STCF对撞区超导磁铁（IRSM）研究进展

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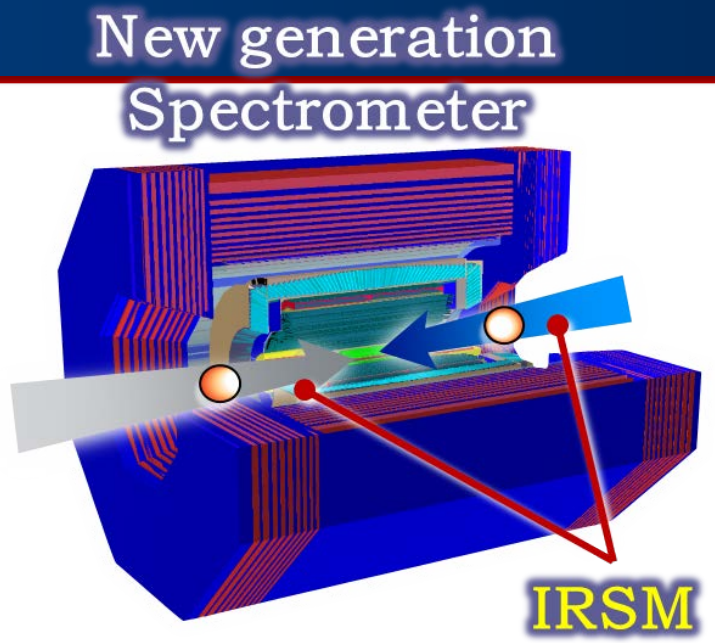
Outline

- Introduction
- Design of IRSM quadrupoles
- Design of IRSM anti-solenoid and correctors
- Summary

IRSM 系统构成



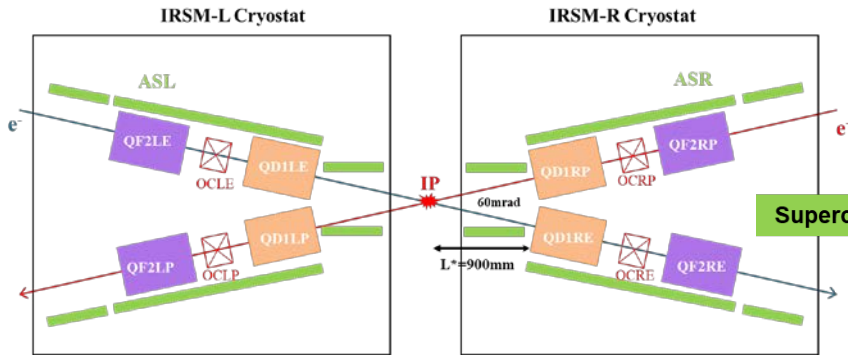
超级陶粲装置（STCF）对撞区超导磁铁系统（IRSM）

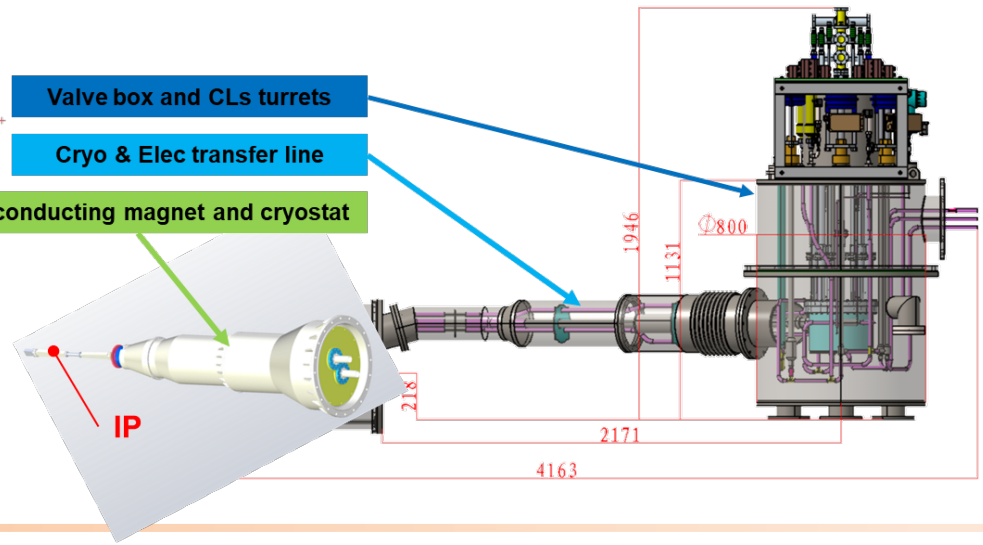
- To squeeze the beam for high luminosity, compact **double aperture high gradient** final focus quadrupole magnets are required on both sides of IP .
- CDR requirements (v4) of **IRSM** Final Focus quadrupoles are based on **L* of 0.9 m**, beam crossing angle of **60 mrad**.

- **Dual-aperture IRSM system**

min coil qty **26**

- **SC quadrupole: x8**
  - QD1: L&R, E&P
  - QF2: L&R, E&P
- **SC Solenoid: x2**
  - ASL: x1; ASR: x1
- **SC corrector: x16**
  - a1/b1/a2/b4: x (OCRP/E, OCLP/E)





借自BEPCII IRSM

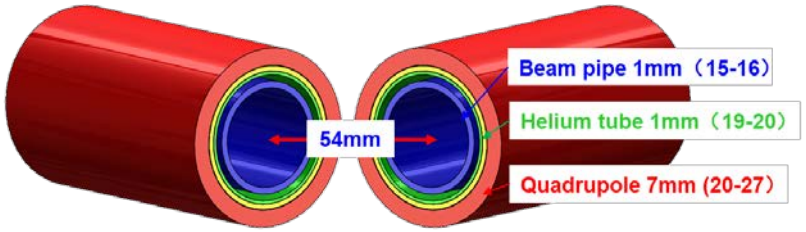
IRSM Requirements

- **Final focus quadrupole** 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**.

- **QD0** is selected as prototype to study

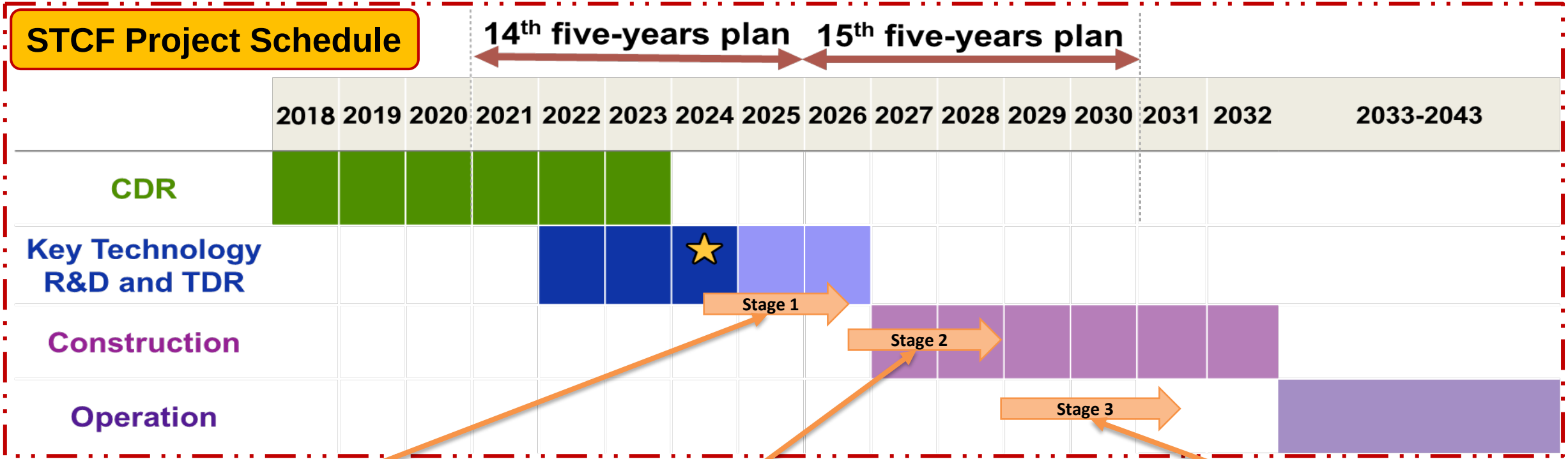
CDR requirements of Interaction Region quadrupole magnets for STCF (@ 7 GeV)

		QD1_e+/e-	QF2_e+/e-
束流管内半径	mm	15	25
磁场梯度	T/m	50	40
除b2外的谐波分量		≤0.2 ‰ @ Ref=10mm	≤0.2 ‰@ Ref=15mm
磁场长度	mm	400±5	300±5
对撞点与磁场中心距离	mm	900±5	1800±5
矫正线圈	阶数	a1,b1,a2,**b4**	a1,b1,a2,**b4**
	强度 @Ref	0.016/0.016/0.6/30	0.03/0.03/0.3/30
反场螺线管		• 各漂移段（**0-0.9m**, **2.1m之后**）Bz积分场小于0.005Tm； • 超导铁内Bz幅值小于**50Gs**.	

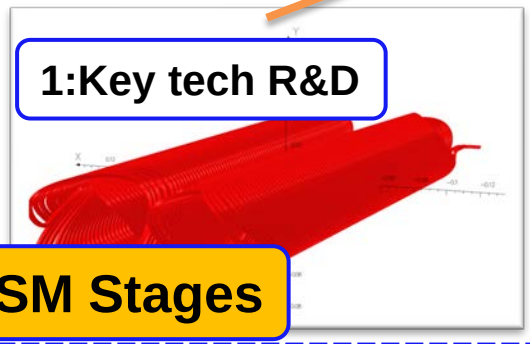


IRSM R&D Stages

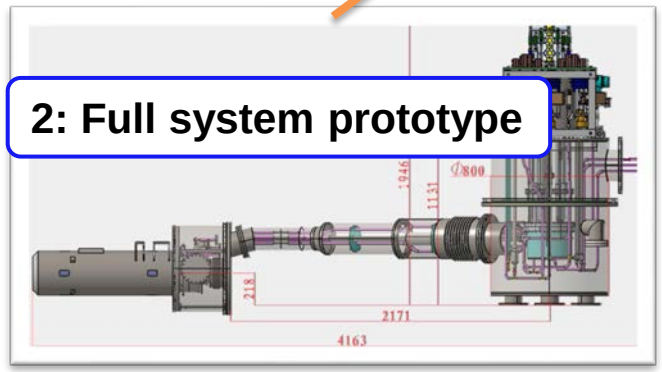
STCF Project Schedule



IRSM Stages

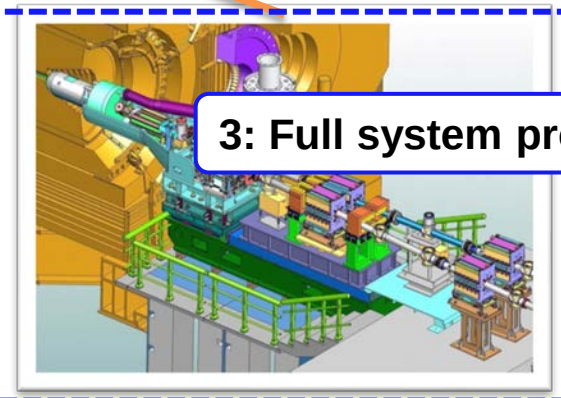


1:Key tech R&D



2: Full system prototype

Pictures borrowed from BEPCII.



3: Full system production

Outline

- Introduction
- **Design of IRSM quadrupoles**
- Design of IRSM anti-solenoid and correctors
- Summary

Design constraints of QD1

- **2θ=60mrad** and **L*=900mm** give minimal distance between two aperture beam lines: **~54 mm**
- Clearance dimensions
  - Beam pipe 15->16mm; Vacuum 16->19 mm; Helium vessel 19->20mm

  → **Leaves quadrupole coil total space: ~7mm (20->27 mm)**

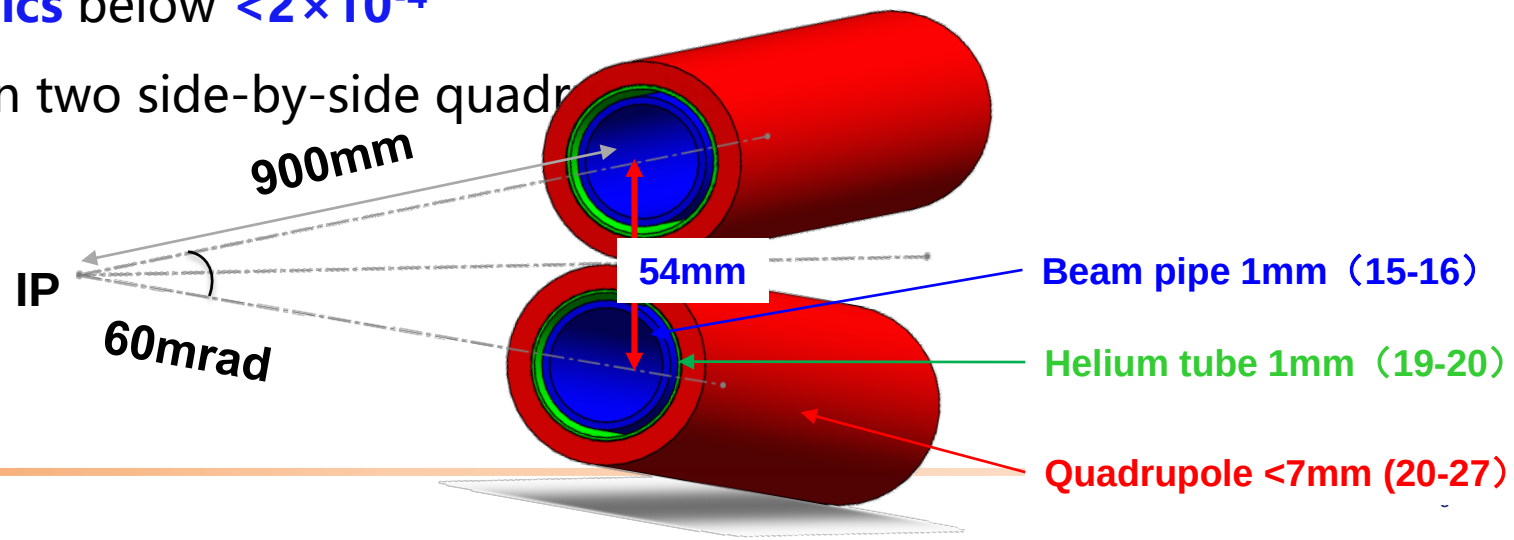
  --about half design space of CEPC and FCC-ee, ~12mm.

- In this limited space to design quadrupoles, with

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

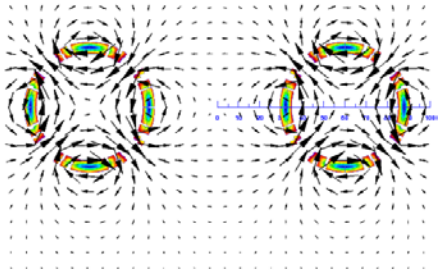
  2) High field quality: all **harmonics** below **$<2\times10^{-4}$**

  3) **Minimum cross-talk** between two side-by-side quadr

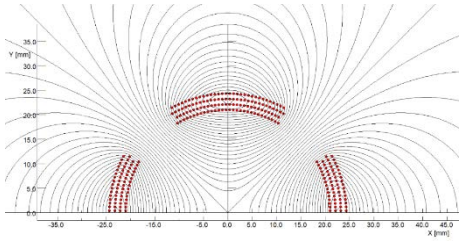


Design of QD1 – techniques selection

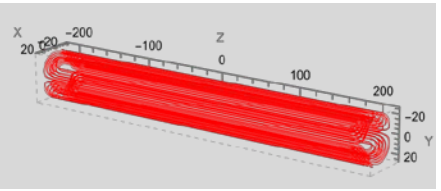
- IR SC magnet techniques selection:
  - Joint effort by experienced persons from several domestic institutions including HMFL (High Magnetic Field Lab), IPP, IHEP, IMP and others
  - Four different techniques studied: CCT, Cos2θ, DCT, Serpentine
  - After two rounds of discussions, considering technology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

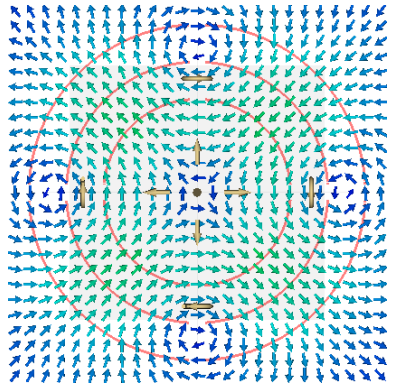


Cos2θ coil EM

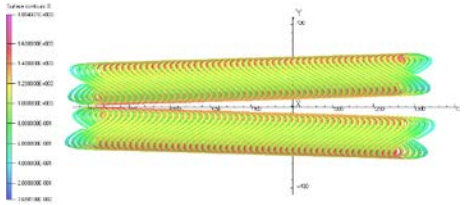


Single aperture serpentine coil EM





Single aperture DCT coil EM

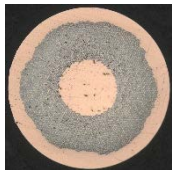


CCT coil EM

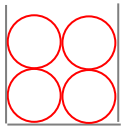
6July2024:
https://indico.pnp.ustc.edu.cn/event/2355/

QD1 Coil Design

- 4 wire co-wound method onto CNC former;
- Two coils for e+ e- beams and two formers in each coil ;
- At 60° canting angle, 80turns, 600A, can generate 50T/m at 400mm magnetic length;
- Length
  - Magnetic 400mm
  - Coil physical 457mm
  - Former 470mm

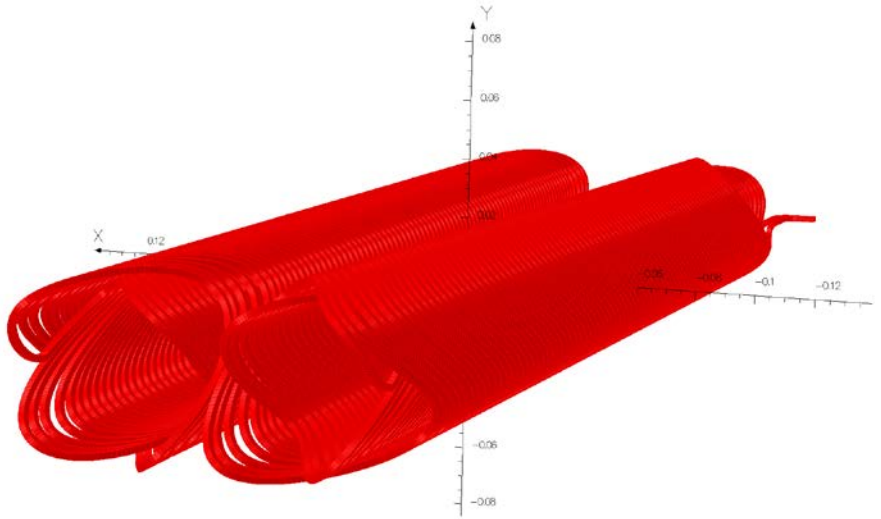


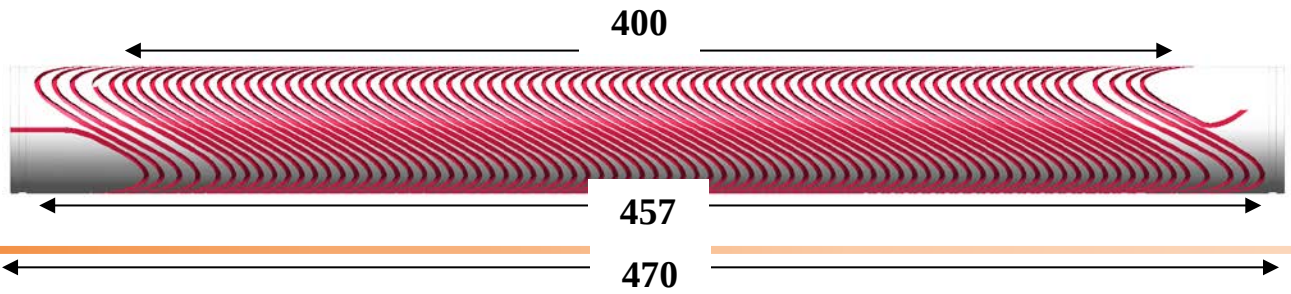
Wire CSA



Wire 2×2

3000+ filament NbTi wire:
Ø0.8mm, I_c >850A @2T,4.2K

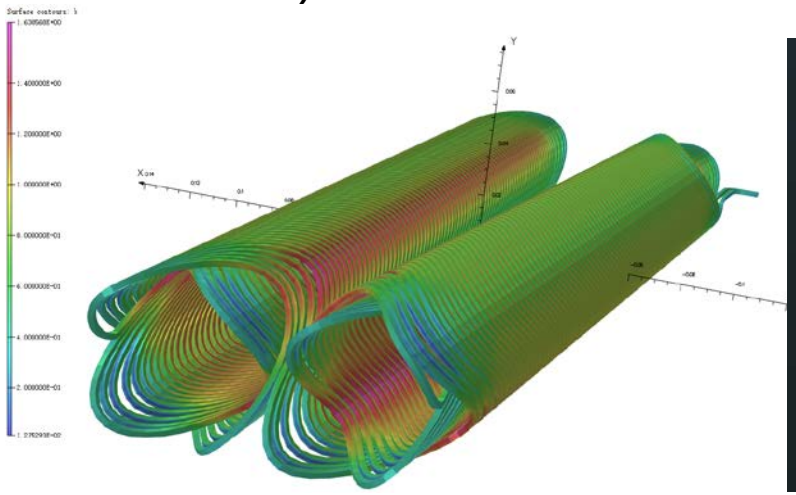




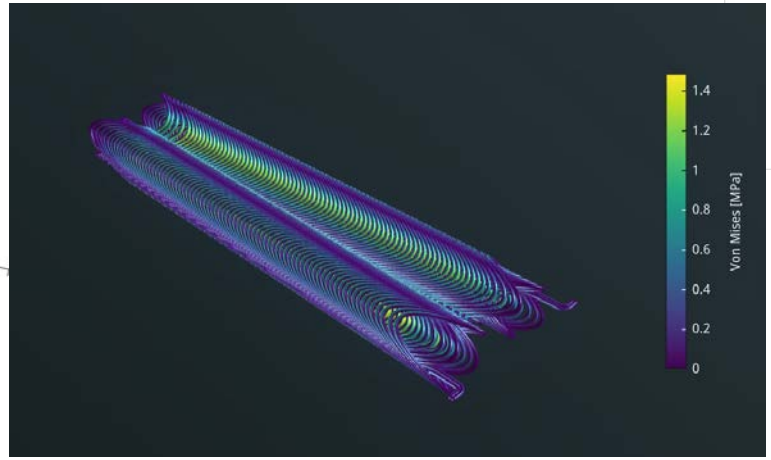
Item	Value
Beam Angle(θ), mrad	60
$R_{ref_}$QD1, mm	10
QD1 Coil1 IR, mm	20.0
QD1 Coil1 OR, mm	23.3
QD1 Coil2 IR, mm	23.5
QD1 Coil2 OR, mm	26.8
Magnetic length, mm	400
Coil physical length, mm	457
Coil former length, mm	470
I, A	**602**
Bmax, T	**1.637**
G,T/m	**50**
SSP(4.2K/4.7K), %	57.4%/67.0%
Turns	**80**
Groove canting angle	**60°**
Groove size	1.9x1.9 mm
Groove wall thickness	≥0.5 mm

QD1 Coil Design

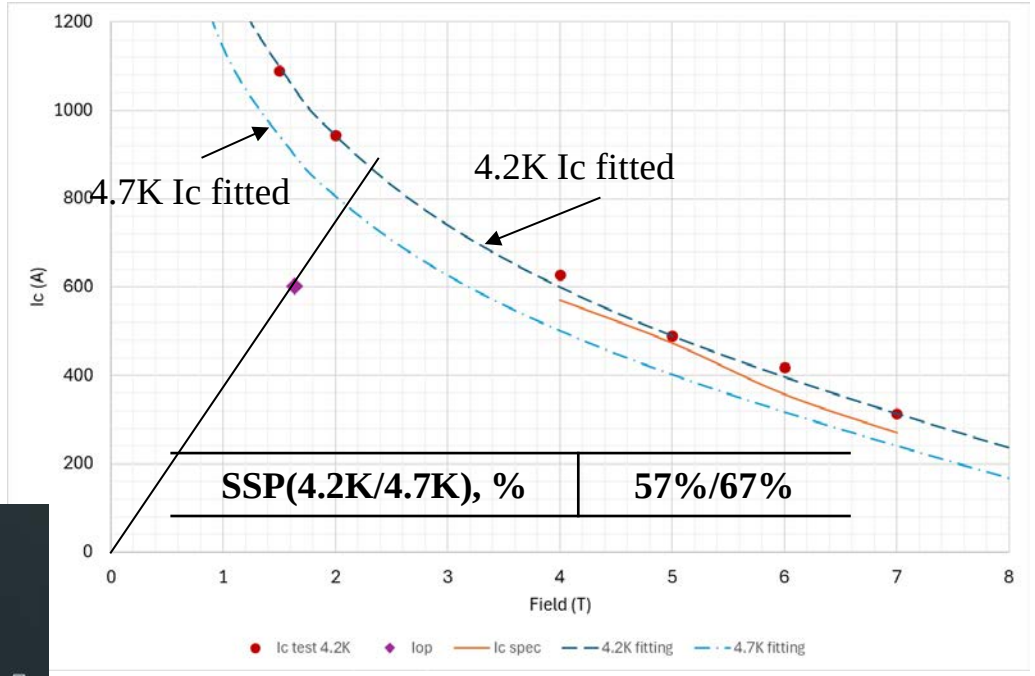
- The maximum field at coil is 1.638 Tesla
- At 602A, the short sample performance is about 57% at 4.2K and 67% at 4.7K.
- Coil has good temperature margin, T_{cs}~6.1K
- Mechanical analysis was performed with input of EM Lorentz force, very low von-Mises stresses (less than 1.5MPa)



Magnetic field contour at 50 T/m
(Bmax=1.638T)



von-Mises stress contour at 50 T/m
(max. stress <1.5MPa)

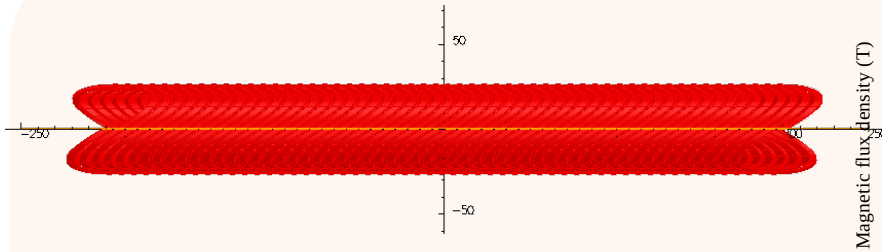


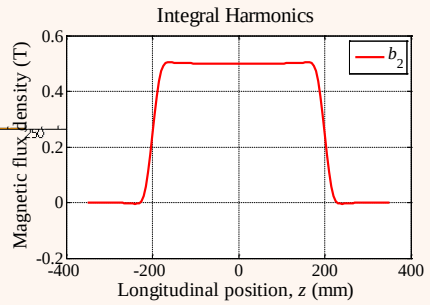
Bc20	Tc0	C0	alpha	belta	gama	n
(T)	(K)	(T)				
14.5	9.2	27.04	0.6238	0.7331	2.4551	1.7

$$J_c = \frac{C_0}{B} b^{\alpha}(1-b)^{\beta}(1-t^n)^{\gamma}$$

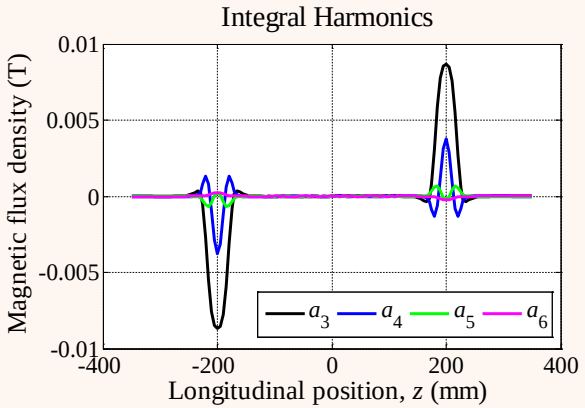
Optimised QD1 - Harmonics

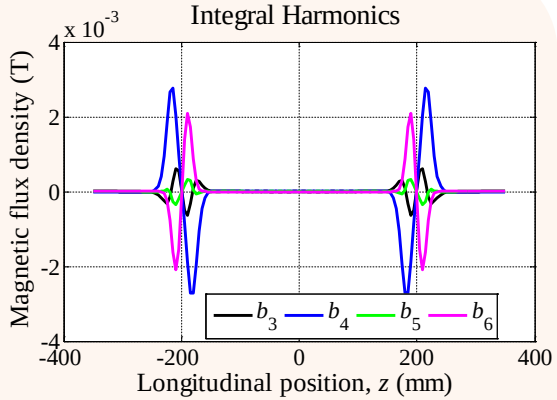
- **Problem: Cross-talk of side-by-side quadrupoles**



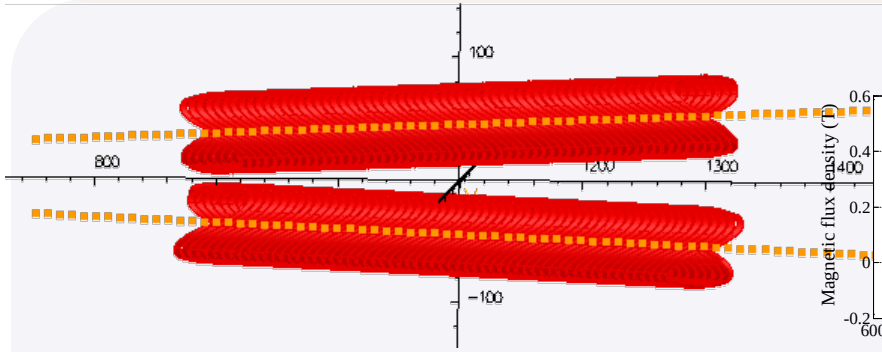


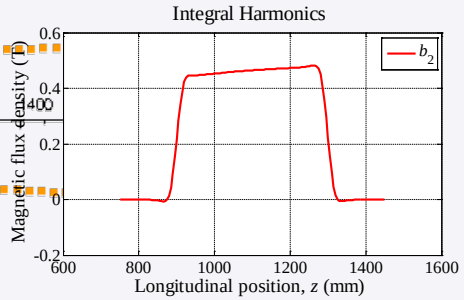
Single aperture



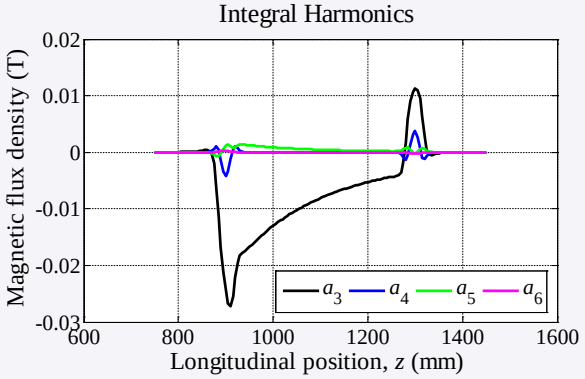


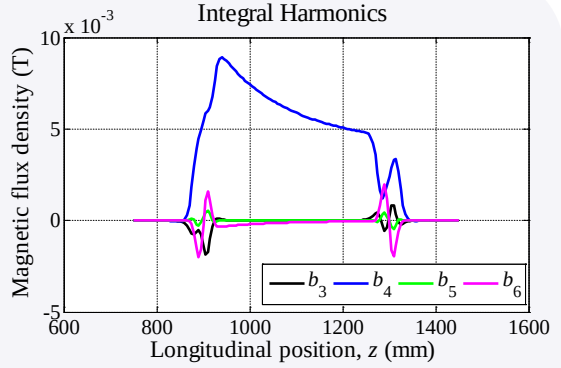
All harmonics below 2 unit (0.2 ‰)





Dual apertures





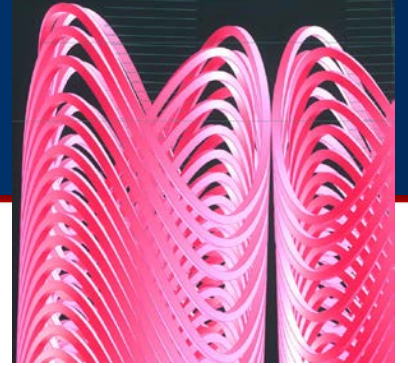
a3=-208 unit; b4=139 unit

$$B_z = \sum_{n=1}^{\infty} (B_n + iA_n)\left(\frac{z}{R}\right)^{n-1}, z = x + iy = re^{i\theta}$$

$(n = 1 : dipole; n = 2 : quadrupole; n = 3 : sextupole, etc.)$ $a_n = \frac{A_n}{B_2} \times 10,000 \quad b_n = \frac{B_n}{B_2} \times 10,000 \; @ \; R = 10mm$

Optimised QD1 - Harmonics

- Local edge correction method was used to optimize field profile;
- Optimised design that all multipoles are below 0.2 units, ~1/10 of specification.



Local edge correction

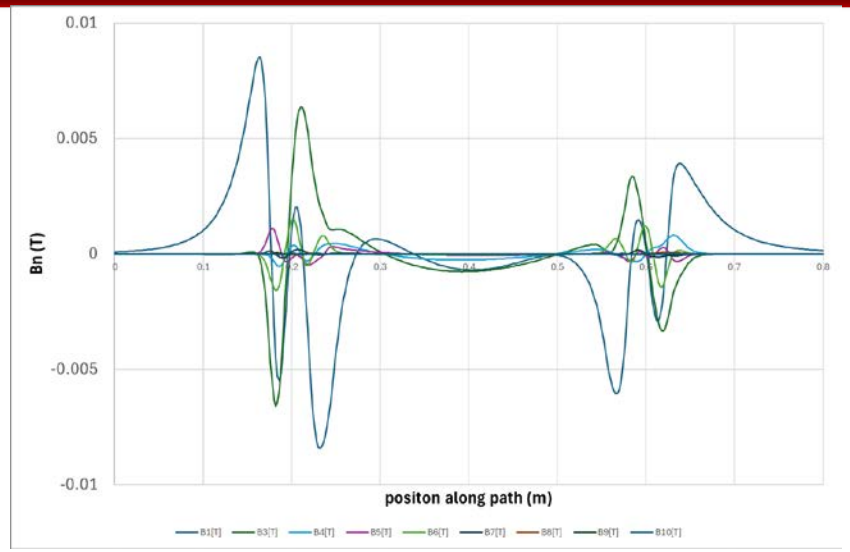
order	An[T.m]	an	order	Bn[T.m]	bn
A1	-7.34E-07	-0.04	B1	2.66E-06	0.13
A2	5.64E-07	0.03	B2	2.00E-01	10000
A3	-3.70E-07	-0.02	B3	-2.98E-06	-0.15
A4	2.28E-06	0.11	B4	2.89E-06	0.14
A5	-2.16E-06	-0.11	B5	-1.68E-06	-0.08
A6	3.34E-07	0.02	B6	1.98E-06	0.10
A7	4.91E-07	0.02	B7	-3.33E-07	-0.02
A8	-6.90E-07	-0.03	B8	3.36E-06	0.17
A9	2.34E-07	0.01	B9	-3.79E-07	-0.02
A10	-9.28E-08	0.00	B10	3.34E-07	0.02

Normal and skew harmonics of the e+ beam at 10mm reference radius

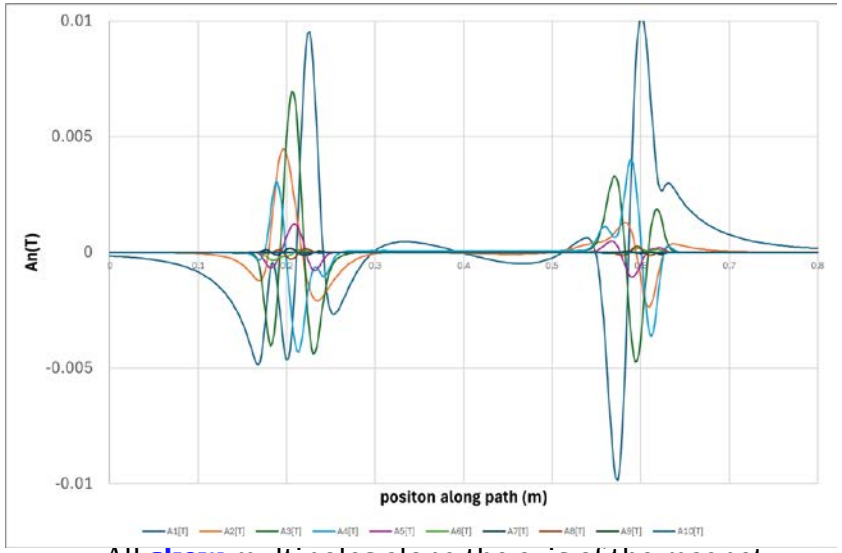
$$B_z = \sum_{n=1}^{\infty} (B_n + iA_n)\left(\frac{z}{R}\right)^{n-1}, z = x + iy = re^{i\theta}$$

$(n = 1 : dipole; n = 2 : quadrupole; n = 3 : sextupole, etc.)$ $a_n = \frac{A_n}{B_2} \times 10,000 \quad b_n = \frac{B_n}{B_2} \times 10,000 \; @ \; R = 10mm$

Optimised QD1 – Field profile



All **main** multipoles (except B2) along the axis of the magnet.

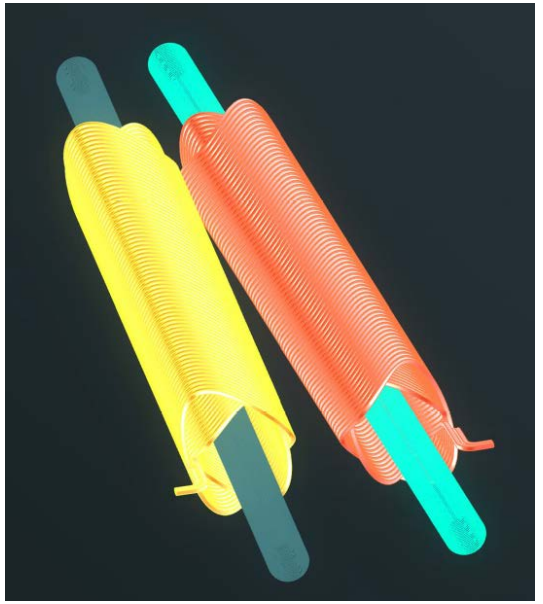


All **skew** multipoles along the axis of the magnet

- The **horizontal** and **vertical** component of the field along the axis of the magnet. The peak value is ~10mT.

EM Robustness Analysis

- CCT coil harmonics are controlled by precision engineered former groove, assume typical mechanical alignment resolution would be 20microns.
- Manufacturing, assembly errors can affect quadrupole harmonics, so necessary to perform coil EM robustness analysis.
- Robustness Analysis with cases of
  - Case1: fixed red and misaligned yellow by 50 μm (measured at red)
  - Case2: fixed yellow and misaligned red by 50 μm (measured at red)
  - Case3: cool down effect



EM Robustness Analysis

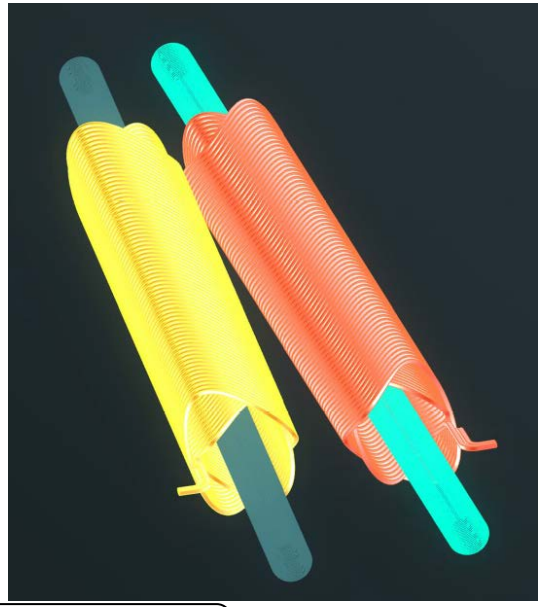
- Case1: fixed one quadrupole (in red) and misaligned the other one (in yellow) by 50 microns (measured at red)
- Case2: fixed yellow and misaligned red (also measured at red)

Case1

Misalignment	Error B1	Error A1	Error A2	Error B3	Error A3	Error B4	Error A4
50μm in x	2.6	-	-	0.6	-	0.2	-
50μm in y	-	2.5	1.7	-	0.6	-	0.2
50μm in z	0.1	-	-	-	-	-	-

Case2 The effect is more pronounced as measure closer to the misaligned quad.

Misalignment	Error B1	Error A1	Error A2	Error B3	Error A3	Error B4	Error A4
50μm in x	47	-	-	0.6	-	0.2	-
50μm in y	-	47	1.6	-	0.7	-	0.1
50μm in z	-	-	-	-	-	-	-



Importance of concentricity btw beam pipe and magnet!

Necessary of orbit correctors!

EM Robustness Analysis

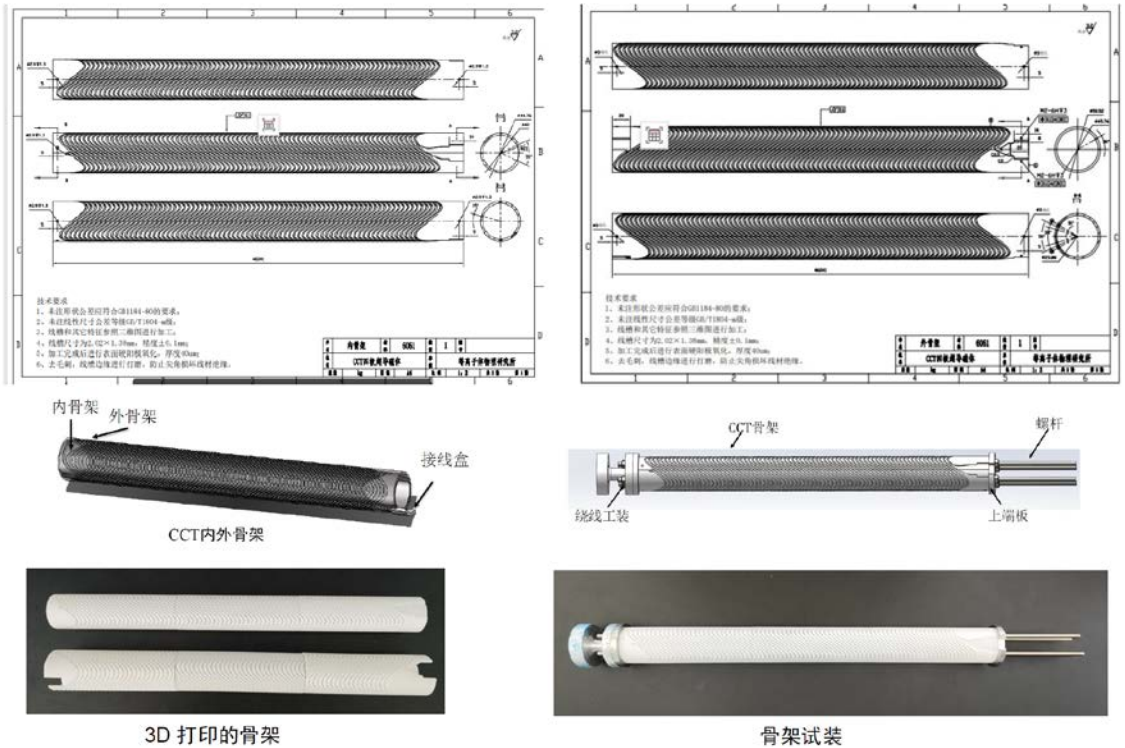
- Case3: cool down effect, with assumptions:
  - The radius and pitch of the magnets have been decreased by the expansion factor of 0.4%
  - The angle of the two magnets with respect to each other (60mrad) does not change
  - The distance between the two magnets for electrons and positrons decreases by the expansion factor
- Analysis results
  - All multipoles are affected by negligible amounts.

	Warm		Cold	
Order	**an**	**bn**	**an**	**bn**
1	-0.04	0.13	-0.08	0.15
2	0.03	10000	0.05	10000
3	-0.02	-0.15	-0.03	-0.11
4	0.11	0.14	0.12	0.12
5	-0.11	-0.08	-0.11	-0.08
6	0.02	0.10	0.02	0.10
7	0.02	-0.02	0.02	-0.02
8	-0.03	0.17	-0.03	0.16
9	0.01	-0.02	0.01	-0.02
10	-0.00	0.02	-0.00	0.02

Harmonics comparison at cold and warm (e+ beam at Ref=10mm)

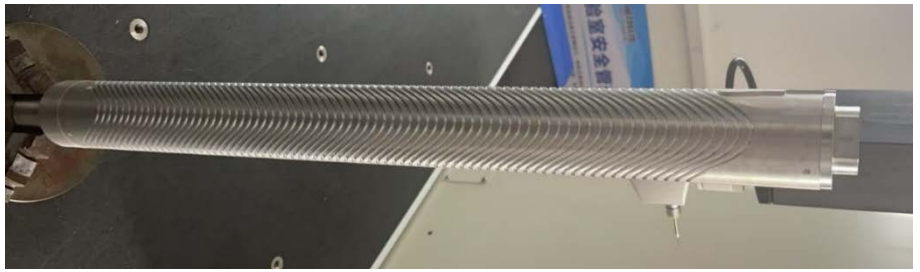
QD1 prototype

- QD1 **pre-**prototyping finished, verified
  - Winding process: start with copper wires, forming multi-wires, elec isolation to ground
  - Feasibility of CNC machine of delicate former, and deformation/error control during machining;



QD1 former drawing and 3D printing dummy former

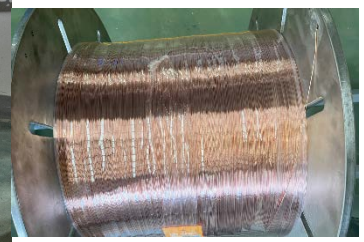
Trial winding on 3D printing dummy former



QD1 former CNC machining

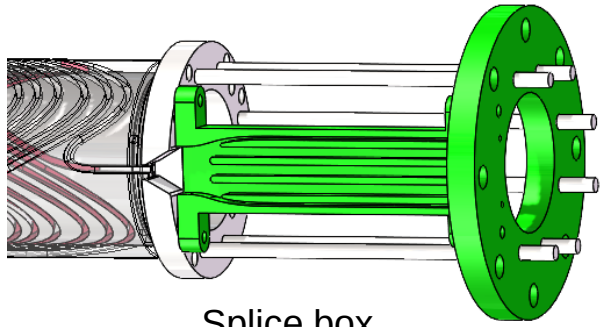
QD1 prototype

- SC conductor manufactured and delivered;
- Mech design
  - 2x2 winding method, connected in series, S&E and 3off NbTi-NbTi joints in splice box
  - Preliminary mech design has finished including mech interface to test dewar.
- First QD1 prototype is underway, to be vertical tested in 2025.

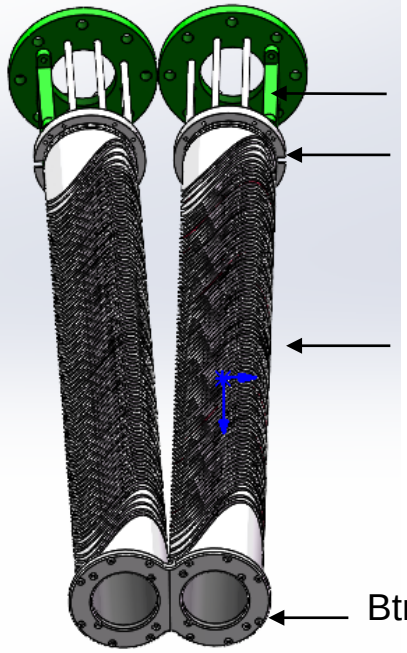


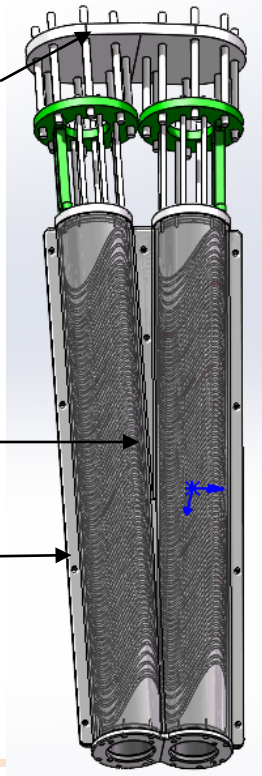
SC conductor delivered

QD1 inner and outer former



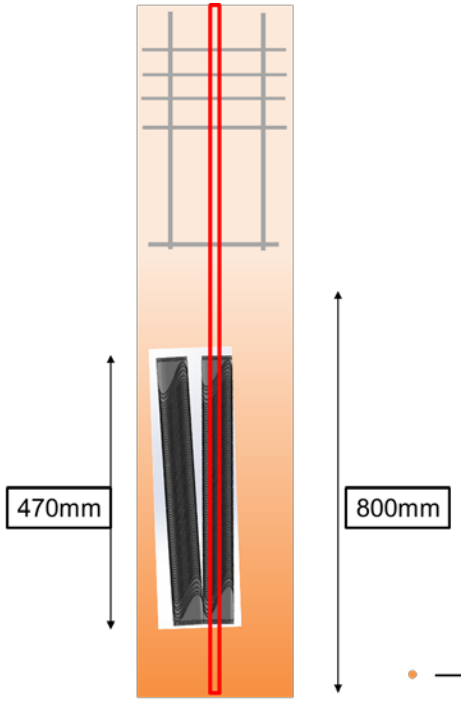
Splice box

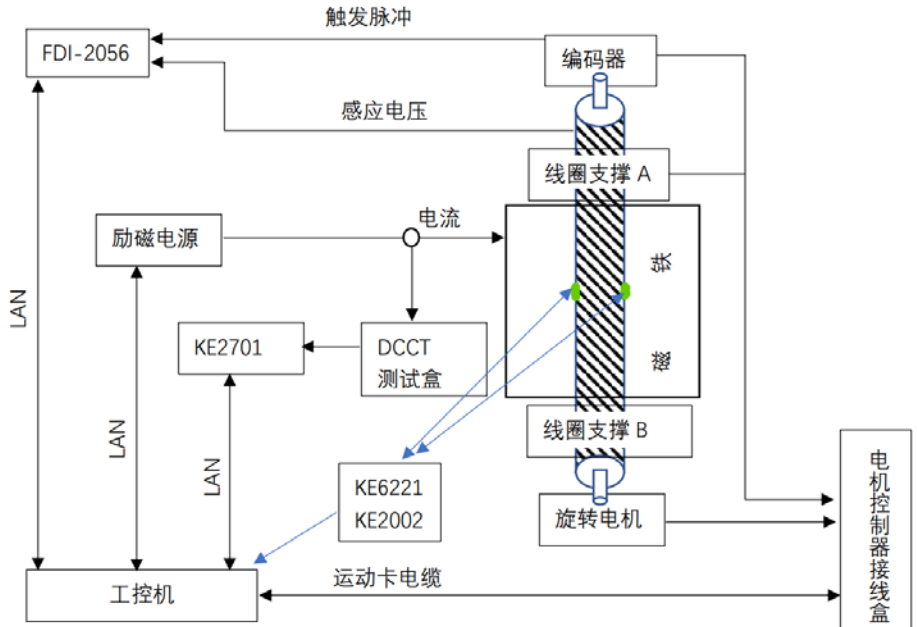


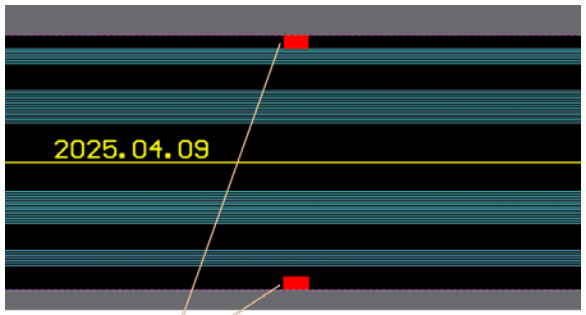


QD1 prototype test

- **IRSM vertical test setup, with rotating probe in RT VTI, key req.:**
  - Field probe OD<=27mm, integral length 800mm, harmonics resolution <0.5 unit
- Probe tech support from SSRF(上海光源), probe manufactured started in June 2025
- **Probe tech:** PCB rotation coil to measure field harmonics and Hall sensor to devise field gradient







2片霍尔片

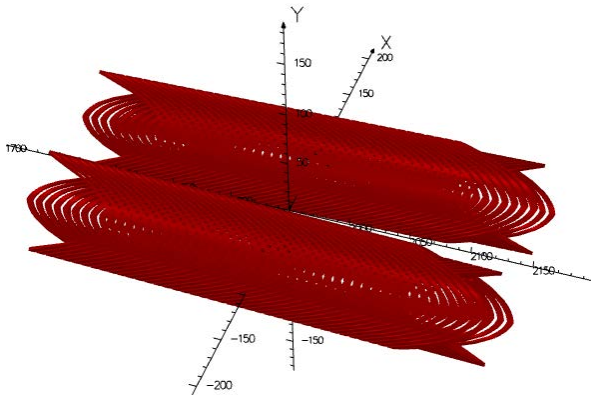
PCB dims：1.86mm*24mm*810mm；
Probe package dims：ID25mm，OD27mm，L2m；

- 一根Φ24PCB旋测线圈→FDI2056 →FFT →积分场结果
- Keithley 6221→2片HG-116C霍尔片→ Keithley2002电压表→梯度G
- 运动系统： PKP569FMN24B五相步进电机 + 驱动器CVD524BR-K + NEMICON编码器NOC-SP10000 + NI PCI 7350控制卡

QF2 design

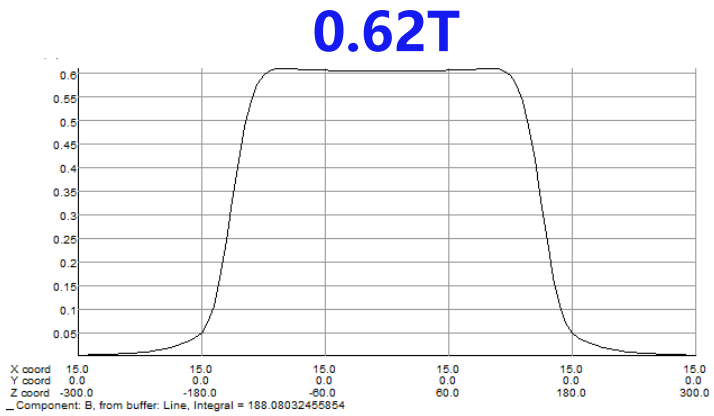
- QF2 L*=1800mm, max allowable radius 53.7mm

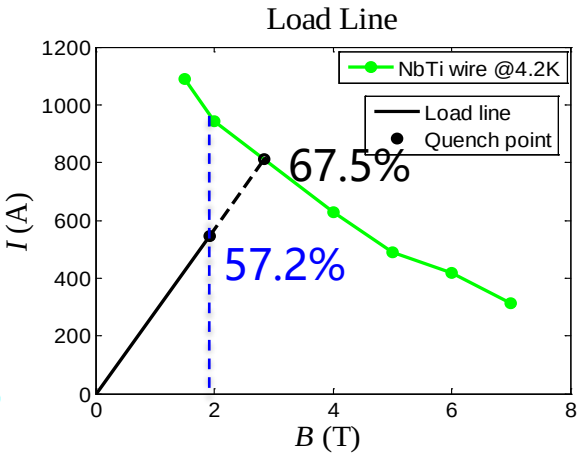
  tan(60/2/1000)*(1800+150-160)=53.7



Item	Value (Φ0.8, 3×3)
Beam Angle(θ), mrad	60
$R_{ref_}$ QF2, mm	15
QF2 Coil1 IR, mm	32
QF2 Coil2 OR, mm	41.1
I, A	**547**
Bmax, T	**1.92**
B, T	0.60
G,T/m	**40**
Load line(4.2K), %	67.5%

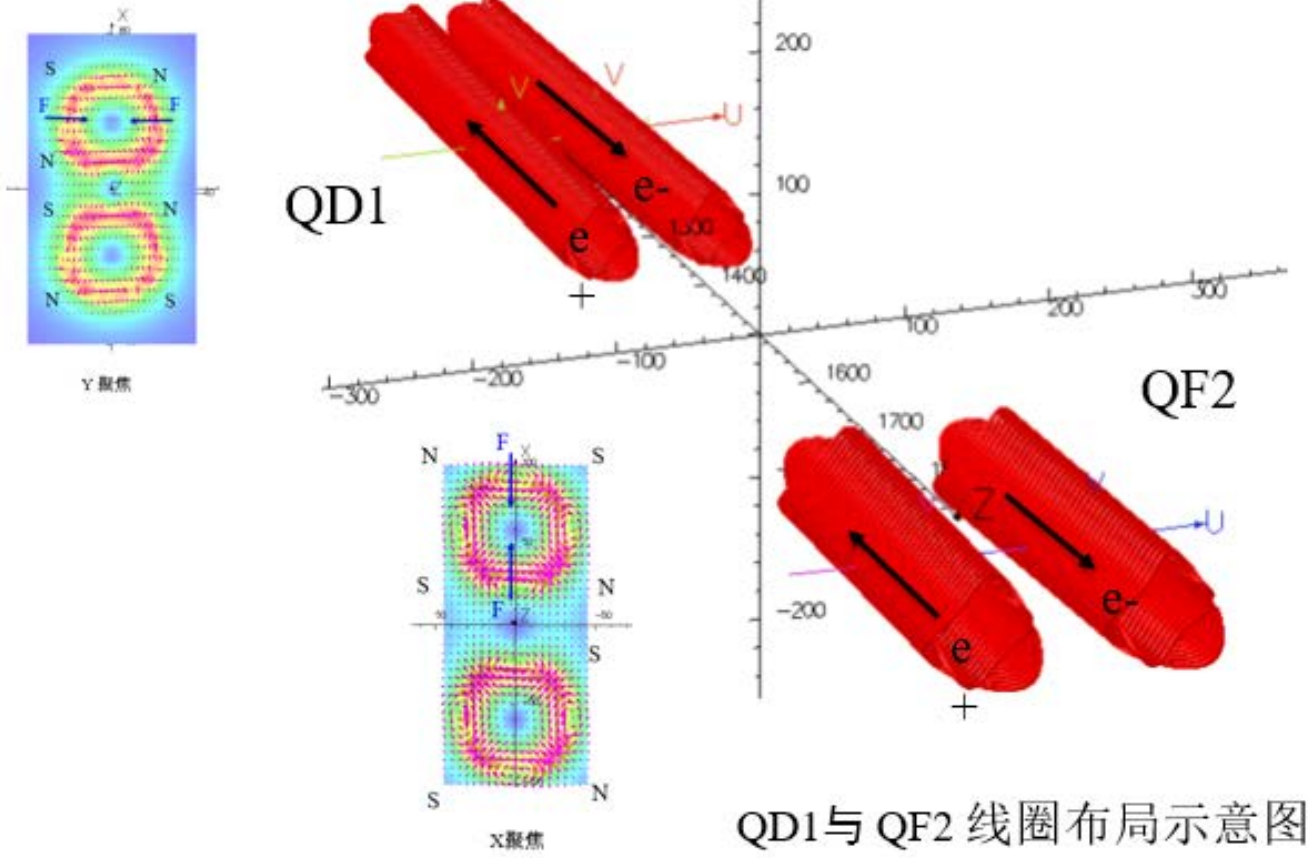
Coil	R_{ref}, (mm)	$R_{beam\ pipe}$	Gradient (T/m)	Effective length (mm)	High harmonics
QD1	10	**15**	50	400	≤0.2 ‰
QF2	15	**25**	40	300	≤0.2 ‰



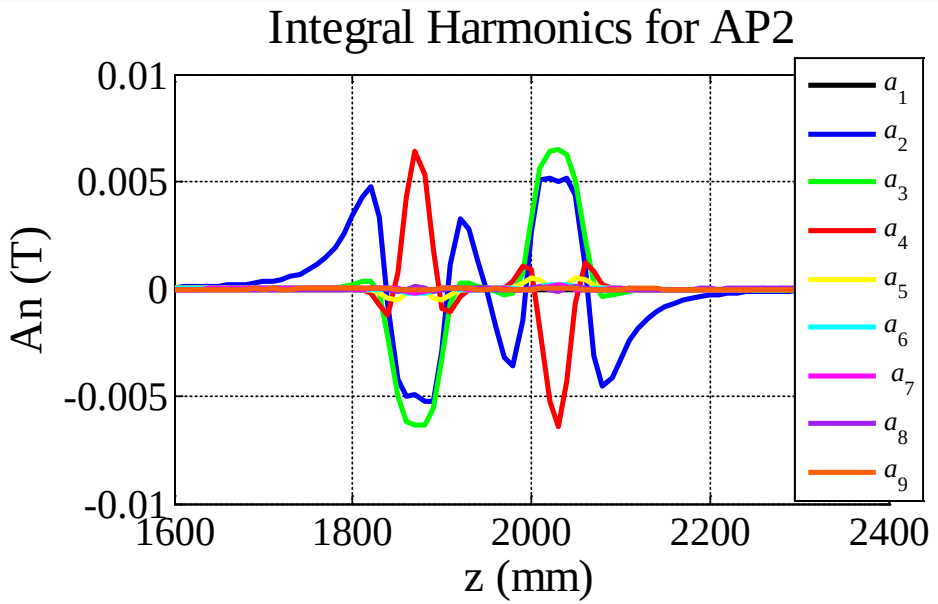


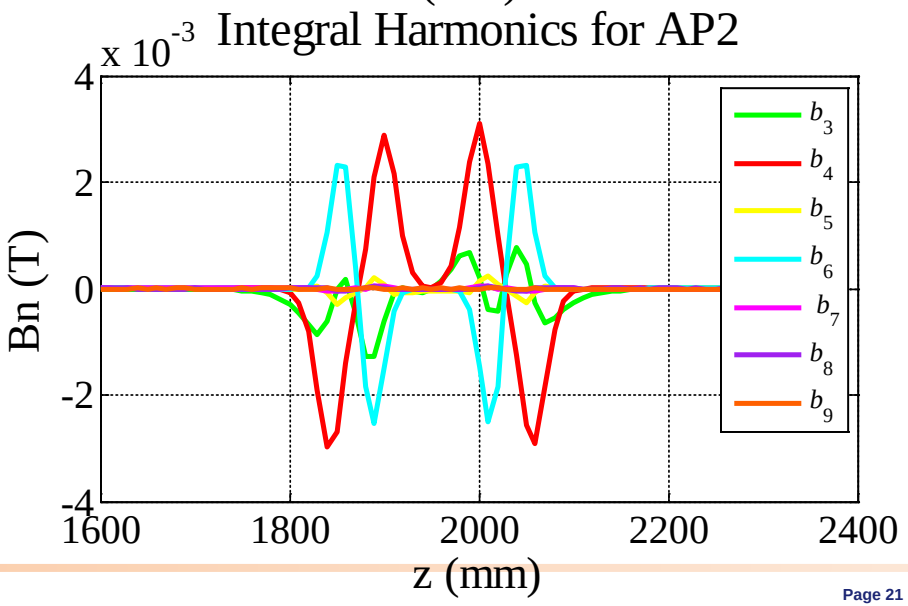
QF2 harmonics optimizing

- QF2 high orders are within spec, more optimization work tbd on low orders



QD1与 QF2 线圈布局示意图





QF2 harmonics optimizing

Order	Before				After			
	Unit (An)	Unit (Bn)	Unit (An)	Unit (Bn)	Unit (An)	Unit (Bn)	Unit (An)	Unit (Bn)
2	3.26	-10000.00	3.79	-10000.00	-0.44	-10000	0.06	-10000
3	-0.98	77.31	0.96	-77.31	-1.03	-0.70	1.00	0.70
4	0.28	-16.60	0.23	-16.60	0.29	-0.21	0.24	-0.20
5	-7.37E-02	3.21	5.43E-02	-3.21	-7.49E-02	0.90	5.50E-02	-0.90
6	1.84E-02	-8.67	1.24E-02	-8.67	2.16E-02	-0.09	1.57E-02	-0.09
7	-4.32E-03	0.10	2.79E-03	-9.98E-02	-4.27E-03	9.59E-02	2.73E-03	-9.57E-02
8	9.49E-04	-8.88E-03	5.96E-04	-8.88E-03	9.23E-04	-6.65E-03	5.63E-04	-6.65E-03
9	-2.16E-04	2.44E-03	1.39E-04	-2.61E-03	-2.08E-04	2.34E-03	1.22E-04	-2.60E-03
10	5.32E-05	-3.08E-01	-1.99E-06	-3.08E-01	-7.43E-05	-4.13E-01	-1.38E-04	-4.13E-01
11	-6.37E-06	6.89E-04	1.60E-05	-7.41E-04	-5.31E-06	-3.79E-03	1.13E-05	3.67E-03

Outline

- Introduction
- Design of IRSM quadrupoles
- **Design of IRSM anti-solenoid and correctors**
- Summary

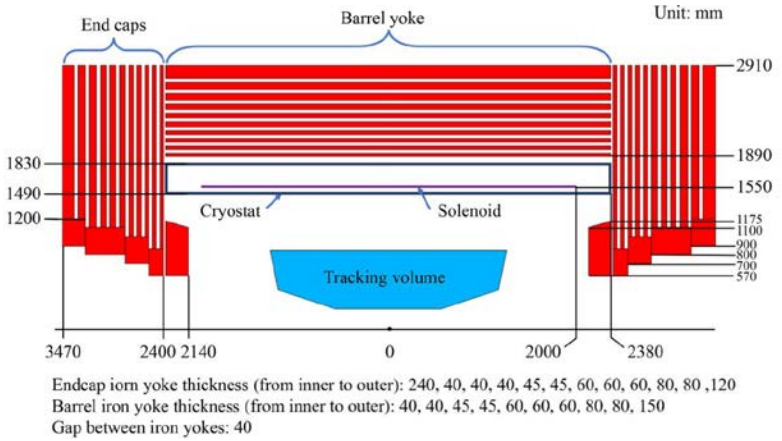
Design of Anti-Solenoid

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 (**below 0.005Tm**), and field derivatives are as gentle as possible.
- The **final focus quadrupoles** should sit in a nearly **zero magnetic field** environment (**below 50Gs**);

Thus, two type solenoids are needed:

- The **screening solenoid**, that cancels out the detector magnetic field (placed outside of quadrupoles)
- The **compensating solenoid**, that integral cancel the effect of the magnetic field of the detector solenoid between IP and L* (placed btw IP & QD1, and after QF2)

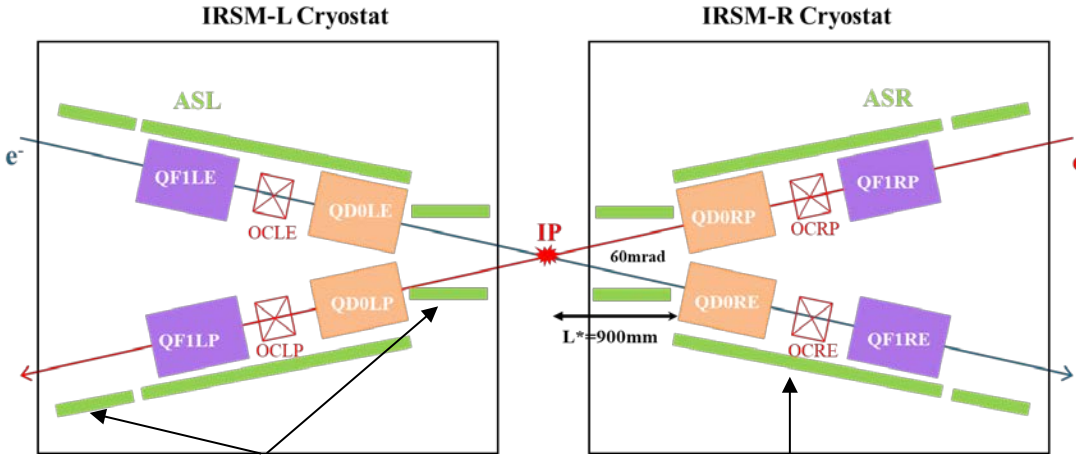


STCF detector solenoid layout

(CDR version)

$$B_t = B_d + B_{as} \rightarrow \begin{cases} \int_0^{0.9} B_t dz < 0.005Tm \\ |B_t| < 50Gs, 0.9 < z < 2.1 \\ \int_{2.1}^{\infty} B_t dz < 0.005Tm \end{cases}$$

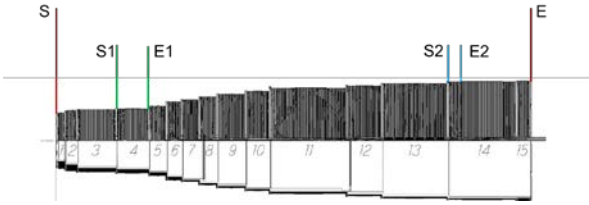
Field objective

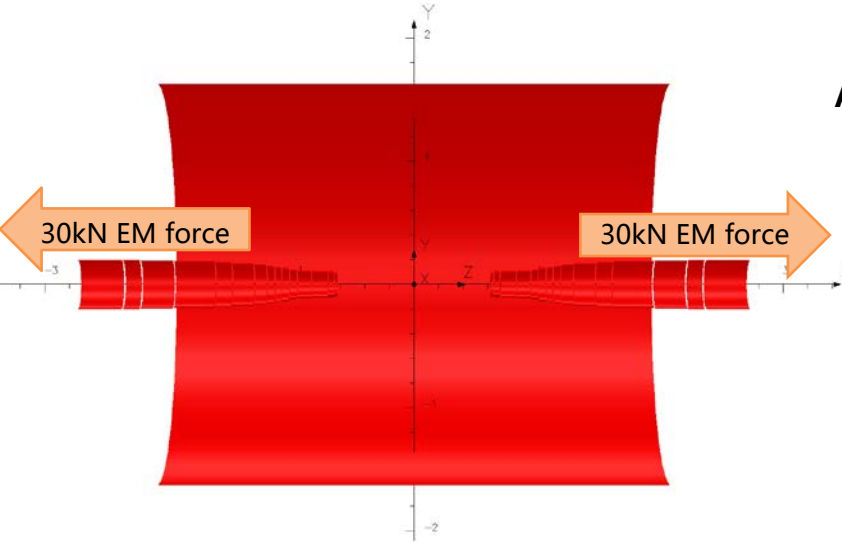


compensating solenoid **screening solenoid**

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;
- The anti-solenoid peak field is 4.11T, operating at 231A, and has a total axial coil length is about 2m due to detector long field tail;
- Design shows
  - Integral field could be lower than **0.001Tm** (**tunable** with extra current leads) btw IP & QD1, and after QF2;
  - Combined field btw QD1 and QF2 are below **150Gs** (to be further optimized below 50Gs);
- The total EM force is about +30 kN (away from IP), similar level as SuperKEKB QCS-R;
- Further iterations are needed to achieve
  - Better AS screening field; Mechanically compatible within the MDI; Mechanically rigid from EM force and environment vibration; etc.

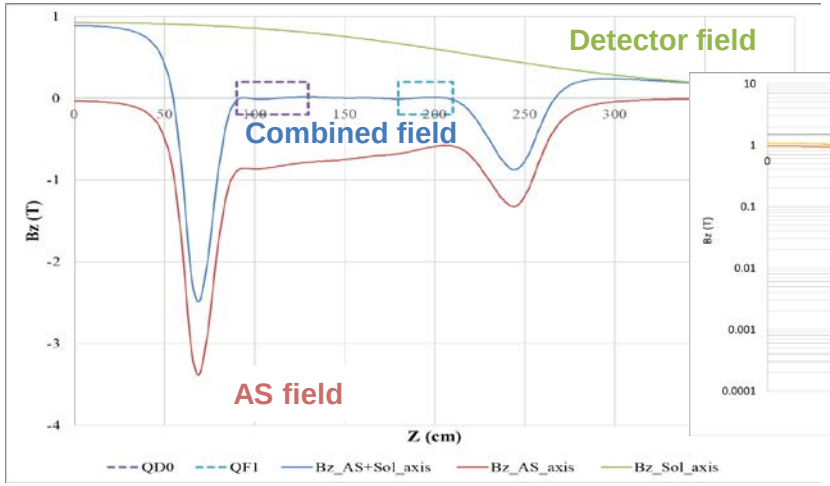


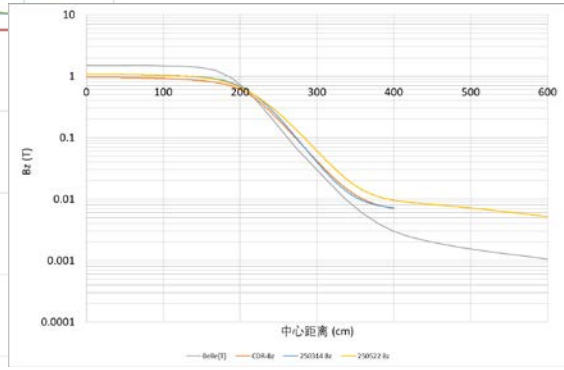


AS coil layout (rev0) with STCF detector coil (DSSM **CDR**)

Anti-solenoid main parameters

Parameter	Value
Bmax	4.11 T
Operating current	231 A
Iop/Ic	20%
Coil qty	15
Coil length	1.905m
Coil inductance	3.04 H
EM stored energy	0.08 MJ





Field distribution along magnet center axis

Beam orbit correctors

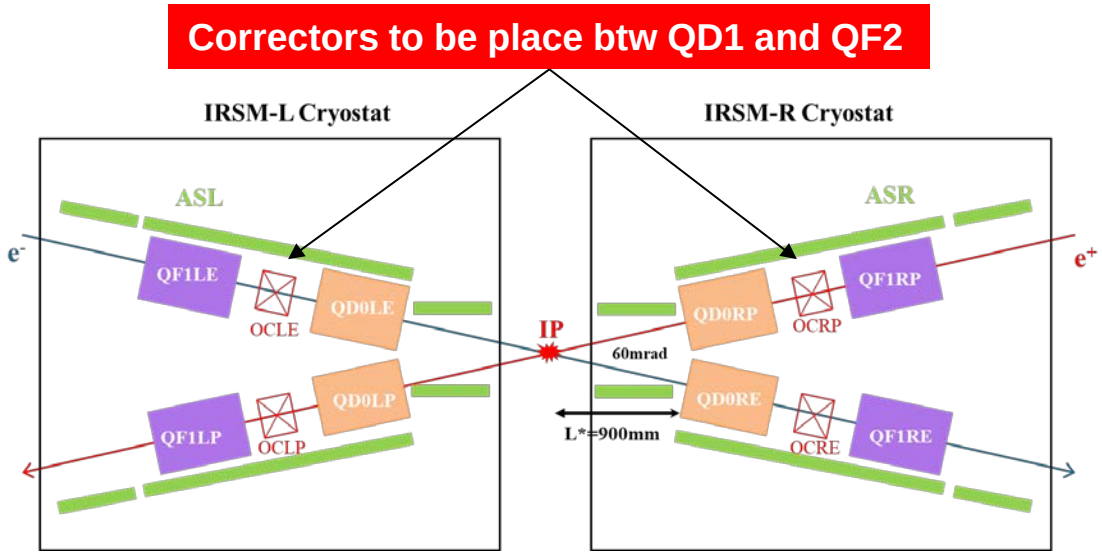
- **Beam orbit correctors**
  - Due to QD1 limited radial space, correctors are placed btw QD1 and QF2 (or end of QD1)
  - Each corrector strength has not finalized, ref to SuperKEKB to start with

Components

- Normal and skew dipoles: correction of the quadrupole center magnetically
- Skew quadrupole: correction of the quadrupole mid-plane angle
- Normal octupole: correction of edge field effect of quadrupole

Orbit correctors orders and strength

Magnet	Rref (mm)	A1 (Tm)	B1 (Tm)	A2 (T)	B4 (T/m2)
QD1	10	0.016	0.016	0.6	30
QF2	15	0.03	0.03	0.3	30

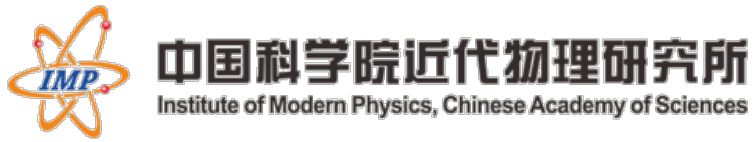


Summary

- 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 QD1 EM design has achieved project requirements;**
  - **QD1 prototype has just started**, will have first dual-aperture QD1 manufactured and tested in 2025.
- Anti-solenoid design began, preliminary design achieved, more optimized iterations in the future;
- Beam orbit correctors design to be started.
- System mechanical design with MDI to be started.

Acknowledgements

- **Magnet**: Shaoqing Wei (ASIPP), Xuyang Liu (CASIC)
- **Cryogenics**: Chongchao He (IASF), Jingxin Zheng (HMFL),
- **Superconductor:** KUAFU Superconductor
- **Consultancy**: M. Koratzinos (MTG), Wei Zhang (SSRF), Yingshun Zhu (IHEP), Wei Wu (IMP), Chengtao Wang (IHEP)
- And, many others to continue…



Many thanks for your attention!

Interaction Region Superconducting Magnet (IRSM)
Wenbin MA on behalf of STCF IRSM team
Xiangtan, July 2025