超级陶粲装置
Super Tau-Charm Facility

# Progress of Interaction Region Superconducting Magnet (IRSM) for STCF

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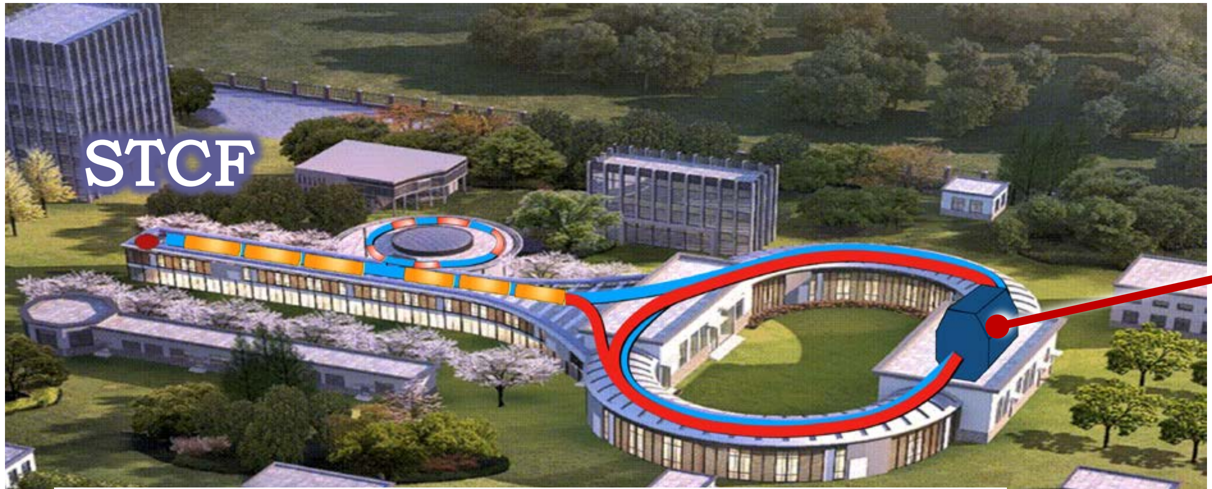
# Outline

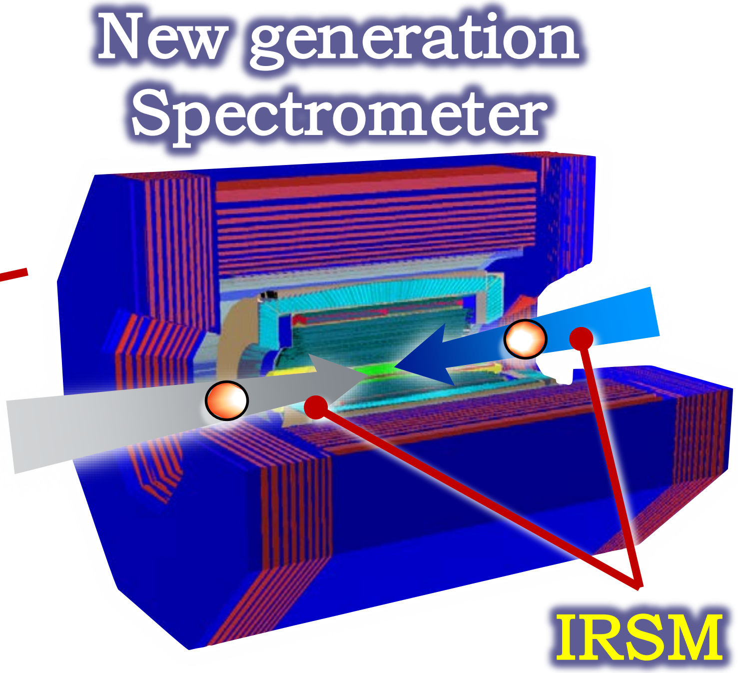
- Introduction
- Design of IRSM QD0
- IRSM anti-solenoid and correctors
- Summary

# STCF Interaction Region Superconducting Magnet (IRSM)

- **STCF** is a new facility under design for tau-charm study with a circumference about 800-900m, beam energy about 2-7 GeV (optimized at 4 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 (v4) of **IRSM** Final Focus quadrupoles are based on **L* of 0.9 m**, beam crossing angle of **60 mrad**.




- $E_{cm}$= 2-7 GeV， $\mathcal{L} > 0.5\times10^{35}$ cm$^{-2}$ s$^{-1}$



# IRSM Requirements

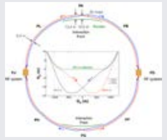
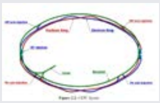
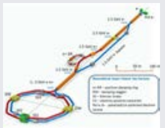
- **Final focus quadrupole** should have quite **high value** of the field **gradient**, the absence or **minimum** values of other multipole **field components**, and be enough **compact** to be placed in a small accessible space inside the detector.
- Quadrupole magnets are operated inside the field 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**.

**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 radius of beam pipe (mm) | Magnetic front to IP (mm) | Minimal distance between two aperture beam lines (mm) |
|---|---|---|---|---|---|---|---|
| **QD0** | **50** | 400 | ≤0.2‰ | 10 | 15 | 900 | **54.06** |
| QF1 | 40 | 300 | ≤0.2‰ | 15 | 25 | 1800 | 108.12 |

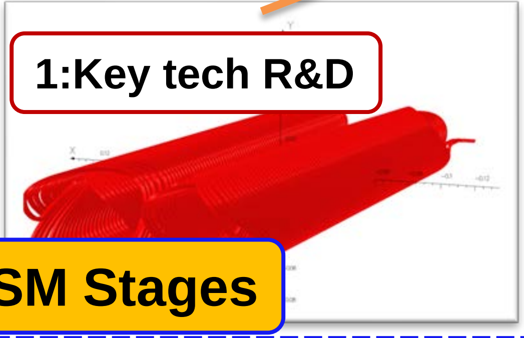
# e-e Collider Dual-aperture IRSM Main Parameters

- 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.

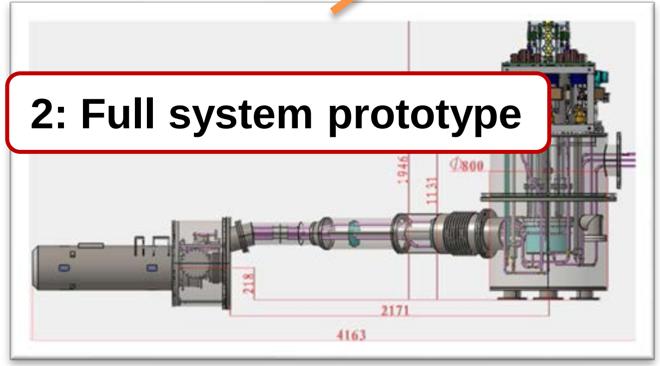
| | SuperKEKB | FCC-ee | CEPC-ee | BINP SCTF-ee | BEPCII | STCF |
|---|---|---|---|---|---|---|
| Status | In operation | CDR | TDR | CDR | In operation (**single** aperture) | CDR |
| Country | Japan | Europe | China | Russia | China | China |
| Beam energy [Gev] e-/e+ | 7.0/4.0 | 104.5/104.5 | 120/120 | 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 |
| **Coil ID [mm]** | **50** | **40** | **40** | **20** | **190** | **~40** |
| **Coil space [mm] Incl. OVB** | **14.5** | **12** | **12** | | | **<7** |
| Coil name | QC1LP/RP | QC1L1 | Q1a | QD0 | SCQ | QD0 |
| |  |  |  |  |  |  |

# IRSM System Schedule

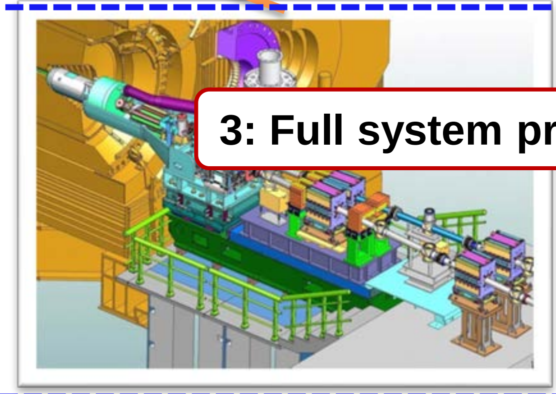
## STCF Project Schedule

1:Key tech R&D



2: Full system prototype



3: Full system production

*Pictures borrowed from BEPCII.*

## IRSM Stages

# Outline

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

# STCF IRSM Concept System

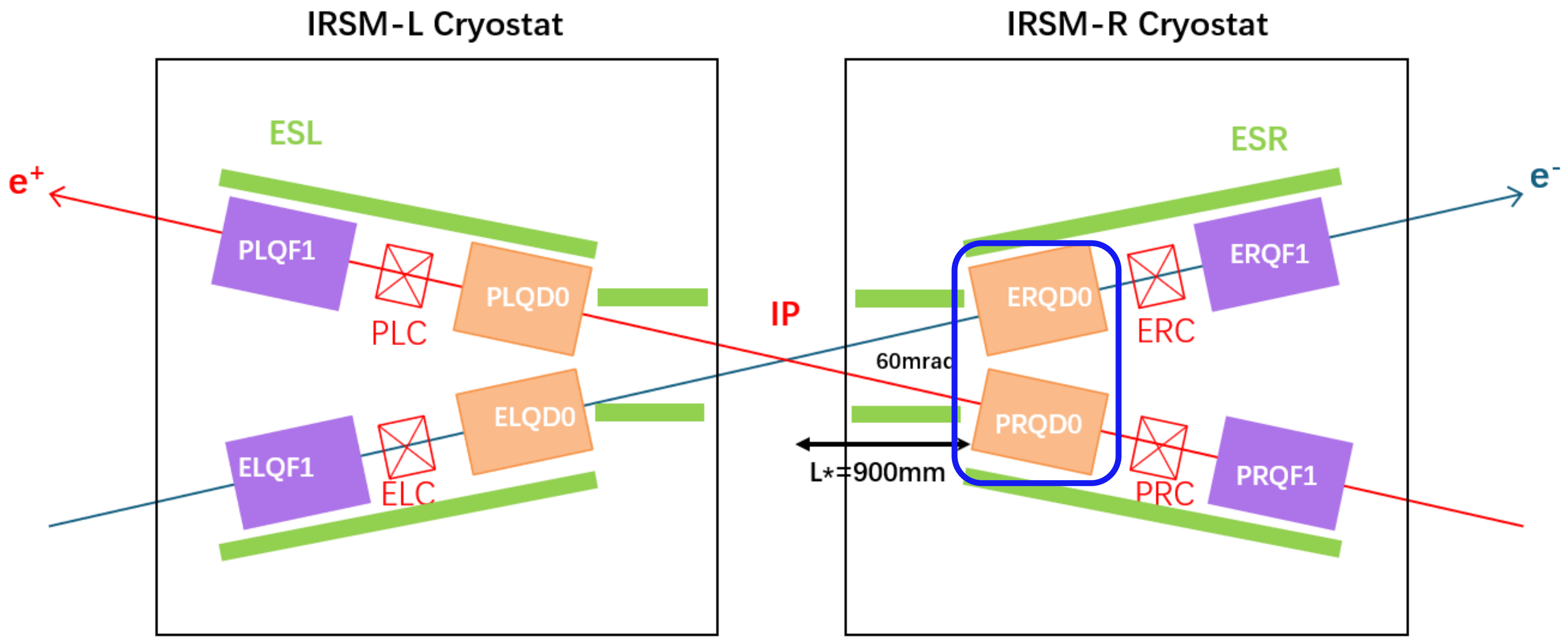
STCF identical energies for the two beams give considerable advantage – **symmetrical layout**.

## 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 constraints 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**

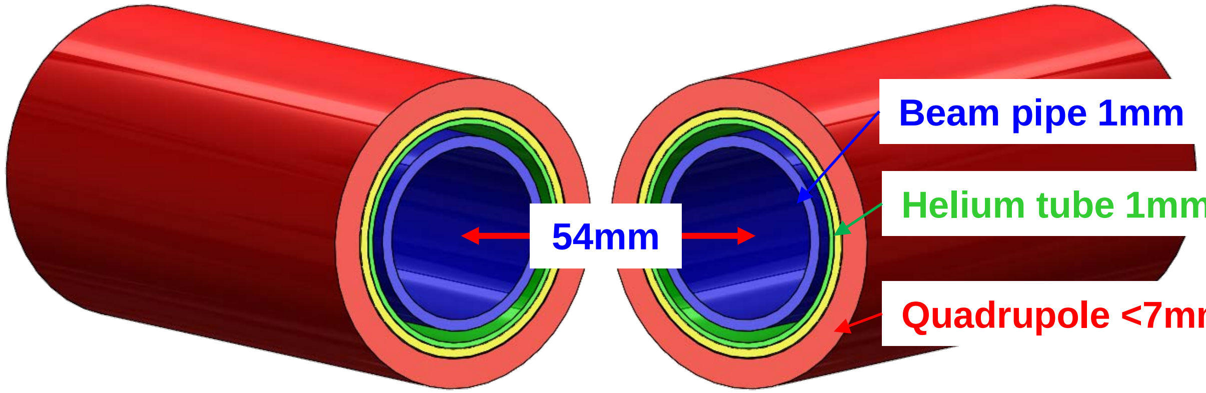
2) Limited radial space: Limited radial space for quadrupole coils

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

3) High field quality

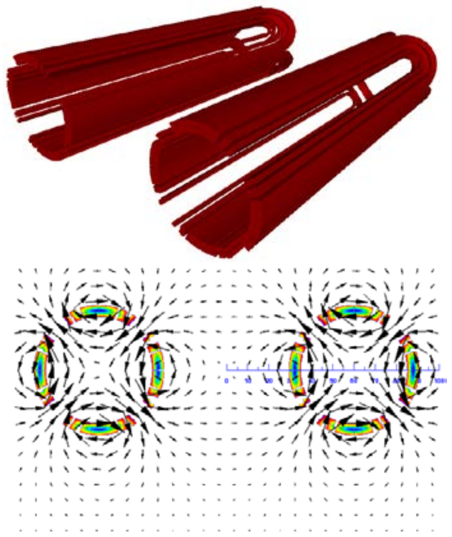
All harmonics below **$<2\times10^{-4}$**

**Can we design it?**

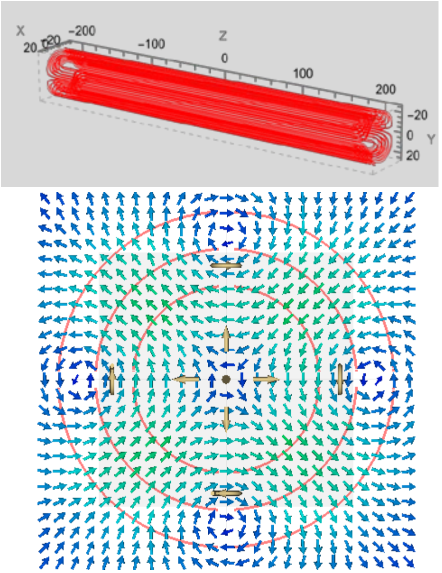


# Design of QD0 – techniques selection

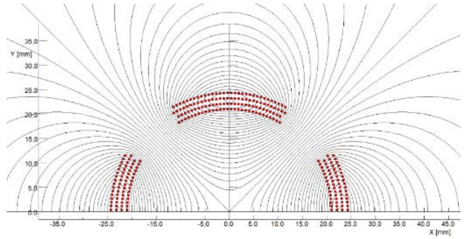
- IR SC magnet techniques selection:
  - Joint effort by experienced persons from several domestic institutions including HMFL (High Magnetic Field Lab), IPP, IHEP, IMP and others
  - Four different techniques studied: CCT, Cos2θ, DCT, Serpentine
  - After two rounds of discussions, considering technology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



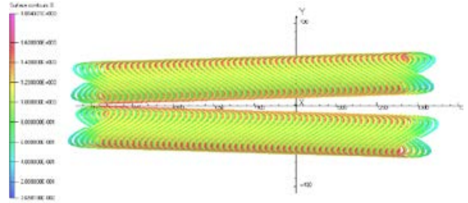
Cos2θ coil EM



Single aperture DCT coil EM



Single aperture serpentine coil EM



CCT coil EM

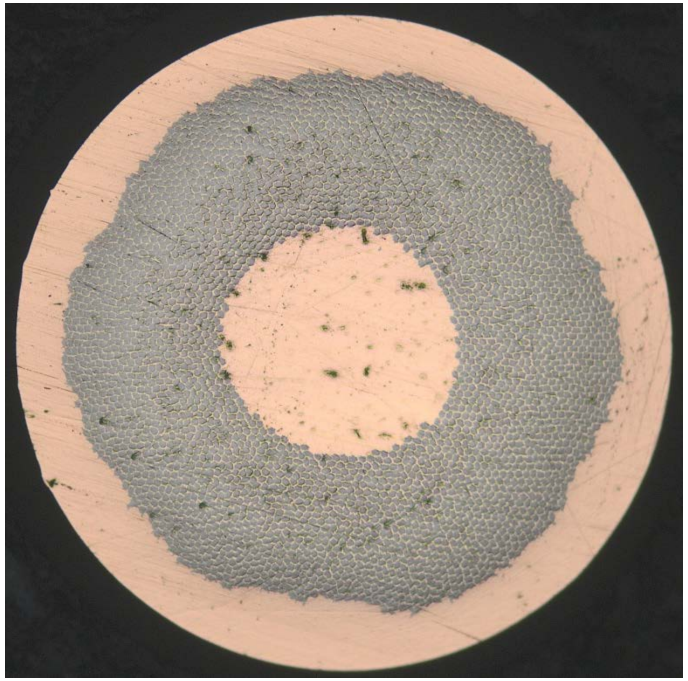
强磁场科学中心 High Magnetic Field Laboratory
中国科学院高能物理研究所 Institute of High Energy Physics, CAS
中国科学院等离子体物理研究所
中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences

# QD0 SC wire selection- F3348/80/1.6

- **Fine filamentary** NbTi chosen to
  - Low magnetization effect and quick field settling
  - Low dynamic coupling with beam and detector magnet
  - Minimize AC loss
- **Thicker** than normal **insulation** to accommodate abrasion during manual winding on metal CCT former
- **Higher Cu/Sc ratio** to improve magnet stability from beam loss, etc.,

| SCN Wire Type | F3348/80 |
|---|---|
| **B (T)** | **Ic (A) @4.2K** |
| **2** | **>850** |
| Stabiliser RRR | >100 |
| Matrix | Copper |
| INSULATION TYPE | Formvar |
| BARE DIA. (mm) | **0.8** |
| INSULATED DIA. (mm) | **0.9**±0.005 |
| TWIST (mm) (nominal) | 15 |
| FILAMENT DIA. (μm) | **8.57** |
| FILAMENT Num. (#) | 3348 |
| Matrix/Sc ratio (nom) | **1.6** |

**Wire spec**

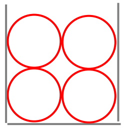


**Wire CSA image**

# QD0 Coil Design

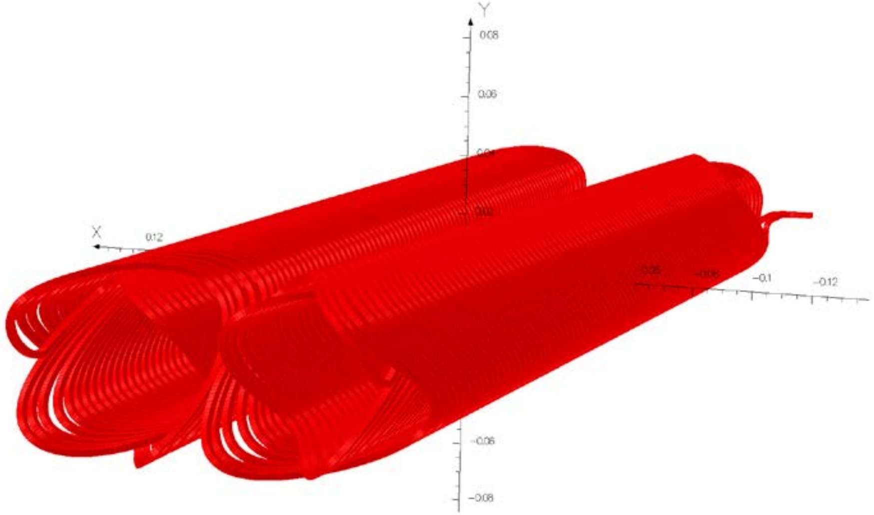
- 4 wire co-wound method onto CNC former;
- Two coils for e+ e- beams and two formers in each coil ;
- At 60° canting angle, 80turns, 600A, can generate 50T/m at 400mm magnetic length;
- Length
  - Magnetic 400mm
  - Coil physical 457mm
  - Former 470mm

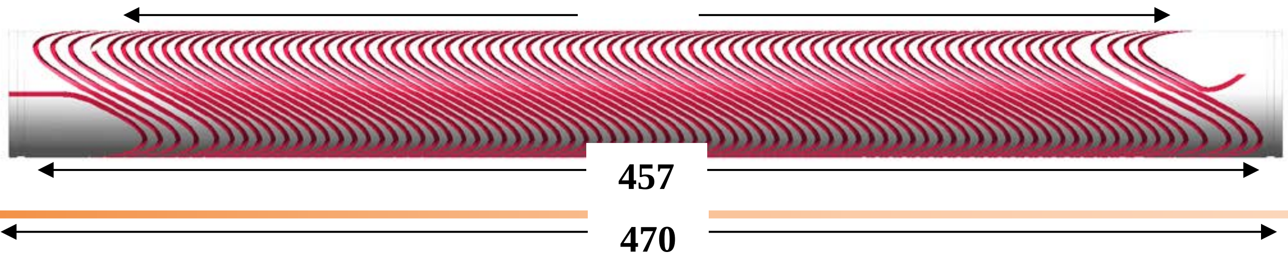
Wire CSA



Wire 2×2

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

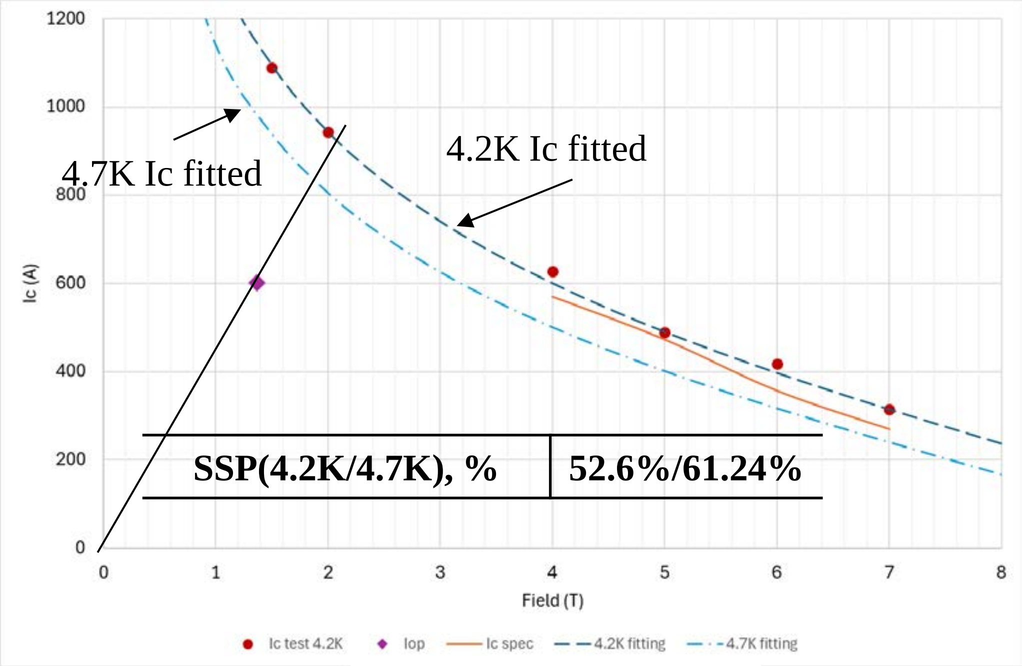



| Item | Value |
|---|---|
| Beam Angle(θ), mrad | 60 |
| $R_{ref_}$QD0, mm | 10 |
| QD0 Coil1 IR, mm | 20.0 |
| QD0 Coil1 OR, mm | 23.3 |
| QD0 Coil2 IR, mm | 23.5 |
| QD0 Coil2 OR, mm | 26.8 |
| Magnetic length, mm | 400 |
| Coil physical length, mm | 457 |
| Coil former length, mm | 470 |
| **I, A** | **602** |
| **Bmax, T** | **1.37** |
| **G,T/m** | **50** |
| SSP(4.2K/4.7K), % | 52.6%/61.24% |
| **Turns** | **80** |
| **Groove canting angle** | **60°** |
| Groove size | 1.9x1.9 mm |
| Groove wall thickness | ≥0.5 mm |

# QD0 Coil Design

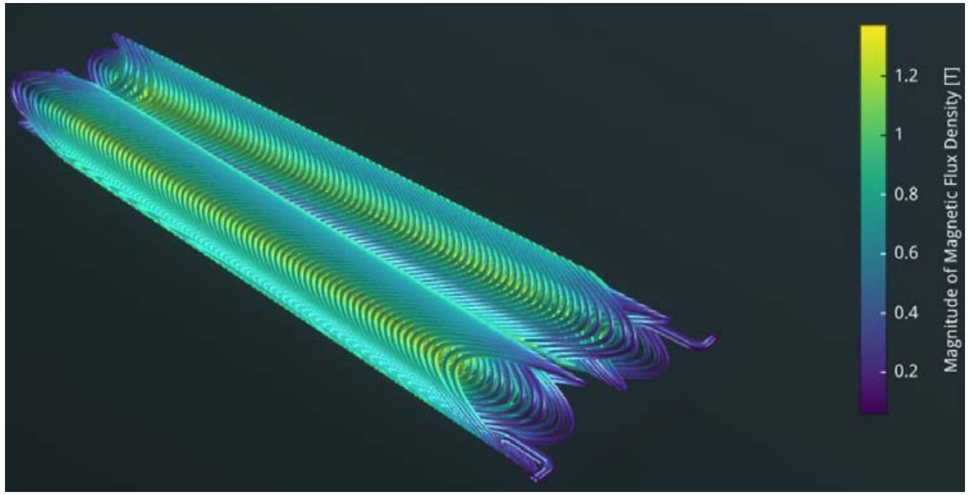
- The maximum field at coil is 1.37 Tesla
- At 602A, the short sample performance is about 52.6% at 4.2K and 61.24% at 4.7K.
- Coil has good temperature margin, $T_{cs}$~6K




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

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

L. Botlura, "A practical fit for the critical surface of NbTi," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, p. 10541057, 2000.

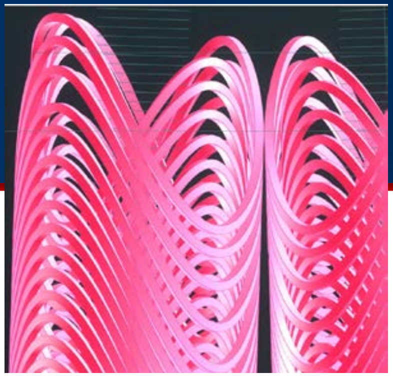



Magnetic field contour at 50 T/m

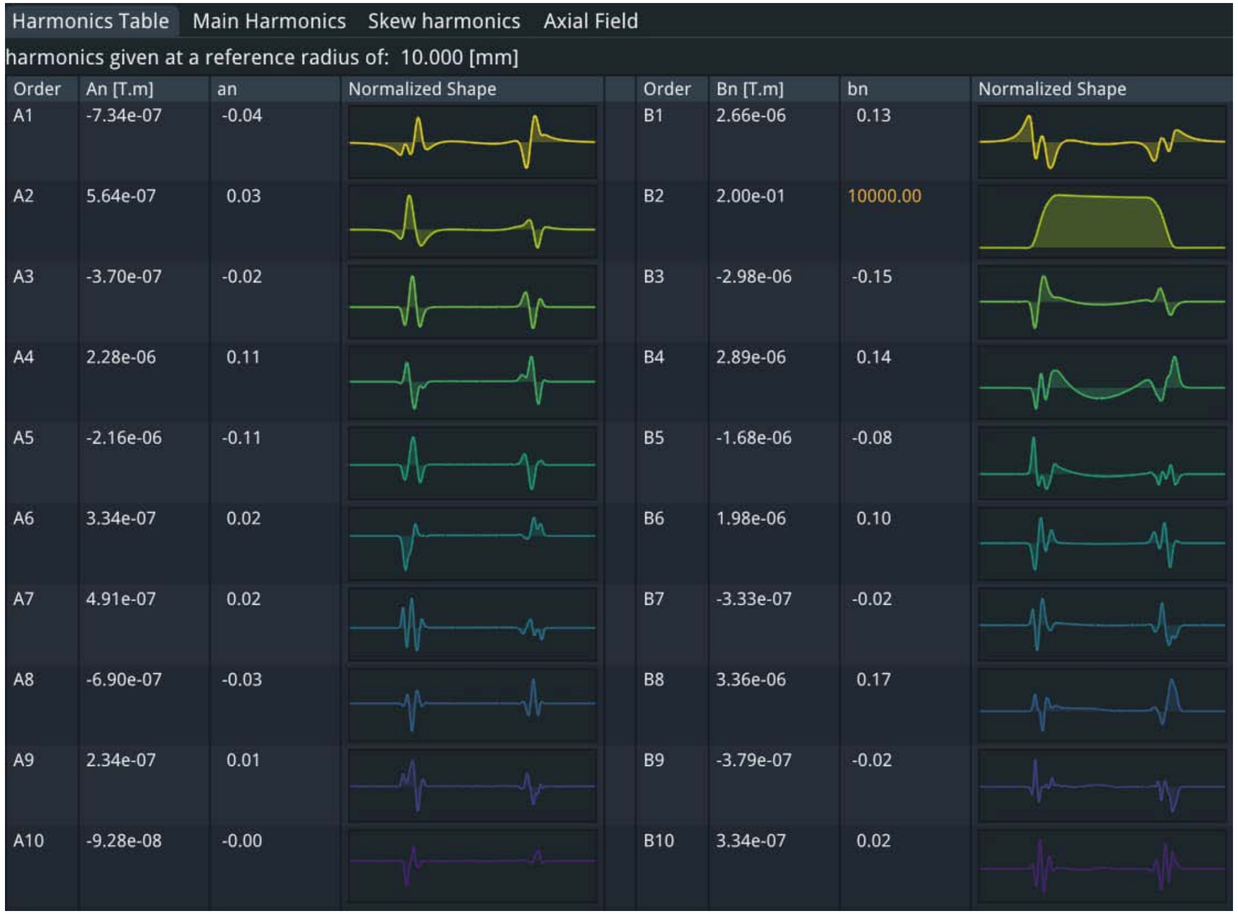
# Optimised QD0 - Harmonics

**Local edge correction**

the distance between turns in the locally corrected coil are different



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



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 | -7.34e-07 | -0.04 | | B1 | 2.66e-06 | 0.13 | |
| A2 | 5.64e-07 | 0.03 | | B2 | 2.00e-01 | 10000.00 | |
| 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 | |

Harmonics of the e+ beam at 10mm reference radius

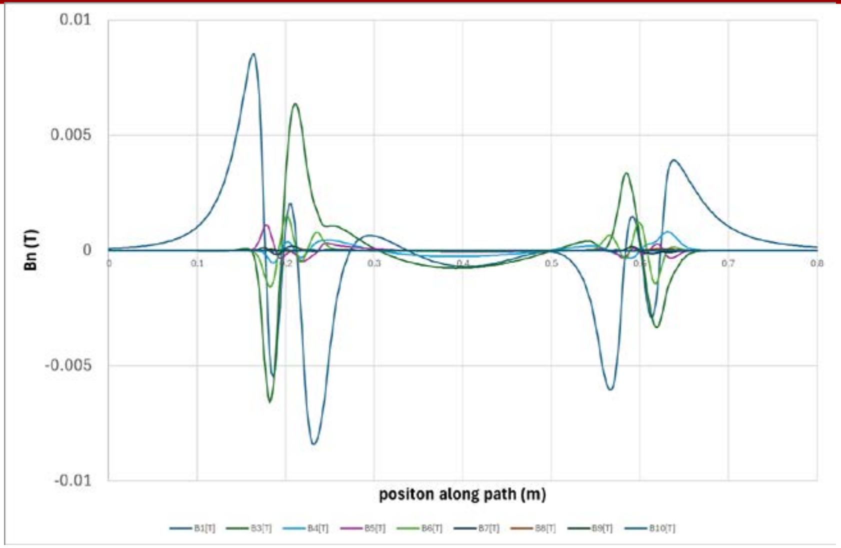
Harmonics Table | Main Harmonics | Skew harmonics | Axial Field

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

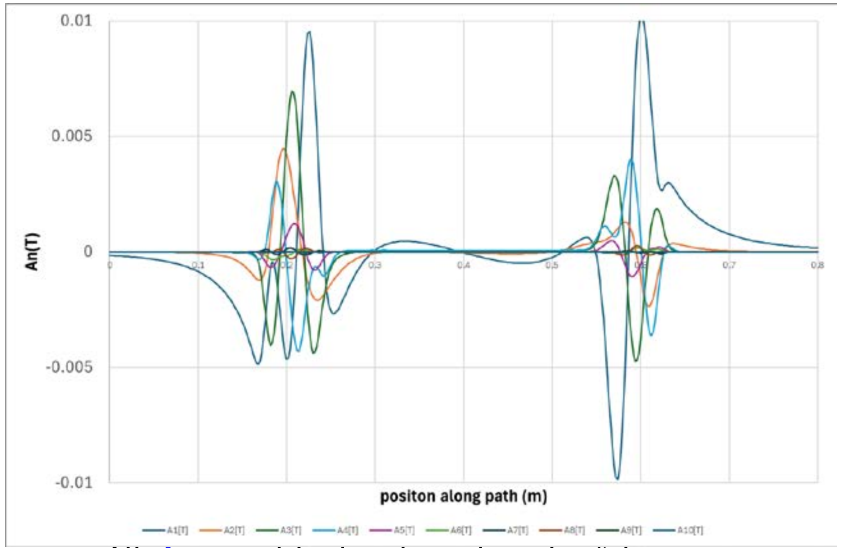
| Order | An [T.m] | an | Normalized Shape | Order | Bn [T.m] | bn | Normalized Shape |
|---|---|---|---|---|---|---|---|
| A1 | -7.34e-07 | -0.04 | | B1 | -2.66e-06 | -0.13 | |
| A2 | -5.64e-07 | -0.03 | | B2 | 2.00e-01 | 10000.00 | |
| A3 | -3.70e-07 | -0.02 | | B3 | 2.98e-06 | 0.15 | |
| A4 | -2.28e-06 | -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 | |

Harmonics of the e- beam at 10mm reference radius

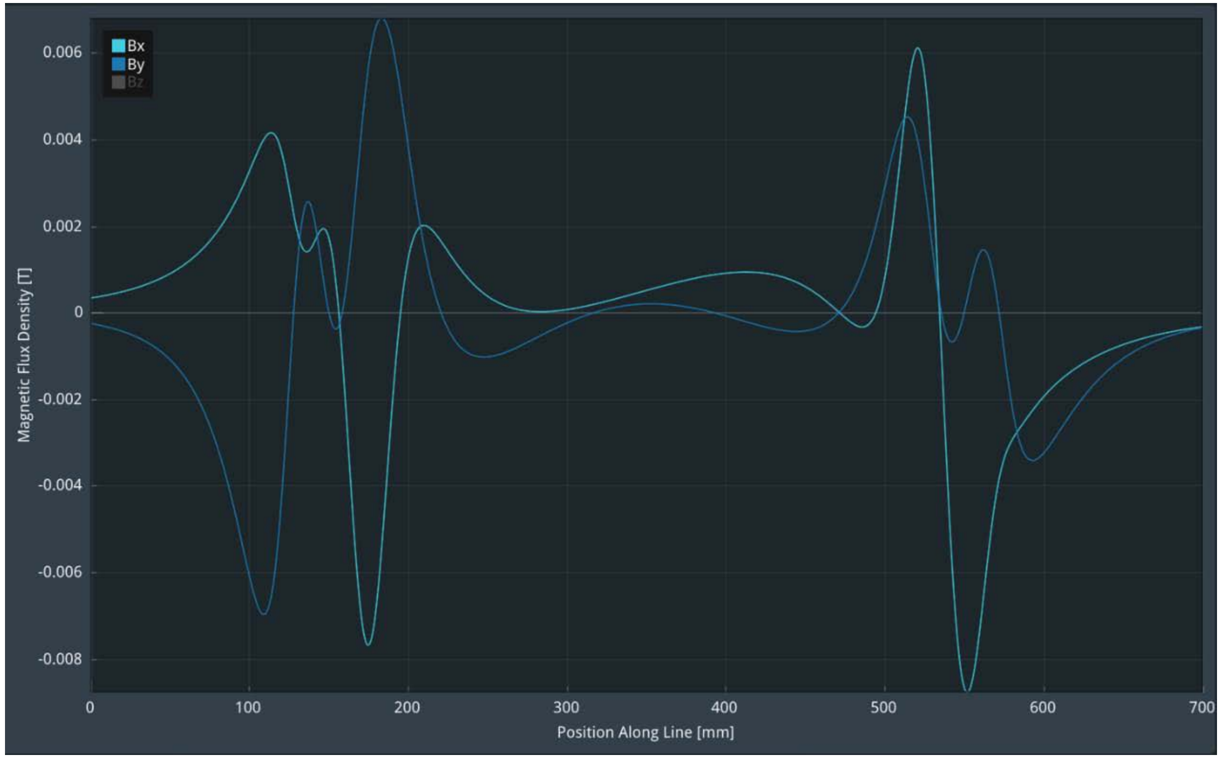
# Optimised QD0 – Field profile




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.

# Harmonics comparison with other $e^+$-$e^-$ IRSMs

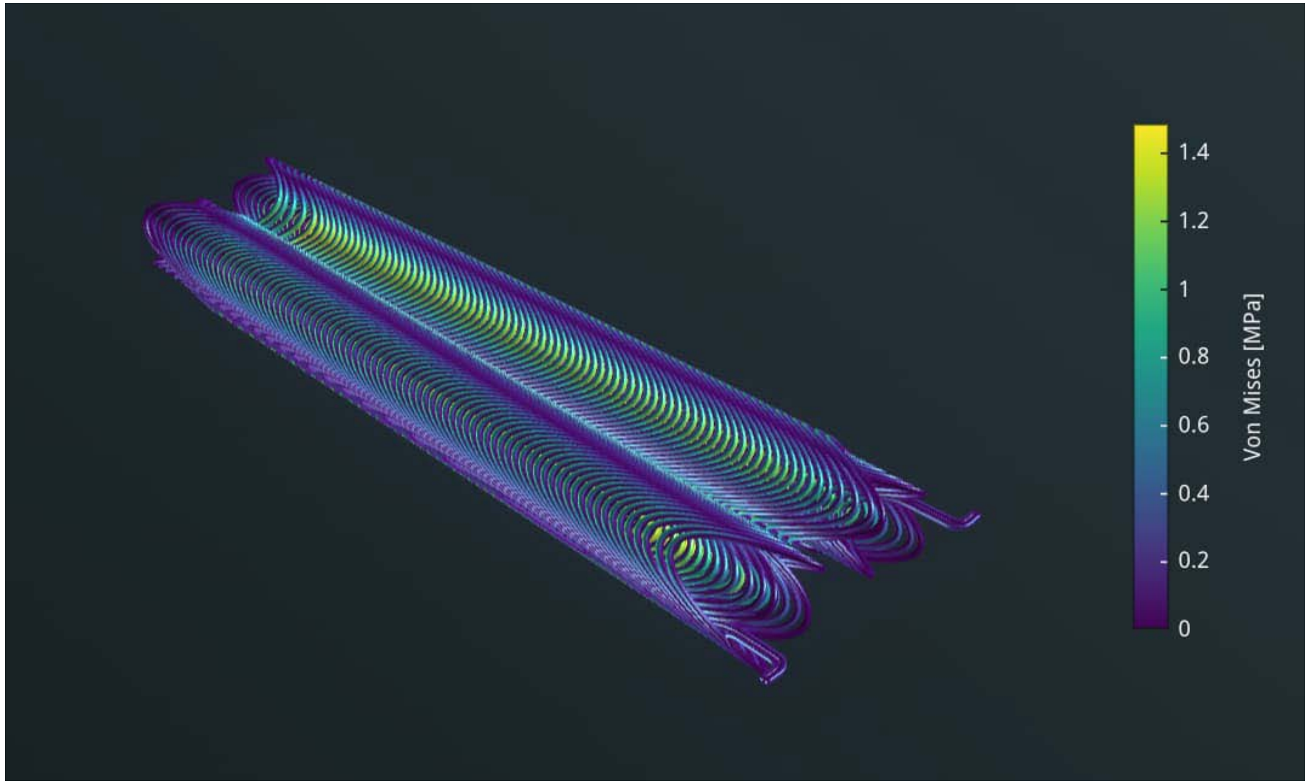
- Harmonics with other projects
  - CEPC from TDR in 2023
  - SuperKEKB from N. Ohuchi published paper in 2021
  - FCC-ee from CDR in 2019

| 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

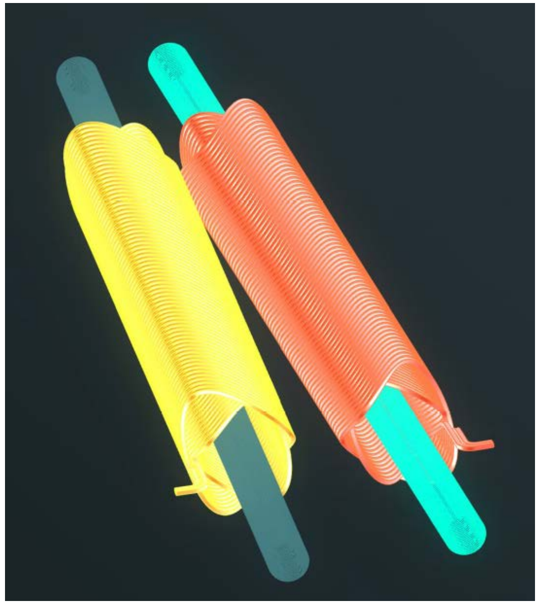
# EM Mechanical Analysis

- Mechanical analysis was performed with input of EM Lorentz force
- Due to the relatively low field and current, von-Mises stresses are low (less than 1.5MPa)



# 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 (tbd)
  - Case4: random error in the manufacturing process (tbd)



# EM Robustness Analysis

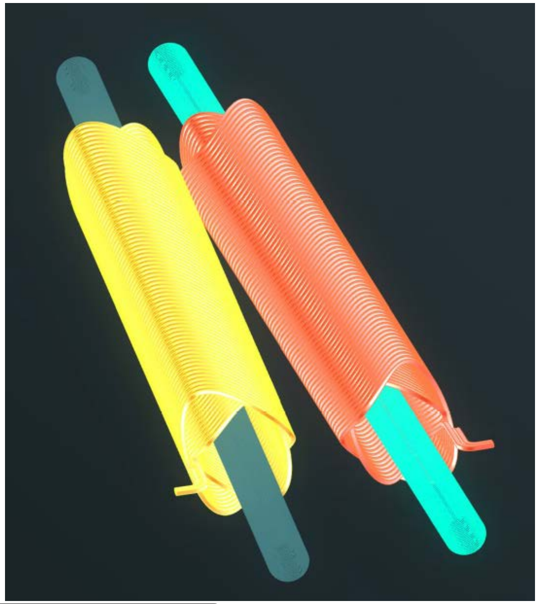
- Case1: fixed one quadrupole (in red) and misaligned the other one (in yellow) by 50 microns (measured at red)
- Case2: fixed yellow and misaligned red (also measured at red)

**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** | - | - | - | - | - | - | - |

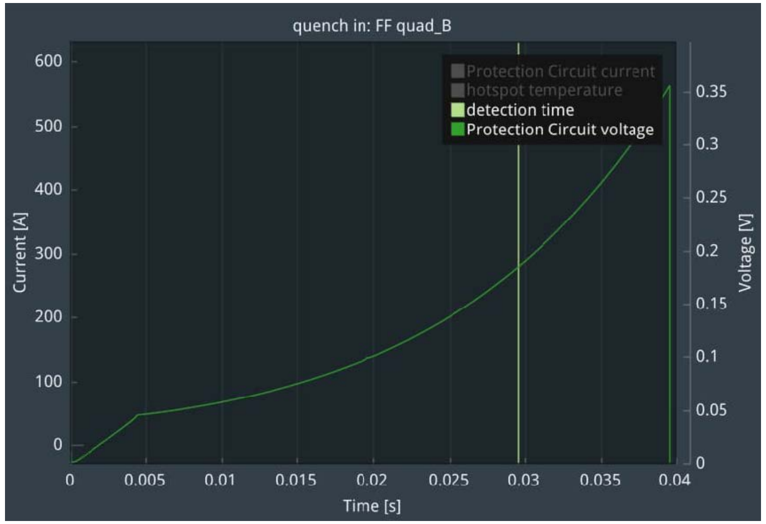


**Importance of concentricity btw beam pipe and magnet!**

**Necessary of orbit correctors!**

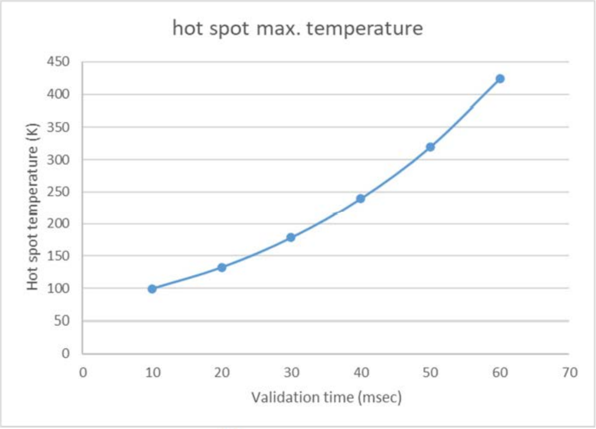
# Magnet Quench Analysis

- **Adiabatic quench simulation at 602A**, with assumptions:
  - 100mV voltage threshold and 10ms validation time.
  - Energy extraction with 75mΩ resistor.
- **Results**
  - The voltage exceeds the threshold of 100mV after 20msec, quench is detected at 30msec, and dump resistance is opened at 40msec.
  - The maximum voltage reached is about 60V and the maximum hot temperature is less than 100 K.

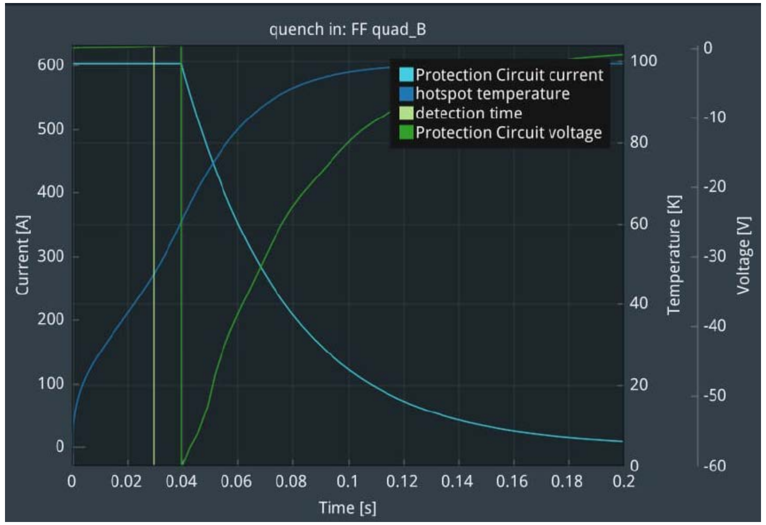


**Initial voltage transient and detection time**

- **Hot spot temperature vs validation time**
  - Validation time needs to be **below 50ms** to keep the hot spot temperature below 300K
    *(or the time between the quench and the activation of the dump resistor needs to be below 60msec)*



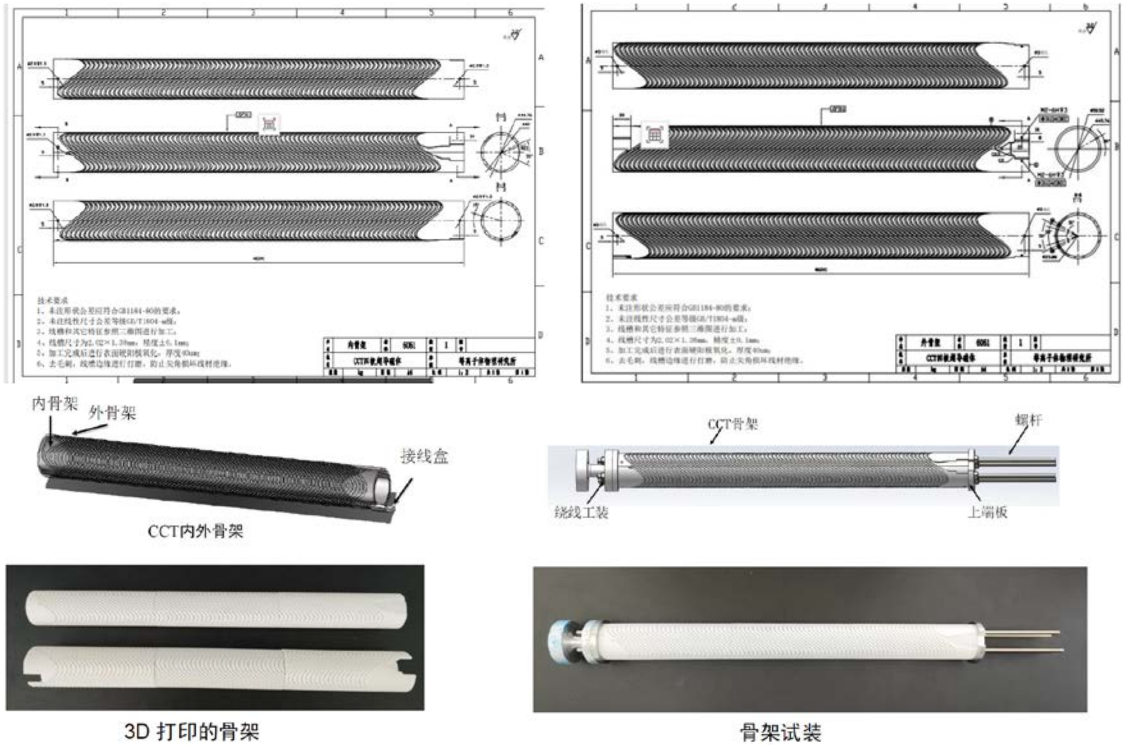
**Hot spot temperature versus validation time**



**Full quench curves (I, U, T)**

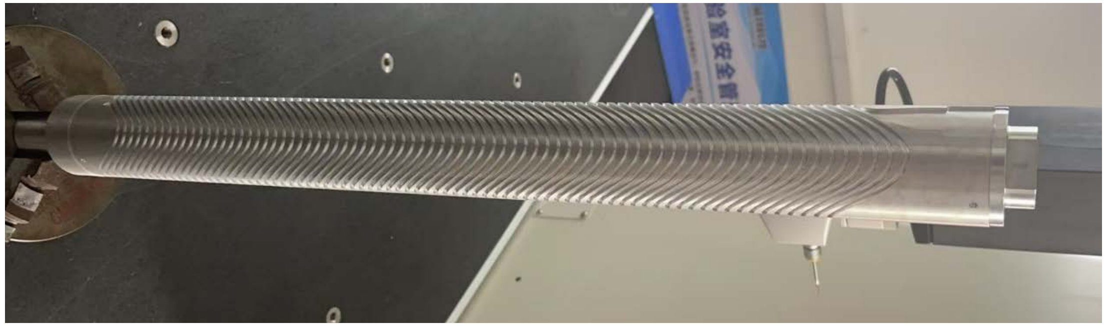
# QD0 prototyping

- QD0 **pre-**prototyping almost finished, to verify
  - 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;
- First QD0 prototype to be vertical tested in August 2025.




**QD0 former drawing and 3D printing dummy former**

**Trial winding on dummy former**



**QD0 former CNC machining**

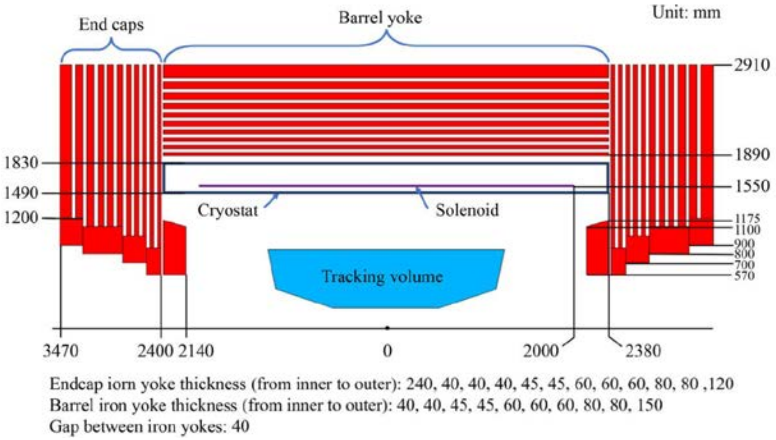
# Outline

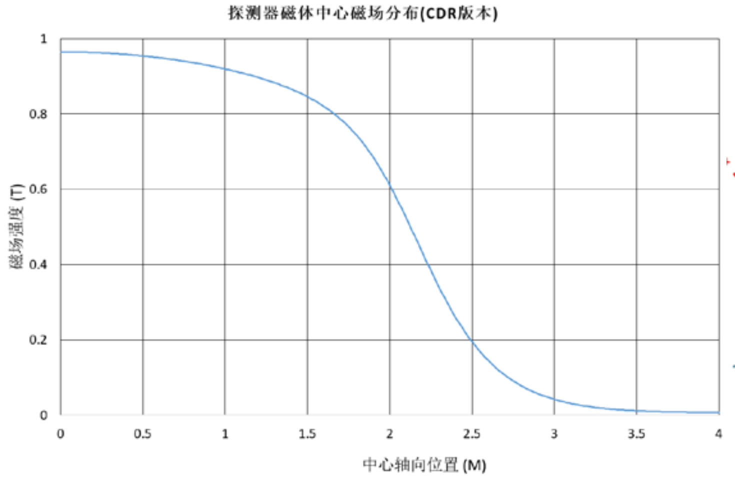
- Introduction
- Design of IRSM QD0
- **IRSM anti-solenoid and correctors**
- Summary

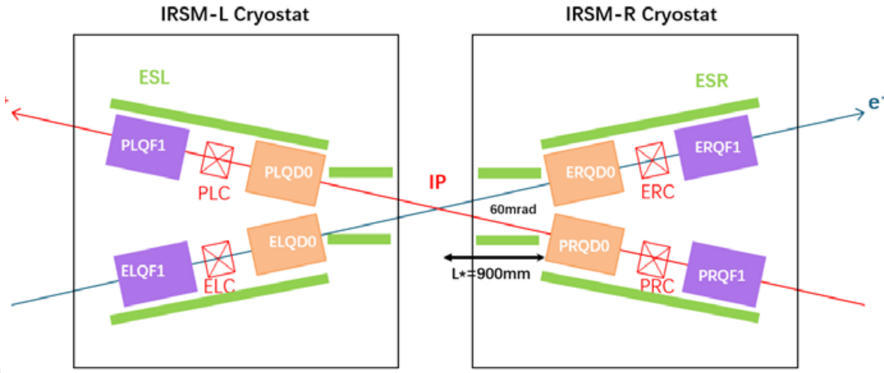
# Design of anti-Solenoid

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, 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 (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 and QD0)



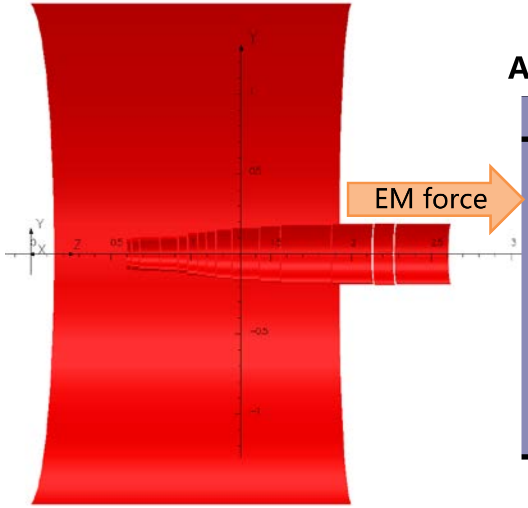




STCF detector solenoid layout and field distribution along central axis

(fr STCF detector CDR)

# Preliminary Design of anti-Solenoid

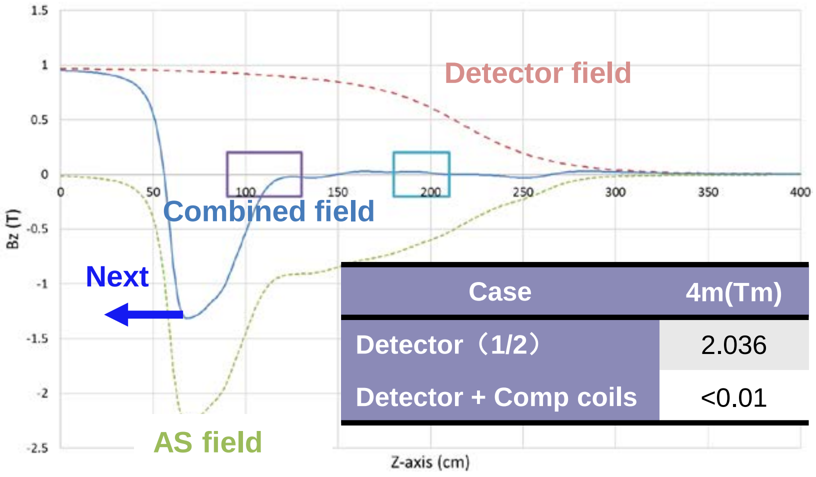
- Based CDR detector field model, the anti-solenoid is divided into 15 sub-coils to reduce magnet size, energy and cost;
- Preliminary design shows integral field could be lower than 0.01Tm (not the limit);
- The anti-solenoid peak field is 2.83T, operating at 230A, and has a total axial coil length 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; Better AS field; Mechanically compatible within the MDI; Mechanically rigid from EM force; etc.




**Anti-solenoid main parameters**

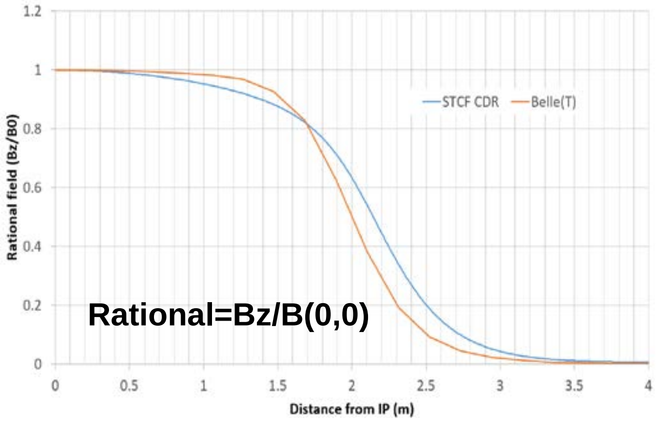
| Parameter | Value |
|---|---|
| Bmax | 2.83 T |
| Operating current | 231 A |
Iop/Ic | 20% |
| Coil qty | 15 |
| Coil length | 2 m |
| Coil inductance | 1.91 H |
| EM stored energy | 0.052 MJ |

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




| 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

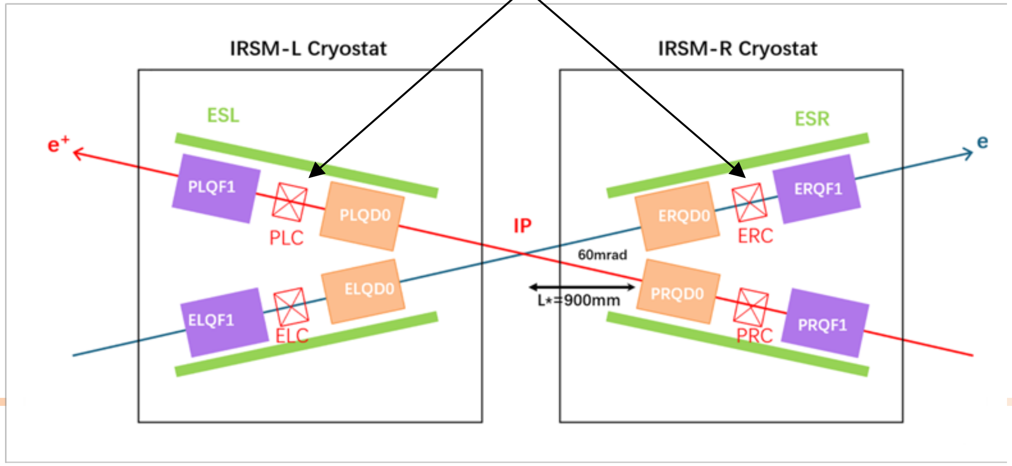
# Beam orbit correctors

- **Field shimming correctors**
  - Corrector coils to shim out gradient imperfection harmonics, induced by manufacture/alignment... errors
  - STCF IRSM has limited radial space, therefore, rely on precision engineered CNC former to achieve field quality. Hopefully, no need of shimming correctors.
    - FCC-ee prototype gives the hope!
- **Beam orbit correctors**
  - Due to QD0 limited radial space, correctors are placed btw QD0 and QF1
  - Normal and skew dipoles: correction of the quadrupole center magnetically
  - Skew quadrupole: correction of the quadrupole mid-plane angle
  - Each corrector strength has not finalized, ref to SuperKEKB to start with

Orbit correctors strength

| Magnet | Rref (mm) | A1 (Tm) | B1 (Tm) | A2 (T) |
|---|---|---|---|---|
| QD0 | 10 | 0.016 | 0.016 | 0.6 |
| QF1 | 15 | 0.03 | 0.03 | 0.3 |

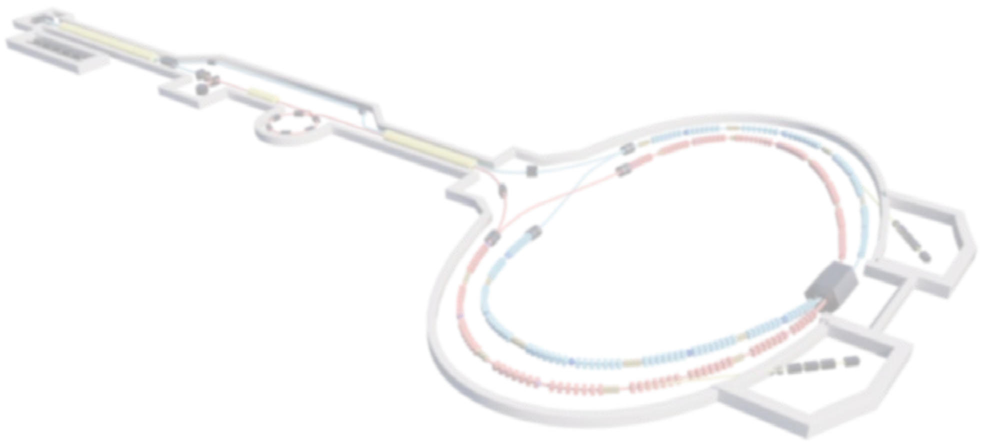
**Correctors to be place btw QD0 and QF1**



# 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;
  - **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;
- Beam orbit correctors design to be started.
- System design with MDI to be started.
- **IRSM system international collaborations are very necessary and welcome!**

# Many thanks for your attention!



**Progress of Interaction Region Superconducting Magnet (IRSM) for STCF**
**Wenbin MA** on behalf of STCF IRSM team
eeFACT-2025, Tsukuba