Development of Insertion Region Superconducting Magnet (IRSM) for STCF

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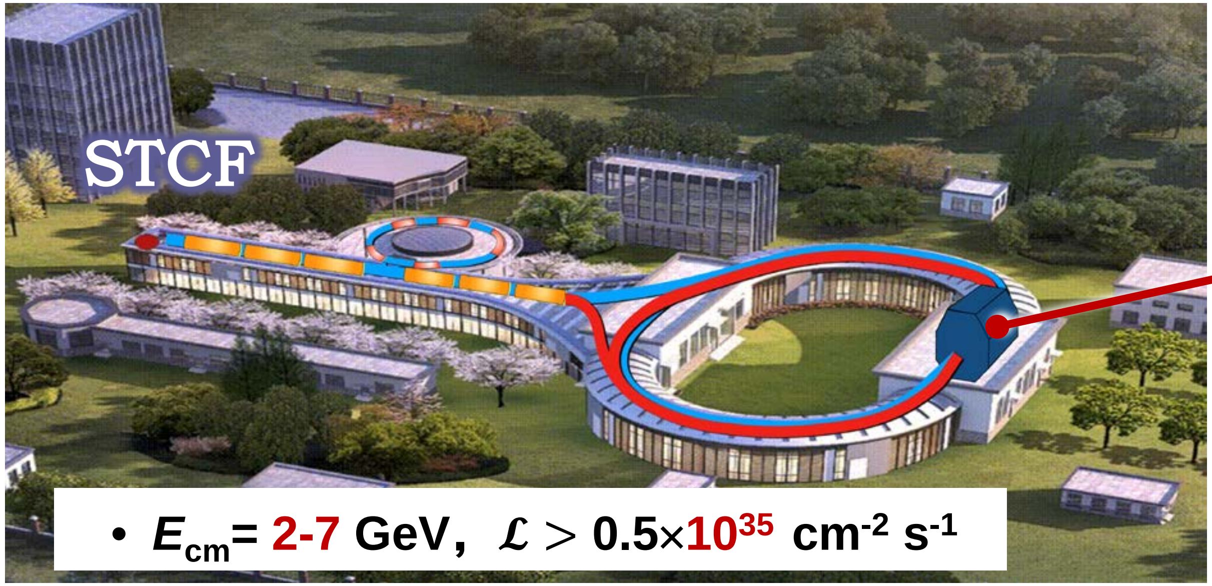
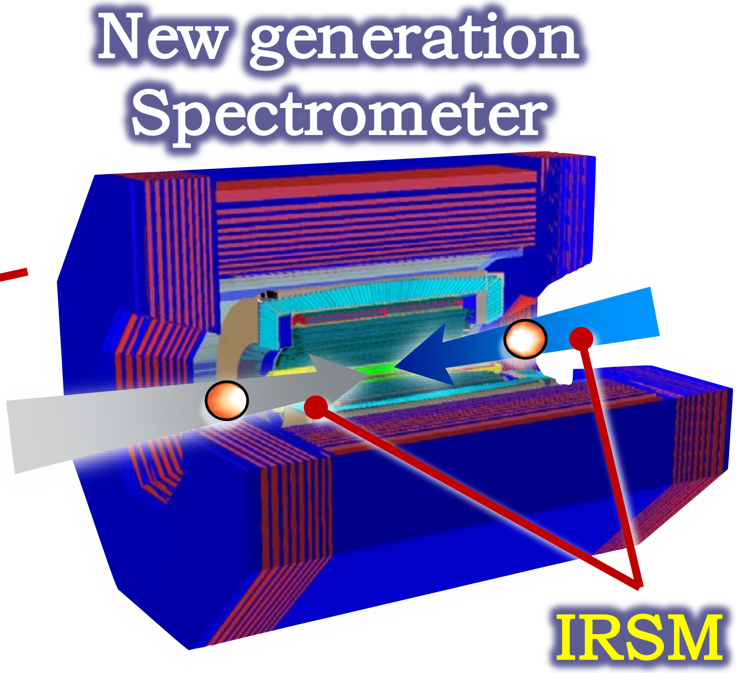
Outline

- **Introduction**
- **Design of IRSM QD0**
- **Design of IRSM anti-solenoid**
- **Summary**

STCF Insertion Region Superconducting Magnet (IRSM)

- **STCF** is a new facility under design for tao-charm study with a circumference about 800-900m, beam energy about 1-3.5 GeV (optimized at 2 GeV), proposed by USTC
- STCF has two type of superconducting magnet systems, Spectrometer magnet and **IRSM**.
- To squeeze the beam for high luminosity, compact **double aperture high gradient** final focus quadrupole magnets are required on both sides of IP .
- CDR requirements of **IRSM** Final Focus quadrupoles are based on **L* of 0.9 m**, beam crossing angle of **60 mrad**.





IRSM Requirements

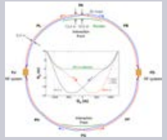
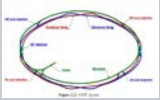
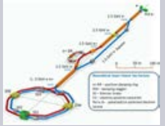
- Quadrupole **lenses of final focus** should have quite **high value** of the field **gradient**, the absence or **minimum** values of other multipole **field components**, and be enough **compact** to be placed in a small accessible space inside the detector.
- Quadrupole magnets are operated inside the field of **detector solenoid** magnet with a central field of **1.0 T**.
- To cancel the effect of the detector solenoid field on the beam, **anti-solenoids** before Quadrupole and outside Quadrupole are needed. So that **total integral field** generated by detector solenoid and accelerator anti-solenoid **is zero**.
- Quadrupoles and anti-solenoid are in **the same cryostat**.

CDR requirements of Interaction Region quadrupole magnets for STCF (@ 7 GeV)

Magnet	Central field gradient (T/m)	Magnetic length (mm)	Harmonics @ Ref	R_{ef}(mm)	Inner diameter of beam pipe (mm)	Magnetic front to IP (mm)	Minimal distance between two aperture beam lines (mm)
QD0	**50**	400	≤0.2‰	10	10	900	**54.06**
QF1	40	300	≤0.2‰	15	25	1800	108.12

e^--e^+ Collider Dual-aperture IRSM Main Parameters

- Most of the latest colliders need dual-aperture IRSM system.
- Except SuperKEKB in operation, all the rest are in the design phase.
- STCF IRSM has minimum space for coils.

	SuperKEKB	FCC-ee	CEPC-ee	BINP SCTF-ee	BEPCII	STCF
Status	In operation	CDR	TDR	CDR	In operation (**single** aperture)	CDR
Country	Japan	Europe	China	Russia	China	China
Beam energy [Gev] e-/e+	7.0/4.0	104.5/104.5	120/120	1.3/1.3	1.89/1.89	3.5/3.5
Beam angle (mrad)	83	30	33	60		60
Z pos from IP, L* [mm]	935	2200	2200	905	958	900
Detector Sol. Field [T]	**1.5**	**2.0**	**3.0**	**1.0**	**1.0**	**1.0**
Quad tech route	**cos2θ**	**CCT**	**cos2θ**	**CCT**	Serpentine	**CCT**
FF field gradient [T/m]	**68.9**	**100**	**142.3**	**100**	**18.7**	**50**
Magnetic length[mm]	334	1200	1210	200	502	400
Operating [A]	1625		2020		477	?
Coil ID [mm]	**50**	**40**	**40**	**20**	**190**	**~40**
Coil thickness [mm] Incl. OVB	**10.5**	**12**	**12**			**<7**
Coil name	QC1LP/RP	QC1L1	Q1a	QD0	SCQ	QD0
						

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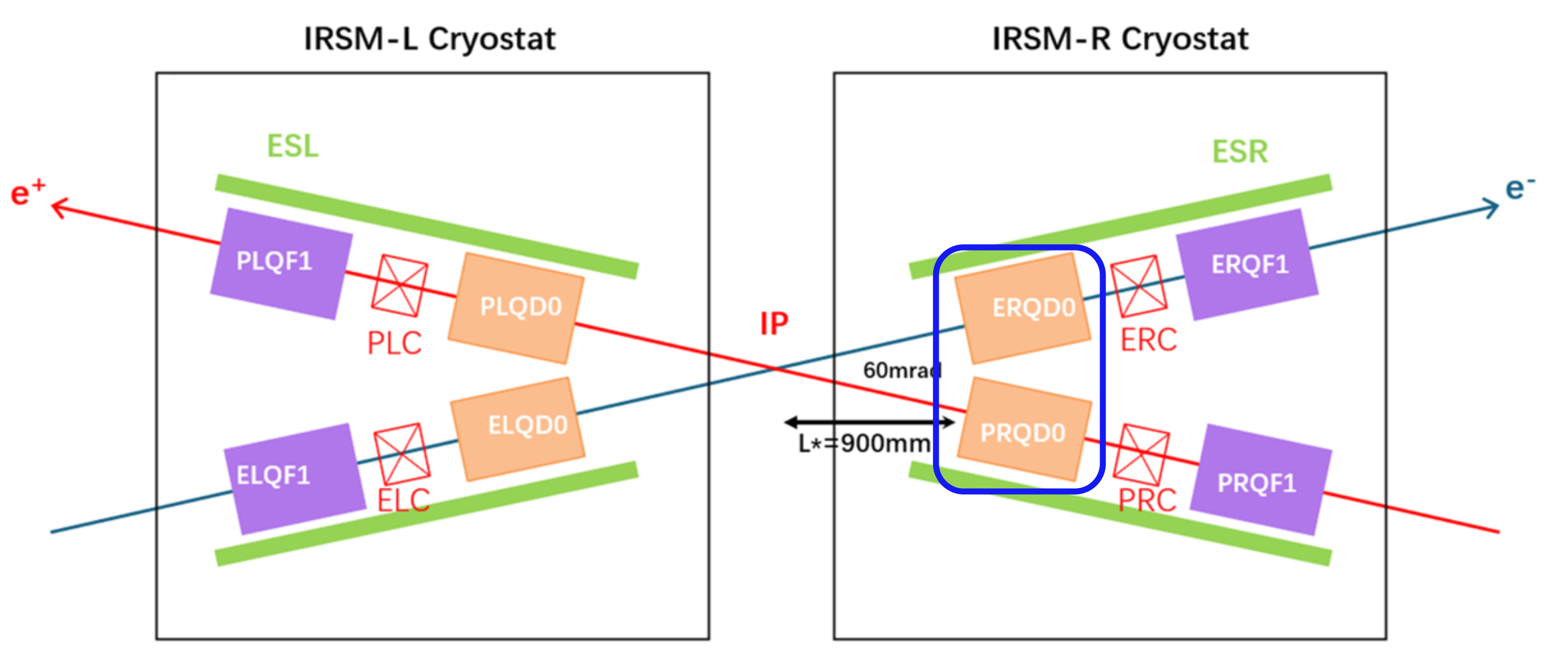
STCF IRSM System

STCF identical energies for the two beams give considerable advantage – **symmetrical layout**.

- **Dual-aperture IRSM system**

  Min coil QTY，24

- **SC quadrupole: x8**
  - QD0: L&R, E&P
  - QF1: L&R, E&P
- **SC Solenoid: x4**
  - ESL: x2; ESR: x2
- **SC corrector: x12**
  - a1/b1/a2: x (PLC, PRC, ELC, ERC)
- QD0 is selected as prototype



SuperKEKB	FCC-ee
4 FF quads per beam line	6 FF quads per beam line
35 corrector coils	12 corrector coils
55coils 8 cancel coils	28coils 0 cancel coils
4 compensation solenoids	4 compensation solenoids
Detector solenoid at 1.5T	Detector solenoid at 2T

M Korazinos, FCC-ee CCT Quadrupole Design and Plans for Experimental Tests, FCC-EIC Joint & MDI Workshop 2022.

Design of QD0

- 2θ=60mrad and L*=900mm give minimal distance between two aperture beam lines: **54.06 mm**
- Take space for beam pipe, vacuum and helium vessel, **quadrupole coil inner radius: 20 mm**
- It is challenging to meet stringent design requirement

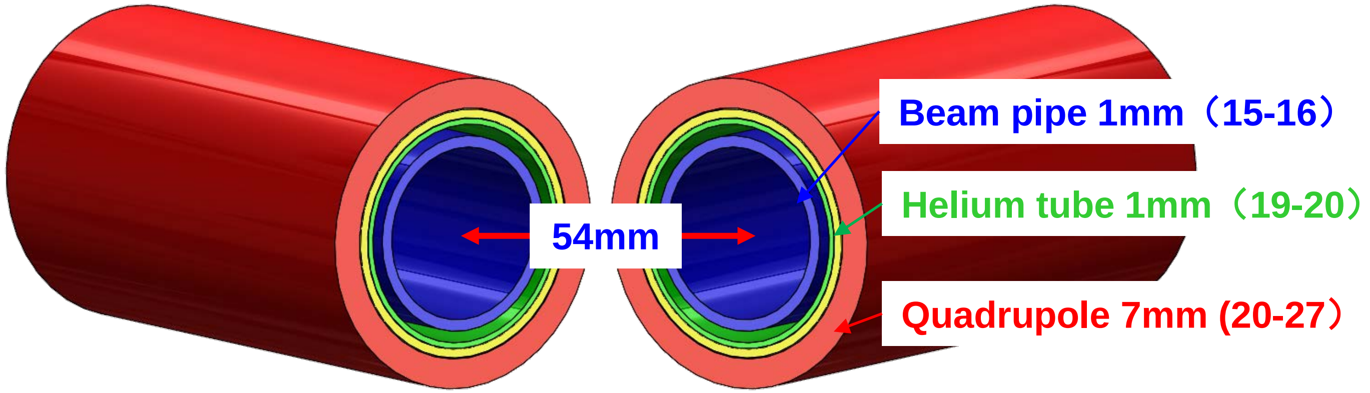
  1) High field gradient: **50T/m**

  2) Limited radial space: Limited radial space for quadrupole coils

  R: [20mm, 27mm], **only <7 mm available** **(incl. coil&former)**

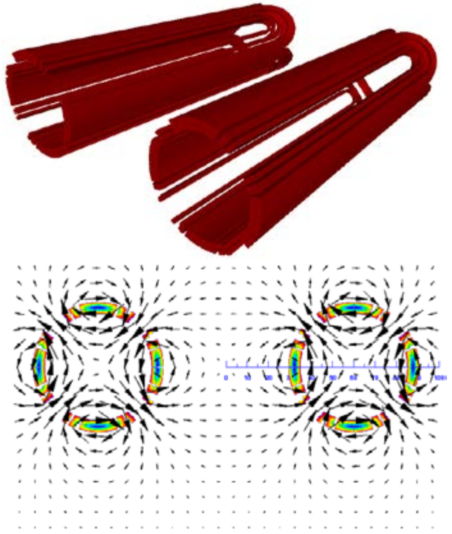
  3) High field quality

  All harmonics below **$<2\times10^{-4}$**

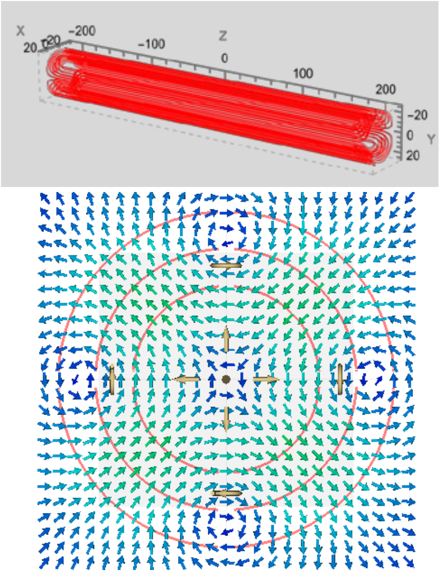


Design of QD0 – techniques selection

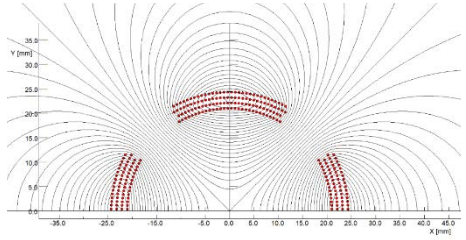
- IR SC magnet techniques selection:
  - Joint effort by experienced persons from several domestic institutions including HMFL (High Magnetic Field Lab), IPP, IHEP, IMP and others
  - Four different techniques studied: CCT, Cos2θ, DCT, Serpentine
  - After two rounds of discussions, CCT was chosen for the further R&D and prototype at this stage (similar to FCC-ee and SCTF)



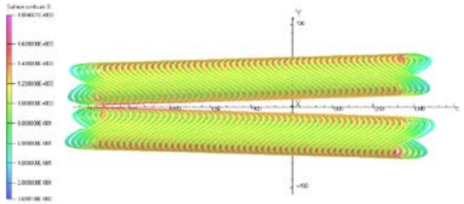
Cos2θ coil EM



Single aperture DCT coil EM



Single aperture serpentine coil EM



CCT coil EM

中国科学院等离子体物理研究所

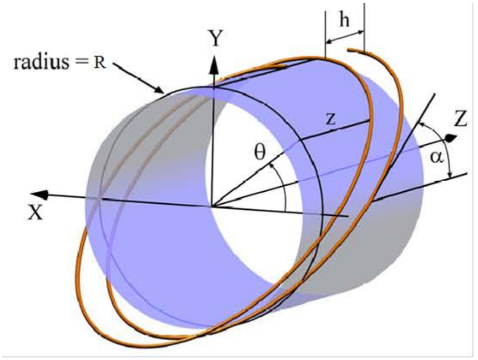
中国科学院高能物理研究所 Institute of High Energy Physics, CAS

中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences

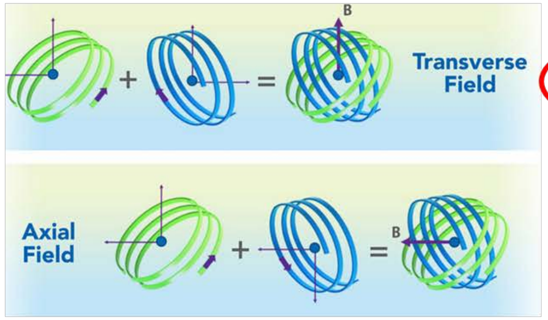
https://indico.pnp.ustc.edu.cn/event/2355/

STCF IRSM – CCT

- **CCT (Canted-Cosine-Theta) coil**
  - Comprise two coils on two concentric cylinders
  - Each coil produces a solenoid field plus an arbitrary multipole field (dipole, quad, sextupole…)
  - The two solenoid fields from the two coils exactly cancel
- **Important advantages of CCTs**
  - Cheap to make – from the magnet design program to CAD to CNC machine with no manual interventions
  - Easy to make – no pre-stress! Stress management is trivial in CCTs
  - Fast to make – few steps, no expensive equipment
  - **Excellent field quality**



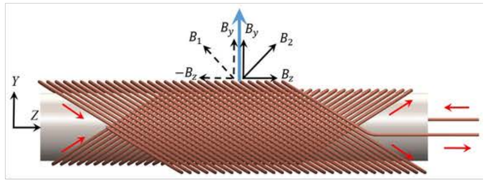
CCT线圈参数示意图



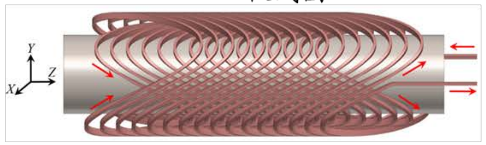
$J_z \sim \cos\theta$

$J_\theta \sim const$

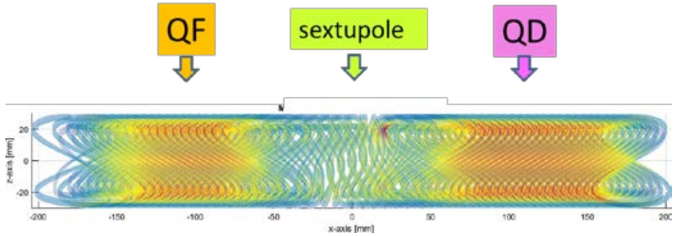
CCT线圈产生磁场原理图



CCT二极线圈



CCT四极线圈

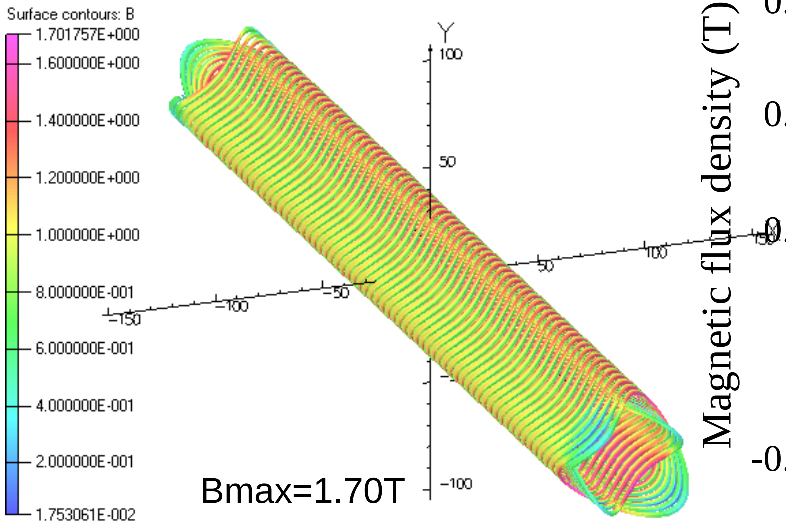


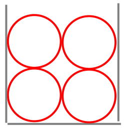
M. Koratzinos, Technologies for MDI magnets, 5th PBC workshop, 26th Sept. 2024.

STCF IRSM – QD0

QD0 – single aperture parameters

Item	Value (Φ0.80, 2×2)
Beam Angle(θ), mrad	60
$R_{ref_}$QD0, mm	10
QD0 Coil1 IR, mm	20.0
QD0 Coil2 OR, mm	26.4
QD0 Magnet OR, mm	26.9
I, A	509
Bmax, T	1.70
B, T	0.50
G,T/m	**50**
Load line(4.2K), %	63.23%
Turns	80
Tilt angle	62°
Groove size	1.9x1.9 mm
Groove wall thickness	≥0.5 mm



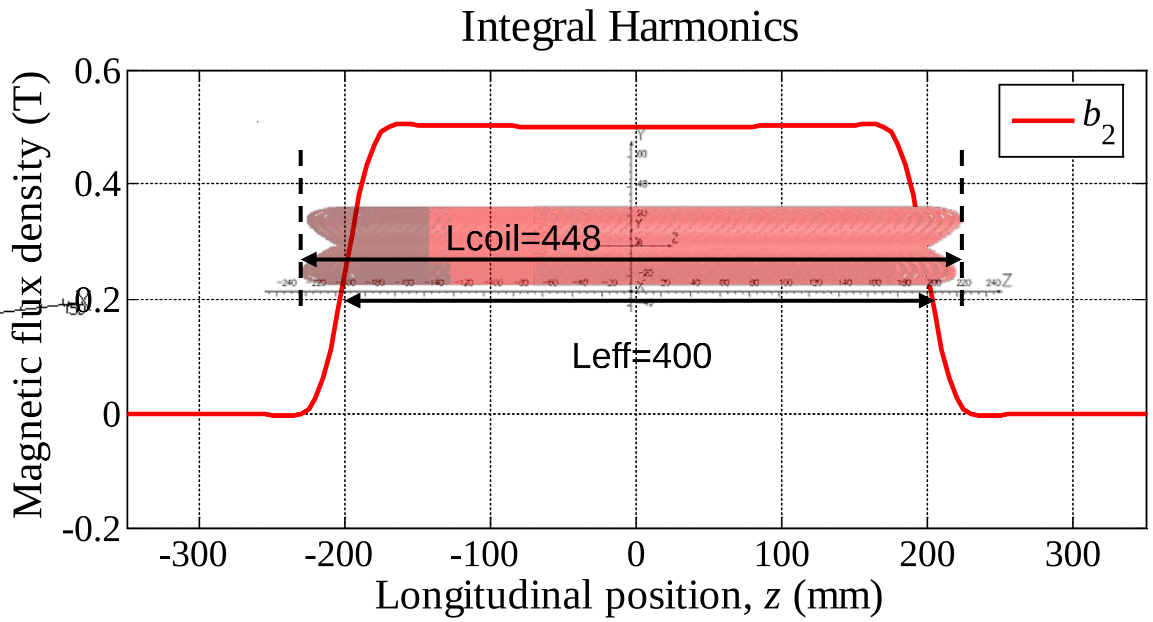


Wire 2×2

Very fine filament NbTi wire: Ø0.8mm, I_c >850A @2T,4.2K

Wire spec

低损耗铌钛线(ITER级)		
裸线尺寸（mm）	0.6	0.8
绝缘层厚（μm）	25~40μm	
铜超比	1.6:1	
芯丝数量	3348芯	
芯丝直径（μm）	≤8	
扭距（mm）	15±2	
扭转方向	右旋	
RRR(273K/10K)	＞100	
临界电流	4T@4.2K>321A; 5T@4.2K>266A; 6T@4.2K>201A; 7T@4.2K>152A;	4T@4.2K>570A; 5T@4.2K>473A; 6T@4.2K>357A; 7T@4.2K>270A;
转变指数	n-value@4.22K&5.0T＞20	

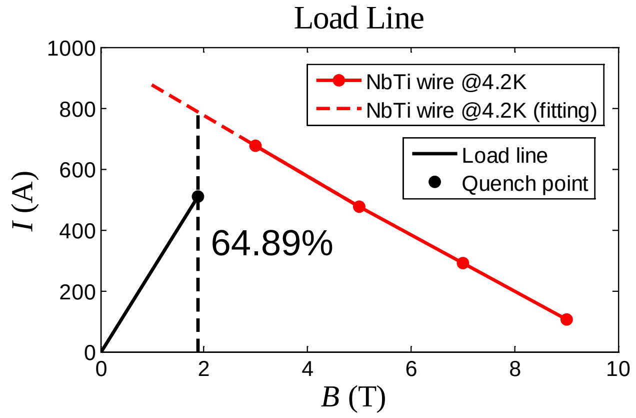


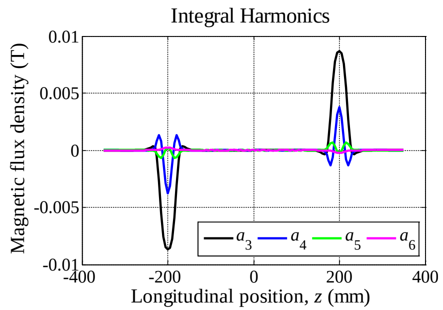
- Magnetic length: Leff=400 mm
- Winding length: 448 mm，Coil length: ~468 mm

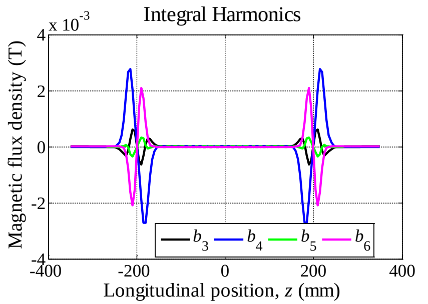
STCF IRSM – QD0

QD0 – dual aperture parameters

- **Dual aperture model (non-optimized)**
  - Beam angle: 60 mrad
  - L*= 1100 mm
  - Bmax=1.89T, SSP=64.89%

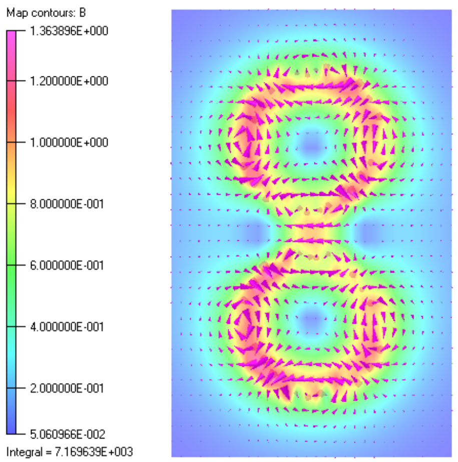




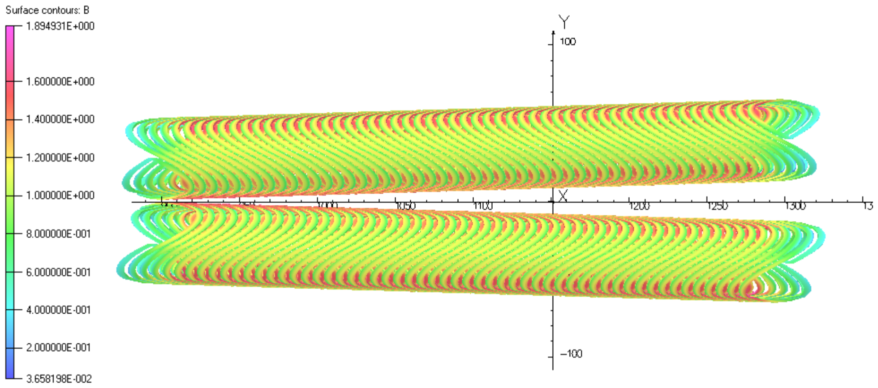


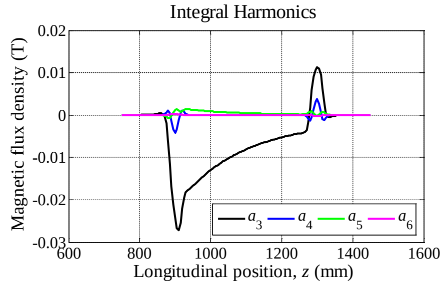
- Single aperture

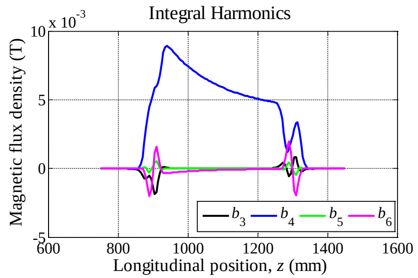
All high order harmonics **below 2 unit** (0.2 ‰)



Bmax=1.89T







- Dual aperture

a3=-208 unit

b4=139 unit

Local edge corrections are needed!

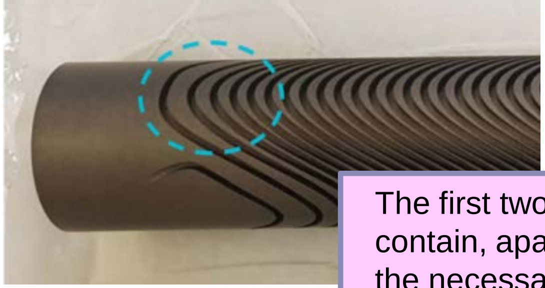
CCT Coil Local Edge Corrections to Minimize Harmonics

- The first two turns of the quadrupole contain, apart from the B2 component, all the necessary components to nullify the edge effects.

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

TABLE I
SIZE OF EDGE CORRECTION (IN DEGREES) FOR THE FIRST AND LAST WINDINGS OF THE MAGNET FOR ALL CORRECTED MULTIPOLES. B2, THE MAIN COMPONENT, IS ALSO GIVEN FOR REFERENCE

	A2	A3	A4	A5	A6	B2	B3	B4	B5	B6
α left	-3.1	19	-38	6	6	60	-5	-3.5	6.5	1.5
α right	3.1	-19	38	-6	-6	60	-5	-3.5	6.5	1.5



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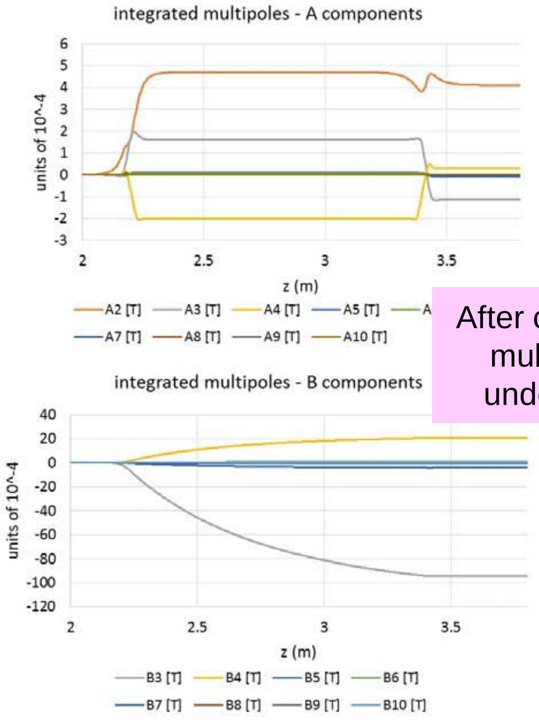
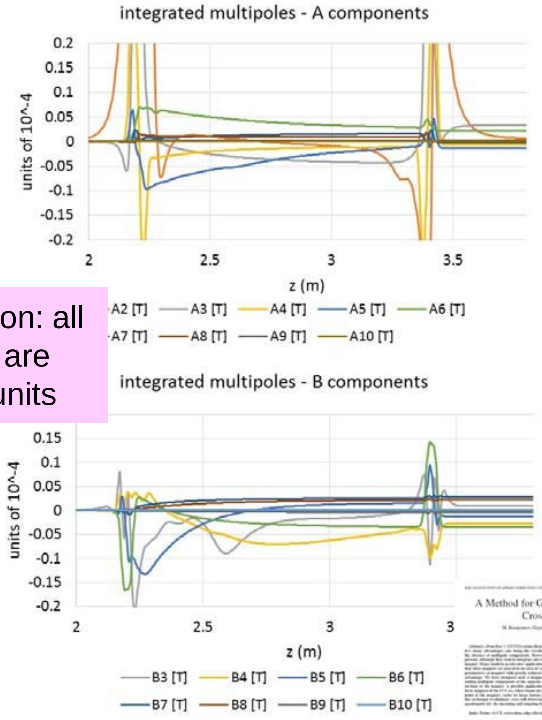


Before optimization

After correction: all multipoles are under 0.1 units

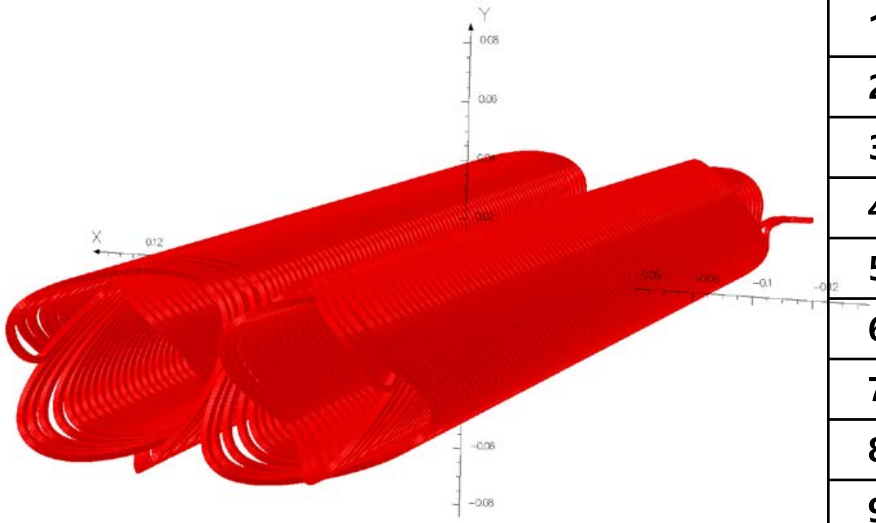


After optimization

[*] M. Koratzinos, ETH Zurich, G. Kirby, J. Van Nugteren, CERN, E. R. Bielert, Univ. Illinois at Urbana. A Method for Greatly Reduced Edge Effects and Crosstalk in CCT Magnets. IEEE Transactions on Applied Superconductivity. Vol.28, No. 3, 2018. April

Optimized QD0

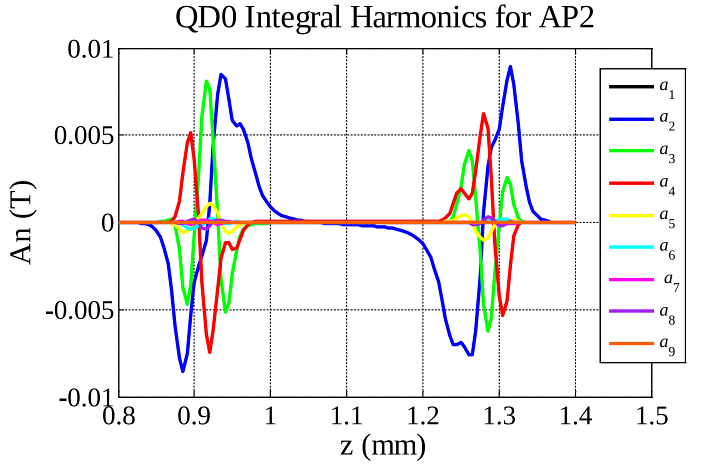
- Consultancy with M. Koratzinos on local edge correction
- Harmonics at 10mm reference radius after local edge correction
- All integral normal and skew harmonics are below 2 unit.

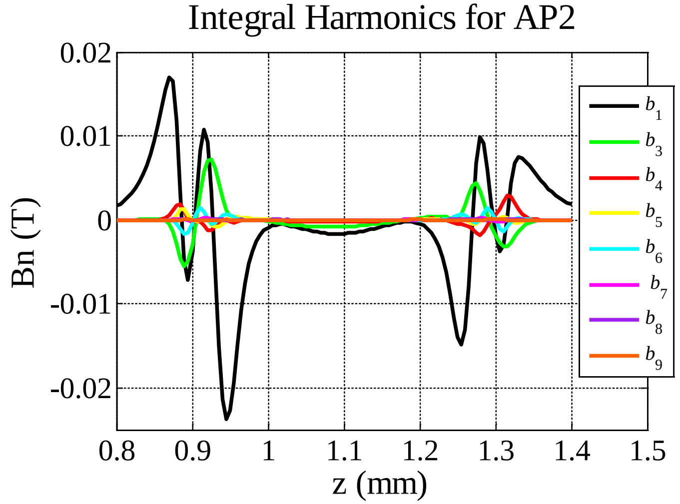


QD0 CCT EM model

Order	Integral harmonics @ R_{ef}=10mm			
	An (T•m)	Unit (An)	Bn (T•m)	Unit (Bn)
1	3.41E-06	0.17	-1.17E-06	-0.06
2	2.80E-06	0.14	2.04E-01	10000
3	-1.56E-06	-0.08	-4.27E-06	-0.21
4	-3.47E-06	-0.17	-2.64E-07	-0.01
5	-3.32E-06	-0.16	3.87E-06	0.19
6	1.13E-06	0.06	-2.98E-06	-0.15
7	4.58E-07	0.02	-2.94E-06	-0.14
8	-6.61E-07	-0.03	2.99E-06	0.15
9	2.20E-07	0.01	-2.70E-07	-0.01
10	-8.51E-08	0	2.97E-07	0.01

Harmonics of the e+ beam at 10mm reference radius after local edge correction





Harmonics comparison with other e^{+}-e^{-} IRSMs

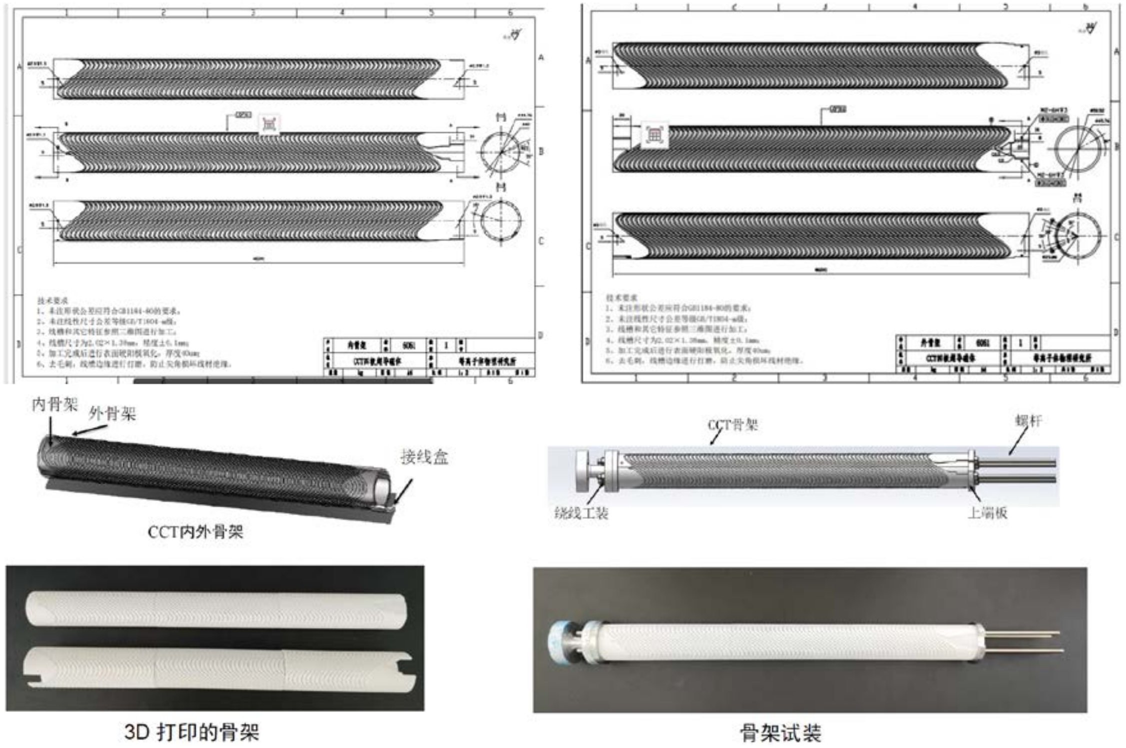
- Harmonics with other projects
  - CEPC from TDR in 2023
  - SuperKEKB from N. Ohuchi published paper in 2021
  - FCC-ee from CDR in 2019

Project		CEPC-ee			SuperKEKB					FCC-ee	STCF-ee
Magnet		Q1a	Q1b	Q2	QC1PL&R	QC1EL&R	QC2PL&R	QC2LE	QC2RE	QC1L1/R1	QD0-2
Coil type		cos2θ	cos2θ	cos2θ	cos2θ	cos2θ	cos2θ	cos2θ	cos2θ	CCT	CCT
Design results											
Integrated field harmonics @Ref											
	b1										-0.06
	b2	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
	b3									0.01	-0.21
	b4				0.24	-0.01	-0.04	0.07	0.05	-0.03	-0.01
	b5									-0.01	0.19
	b6	-0.61	0.25	-0.52	0.54	-0.03	0.18	-0.04	-0.09	-0.03	-0.15
	b7									0.03	-0.14
	b8				0.01	0.04	0.08	0.06	0.04	0.02	0.15
	b9									<0.01	-0.01
	b10	-0.24	-0.14	-0.49	-0.21	-0.33	-0.96	-1.88	-1.3	<0.01	0.01
	b12				0	0.04	0.02	0.03	0.02		
	b14				0	-0.06	-0.07	-0.05	-0.03		

[1] Gao, J. CEPC Technical Design Report: Accelerator. Radiat Detect Technol Methods 8, 1–1105 (2024). https://doi.org/10.1007/s41605-024-00463-y
[2] N. Ohuchi, et al, SuperKEKB beam final focus superconducting magnet system, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,Volume 1021, 2022, 165930, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2021.165930.
[3] Abada, A., Abbrescia, M., AbdusSalam, S.S. et al. FCC-ee: The Lepton Collider. Eur. Phys. J. Spec. Top. 228, 261–623 (2019). https://doi.org/10.1140/epjst/e2019-900045-4

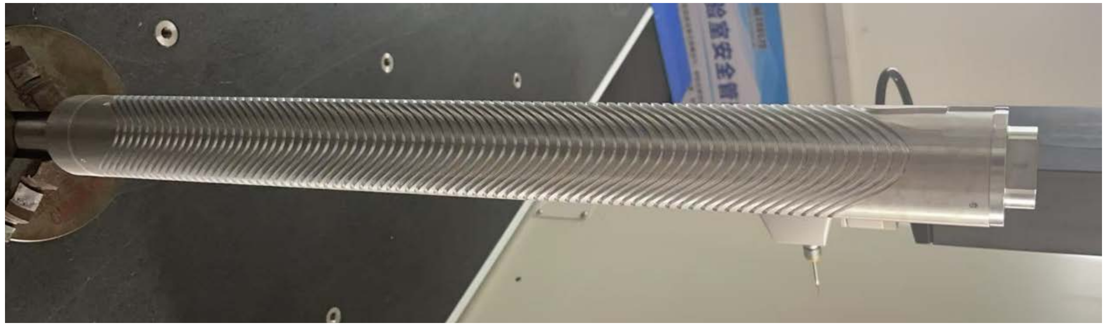
QD0 prototyping

- QD0 prototyping started before optimized achieved (based on non-optimized EM model), to verify
  - Feasibility of CNC machine of delicate former, and deformation control during machining;
  - Winding process: start with copper wires, forming multi-wires, elec isolation to ground…



QD0 former drawing and 3D printing dummy former

Trial winding on dummy former



QD0 former CNC machining

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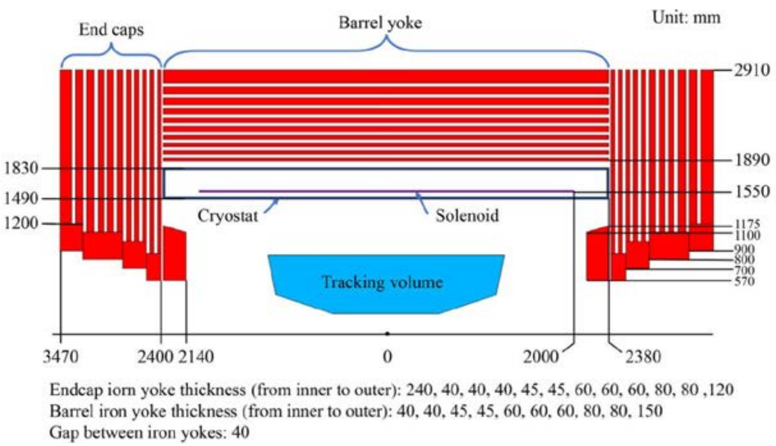
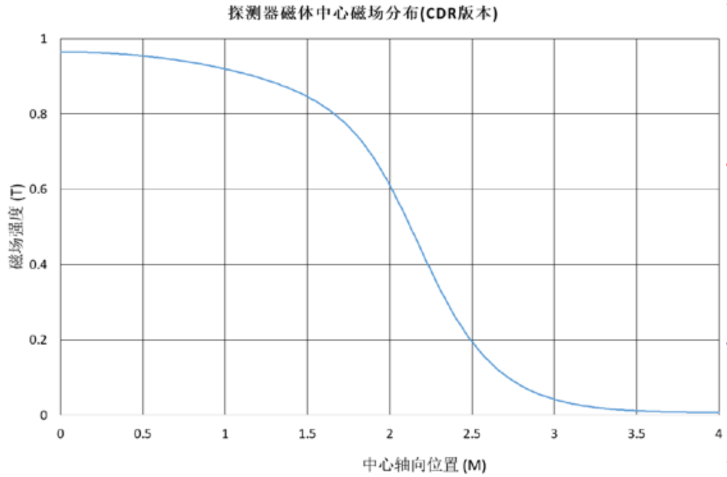
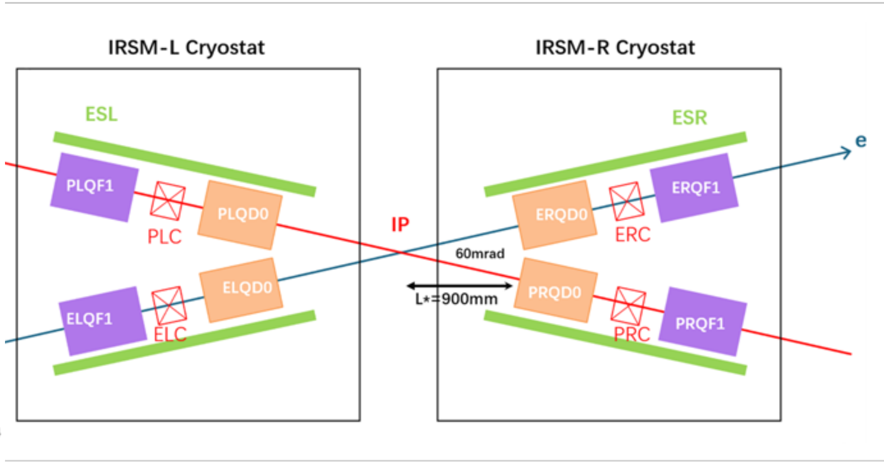
Design of anti-Solenoid

To minimize vertical emittance blow up, key design requirements of the anti-solenoids:

- The **total integral solenoid field** generated by the detector solenoid and anti-solenoid coils is close to zero, and field derivatives are as gentle as possible.
- The final focus quadrupoles should sit in a **zero magnetic field** environment;
- Thus, two type solenoids are needed:
  - The screening solenoid, that cancels out the detector magnetic field (outside of quadrupoles)
  - The compensating solenoid, that integral cancel the effect of the magnetic field of the detector solenoid between IP and L* (btw IP and QD0)





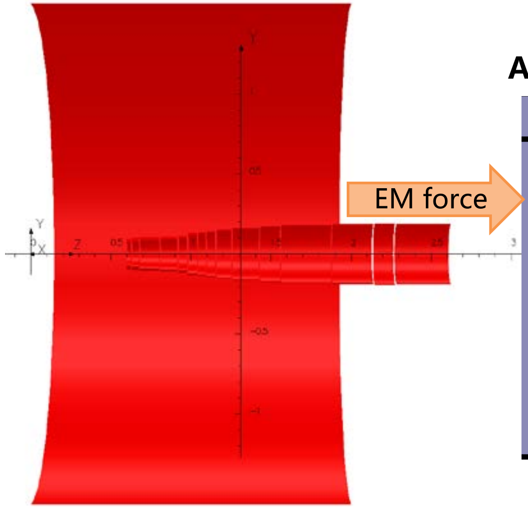


STCF detector solenoid layout and field distribution along central axis

(fr STCF detector CDR)

Preliminary Design of anti-Solenoid

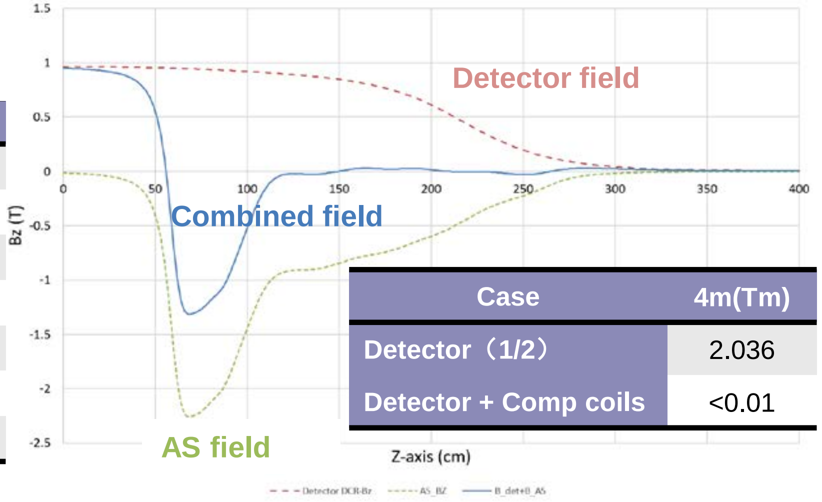
- Based CDR detector field model, the anti-solenoid is divided into 15 sub-coils to reduce magnet size, energy and cost;
- Preliminary design shows integral field could be lower than 0.01Tm (not the limit);
- The anti-solenoid peak field is 2.83T, operating at 230A, and has a total axial coil length is about 2m due to long field tail;
- The total EM force is about +30 kN (away from IP), similar level as SuperKEKB QCS-R.
- Preliminary anti-solenoid design has just started, iterations needed:
  - Better detector field tail; Mechanically compatible within the MDI; Mechanically rigid from EM force; etc.



AS coil layout (rev0) with STCF detector coil (1/2 model, **CDR**)

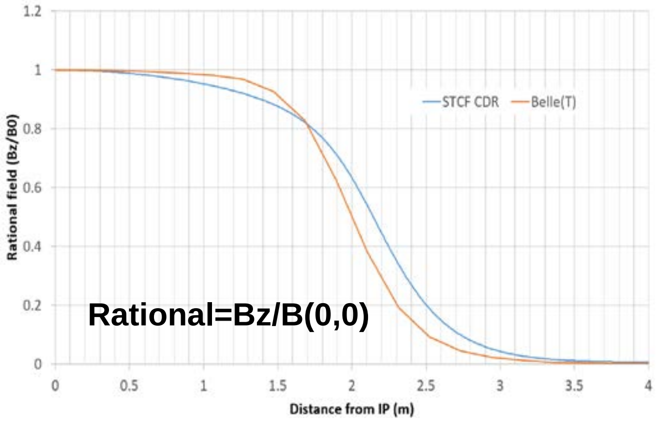
Anti-solenoid main parameters

Parameter	Value
Bmax	2.83 T
Operating current	231 A
Iop/Ic	20%
Coil qty	15
Coil length	2 m
Coil inductance	1.91 H
EM stored energy	0.052 MJ



Case	4m(Tm)
Detector（1/2）	2.036
Detector + Comp coils	<0.01

Field distribution along magnet center axis



STCF and BELLE axial field comparison

Summary

- STCF is now under design as the next generation e^+-e^- collider
  - *Target luminosity:* $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1}, e-e beam collide with 60mrad angle;
- **IRSM magnet system** is the top important and complicate hardware in STCF
  - For STCF IRSM, challenging to meet design requirements, due to extremely limited space, only **<7mm** for high field quality quadrupole coils;
  - **CCT route was selected** as STCF IRSM prototype at this stage, as its advantages in coil simplicity and field quality;
  - Dual-aperture CCT QD0 EM design has achieved project requirements, in terms of field gradient, field harmonics and cross-talk;
  - **QD0 prototype** has just started, will have first dual-aperture QD0 manufactured and tested in 2025.
- Anti-solenoid design just began, preliminary design achieved, more optimized iterations in the future;

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- **Cryogenics**: Jingxin Zheng (HMFL), Chongchao He (IASF)
- **Manufacturing**: Anhui Pinte Precision Technology
- **Consultancy**: M. Koratzinos (MTG)
- And, many others to continue…

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CASIC 中国科工航天三院

MTG SOLUTIONS

Many thanks for your attention!

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