

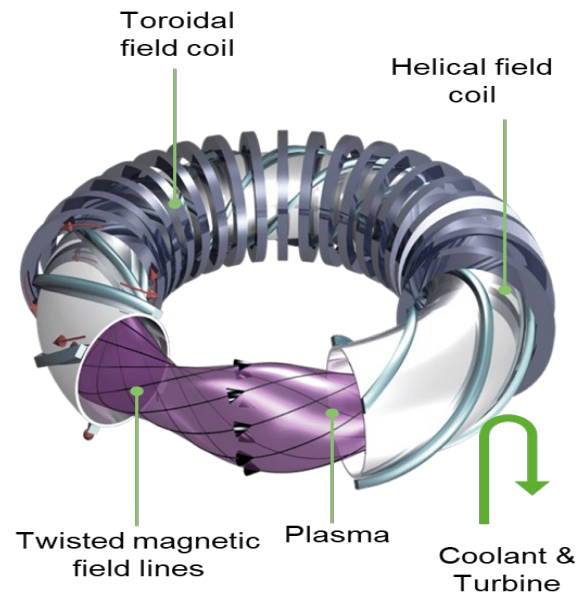
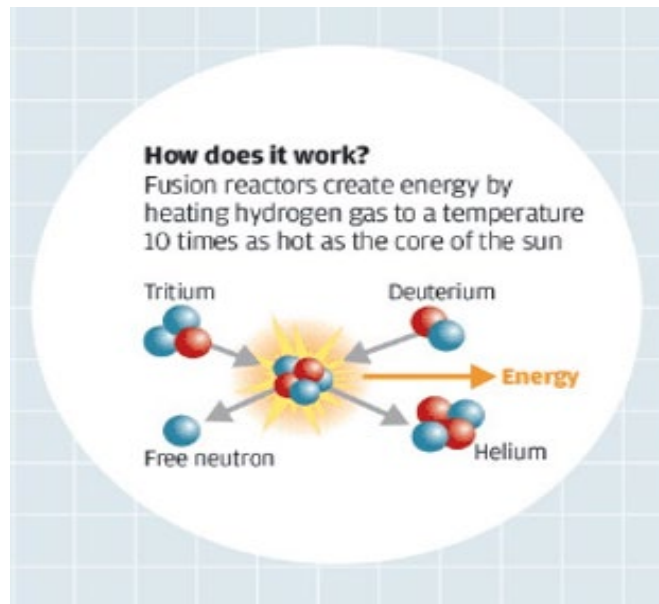
Superconducting Magnets: Key Technology for Fusion

Neil Mitchell (Head of Magnets, Gauss Fusion) & the Gauss Fusion Team

Introduction to Magnetic Confinement Fusion

Components of a fusion reactor

- Superconducting magnets contain a plasma suspended in a very, very clean vacuum
- Plasma contains deuterium and tritium ions – when heated they fuse
- Energy comes out as energetic neutrons
- These have to be stopped (causing heat, which has to be turned into electricity) and absorbed to create more tritium

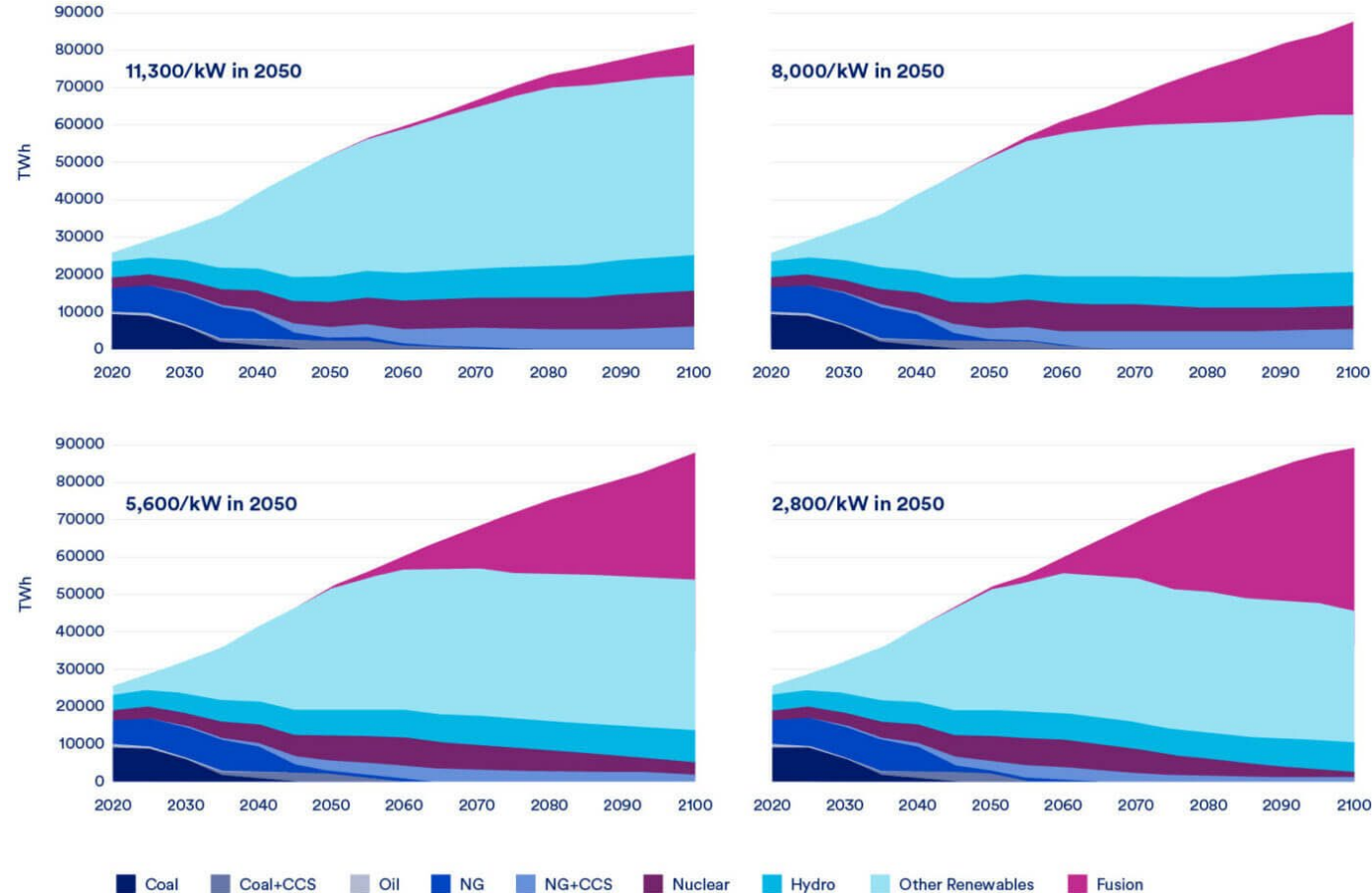


Gauss Fusion is developing a high-field Stellarator based on proven superconducting technology

What is new with magnetic confinement fusion?

Characteristics of an early fusion economy

- Fusion fuels (Deuterium and a means to breed Tritium, likely Lithium) are widely distributed on the planet
- Particularly for energy resource poor regions (China, Europe), fusion offers independence
- Nuclear waste is (compared to fission) relatively low level and manageable
- Ultimately, the dream is deuterium fuelled reactors but >2nd generation FPP



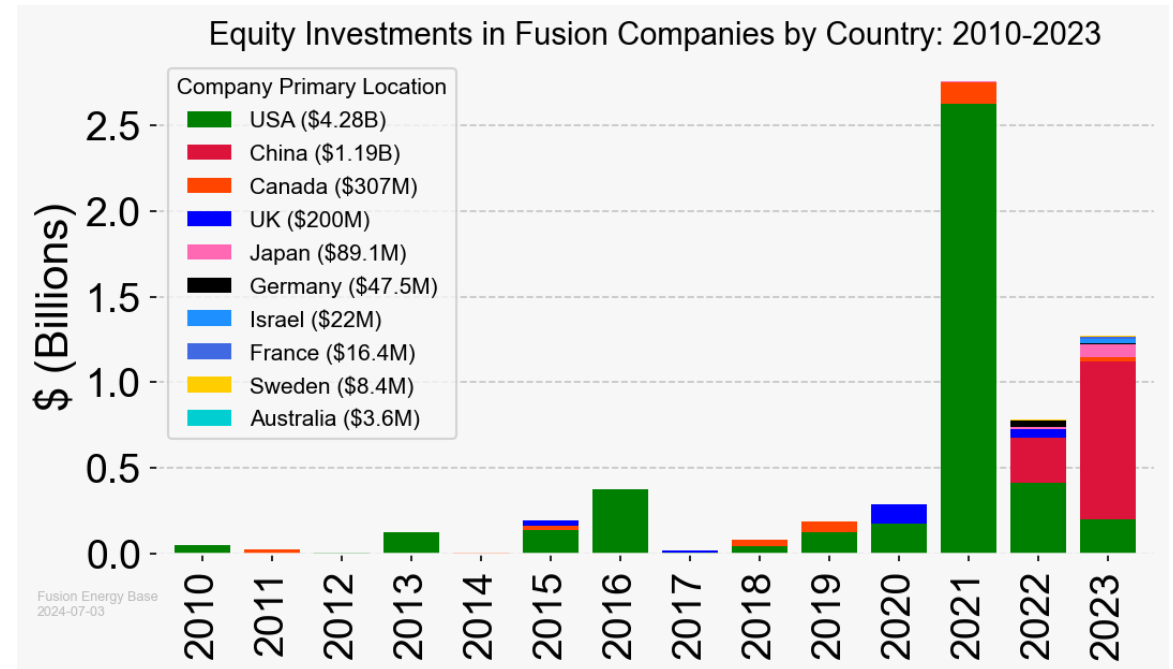
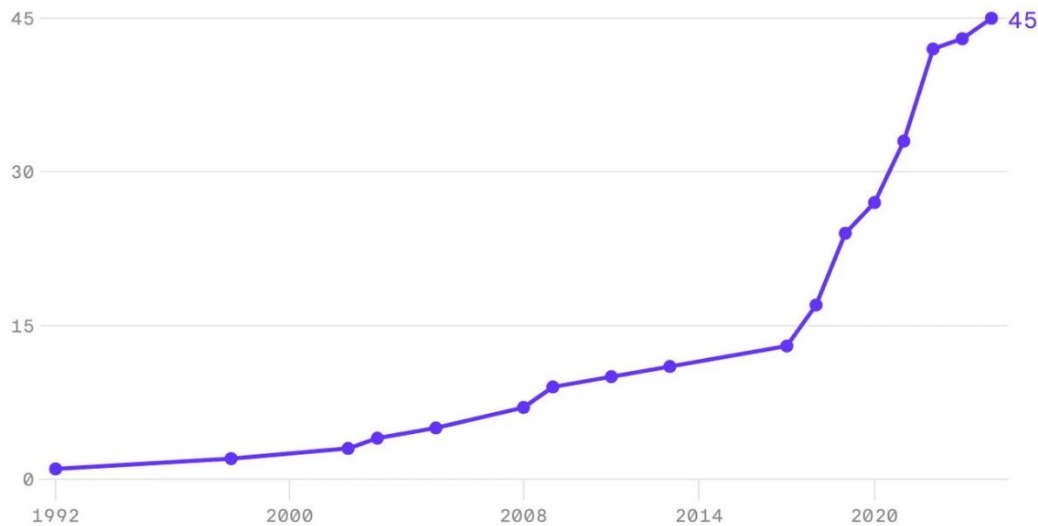
The figure shows four different viable costing scenarios for fusion power plants and the resulting penetration of fusion energy in global electricity markets (finance costs not included).
<https://www.catf.us/resource/fusion-engine-growth-european-industrial-strategy-fusion-energy/>

Changing landscape for funding

- Not only are fusion companies increasing
- They are increasingly aiming to **REPLACE** institutions as device constructors

- **STILL TO BE NOTED**
- Public funding of fusion dwarves private (real ITER budget >2B/year for 15 years)

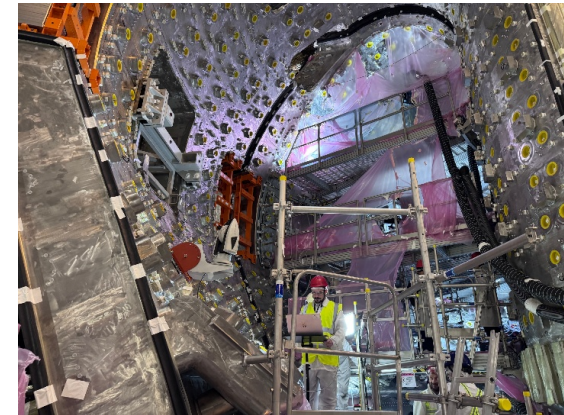
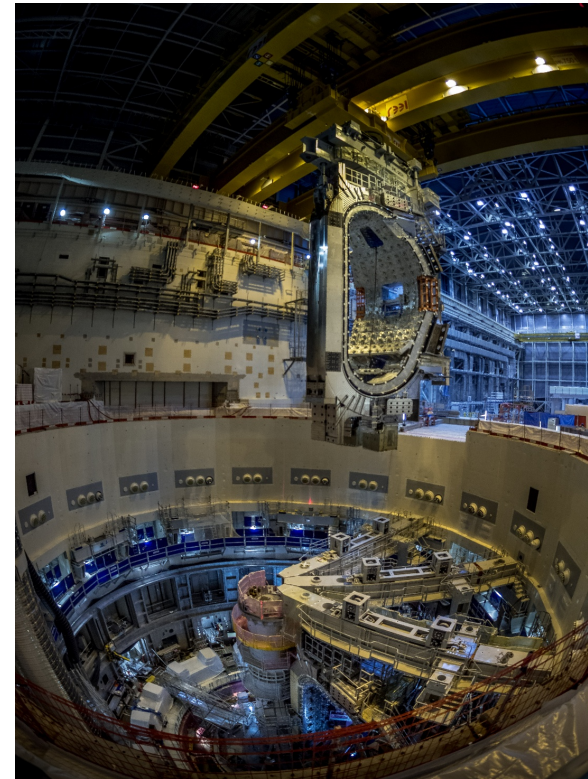
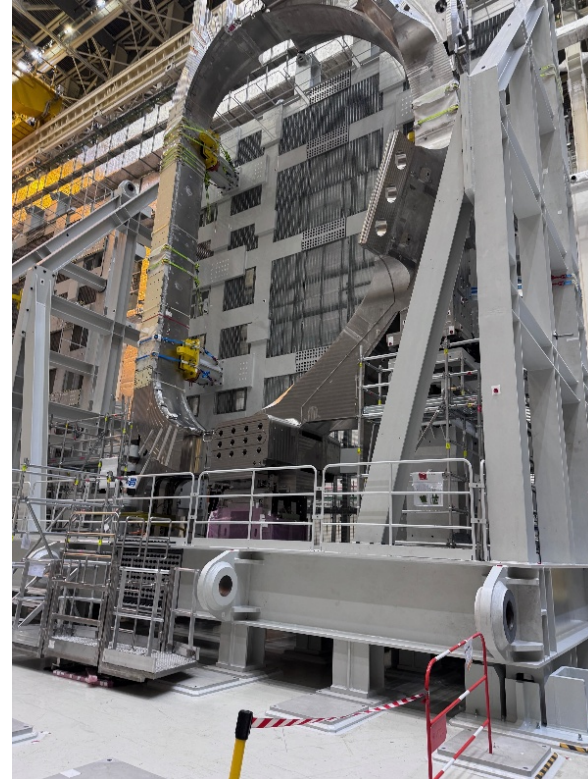
Number of private fusion companies, 1992-2024



<https://www.fusionenergybase.com/articles/equity-investments-to-fusion-energy-companies-2010-2023-by-country>

What does a fusion device really look like?

- ITER project illustrates the highly complex reality of a nuclear fusion power plant over the dreams



Acknowledgment: ITER Project

Where are the problems for a power plant?

The main issues are:

- The plasma (confining, fuelling, exhaust and heating)
- The plasma facing components
- The tritium breeding blanket
- Repair and Maintenance

Magnets have a relatively high TRL

They can in principle be fully tested in advance and there are now industrialised new superconductors that expand the magnet operating range

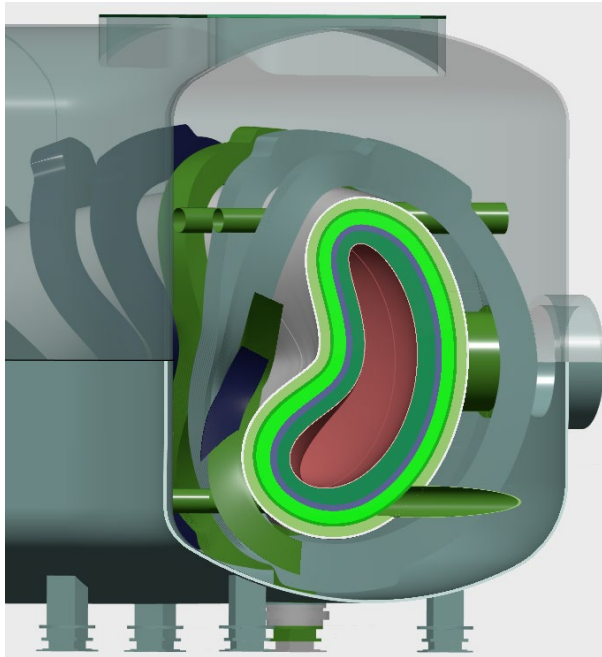
HOWEVER

Integrating magnets into a confinement device creates many constraints on the low TRL components

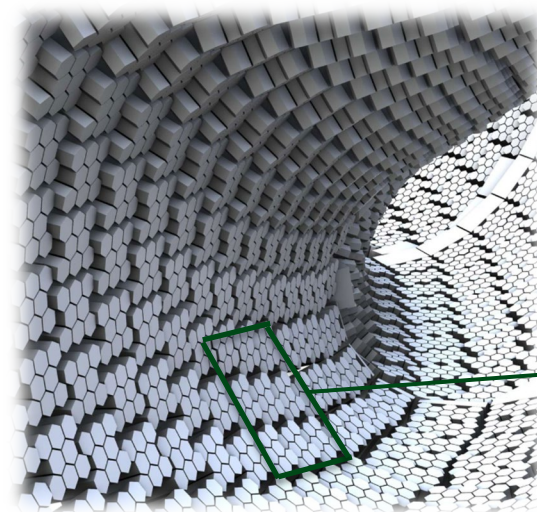
So, magnet technology needs to be adapted for device integration... to assist the design of the low TRL parts

The role of magnets is not an R&D driver but an ENABLER

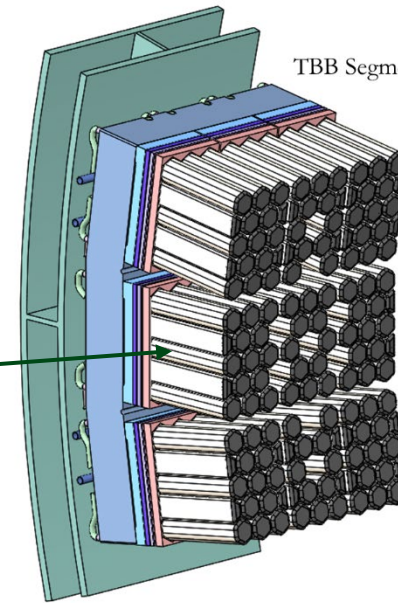
Tritium Breeding Blanket: Segment, Module and Pin overview



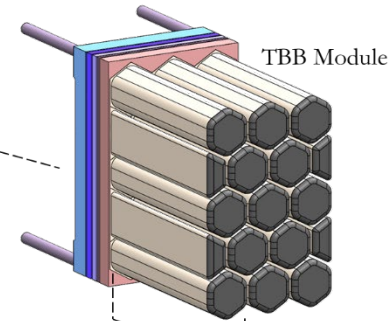
Homogeneous model



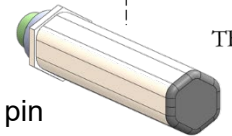
Adaptation to the shape of the vessel



TBB Segment



TBB Module



TBB Pin

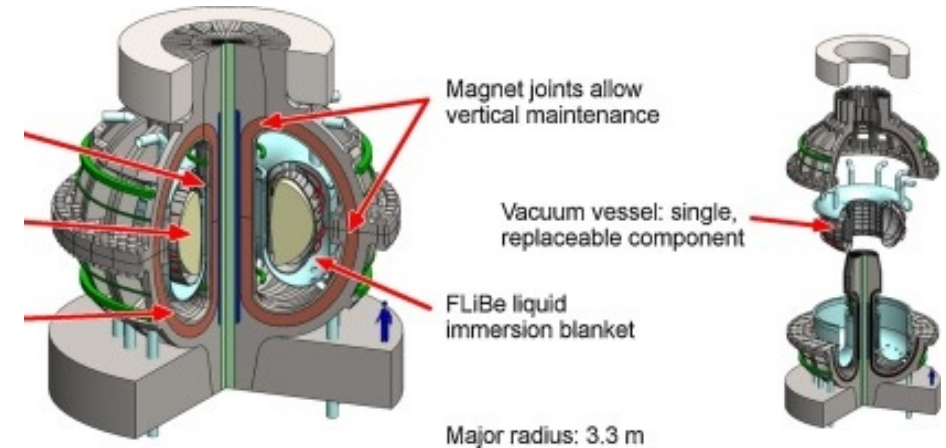
Prototypic pin

- Pins are attached to backplates to form modules
- Modules are further grouped into segments **to enable manufacturing and maintenance**

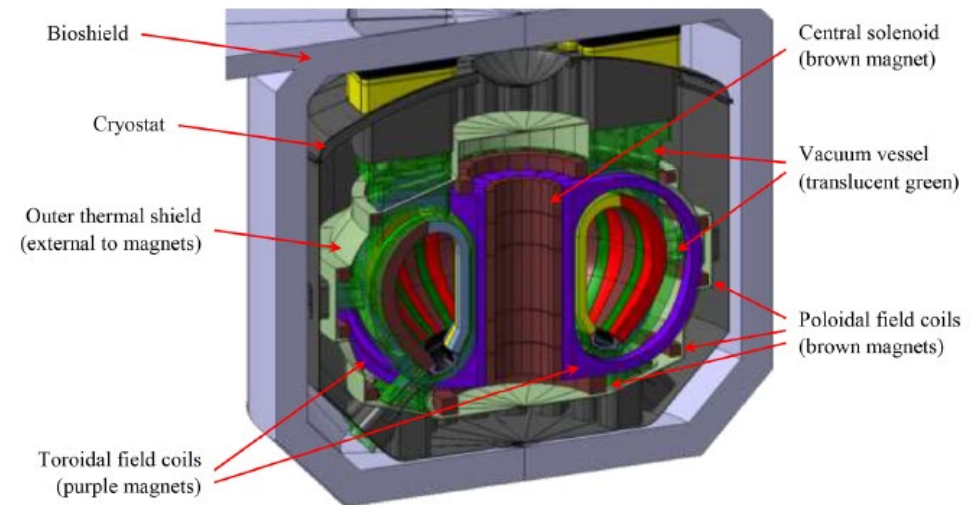
- All of this is LOW TRL, and a MAJOR INTEGRATION ISSUE
- Anything the MAGNETS can do to improve the environment is critical
- Increasing even more the TBB design requirements (ultra high-field, less space and higher power density) is not credible

Large with high-field vs. small with ultra high-field

- Core problem that gains prominence as new superconductors become available
- **New HTS SC can be exploited to operate at ultra high-field but still very low temperature (20T and 20K)**
- **Or new HTS can work at high field and much higher temperature (12T & 40-50K). Here LTS provides a solid high TRL basis for magnet technology development at 5K**
- Advantage of ultra high-field is that plasma becomes denser, much higher power density so device shrinks. But then the radiation lifetime becomes a few years, much shorter than FPP economic life
- Advantage of (real) high temperature is reduction in cryogenic power and potentially much easier machine design (no thermal shield). But, so far, we are still below the 77K LN2 threshold... not really 'high' temperature
- **Advantage of LTS and 5-6K is that conductor becomes a proven, industrialised solution, allowing focus on integration and power plant delivery.**
- **For a power plant, priority is a high-field solution that works reliably at scale**



ARC, ultra high-field low temperature



EU Demo high-field low temperature LTS

Taking fusion to energy production: Nuclear Devices

	Project	Burning Plasma Experiment	Electricity Generating Demonstration	Fusion Power Plant
In Construction	SPARC (CFS)	Q=2, P _{fus} 140MW		
	BEST (China)	Q=5, P _{fus} 100MW		
	ITER (public)	Q=10, P _{fus} 500MW (material testing)		
Planned	CFEDR (China)			>500MW electric
	STEP (UKAEA)		1GW thermal, 400MW electric	
	VNS (EU)	30MW (material tests)		
	ARC (CFS)			400MW electric
	ALPHA (Proxima)	Q=1		
	Infinity 1 (Type One)	Not available		
	GIGA (Gauss Fusion)			1GW electric
	THEA		1.1GW thermal, 390MW electric	
	Stellaris (Proxima)			1GW electric
	Infinity 2 (Type One)			350MW electrical
Helical fusion		0.3GW thermal, 50MW electric		

- Some of this is optimistic and some is dreams

BUT

- For the first time ever, fusion has three *superconducting* nuclear devices in construction
- Good chance that >1 will work

Taking fusion to demonstrator and power plant: Promised Schedules

Project	Status	Promised first plasma date
BEST (China)	In construction	2027
ITER (public)	In construction	2034
SPARC (CFS)	In construction	2027
ARC (CFS) ↓	Planned	Early 2030s
CFEDR (China)	Planned	Mid 2030s
STEP (UKAEA)	Planned	2040s
VNS (EU)	Planned	(no schedule given)

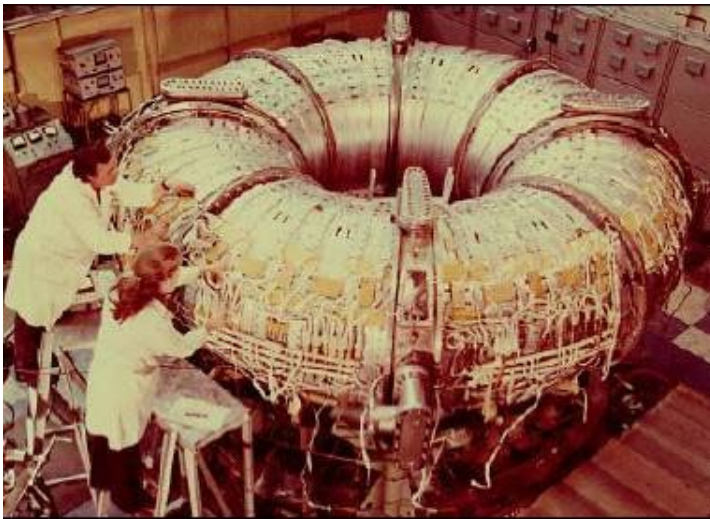
Project	Status	Promised first plasma date
ALPHA (Proxima)	Planned	2031
Stellaris (Proxima) ↓	Planned	2030s
Infinity 1 (Type One)	Planned	2028
Infinity 2 (Type One) ↓	Planned	Mid 2030s
GIGA (Gauss Fusion)	Planned	Early 2040s
THEA	Planned	2030
Helical Fusion	Planned	Early-mid 2030s

- Some of these schedules will be challenging to achieve, with significant components presently only at TRL~2 level
- A number of approaches involve 2 steps and are shown ↓
- As fusion moves towards the power plant level, it needs to show credibility in schedule management if investor & government confidence is to be maintained

Superconductivity and Fusion

The key to economically viable fusion

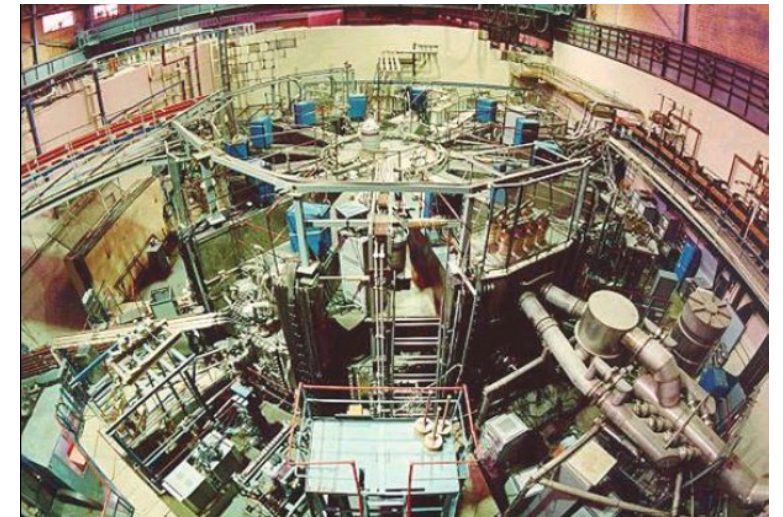
- Long recognised as a key technology for economically viable fusion power plants (first papers published in 1970s)
- First SC tokamaks in 1970s and early 80s (T7, Tore Supra, T15, Triam)
- Last 20 years have seen a big expansion (ITER, W7X, LHD, KSTAR, EAST etc)



T-7 Kurchatov 1979 NbTi TF



Tore Supra, CEA Cadarache 1988 NbTi TF coils 1.8K



T15, Kurchatov, 1988, Nb₃Sn TF coils

Factors behind the development of SC

- Industrialisation of first high-field/less low temperature superconducting material (Nb₃Sn)
- Improved cryogenic technology
- Higher field on plasma (larger stored energy in the magnet system) and need for more compact magnets
- Research requirement for long plasma pulses (many hundred of seconds)
- Improved confidence in application of superconducting technology (designing magnets that work)

Now expect the next big step... magnetic fusion devices with... fusion

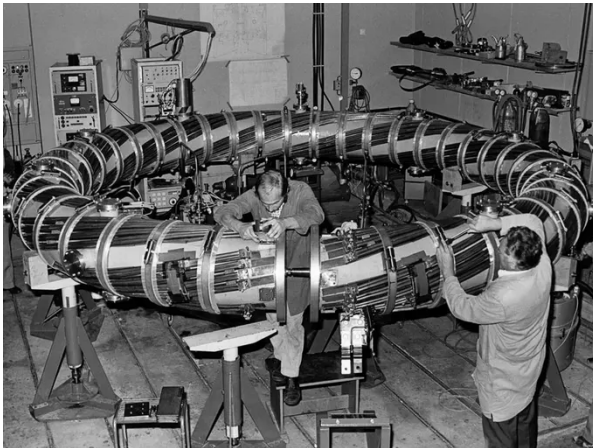
To note... the ONLY devices to achieve measurable fusion so far (JET, TFTR) were COPPER

History of Stellarators in Germany

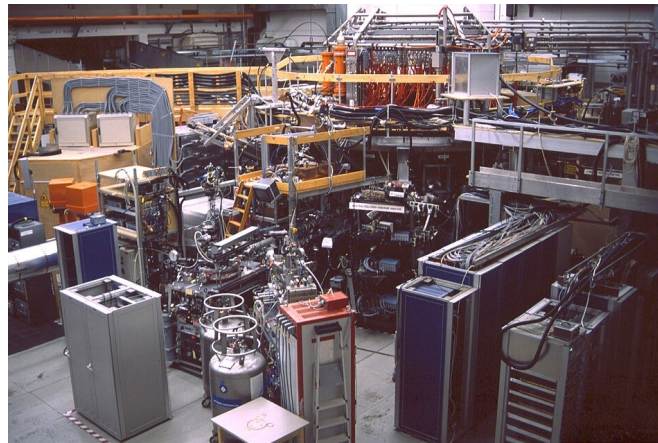
- First stellarator US invention
- Long history in Germany
- From low-field copper to mid-field W-7X with NbTi to high-field (up to 13T at coil) GIGA Stellarator with industrial RRP

Decision point (as with tokamaks)

- Is physics basis good enough to go to a FPP?
- Or do we need (yet) another intermediate research device?



WVII-A – 1980s COPPER



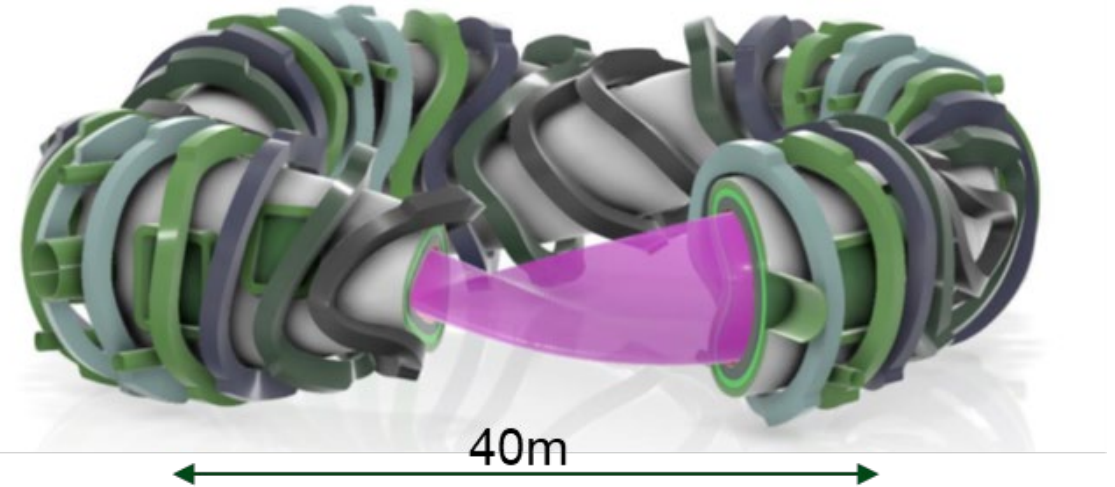
W7-AS 1990s COPPER



W7-X 2010s NbTi

Gauss Fusion's Stellarator Based GIGA FPP

- High-Field Stellarator: 3GW plasma power with 6T in plasma, peak field 13T, Magnetic energy 2.75GJ/coil
- Wall load limits to align with 4.5y lifetime of in-vessel components (strong limit on geometry!)
- VV, coils lifetime components (40yrs) -> shielding requirements
- Target ~2.5m plasma-coil centreline distance to permit VV shielding
- ~50 MW ECRH to burn @ 170 GHz
- Based on high-field Nb₃Sn (RRP), with optional HTS when qualified
- Cross-section is no larger than ITER (magnets, VV transport limits)



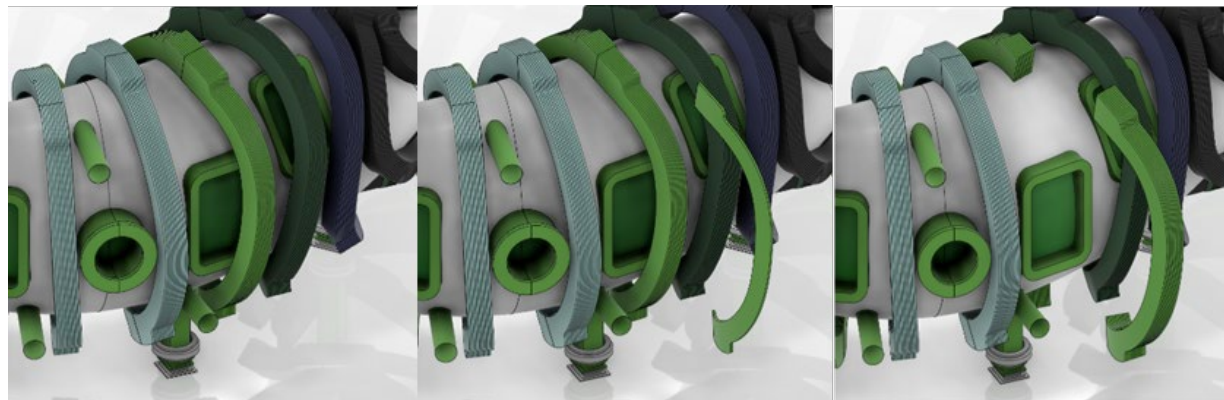
GIGA: Leading example of a Stellarator FPP

Conservative on Plasma Configuration, based on W7-X

- Power plant, not a burning plasma experiment or a demonstrator
- Sensible commercial life using present technology
- Avoids tokamak power plant pulsed operation issues
- Realistic solutions for remote handling, divertor and tritium breeding

Conservative baseline: industrialised Nb₃Sn (RRP), with conditional HTS option

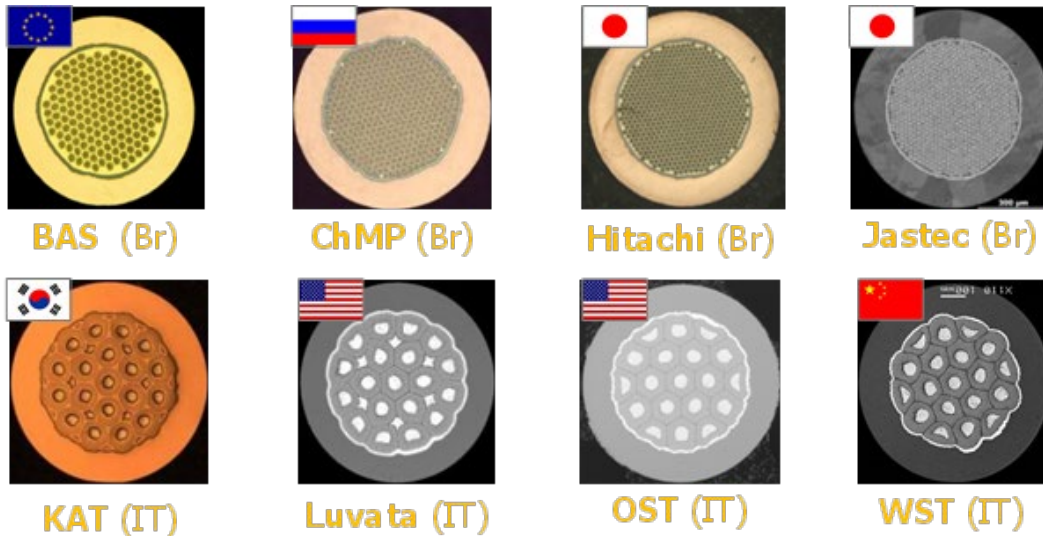
- Need about 750t of Nb₃Sn (at 5K)
- HTS is not yet demonstrated for reliable stellarator power plant magnets at scale and should only be considered if:
 - (a) large-scale magnet performance is demonstrated
 - (b) quench protection and survivability are proven
 - (c) European supply chain is established



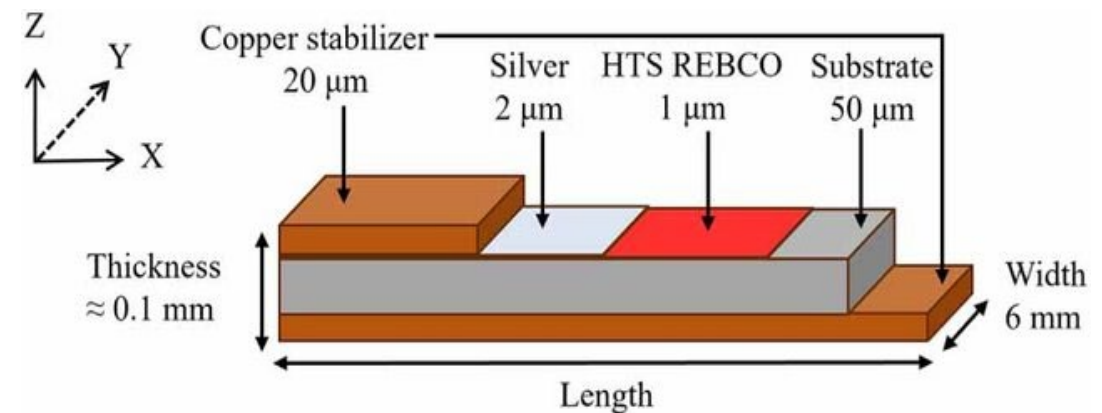
GIGA coil being dismantled plate by plate, releasing access to large hatches in VV

Superconducting technologies I: Base Building Blocks

- Many known SC materials
- Only a few become products that can be used for current transport
- Even fewer can be considered industrial products and some have supply chain issues
- What we have now: **NbTi**, **Nb₃Sn**, MgB₂, Bi2223, REBCO.
- The **successful** ones all have multiple industrial suppliers well distributed internationally



ITER Nb₃Sn Strands & Suppliers: Diameter 0.81mm, Cu:non Cu 1.0

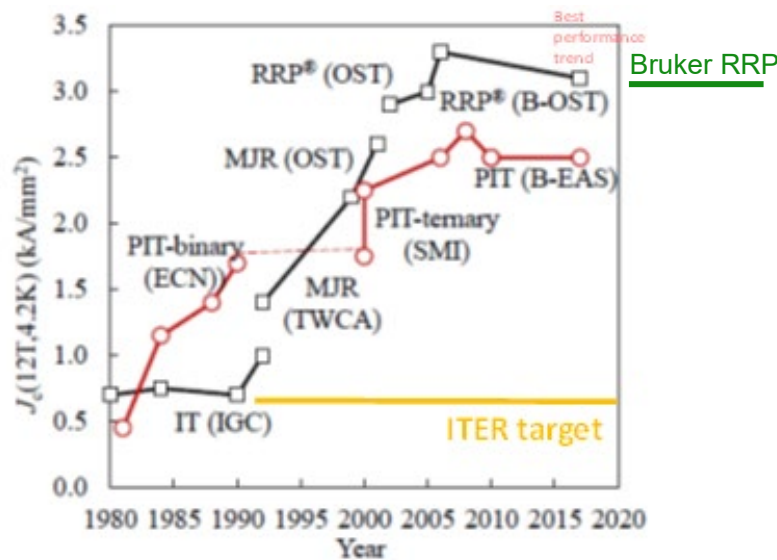


REBCO TAPE: Three-dimensional electromagnetic–mechanical coupled modelling of multilayer HTS REBCO coated conductors considering strain effects March 2026 Superconductor Science and Technology 39(3) DOI: 10.1088/1361-6668/ae49bd

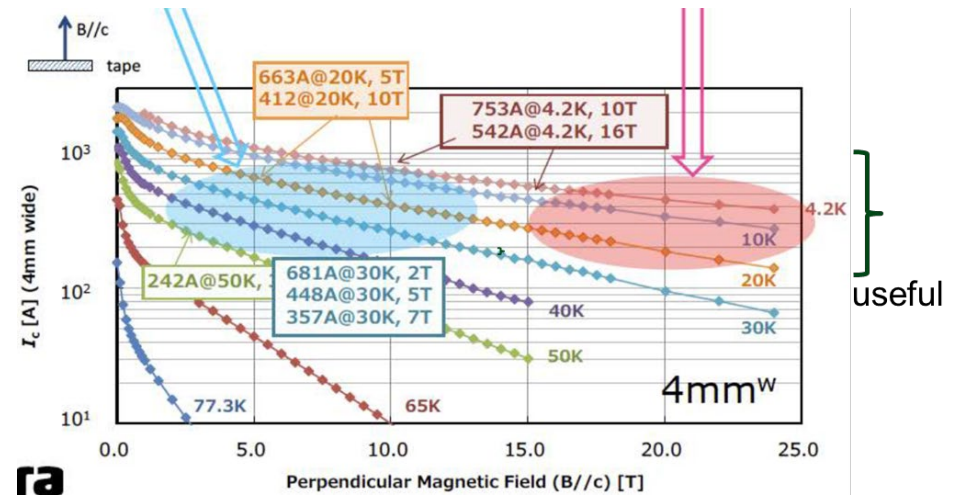
Performance development: LTS & HTS

- Nb3Sn (RRP) is a high-performance, industrialised conductor, already used in leading high-field applications
- Magnet application is not easy but is developed
- Continuous improvement over 25 years, now levelled off
- Final product form for GIGA is **Bruker RRP** as used in CERN Hi Lumi and BEST in China

- HTS REBCO early stages of industrialisation
- Still at stage of manufacturing improvement & rapid change (unit lengths, uniformity, anisotropy, degradation)
- Application in early stages, critical areas to be qualified
- Supply chains weak in Europe



Nb3Sn (RRP) enables high-field, industrial-scale magnets suitable for a FFP, not just experimental devices



Example REBCO tapes with APC Fujikura FESC type
Acknowledgement: Satoshi Awaji, IAEA Ninth DEMO and Fusion Plants Workshop

Superconducting technologies II: Coils

- Superconducting building blocks, strands and tapes, typically carry currents of few hundred A, similar area 1mm²
- This seems to be quite a universal rule and is probably associated with the flexibility in multiple applications
- For fusion, these blocks have to be built up into cables with many strands and tapes in parallel (between 100 and 1000) to minimise internal voltages and with internal current transfer to adapt to local damage

LTS: Well understood and qualified

HTS: Testing ongoing, quench and degradation issues to be fixed

Example LTS cable
Established technology – CICC

1mm Nb₃Sn strands

Sc Strand

Cu Strand

Sub-Cable Wrap

Cooling Spiral

Stainless Steel Conduit

Acknowledgement: ITER

Example HTS cable
Soldered stack concept

12 mm HTS stacks

Cu spacers

30-tape stack

slotted core

wrapping

jacket

Tape 12 mm x 3 mm
Variant 1

- 6 stacks of about 25 tapes arranged at as low a radius as possible to minimize bending stresses
- Copper cap
- Solder filled

Cu stabilisation (optional)

Ag cap layer

REBCO layer

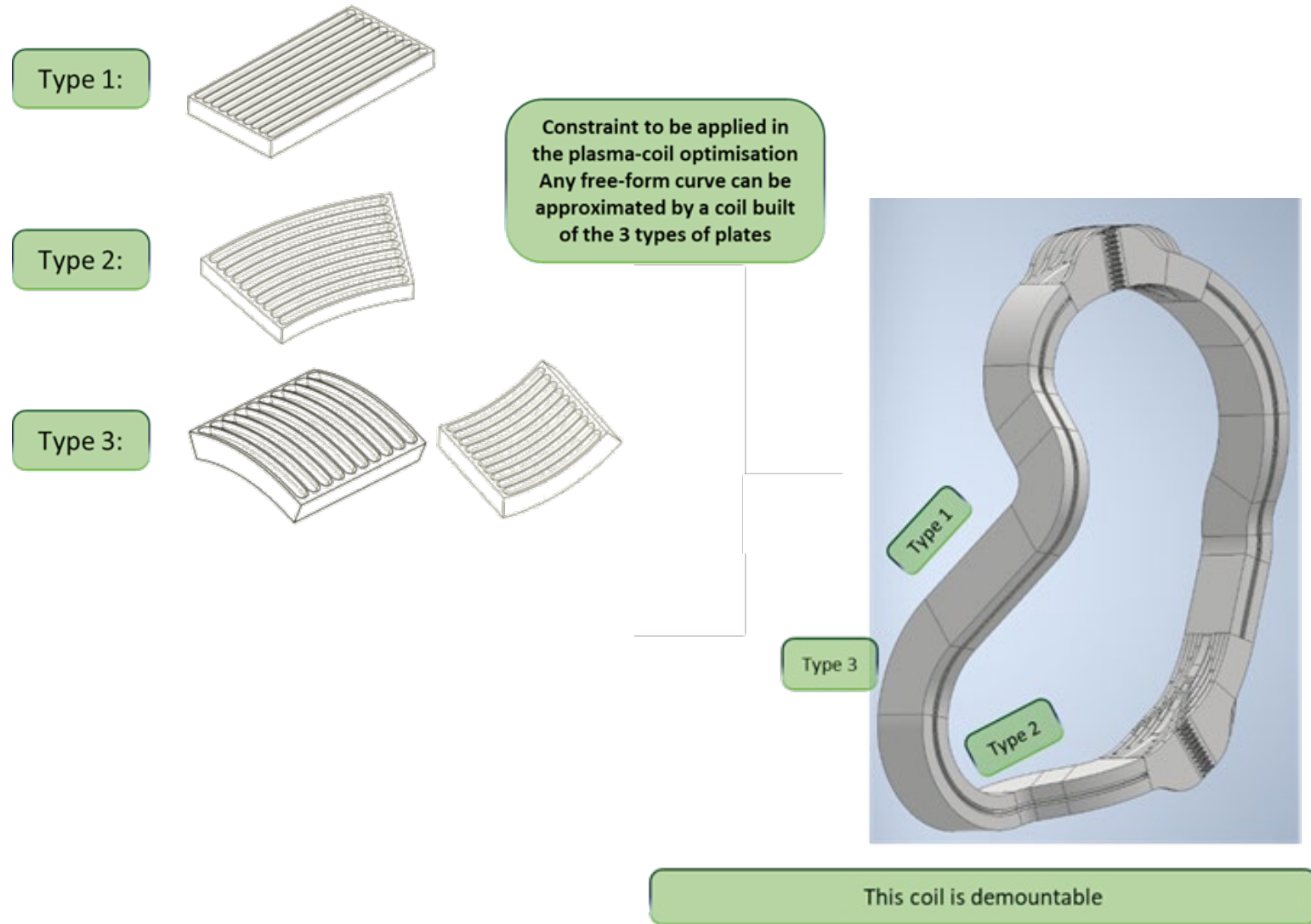
buffer layer stack

substrate

G. Celentano et al., "Design of an Industrially Feasible Twisted-Stack HTS Cable-in-Conduit Conductor for Fusion Application," 2014

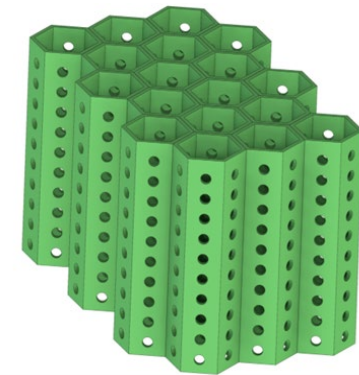
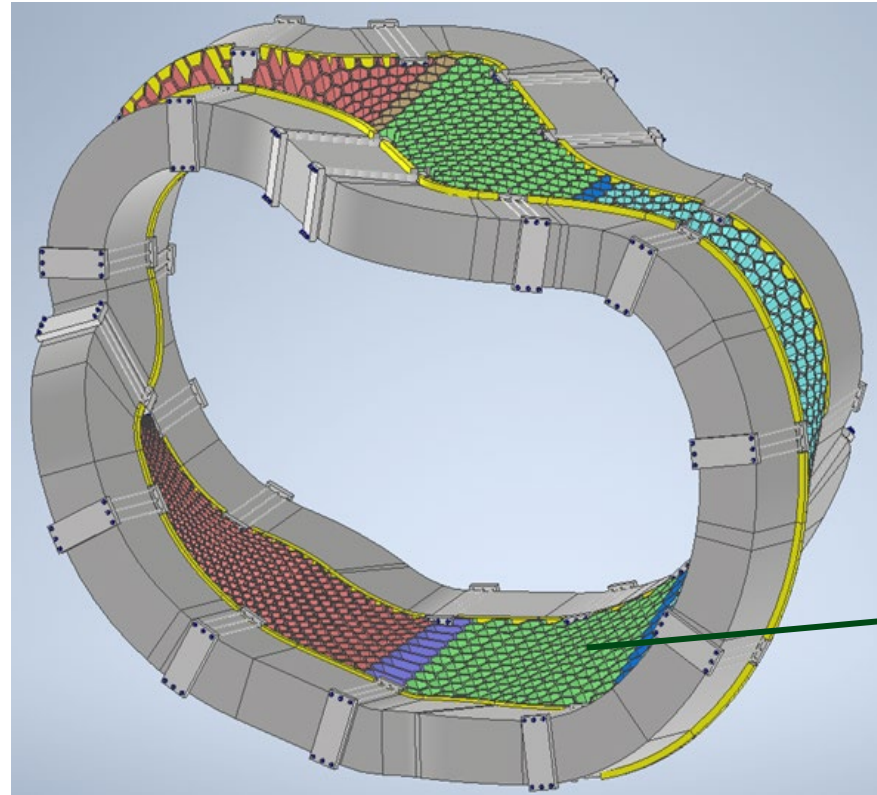
Superconducting technologies III: Structures

- Stainless steel and make up >50% of the magnet cost
- **Worth noting that Stainless Steel was invented 2 years AFTER the discovery of superconductivity**
- Many lessons can be learned from ITER TF coil cases and VV (controlling welding distortion and achieving tolerances at reasonable cost being the main one)
- GIGA coil structures are innovative to solve some of these problems
- Structural design enables Demountable Coil magnets, critical for maintenance and power plant operation
- Still need work on forging and joining technologies
- German industry a leader in this area



Highly modular concept for the intercoil structures between the coils

- Compatible with demounting in small (and variable) sections by remote handling
- Adaptable to the 3D curves and variability of the gap between the coils and multiple large and small penetrations.
- Easily allows large and small penetrations to the vessel
- Forms part of Gauss Fusion's Demountable Coil magnet architecture



Bolted 'breathable' honeycomb structure to provide intercoil support, easy integration of permanent ports and removable for large hatches

Superconducting technologies IV: Energy Management

Increasing magnet size and field



increasing magnetic energy stored in the magnet system



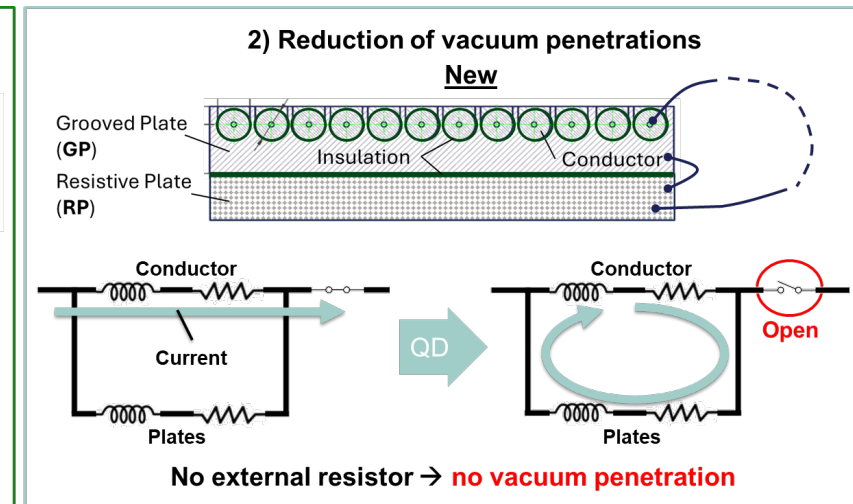
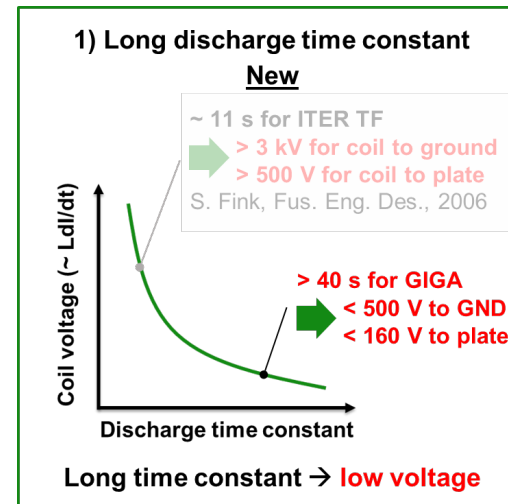
increased damage potential if the superconductor unexpectedly stops superconducting

Improved superconductor margins (illogical) increase the risk as the magnetic energy turns to heat in a more localised way... the better the superconductor, the more unlikely a quench, but the more difficult to detect and the worse the consequences if it happens

So far, EVERYONE needs quench detection

Assorted solutions

- Non-insulated coils (only at small scale)
- Non-insulated coils with active heaters for protection (CFS, Proxima, STEP)
- Low voltage coils using structural components for protection (Gauss)
- High voltage energy extraction to external resistors (ITER)



Gauss GIGA Solution

Gauss GIGA is a leader in applied superconductivity

Integrate: Magnets and access in-vessel



Assemble: Get magnets around the vessel in the first place



Maintain: Repair magnet faults

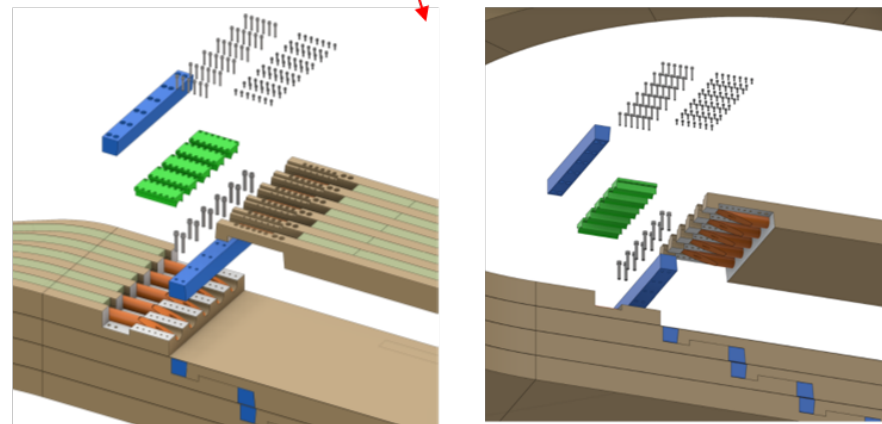
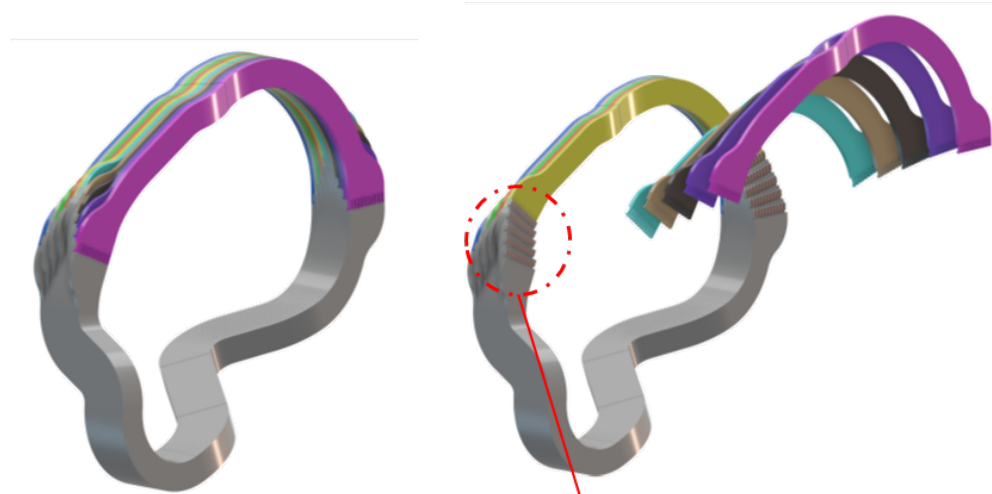


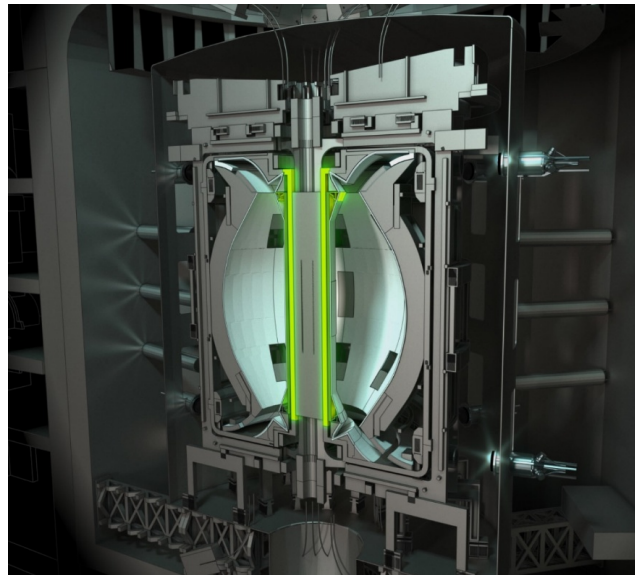
Illustration of a Mount-Once/Mount-Many Concept, with coil split into separate plates once the clamps are removed

Demountable Coil magnets are a defining feature of the GIGA design, enabling maintenance, access and reliable power plant operation

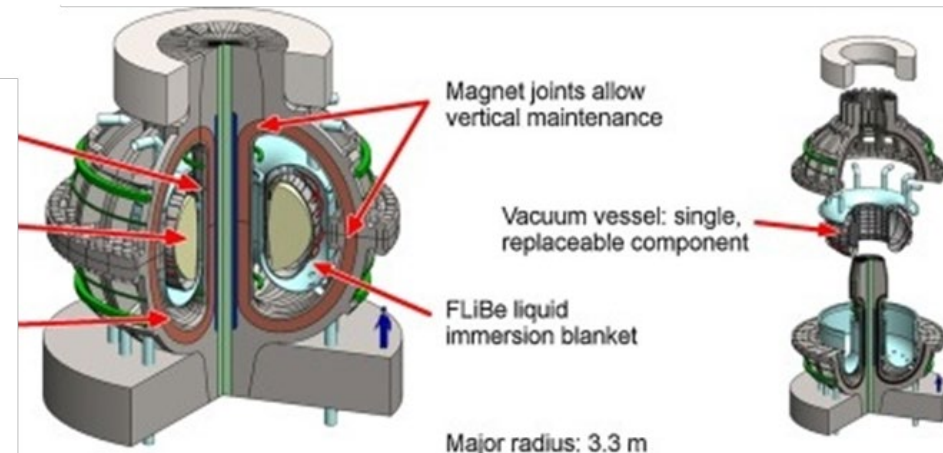
DEMOUNTABLE COIL MAGNETS ARE A DEFINING FEATURE OF GAUSS FUSION'S HIGH-FIELD RRP STELLARATOR DESIGN

ITER EXPERIENCE ON 100s OF LOW RESISTANCE SUPERCONDUCTING JOINTS (MOSTLY IN Nb₃Sn) GIVES GENERAL CONFIDENCE THAT THE TECHNOLOGY IS MATURING

SEVERAL POWER PLANT DESIGNS INCLUDE IT AS A BASELINE



STEP UK (Spherical Tokamak)



ARC (CFS, U.S)

Designing a FPP for future progress

When designing the GFG GIGA FPP we consider possible future superconductor technology advances BUT do not rely on them

GFG GIGA will be based on technologies with present TRL 3 and above

The use of high-field Nb₃Sn (RRP) enables the implementation of Demountable Coil magnets, which are central to achieving a maintainable and economically viable fusion power plant

Jointed coils:

Mount once or mount many

Nb₃Sn joints demonstrated at 1nOhm level

Modular structural design for coils and intercoil supports:

Scalable, applicable to any stellarator or tokamak

Generalised conductor, highly adaptable:

LTS Nb₃Sn (RRP) as baseline, HTS only if performance, protection and supply chain are demonstrated

For all, need only short unit lengths, & high- (not ultra high) field

Low voltage insulation:

Non-insulated coils are a technology that does not scale

GIGA uses conventional engineering to achieve low voltage insulation requirements capable of nuclear hardening

Robust quench protection:

Long discharge times, multiple QD options, predictable and controllable thermal conversion of magnetic energy

Most promising route to apply to HTS in future

Focus: Power plant relevant technology
Remote handling
Effective structural design



Focus: Move TRL~3 to TRL~5
Quench detection demonstrator
Test of relevant model coils (i.e. Quench Protection and demountability, structure integration, high-field, LTS and HTS if supply chain and QD resolved)
Cryogenic technology demonstrator

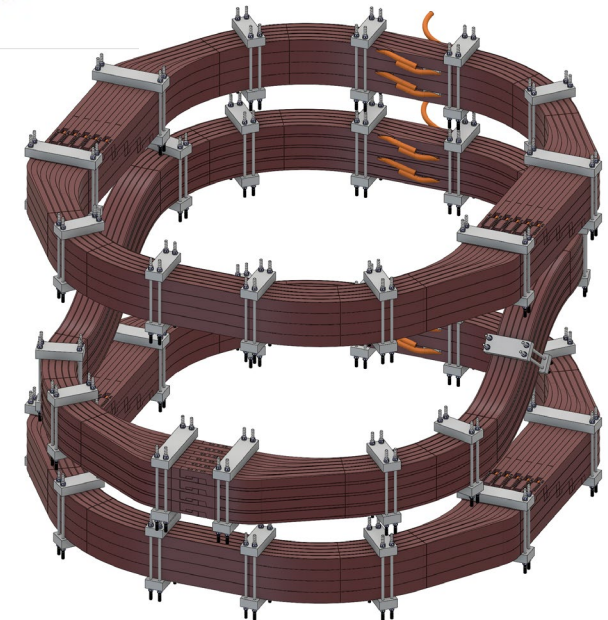
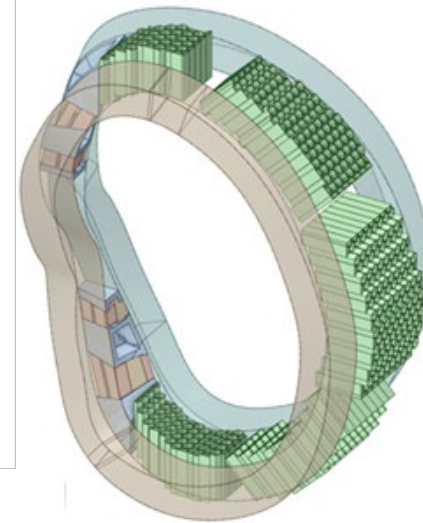


Focus: Establish European supply chains

Good Basis:
LTS SC
Structural Materials
Remote Handling

Weak Basis:
HTS SC

Ensure that European investments enhance European supply chains



Conclusion and Takeaways

For the first time, fusion devices that will actually achieve significant fusion reactions are under construction, targeting to achieve this in the current decade (a 10 year advance on ITER). Several private companies involved with varying degrees of investment & government support

All of this depends on superconductivity. The promise of a large future market is supporting magnet supplier investment

The next critical step – for superconductivity – is in the application, turning SC materials into magnets that can readily be exploited in an FPP (whose owners will buy the SC materials).

Public support likely critical to assist private companies to develop innovative solutions:

- In magnetic energy management (Quench Protection)
- In magnets far more user friendly to the main issues of a FPP (maintenance and access to in vessel)
- In magnets with reduced manufacturing risk (i.e. repairable and testable during manufacture)

Superconductors are a TOOL and should not become a DESIGN DRIVER nor a MANUFACTURING CONSTRAINT

- European strand, cable and coil supply chains exist for Nb₃Sn, together with manufacturing know how
- HTS (REBCO) may become an option in future, subject to successful demonstration of performance, protection and supply chain maturity; reducing cryogenic heat loads with operation at >20K
- European supply chains do not so far exist and some technical issues (QD & QP in particular) have to be definitively resolved
- Magnet technology is much more than the superconducting material and these other areas need investment