IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at MT29, Boston, MA, USA, July 2025.

GAUSS FUSION

The Gauss Fusion GIGA Magnet System

Neil Mitchell, Tommaso Bagni, Fares Elattab , Shin Hasegawa, Albrecht Herrmann, Luisa Huebner, Jan Jankovsky, Cees Jong, Filippo Levi, Werner Schubert, Heinrich Torlage

MT-29 5 July 2025

Sat-Mo-Or2-01

Content

GAUSS FUSION

- Stellarators as Fusion Power Plants
- Features of GFG GIGA Stellarator Magnets
- Conductors
- Coils
- Demountable Coils
- Coil Protection
- Magnet Schedule and Development Program

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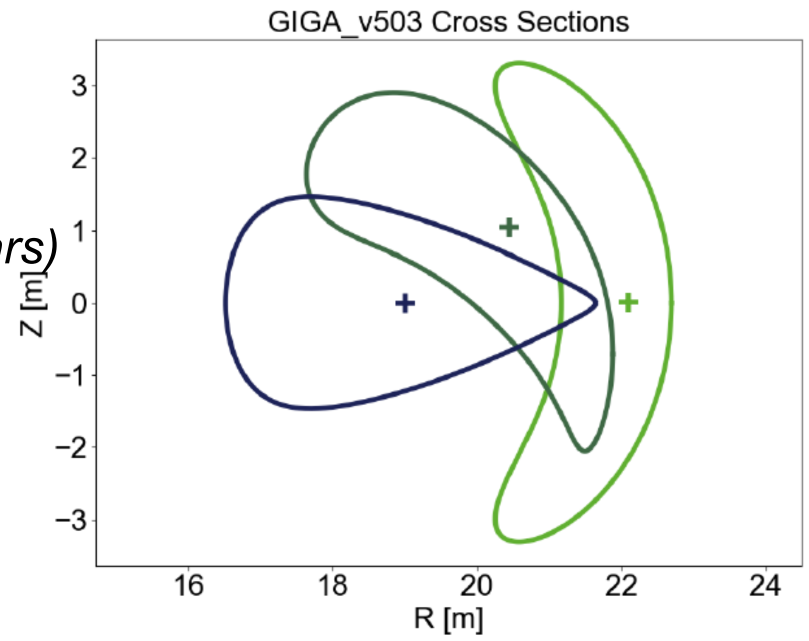
Stellarators have good potential for Fusion Power Plants

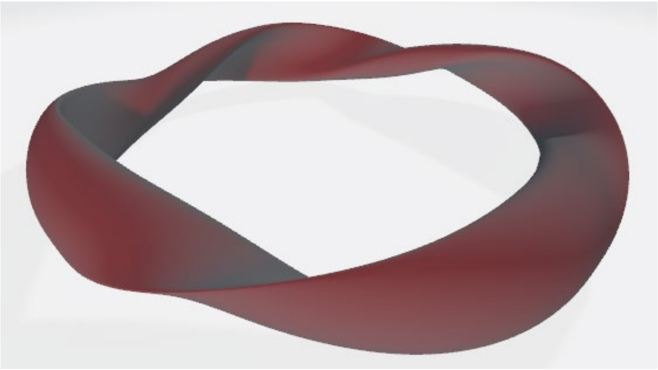
- Steady state (no thermal cycles, no supply interruption)
- Stable (no plasma current to control, no disruptions, no control voltages)
- Sizing of GFG Stellarator GIGA
  - *3GW thermal, 1GW electric*
  - *First wall neutron load 1MW/m2 (consistent with FW/blanket life of 5 years)*
  - *Magnet and vacuum vessel life 40years*
  - *Volume: 1500 m3*
  - *Field periodicity: 4*
  - *Coil Current 12.2MAT*
  - *Max B-field on axis: 6 T (170 GHz ECRH), about 11.5T on coils*
  - *High aspect ratio, all round access*



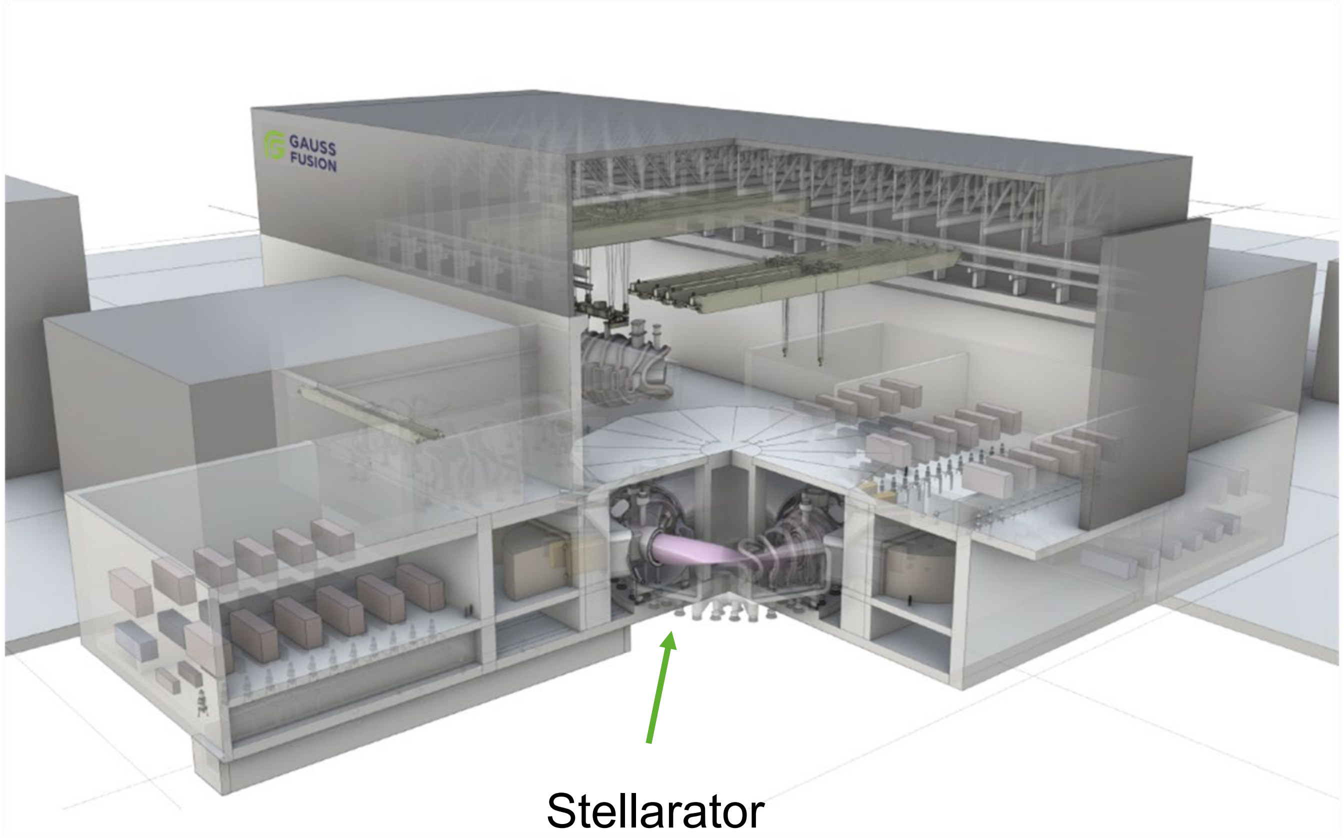
Plasma performance not (quite) demonstrated at tokamak levels. Issues are mainly technology

- *Complex 3D fields at plasma generally require many shaped coils…block access to in-vessel tritium breeding and energy conversion systems*
- *Plasma surface shape is convoluted, tends to drive VV and shielding shape*

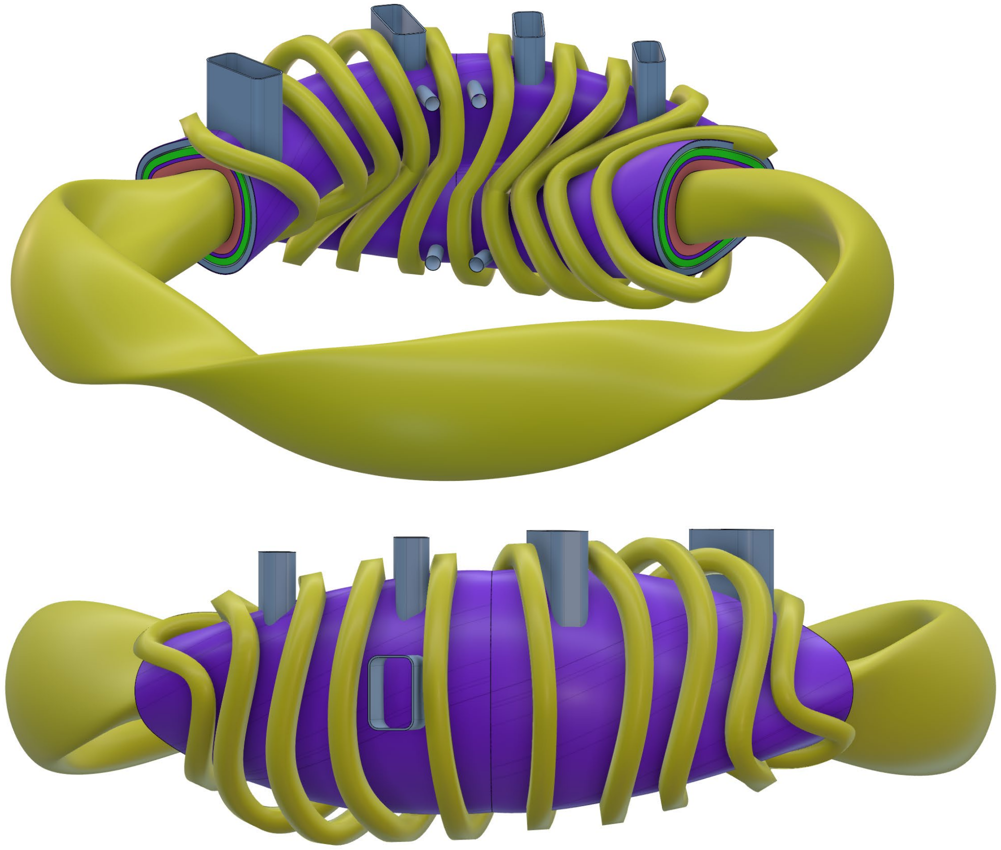
With its GIGA FPP, GFG is addressing these issues as a priority for the magnets



Conceptual Reactor Building



Conceptual VV and Coil Layout



Target to reduce size by use of advanced maintenance concepts

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GFG GIGA Stellarators Magnet Provisional Baseline

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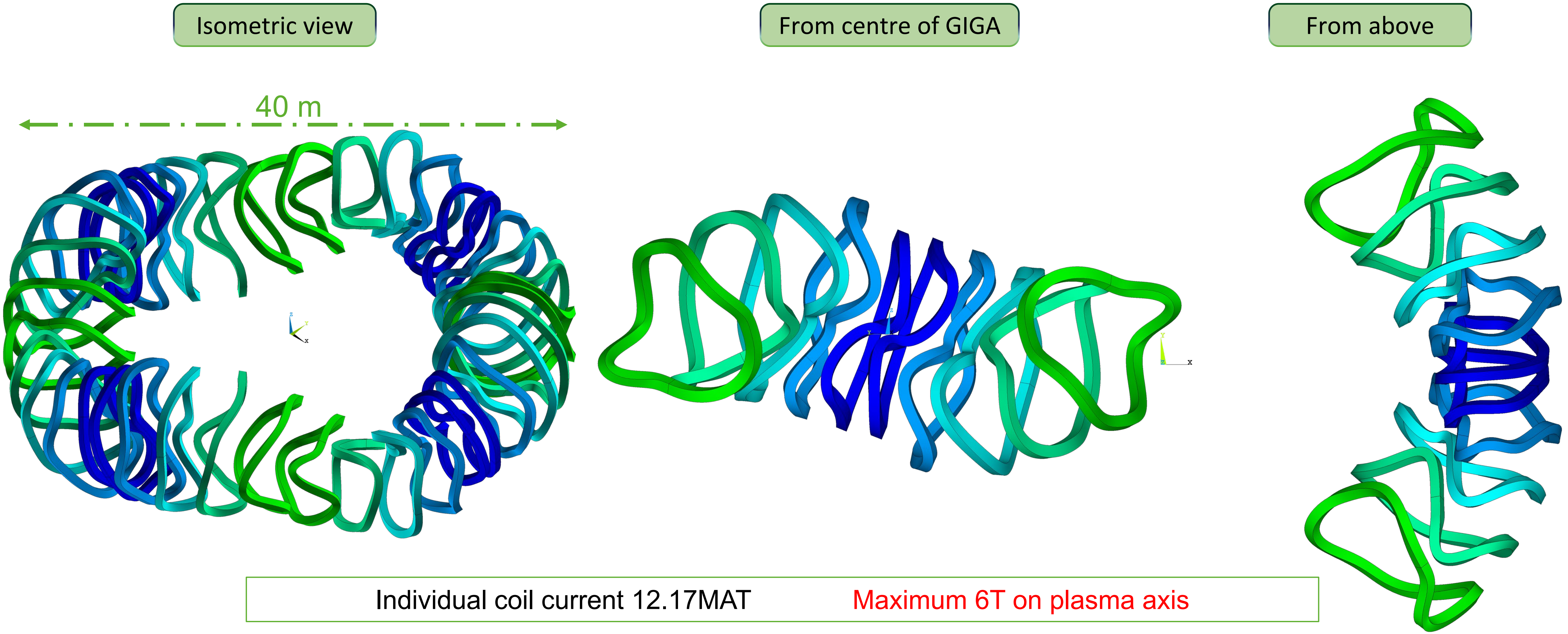
Basic magnet set (5 coils, 8 times repeated)



Individual coil current 12.17MAT Maximum 6T on plasma axis

Force distribution – global reference frame

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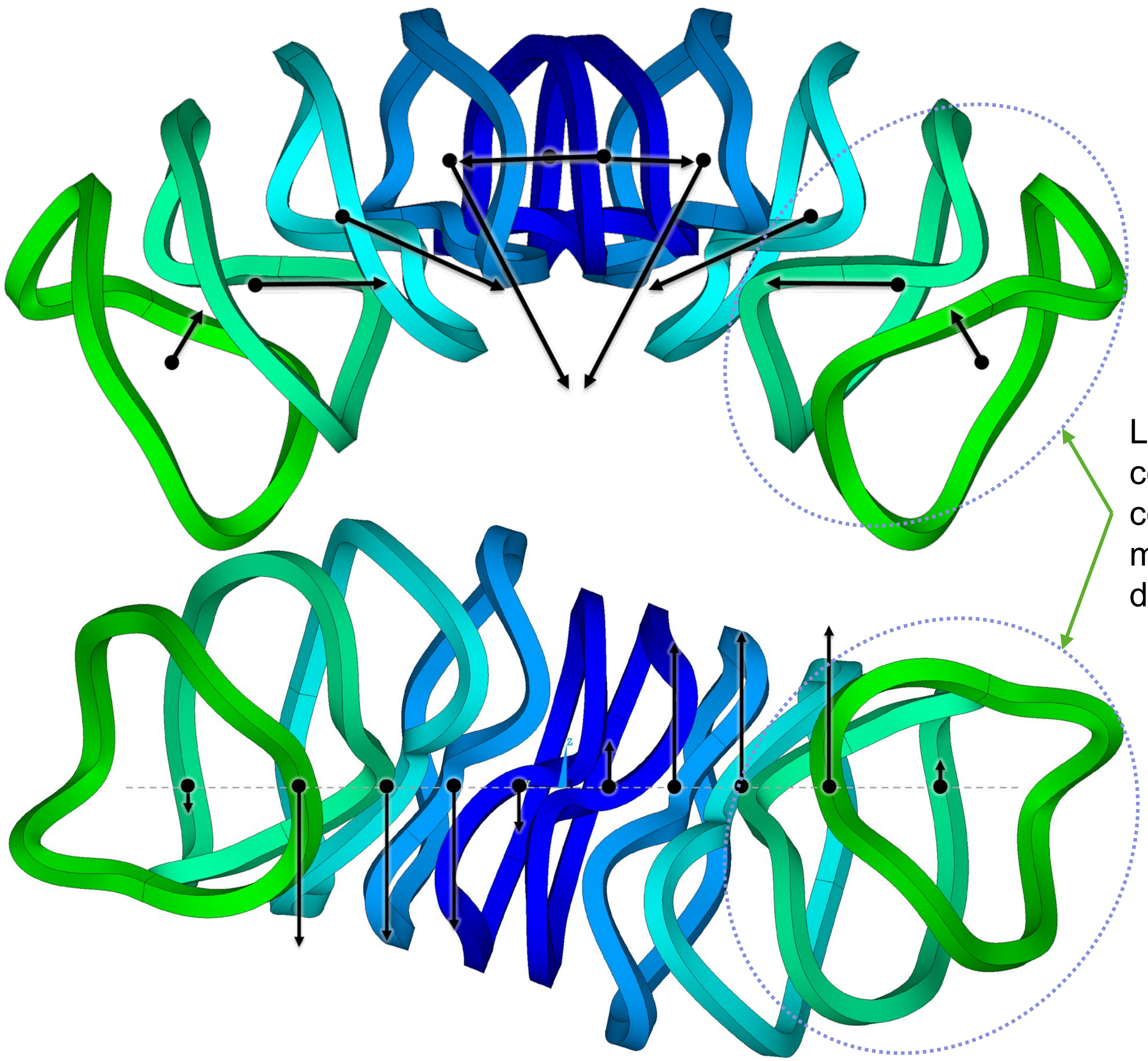
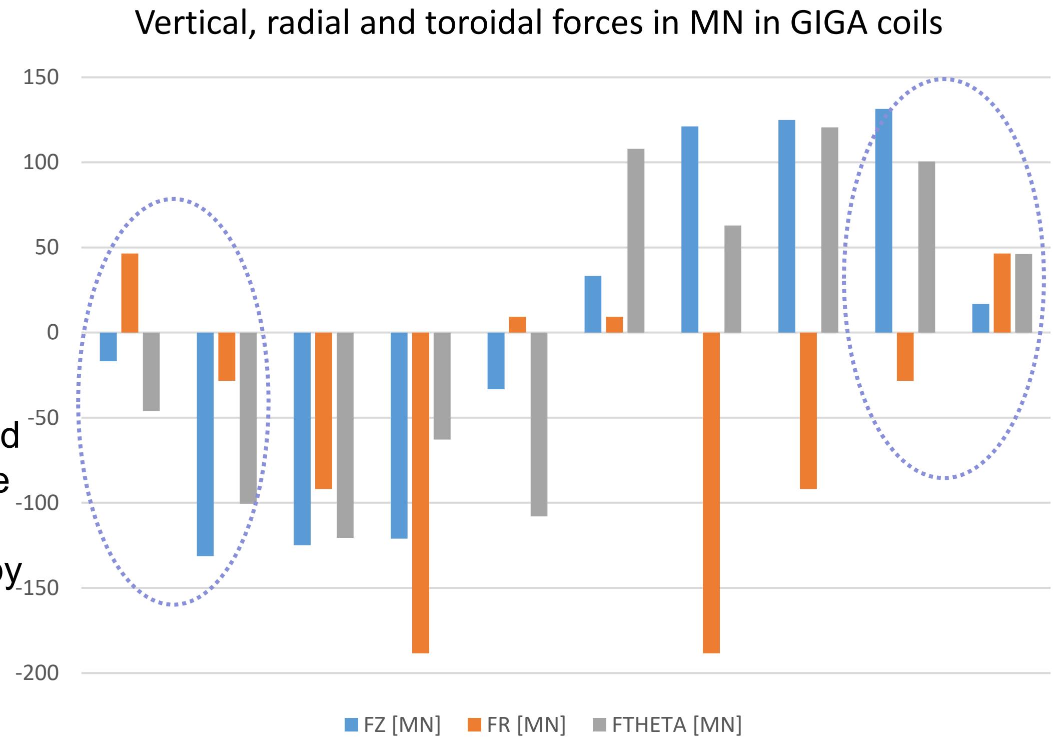


Low-radial-load coils where we concentrate main access by demounting



These forces are similar in magnitude to those of ITER (where for example the centring force on one TF coil is 400MN)

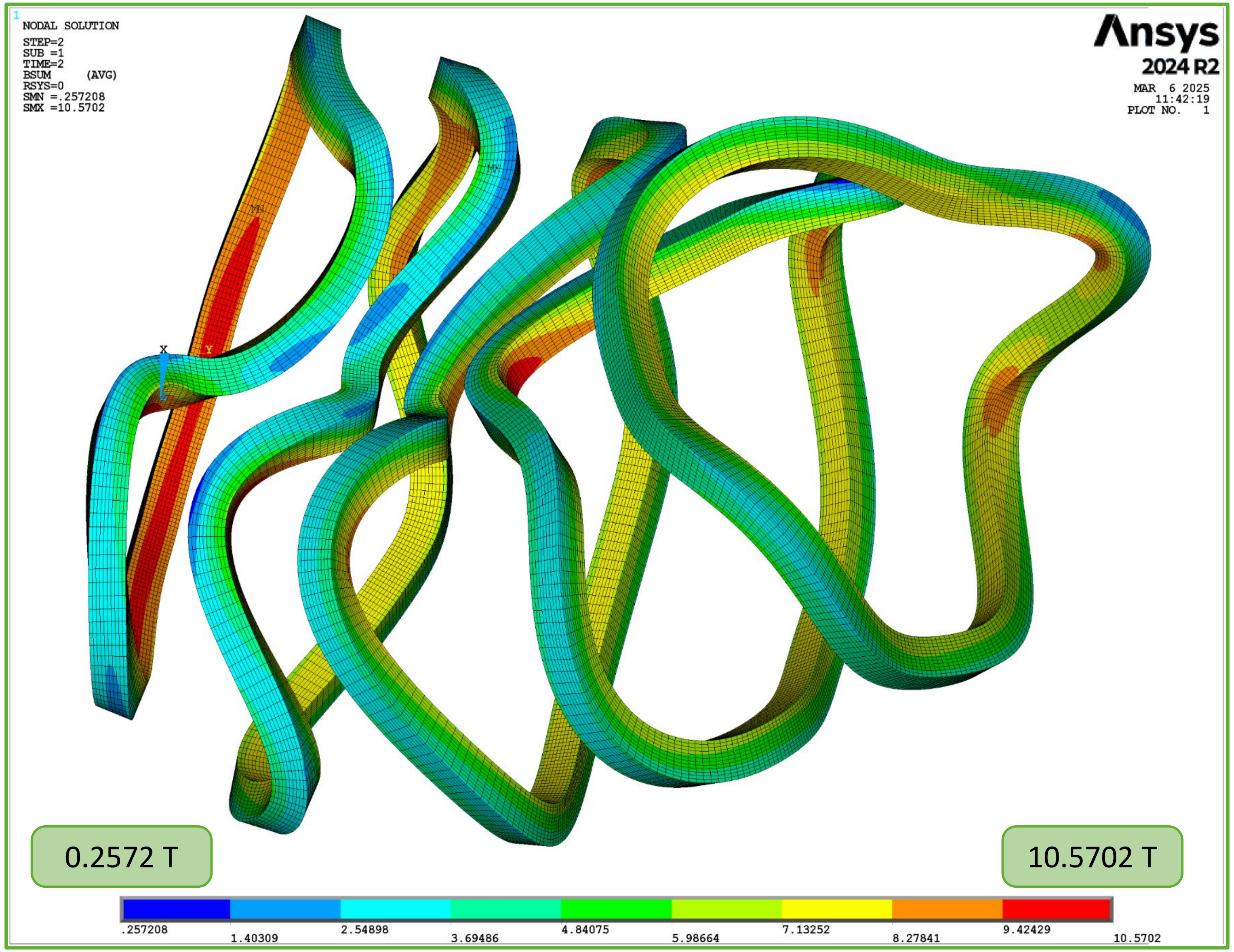
Field distribution and magnetic energy

Peak field in each coil				
Coil 1	Coil 2	Coil 3	Coil 4	Coil 5
10.4 T	10.6 T	10.1 T	10.2 T	10.2 T

(while coils are still being optimised take 12T for conductor design basis)

Magnetic energy of the entire coil system is about 110GJ, close to 2.8GJ/coil

Comparison to ITER TF system 2.3GJ/coil



Engineering Design & Integration, Technological Development and Qualification

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Design of Baseline Magnet System

- Optimisation of Coils-Plasma (and optimisation targets)
- Engineering Magnet Analysis (real fields and inductances)
- Coil Structure Concepts & Efficient Manufacturing/Assembly Routes
- Coil Tolerances and 'Tuning' needs (requirements to adjust plasma, impact of coil tolerances and operational movements)
- Structural Analysis and optimisation (efficient structural design, matching access (to in-vessel) & repair requirements)
- Conductor Concepts (LTS & HTS) and cost optimisation

Large potential impact projects with low TRL

- *Develop*
- *Assess*
- *Maybe Exploit*

Demountable Coils Project (DCP)
Low Voltage Coils for thermal protection
Dispersed Structure Windings

Next Step Engineering Qualification: Model Coil Program

Critical engineering technology qualified at local full scale in integrated coil environment

- Model coils
- Coil structure technology
- Conductor tests

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Conductors

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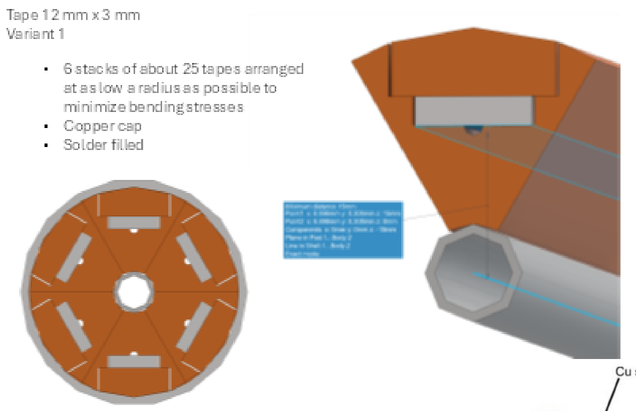
HTS Rebco and LTS Nb3Sn concepts, both being procured for demountable coil trials

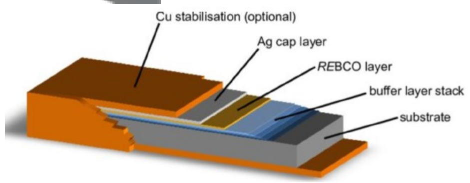
- Magnet design common to LTS and HTS conductors, operating temperature different (~7K vs ~20K)
- At ~12T, most of cable is copper for thermal protection, hot spot limit 150K, discharge time constant >30s, OD<65mm
- DC coils simplifies composite cable design: twisting can be limited (transposition allows faster current ramp)
- Choice likely to be commercial (HTS seems potentially cheaper, but lower TRL in cables: tape local quench tolerance and protection of HTS coils is not yet demonstrated in large cables)

Example HTS cable

Soldered stack concept



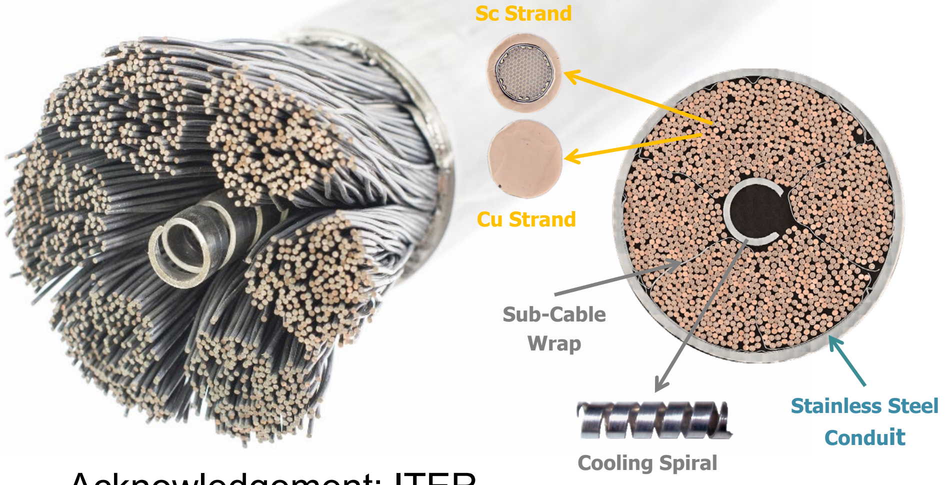
12 mm HTS stacks



Example LTS cable

Established technology – CICC

1mm Nb3Sn strands



Acknowledgement: ITER

Superconducting Material

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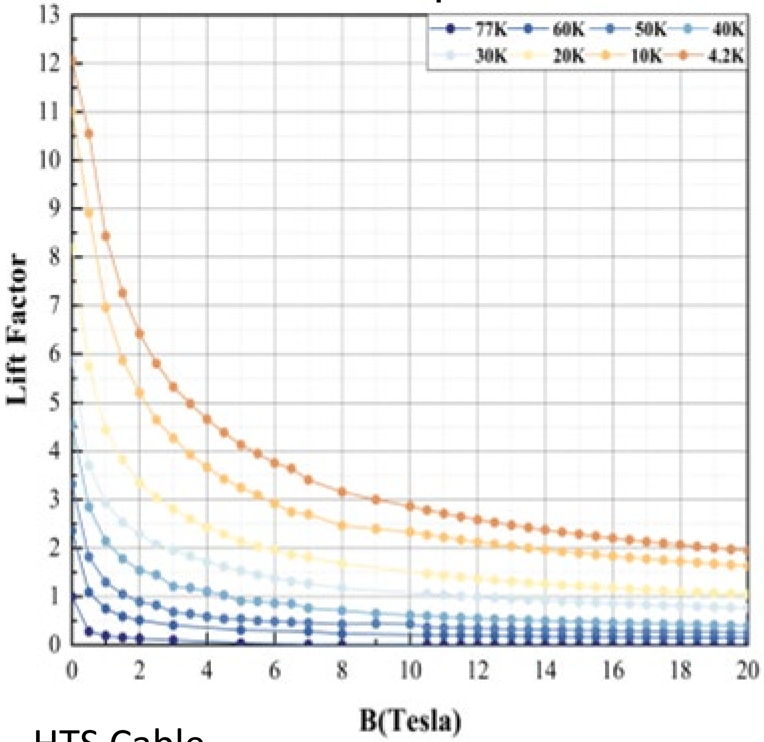
HTS Tape

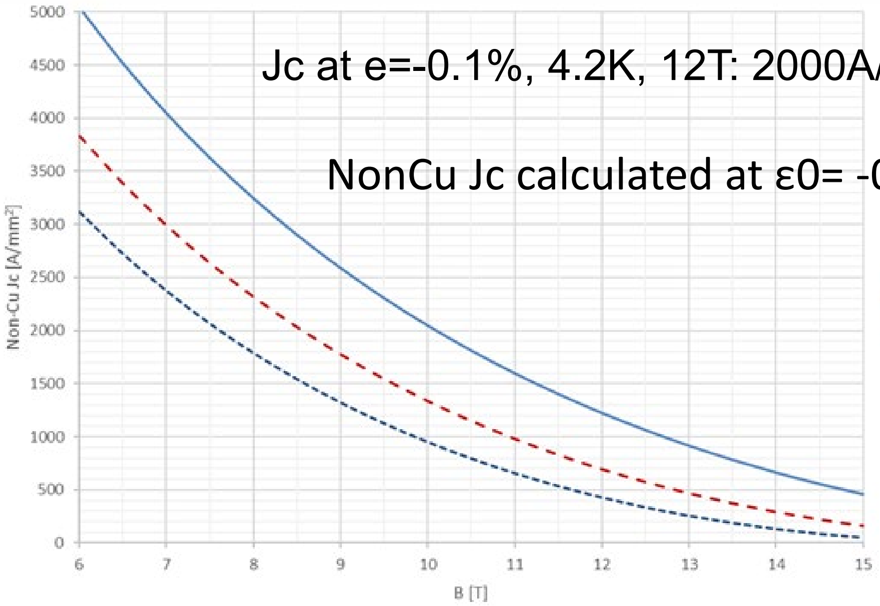


Lift Factor SST 12mm tape (750A at 12T and 20K, 550A at 77K and SF, 12mm width)

HTS Cable

- At 12 T and 20 K. 168 tapes of 12 mm width produce a nominal cable I_c = 126kA with a transport current of 100 kA (25% margin on possible degradation)

Nb3Sn strand



Jc at e=-0.1%, 4.2K, 12T: 2000A/mm2 (non Cu)

NonCu Jc calculated at ε0= -0.55%

LTS cable

- 600 superconducting wires–with 1.0mm diameter, Cr coated (2μm)
- 1275 Cu wires
- Cable layout: (1s.c.+2Cu)x4x5x(5+Core)x(6 + spiral)
- Core = 15 Cu wires
- Spiral: outer diameter 10 mm ; thickness: 1 mm
- Twist pitch values: 25 mm / 55 mm / 105 mm / 205 mm / 475 mm
- Outer cable diameter (after conductor compaction): 54.6 mm
- local Void Fraction in cable bundle about 30%.

Top 6K, Tcs 7K, (Iop/Ic)= 0.6 at 12T and 6K

Opportunity with Demountable Coils

- Conductor (and strand/tape) unit lengths become short, <30m.
- Little impact on Nb3Sn cables but significant easing of requirement for HTS tapes and cable manufacture

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3D Coils

Acknowledgement M. Wanner

Problems to be solved

3D shaped coils now made by

- Winding (by three-dimensional bending) a superconductor
  Bonding the conductor with resin or solder
- Inserting the winding package into a steel case

Fitting W7X WP in case

As stellarator coil sizes increase, this design and manufacturing route becomes increasingly unattractive:

1. Coil magnetic energy increases. To reduce discharge voltages, composite cable is required with as high a current as possible (>50kA).
   - ❑ *Adding a jacket, then accurate 3D bending difficult*
2. Case size increases
   - ❑ *Making a 3D coil case once the weight exceeds 100t is complex (and expensive).*
   - ❑ *Fitting it to the winding pack (and welding it closed) is another difficult operation.*
3. If demountable coils are required
   - ❑ *Case is another huge complexity to be included*
4. VV assembly
   - ❑ *Getting the coils around the VV another challenge*

Threading W7X coil over VV

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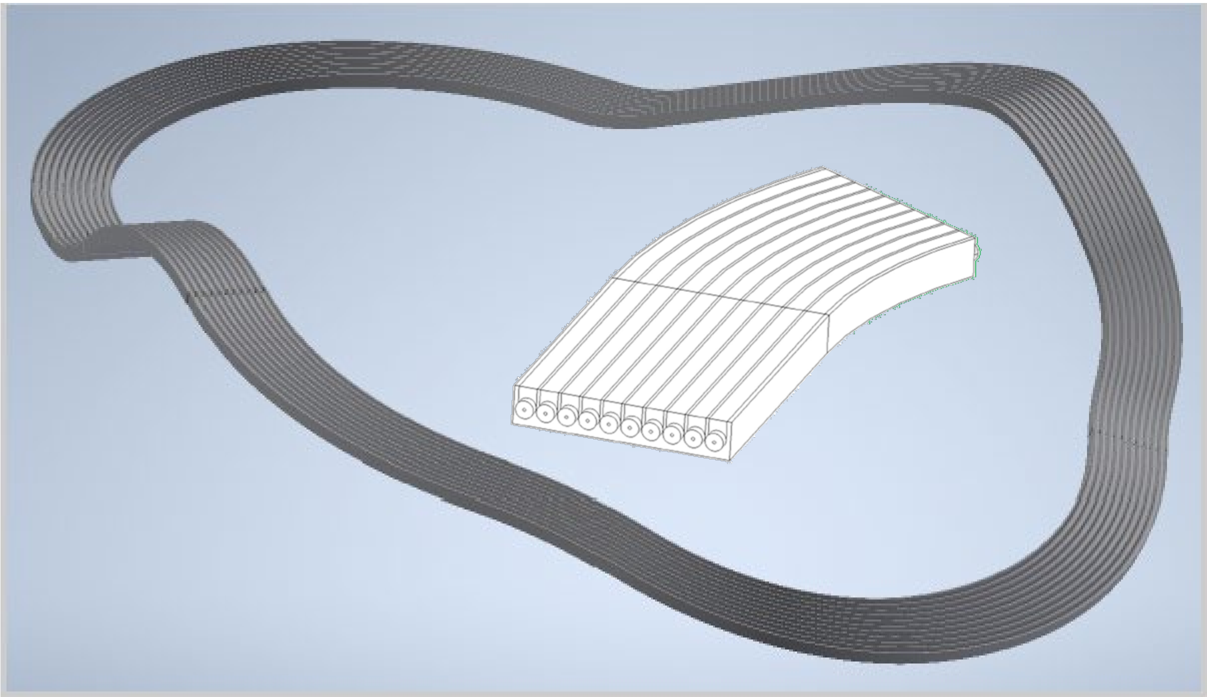
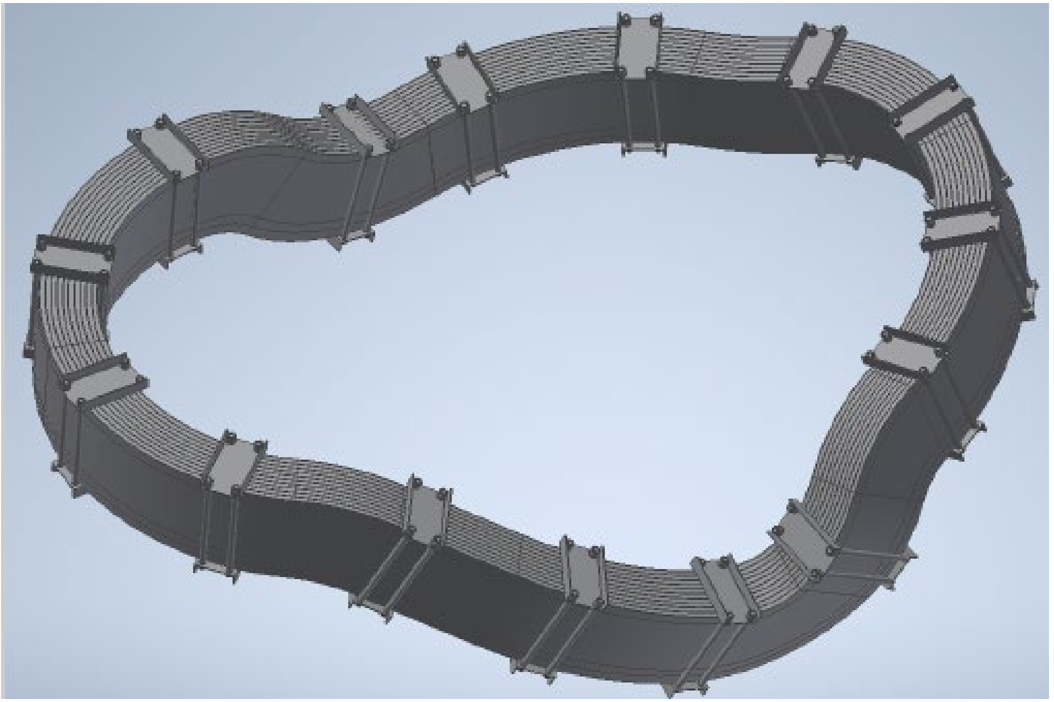
3D Coils

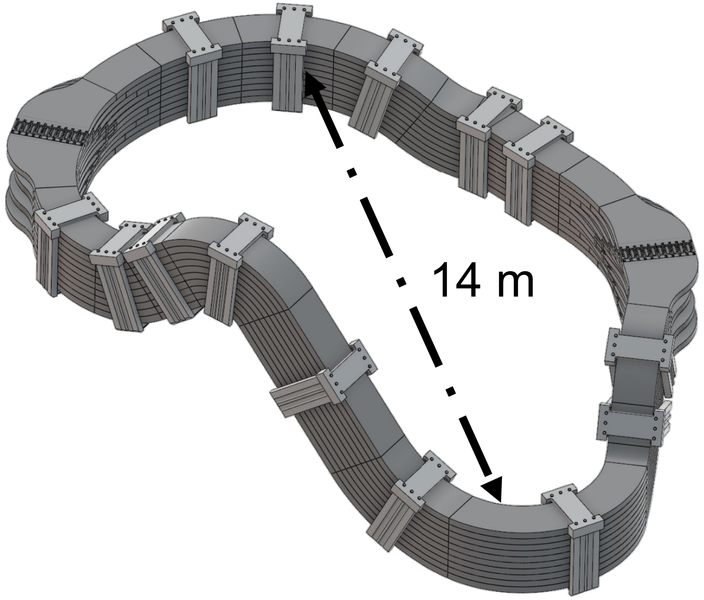
Solution

- GFG coil concept avoids the case by distributing the structural support to the winding package while maintaining a conductor that is reasonably easy to bend with a thin steel jacket and circular cross-section.
- A circular conductor is contained by a series of grooves in a 3D curved plate. The conductor is insulated from the plate and after being placed in the grooves, is fixed in place by a welded cap.
- Plate provides the structural support
- *Plate is multipurpose, enabling a demountable joint and internal quench protection.*





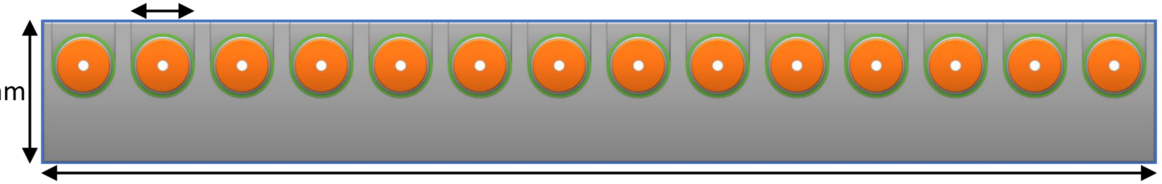
Coil Concept is based on conductor-in-curved plate



Coil formed from stacked plates clamped together (not bonded)

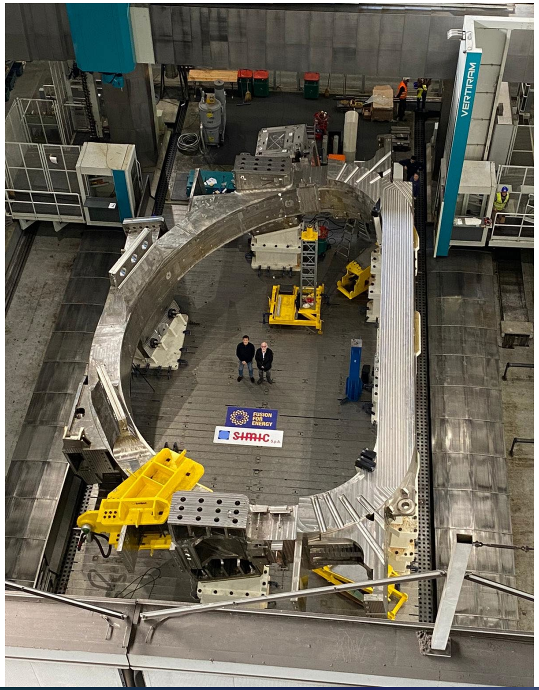
There is no case ➔ avoid very difficult fitting of winding in 3D case

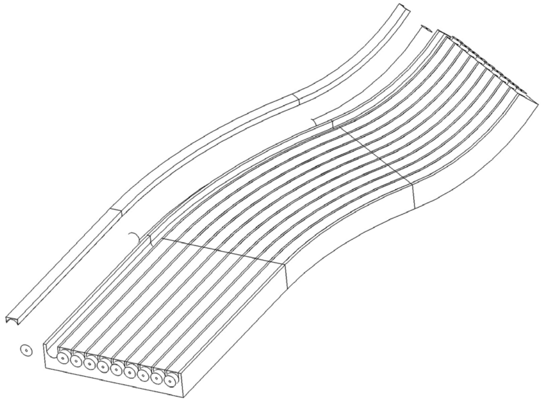
Conductors arranged in grooves in the plate



Example 108kA conductor ➔ 8 pancakes of 14 turns
Approximately 1.1x1.1m

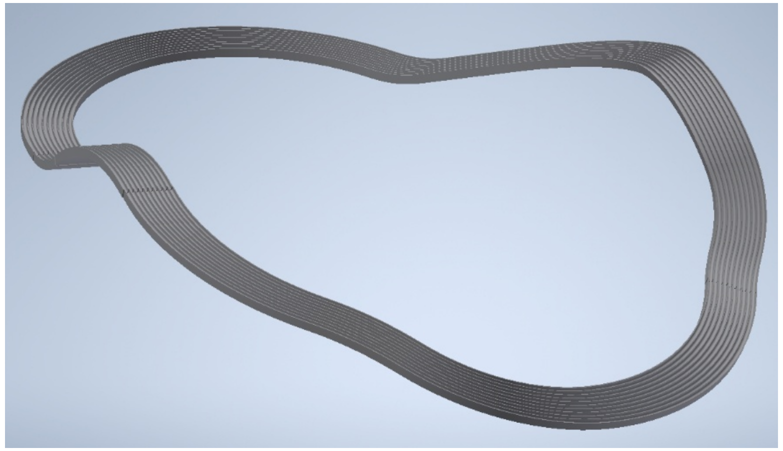
Anticipate each coil ~350t, about the same as 1 ITER TF coil *but without a case*





Conductor in a curved plate concept showing (left to right) Type 1, Type 2 and Type 3 curved segments

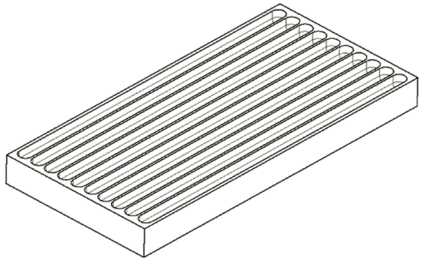
Single 3D plate



Main features of a plate-based coil

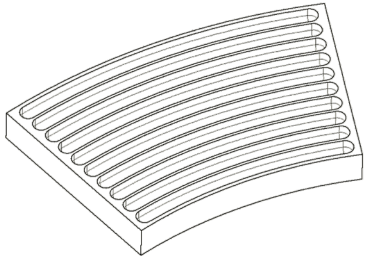
- To be sure that the coil is **easily manufacturable** we want each plate to be made of **segments** of **three** specific **types**:

Type 1:

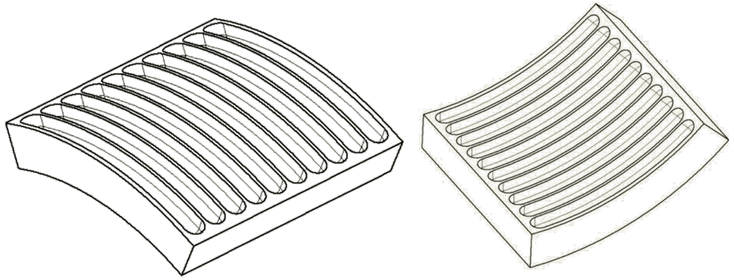


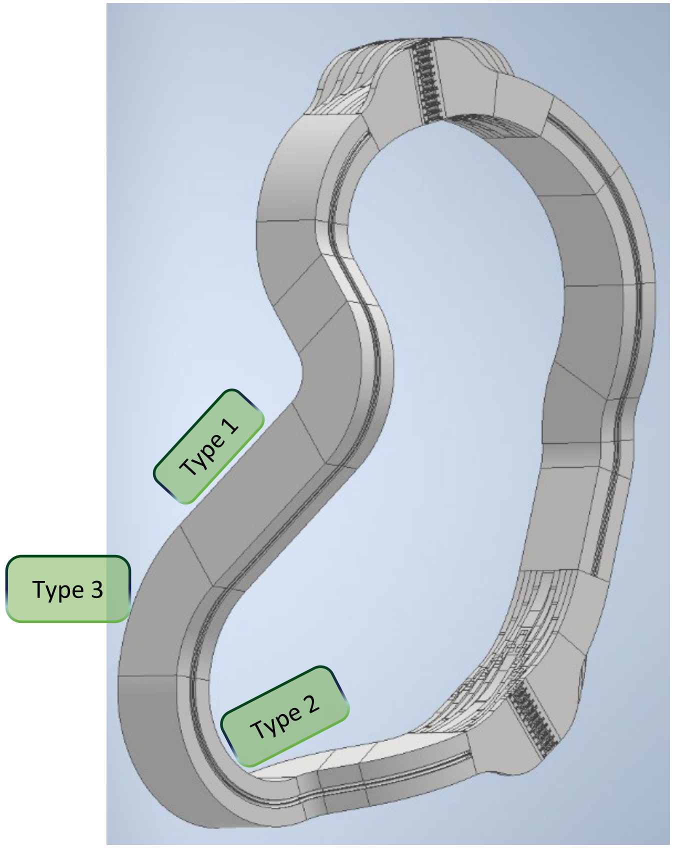
Constraint to be applied in the plasma-coil optimisation

Type 2:



Type 3:





This coil includes demountable joints

Conceptual Layout of Central Support Structure

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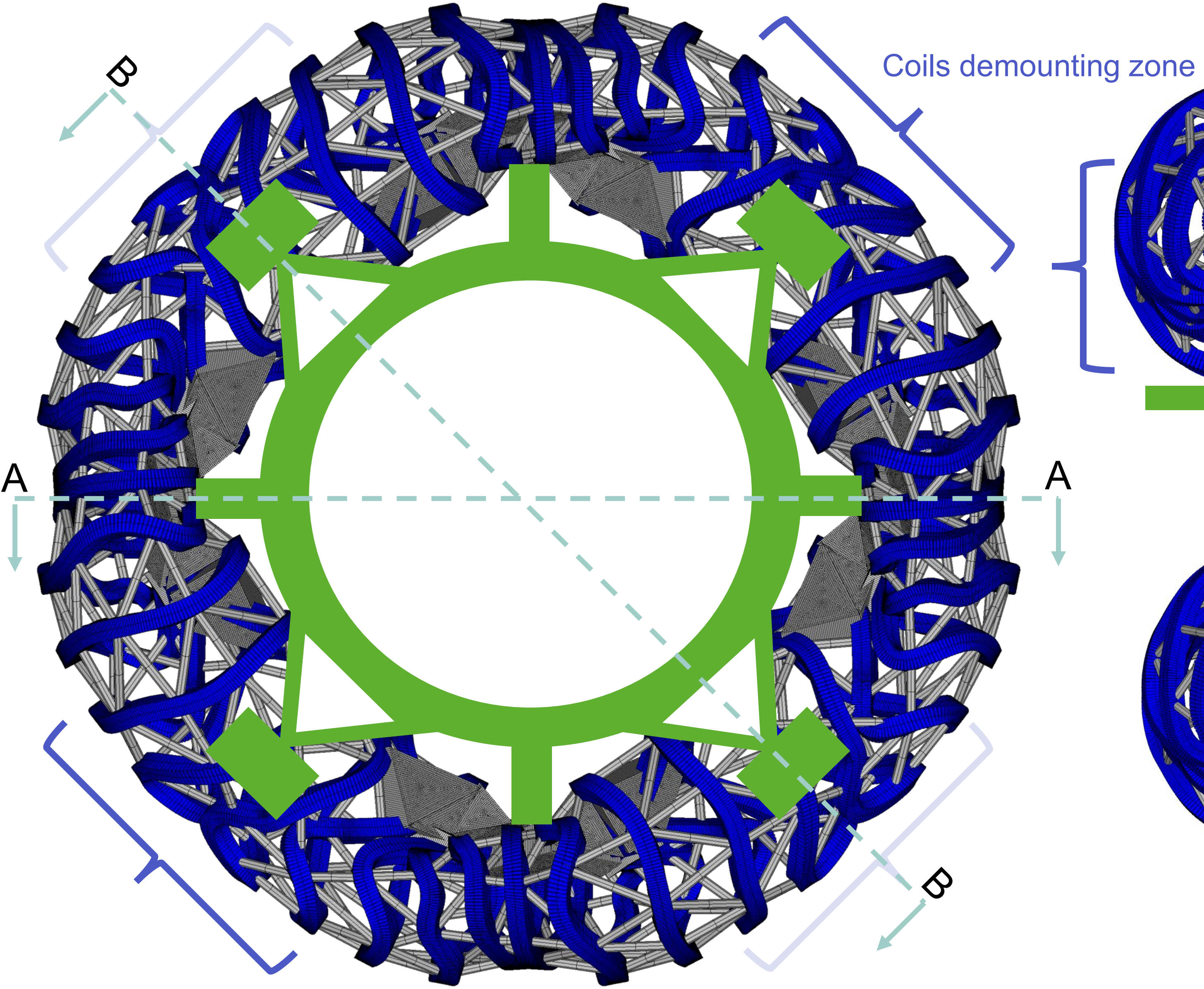
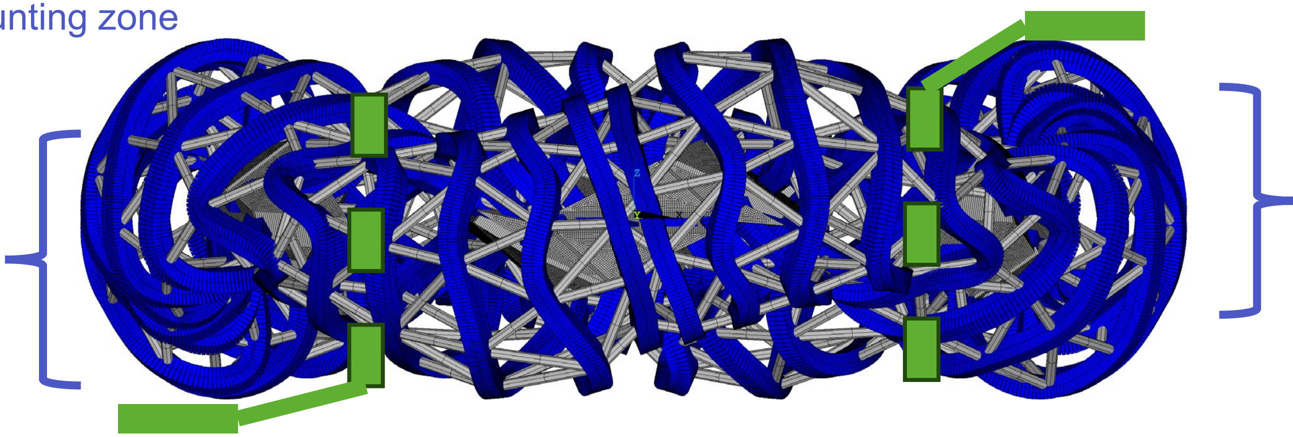
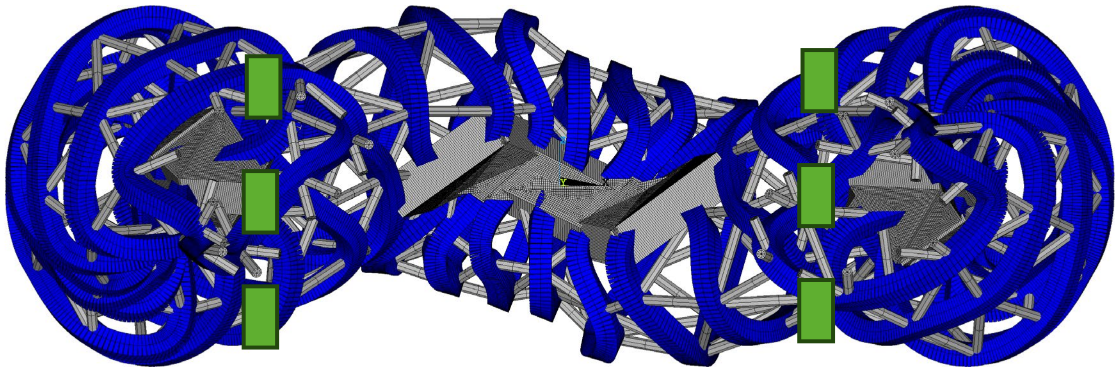




View on BB



View on AA

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Demountable Coils

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- Much easier maintenance/repair both of the coils and of in-vessel trapped components
- Lifting of multiple 20t segments is much easier than >350t
- Vacuum vessel assembly largely simplified (no access problems)
- Coils can be made off site and more easily transported
- Coil manufacturing changed from a winding process to a lay-up process
- Conductor grading possibilities greatly extended
- Advantage is larger for stellarators (which have more coils) than tokamaks

Even if only subset of the coils are demountable, or coils are just mountable-once

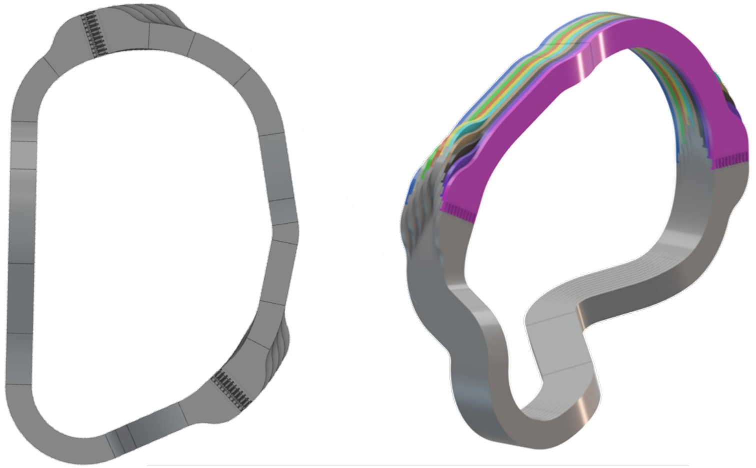
→ Assembly, maintenance and repair options are substantially improved

Key problems to be solved

- Individual joint resistance (target <1nOhm)
- Coolant (He) containment
- Coil load transmission
- Compact design
- Remote handling compatible

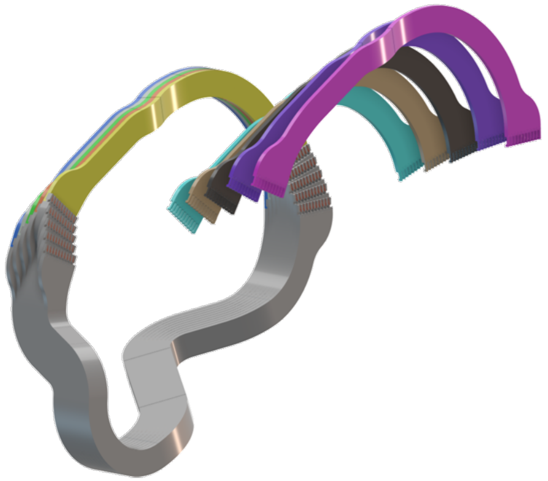
GFG demountable coil

- Exploits plate concept to achieve compact in line joint
- Joints built up plate by plate



Staggered joints allows plate removal one by one
Each part <20t

Plates removed from left and right to speed operation



GFG in-line joint concept common to LTS and HTS

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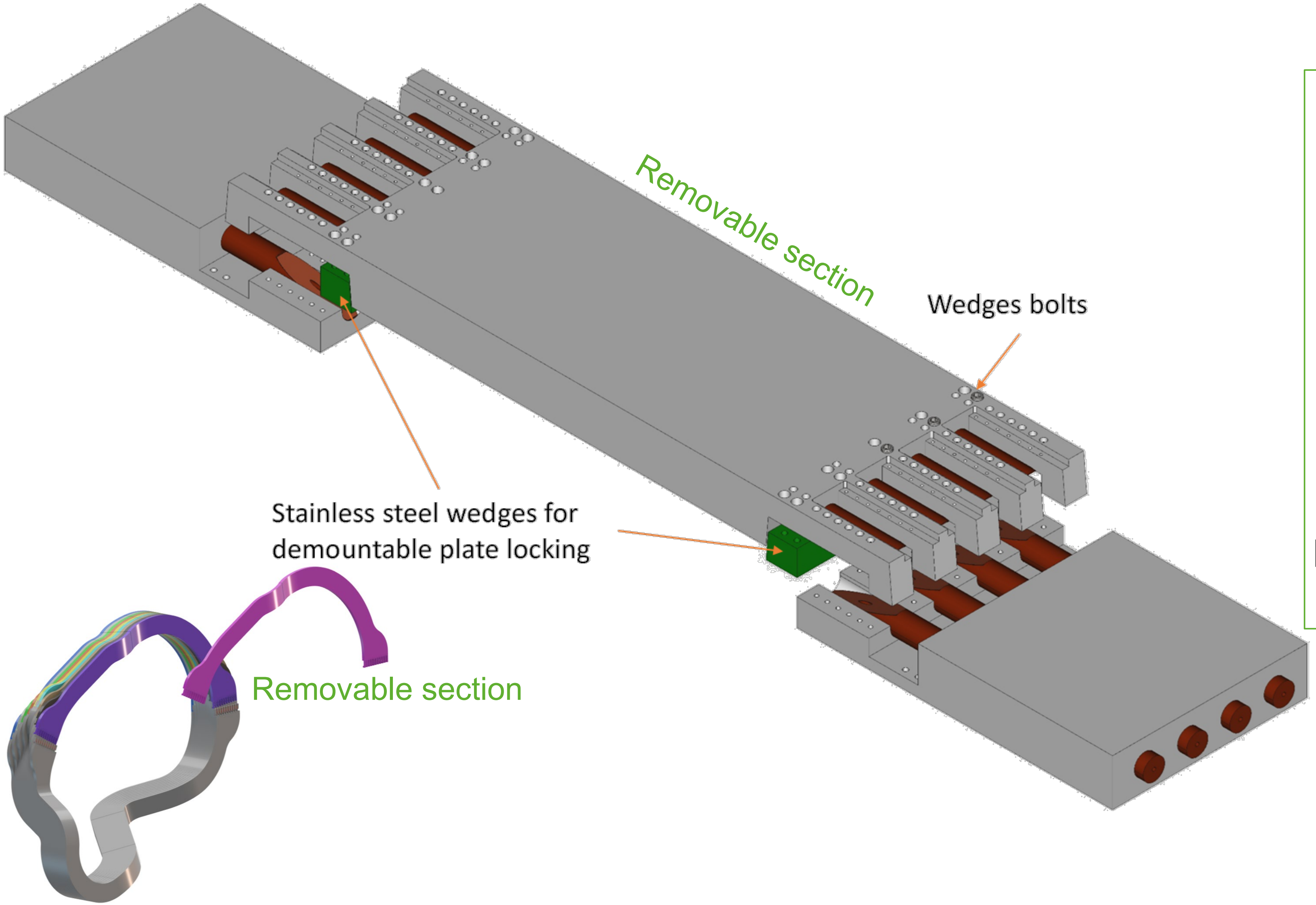
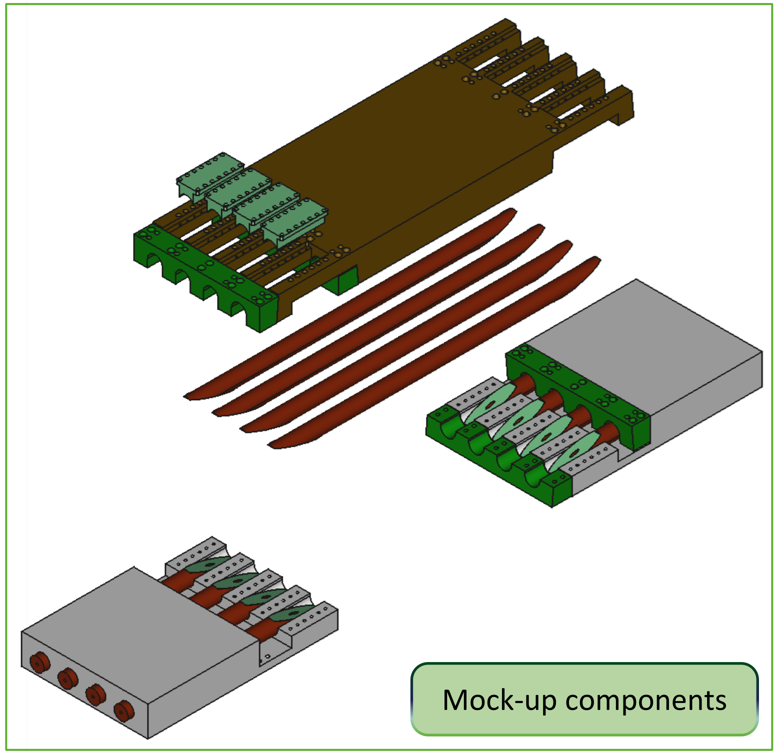
Joint Assembly Step 2





Joint Assembly Step 7

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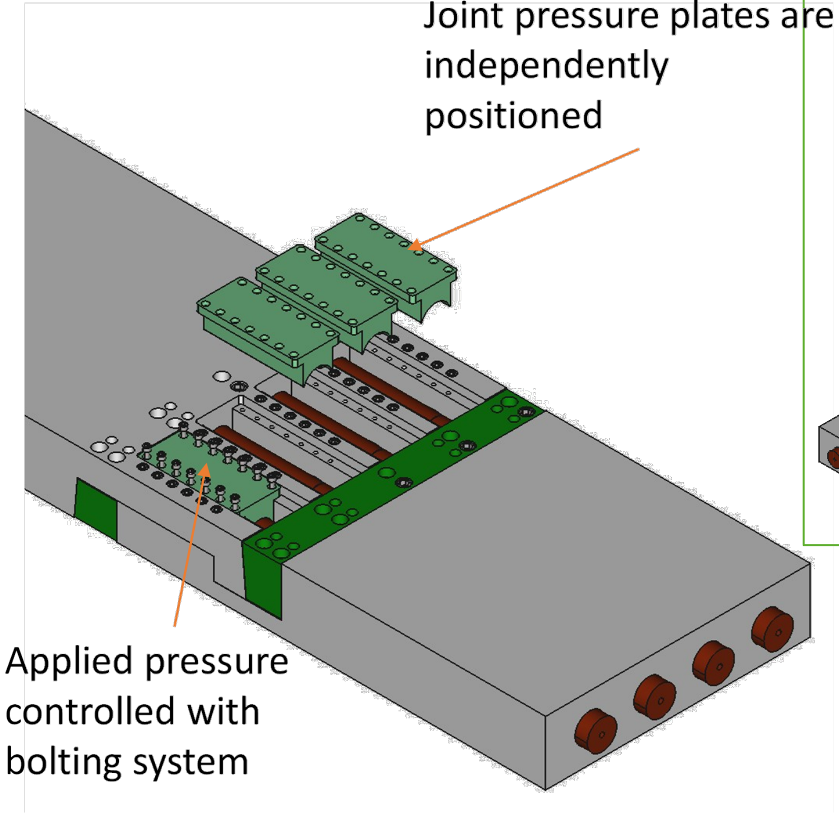

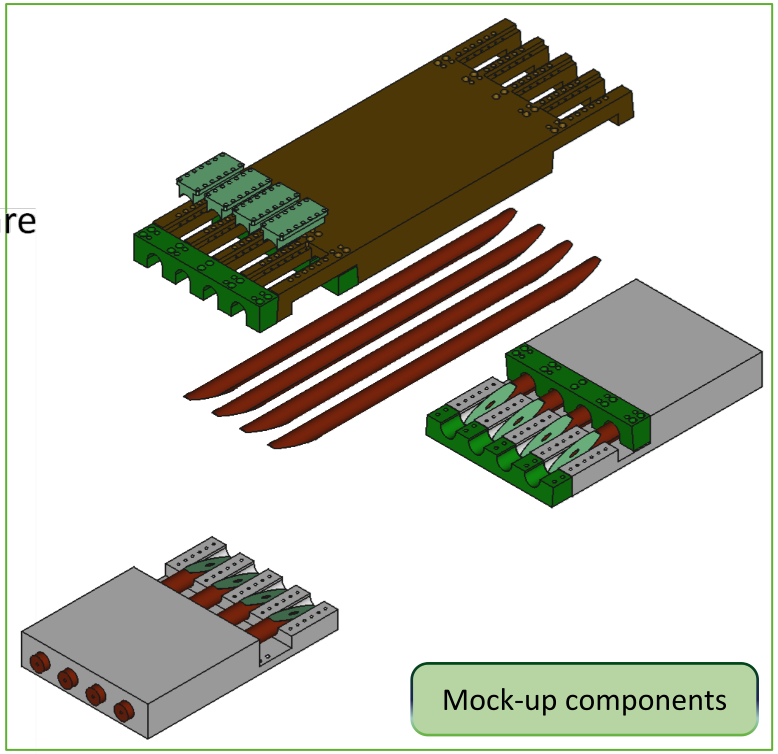

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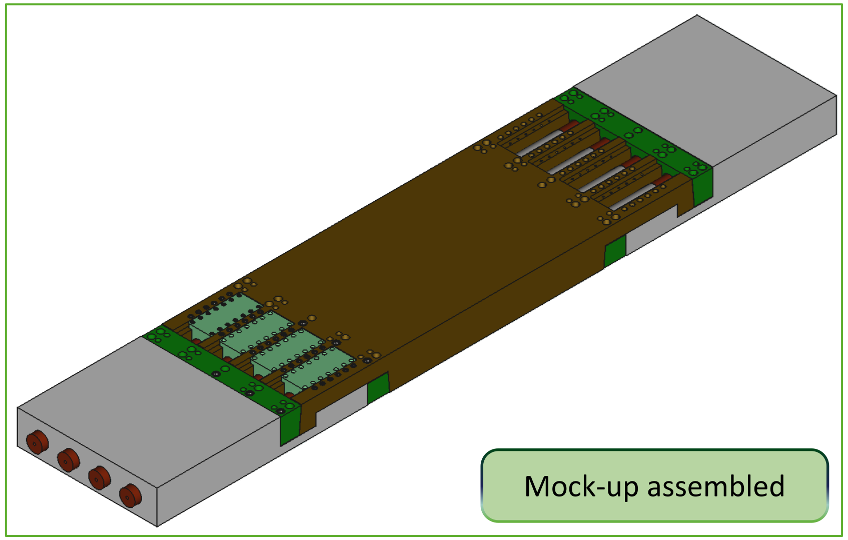
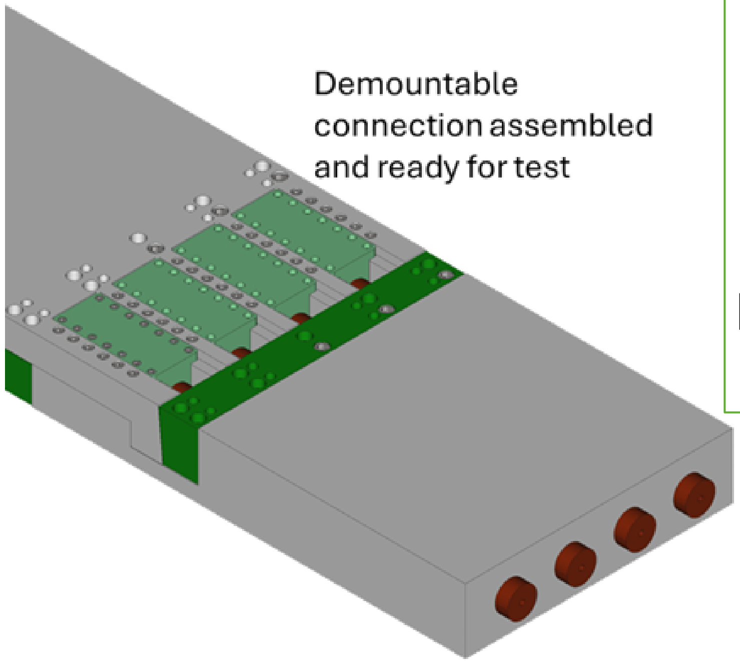
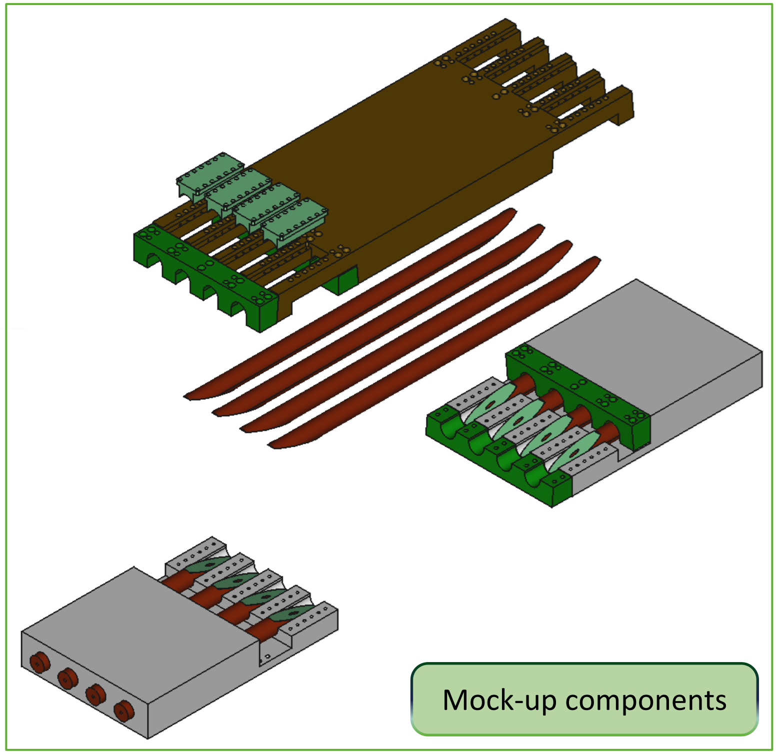
Joint Assembly Step 8







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Exploiting Demountable Coils

Installation of first demountable plate

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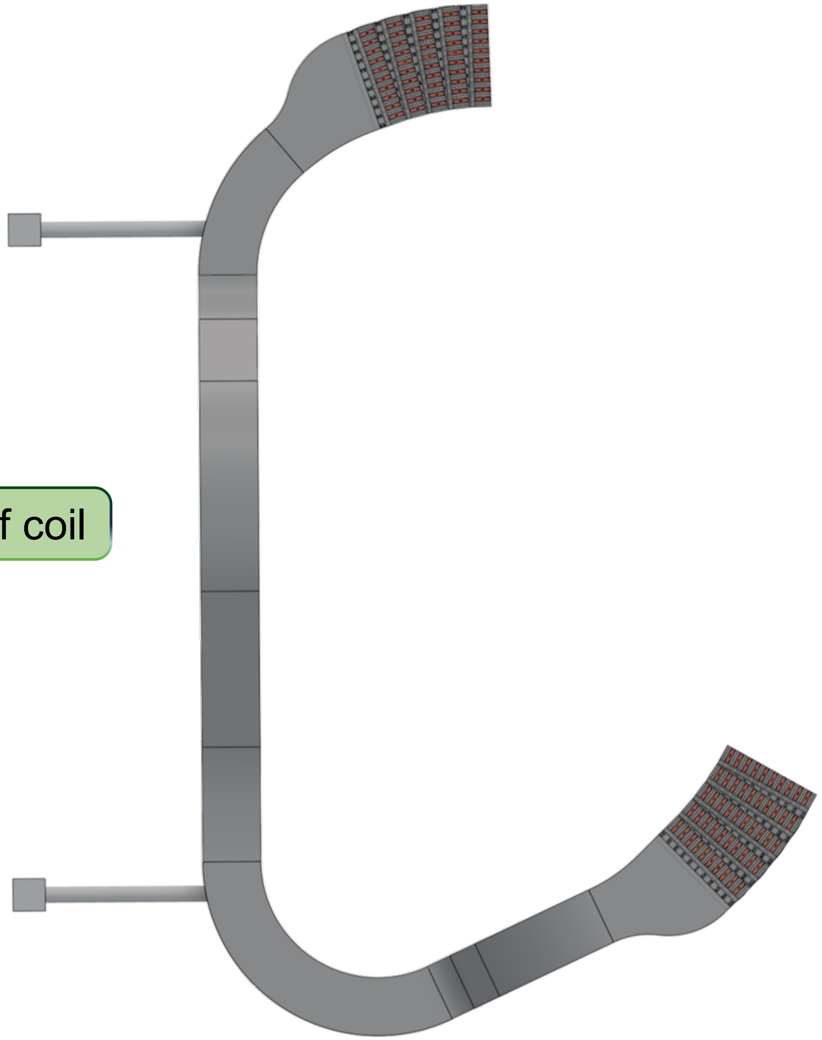
Install-once part of coil



Alignment frame to stack and clamp install once part of coil (demountable part on right comes later)

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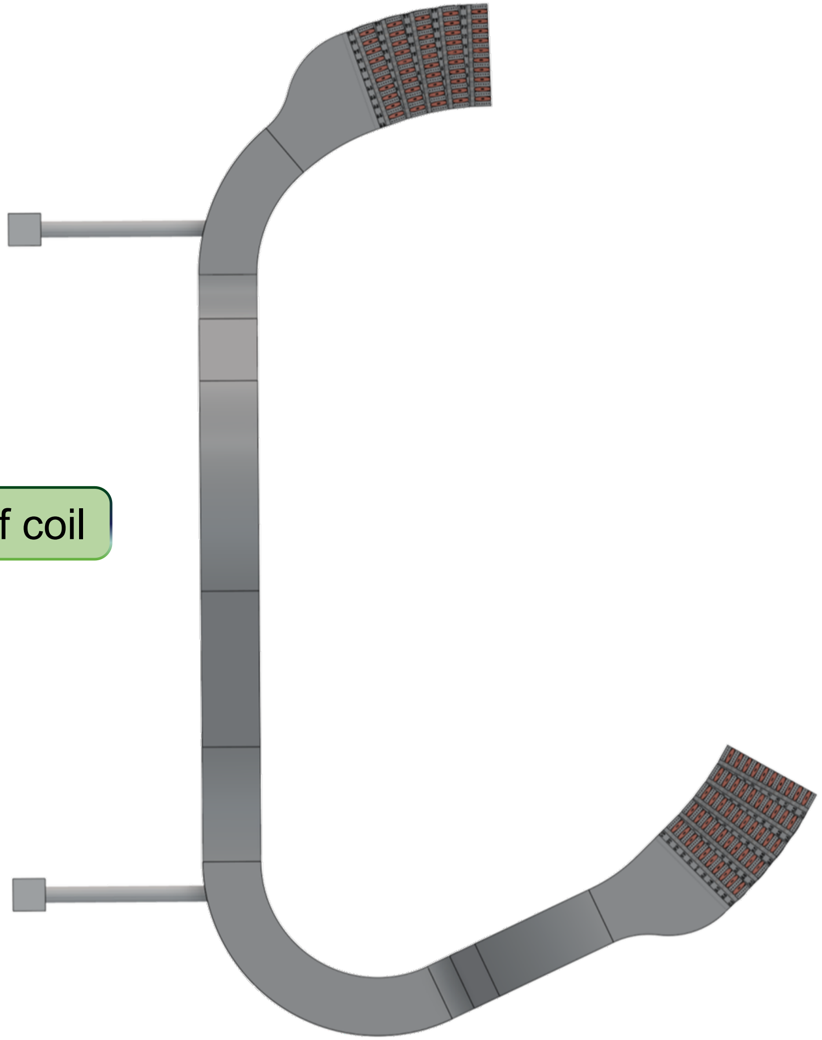

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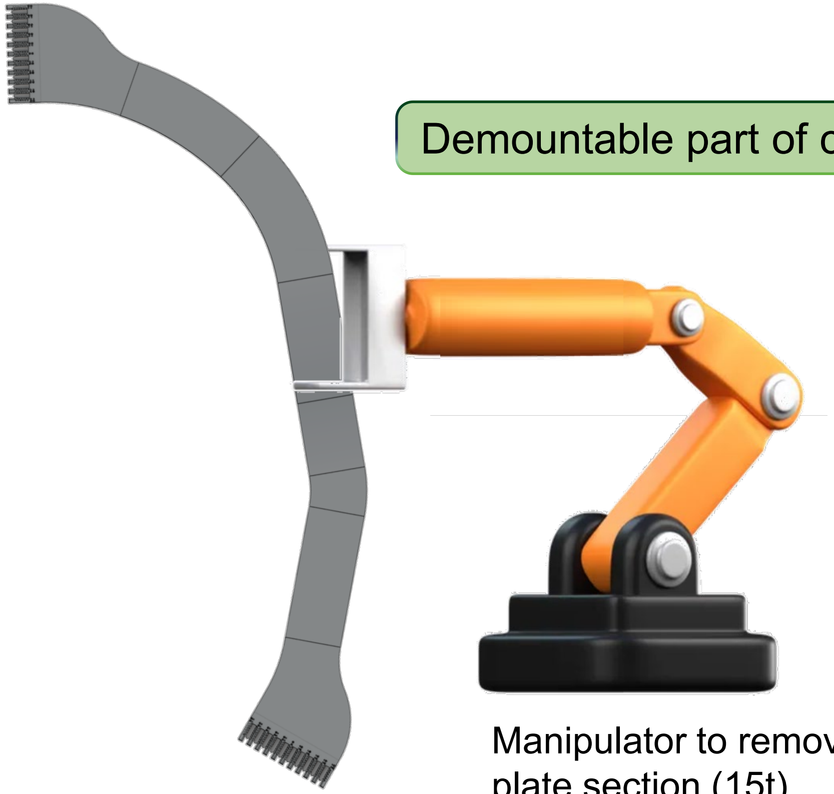
Demountable part of coil



Manipulator to remove/place/align plate section (15t)

Exploiting Demountable Coils

Installation of first demountable plate

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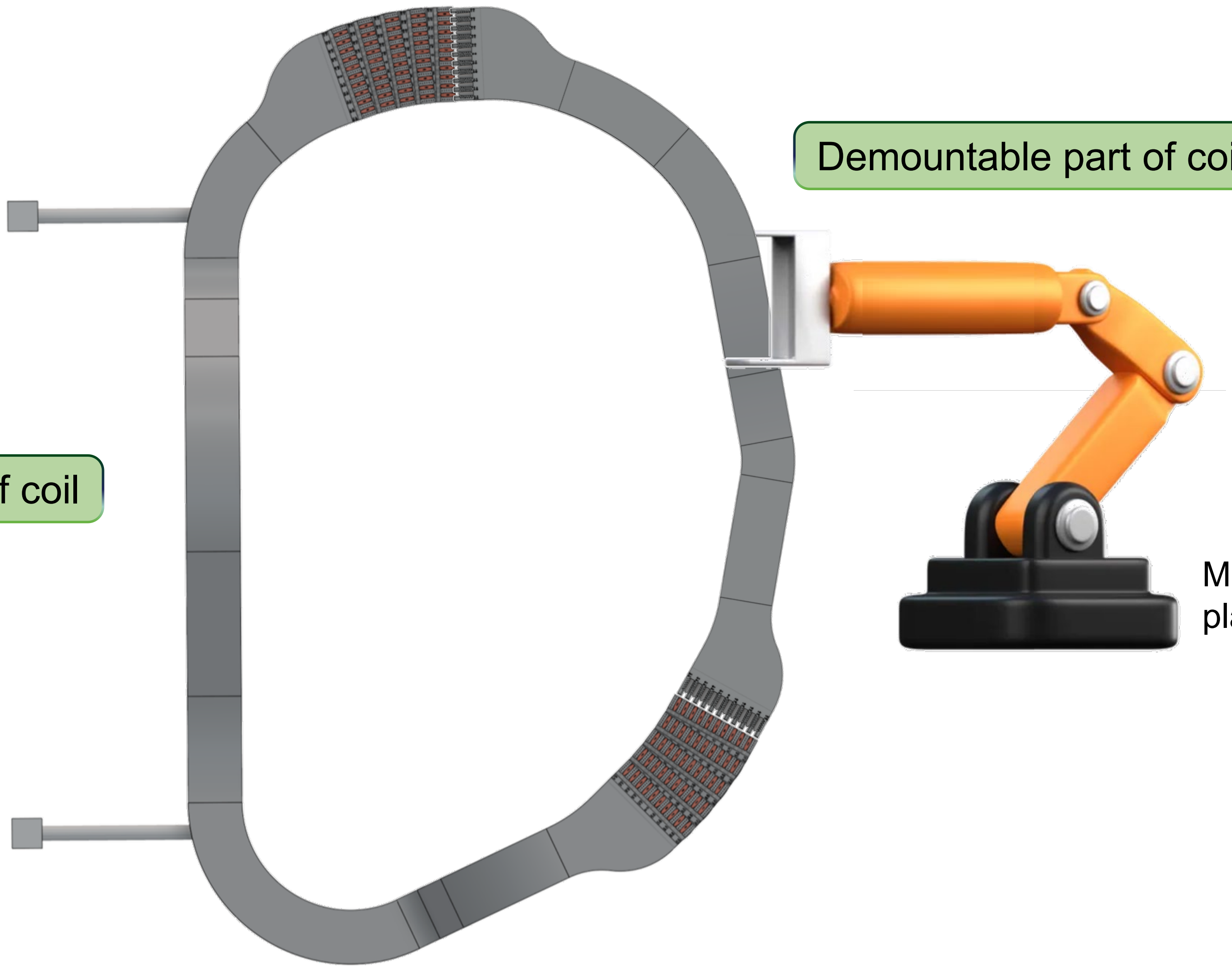


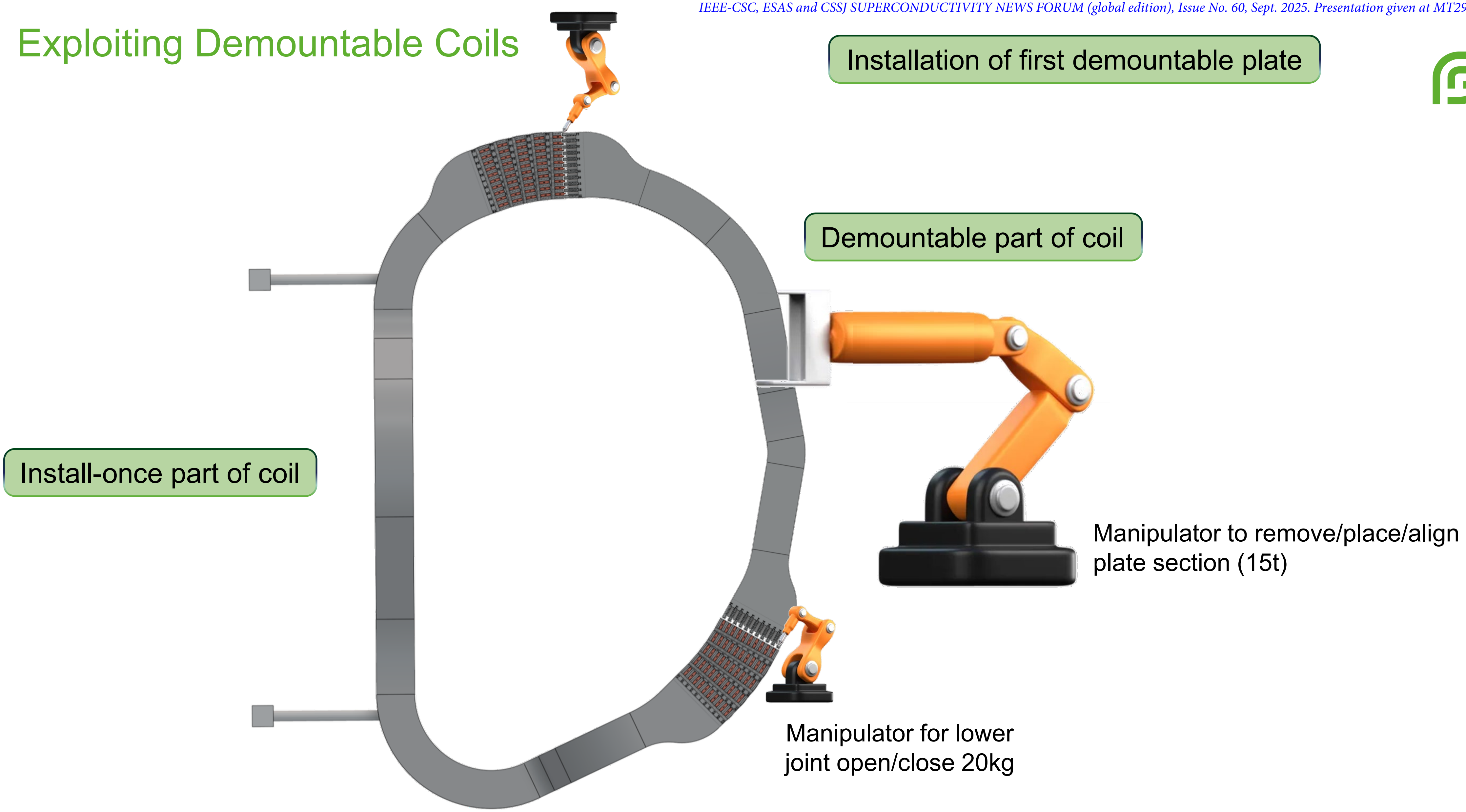
Demountable part of coil

Install-once part of coil

Manipulator to remove/place/align plate section (15t)

Alignment frame to stack and clamp install once part of coil (demountable part on right comes later)

Exploiting Demountable Coils



Alignment frame to stack and clamp install once part of coil (demountable part on right comes later)

Exploiting Demountable Coils

Full coil mounted

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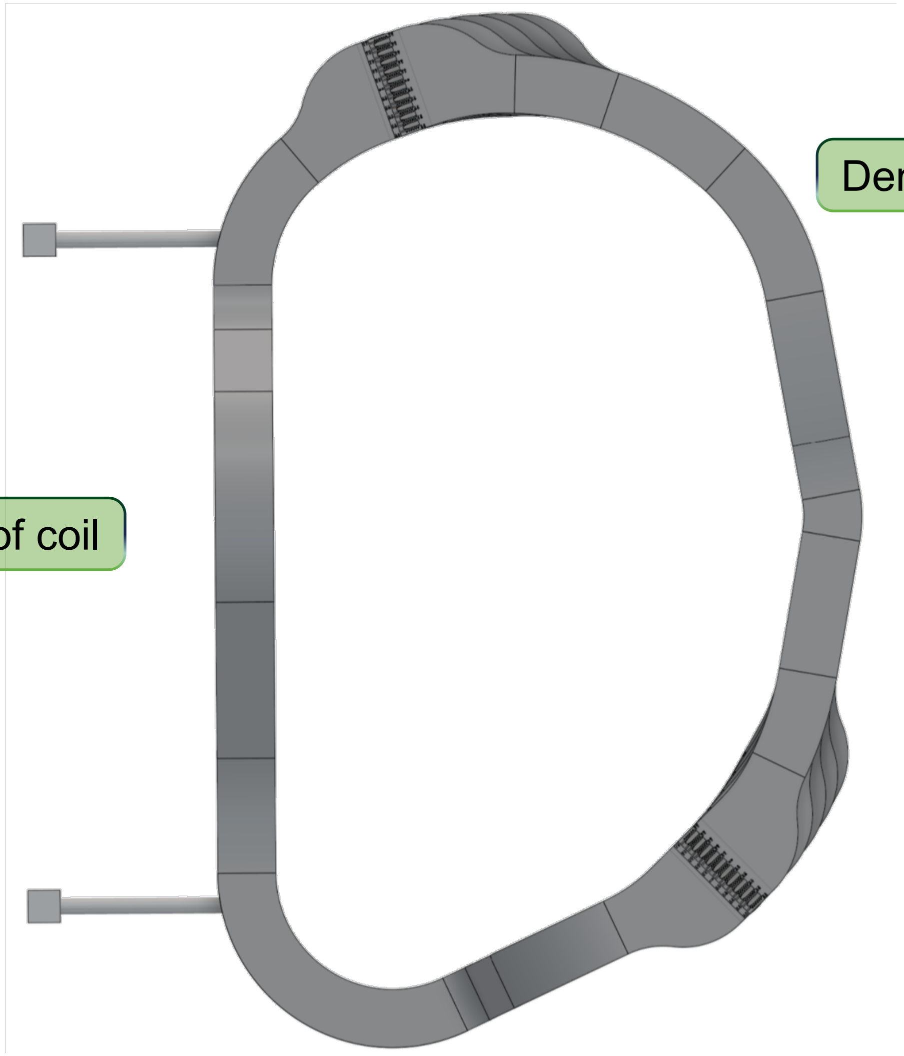

Demountable part of coil

Install-once part of coil

Alignment frame to stack and clamp install once part of coil (demountable part on right comes later)

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Alignment (and Tolerances)

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Key Issues to be solved in demountable coils

- Mechanical locking and avoiding stress concentrations
- Alignment, with multiple tolerances to match simultaneously
- Quality checks (during process)

GFG joint can absorb tolerances at multiple points in the manufacturing and assembly

- Shimming during stacking of the plates (between the plates) based on metrology and bonded G10 flexible plates.
- Shimming of the joint surfaces based on individual metrology. There is an indium washer at each joint surface which can be compressed by the individual joint clamps to bridge any small gaps (2-3mm).
- Compression of the joint surfaces by the clamps using joint and conductor end flexibility. The joints are compressed by clamps acting on a shell over the outside of the conductor at the joint. This shell can be shimmed, and the conductor/joint will have some flexibility to allow the clamp compression to be used to close larger gaps (up to 0.5mm).
- Compression of the plates during stacking (ultimately locked by clamps) using plate flexibility. Final coil alignment +/-5mm on coil current body centre)

Content

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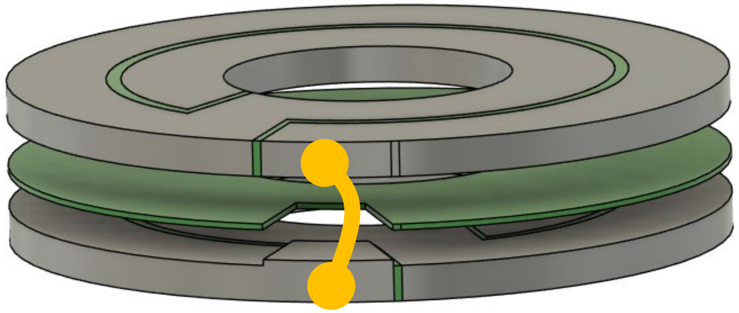
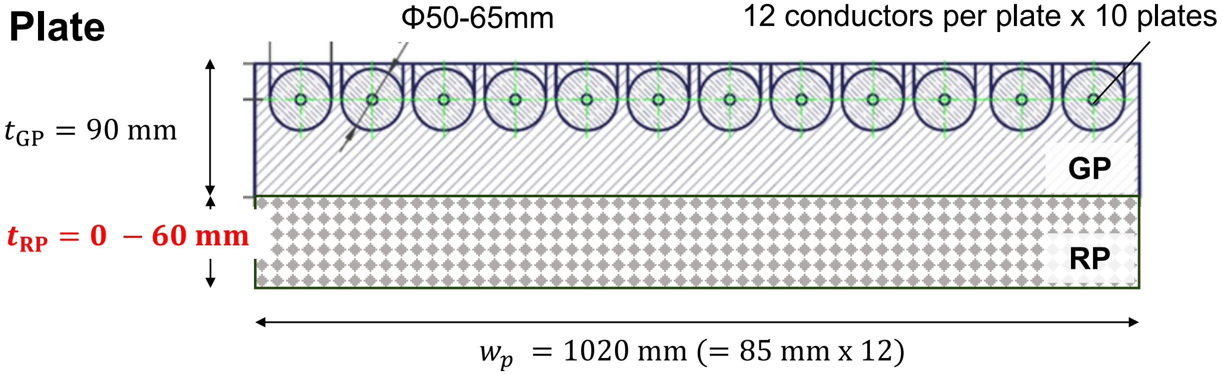
Energy Management

- Low voltage protection
- Active quench protection
- Conductor is designed with extra copper, long discharge time constant (50s>τ>30s)
- Reasonable hot spot limit (<150K)
- Structural plates are used as a discharge resistor
- QD opens circuit between each coil and current flows in conductor and back through plates
- Inductive voltage balances resistive, low ΔV in winding
- Target low coil ground voltages (<1kV, if possible <500V)

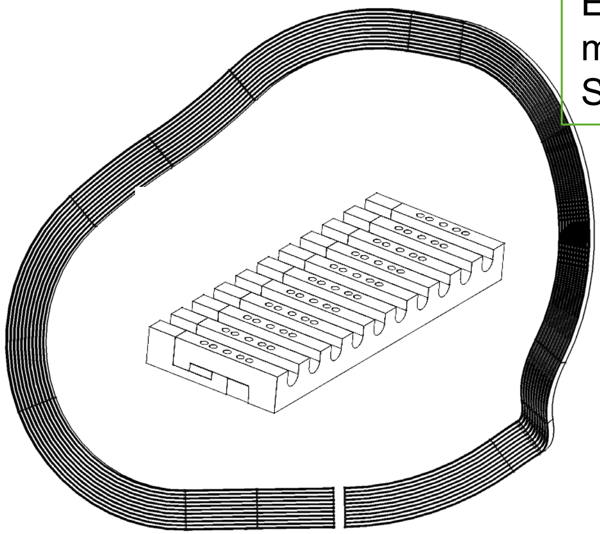
Connection of plates in reverse winding to conductor

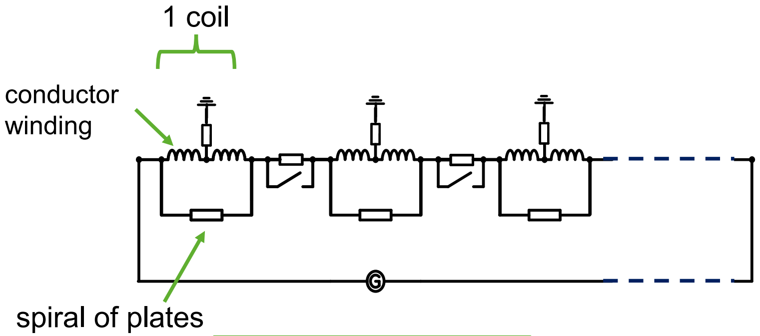


Two plates, one with grooves one without, bonded or keyed

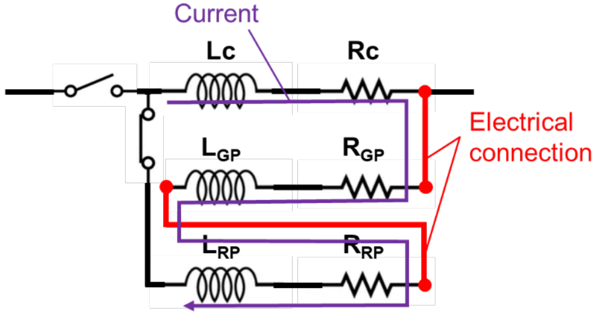


Each plate has an insulated mechanical joint
Staggered to avoid structural weakness





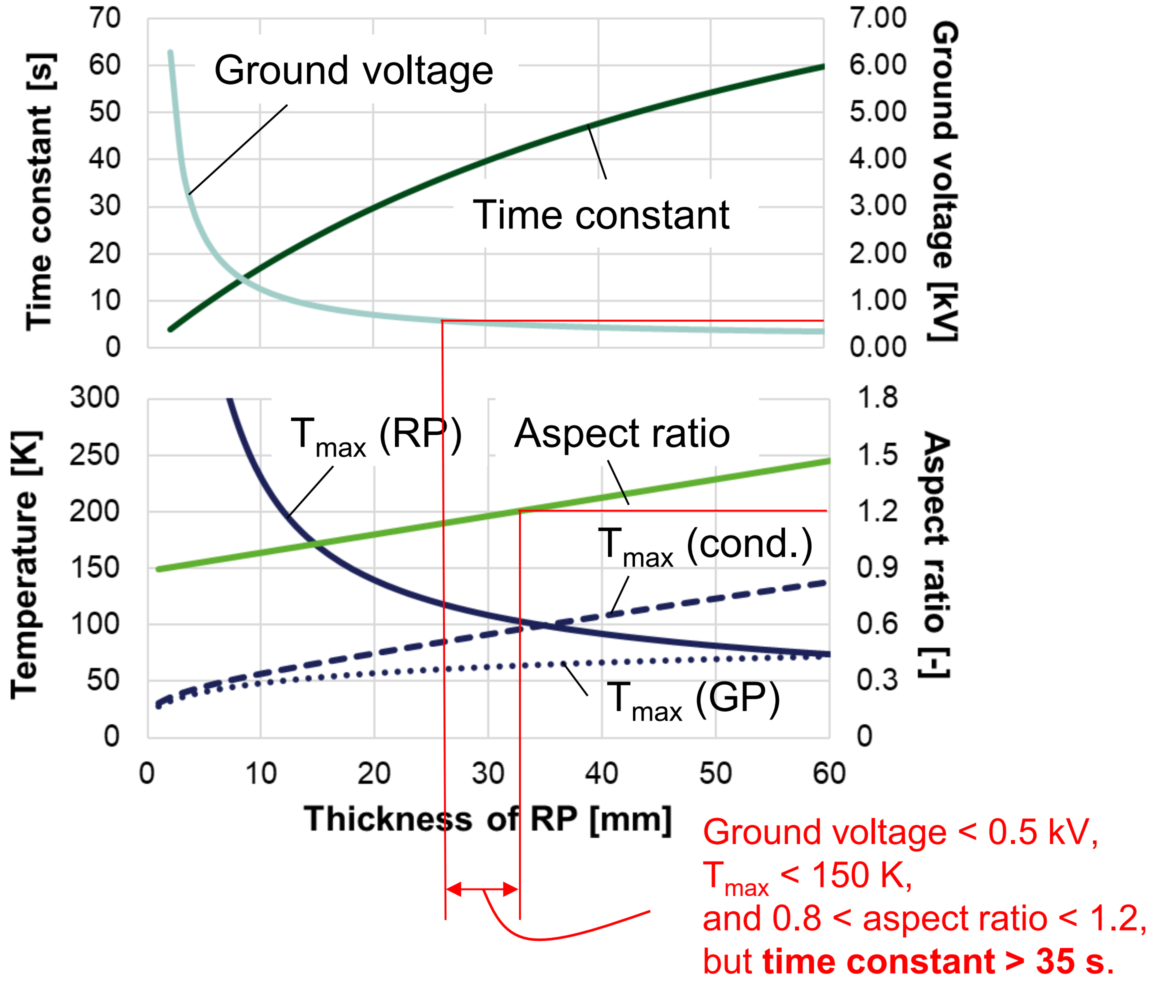
Discharge circuit



(b) Simplified circuit

Balancing Conductor Discharge Time Constant with Plate Resistance with Structural Support

Aim for coil X-section aspect ratio 0.8<AR<1.2
Aim for coil engineering current density 12MA/m2
➔ Range of design options available (and can adapt to different coil layouts)



Considering a 50 K margin to 150 K for QD, the time constant can be increased up to 45 s (> 35 s) in the case of the nominal conductor.

If the diameter of copper stabilizer is increased to ~59 mm (~63 mm in conductor diameter), the allowable time constant becomes ~ 80 s.

Allowable time constant (T_{max} < 100 K)	Diameter of copper stabilizer	Diameter of conductor with 2 mm-thick SS jacket
30 s	~ 46.5 mm	~ 50.5 mm
45 s	~ 51 mm (baseline)	~ 55 mm (baseline)
50 s	~ 52.5 mm	~ 56.5 mm
60 s	~ 55 mm	~ 59 mm
80 s	~ 59 mm	~ 63 mm

Content

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IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at MT29, Boston, MA, USA, July 2025.

Model Coils to test (1) demounting (and remounting) with RH (2) Coil protection system (3) 3D plate manufacturing

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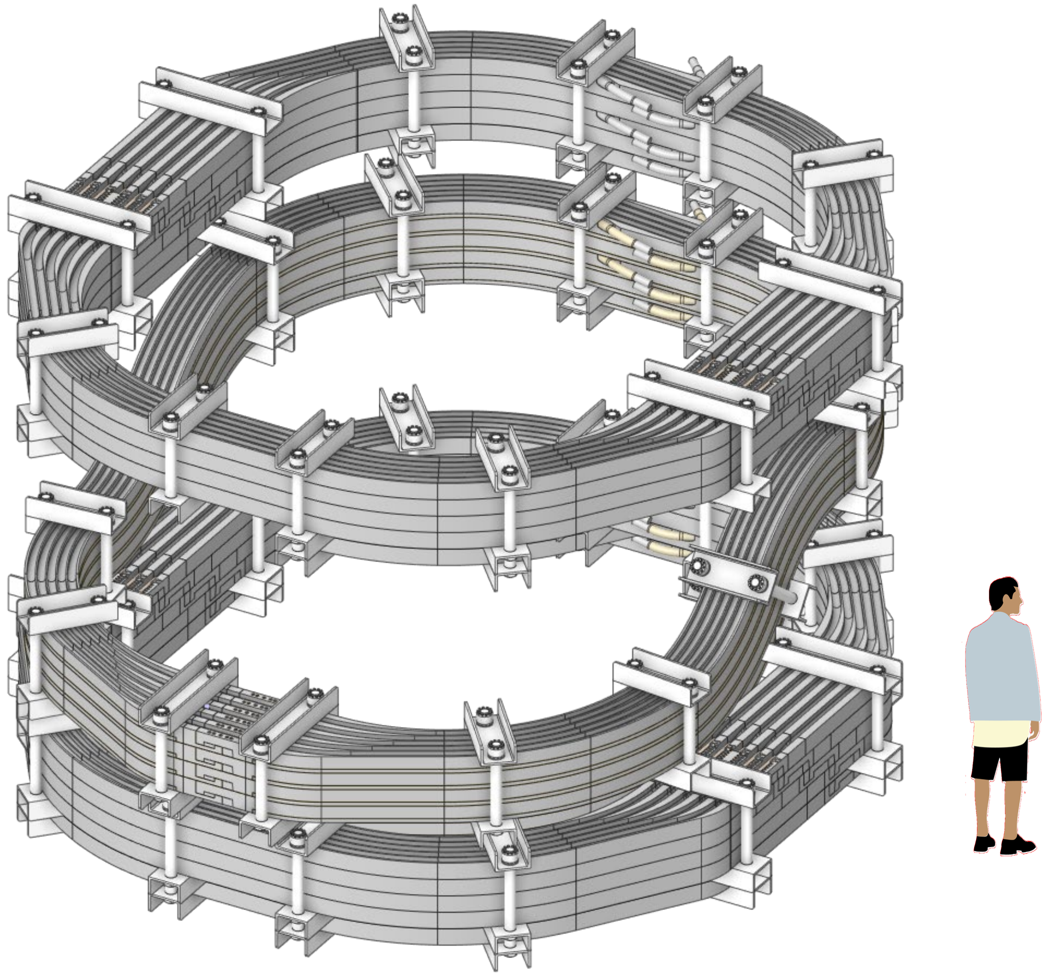
- **Target 1/2 full size** (17.5m perimeter, non-circular 6m diameter) to keep plate and conductor curvature reasonable
- Large enough to ensure use of full-scale relevant tooling and full-scale manufacturing challenges
- Full size conductor and joints
- Make 3 coils, either all HTS or 2 HTS, 1 LTS.
  - One is to test quench detection, protection and resilience, and 3D manufacturing
  - Two are to demonstrate full demountability (one could be LTS)



GFG Magnet Development and Construction Timeline

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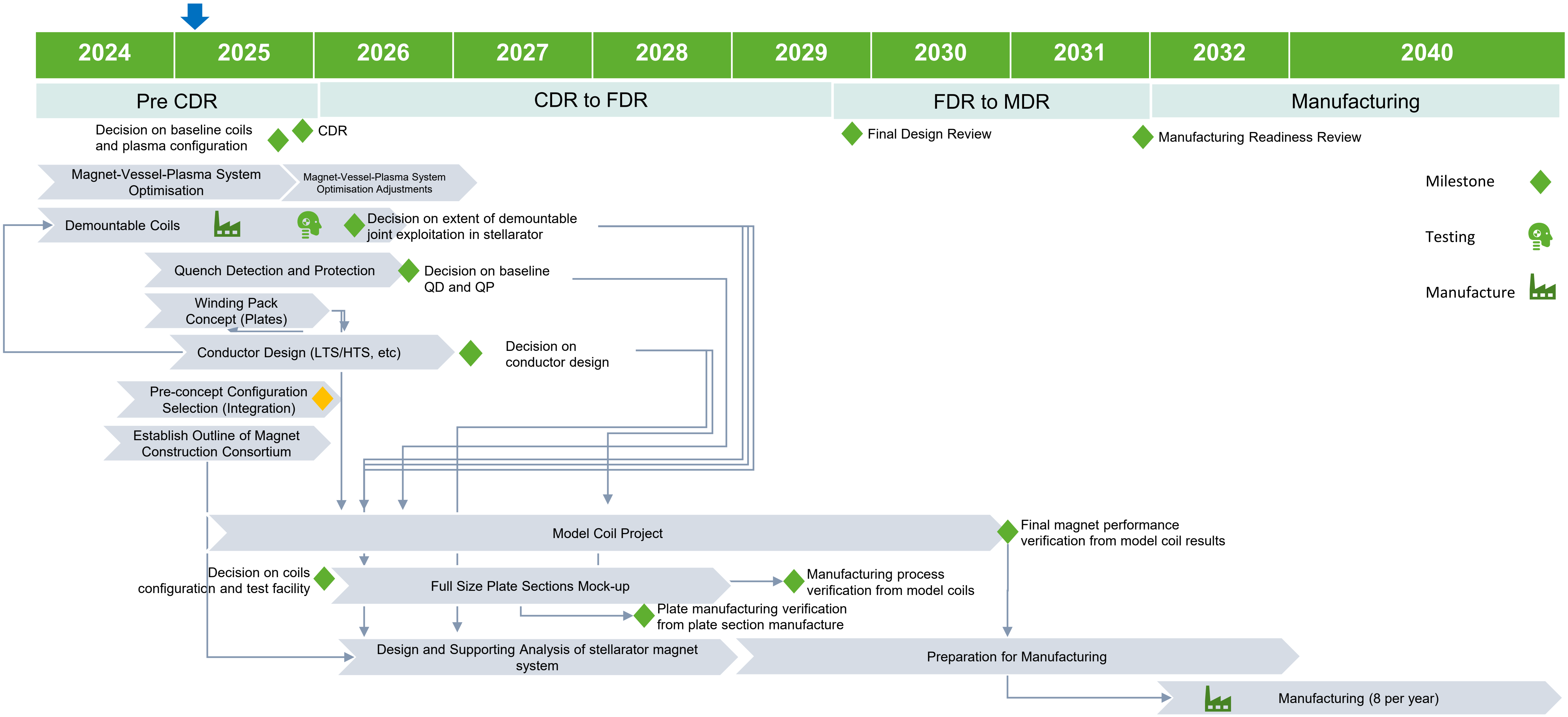

Conclusions

- GFG has an outline design of the main systems for a stellarator based FPP
- This is being integrated to a consistent and realistic conceptual design by end of 2025
- Magnet design
  - ❑ Exploits positive stellarator features: Steady state, electromagnetically stable, all round access
  - ❑ Resolves negative features: Complex 3D coils, large stored energy, difficult plasma access
- To achieve commercially acceptable nuclear component life times, field levels are moderate (11-12T) so both HTS and LTS superconductors can be used. Solutions for both are being developed and demonstrated.
- GFG is preparing a model coil program 2026-2030 that will qualify to a ‘ready to manufacture’ state critical technologies for the coils (including manufacturing routes). The MC are about half full size on linear dimensions and use full size conductors. They achieve relevant current density and quench energy/unit mass
- The model coil program will be complemented by full field conductor tests and full size structural elements of the coils