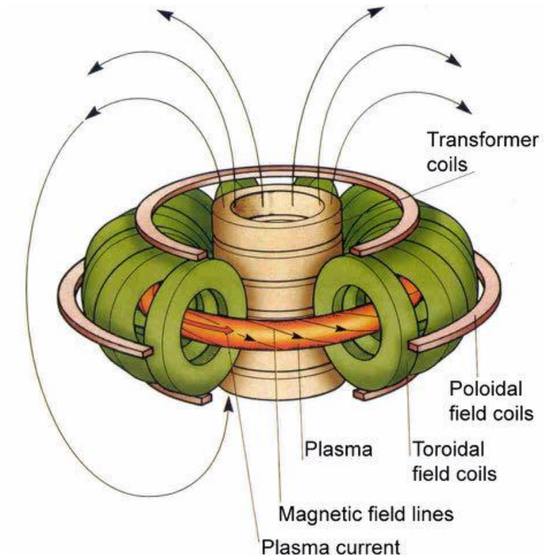
Unlocking Fusion Energy with High-Temperature Superconductors

May 2025 / victor.prost@renfusion.eu / ICTP-IAEA Fusion Energy School/ renfusion.eu

Overview

- Relevance of superconductivity in fusion machines
- Basics of superconductivity
- From superconductor to cables and magnets
- High temperature superconductivity unlocking new fusion possibilities
- Renaissance Fusion’s approach to HTS stellarator magnets

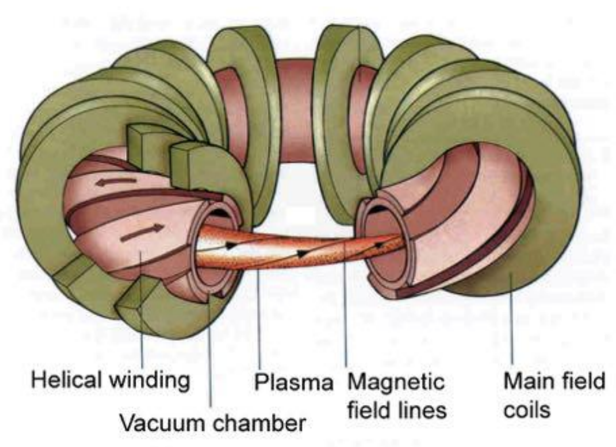
The two main fusion machine concepts rely on magnetic confinement to maintain hot plasmas



Tokamak:

Field twist by current in plasma caused by dB/dt in central solenoid (transformer coil)

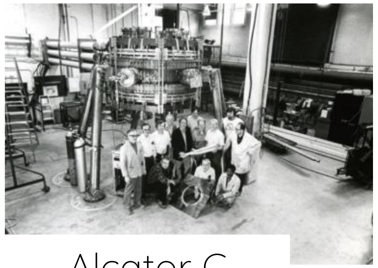
→pulsed machine



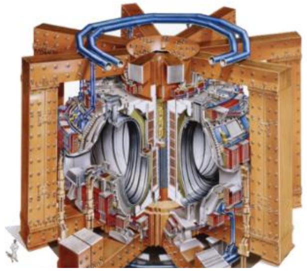
Stellarator:

Field twist by helical winding difficult to construct

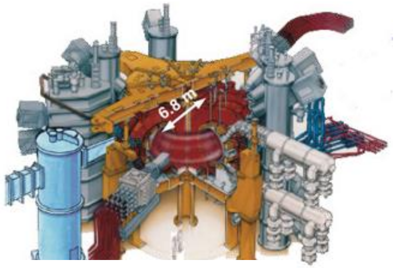
→works continuously



Alcator C
0.7 m
12 T (20 peak)



JET
3 m
3 T (6T peak)



JT60
3.4 m
3 T (6T peak)

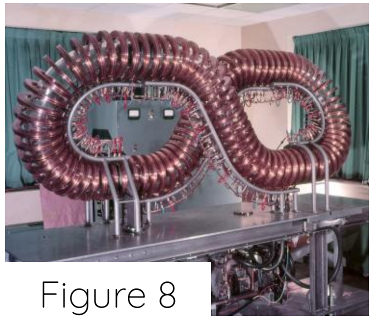
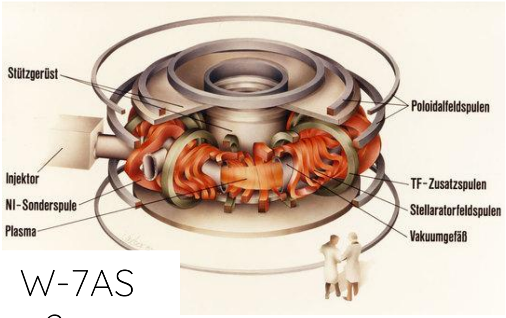


Figure 8
0.1 T

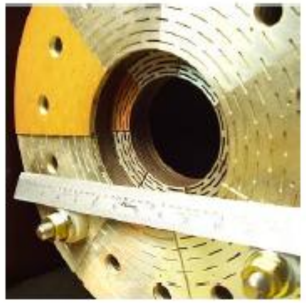


W-7AS
2 m
2.5 – 3 T

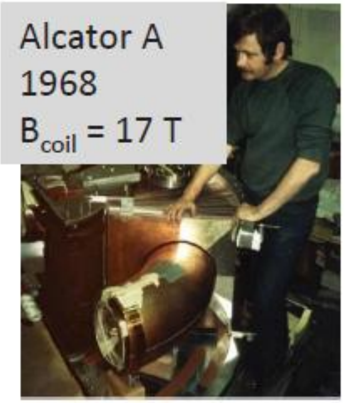
Conventional (copper) magnets could only operate for few seconds requiring immense power supplies

1950-1960s:
Copper wire and bars
The pioneers
Most copper machines

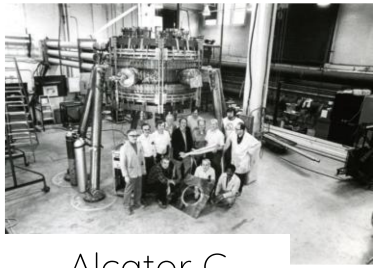
1960-1980s:
Cryogenic Bitter plate magnets
The Alcators at MIT



Stellarator A 1953
B_{coil} = 0.1 T



Alcator A
1968
B_{coil} = 17 T



Alcator C
0.7 m
12 T (20 peak)

Copper TF magnets
- 12 T
- 4 seconds
- ~225 MW

LHC HTS cable at 4.2 K

→ 2-3 orders of magnitude lower power requirements !!

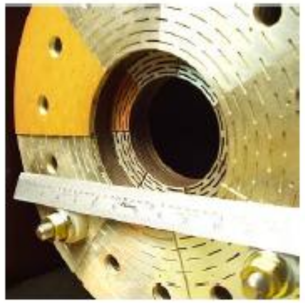
Bob Mumgaard, 2022, "magnets, How do they work"

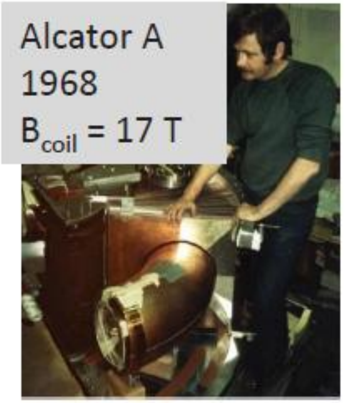
Superconductivity enables fusion machines with high fields and longer operations

1950-1960s:
Copper wire and bars
The pioneers
Most copper machines

Stellarator A 1953
B_{coil} = 0.1 T

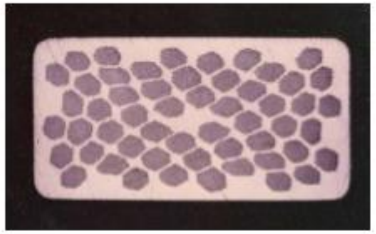
1960-1980s:
Cryogenic Bitter plate magnets
The Alcators at MIT





Alcator A
1968
B_{coil} = 17 T

1980-2000s:
NbTi superconductors
First superconducting devices

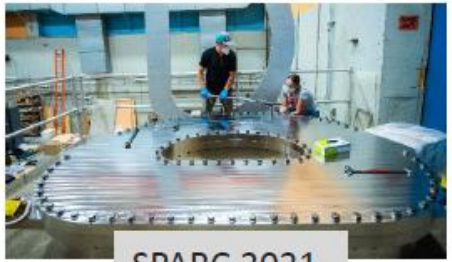


Tore Supra 1988
B_{coil} = 9 T

1990s-2010s:
Nb_3Sn for higher field
Reactor-class devices

ITER 2015
B_{coil} = 13 T

2010-2020s:
REBCO for very high field

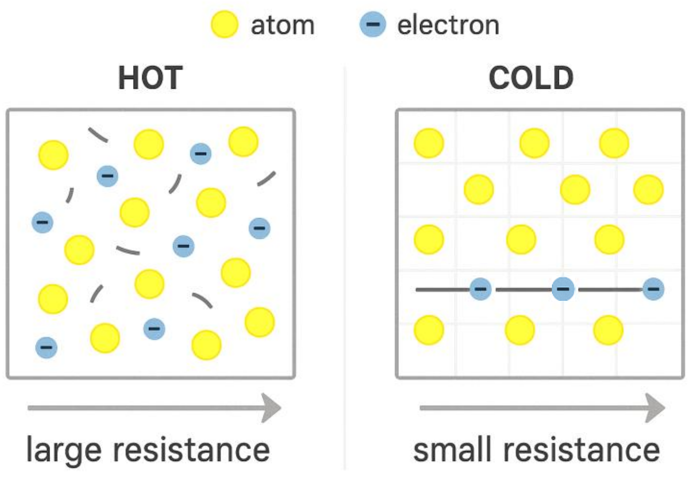


SPARC 2021
B_{coil} > 20 T

Bob Mumgaard, 2022, "magnets, How do they work"

Resistance and its temperature dependence

Resistance
The electrons are accelerated by the electric field, bump against atoms, transfer energy to these atoms which heats the wire



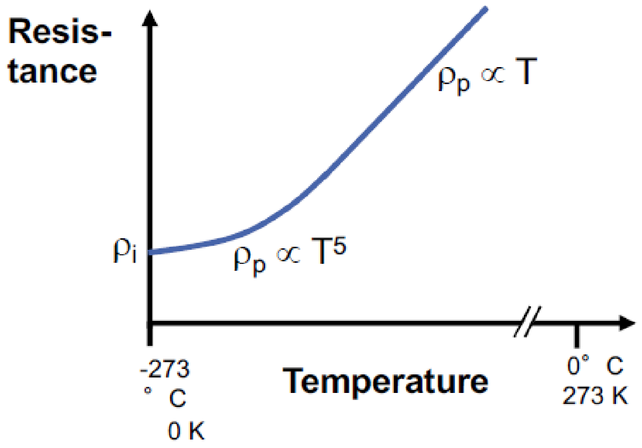
What is the origin for that scattering?

- Electrons are scattered by impurities (not temperature dependent)

  → Use of pure materials

- Electrons are scattered at lattice oscillations (temperature dependent)

  → Cool down to limit oscillations

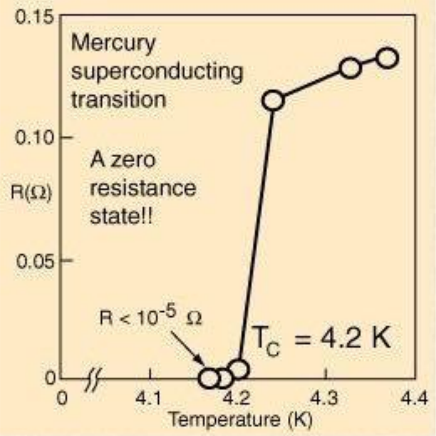


→ limited by impurity scattering

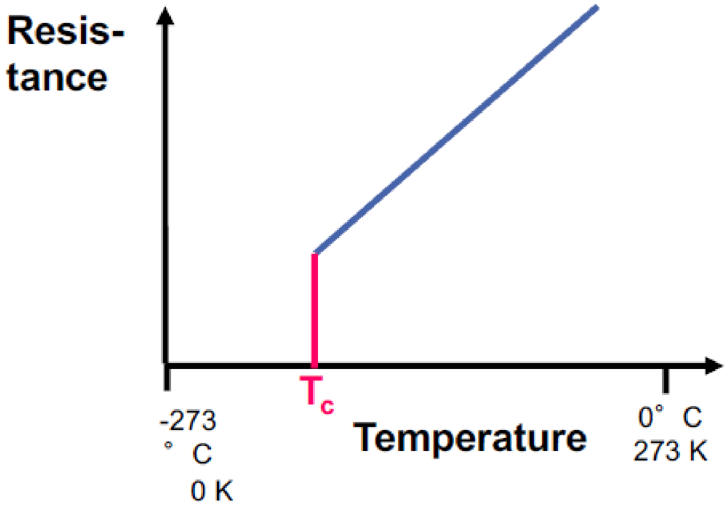
Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

Discovery of superconductivity

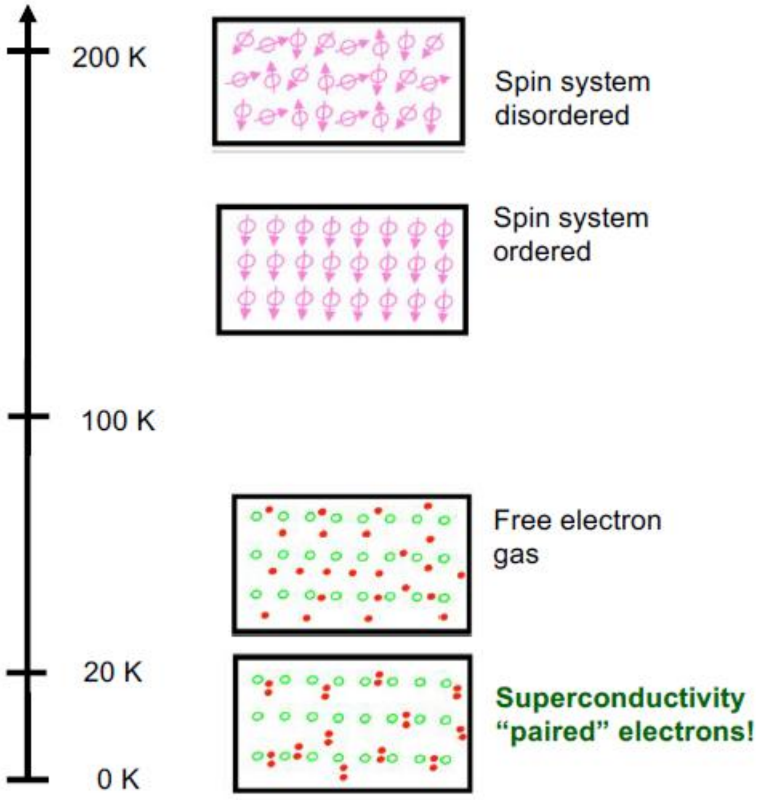
Experimentally it was found in 1911 by Kammerling-Onnes that resistance of pure mercury vanishes completely at low temperature



H.K. Onnes, Commun. Phys. Lab. 12,120, (1911)



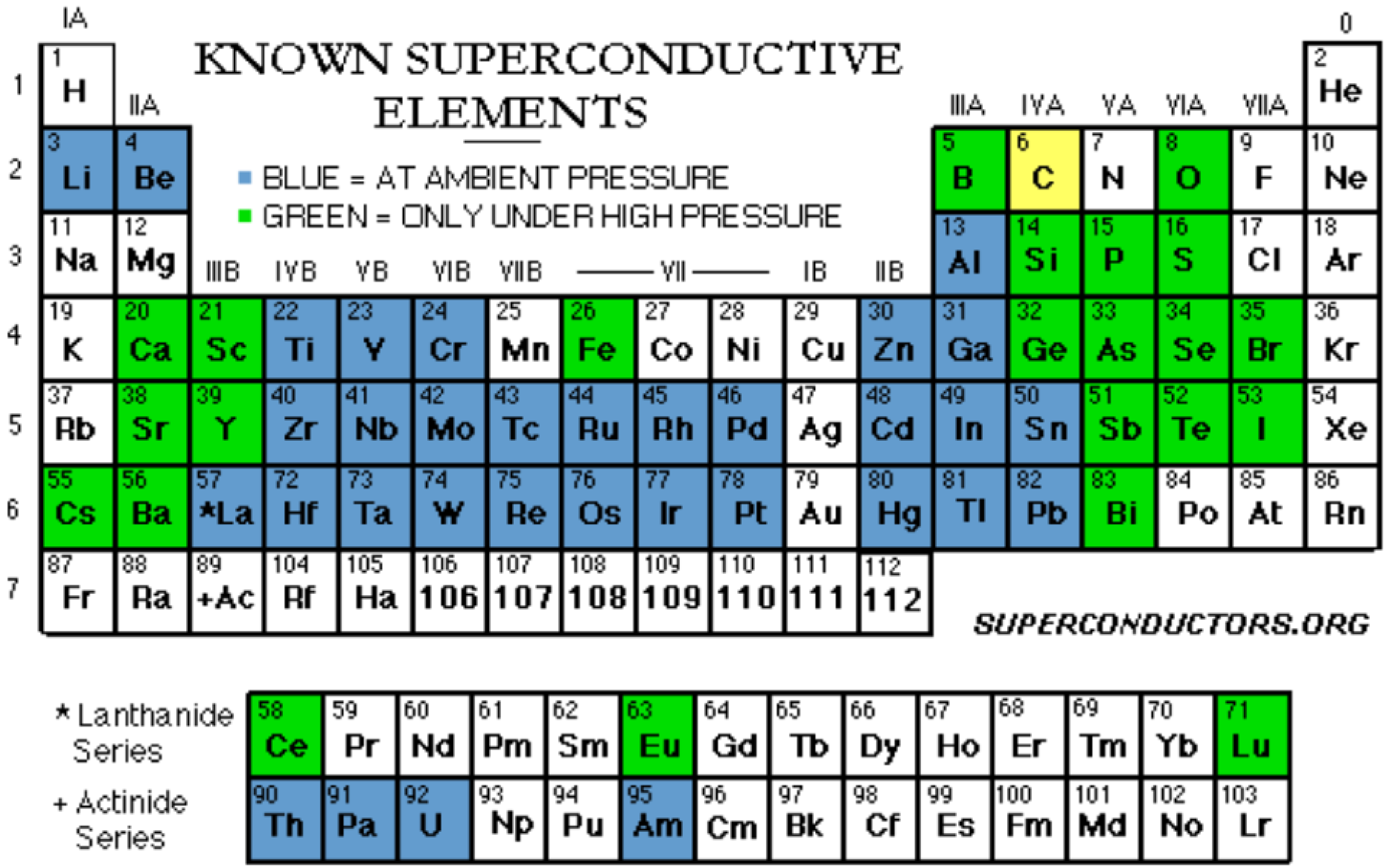
Lowering temperature unveils "hidden" interactions



Superconductivity: Resistance drops to zero at the critical temperature T_c

Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

Superconductivity is not an exception

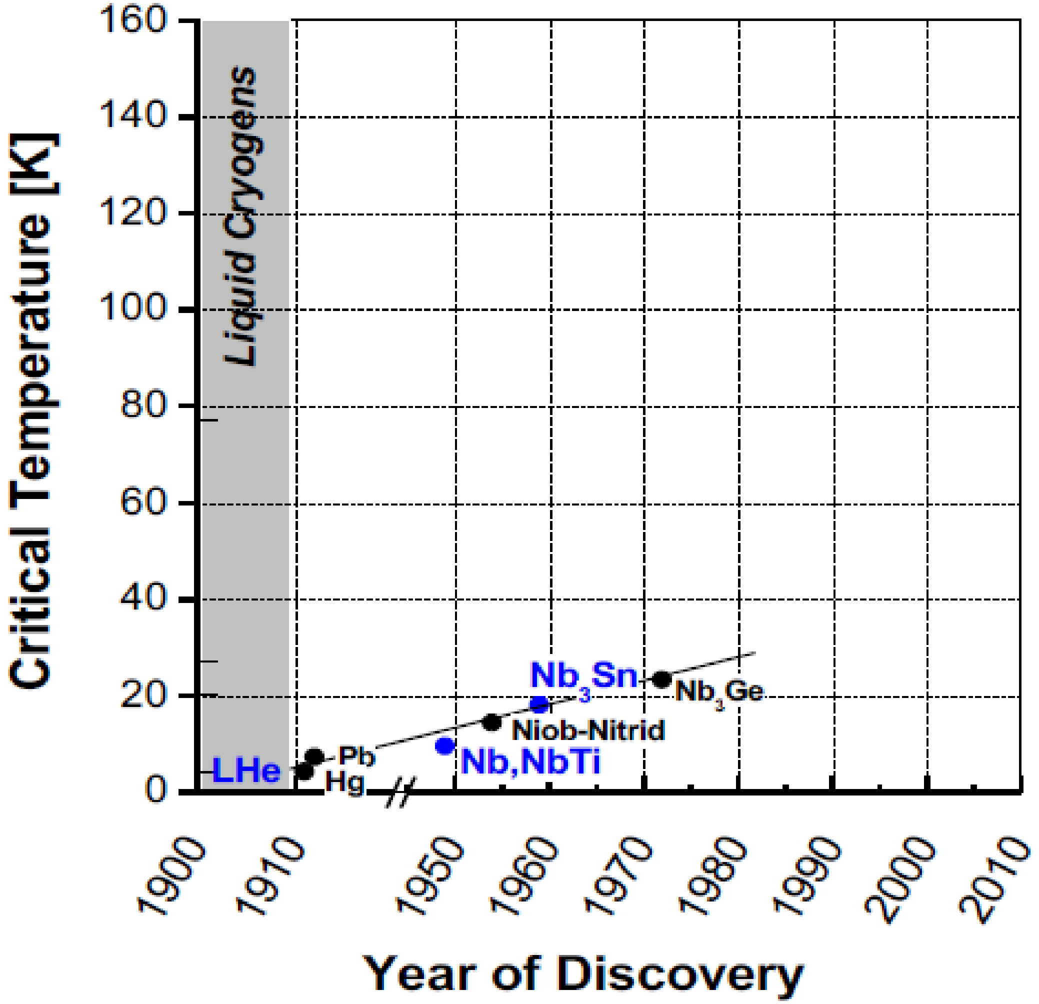


Lead (Pb)	7.196 K
Lanthanum (La)	4.88 K
Tantalum (Ta)	4.47 K
Mercury (Hg)	4.15 K
Tin (Sn)	3.72 K
Indium (In)	3.41 K
Aluminum (Al)	1.175 K
Gallium (Ga)	1.083 K
Molybdenum (Mo)	0.915 K
Zinc (Zn)	0.85 K
Zirconium (Zr)	0.61 K
Cadmium (Cd)	0.517 K
Titanium (Ti)	0.40 K
Uranium (U)	0.20 K
Iridium (Ir)	0.1125 K
Tungsten (W)	0.0154 K
Platinum (Pt)*	0.0019 K
Lithium (Li)	0.0004 K

Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

RENAISSANCE FUSION

Superconductivity – T_C evolution



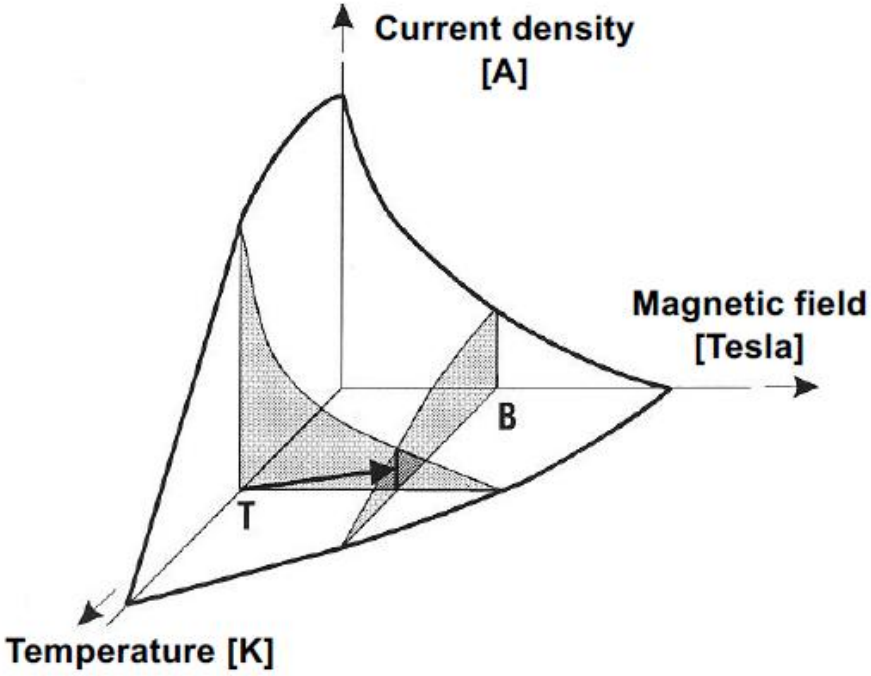
Discovered in 1911 T_C increases well above 20 K for Nb_3Ge– but until the 1980's everybody believes T_C can never go above 30 K.

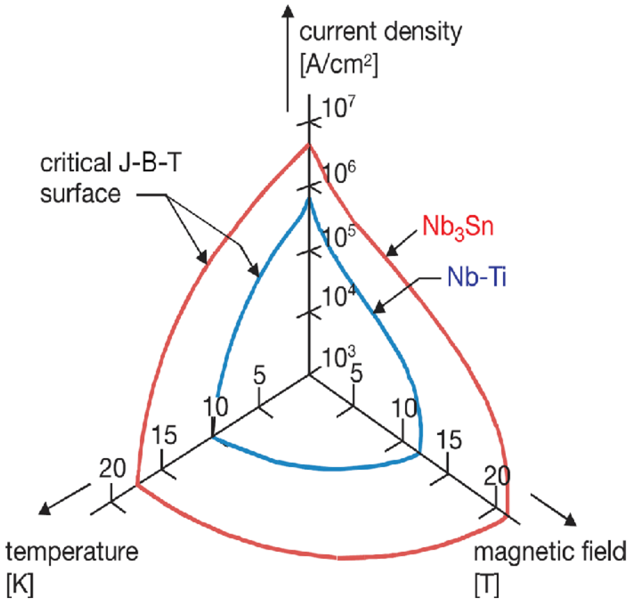
NbTi and Nb_3Sn are the two superconductors used for fusion magnets

Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

Boundaries of superconductivity

T_c depends on the applied field and current. Also, the critical current I_c and the critical field B_c depend on the other two quantities.





The boundaries:

- T_c= critical temperature
- I_c= critical current
- B_c= critical field

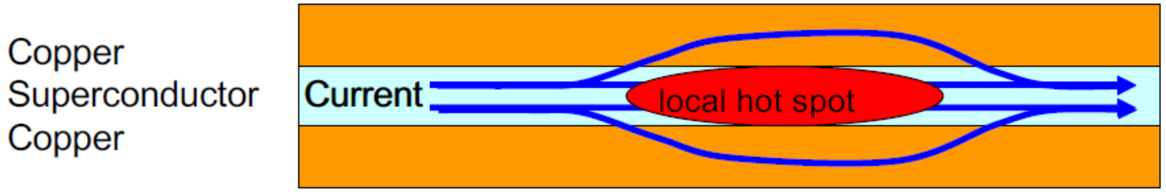
On operation conditions the critical current is given at the chosen temperature and field, e.g.: I_c(5 K, 10 T) = 5 kA

Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

From superconducting filaments to cables

Stabilization of superconducting cable and quench

Copper wire: 1mm cross section -> 10 A
Superconductor: 1mm cross section -> 500 A

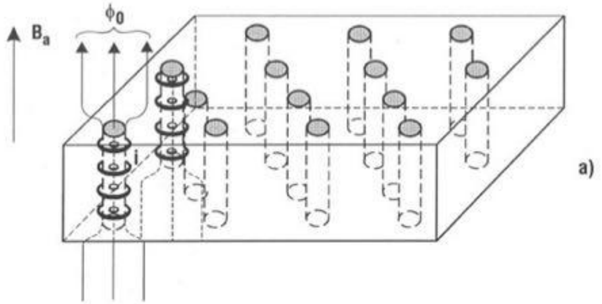


- Heat dissipation
- Current Sharing
- Thermal stability

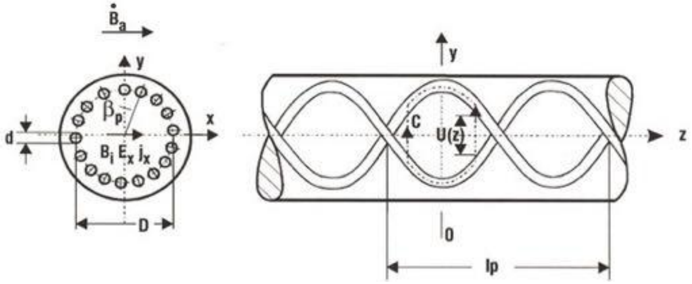
→ Still in case a local hot spot cannot be stabilized and starts to grow, the current has to switched off immediately.
→ Burning of the coil : "Quench"

Main considerations in case of ac currents

- Eddy Current Losses
- Type I vs Type II superconductors



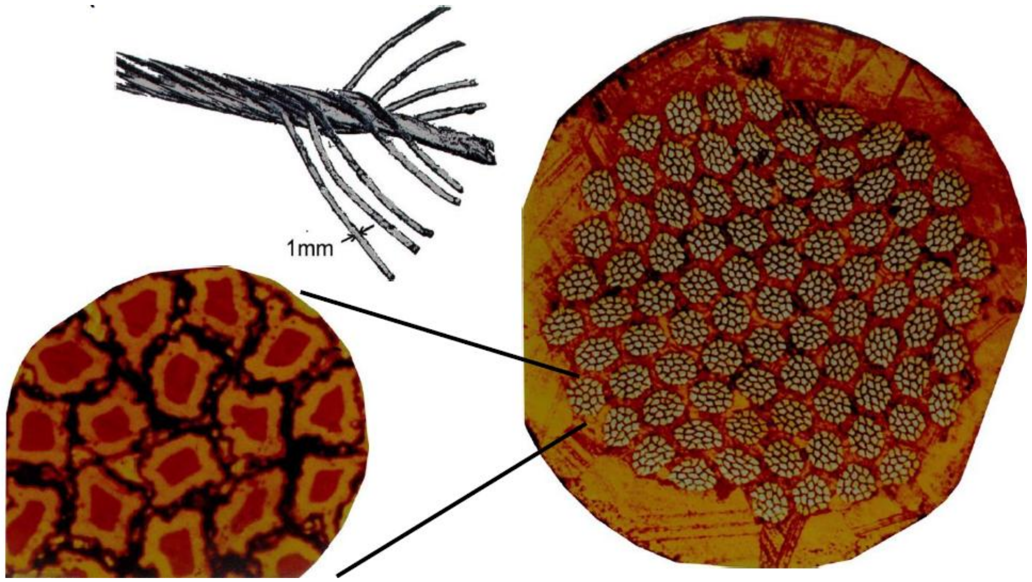
- Coupling losses (reduce current loops)



Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

Reducing operating costs and power requirements

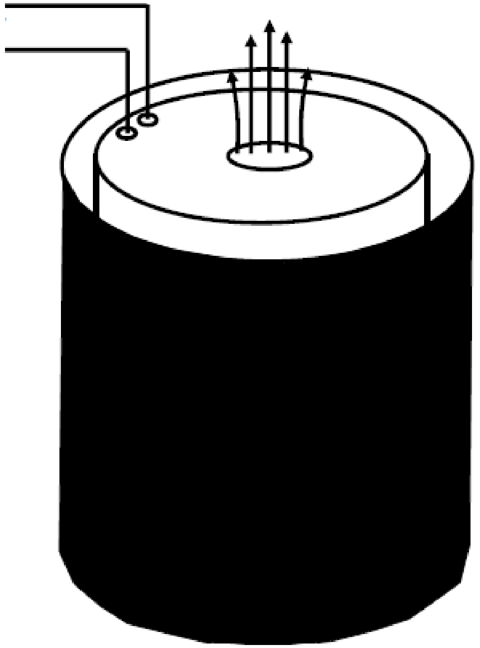
NbTi (multi filament) in Cu matrix



Electro-magnet (10 Tesla):

1 MW electric power

10 kW for refrigerator to balance He losses



Operating cost:
100€/h conventional magnet

1€/h superconducting magnet

Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

Design considerations for fusion magnets SC cable

Inductance considerations

$$U = L\,\frac{dI(t)}{dt}$$

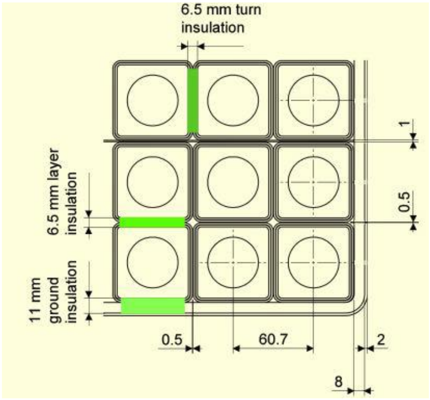
$\tau = L/R_L$	Time constant	$L \searrow \quad R_L \nearrow$
$U_0 = I_0\,R_L$	Initial voltage	$R_L \searrow$
$L \sim n^2 A/l$	Inductance dependence on winding number	$n \searrow$

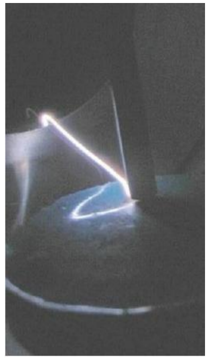
→ High current cables with low number of turns and low discharge resistance

Structural considerations

Radial support plates

Insulation considerations





In Paschen conditions (≈0.1-50 mbar) voltages around 100 V can cause arcing!

No failure at 30 kV when tested in good vacuum or ambient pressure. Under Paschen conditions breakdown occurs around 2 kV!

Thermal considerations

Cable in conduit (flowing cooling)

C. Lange et al., Paschen Problems in Large Coil Systems, IEEE TAS 22(3) 2012, 9501504

RENAISSANCE FUSION

Overview of LTS superconducting cables for fusion

LCT

NbTi, 11.8 kA @4.5 K
16 kA @3.5 K, 19 kA @1.8 K
in stainless steel jacket
with forced flow cooling

POLO

NbTi, 15 kA (test: 22 kA!)
in stainless steel jacket
with two phase forced flow cooling

W7-X

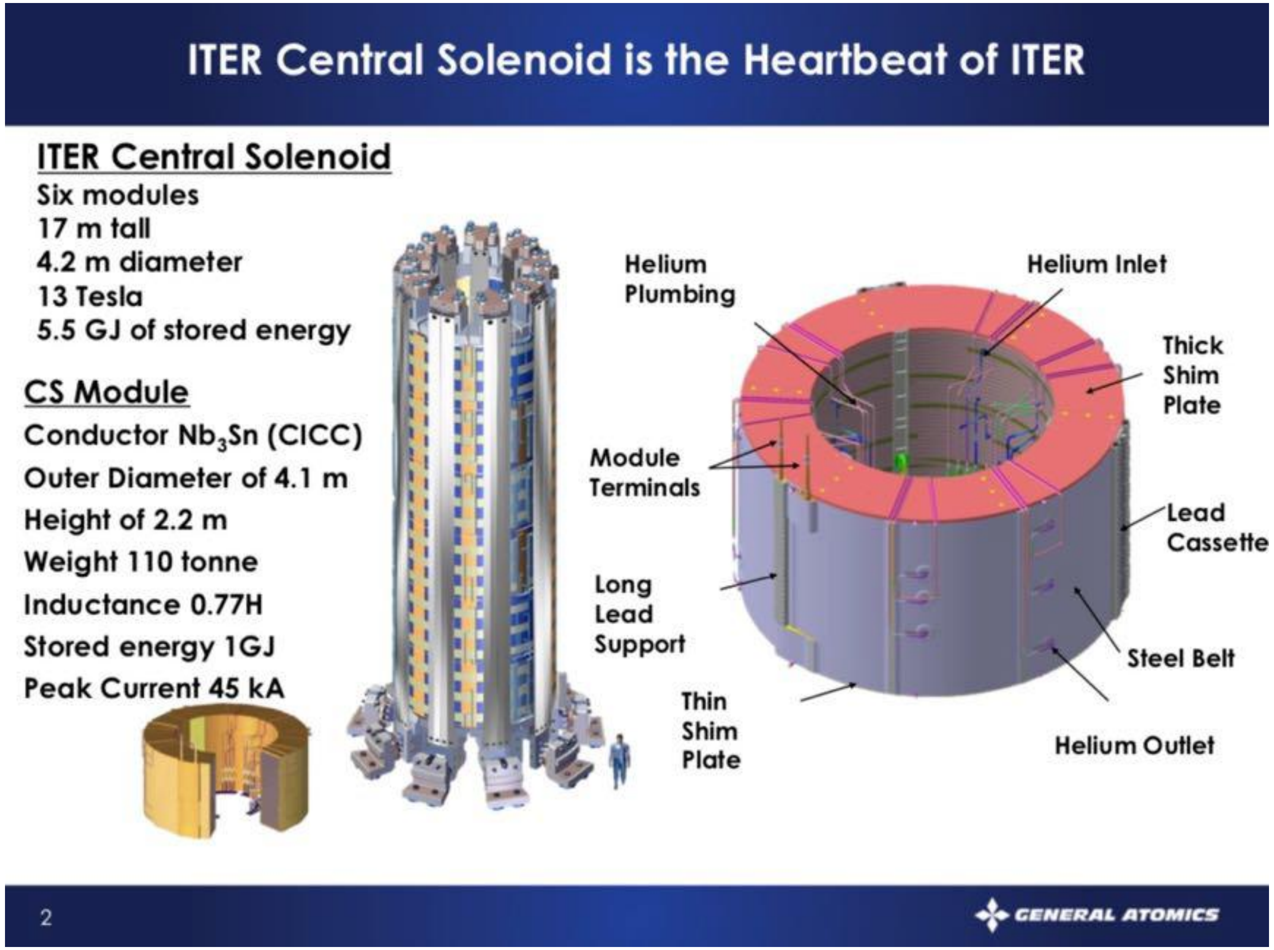
NbTi, 19.9 kA
in Aluminium jacket
with forced flow cooling

TFMC

Nb_3Sn, 68 kA, (test 80 kA)
in stainless steel jacket
with forced flow cooling

Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

ITER central solenoid example of inductance, cable current and high voltage trade-offs



John Smith, 26th IAEA Fusion Energy Conference, Kyoto, Japan, October 17, 2016
https://conferences.iaea.org/indico/event/98/contributions/12153/attachments/6167/7549/Smith_FIP1-2.pdf

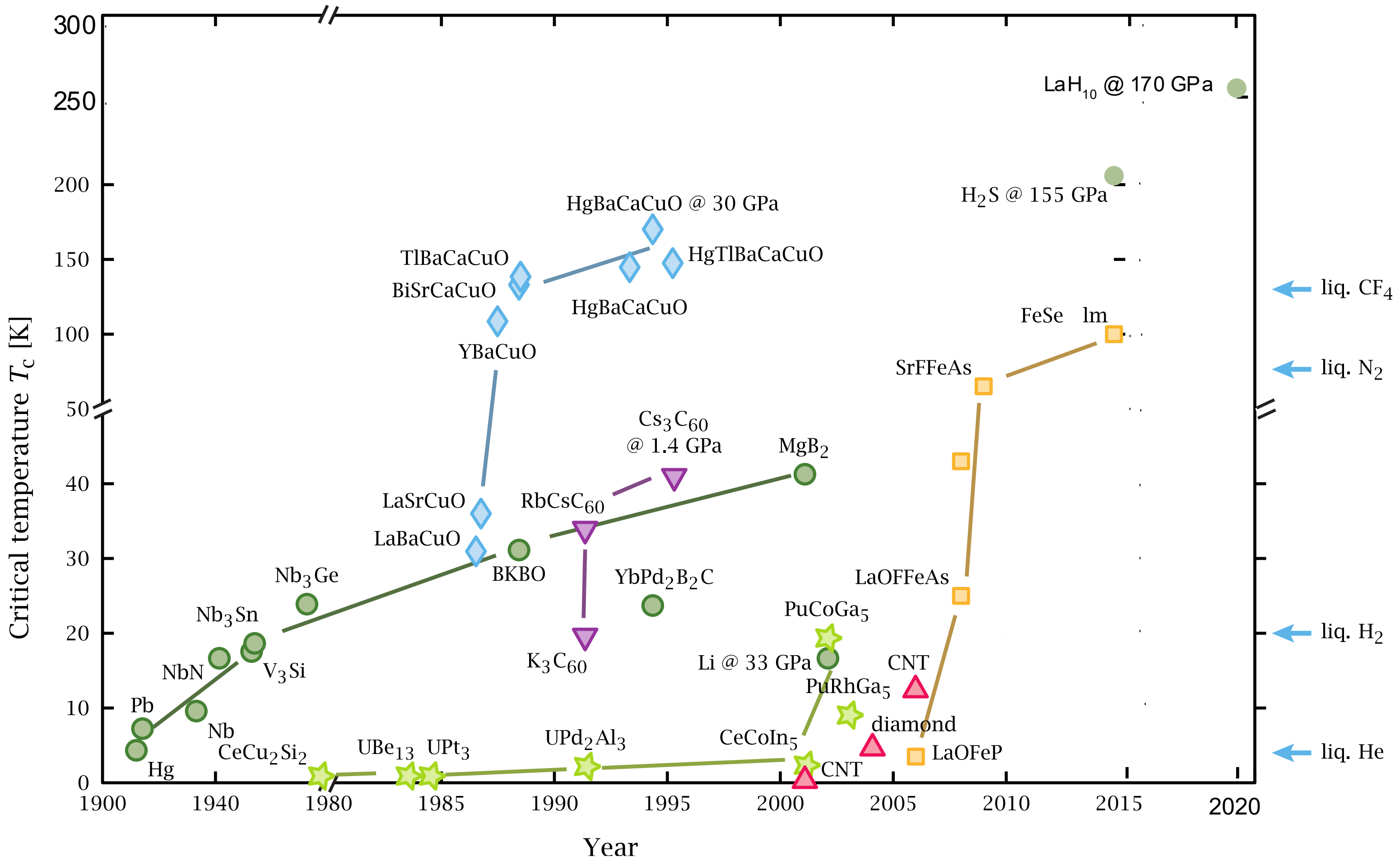
- 20 MA overall current in one CS module
- 45 kA cable using 549 turns per CS module
- limits the inductance of one module to 0.77 H
- CS modules with a discharge voltage of 11 kV

TABLE V
MAXIMUM COIL VOLTAGES kV

Coil	Max in Normal Conditions	Max with Control Fault	Max with Interlock or PS Hardware Flt
TF (1 coil)	4.0	4.0	4.0
CS1U,L	11	13.4	18.9
CS2U,L	11	21.4	26.9
CS3U,L	11	13.4	18.9

P. Libeyre et al., IEEE Trans. Appl. Supercond., 18(2), 2008, p. 479

High temperature superconductivity



1986 Discovery of “High-Temperature Superconductivity” below 35 K in the La-Ba-Cu-O system by J. G. Bednorz and K. A. Müller

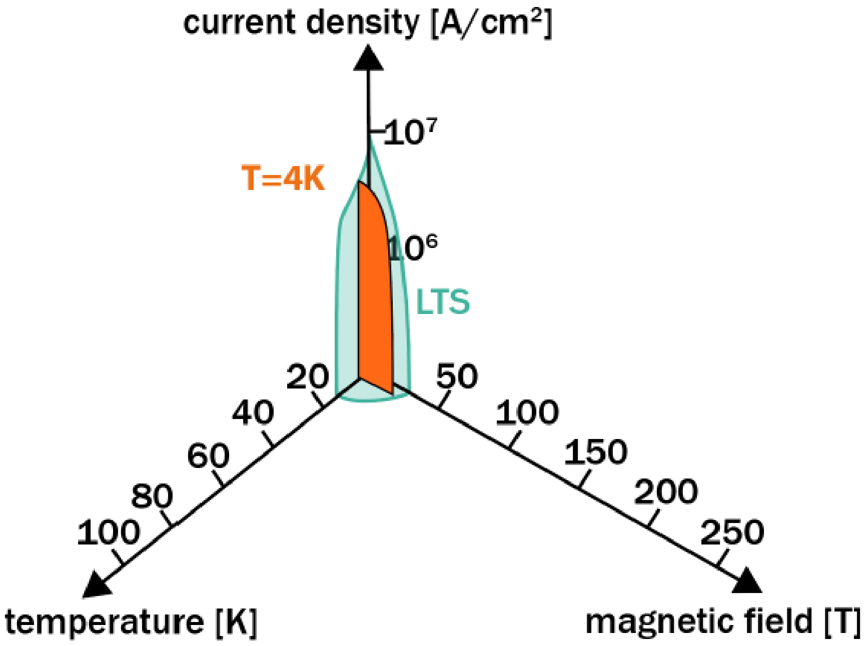
1987 Discovery of Superconductivity in Y-Ba-Cu-O by C. W. Chu and M. K. Wu

Material	Critical temperature
REBCO (Y, Gd, Eu, Sm…)	88-96
BiSCCO	85-110

Sharma, R.G. (2021). High-Temperature Cuprate Superconductors and Later Discoveries. In: Superconductivity. Springer Series in Materials Science, vol 214. Springer, Cham

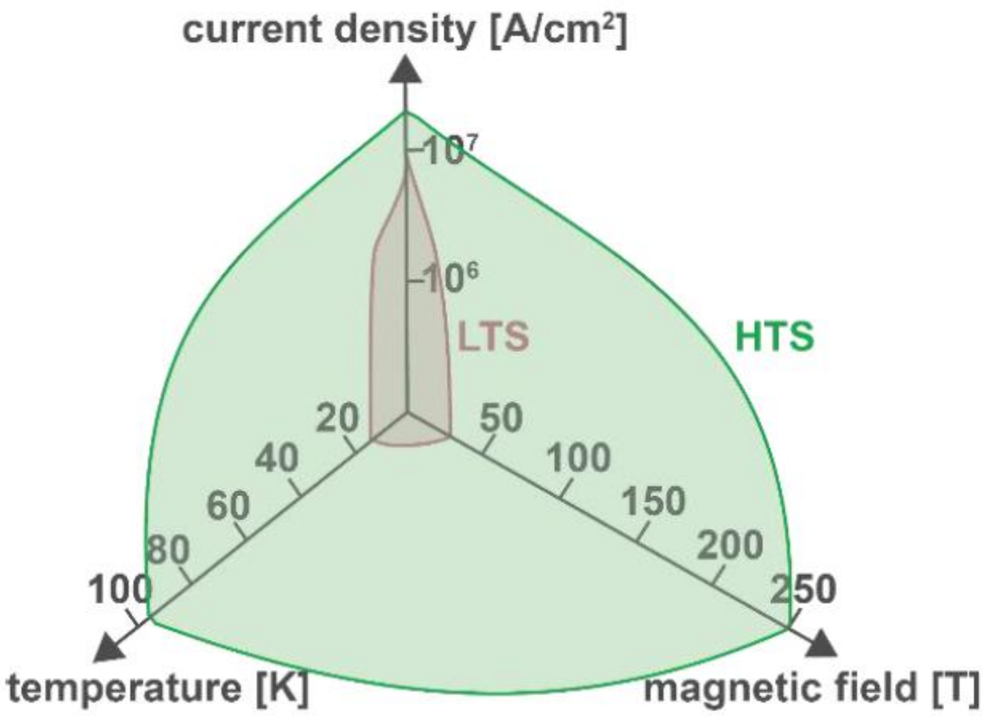
RENAISSANCE FUSION

Not only increased critical temperatures but also critical field and current



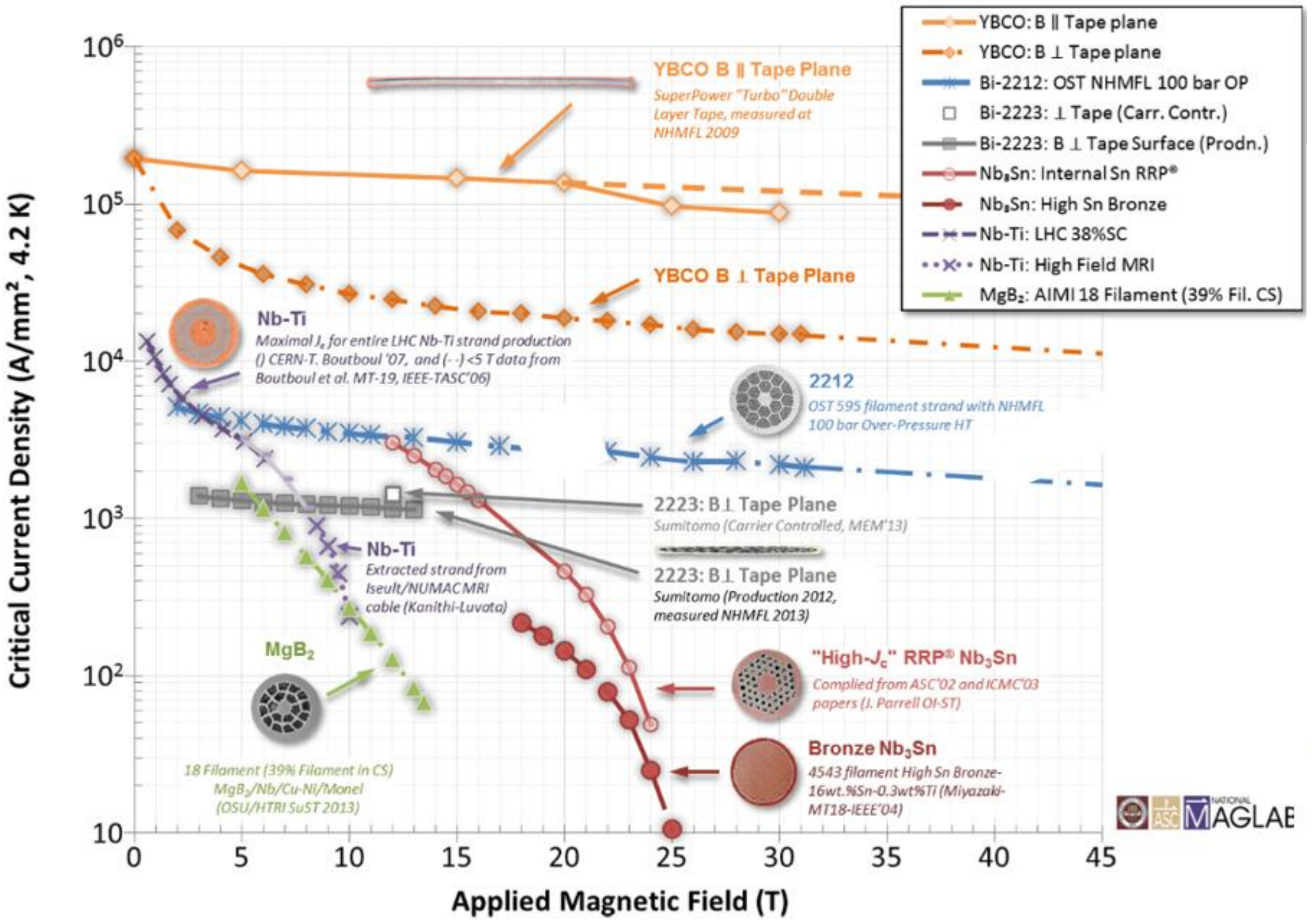
Bob Mumgaard, 2022, "magnets, How do they work"

Not only increased critical temperatures but also critical field and current



Bob Mumgaard, 2022, "magnets, How do they work"

Not only increased critical temperatures but also critical field and current



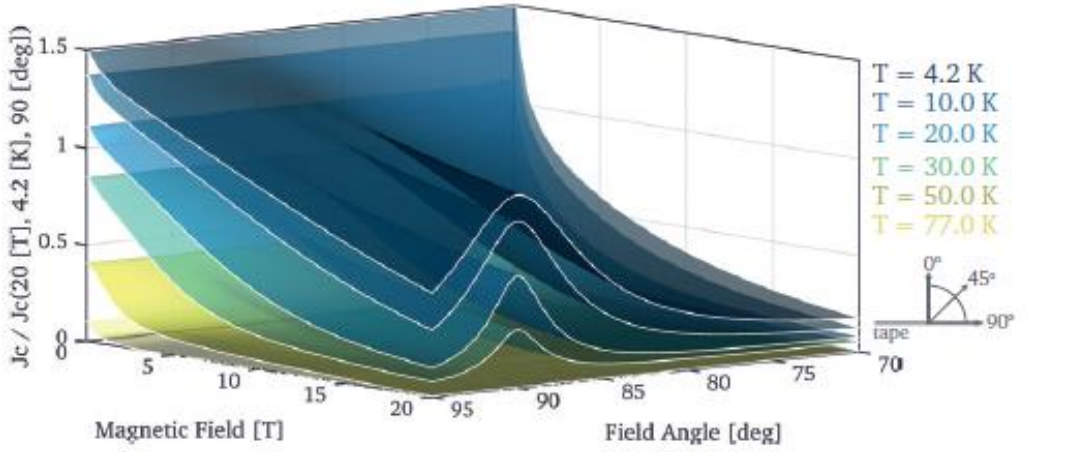
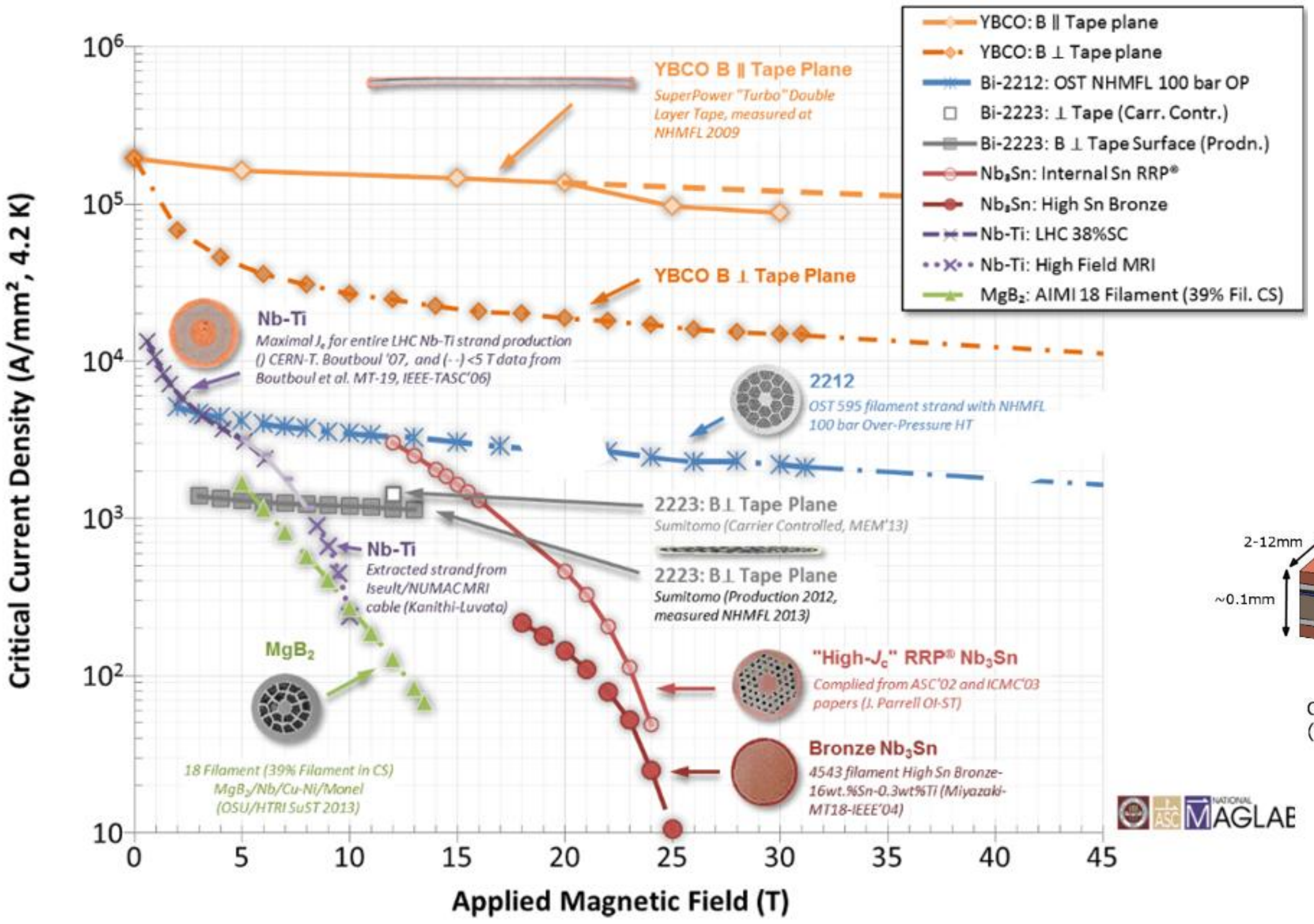


Figure 1.8. *Normalized critical current as function of magnetic field, temperature, and field angle of state of the art ReBCO coated conductor source data [28].*

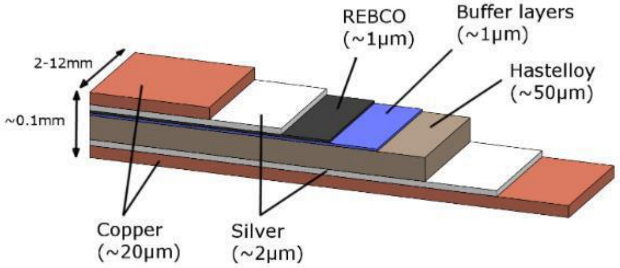
Nugteren - 2016 - HTS Accelerator Magnets

Not only increased critical temperatures but also critical field and current



2000s Companies started making reproducible tapes

2010s Companies started making reproducible tapes in quantity and length that mattered



Advantages of HTS

High field:
Constraint on magnetic field is now a structural issue, not a quantum mechanical issue.
Can conceive of designs to arbitrarily high magnetic fields

High current density:
More space for structure and other components
More compact, higher-field magnets

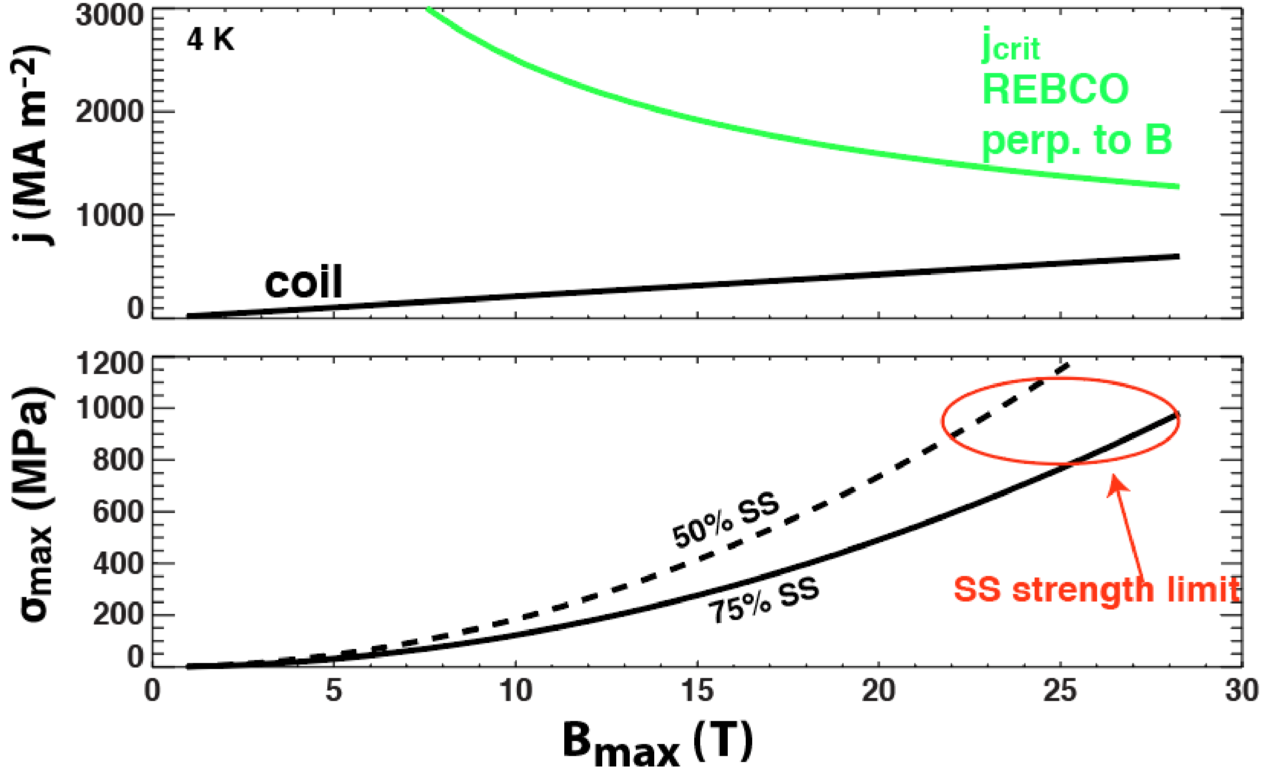
High Temperature:
Wider flexibility in design of cooling system (various cooling fluids), or large heat loads (nuclear, joints)
Much more stable design and much larger margins
Reduced cryogenic system (factors of 5-20)

Made from steel ribbons:
Superconductor can become part of structure and can design to higher stress and thus smaller magnets.
Must design the magnets and cables differently than LTS

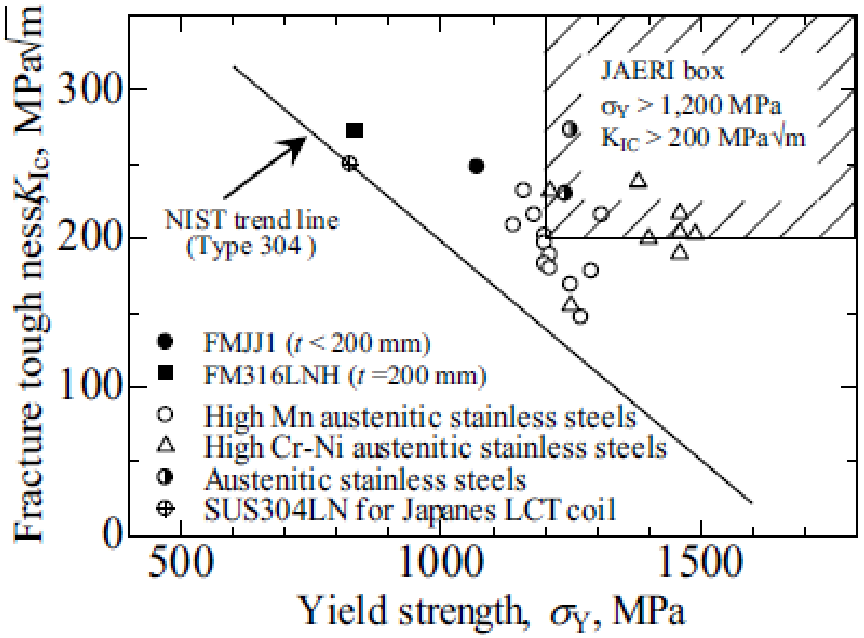
Thin film process:
Can get to very low-cost parameters.
Make it and use it - no heat treatments etc

HTS is no longer the bottle neck but rather structural materials for HTS magnets

Elastic limit of material is now critical (higher temperature is detrimental)



Combination of fatigue and elastic limit matters for fusion reactors



Source:
A. Nishimura, AIP Conference Proceedings 1574, 333 (2014)

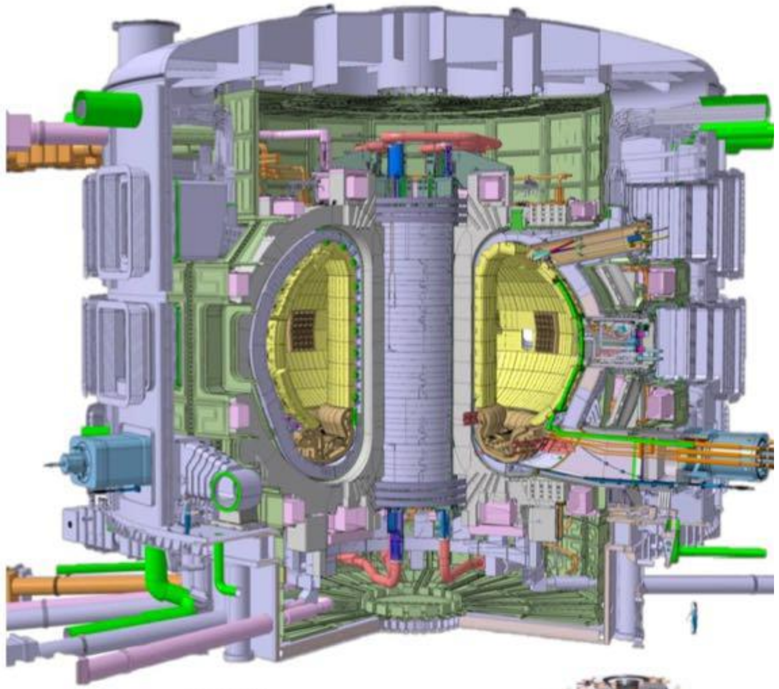
→ Design limits or R&D

Bob Mumgaard, 2022, "magnets, How do they work"
Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

New possibilities for high-field compact fusion machines

Energy gain $nT\tau_E \sim R^{1.3}B^3$ (Tokamaks)

Power density $\frac{P_{fusion}}{S_{wall}} \sim R\ B^4$



ITER

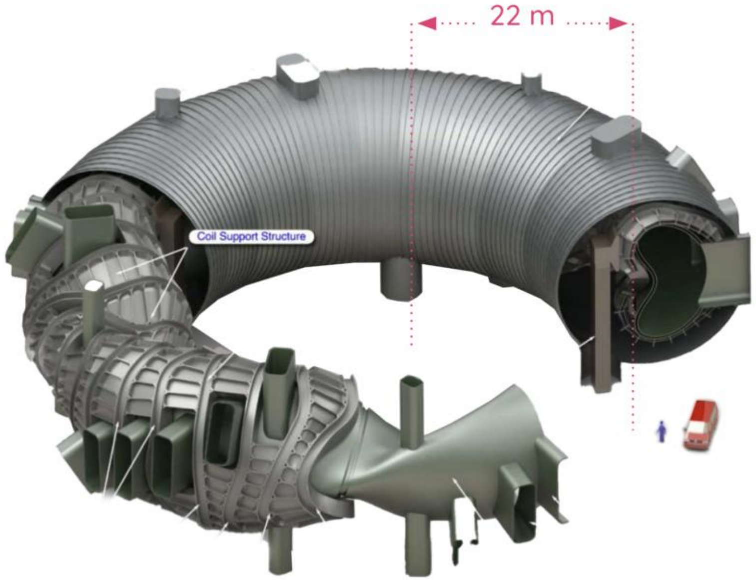
V_{plasma} ~ 840 m^3

B~ 5.3 T

SPARC

V_{plasma} ~ 20 m^3

B~ 12.2 T



HELIAS B=5T

V_{plasma} ~ 1410 m^3

Renaissance Fusion's reactor
Simplified W7X, with 10 T on axis

V_{plasma} ~ 100 m^3

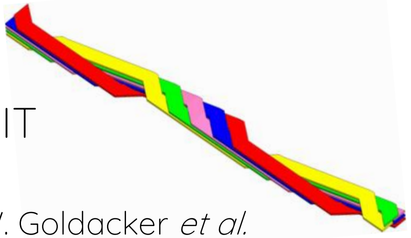
RENAISSANCE FUSION

Similar development as LTS from HTS tapes to cables

CORCC cables
Conductor on Round Core

Roebel cable

KIT



W. Goldacker *et al.*
J Phys. Conf. Ser. 43 (2006) p. 901

CERN

VIPER cable
vacuum pressure impregnated, insulated, partially transposed, extruded, and roll-formed

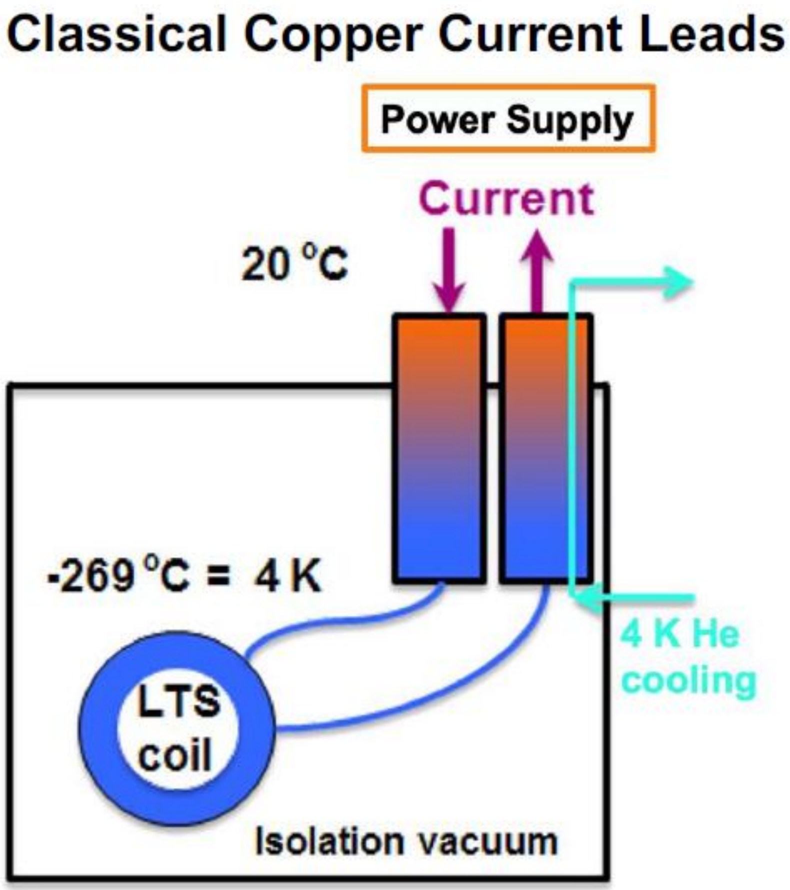
KIT (Germany)

EPFL (Switzerland)

NIFS (Japan)

ENEA (Italy)

HTS allows for more efficient current leads



Wiedemann – Franz – Law

$$\frac{\lambda}{\sigma} = L \cdot T$$

λ : thermal conductivity

σ: electrical conductivity

L: Lorenz number

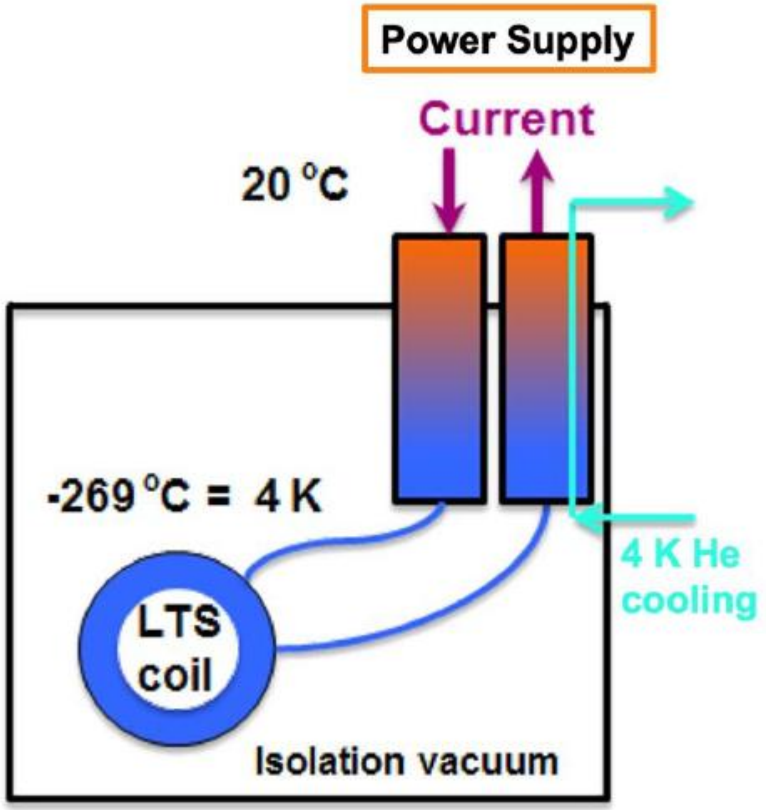
NB: Not strictly true at low T

→ large ohmic heating for tens kA
→ large Cu cross section:
massive heat load from 300°C to 4K

Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

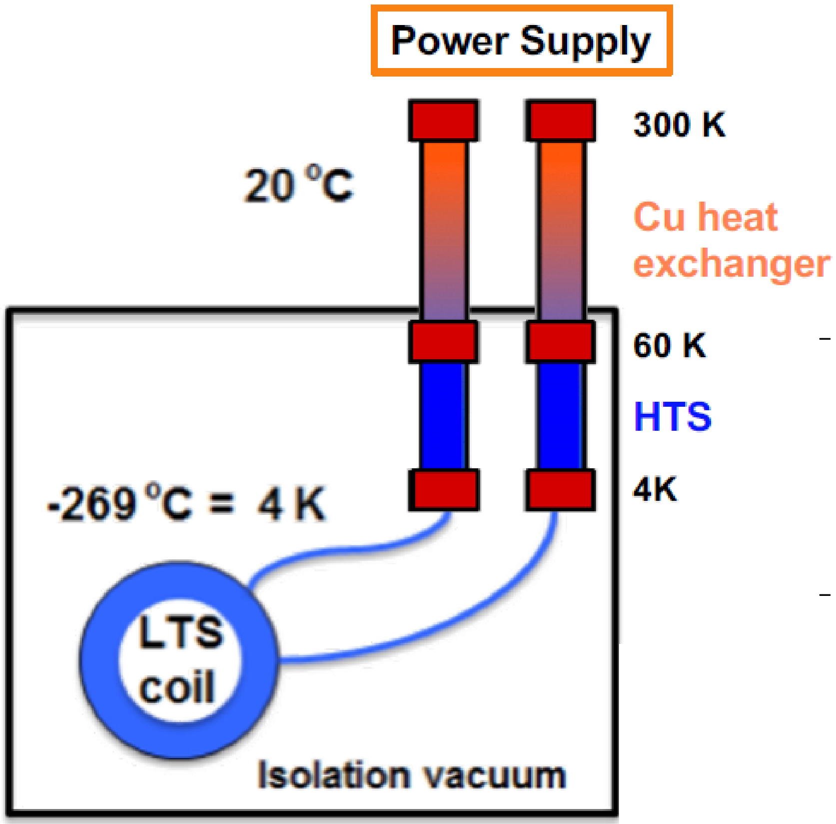
HTS allows for more efficient current leads

Classical Copper Current Leads



→ large ohmic heating for tens kA
→ large Cu cross section:
massive heat load from 300°C to 4K

HTS for Current Leads (CL)



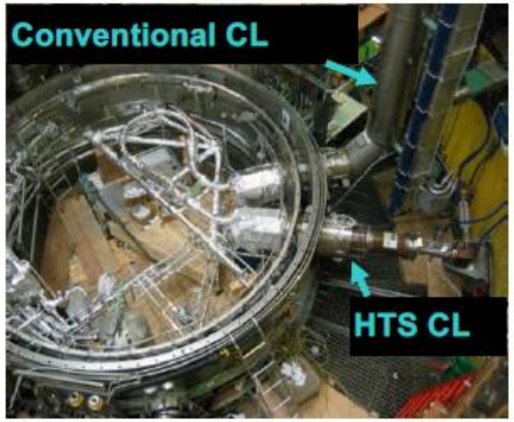
- Cooling of the heat exchanger @ 60–300 K has a much higher efficiency.
- Active cooling of HTS part not necessary (conduction cooling from the cold end is sufficient)

HTS gives no ohmic losses and has small cross section with low heat conduction

→ Reduction of heat load by a factor of 10

Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

HTS allows for more efficient current leads



80 kA with Bi-2223
World record for HTS

HTS for efficient current leads

- 70 kA HTS CL Demonstrator for ITER
  R. Heller et al. IEEE Trans. Appl. Supercond. 15(2) (2005) 1496

- W7-X
  R. Heller et al., IEEE Trans. Appl. Supercond. 21(3) (2011) 1062-1065

- JT-60SA
  R. Heller et al., IEEE Trans. Appl. Supercond. 28(3) (2018) 4800105

- ITER
  P. Bauer et al. , IEEE Trans. Appl. Supercond. , 20(3) (2010), pp. 1718–1721

Impact for ITER: cost saving

ITER HTS current leads:

9 TF CL pairs (68kA)

6 CS CL pairs (45kA)

6 PF CL pairs (52kA)

Estimate of average power over one year assuming ITER duty cycle (for TF 32% and for the other coils 6% duty time per year)

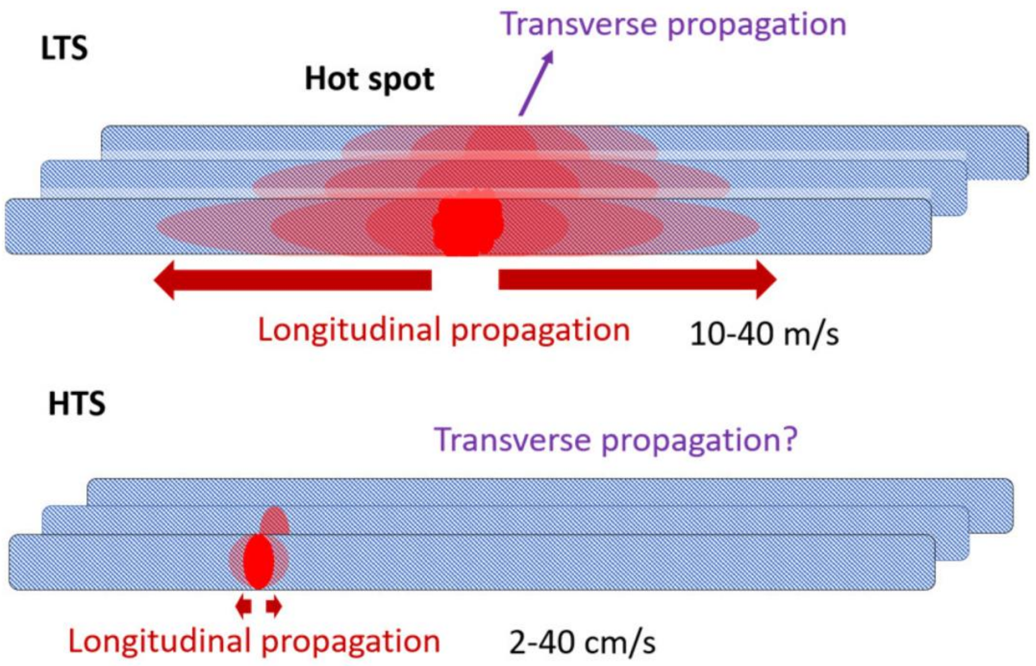
Using HTS current leads will

- need higher investment costs (4 M€)
- save investments for refrigerator power (10 M€)
- lower operational costs (0.8 M€ per year)

The ITER feeder package is in the hands of China

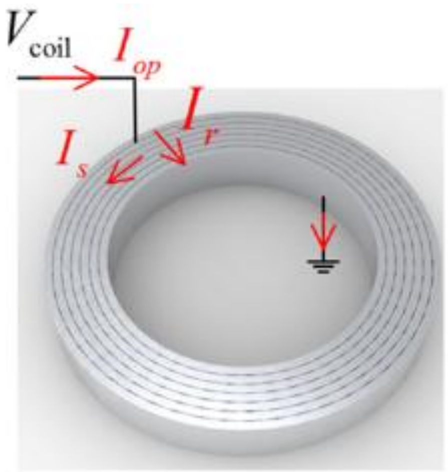
Klaus-P. Weiss, 2022, "Superconductivity and Magnet Technology"

HTS tape suffer from low normal zone propagation velocity preventing their use as insulated coils

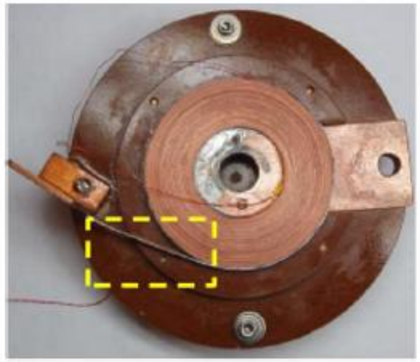


→ Diffi cult to detect quench
→ Fully insulated magnets challenging

No-Insulation (NI) REBCO coils (~ 2009)

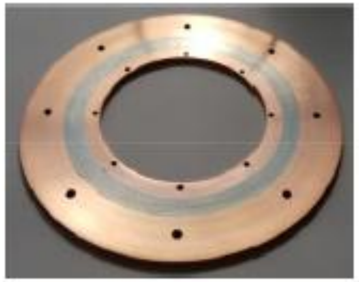


The first NI coil (Hahn, Park)
3T, 1580 A/mm², 4.2 K



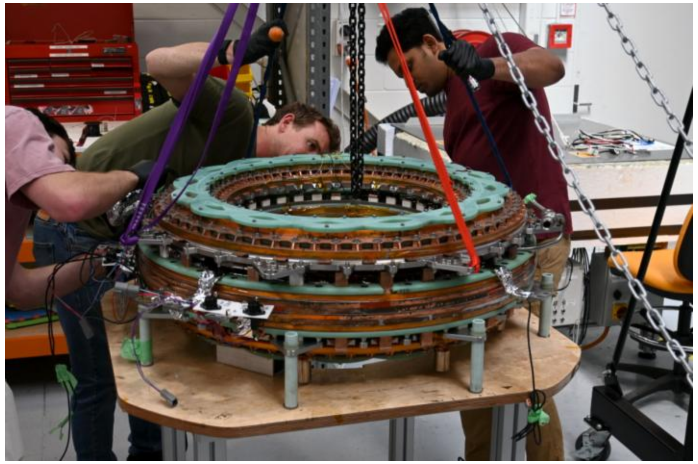
→ Tolerant to quench
→ High current densities
→ Low voltage drops

No-insulation HTS magnets research and active field of development

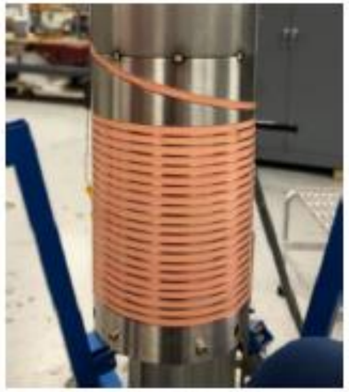


CERN (Switzerland)

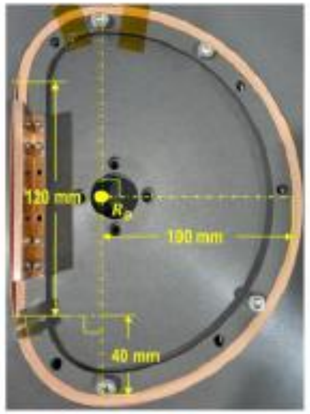
Tokamak Energy (England)



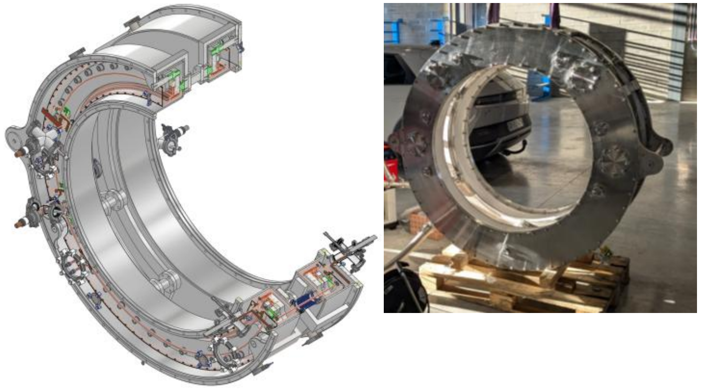
Open star technologies (NZ)



National High Field Magnet Laboratory (USA)



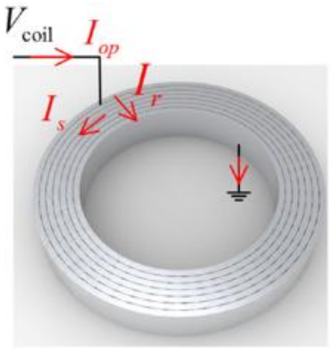
Seoul National University (Korea)



Renaissance Fusion (France)

HTS magnets architecture and type

No-Insulation (NI) Coils

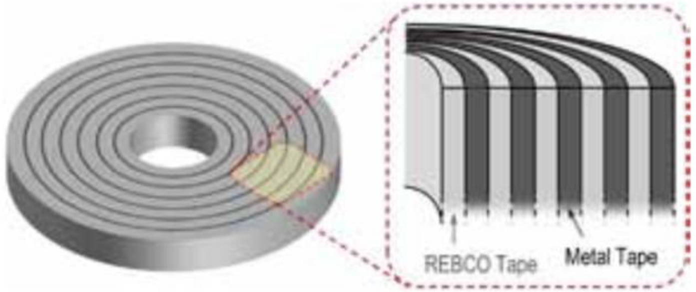


Advantages
- Thermal stability
- Self-protection
- Higher current density
- More compact magnets
- Simplified fabrication

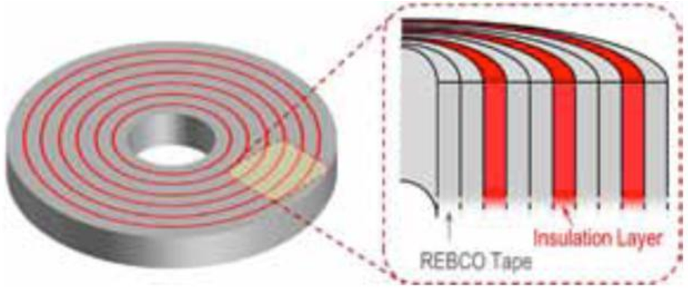
Challenges
- Longer time constants
- potential for complex current distribution within the coil
- subject to contact resistance

→ Active field with new options, metal in transition materials…

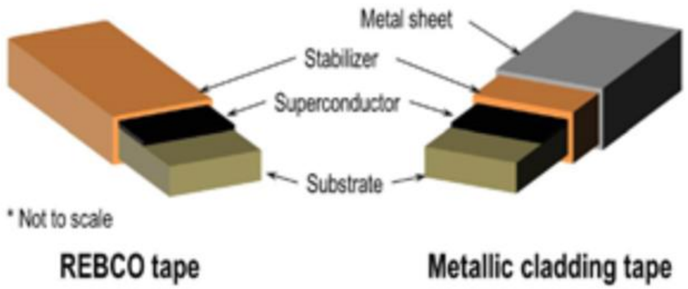
Metal-as-Insulation (MI) Coils:



Partial insulation (PI) Coils:



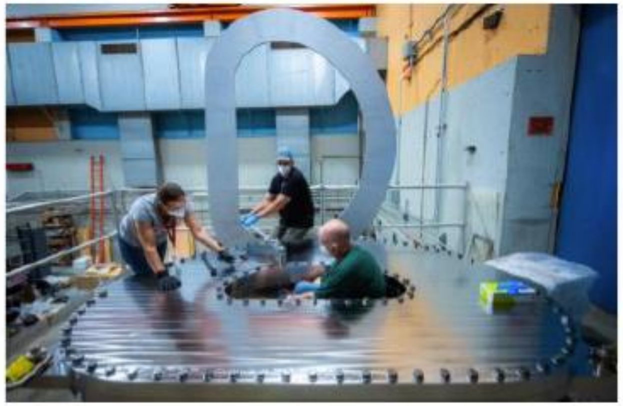
Metallic Cladding Insulation (MCI):



RENAISSANCE FUSION

Fusion magnet development

MIT / CFS building an HTS TFMC demonstrator

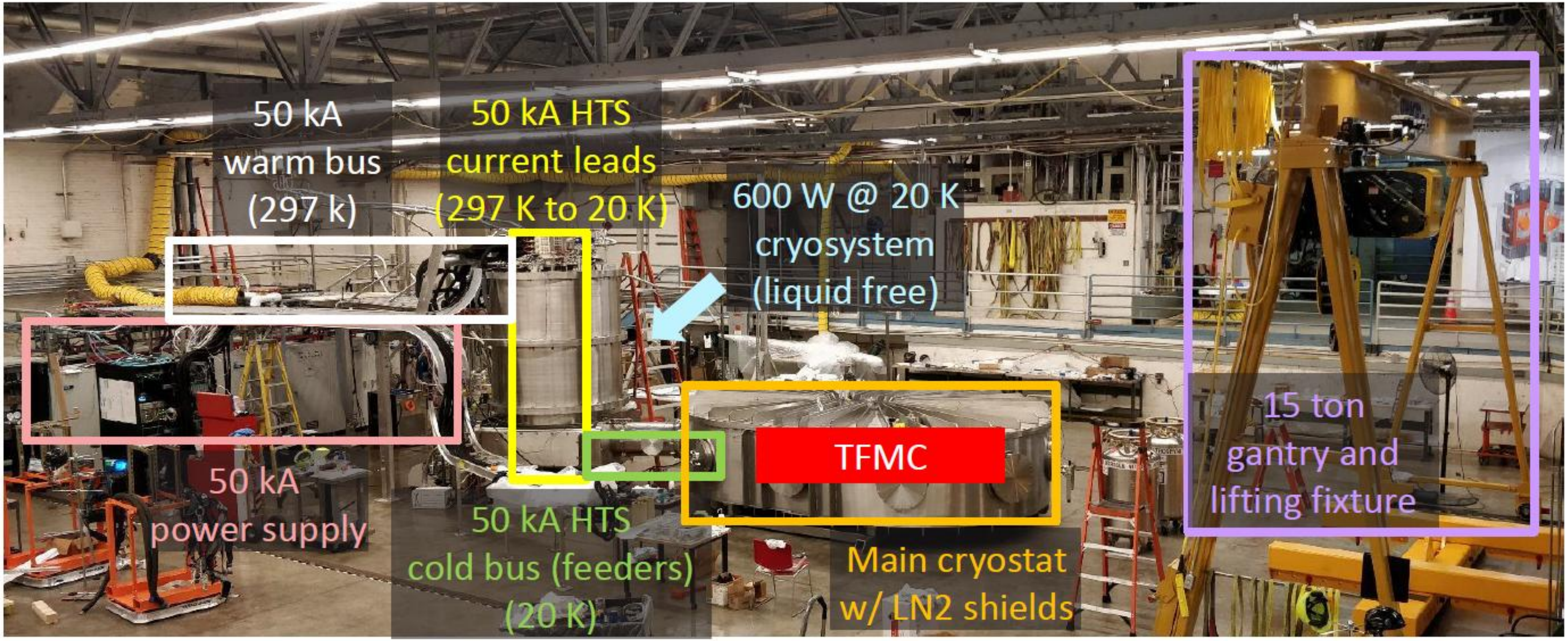


Parameter	Value
Number of pancakes	16
Total turns	256
Total REBCO tape	270 km
Operating temperature	20 K
Coolant type	Supercrit. He
Operating coolant pressure	20 bar
Operating azimuthal current	40 kA
Peak magnetic field	20 T
Peak IxB force on REBCO	800 kN/m
Inductance	0.14 H
Magnetic stored energy	110 MJ
WP mass	5113 kg
WP + case mass	9265 kg
WP current density	153 A/mm^2

~1.5x ITER

~10x ITER

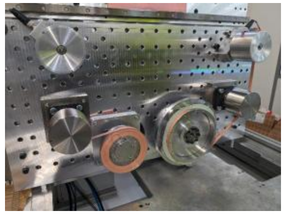
HTS magnets are a small part of the entire magnet system

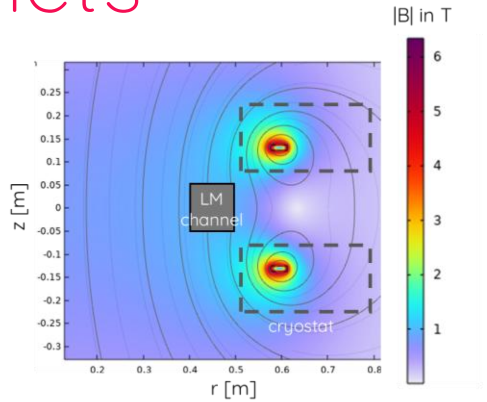


Not shown: SHe and LN2 distribution systems; Vacuum systems; I&C system; Safety systems; Control Room

1/21/2022 49

From superconductors to HTS magnets





Magnet design target

Winding pack space

Superconductor choice and operating point

I_{op} vs $I_c(B, T, \theta)$

Magnet architecture and type

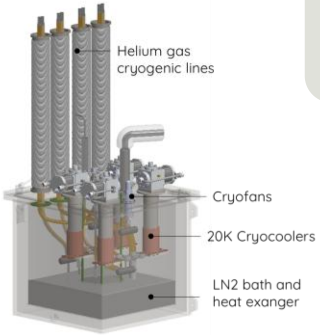
Current leads, joints and connections

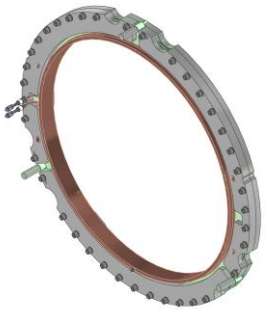
Thermo-mechanical design

Cryogenics and cooling

Quench mitigation

Cabling, winding operation, cycling





RENAISSANCE FUSION

Renaissance Fusion develops a simplified compact HTS stellarator with plasma-facing liquid walls

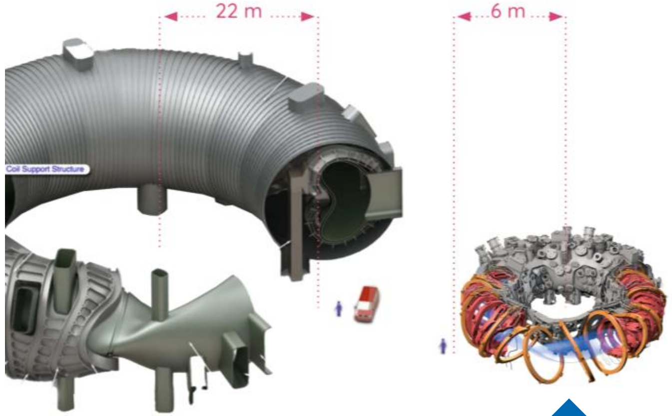
PROBLEMS

Low-field tokamak and stellarator reactors are large and expensive.

D-T fusion neutrons induce radioactivity and damage to solid parts.

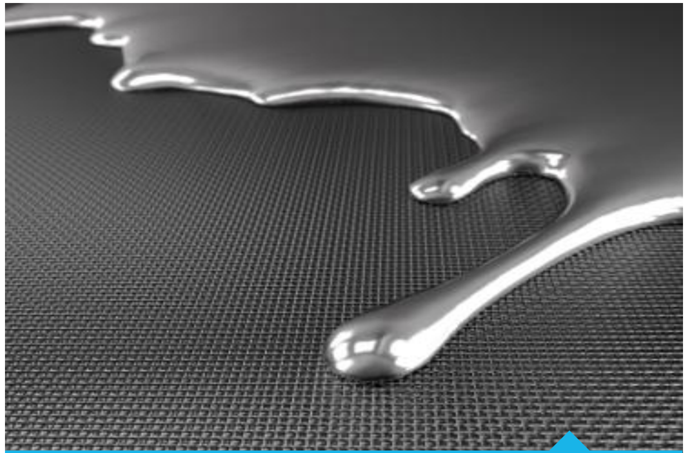
Stellarator coils have complex 3D shapes.

SOLUTIONS



High Temperature Superconductors (HTS)

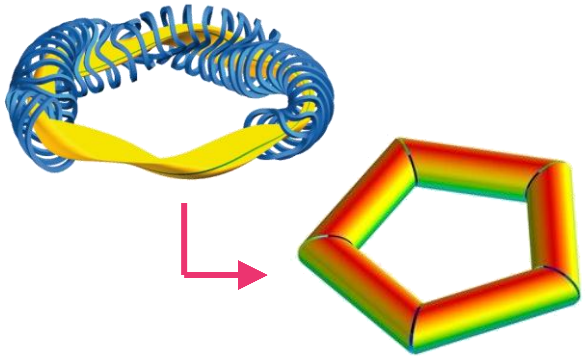
HTS generate stronger fields, unleashing the same power from smaller devices.



Liquid Metals (LM)

Plasma-facing, thick Lithium-based walls absorb neutrons without getting activated, making reactors safer.

Bonus: resilient to non-uniform α particle losses.



Simplified Stellarators

of simpler “coil winding surfaces” are easier to build, by wide HTS deposition & laser engraving.

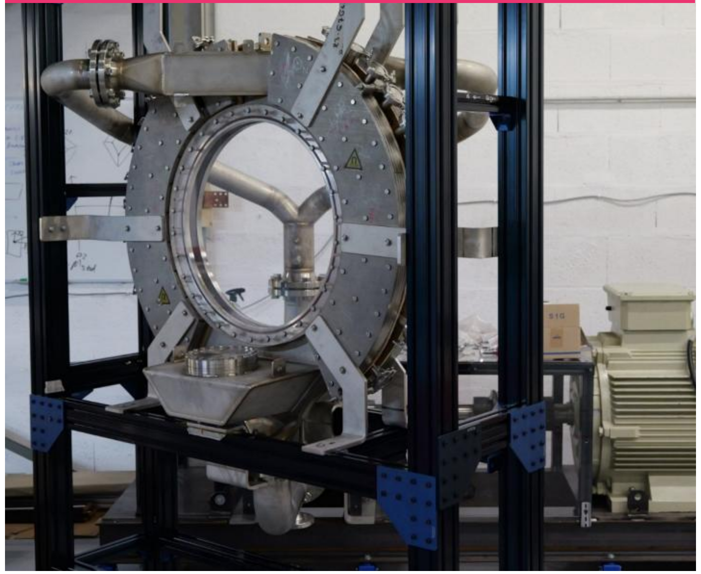
Developing and validating key building block technologies to enable simplified stellarators

HTS manufacturing

Designed, modeled and now building the first machines ever for meter-wide HTS deposition.

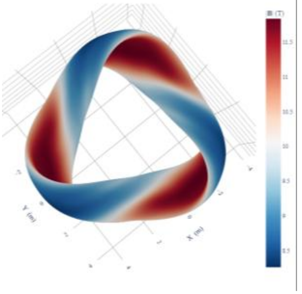
Free-surface flowing liquid walls

Levitated, in 1 m diameter chamber, a 10 cm thick layer of liquid GaInSn.



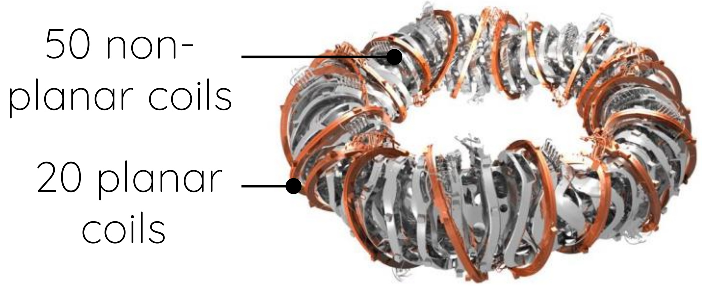
Simplified stellarator design & modelling

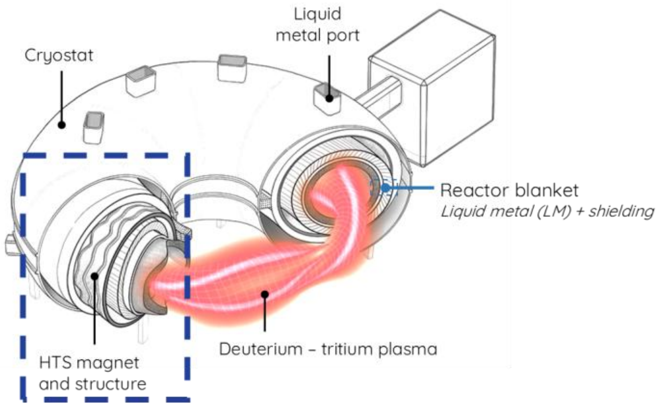
Simplified compact stellarator configurations using corrugated copper cylindrical magnets



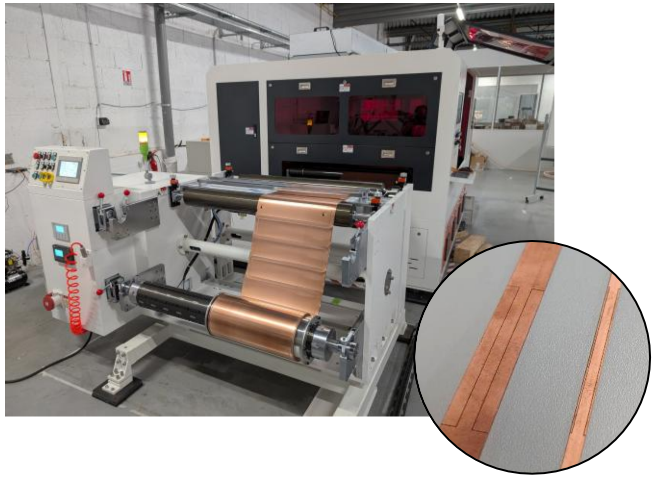
3-step program for simplified stellarator magnets

W7X stellarator



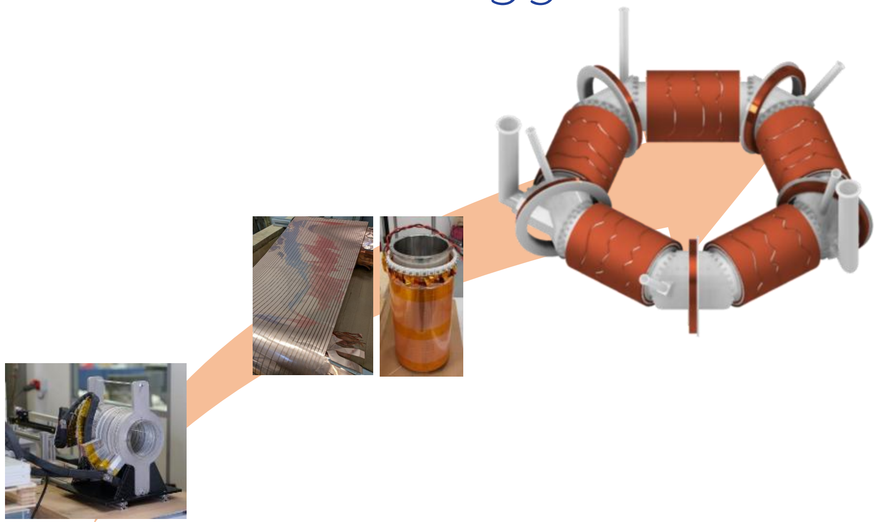


Laser patterning and winding machine

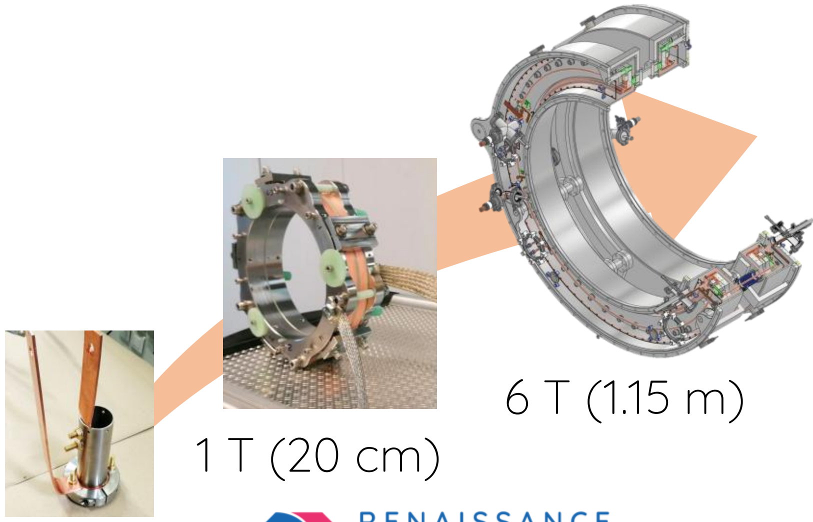


Laser engraved commercial HTS

Grooved magnet technology



Robust high-field HTS magnets



0.5 T (4 cm)

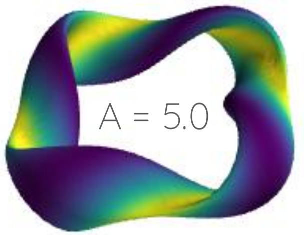
1 T (20 cm)

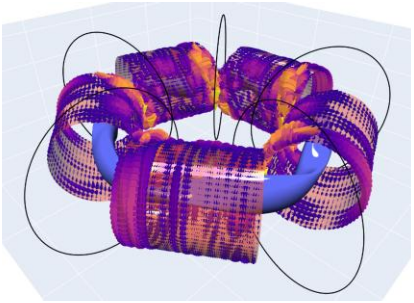
6 T (1.15 m)

Ongoing R&D development programs

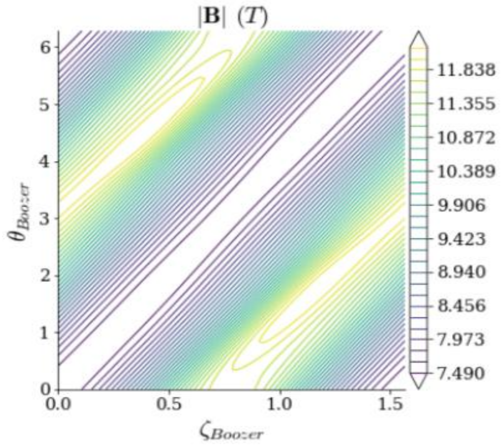
Stellarator magnetic configuration optimization for compact high-field reactors and simplified coils

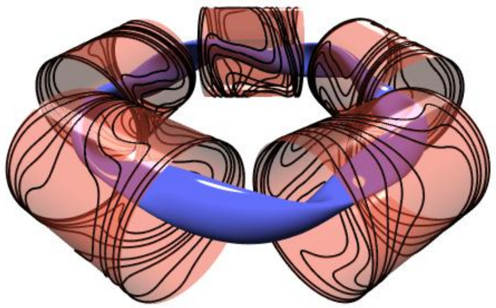
QH-4



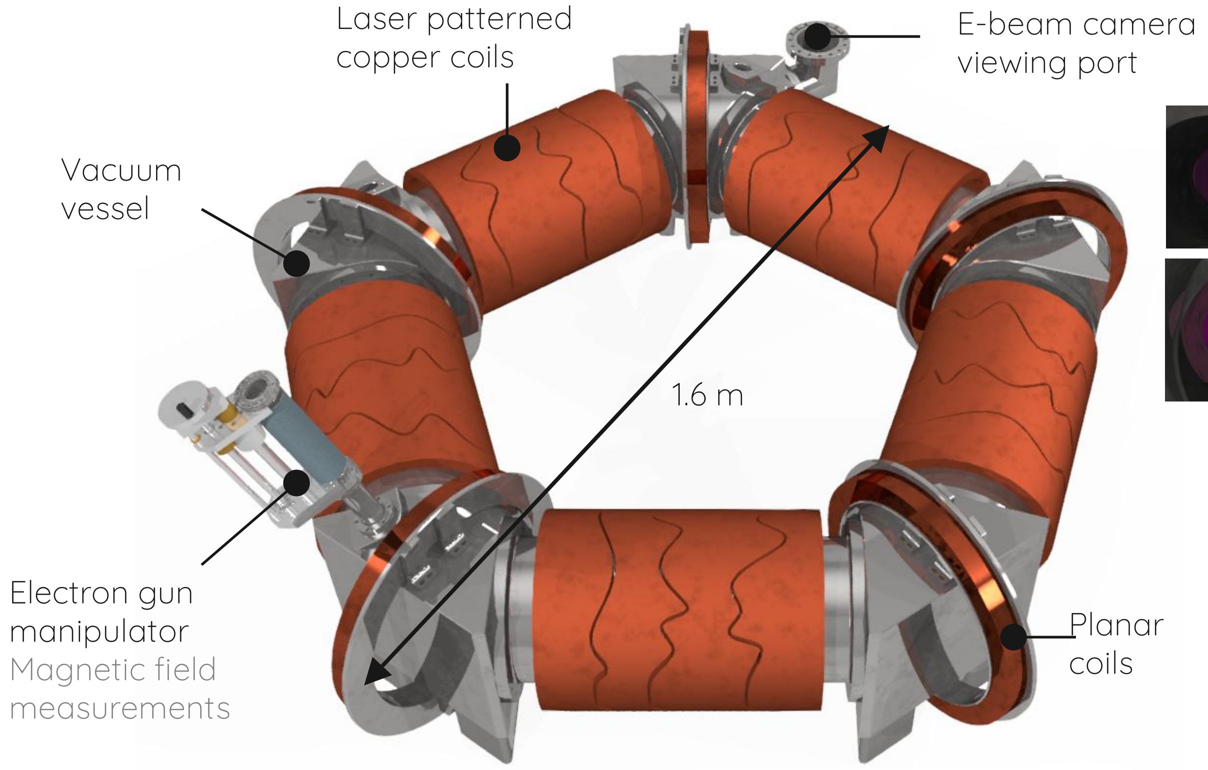


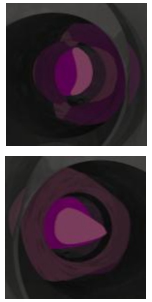
R = 4 m, B = 10 T





Simplified compact stellarator configurations using corrugated copper cylindrical magnets. Realizing W7X magnetic configuration with a 10-4 magnetic field accuracy





Thank you!

Want to learn more?

victor.prost@renfusion.eu

FAQs renfusion.eu/faq

YouTube video