frac{\omega}{360}\theta$$



CCT dipole

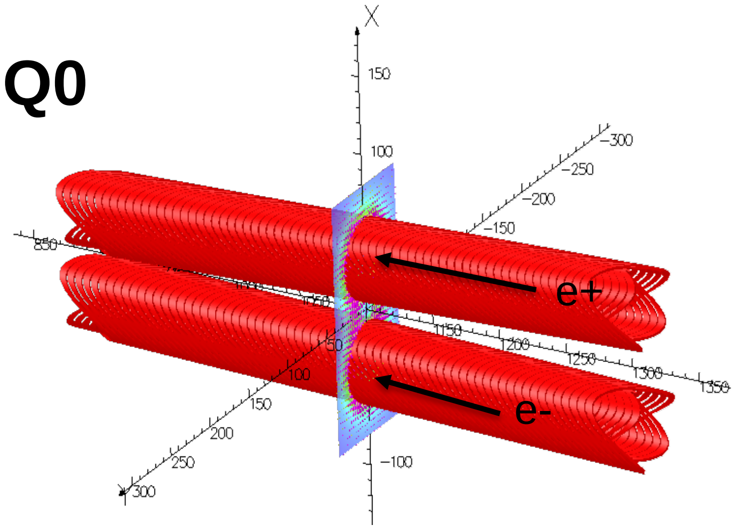


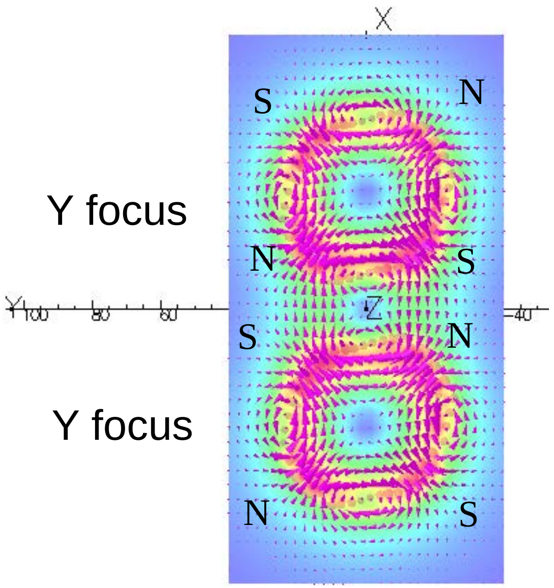
CCT quadrupole

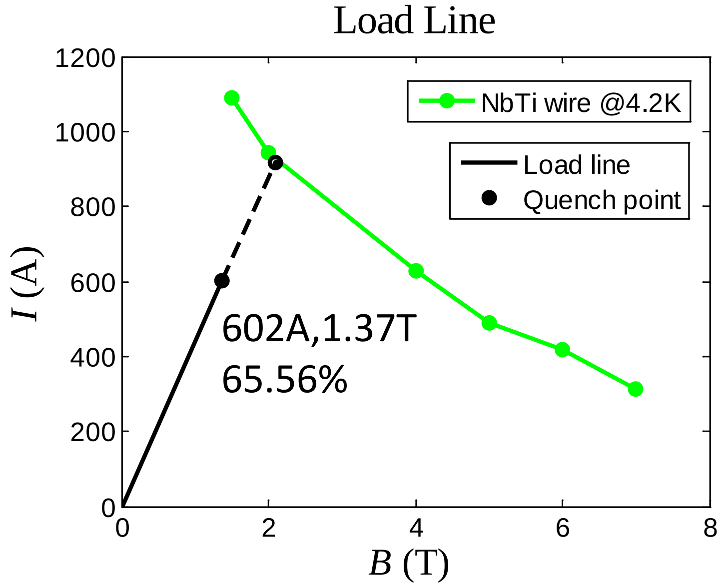
Design CCT Coil for DQ0

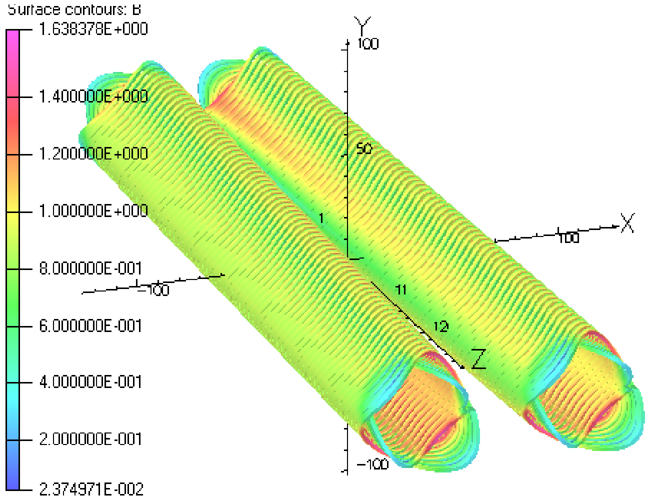
◻ The main parameters of CCT DQ0

Item	Value
R_{ref}_QD0 (mm)	10
Insulated Dia. (mm)	0.9
Filament Dia. (μm)	8.57
Min limit radius (mm)	20
Max limit radius (mm)	26.26
Gradient (T/m)	50
Effective length (mm)	400
Current (A)	602
Max field in coil (T)	1.37



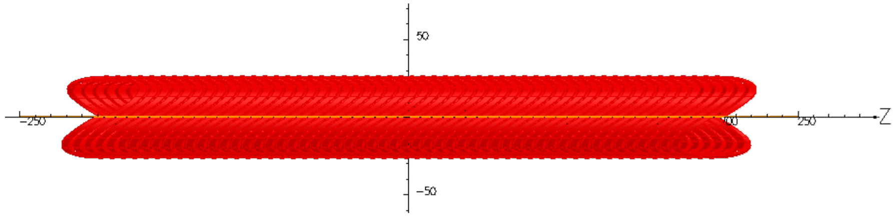


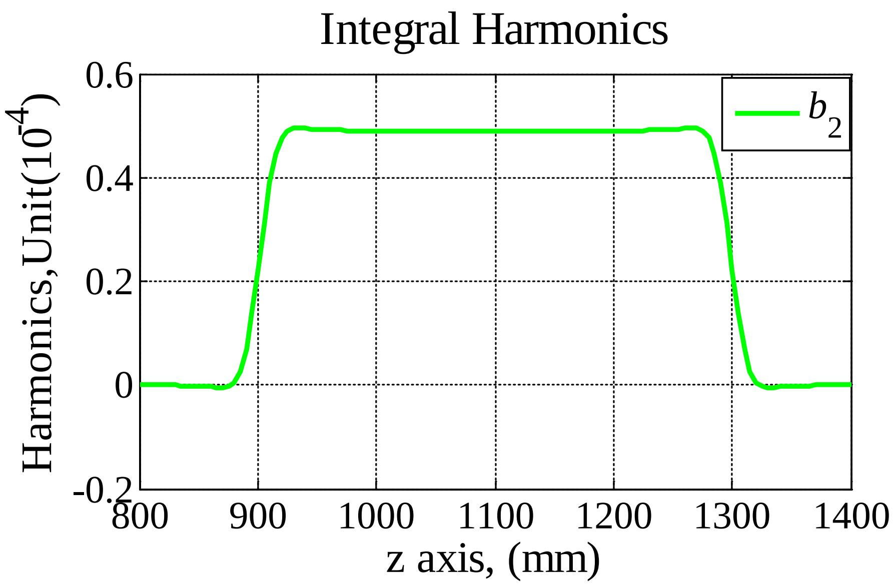




The Design of DQ0 CCT Coil

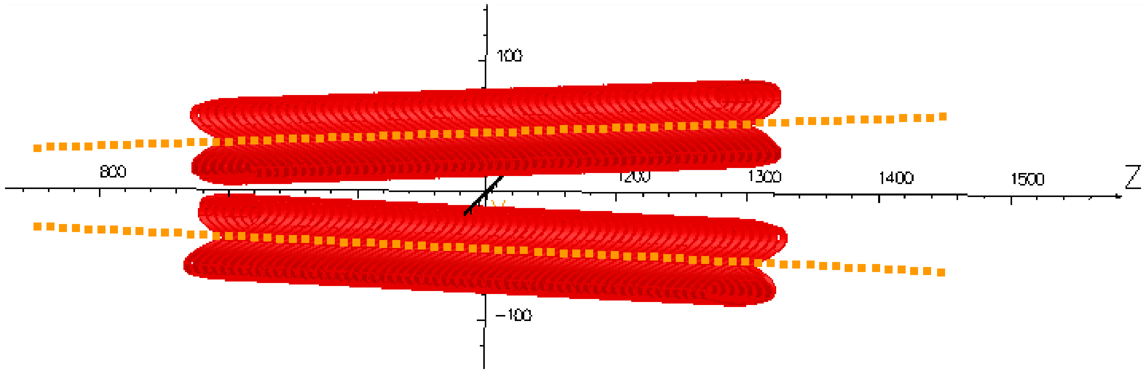
- **Single Coil**

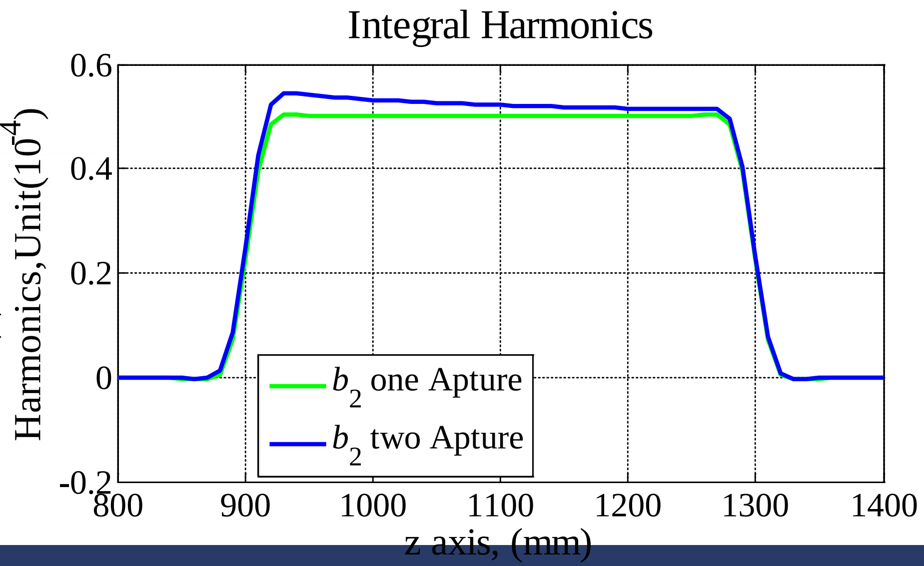




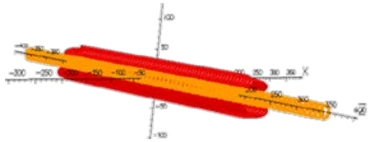
- **Double Coil**

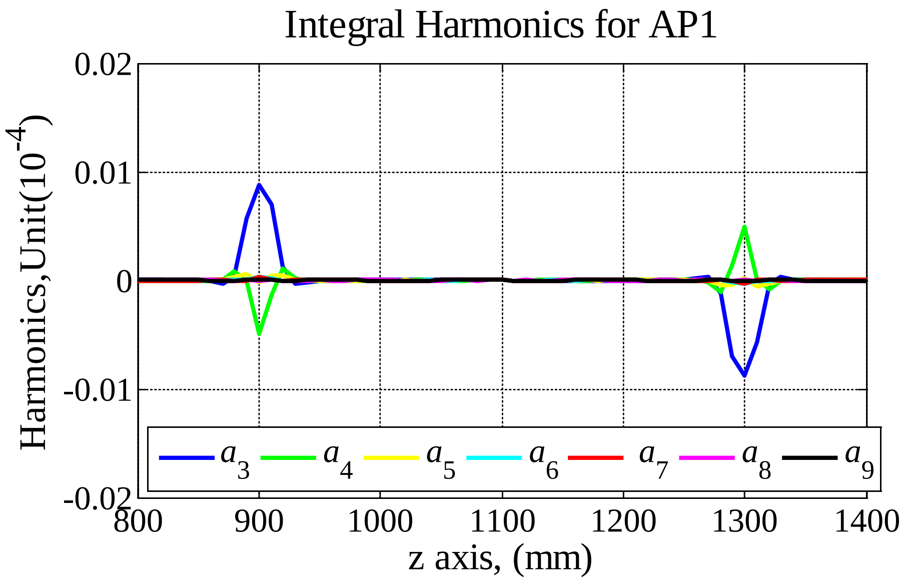
(60 mrad，distance from IP 1100 mm)

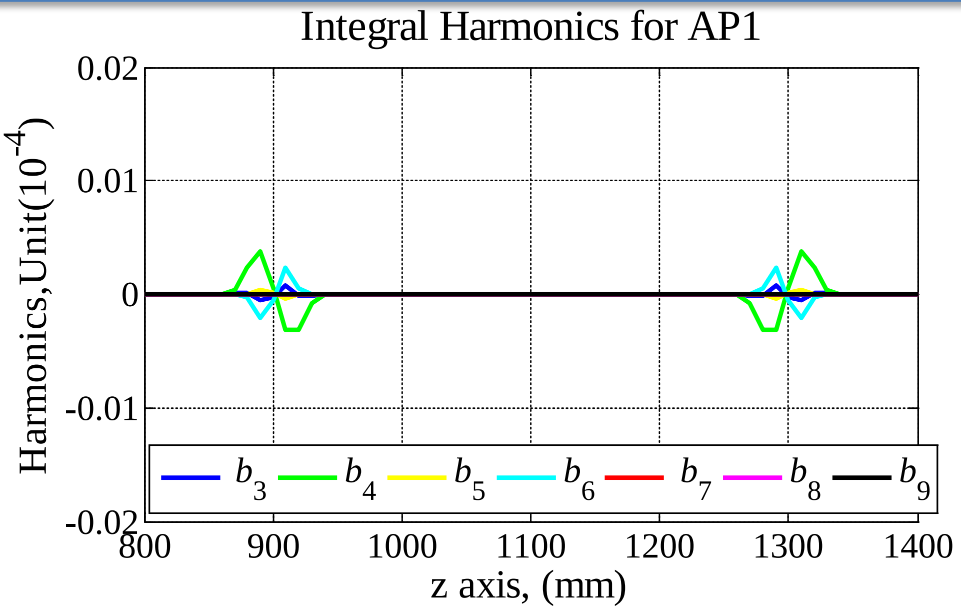




The Harmonics Analysis

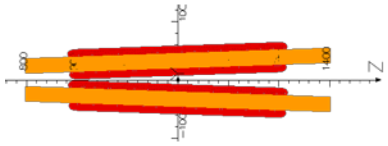


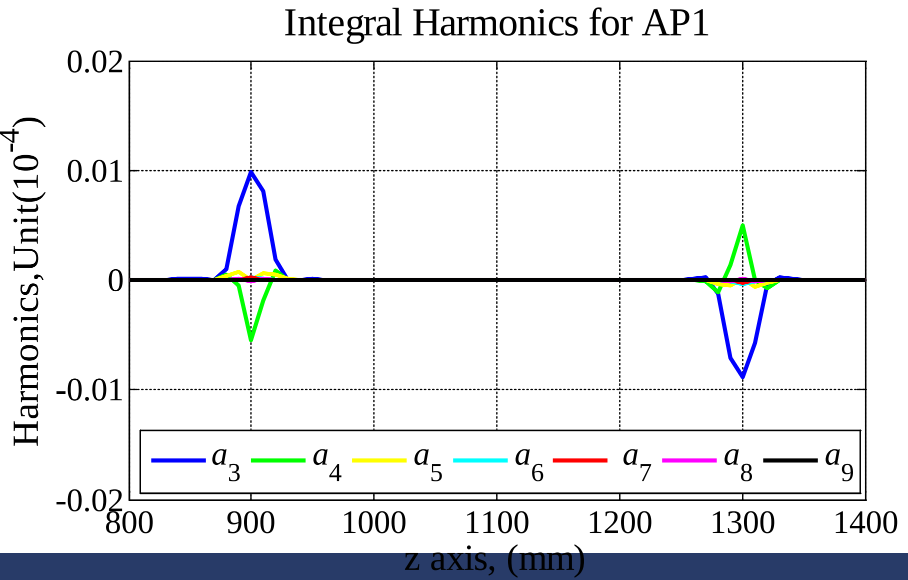


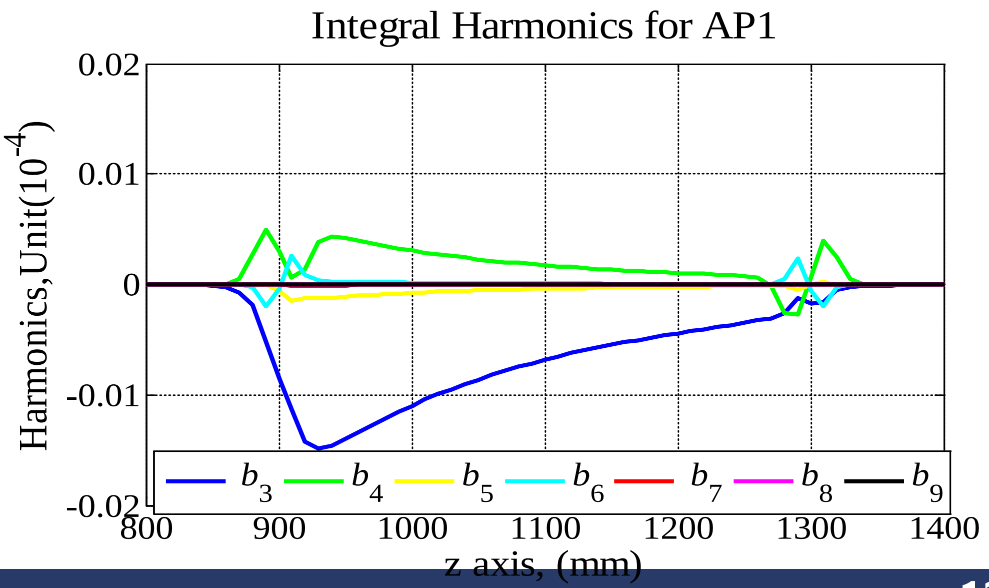


Single

< 0.1 $\times 10^{-4}$







Double

< 154 $\times 10^{-4}$

Harmonics Optimization (1)

- The cross-talk was optimized, by adding the reverse harmonic component, and change the winding trajectory equation

$$z = \sum_{n_b}\left[K_n \frac{r\sin(n_b\theta)}{n_b\tan\alpha}\right] + \sum_{n_a}\left[P_n \frac{r\cos(n_a\theta)}{n_a\tan\alpha}\right]$$

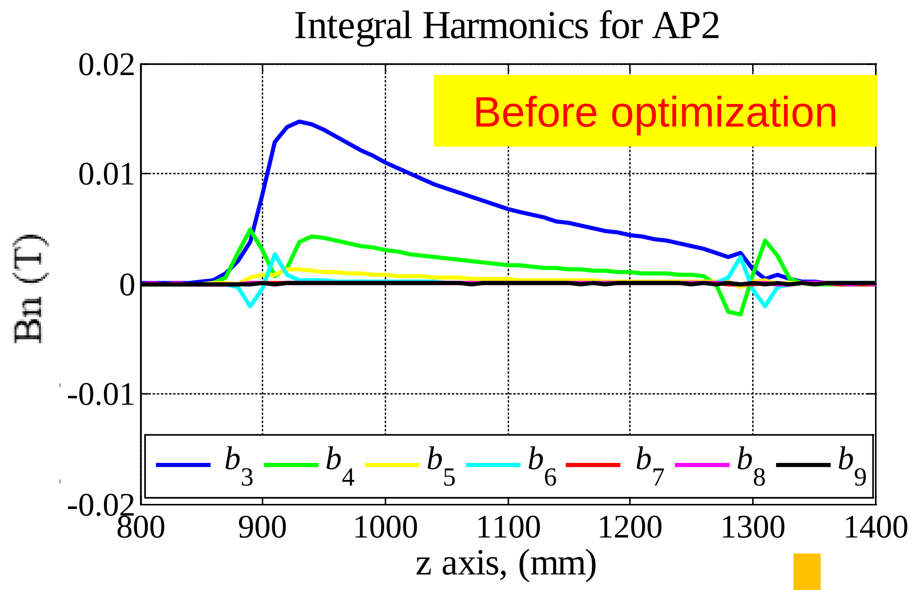
K_n / P_n	Integral AP1				
	b_3	b_4	b_5	a_2	a_3
0	-152.69	125.66	-10.24	-6.13	2.44
0.0362	0.99				
-0.0231		-1.51			
-0.0136			-0.80		
-0.0007				-0.22	
0.00062					0.16

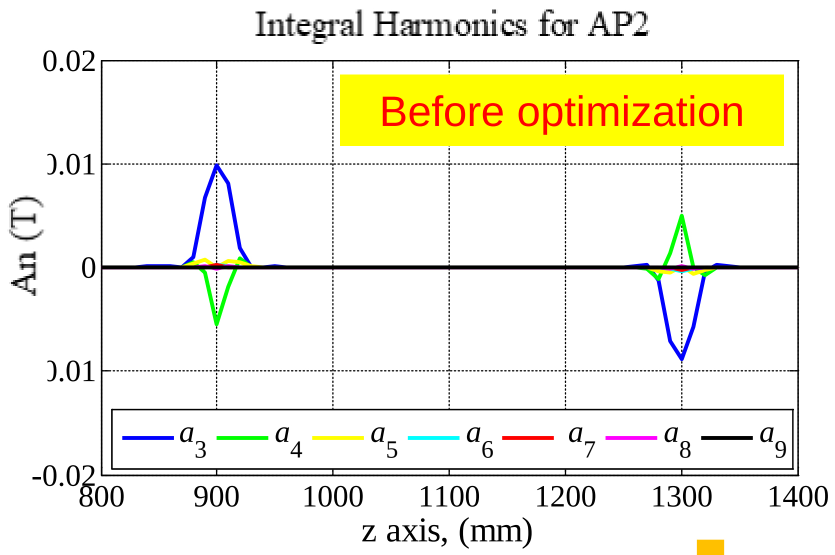
- All the high order harmonics are all less than 1.6 $\times 10^{-4}$. (Requirements < 2 $\times 10^{-4}$)

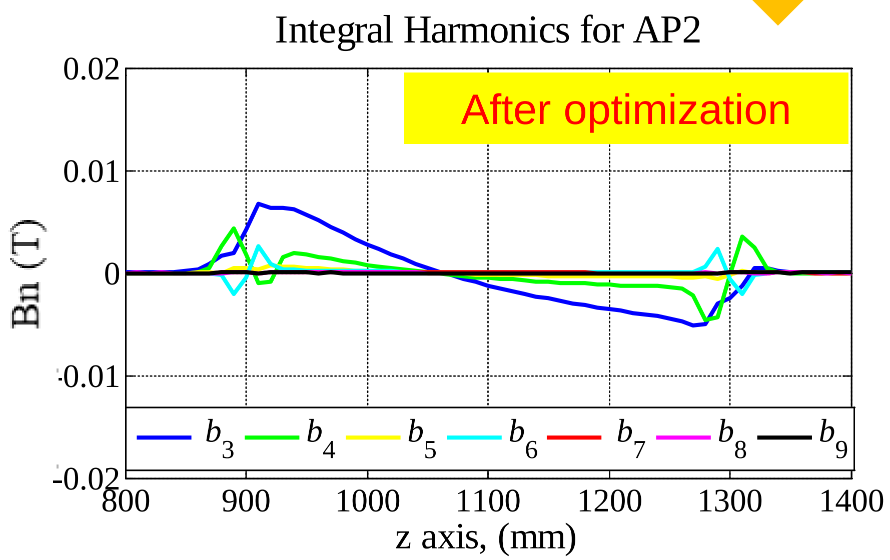
unit: 10^{-4}

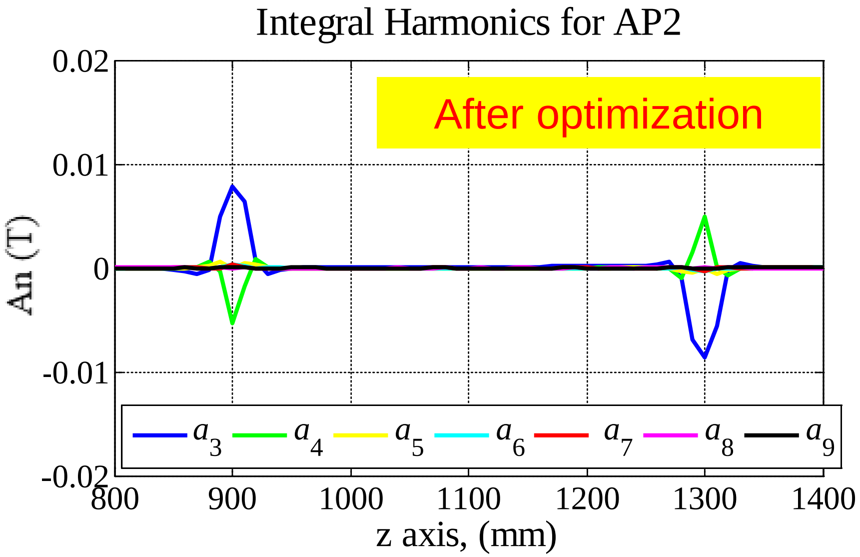
Terms	AP1		AP2	
	Cross-talk	After optimized	Cross-talk	After optimized
a_2	-6.34	-0.22	-6.46	-0.25
a_3	2.55	0.16	-2.06	0.35
a_4	-0.96	-0.99	-0.62	-067
b_3	-153.22	0.99	153.19	-1.02
b_4	41.27	-1.51	41.27	-1.52
b_5	-10.08	-0.80	10.10	-0.77

Harmonics Optimization (1)





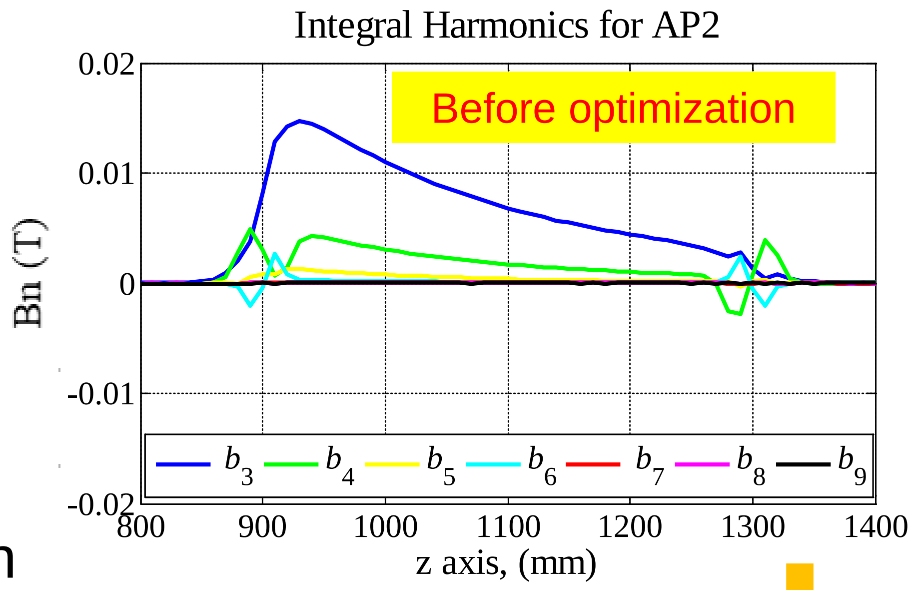


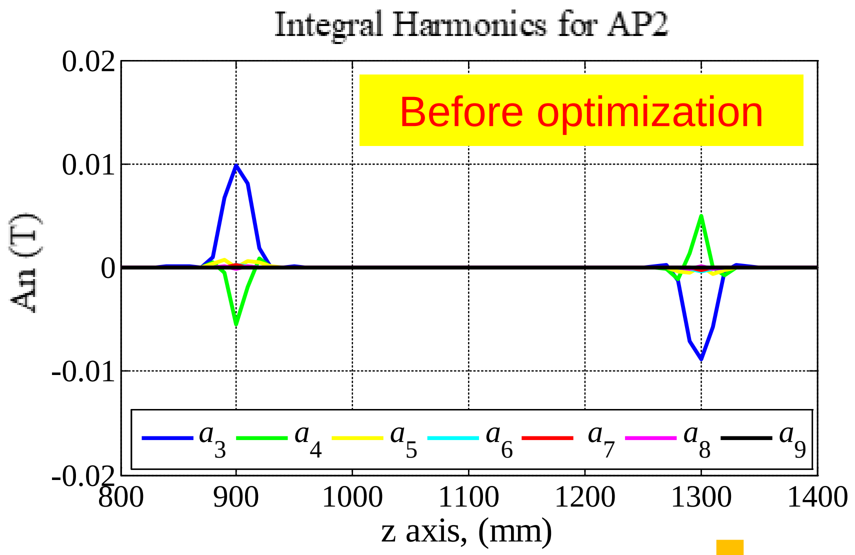


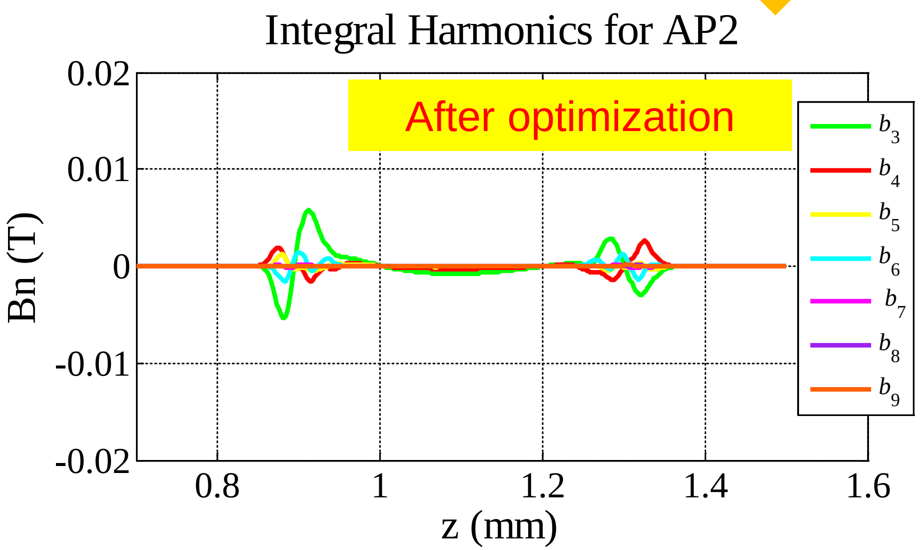
- The high order harmonics An & Bn distribution.
- All the integral harmonics are less than 0.5×10^{-4}.

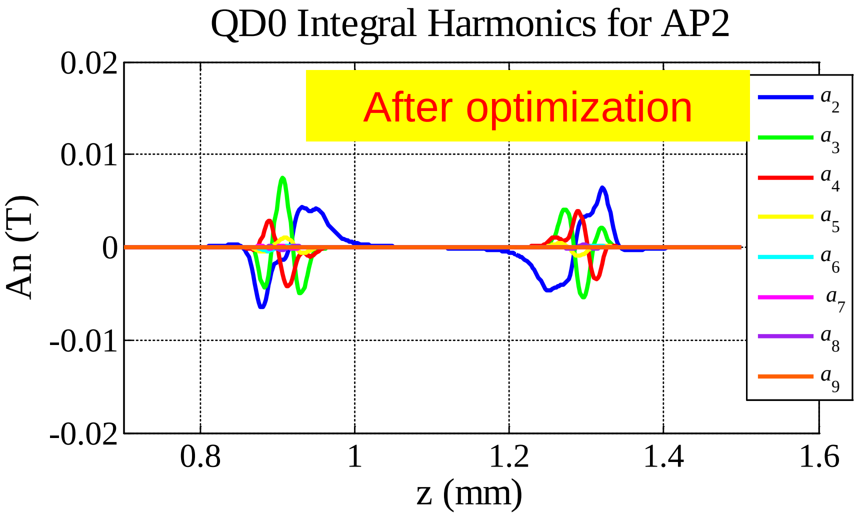
Harmonics Optimization (2)

- Next, the local harmonics of DQ0 are further optimized
- All the integral high order harmonics are all less than 0.5 $\times 10^{-4}$.









Harmonics Optimization (2)

- All the harmonics are all less than 0.35 $\times 10^{-4}$. (Requirements < 2 $\times 10^{-4}$)

Order	AP1				AP2			
	An (T·m)	Bn (T·m)	Unit (An)	Unit (Bn)	An (T·m)	Bn (T·m)	Unit (An)	Unit (Bn)
1	0	5.13E-06	0	0.258	0	-5.13E-06	0	-0.258
2	-8.85E-07	0.199	-0.044	10000	8.85E-07	0.199	0.044	10000
3	-4.95E-07	5.46E-06	-0.025	0.274	-4.95E-07	-5.46E-06	-0.025	-0.274
4	-2.25E-06	6.67E-06	-0.113	0.335	2.25E-06	6.67E-06	0.113	0.335
5	-2.20E-06	3.78E-06	-0.110	0.190	-2.20E-06	-3.78E-06	-0.110	-0.190
6	-2.87E-07	5.63E-06	-0.014	0.283	2.87E-07	5.63E-06	0.014	0.283
7	3.89E-07	1.03E-06	0.020	0.052	3.89E-07	-1.03E-06	0.020	-0.052
8	6.83E-07	6.76E-06	0.034	0.340	-6.83E-07	6.76E-06	-0.034	0.340
9	2.19E-07	-1.14E-06	0.011	-0.057	2.19E-07	1.14E-06	0.011	0.057
10	1.33E-07	5.11E-07	0.007	0.026	-1.33E-07	5.11E-07	-0.007	0.026

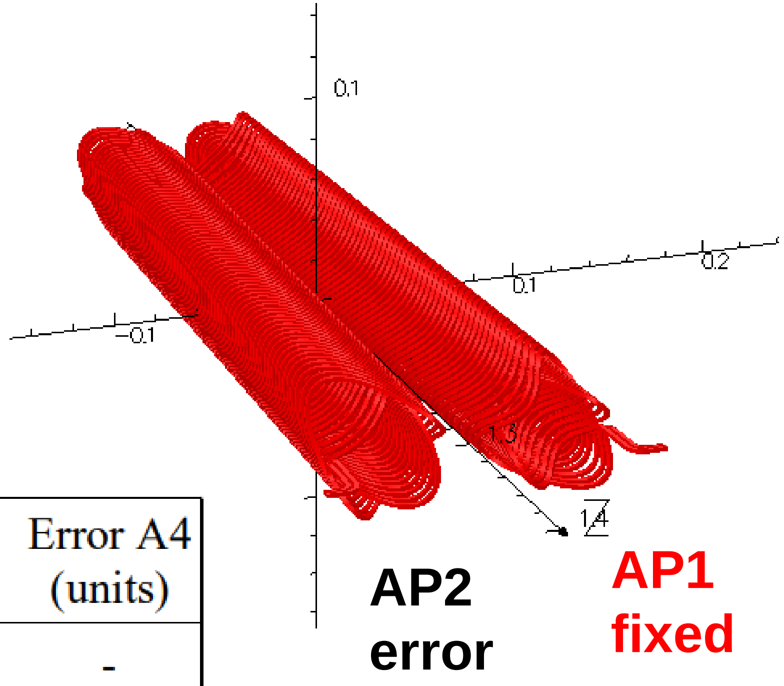
Error Analysis

- Machining error of CCT former in x, y and z directions

Fixed AP1, AP2 has 50 microns machining error in x, y and z directions:

(1) Measure harmonics in AP2

misalignment	Error B1 (units)	Error A1 (units)	Error A2 (units)	Error B3 (units)	Error A3 (units)	Error B4 (units)	Error A4 (units)
50um in x	2.6	-	-	0.6	-	0.2	-
50um in y	-	2.5	1.7	-	0.6	-	0.2
50um in z	0.1	-	-	-	-	-	-



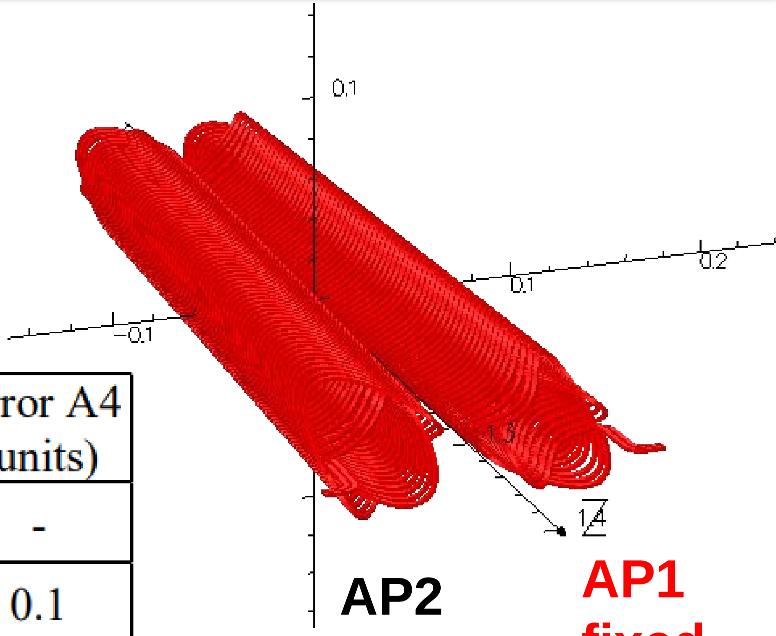
- The maximum harmonics (A1 and B1) is increased by 2 unit (1×10^{-4}).

Error Analysis

- Machining error of CCT former in x, y and z directions

(2) Measure harmonics in AP1

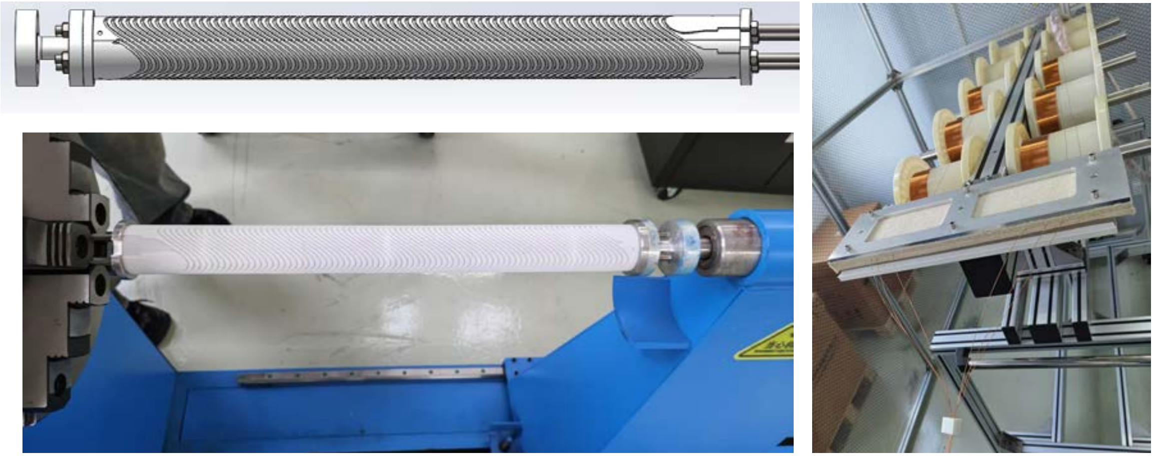
misalignment	Error B1 (units)	Error A1 (units)	Error A2 (units)	Error B3 (units)	Error A3 (units)	Error B4 (units)	Error A4 (units)
50um in x	47	-	-	0.6	-	0.2	-
50um in y	-	47	1.6	-	0.7	-	0.1
50um in z	-	-	-	-	-	-	-



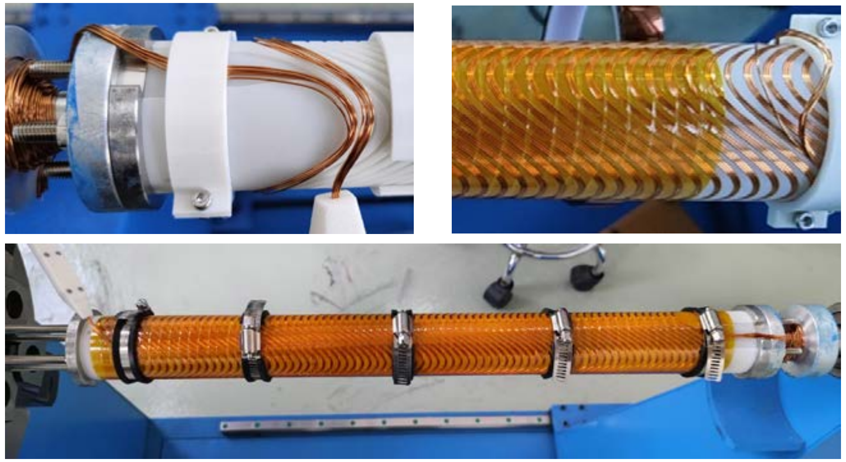
- The maximum harmonics (A1 and B1) is increased by 47 unit (1×10^{-4}).
- Therefore, the machining error (0.05 mm) in x and y direction can affect the harmonies a lot.

CCT Test Coil

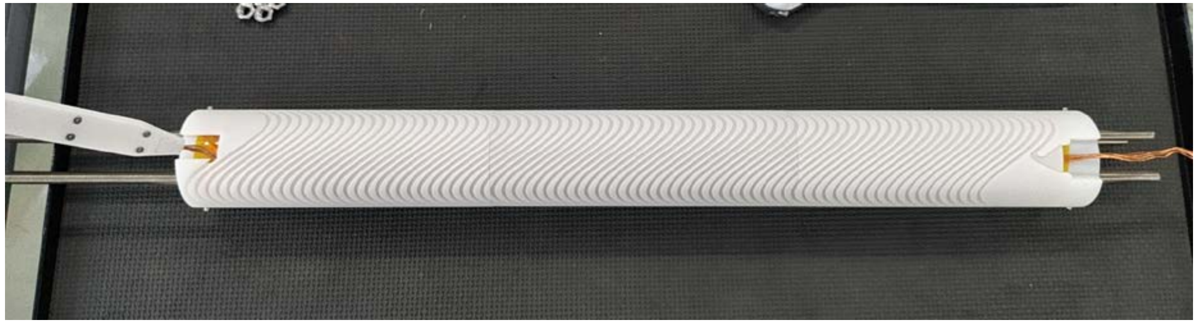
□ Copper coil winding



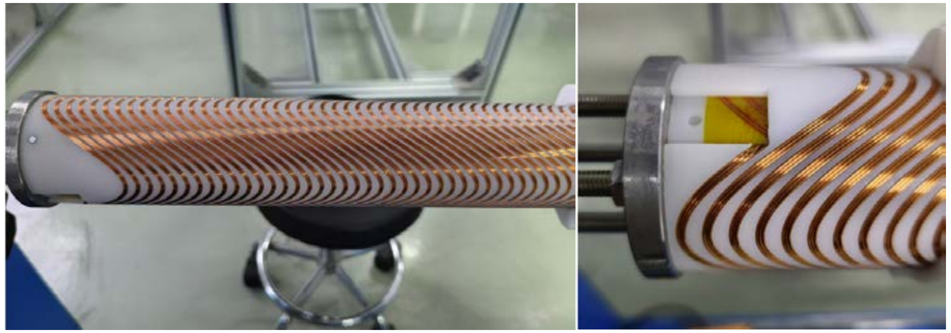
CCT former



Inner coil



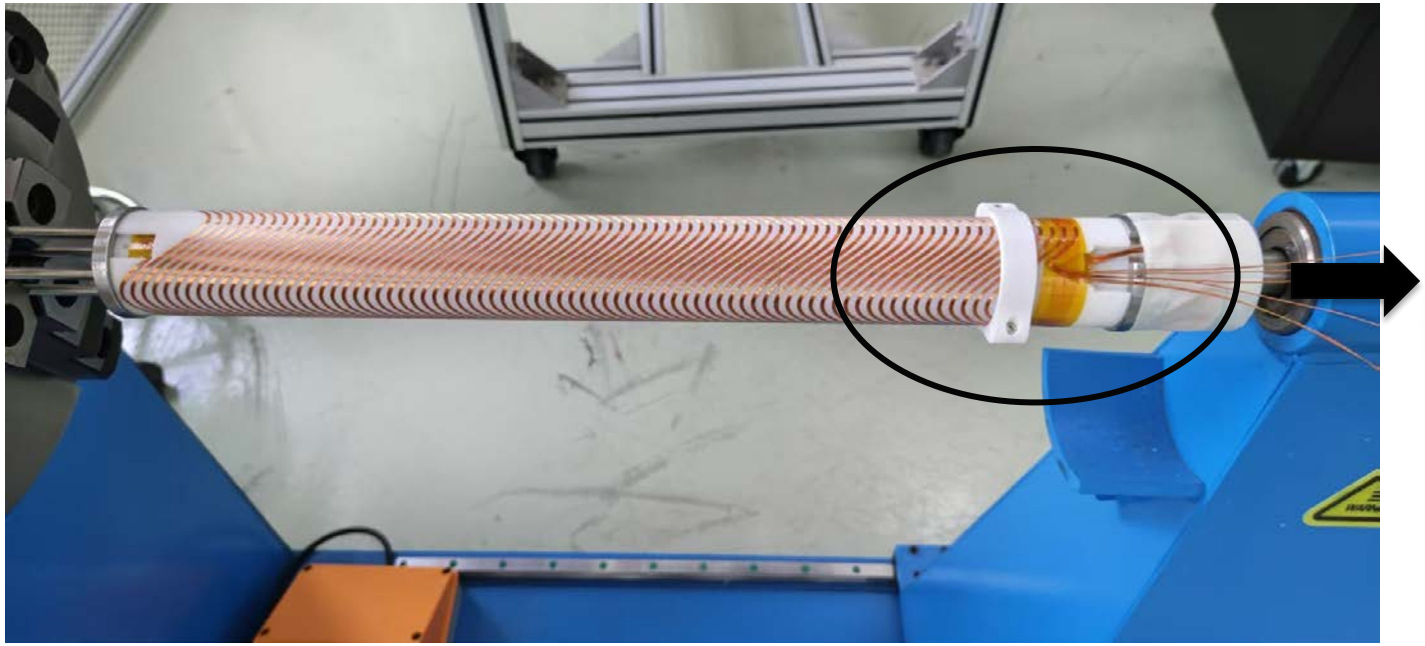
Nesting outer former



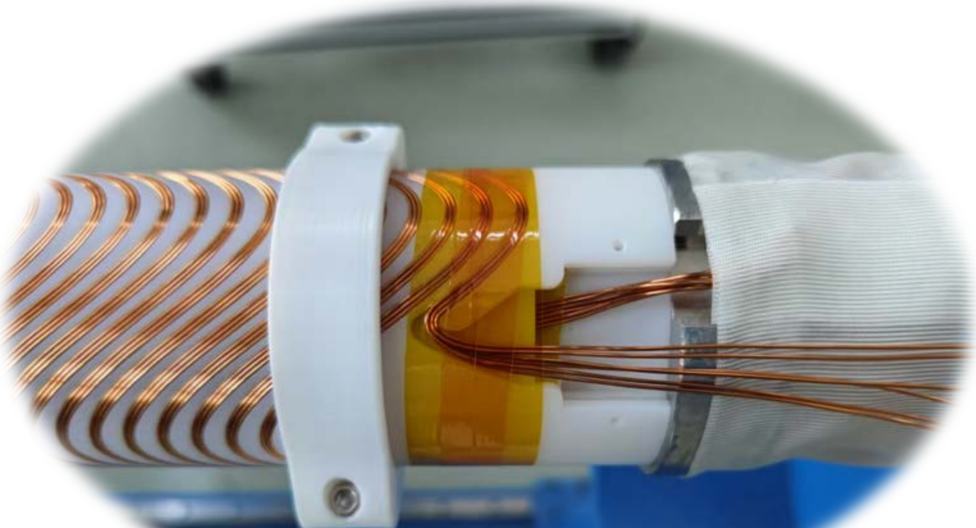
Outer coil

CCT Test Coil

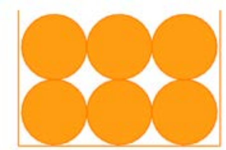
- ☐ **Copper coil winding**



Finishing winding



Enlarge



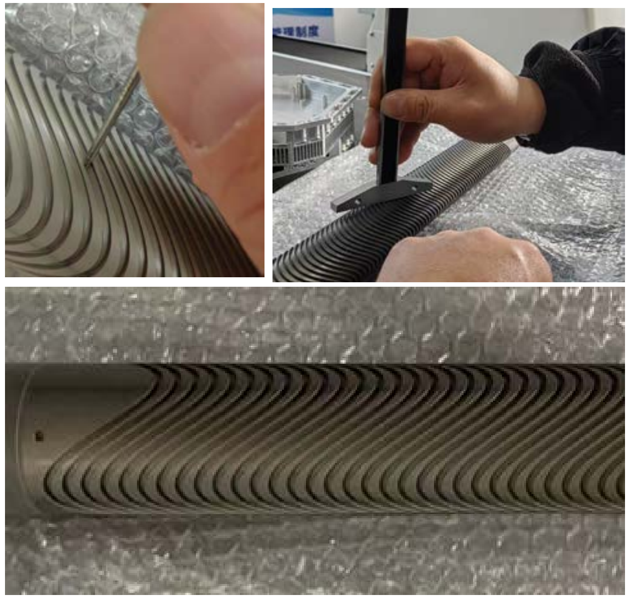
wire section

- ☐ **Next, we will develop the superconducting coil test coil.**

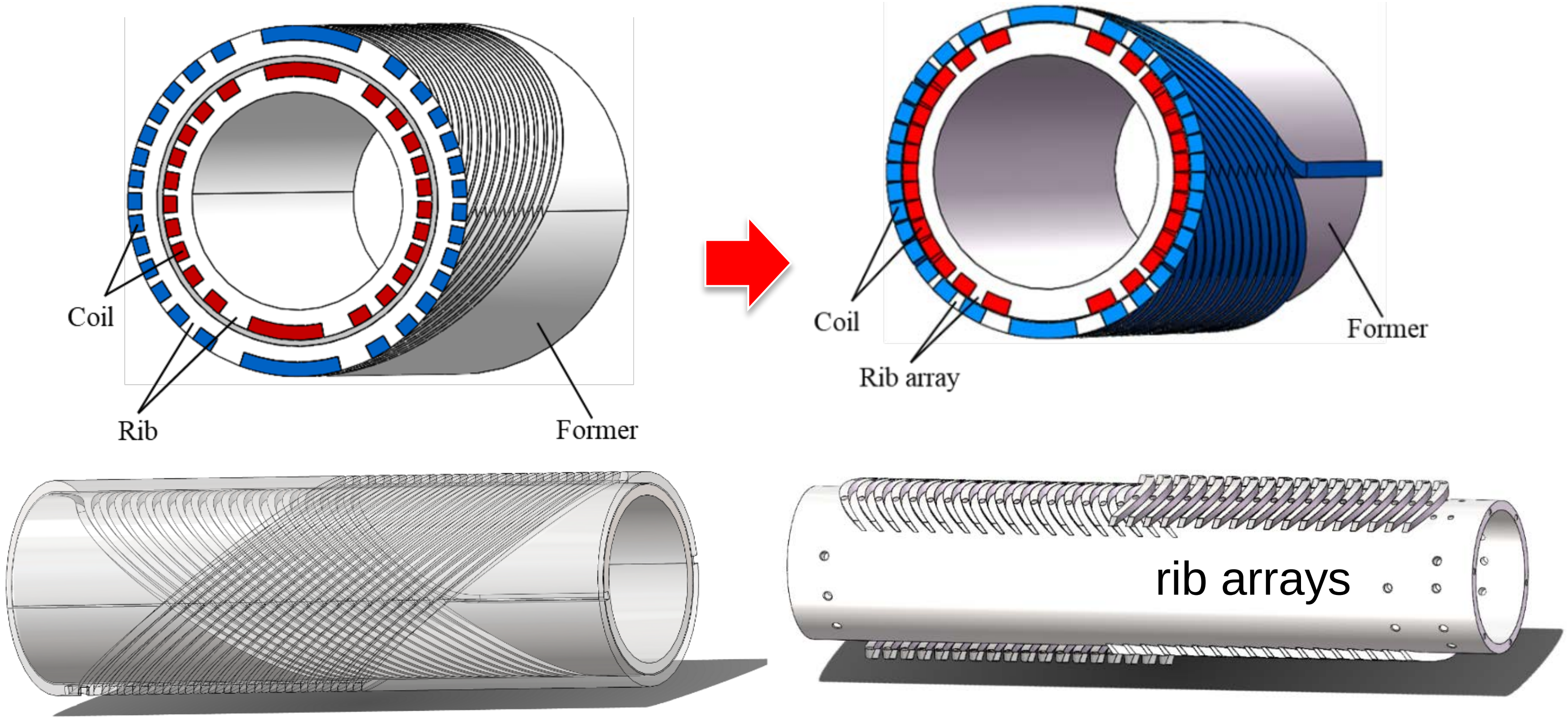
Contents

A Novel CCT Coil : Slot-less CCT Coil

- **To make the CCT coil structure more compact, and to increase the electromagnetic efficiency, a novel design of CCT with slot-less coil was approached.**



CCT former



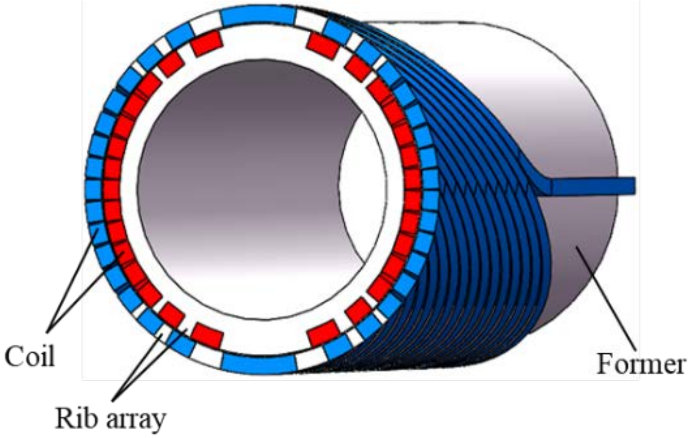
CCT with **slot** structure

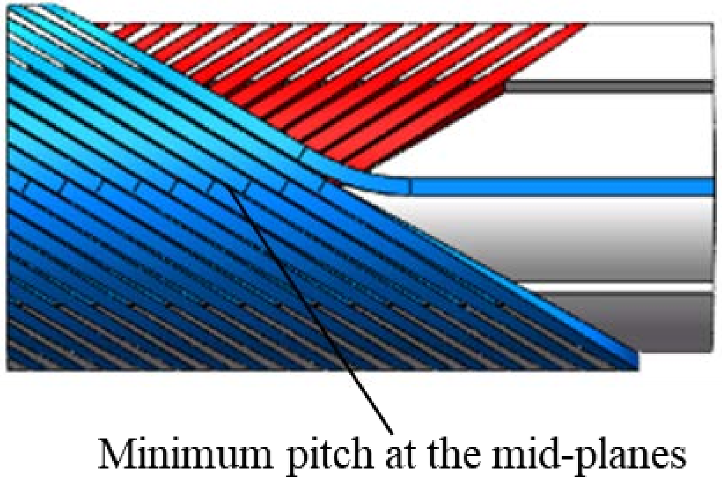
CCT with **slot-less** structure

A Novel CCT Coil : Slot-less CCT Coil

□ The advantages of the CCT with slot-less coil

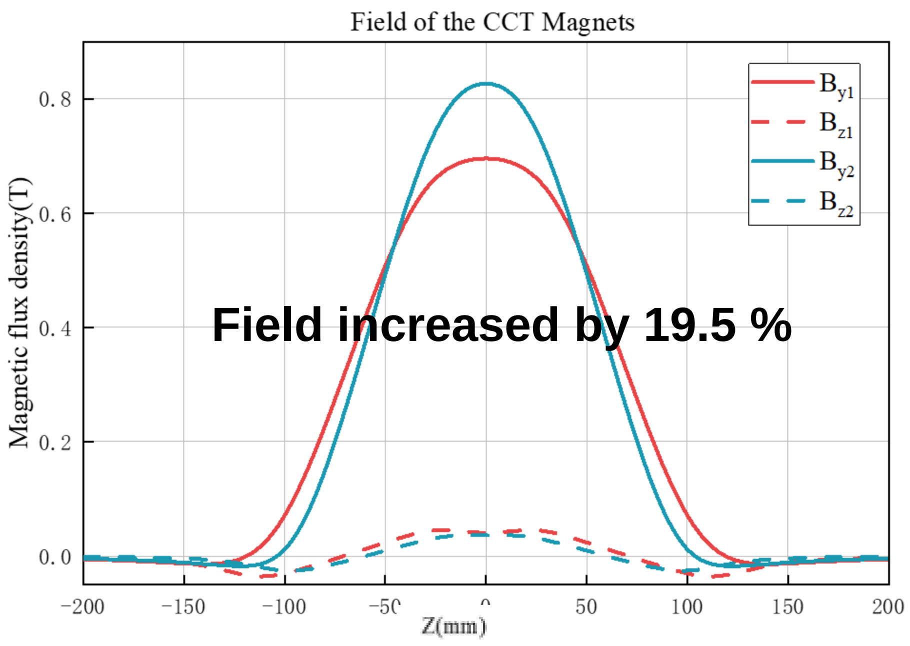
- Do not need inner and outer formers, (using rib arrays instead of formers). so simplified skeleton processing.
- The coil can be densely packed winded on the side.
- The electromagnetic efficiency is improved.
- The radial and axial coil length can be decreased.
- Smaller size and lighter weight.



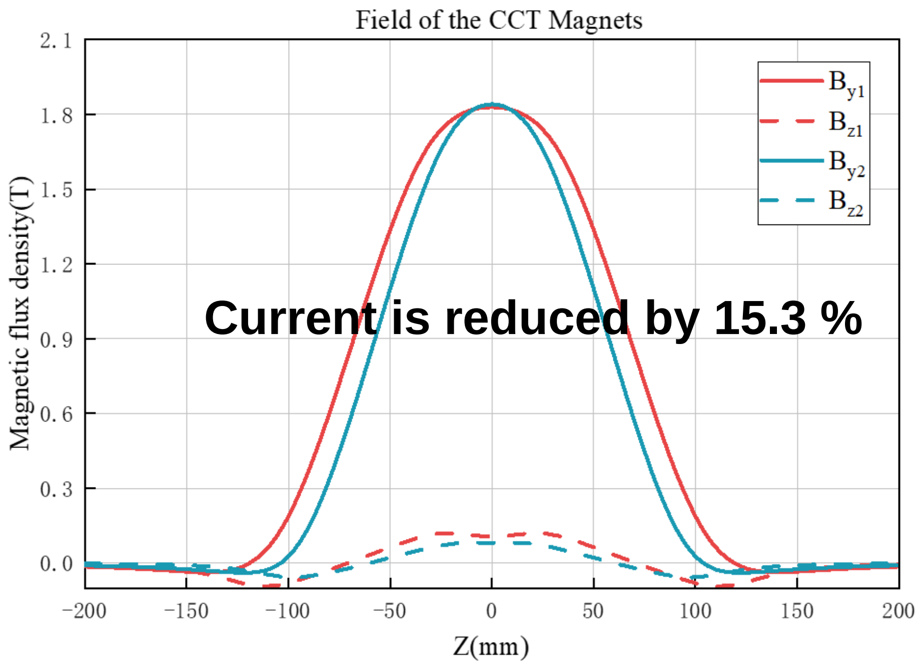


Comparison of two Structures

□ Magnetic analysis comparison of the slotted CCT and Slot-less CCT



Case 1： with the same current



Case 2： with the same field

Red line： *Slotted CCT*
blue line： *Slot-less CCT*

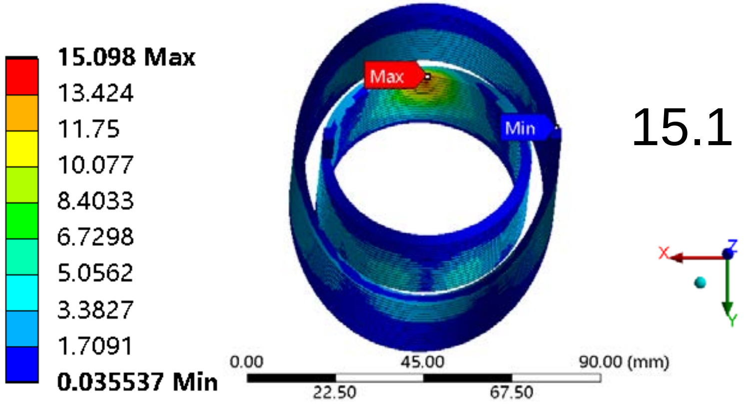
- **Case 1 : The magnetic field of the Slot-less CCT increased by 19.5 %.**
- **Case 2 : The operating current of the Slot-less CCT is reduced by 15.3 %.**

Comparison of two structures

◻ Stress analysis comparison of the slotted CCT and Slot-less CCT

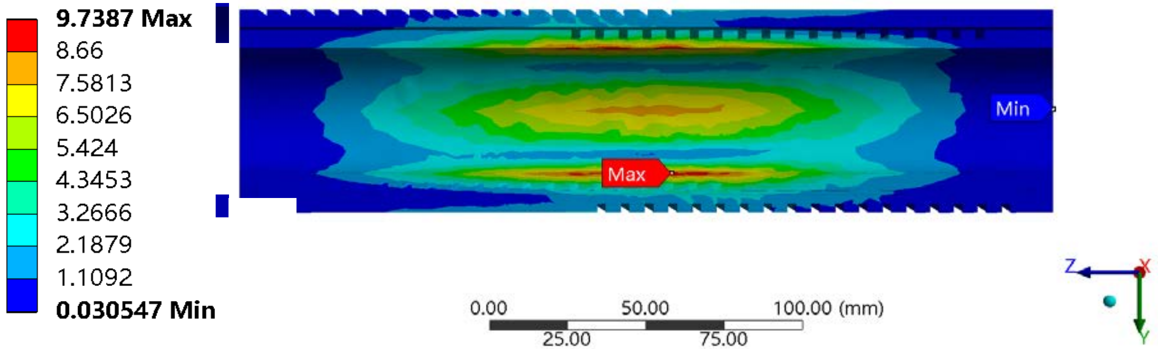
- Case 1 : with the same current
- Case 2: with the same field

Slotted

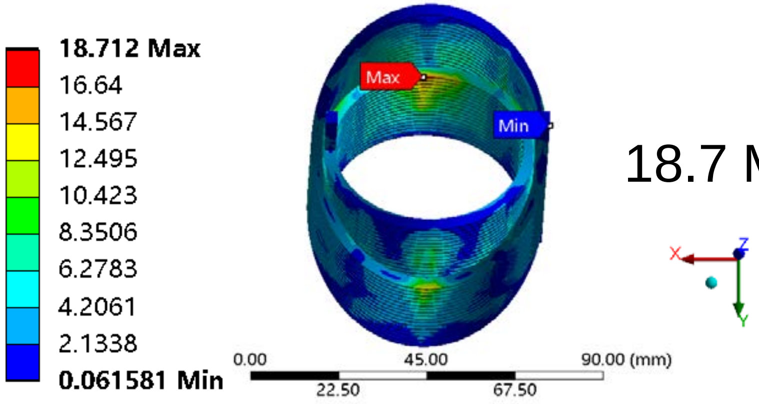


15.1 Mpa

9.74 Mpa

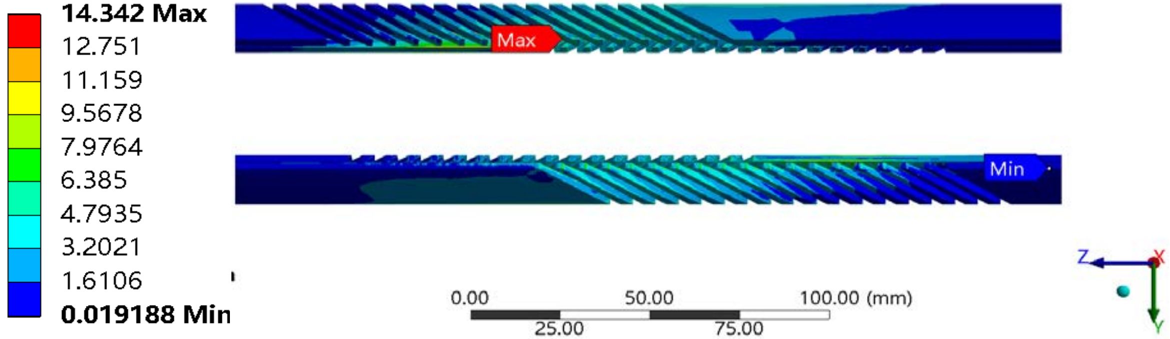


Slot-less



18.7 Mpa

14.34 Mpa



Comparison of two structures

- Compared to the slotted CCT , the slot-less CCT has higher field, smaller size, lower current.

Item	Case I		Case Ⅱ	
	Slotted	Slot-less	Slotted	Slot-less
1	330	330	868	735
Central field (T)	0.692	0.827	1.828	1.828
Peak field (T)	1.044	1.210	2.657	2.647
Inductance (mH)	1.8	1.9	2.6	1.9
Maximum Coils stress (MPa)	15.098	18.712	32.414	34.856
Maximum Mandrels stress (MPa)	0.830	5.162	9.739	14.342

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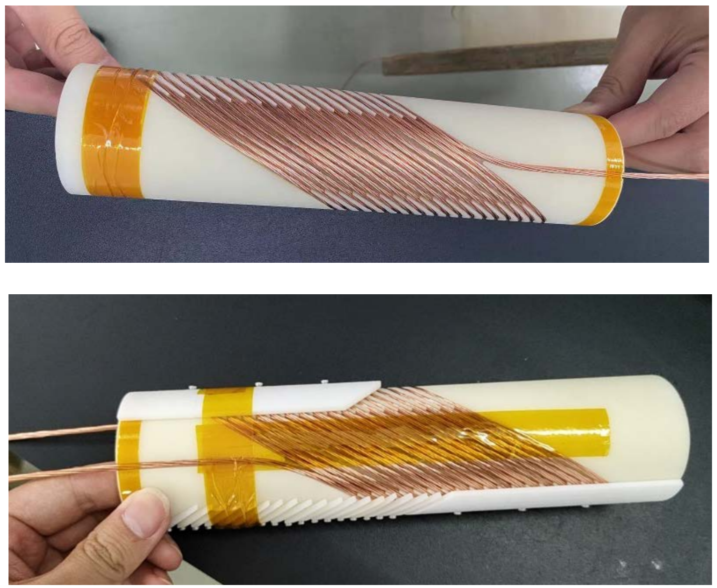
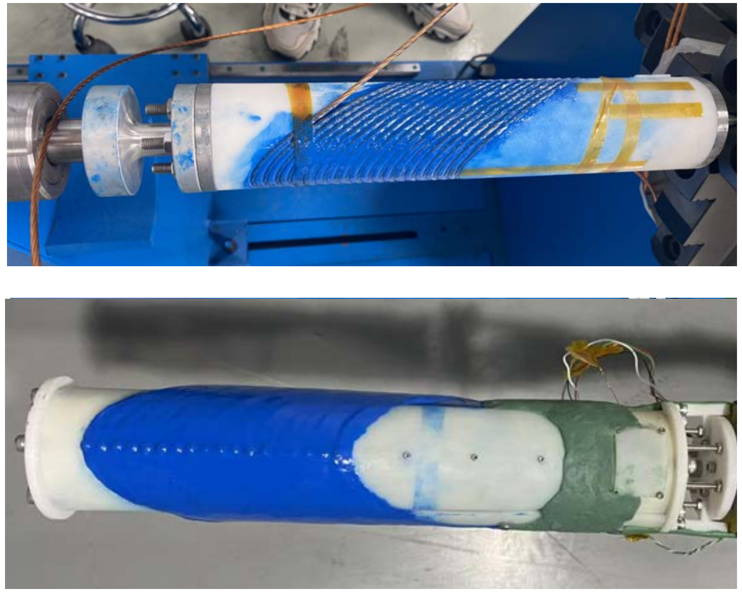
Fabrication and Cold Test

Unpublished

- **We make a superconducting Slot-less CCT dipole test coil and test it at 4.2K Liquid Helium temperature.**



Dry winding



Wet winding

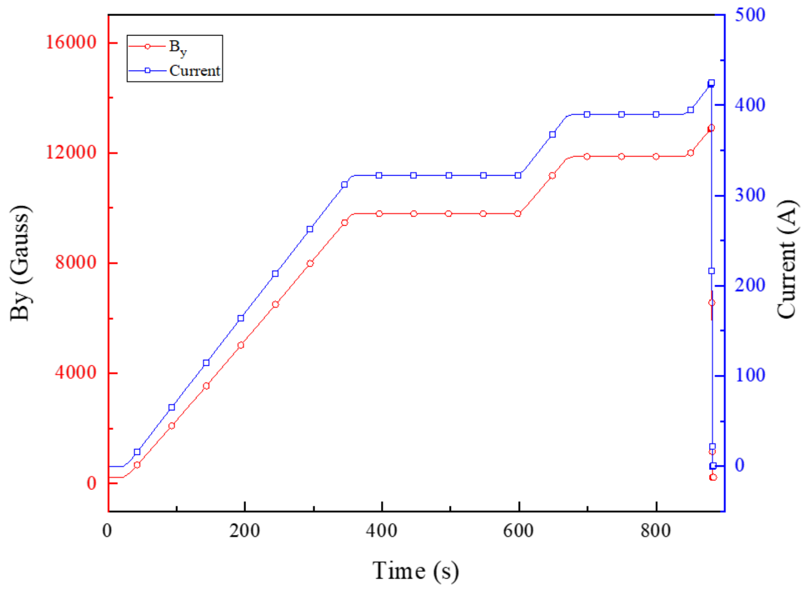
Cold test

Fabrication and Cold Test

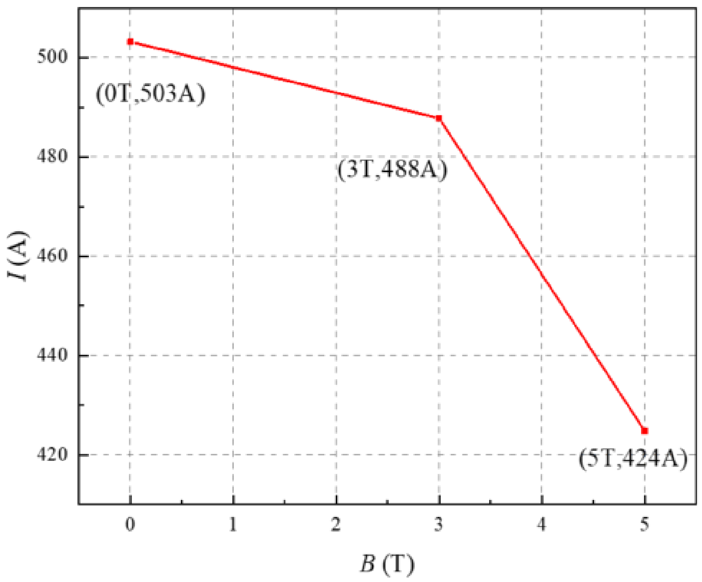
Unpublished

☐ We get good test results

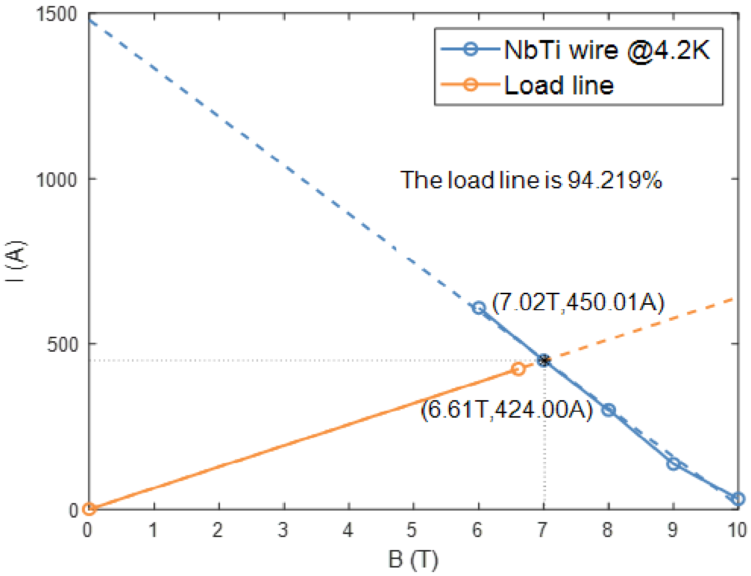
- **At self field, the current reached 503A, Central field is 1.53T.**
- **At 3T background field, the current reached 488 A, the load line reached 83%.**
- **At 5T background field, the current reached 424 A, the load line reached 94%.**



Measured fields



Training results



Load line

Conclusion

- The concept design of the CCT quadrupole coil of STCF interaction region is approached in this study.
- All the harmonics in the design CCT coils are less than 0.5×10^{-4} , which satisfied the requirement ($< 2 \times 10^{-4}$).
- There will be many challenge during the development of the IR CCT coil in STCF.
- A novel design of CCT with slot-less coil was explored. It can be a reference for the STCF CCT magnet.

Thanks for your attention!

Backup Sliders

Background

☐ Super Tau Charm Facility (STCF)

- A third-generation circular electron-positron collider STCF with the E_{cm} = 2~7 GeV and $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1} is being developed in China.

- The QD0 is the nearest magnet from IP. It needs 50 gradient with all the harmonics $\leq 2\times10^{-4}$.

Coil	R_{ref}, (mm)	Gradient (T/m)	Effective length (mm)	High harmonics	Crosstalk (Gauss)
QD0	10	50	400	≤0.2 ‰	30
QF1	15	40	300	≤0.2 ‰	30

Harmonics Optimization (1)

- By adding reverse harmonic components,

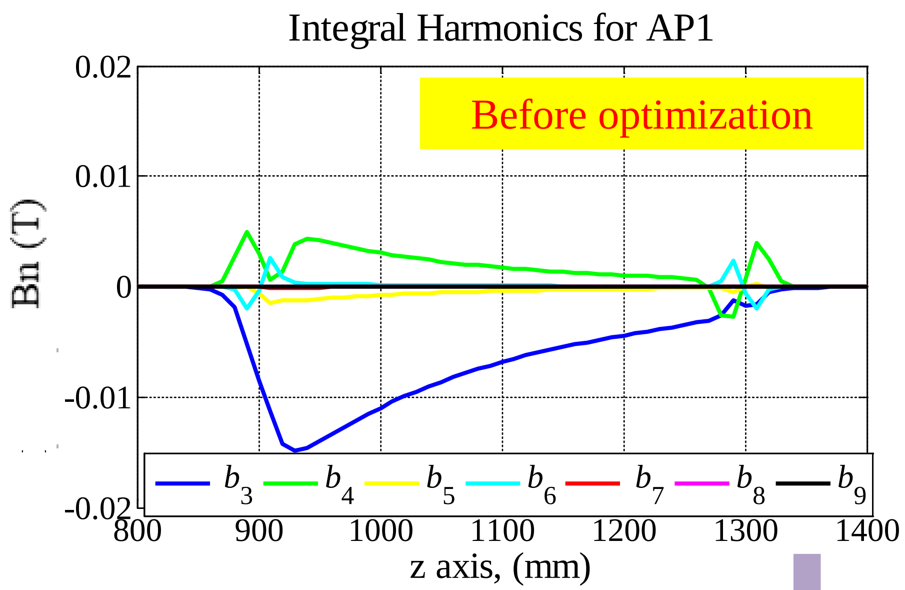
$$z=\sum_{n_b}\left[K_n\frac{r\sin(n_b\theta)}{n_b\tan\alpha}\right]+\sum_{n_a}\left[P_n\frac{r\cos(n_a\theta)}{n_a\tan\alpha}\right]$$

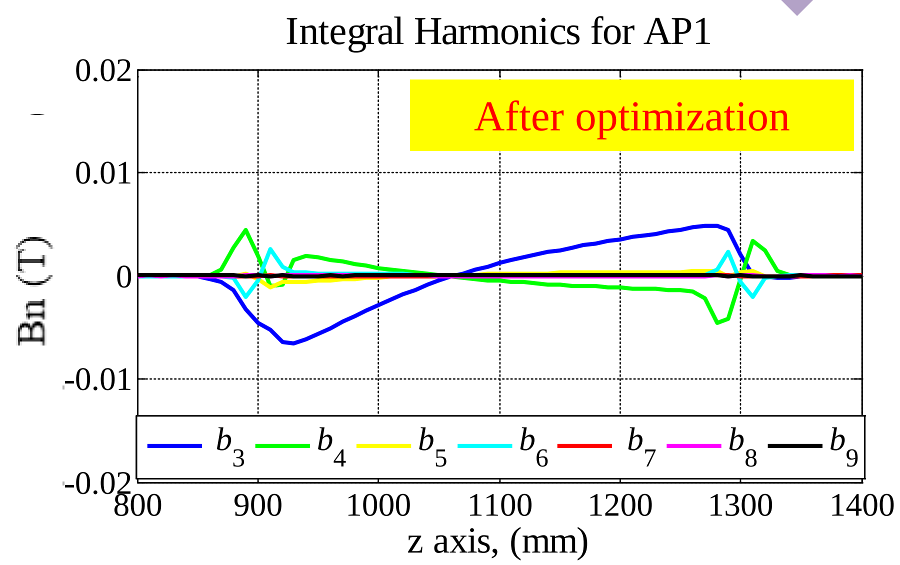
High order harmonics are all less than 1.6 $\times 10^{-4}$

(Requirements < 2 $\times 10^{-4}$)

unit: 10^{-4}

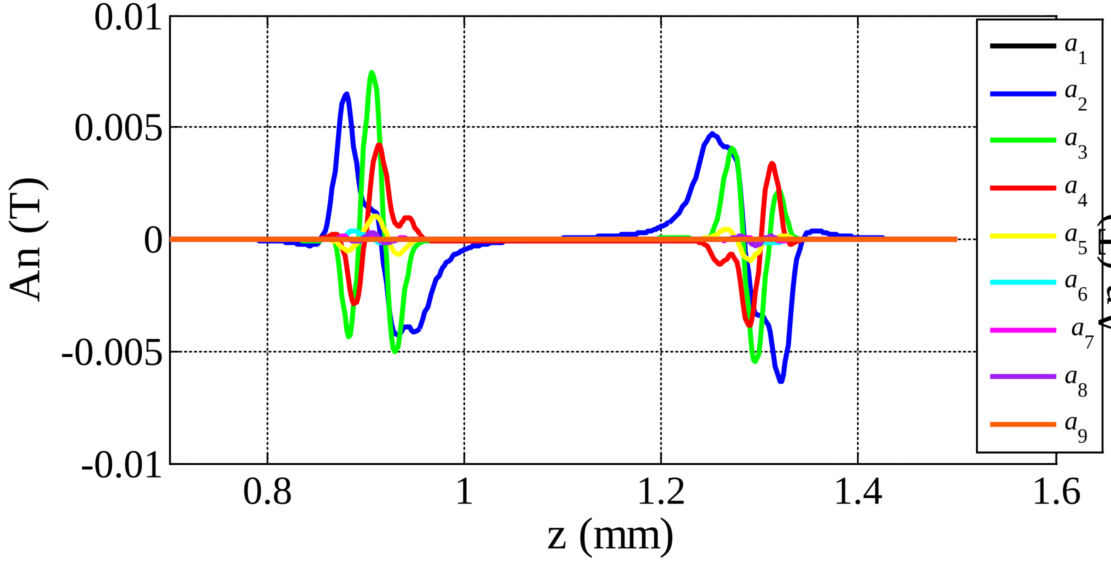
Terms	AP1		AP2	
	Cross-talk	After optimized	Cross-talk	After optimized
a_2	-6.34	-0.22	-6.46	-0.25
a_3	2.55	0.16	-2.06	0.35
a_4	-0.96	-0.99	-0.62	-067
b_3	-153.22	0.99	153.19	-1.02
b_4	41.27	-1.51	41.27	-1.52
b_5	-10.08	-0.80	10.10	-0.77



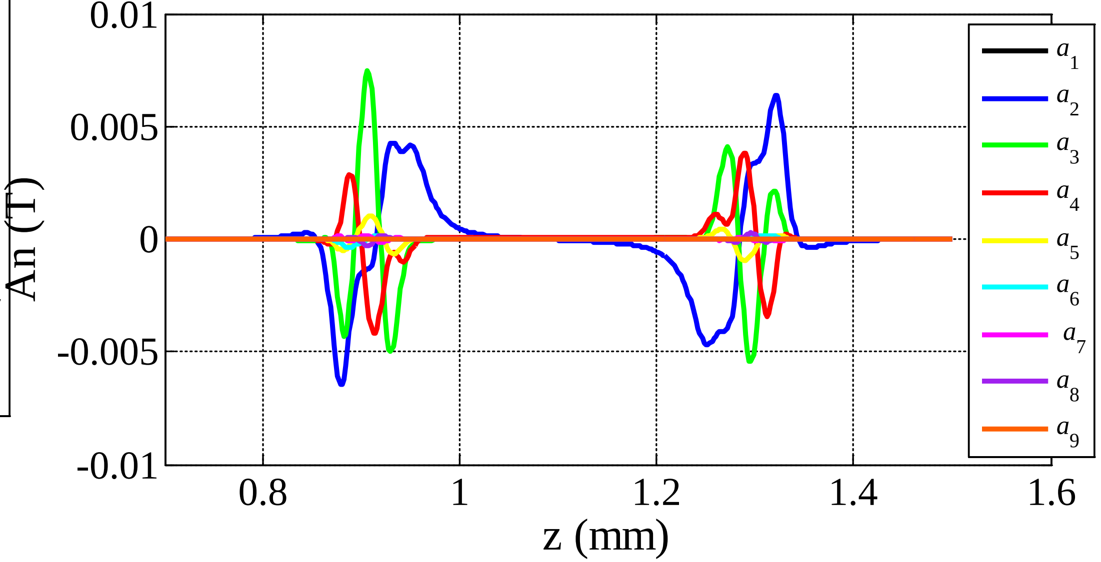


Harmonics Optimization (2)

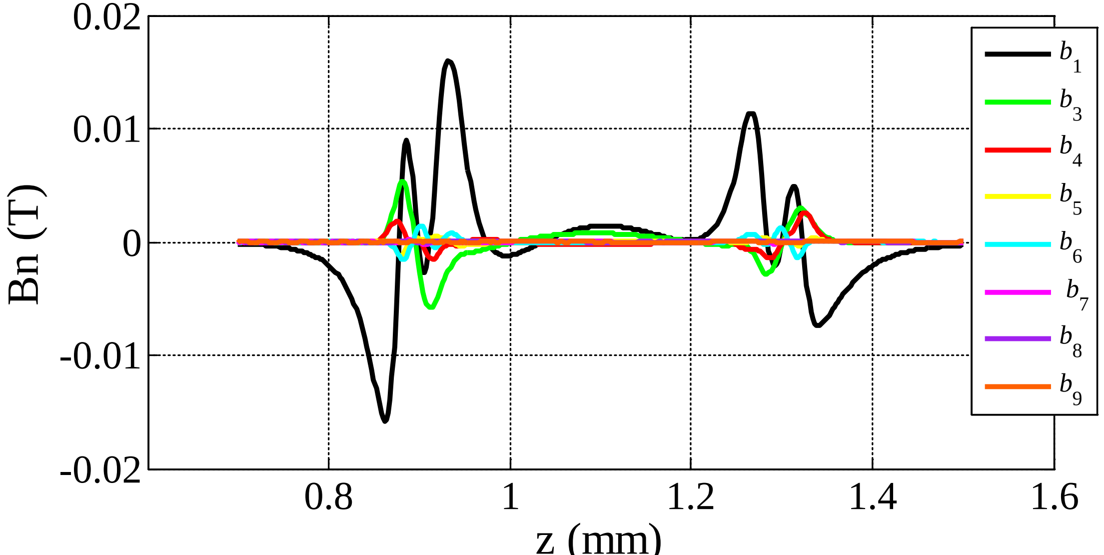
QD0 Integral Harmonics for AP1



QD0 Integral Harmonics for AP2



Integral Harmonics for AP1



Integral Harmonics for AP2