FUTURE CIRCULAR COLLIDER

FCC Week 2025

May 19, 2025, 8:00 AM → May 23, 2025, 1:00 PM Europe/Vienna

Hofburg Vienna

Frank Zimmermann (CERN), Michael Benedikt (CERN)

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

MDI efforts at Magnet Division, BNL: Corrector Magnets and Screening Solenoid design for Interaction region of FCC-ee

Vikas Teotia

Superconducting Magnet Division

Major activities being pursued at Brookhaven for FCCee-IR

1. Development of Platform for design of combined function canted cosine theta direct wind magnets with longitudinally varying harmonics.
2. Design, fabrication and testing of a concept-magnet for annulling cross-talk harmonics of an existing direct wind quadrupole magnet on adjacent beam axis
3. First design of corrector magnet set for first final focus quadrupole
4. Design of screening solenoid and compensation solenoid for IR
5. Possible interest of FCCee in nano-meter level Magnetic Field vibration measurements (BNL-KEK experience)

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Magnets for FCC-ee IR @ Brookhaven

1. Vertical and Horizontal Dipole Correctors
2. Skew Quadrupole correctors
3. Normal Quadrupole correctors
4. Cancelation of cross-talk in adjoining beam axis
5. Realistic Magnetic field mapping of detector solenoid leading to Screening Solenoid Design
6. Compensating Solenoid
7. We would like to start building a complete magnet model for the IR encompassing detector, screening, compensating, quadrupoles and correctors.

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Layout of Magnets in FCC-ee IR

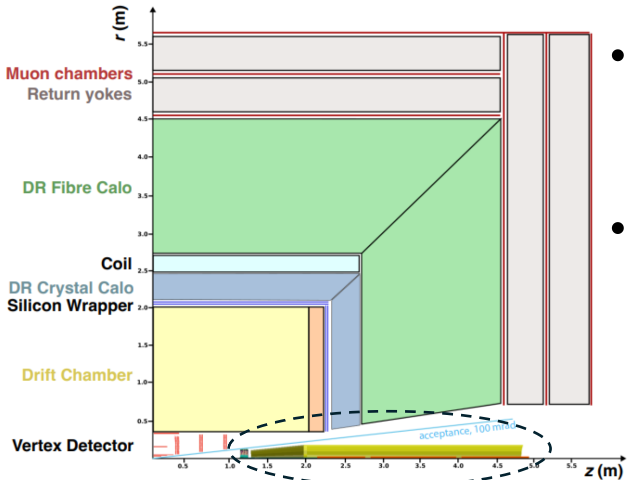
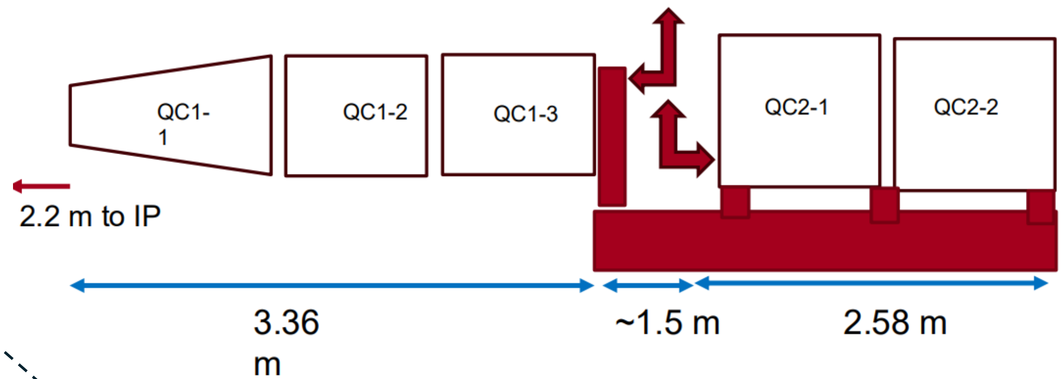
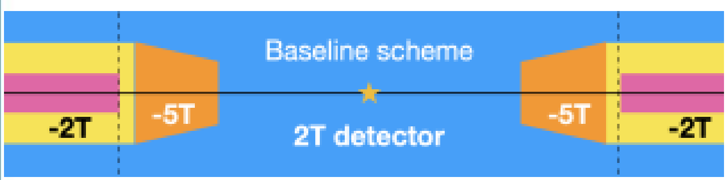


Figure 3: Overview of the IDEA detector layout.

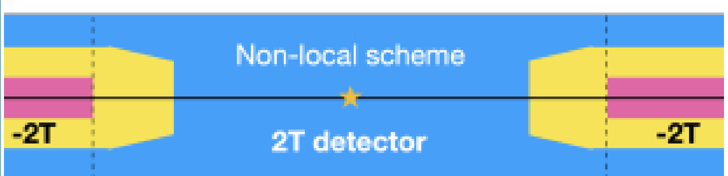
The IDEA detector concept for FCC-ee :The IDEA Study Group*

- QC1 consists of three Quadrupoles (shown below) is yoke free
- QC2 consists of two Quadrupoles (not-shown here) are away from IP and have iron yokes

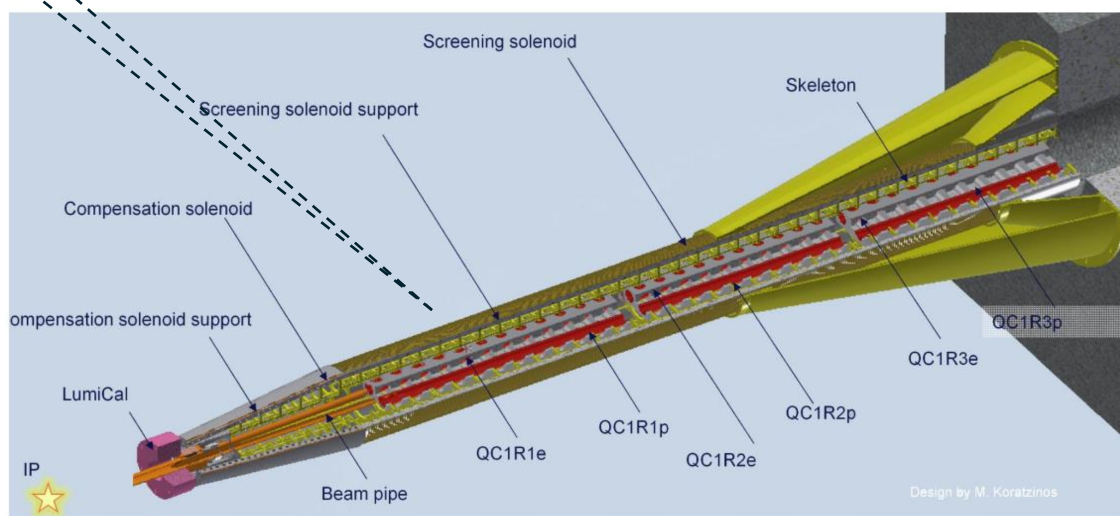




Local-compensation scheme



Non-Local compensation scheme



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Correctors : Assumptions and requirements

- The cross-talk due to equal gradient main quadrupoles are self consistently compensated. (m Koratzinos)
- We need normal quadrupoles correctors to make un-equal gradient especially at higher energies (top energy, tapering). Need quadrupole correctors if we cannot neglect the errors. (refer next slide)
- Skew Quadrupoles are critical in non-local scheme to take care of beam eigen-plane rotations. They are needed for local scheme to take care of errors.
- Normal and skew dipole correctors are needed for both, but more crucial for non-local scheme.
- Dedicated dipole correctors (HV) are part of the lattice towards IP side in non-local scheme.

Salient features of the IR Corrector magnets

1. The IR magnet (QC1) of FCC-ee does not have iron yoke. Thus, nearby beam is not passively shielded.
2. The Corrector coil(s) magnets need to cancel this cross-talk beside generating the field of intended polarity.
3. The beam-axis to beam-axis distance is non-constant thus the strength of cross-talk correction harmonics need to vary with longitudinal spacing.
4. The double helical magnets provides better local control for longitudinal variation of harmonic(s).
5. The QC2 cryostats could have Serpentine style correctors because they have yokes and cross talk can be handled by more conventional methods.

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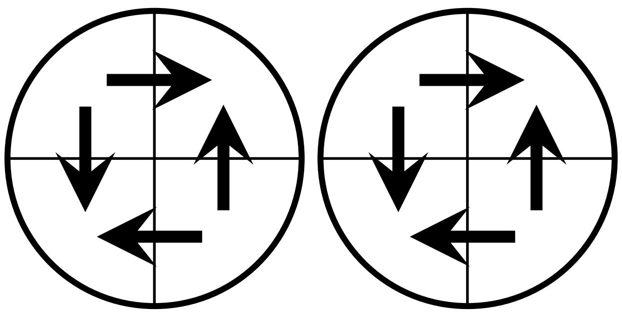
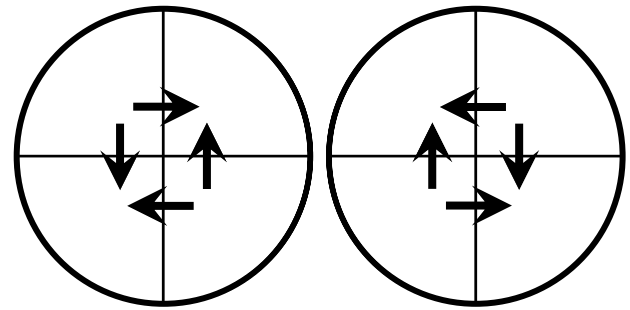
Main Quadrupole Gradient Fine-Tuning

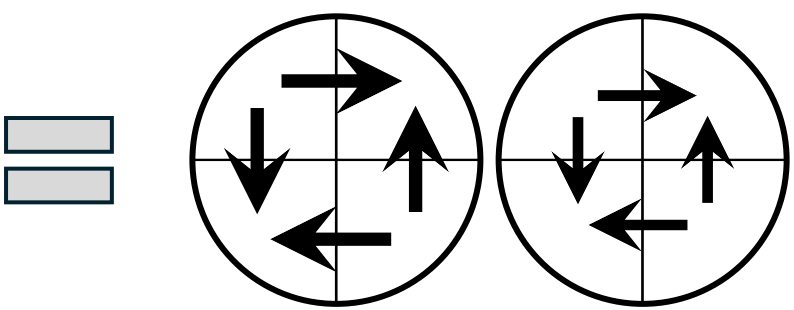
Main Quad (Same Gradient)



Corrector Coil (Opposite Gradient)

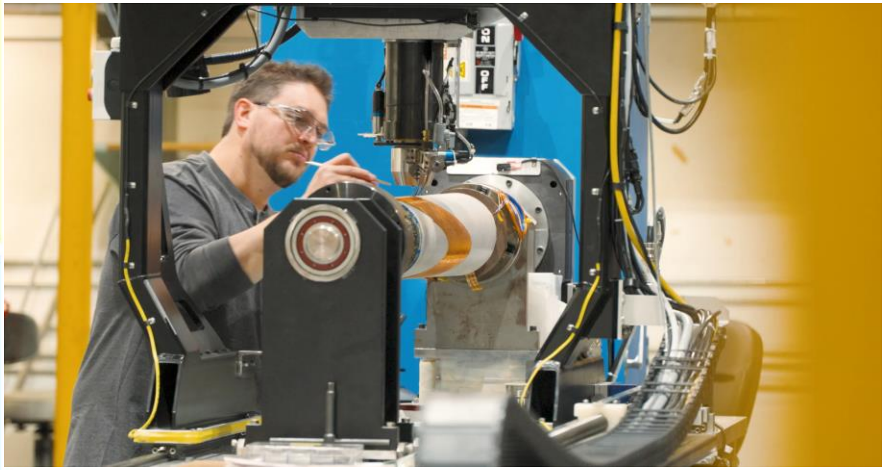


Net Gradient in Each Aperture (Tunable to desired strength)



Is it useful to have a quad corrector with opposite gradient and same polarity symmetry to be able to make the gradients slightly different in each aperture without adding dipole kick and non-linear field components in the other aperture?

BNL Direct Wind Magnet Technology



We place superconductor (round wire or cable) on a support tube under computer control.

- General purpose, e.g. no need for costly tooling.
- Very good field quality (correct during production).
- Compact coils (force management without collars).
- Easily nest coils (e.g. b_1, a_1, b_2, a_2, b_3, a_3, b_4...).
- Vary aperture along length (wind on tapered tubes).
- Vary field along length (SuperKEKB, EIC, FCC-ee).
- Technology appropriate for doing "one off magnets."
- Used for decades in accelerators around the world.

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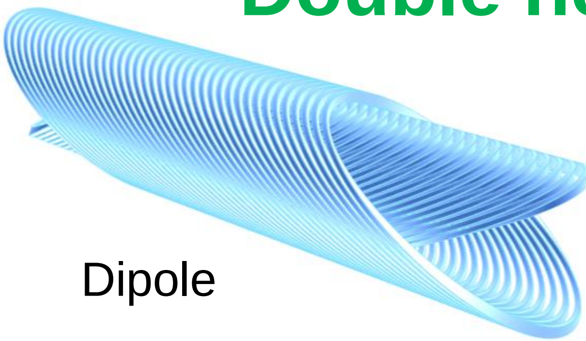
Project	Status	Salient feature
RHIC, BNL (All the main ring correctors)	Deployed, Operational	• First DW magnets (flat coils → wrapped) • Many coils and many years of operation
HERA-II, DESY (IR magnets, correctors)	Deployed, Fulfilled Misson	• IR magnets need high-uniformity field • Only possible directly winding on tube
BEPC-II, IHEP/Beijing (IR magnets, correctors)	Deployed, Operational	• Required even more compact coils → • Invented efficient Serpentine patterns
Alpha, 3 generations, CERN (Anti-H trap octupoles)	Deployed, Operational	• Rugged coils: survived thousands of deliberate quenches (no degradation)
JPARC, KEK (beamline correctors)	Deployed, Operational	• Conduction cooled coils that can take advantage of interconnect region space
ILC, KEK-ATF2, BNL/KEK (IR magnets and correctors)	Design and prototypes	• Compact, high-gradient coils to enable small crossing angle via active shielding
SuperKEKB, KEK (IR correctors)	Deployed, Operational	• Challenging field quality requirements • 43 coils were wound in nested groups • Some shaped longitudinal field profiles
EIC, BNL/JLAB (IR magnets and correctors)	Design and prototypes	• Actively shielded Nb_3Sn high-gradient quad (inner 9.3T → external few gauss) • Double Helical tapered magnets
FCC-ee	Design	• Combined function CCT magnets
US-Magnet Development Program	Exploratory studies	• HTS • Nb3Sn • Conductor development

Double helical (CCT) magnet designs

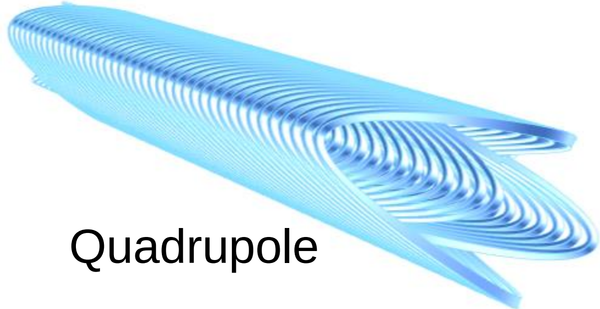


Dipole

Order	Bn [T.m]	bn	Normalized Shape
B1	1.68e-01	10000.00	
B2	9.51e-07	0.06	
B3	-1.83e-07	-0.01	
B4	3.73e-07	0.02	

Order	Bn [T.m]	bn	Normalized Shape
B1	1.68e-01	10000.00	
B2	9.53e-07	0.06	
B3	-1.92e-07	-0.01	
B4	3.75e-07	0.02	

Order	Bn [T.m]	bn	Normalized Shape
B1	1.68e-01	10000.00	
B2	9.55e-07	0.06	
B3	-2.00e-07	-0.01	
B4	3.70e-07	0.02	

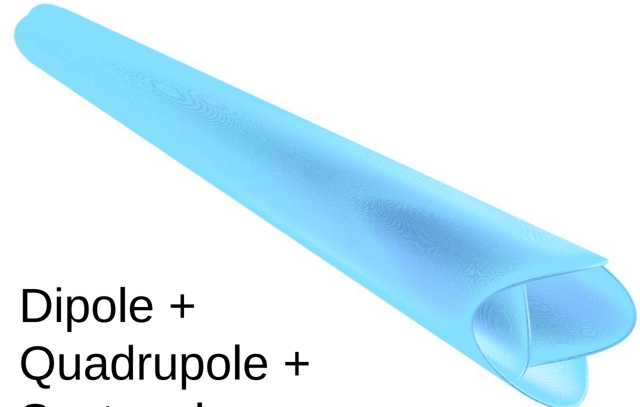


Quadrupole

Order	Bn [T.m]	bn	Normalized Shape
B1	1.91e-06	0.18	
B2	1.06e-01	10000.00	
B3	6.50e-07	0.06	
B4	-3.68e-07	-0.03	

Order	Bn [T.m]	bn	Normalized Shape
B1	2.00e-06	0.19	
B2	1.06e-01	10000.00	
B3	6.49e-07	0.06	
B4	-3.66e-07	-0.03	

Order	Bn [T.m]	bn	Normalized Shape
B1	2.24e-06	0.21	
B2	1.06e-01	10000.00	
B3	6.53e-07	0.06	
B4	-3.62e-07	-0.03	

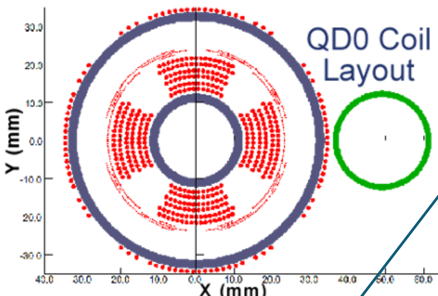


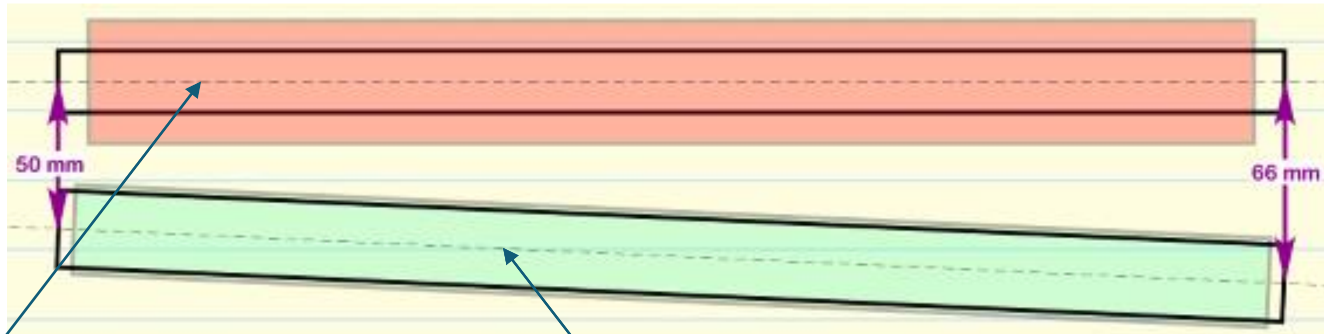
Dipole + Quadrupole + Sextupole

Order	Bn [T.m]	bn	Normalized Shape
B1	5.58e-02	10000.00	
B2	3.57e-02	6393.20	
B3	2.28e-02	4088.38	

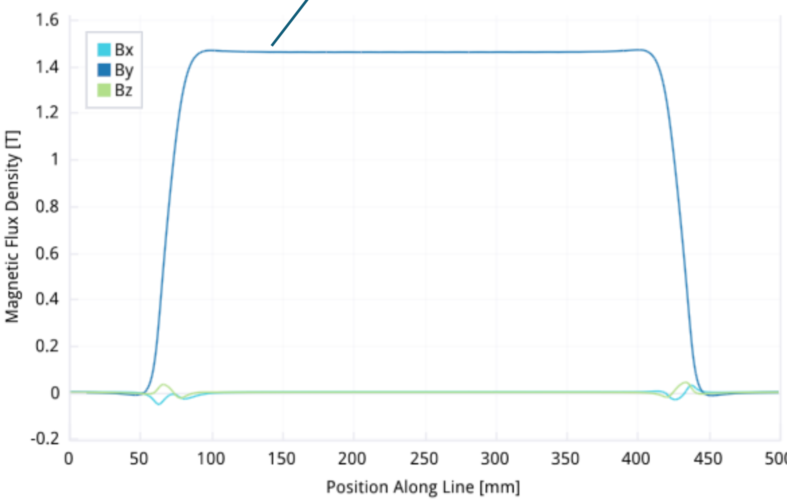
Order	Bn [T.m]	bn	Normalized Shape
B1	5.02e-02	10000.00	
B2	4.45e-02	8860.56	
B3	1.88e-02	3739.65	

Design of Double Helical Compensating Magnet

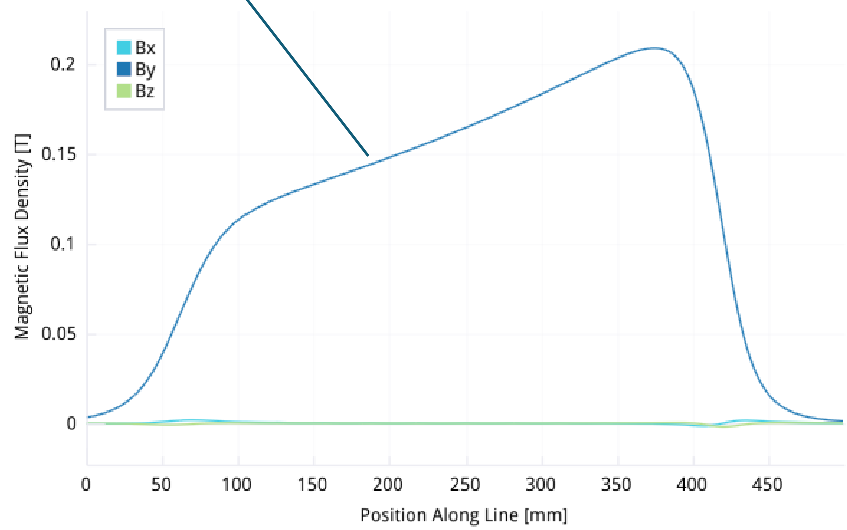




Side-by-side beam tubes



Magnetic Field along the magnet axis



Magnetic Field along the adjacent beam axis

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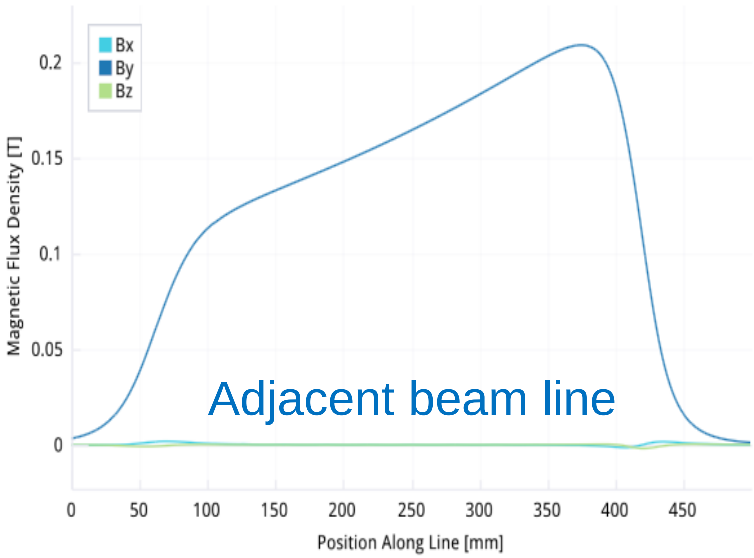
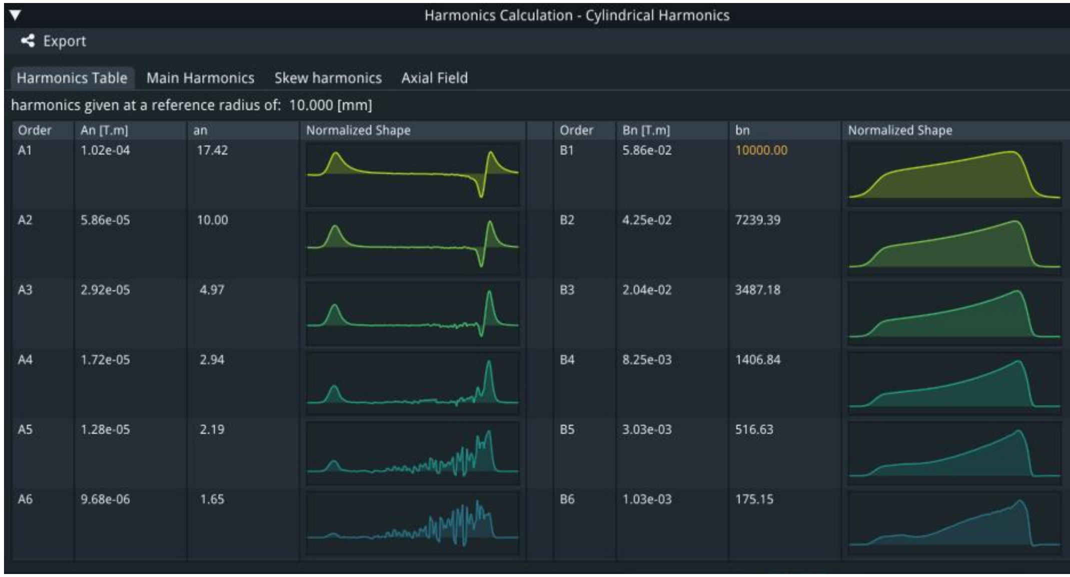
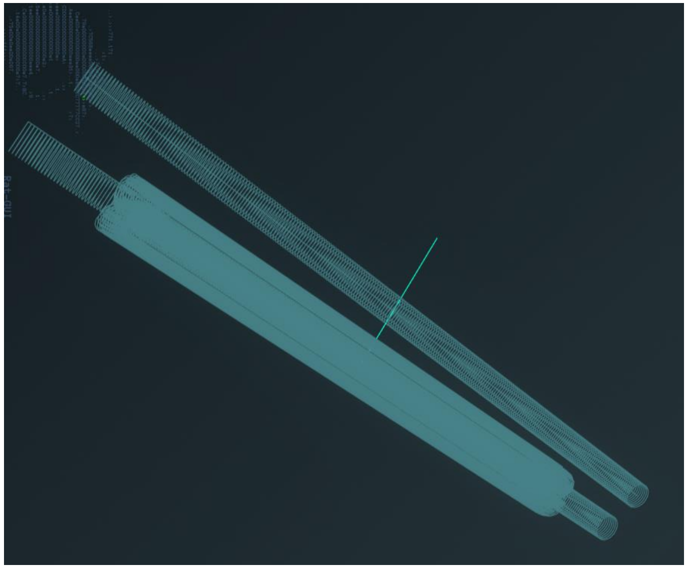
Harmonics along adjacent beam axis (Ref Rad=10mm)

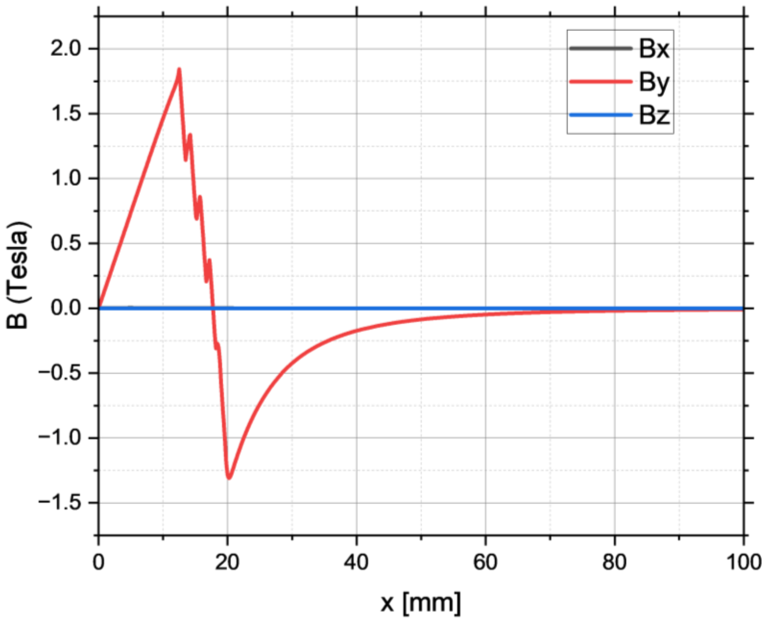




Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	1.02e-04	17.42		B1	5.86e-02	10000.00	
A2	5.86e-05	10.00		B2	4.25e-02	7239.39	
A3	2.92e-05	4.97		B3	2.04e-02	3487.18	
A4	1.72e-05	2.94		B4	8.25e-03	1406.84	
A5	1.28e-05	2.19		B5	3.03e-03	516.63	
A6	9.68e-06	1.65		B6	1.03e-03	175.15	

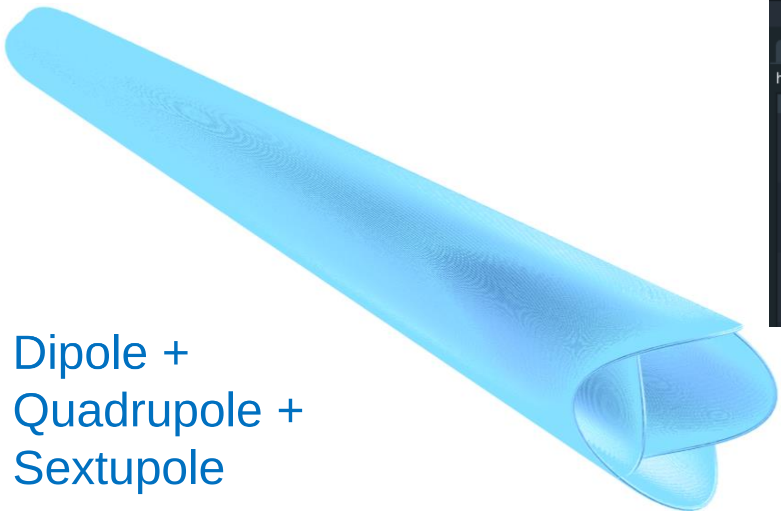


RAT-GUI model

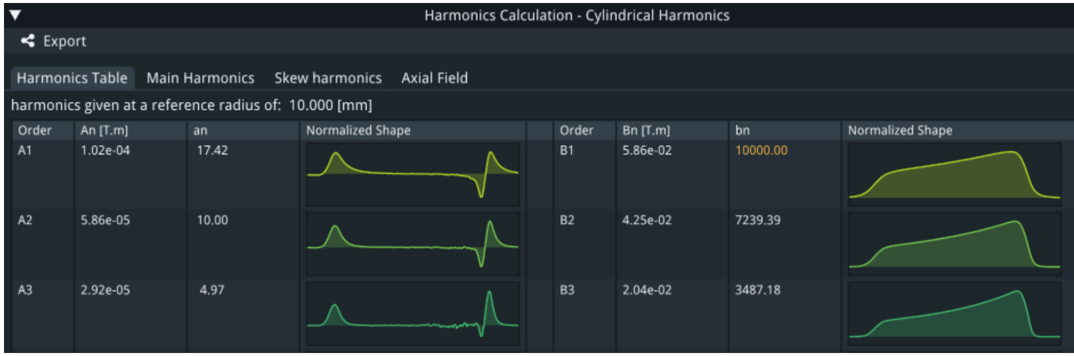


Along transverse

Design of concept compensator magnet (work in progress)



Dipole +
Quadrupole +
Sextupole



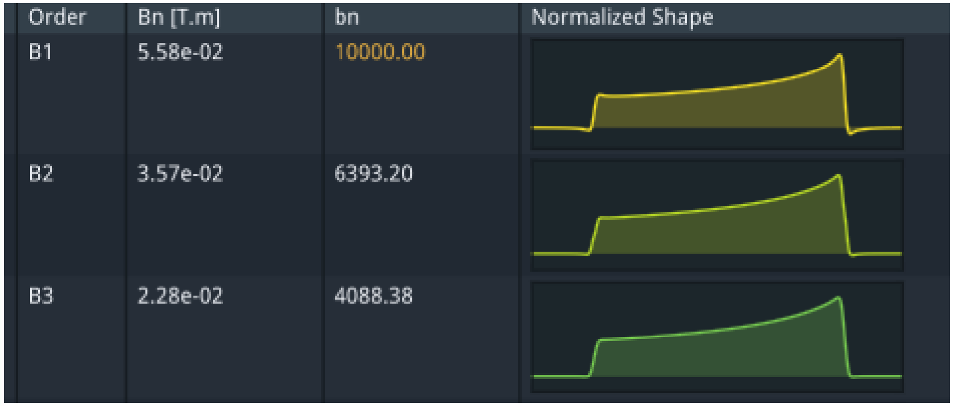
Harmonics Calculation - Cylindrical Harmonics

Export

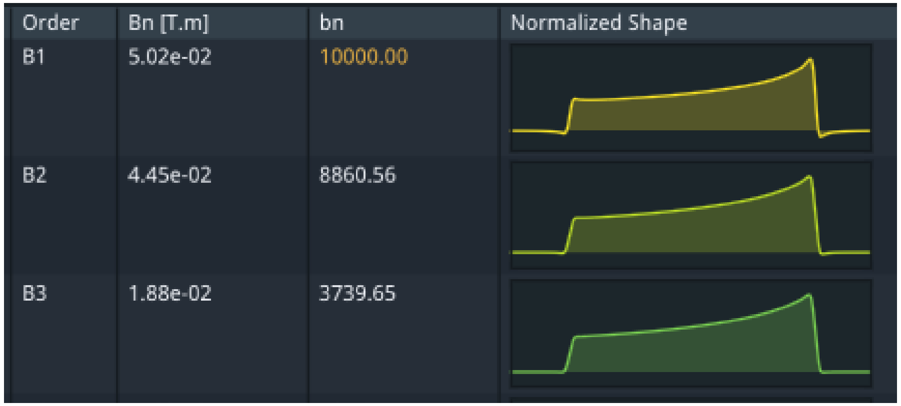
Harmonics Table | Main Harmonics | Skew harmonics | Axial Field

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

Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	1.02e-04	17.42		B1	5.86e-02	10000.00	
A2	5.86e-05	10.00		B2	4.25e-02	7239.39	
A3	2.92e-05	4.97		B3	2.04e-02	3487.18	



Order	Bn [T.m]	bn	Normalized Shape
B1	5.58e-02	10000.00	
B2	3.57e-02	6393.20	
B3	2.28e-02	4088.38	



Order	Bn [T.m]	bn	Normalized Shape
B1	5.02e-02	10000.00	
B2	4.45e-02	8860.56	
B3	1.88e-02	3739.65	

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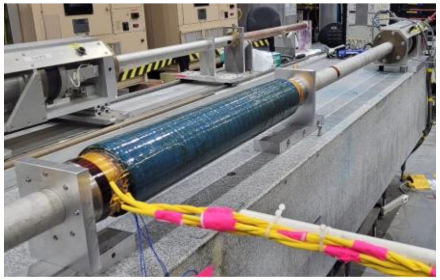
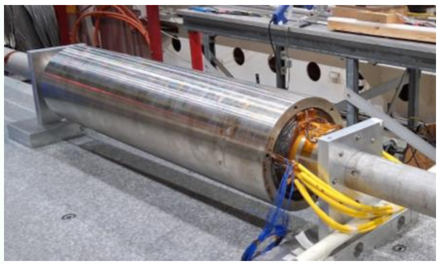
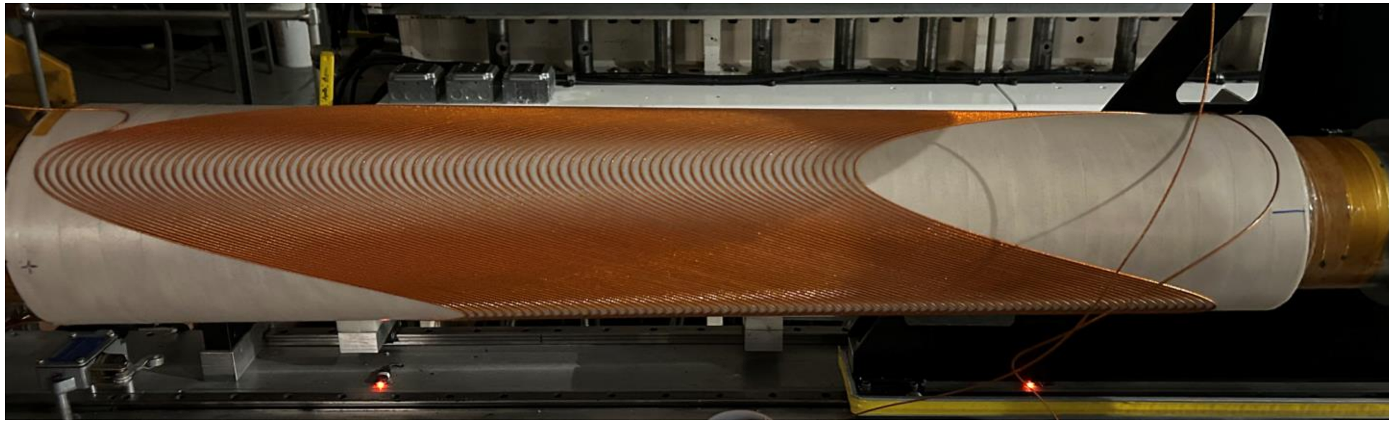
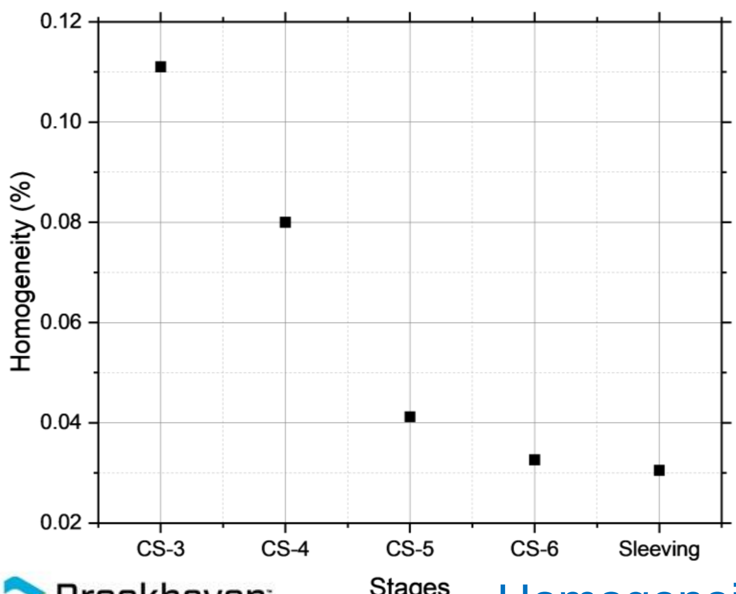
Recent tapered Double Helical Magnet for EIC



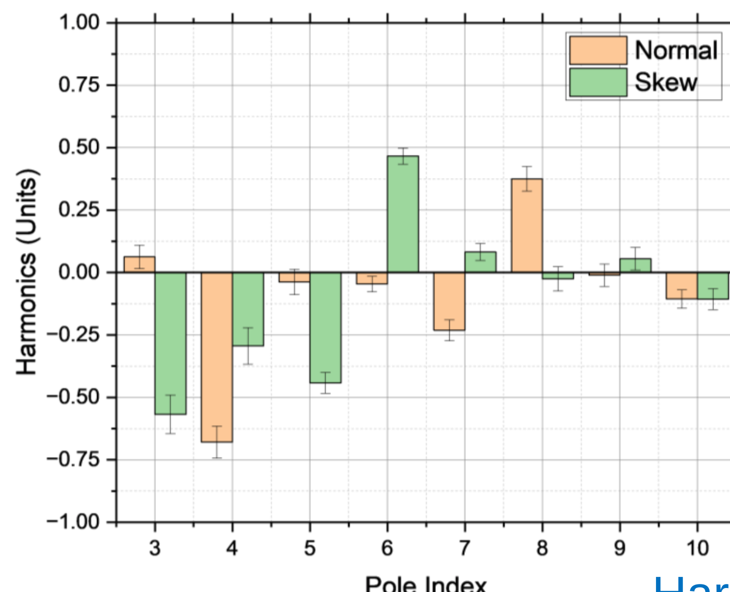




1. Length : 0.8 meter
2. Number of layers : 12 (6 coil sets)
3. Gradient : ~90 T/m



Homogeneity



Harmonics

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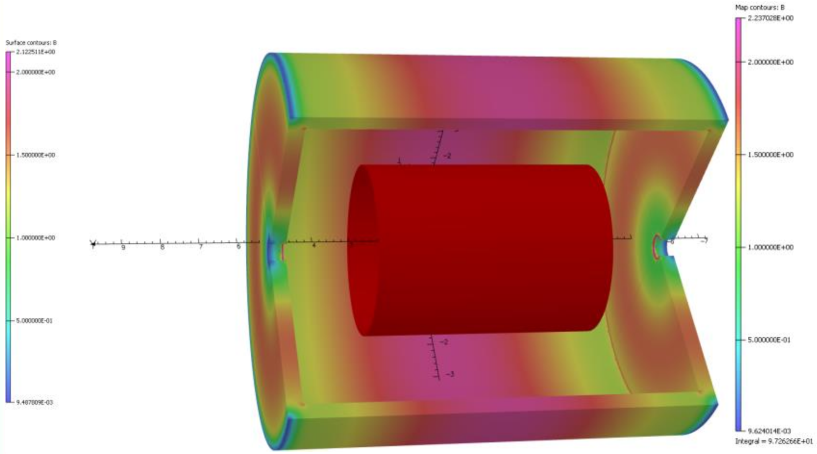
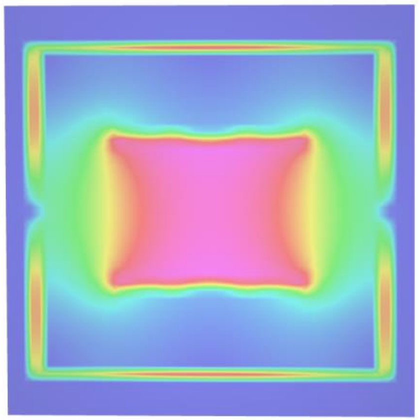
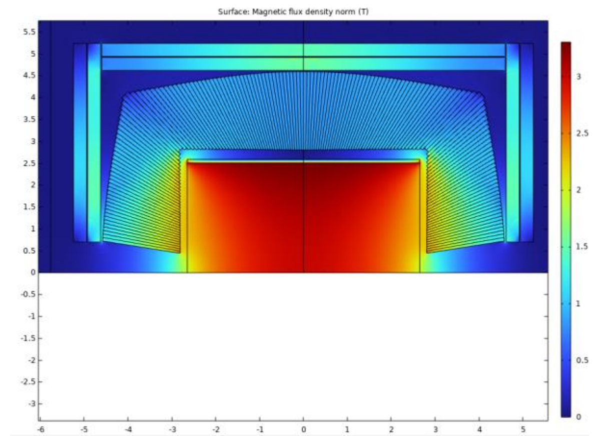
Physics Design : EIC project Magnet Group

Vikas Teotia, FCC week 2025, Vienna

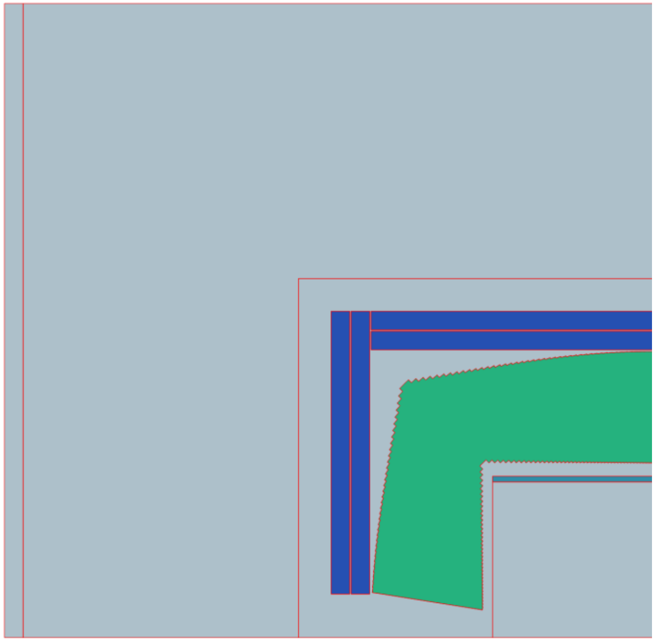
Screening Solenoid design







Detector magnet field profile (COMSOL, Samuele)



Detector magnet field profile (Opera, BNL)

- Design of Screening solenoid and detector solenoid goes together.
- Collaboration with detector group established for detector magnet design sharing.
- To establish design philosophy, approach is to follow most mature and most likely detector concept.
- Each IR will need its own screening solenoid

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Interaction with CERN/PSI/INFN colleagues

Having active engagement for

- Final focusing magnets (Mike), and
- Screening/Compensating solenoid magnet design (Matthias, Samuele, Lucio)
- Crab waist Sextupole

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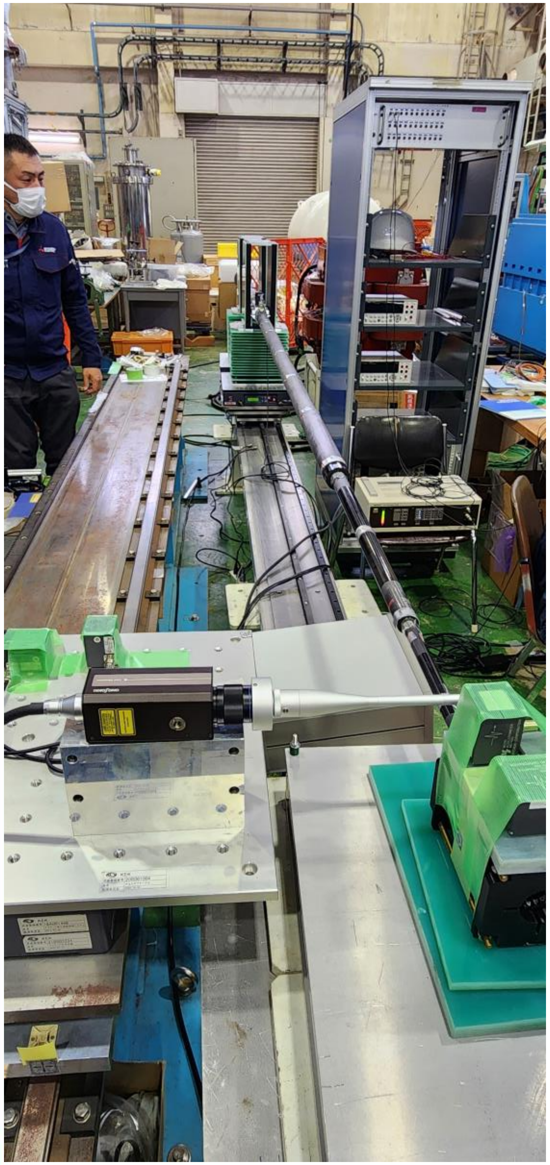
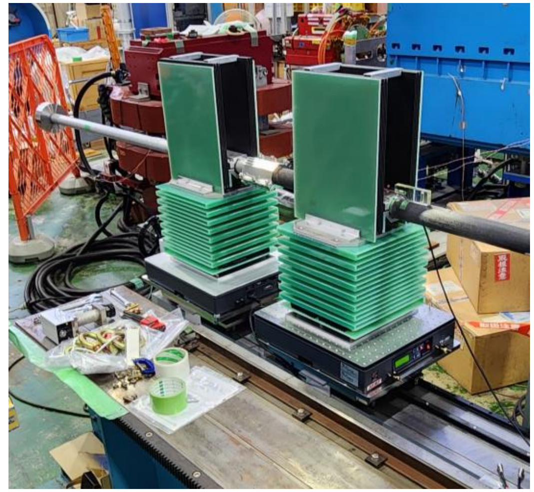
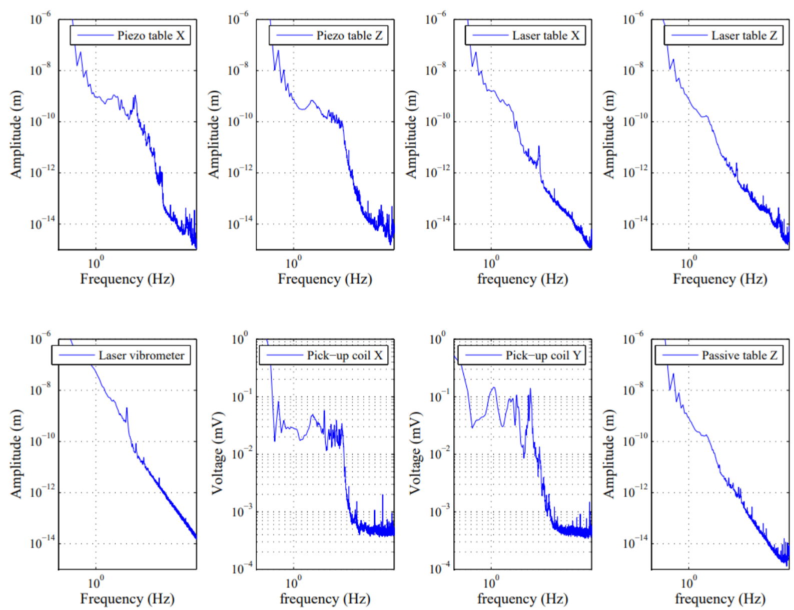
Nano-meter level Magnetic Field vibration measurement (BNL, KEK)







Measurement results

Pick-up coil and Quadrupole

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Summary

1. BNL is having state of the art facilities for design, production, testing and measurement of Superconducting Magnets including direct wind magnets.

2. A tapered CCT test magnet is developed for EIC. CCT magnets are choice for correctors in FCCee.

3. Status of FCC-ee IR MDI work packages at BNL

SN	Packages	Status
1.	Corrector Magnets	• EM Design platform (FY25) • Measurement of cross talk in existing Quadrupole (preparations underway) (FY25) • Design of compensator magnet for annulling the cross talk above (Planned) (FY25) • Fabrication of compensator magnet (Planned) (FY26) • Testing of the compensator magnet (FY26-FY27)
2.	Design of screening/ compensating solenoid magnet	• Preliminary simulations, gathering latest information
3.	Magnetic Field vibration measurement	• Basic hardware for preliminary measurements exists • Proposed for FY26

4. As separate exercise, we are exploring possibilities of HTS based Direct wind magnets

Thanks for your kind attention!