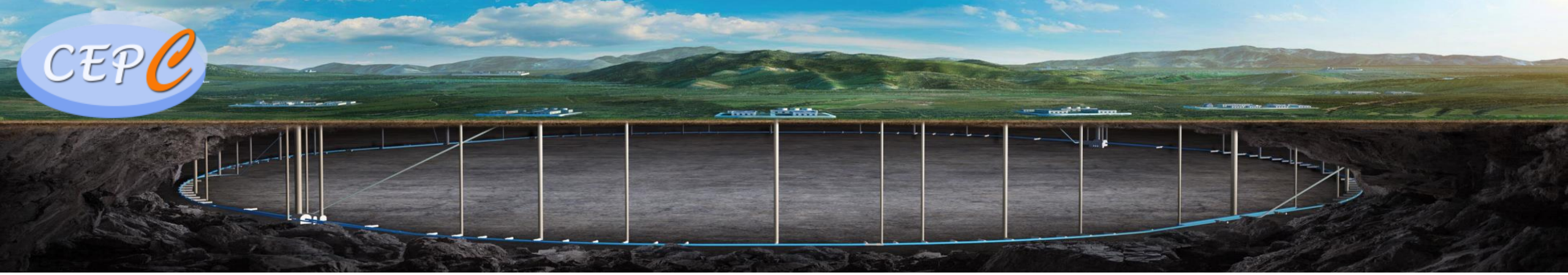

Development of the CEPC Booster Prototype Dipole Magnets and the Automated Magnet Production Line

Zhihui Mu

on behalf of CEPC Booster magnet group

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Content

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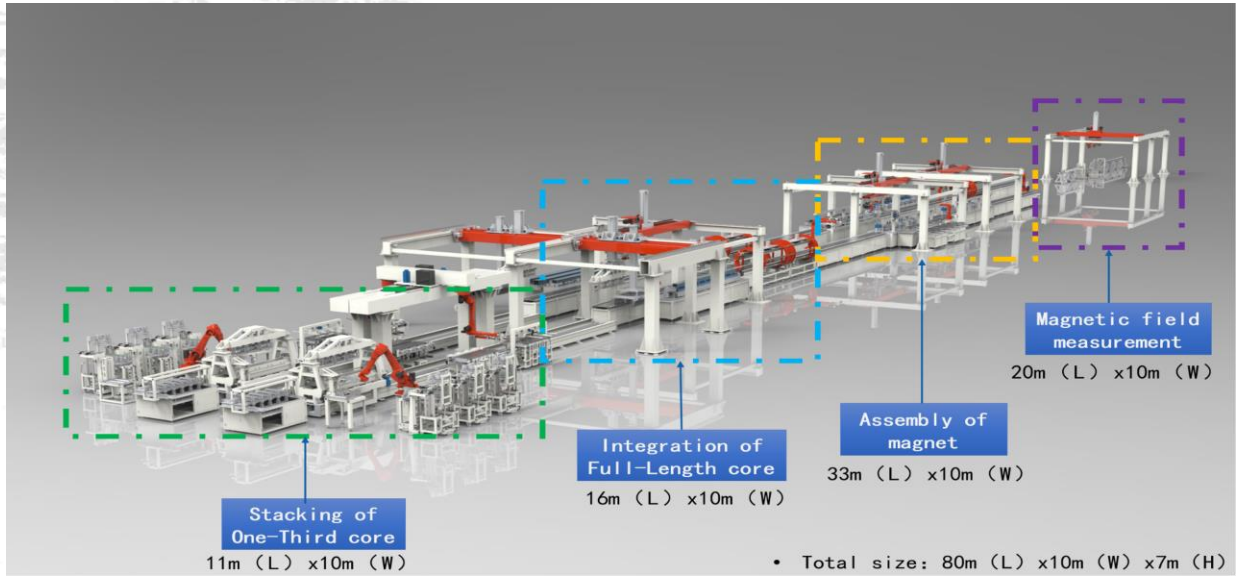
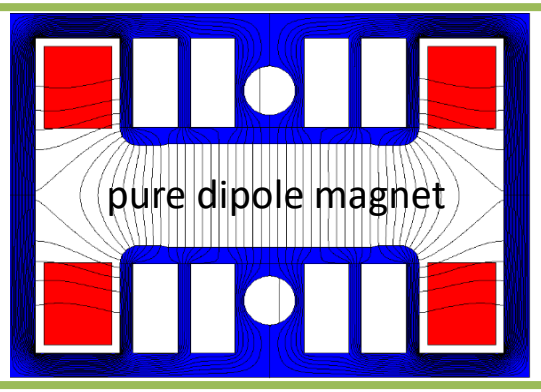
- **Introduction**
- **Prototype Dipole Magnet**
  - Optimizations
  - Manufacture
  - Measurement Results
  - Work Plan
- **Automated Production Line**
  - Four Workstations
  - Capability
  - Optimimations
  - Time schedule
- **Summary**

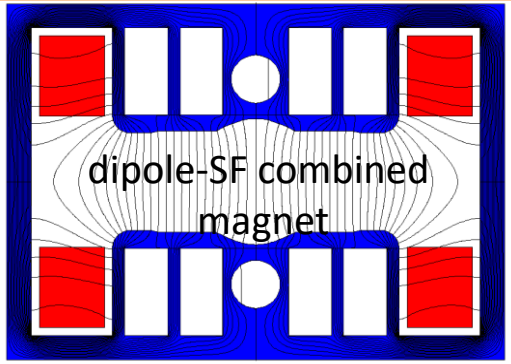


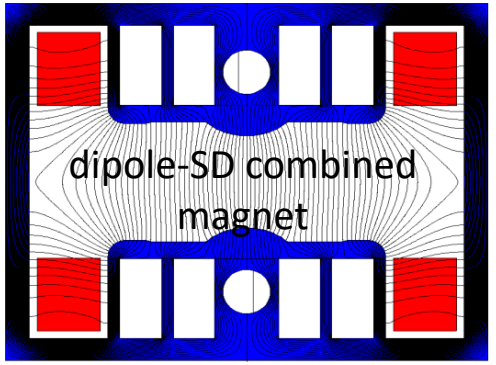
Overview of Magnets in CEPC Booster

- The CEPC Booster has 15000 dipole magnets with length of 4.7m, which is expected to be produced in 5 years. Increasing production efficiency and reducing manufacturing costs are two key targets.
- The field of Booster magnets will change from 95 G to 376 G with the beam energy during the acceleration of particle beams. In order to reduce eddy current, the cores of all magnets will be produced by lamination not by solid iron.

✓ The prototype manufacture was successfully completed in 2022







The Cross-section of the Dipole Magnet

- Booster dipole magnets are grouped into three families.
- Compared to pure dipole magnets, dipole-sextupole combined magnets require higher mechanical precision (especially in terms of lateral misalignment accuracy) and are more challenging to manufacture. Therefore, a prototype combined magnet was produced manually to validate rationality of the design and accumulate experience for automated production line.

Prototype dipole-sextupole combined magnets for the CEPC Booster

Issues Identified on the Prototype Pure Dipole Magnet

Long core fabrication (4.7 m): difficult

- **Stacking precision**: Overall lamination stacking resulted in **cumulative errors.**
- **Tie rod installation**: Installing full-length tie rods was difficult and required more than 10 m of space.
- **Draw bars**: Both manufacturing and installation were problematic.

Challenges in on-site operations

Lamination material and manufacturing costs: higher than expected

Ferromagnetic laminations: 0.5 mm silicon steel

Non-ferromagnetic : 1 mm pure aluminum

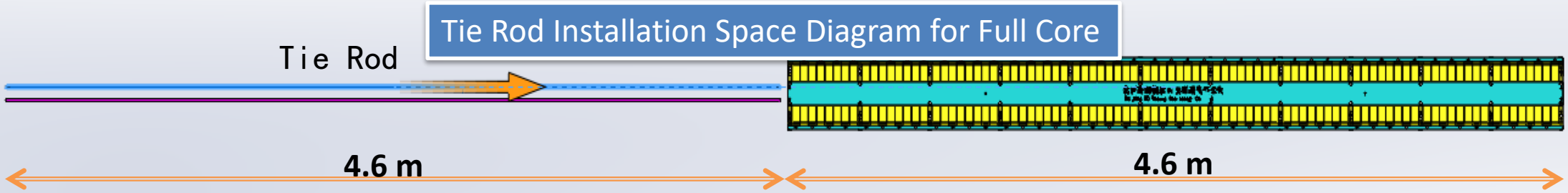
Approximately 12,000 laminations are required per magnet.

Coil joints located inside the iron core : suffered from severe overheating

Coil insulation: performance was poor.

All the aforementioned issues have been addressed in the design and manufacturing of the dipole-sextupole combined magnet prototype.

Tie Rod Installation Space Diagram for Full Core

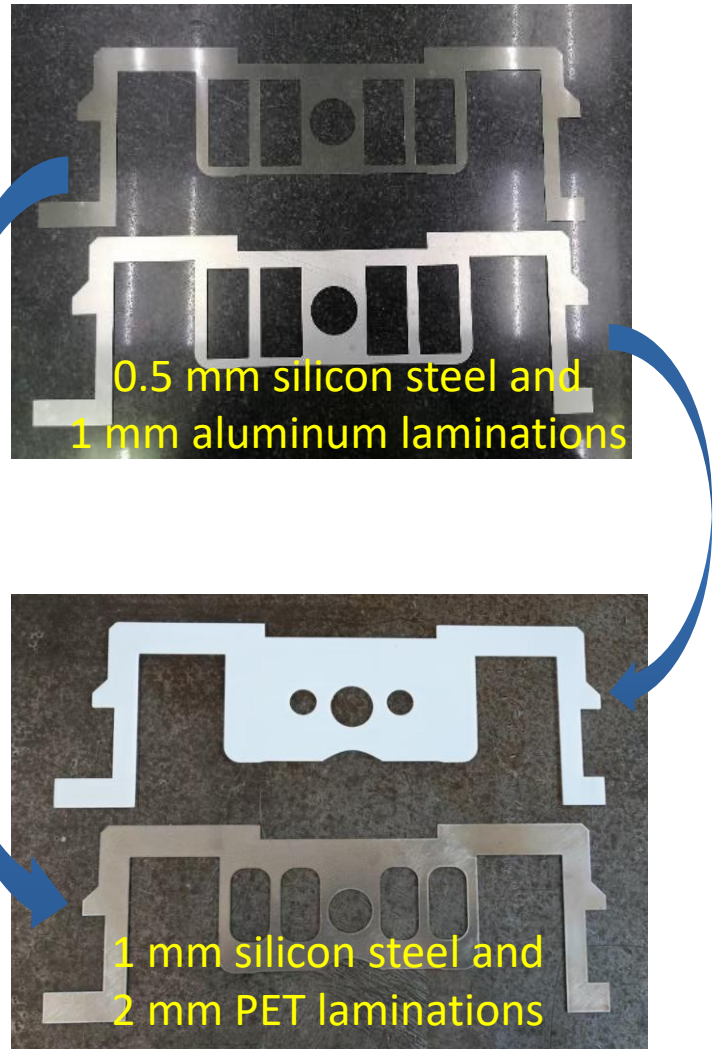


Optimizations in Material selection

Due to the very low magnetic field, the yoke is composed of ferromagnetic and non-ferromagnetic laminations with a ratio of 2:1.

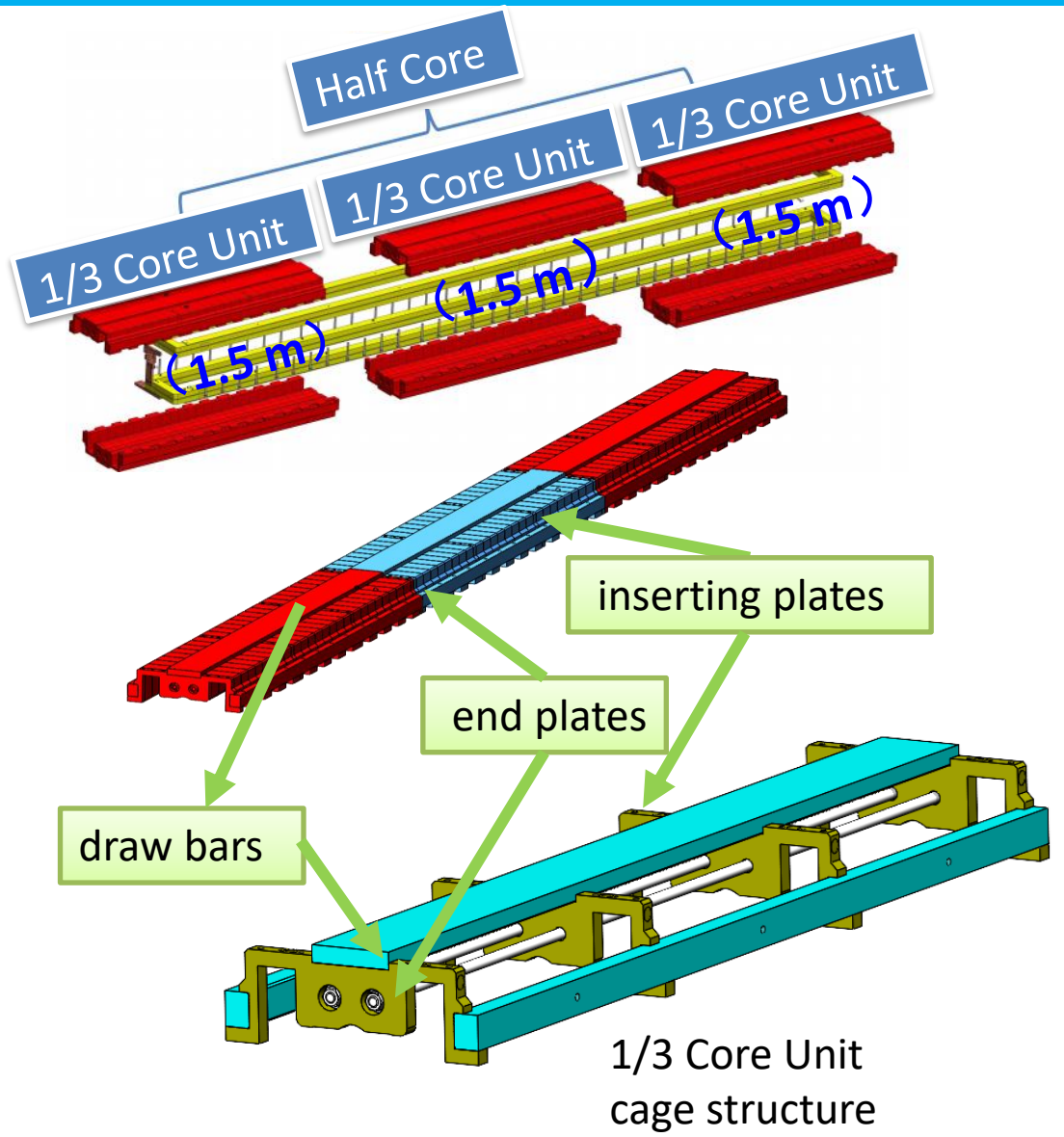
To further reduce costs, we have implemented the following improvements：

- ✓ **For slower field variations, 1 mm thick steel sheets were proposed and validated through prototype testing, confirming they meet field requirements.**
- ✓ **By optimizing the PET material formulation, it now meets manufacturing requirements and performs reliably under high radiation conditions, making it a suitable filler material. It can also effectively reduce magnet weight.**
- ➢ **One magnet needs only 6,000 laminations, halving the punching cost; moreover, in mass production it cuts the fill-material expense by 40 %.**



Optimizations in Core Structure Design

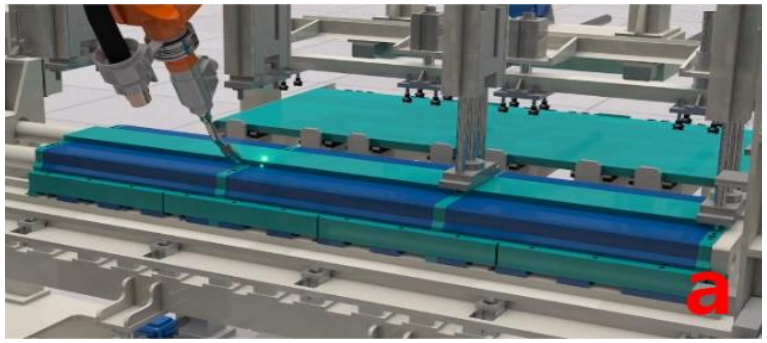
- ✓ The magnet has a two-in-one H-type structure, with a length is 4608mm and a gap is 63mm.
- ✓ To reduce machining difficulty and facilitate automation, the long core was splited into three shorter core units. As a result, the actual length of the stacked cores is shortened from 4608 mm to 1536 mm (1/3 Core Unit).
- ✓ Since PET sheets cannot withstand high temperatures and are unsuitable for traditional core welding processes, it is proposed to use DT4 plates and carbon steel surrounding draw bars to weld the core into a "cage structure", which will restrain the laminations.
- ✓ After the one-third length cores are finished, they will be assembled and welded into a full length core.

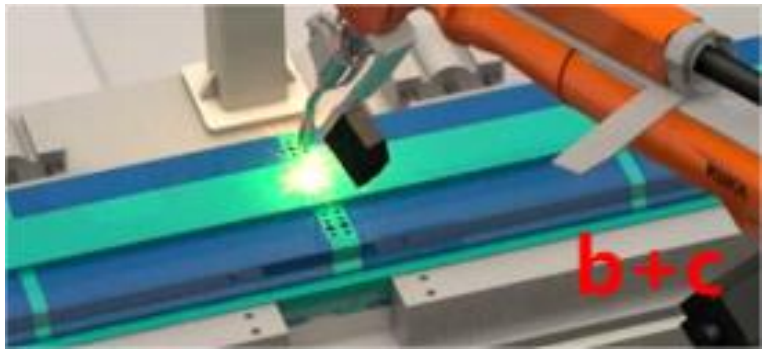


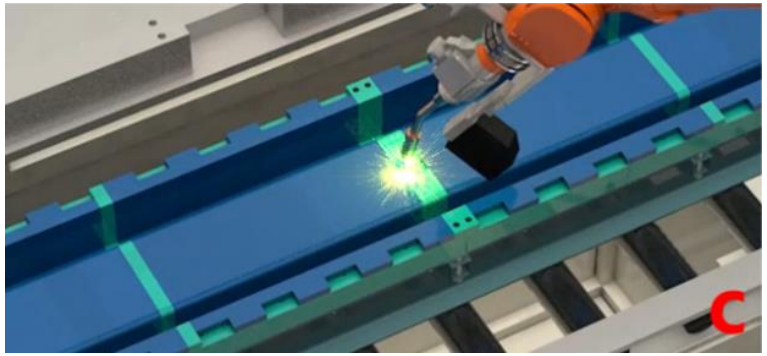
1/3 Core Unit
cage structure

Optimizations in Core Structure Design

- Magnet cores are assembled via welding. It is critical to ensure that the welding heat does not affect the nearby plastic laminations.
- In the new magnet production process design, welding is strictly limited to:
  a. Joints between DT4 inserting/end plates and the surrounding draw bars
  b. Joints between the surrounding draw bars themselves
  c. Joints between DT4 end plates
- ✓ All these weld locations will ensure a minimum arc distance exceeding 10 mm from the plastic laminations.



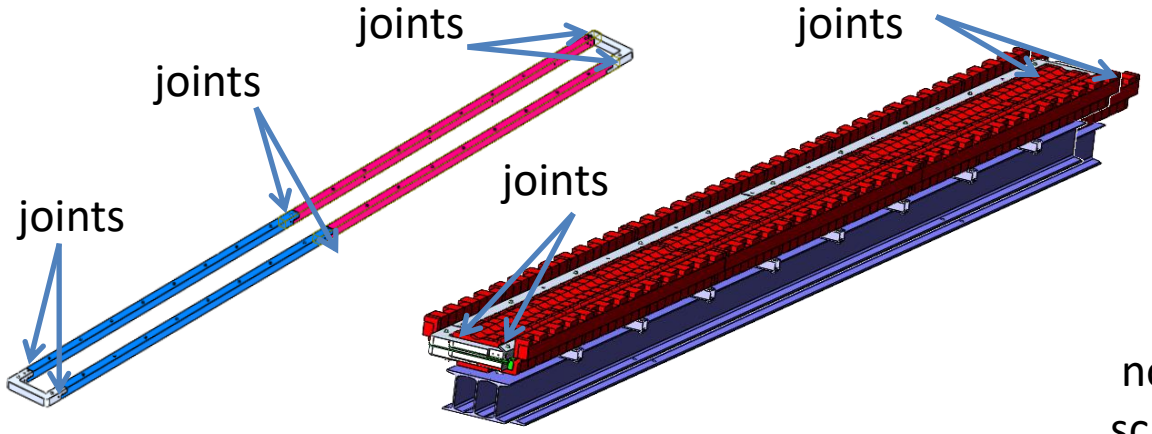




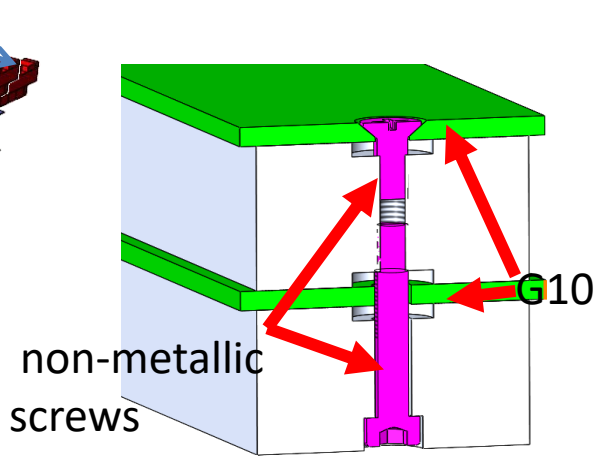
Optimizations in Coil Structure Design

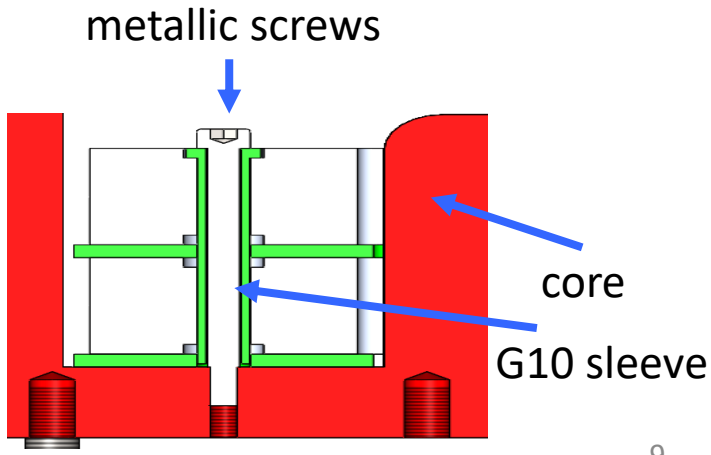
As previously noted in the presentation, the original spliced coil suffered from severe internal overheating within the iron core.In the new prototype, the following key design changes:

- **Coil Improvement:The coil is now fabricated from a custom-extruded long aluminum profile, which relocates all lap joints to both ends of the magnet. Contact surfaces are silver-plated to minimize joint resistance.**
- **Insulation Scheme:Unlike the traditional vacuum epoxy casting process, the insulation between turns as well as between the coil and the iron core is simply achieved using G10 plates. The two-turn coil and the G10 plates are assembled into an integrated structure using non-metallic screws.**
  G10 sleeves are inserted into all mounting screw holes to ensure reliable coil-to-core isolation.
  These modifications allow the design to achieve a withstand voltage greater than 1000V.



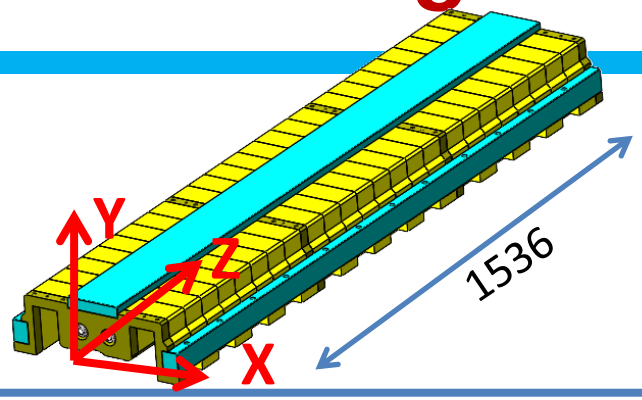
Original Design vs. Optimized Design





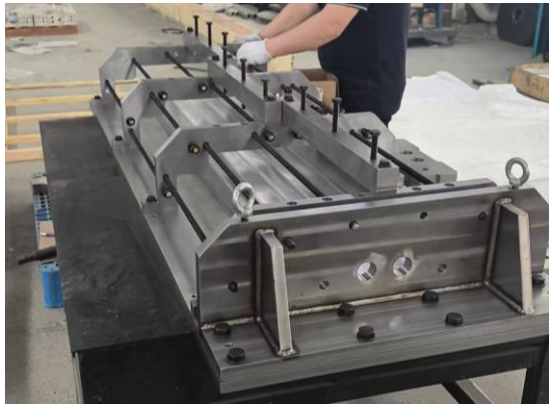
Manufacture of the Prototype Combined Magnets

☐ 1/3 Unit of the Half-Core

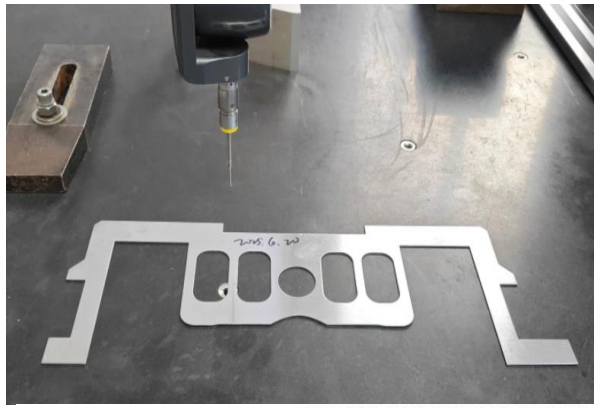


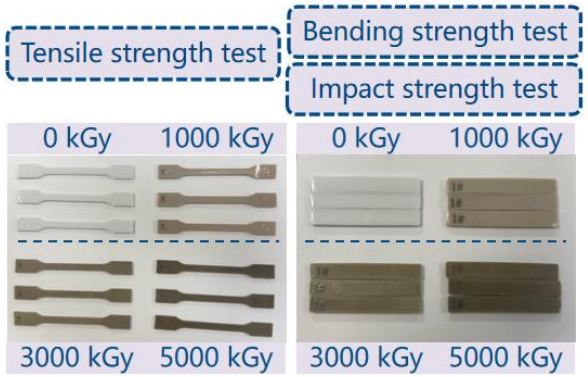
The manufacturing error obtained through actual measurement：
Length Tolerance = ±0.50 mm， 1/2 Gap Tolerance = ±0.03 mm，
Y straightness along Z = 0.05 mm， X straightness along Z =0.1 mm

Tooling &Parts Preparation

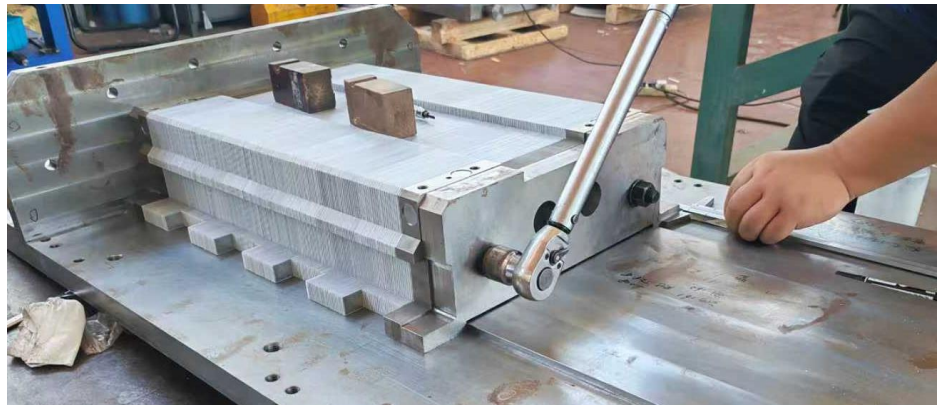


Dimensional &Performance Inspection





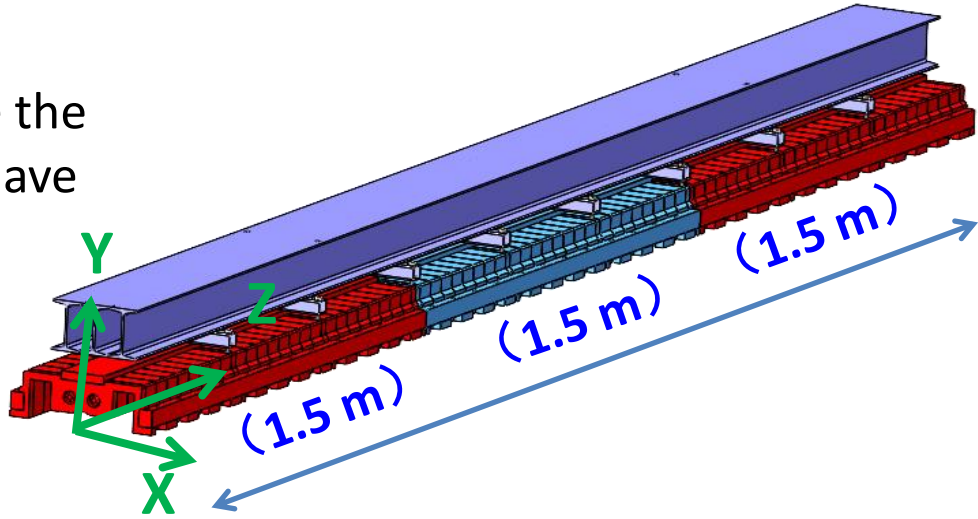
Stacking & 1/3 Unit Final Assembly



Manufacture of the Prototype Combined Magnets

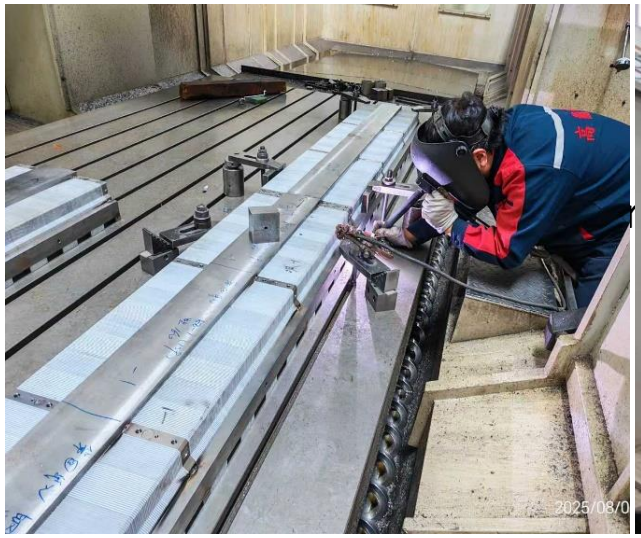
☐ Half-Core

- After welding, the half-core is fixed to the hanger/holder to enhance the overall structural strength and to correct any deformation that may have occurred in the Y-direction.
- The manufacturing error obtained through actual measurement：
  Upper-core /Lower-core length error= -0.5 mm, 0.1 mm
  Y straightness along Z = 0.1 mm
  X straightness along Z = 0.3 mm



Alignment Before Welding

Core Assembly Welding



Hanger/Holder Installation

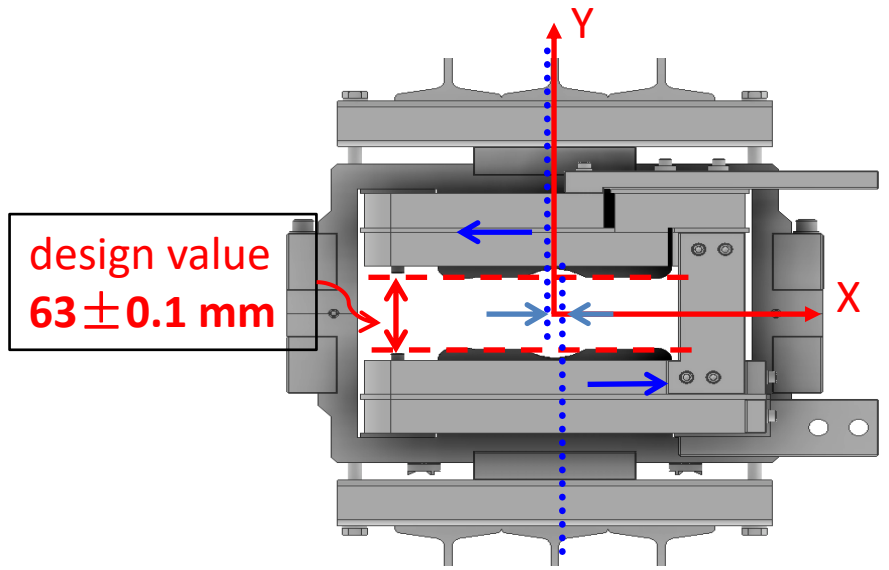
Dimensional Inspection

Manufacture of the Prototype Combined Magnets

☐ Entire Magnet

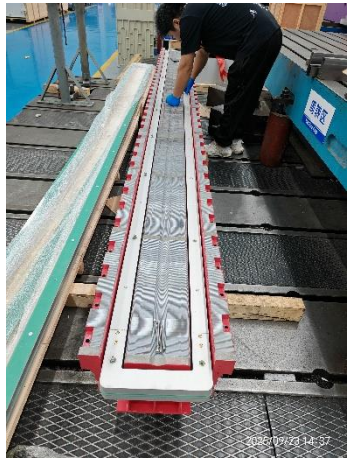
Completed in October 2025

- The upper and lower iron cores are assembled using 36 sets of bolts(72 bolts) , which helps to reduce the variation in gap.
- The entire manufacture tolerance, which is the combined effect of machining error, assembly error, welding deformation, is as follows:
  Length error= ± 1 mm， Gap(Y) error= -0.07 mm，
  X Misalignment error ＜0.3 mm
  Y straightness along Z=0.2 mm， X straightness along Z=0.6 mm



Upper-and-Lower-Core Pre-assembly

Coil-and-Core Assembly



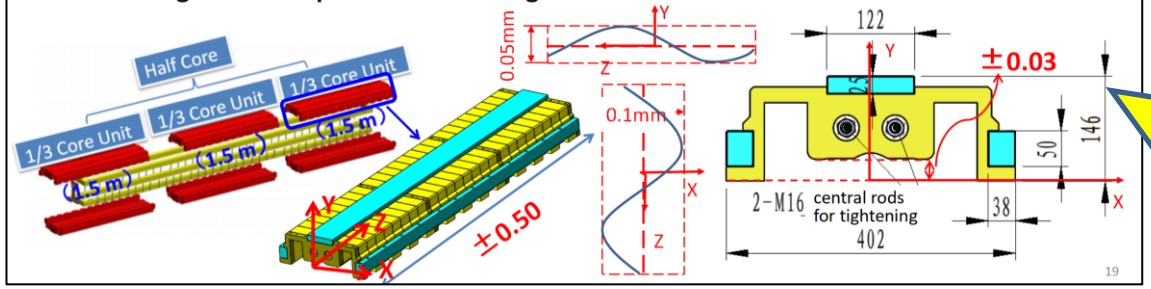
Magnet Assembly

Insulation Performance Test

Prototype Mechanical Dimensional Results

◆ May 29th,2025, Beijing, Mini-Review for CEPC Booster Combined Magnets--Tolerance analysis

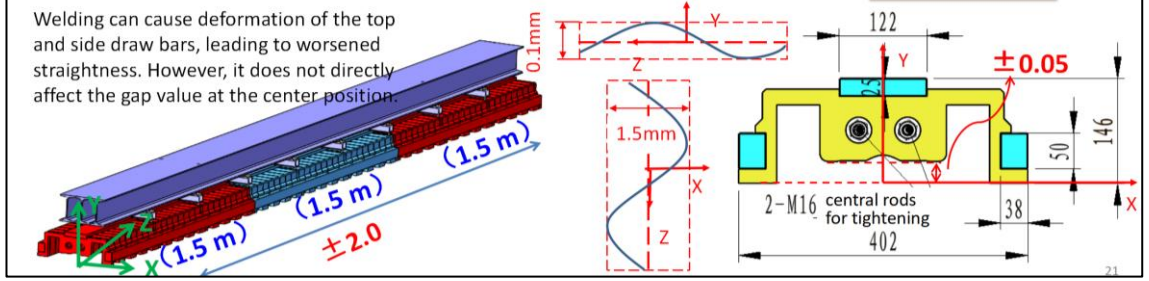
- We have manufactured many 1.5 meter long magnets in a single stack.We can use these experiences to evaluate the production errors of one-third of the half-core:
  Length Tolerance=±0.50 mm， 1/2 Gap Tolerance=±0.03 mm，
  Y straightness along Z=0.05 mm， X straightness along Z=0.3 mm
- We lacked the experience of assembling and welding together three short ones（1.5 m）.
- Therefore, we developed a special welding positioning platform for the process of combining three components into a single half iron core.



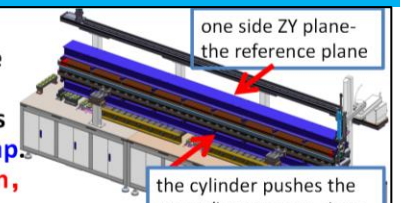
- The welding deformation caused by the three-stage integration is difficult to predict, and there is no use of physical experiments to get the actual data.
- After welding, the half-core is fixed to the hanger/holder to enhance the overall structural strength and to correct any deformation that may have occurred in the Y-direction.
- After comprehensive analysis, the estimated tolerance of the half-core is
  Length Tolerance=±2.0 mm， 1/2 Gap Tolerance=±0.05 mm，
  Y straightness along z=0.1 mm， X straightness along z=1.5 mm

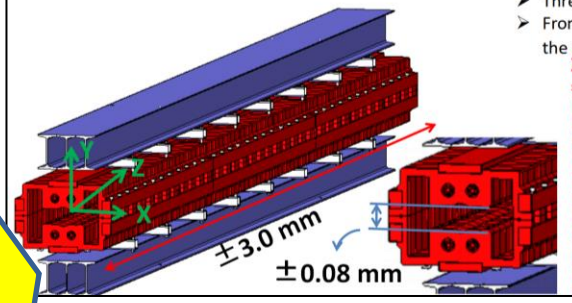
more difficult to control

Welding can cause deformation of the top and side draw bars, leading to worsened straightness. However, it does not directly affect the gap value at the center position.

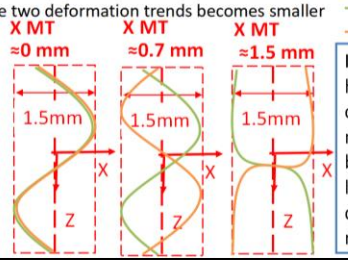


- Taking one side ZY plane as the reference plane, the upper and lower cores are positioned close to the reference plane with the help of cylinders to ensure the straightness.
- The upper and lower iron cores are assembled using 36 sets of bolts(72 bolts) , which helps to reduce the variation in gap.
- Length Tolerance=±3.0 mm， Gap(Y) Tolerance=±0.08 mm，
  X Misalignment Tolerance MAX=1.5 mm





- Three typical combinations of deformation
- From left to right, the overlapping range of the two deformation trends becomes smaller



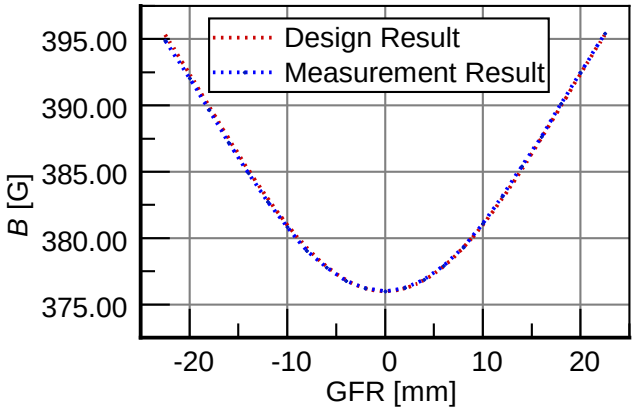
If the straightness of the half-core is 1.5 mm, the cumulative X misalignment tolerance between upper and lower cores along the Z direction after assembly ranges from 0 to 1.5 mm.

Through actual measurement, we obtained manufacturing errors at each stage.: meet or exceed all target tolerances

Components	Parameter	Analysis Tolerance	Prototype Quality	Comparison
1/3 Unit of the Half-Core	Length	±0.5	±0.5	Equal
	1/2 Gap	±0.03	±0.03	Equal
	X-Straightness	0.3	0.1	Better
Half-Core	Length	±2.0	±0.5	Better
	1/2 Gap	±0.05	±0.05	Equal
	X-Straightness	1.5	0.3	Better
Entire Magnet	Length	±3	±1	Better
	Gap	±0.08	-0.07~ -0.06	Better
	X-Straightness	1.5	1.1	Better
	X-Misalignment	1.5	0.3	Better

Prototype Magnetic Field Quality Measurement Results

- The measured center-field distribution of the magnet agrees well with the simulation. For the same dipole field, the measured sextupole component is slightly lower, reduced by about 1.7 %.
- The integral field distribution is essentially identical to the center-field distribution; the effective magnetic length is 4713 mm for the dipole and 4691 mm for the sextupole.



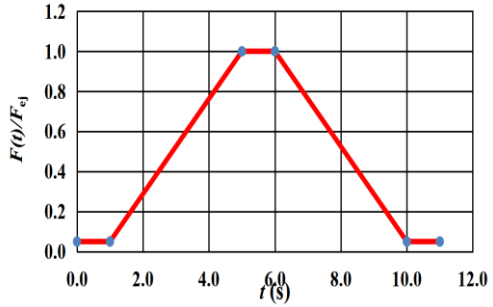
	Design Requirements	Simulation Results	Prototype Magnetic Field	Error
B0[Gs]	376.00	376.00	376.00	/
S[Gs/mm^2]	0.106925	0.106928	0.105114	1.7% ↓

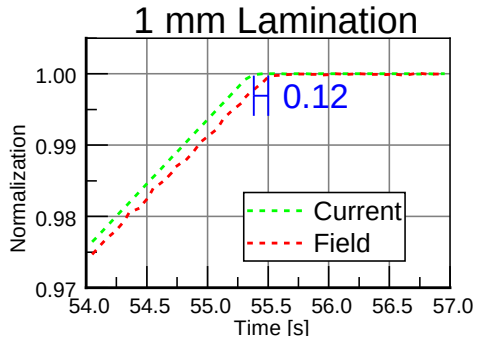
Possible causes of the sextupole drop:

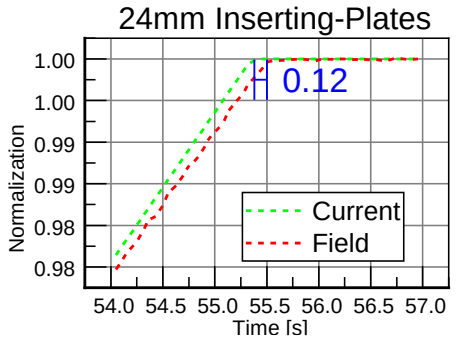
① higher aperture sensitivity
② transverse misalignment
③ model vs. actual lamination B–H mismatch

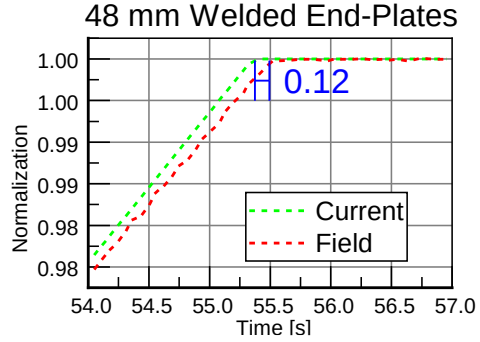
The sextupole field can be corrected using independent sextupole magnets.

- Owing to the Booster magnets' slow field variation, the magnetic-field lag was measured at the 24 mm spacer, the 48 mm welded end plate and the 1 mm lamination while the ramping speed was kept constant. In every case the lag between field and current was essentially identical, approximately 0.12 s.





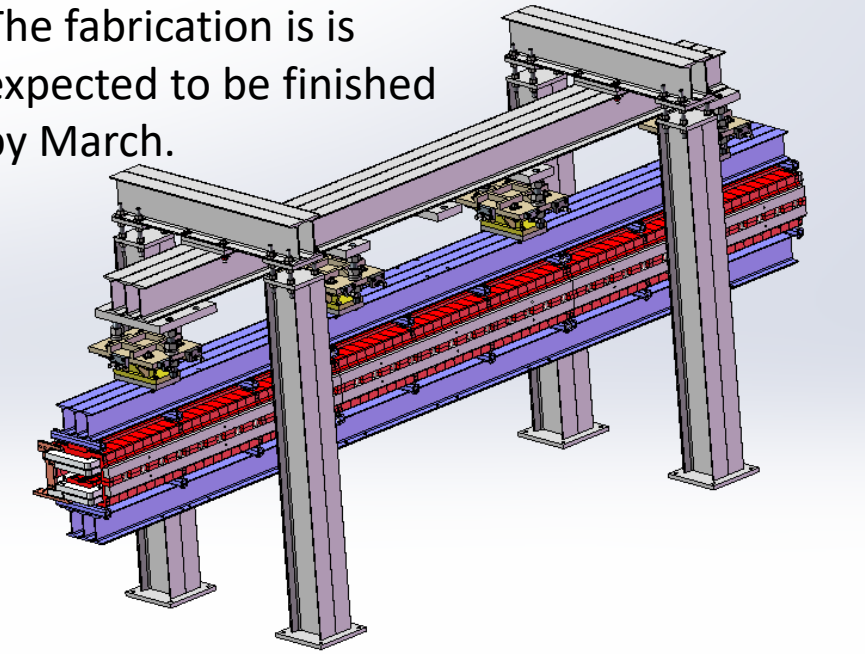


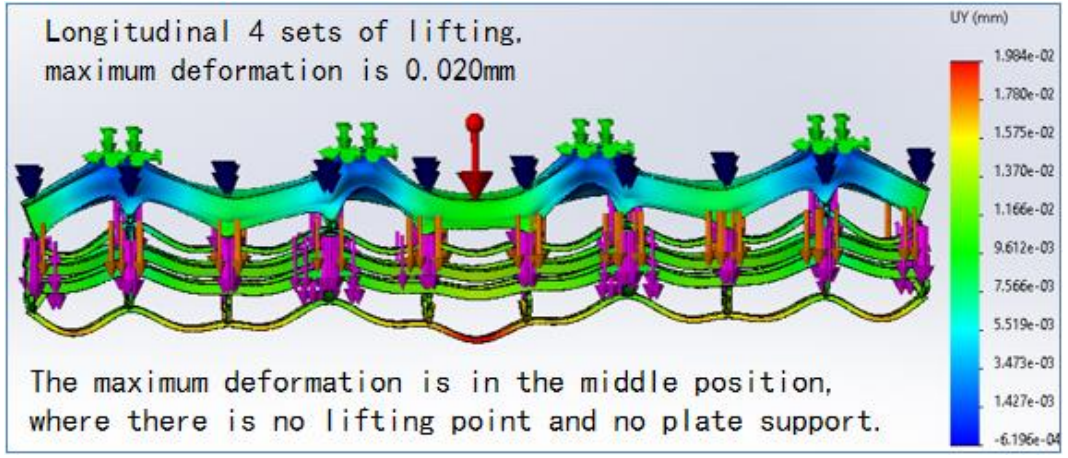


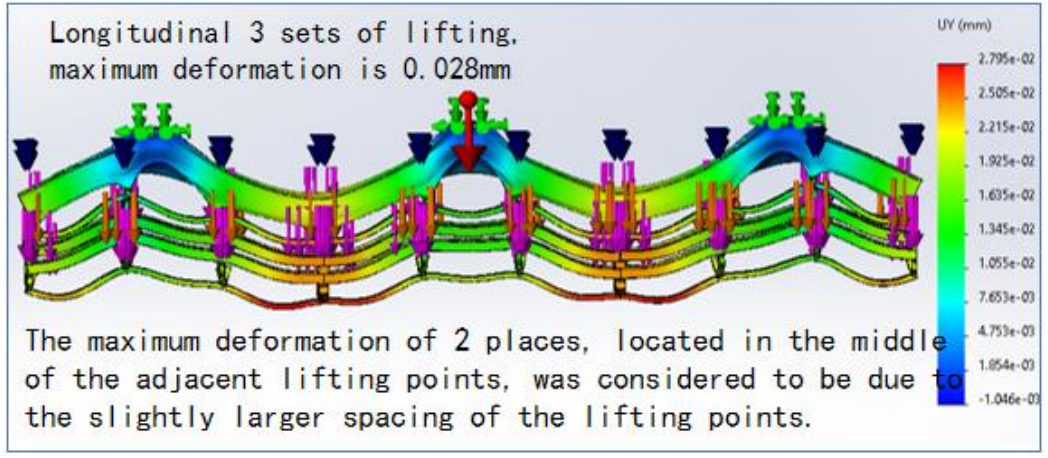
Work Plan for the Prototype Magnet

- **The prototype uses PET laminations that reduce rigidity. ?**
- **The core is encircled by inserting plates and end plates, central and surrounding draw bars to form a stable support frame structure.**
- **We performed coupled simulations incorporating both gravity and magnetic forces to evaluate magnet support frame structure deformation.For the 4-point and 3-point lifting configurations, the maximum deformations are 20 μm and 28 μm, respectively. Correspondingly, the magnetic gap changes are 10 μm and 15 μm.**
- **The next step is to fabricate a dedicated lifting frame, hoist the magnet with four-point and three-point slings while monitoring mechanical deformation in real time, and measure the magnetic field under load to quantify any impact on performance.**

The fabrication is is expected to be finished by March.







Automated Production Line

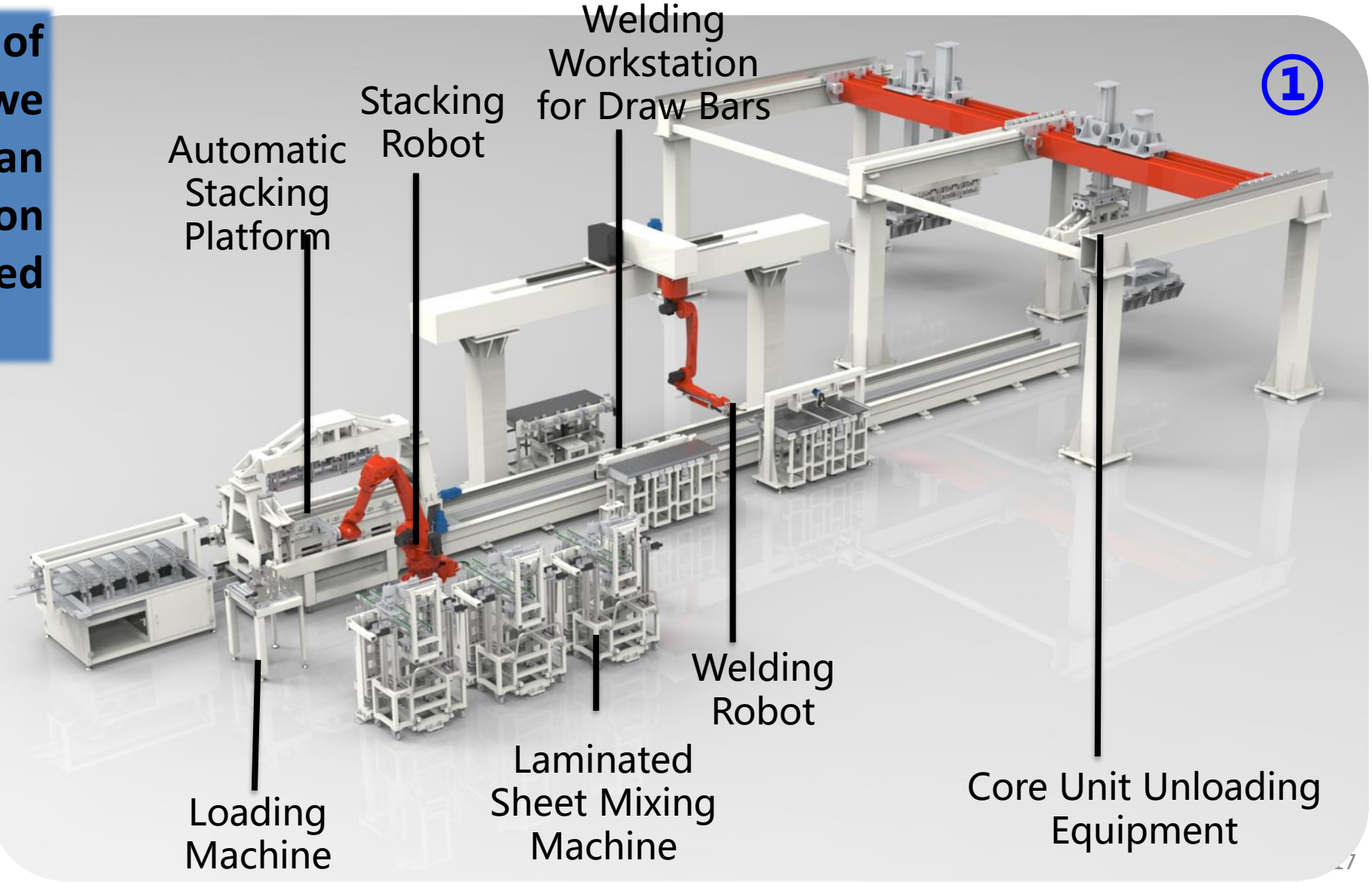
for CEPC Booster dipole magnets

Workstations of the Automated Production Line

To meet the needs of mass production, we are developing an automatic production line, which is composed of four main sections.

station 1

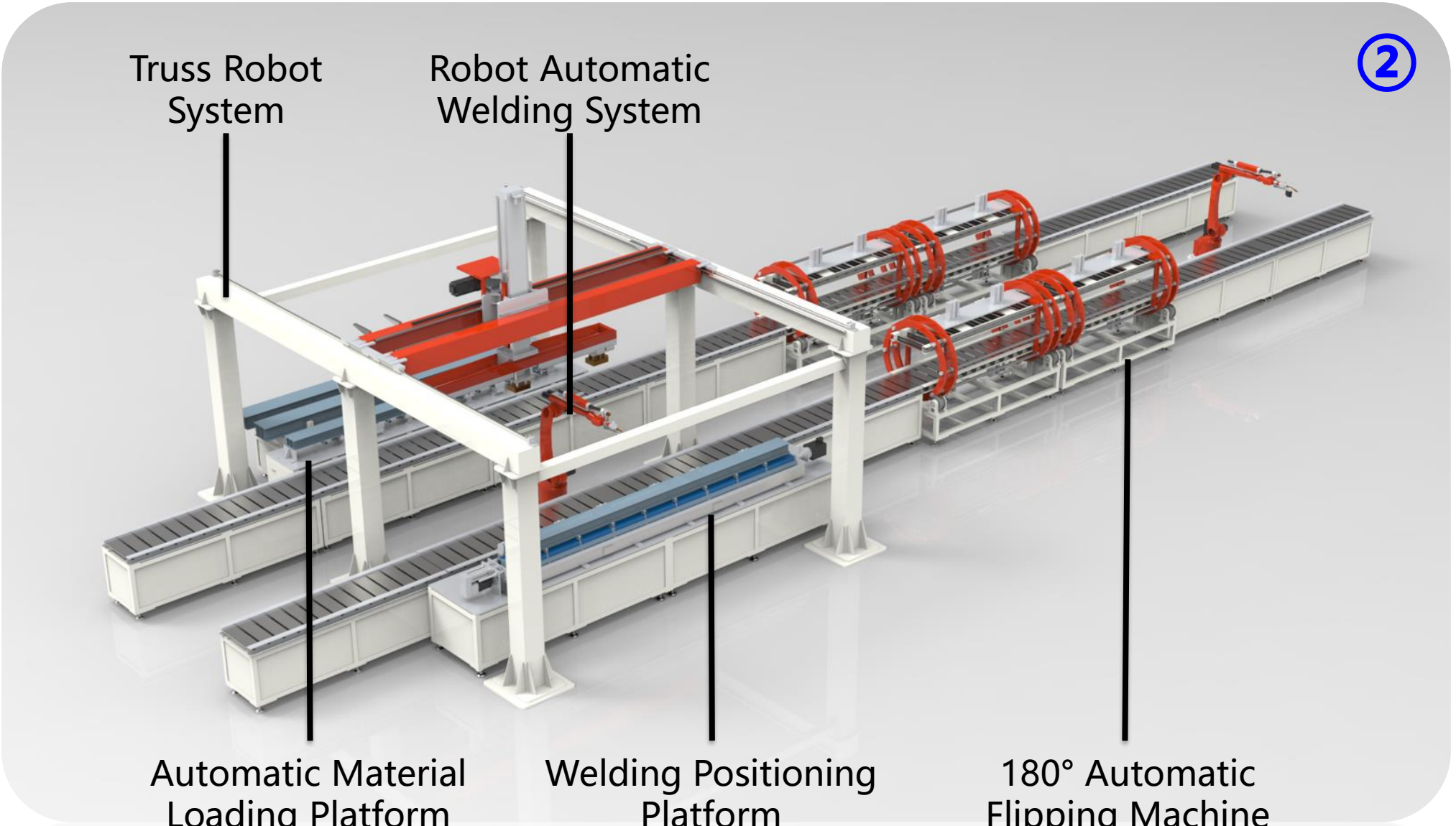
Automatic Stacking of one-third length core



Workstations of the Automated production line

station 2

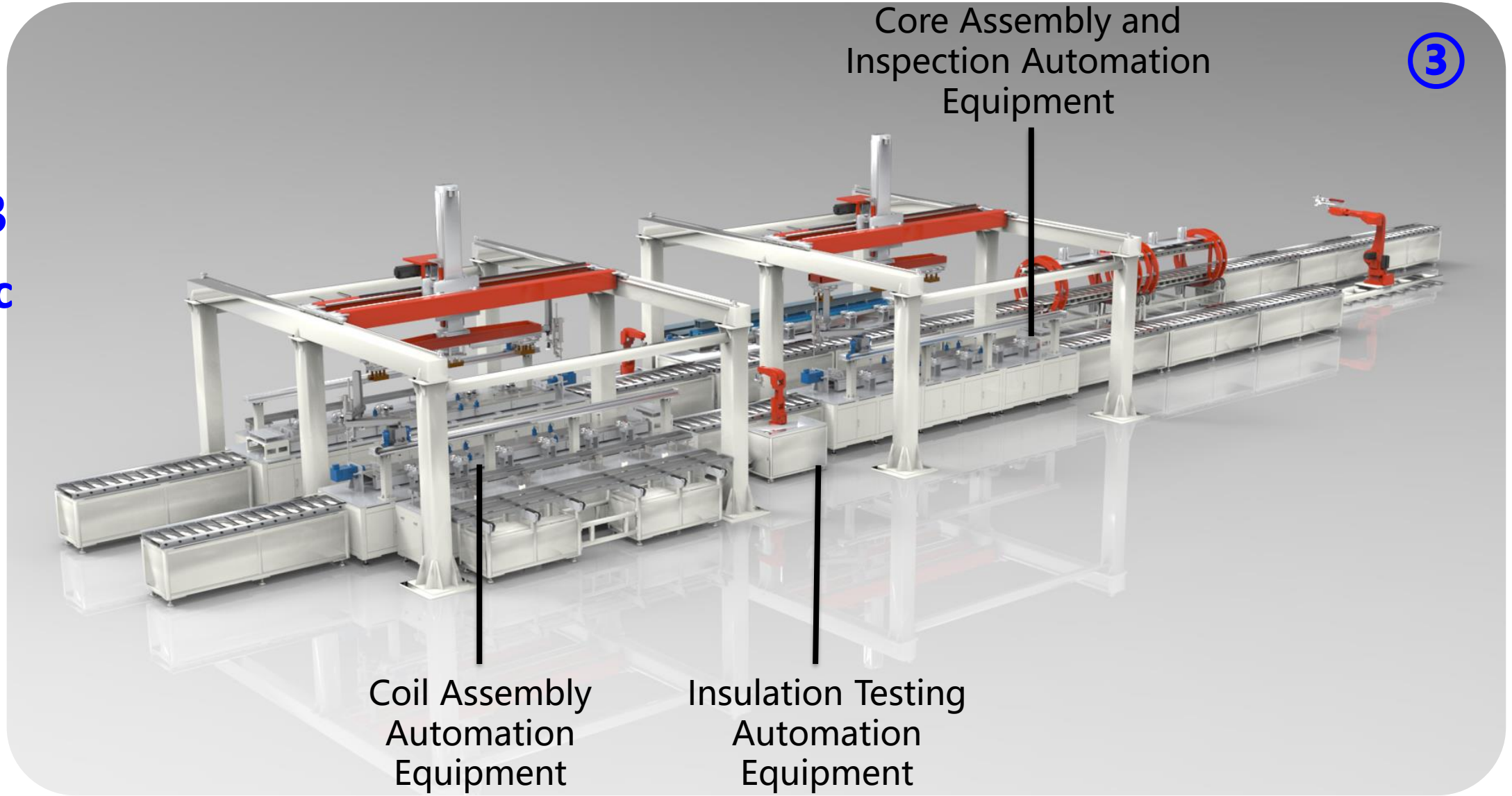
Automatic Integration of Full Length Cores



Workstations of the Automated Production Line

Station 3

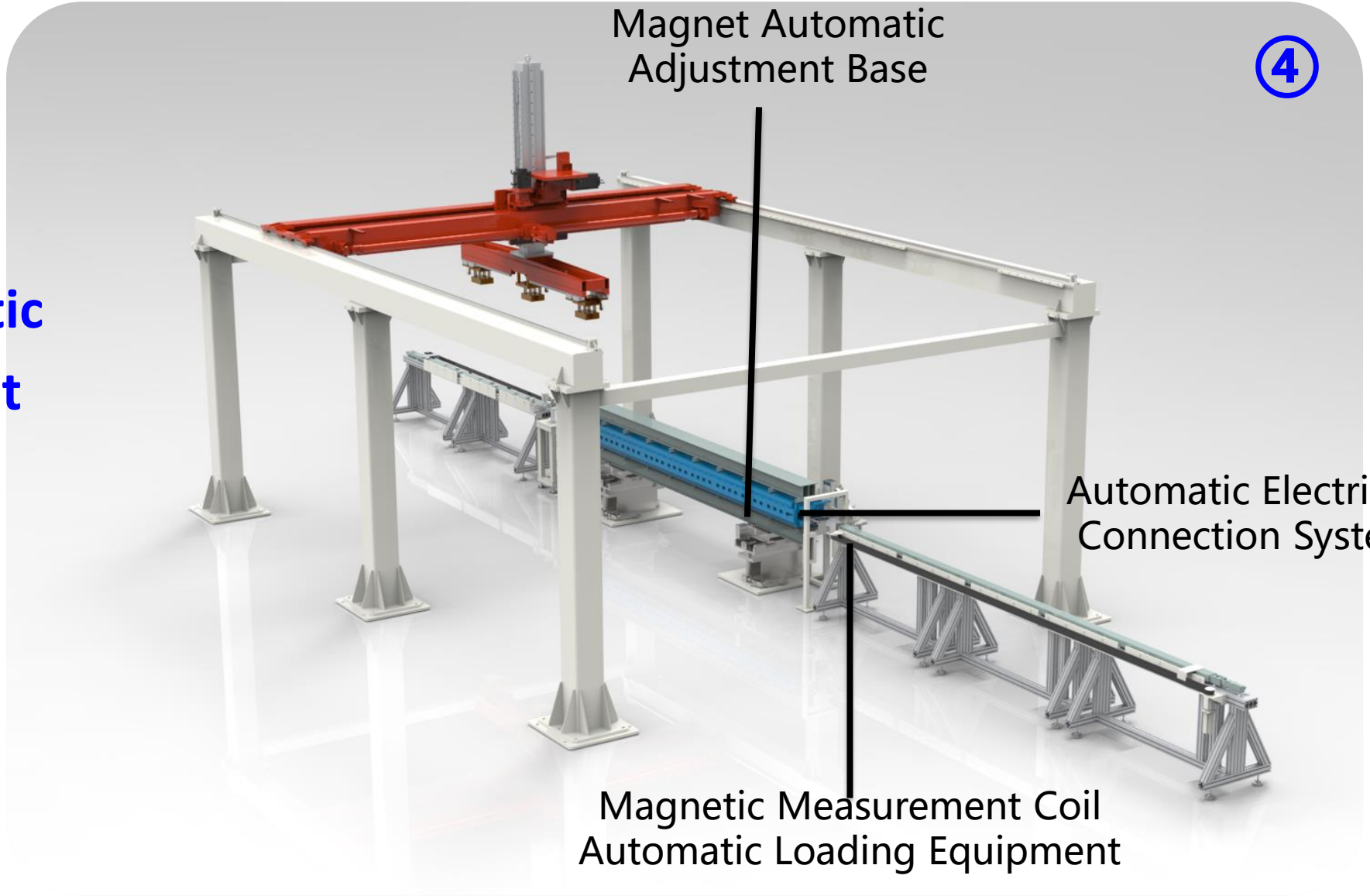
Automatic Assembly of the Magnet



Workstations of the Automated Production Line

Station 4

Automatic Magnetic Field Measurement



Analysis of the Production Capability

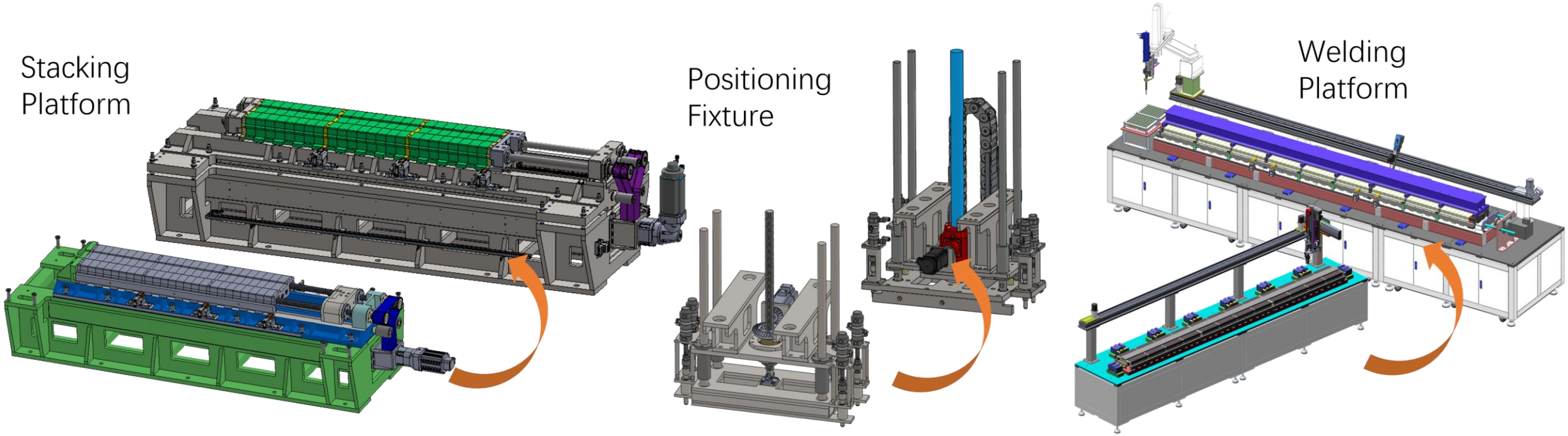
☐ According to the established manufacturing process of the workstations, the production cycle for each station is evaluated as follows.

Workstation	Number of line	Production period
Stacking of one-third length core	2	345 min.
Integration of full length core	2	231 min.
Assembly of the magnet(coil inst.)	2	120 min.
Assembly of the magnet(two halves ass.)	1	110 min.
Magnetic field measurement	1	331 min.

- Since the magnet can be divided into upper and lower halves, two sub-lines are utilized to produce both halves simultaneously in order to improve production efficiency.
- The one-third core stacking workstation has the longest production cycle, at 345 minutes (approximately 6 hours). As a result, the overall line capacity is about four magnets per day.

Optimization in Automated Production Line Design

- **Achieving the Production Quality Control Target poses significant challenges. Therefore, design refinements and debugging will remain an ongoing, iterative process throughout.**
- **Issues identified in the hand-made prototype were addressed through timely design adjustments. These improved designs facilitate easier stacking of the laminations and welding of the iron core, thereby effectively enhancing production precision and reliability.**



Production Quality Control Target Length Tolerance=±3.0 mm Gap(Y) Tolerance=±0.1 mm
X Misalignment Tolerance MAX=1.5 mm Y straightness along z=0.2 mm X straightness along z=1.5 mm

Time schedule of the Automated Production Line

Time	Items
By the end of 2024	The overall model design have been completed. The contract for development of the production line with a qualified company was signed.
In March 2025	The process design review for the production line was completed.
In May 2025	The manufacturing tolerances of the magnets were analyzed and evaluated, leading to the final confirmation of the quality control targets .
Current stage	The machining drawings for the first workstation have been completed, and some components have already been manufactured.
Before the Spring Festival	The assembly of the lamination stacking section is scheduled to be completed， after which it will enter the debugging phase.
By the end of 2026	The assembly and commissioning of the remaining three workstations will be finished.
In 2027	The integrated commissioning of the entire production line will commence.

Time schedule of the Automated Production Line

- Experimental verification of key processes has been carried out progressively, and all components of Station 1 have been processed and completed in batches.










Summary

1. In mid-2025, we established the manufacturing precision targets for the dipole-sextupole combined magnet. Given that such a 4.7-meter-long combined magnet had never been fabricated before and posed significant challenges, we proactively advanced prototype development and implemented multiple design optimizations. By the end of 2025, we had completed both manufacturing and testing. Without considering lifting conditions, the mechanical performance of the prototype far exceeded the target specifications, and the magnetic measurement results also met expectations.
2. The successful development of the prototype has not only provided valuable experience for the automated production line but also boosted team morale. We will proceed with the assembly and commissioning of the first workstation in the first quarter of this year.

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Institute of High Energy Physics
Chinese Academy of Sciences

Thank you very much!