The High Magnetic Field Approach to Fusion Energy on the Grid

Joseph V. Minervini

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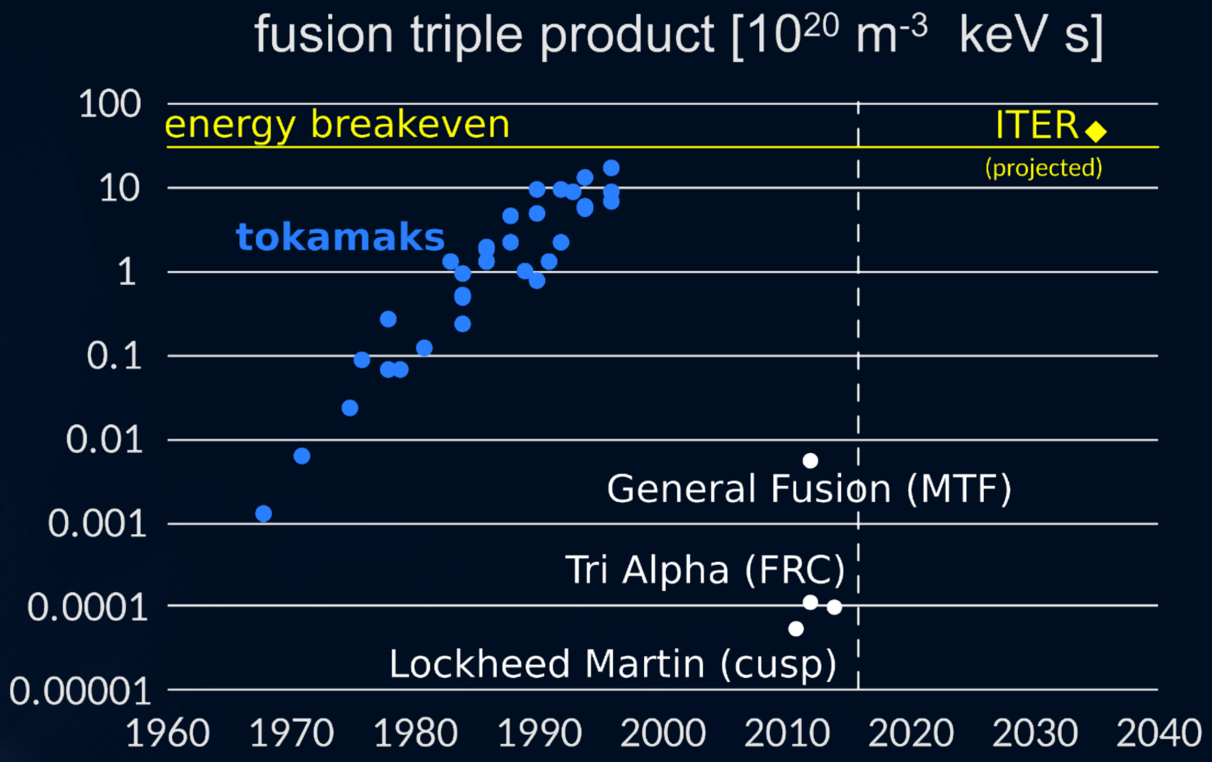
Massachusetts Institute of Technology
PSFC Plasma Science and Fusion Center

The Big Idea

1. The world needs a new energy source to combat climate change
2. Fusion energy is the most sustainable, safest, cleanest energy source
3. The current fusion paths require big, slow, expensive steps or extremely large science risk on unproven fusion concepts
4. New superconductor technology enables order of magnitude decrease in size and cost while using a proven fusion concept
5. The ARC fusion device concept will obtain net fusion energy utilizing these superconductors

Progress in Fusion has stagnated, not stalled…..



The perception is "too big, too unproven, and always 30 years away"

We believe there is a new pathway that retires this perception risk.

We understand the physics of fusion: The magnetic field is key.

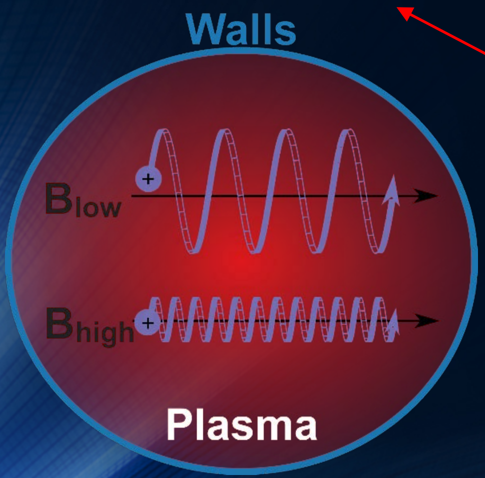
How well a plasma is insulated:

Make many of these fit inside the device

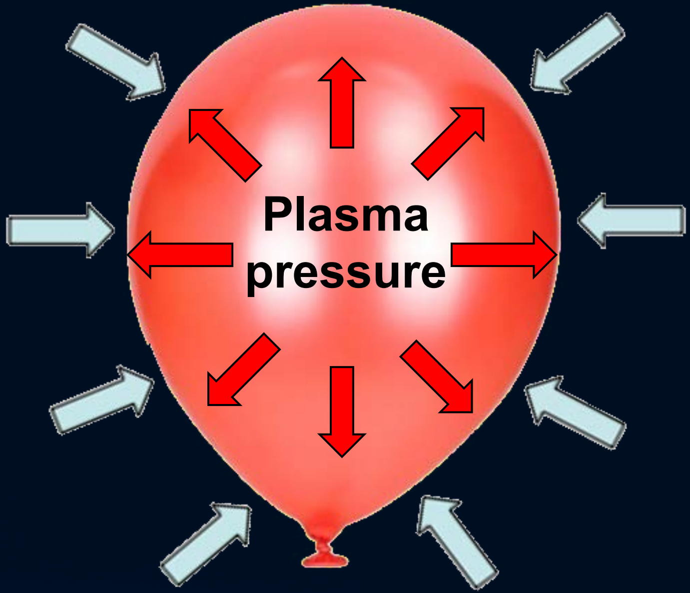
$$r_{ion} \approx \frac{\sqrt{T}}{B}$$

Plasma temperature, Set by fusion nuclear cross-section

Magnetic field, set by engineer



How reactive and stable the plasma is:



Magnetic pressure ~ B^2

Fusion rate $\propto$ (plasma pressure)$^2 \propto B^4$

The Way to Decrease the Size of Fusion Devices, and Accelerate Fusion Energy Development, is to Achieve Higher ***Magnetic Field Strength***

Fusion power density

$$\frac{\beta_N^2}{q_*^2} R B^4$$

Physics parameters

R = linear size, volume & cost $\propto R^3$

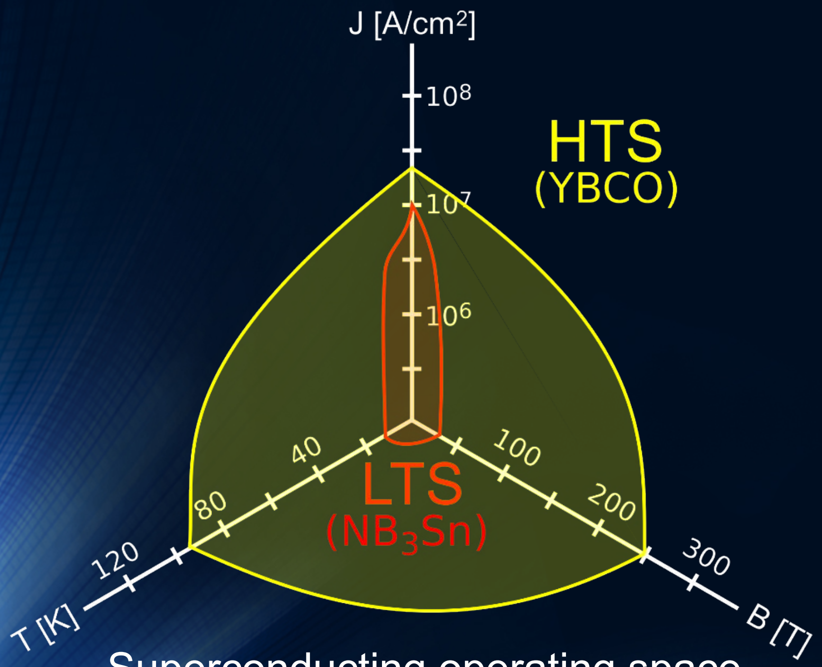
B = magnetic field strength

Increase B two-fold → Gain 2^4 = 16 advantage!

Well known 20+ years ago but could only be done in resistive, energy consuming copper coils → no net energy

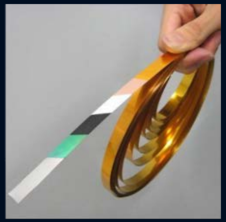
HTS is a game-changing technology for fusion

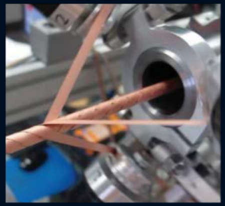
Higher magnetic
field superconducting fusion devices



Superconducting operating space

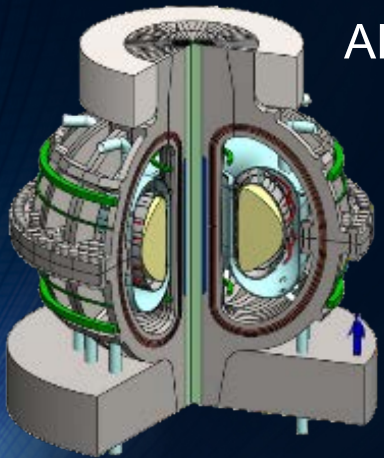
Now a mature commercially available technology



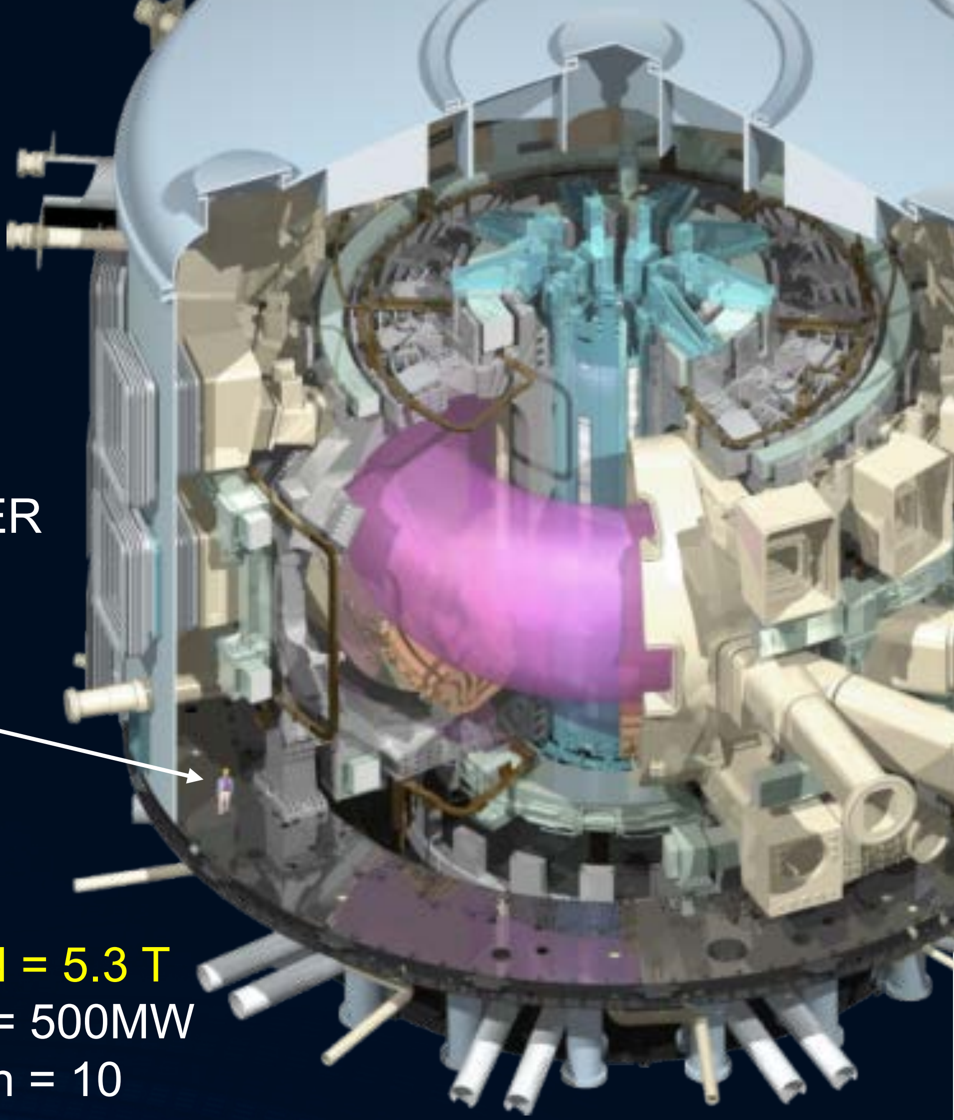


HTS can dramatically reduce fusion reactor size

ARC



ITER



Human for scale

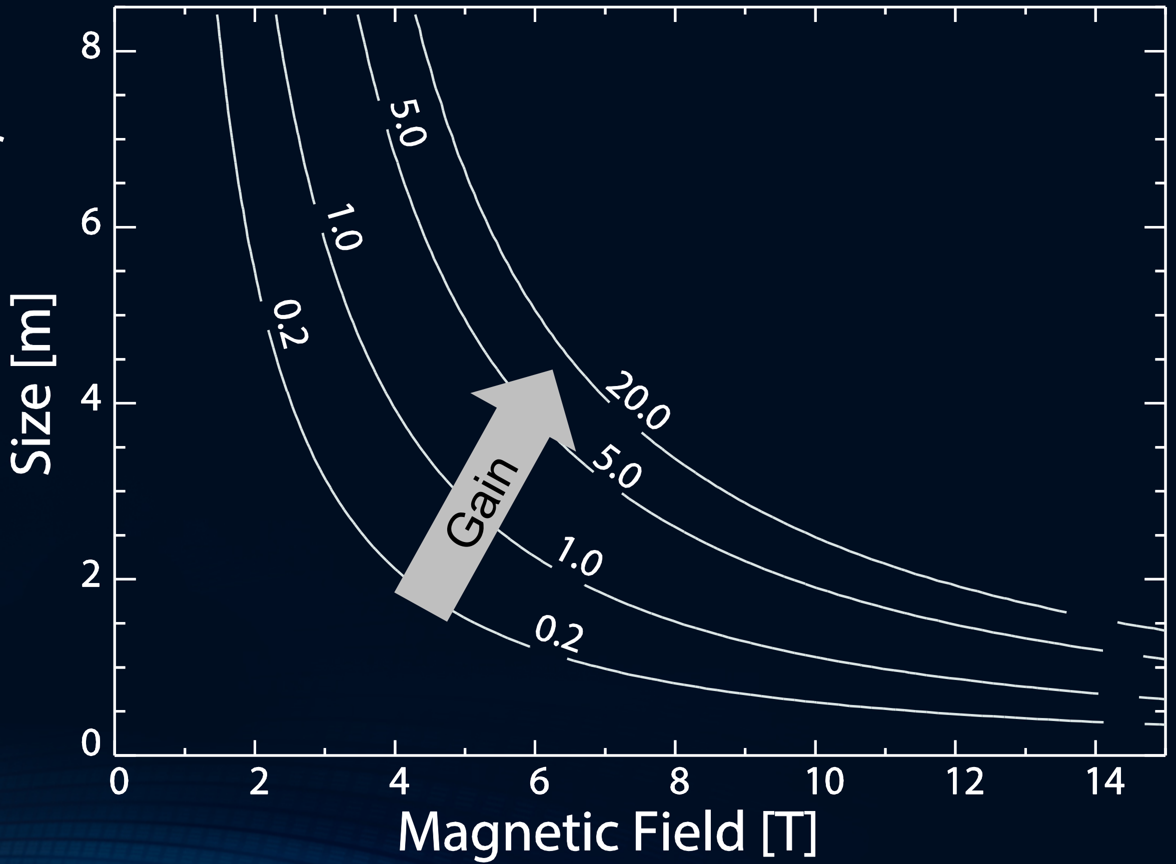
Magnetic field = 9.2 T
Fusion power = 500MW
Energy gain = 10

Magnetic field = 5.3 T
Fusion power = 500MW
Energy gain = 10

High magnetic field opens attractive design space with the same high confidence in physics

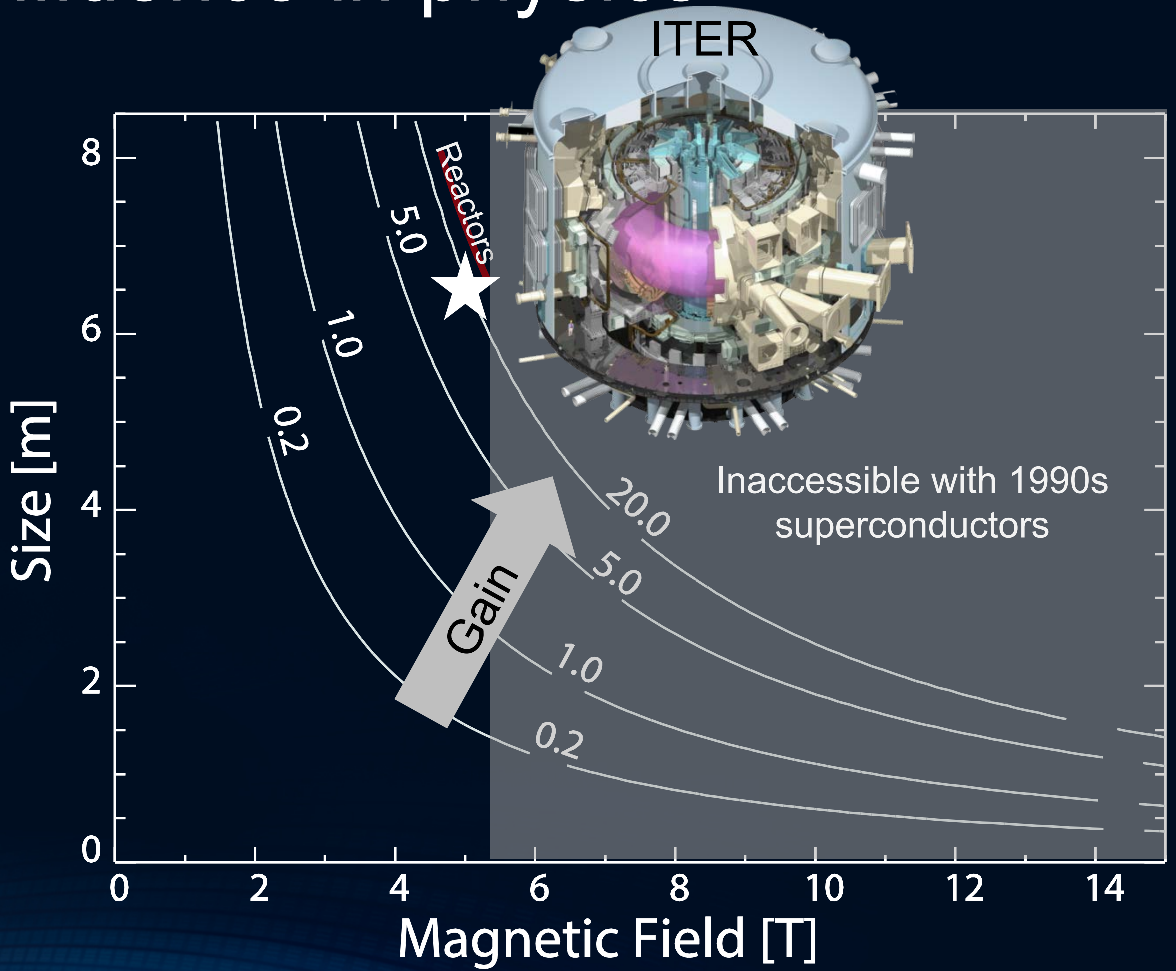
HTS opens new design spaces for fusion with the same physics confidence

High-field allows fusion at small scale with high physics confidence



High magnetic field opens attractive design space with the same high confidence in physics

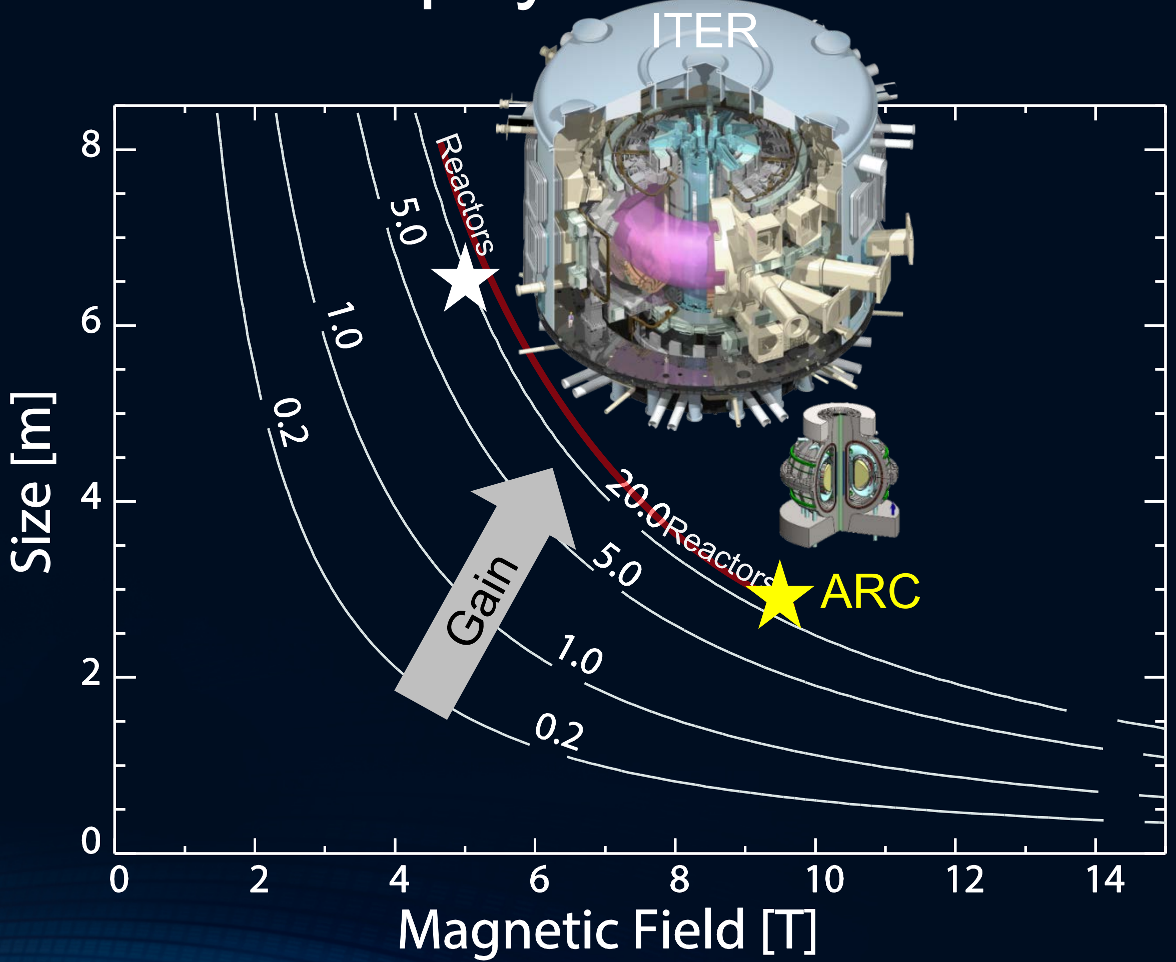
But these were previously inaccessible due to limitations in the superconductor.



High magnetic field opens attractive design space with the same high confidence in physics

But these were previously inaccessible due to limitations in the superconductor.

HTS enables smaller reactors to be built using the same proven physics.

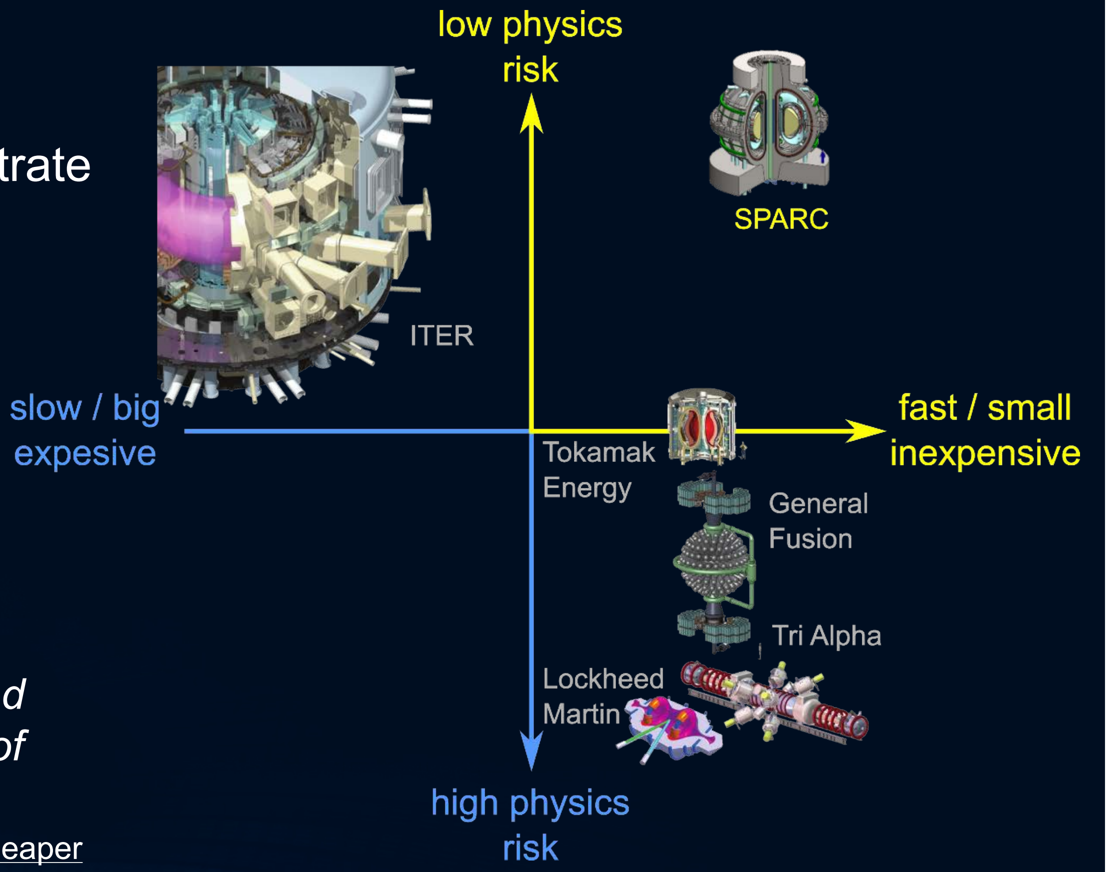


The breakthrough technology

ARC leverages advanced superconducting technology to achieve low physics risk in a faster/smaller/lower-cost mission to demonstrate net fusion energy gain.

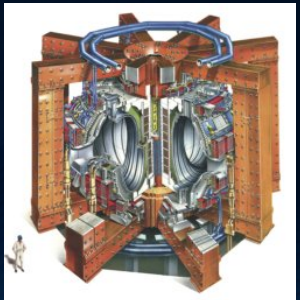
"High temperature superconductivity will provide cheap power transmission and rapid transport, and nuclear fusion would give us an unlimited supply of clean energy." **Stephen Hawking**

Evening Standard "Stephen Hawking: We will have cleaner and cheaper power in 10 years" October 20, 2014.



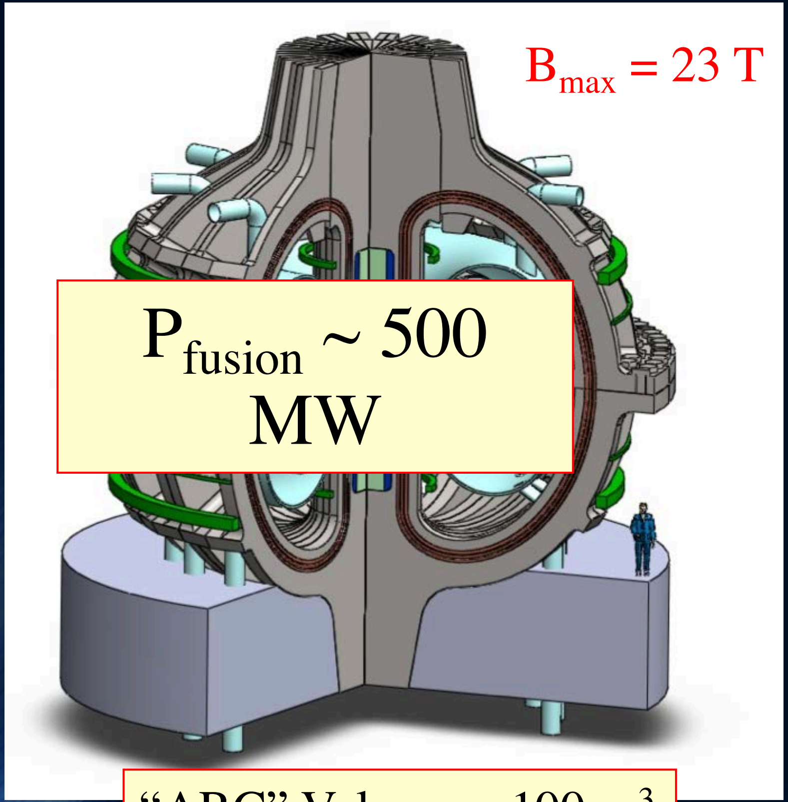
Smaller, Modular Fusion Devices are the Key to Accelerating Fusion Development for Net Energy on Decade Timescale

	Shippingport: 1954 "Pilot" Fission Plant	ITER
$P_{thermal}$ (MW)	230	500
Core volume (m^3)	60	1000
Cost (2012 US B$)	0.6	~ 20
Cost / volume (M$/$m^3$)	10	~ 20
Construction time (y)	3.5	> 20

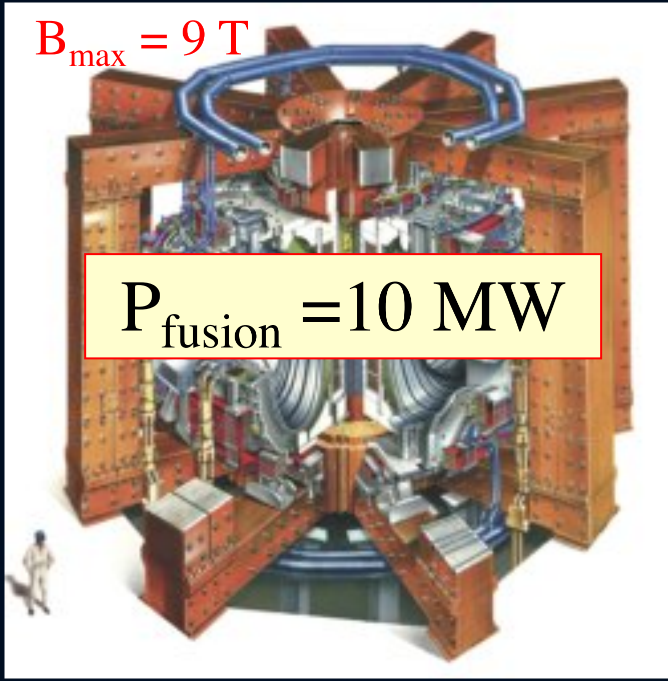


JET tokamak: 100 m^3 ✓
~4 years construction ca. 1980 ✓
But only 10 MW fusion power

Breakthrough *Superconductor* Technology Provides a Stronger Magnetic Bottle That Does Not Use Electricity → Smaller, Sooner Fusion Energy



"ARC" Volume ~ 100 m^3

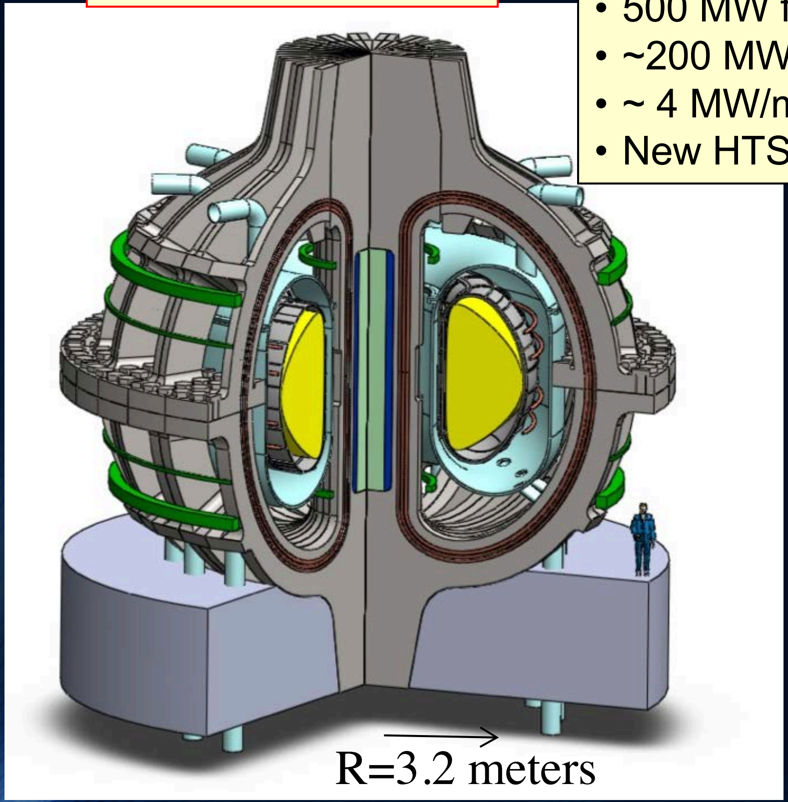


JET (UK): Volume ~ 100 m^3

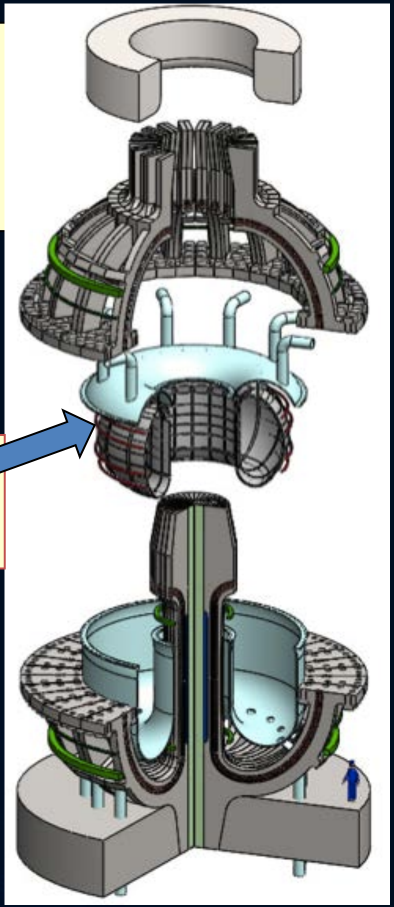
The ARC conceptual design:
Fusion power at small size = Power density

B. Sorbom et al FED 2015

- 500 MW fusion power
- ~200 MW electricity
- ~ 4 MW/m^2 fusion power density
- New HTS magnet at~23 T, 20 K



Replaceable "core" module

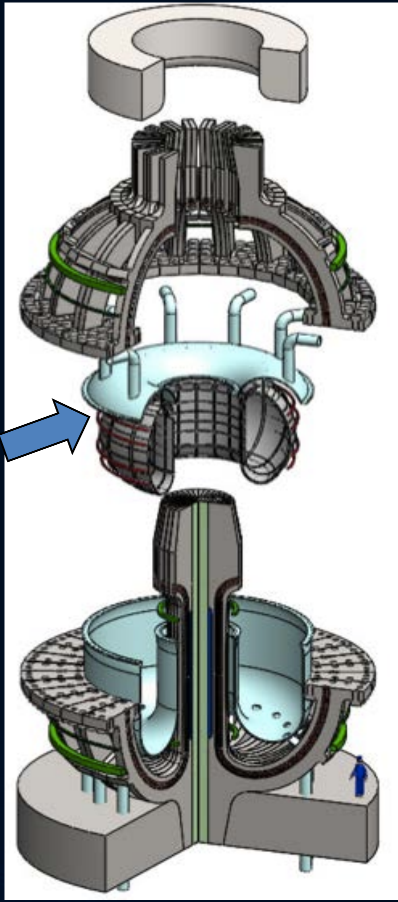


Demountable Superconductor Coils Have a Profound Effect on Modularity of Fusion Design

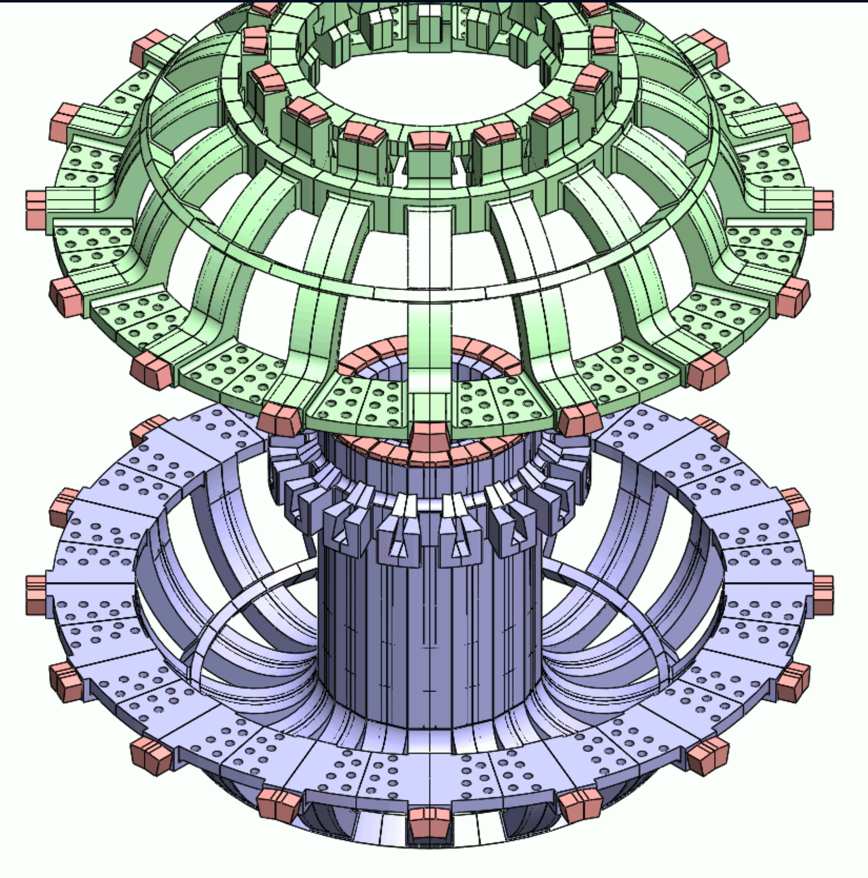
- Core is designed as a single integrated unit
  - Synergy with keeping design of small total mass and volume

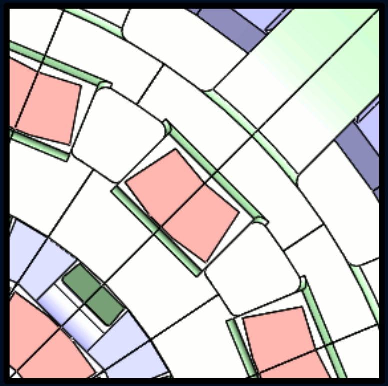
- **Fabrication + qualification done completely off-site**

Replaceable "core" module



Tape Superconductors → Demountable Coils → Open the Magnetic Bottle!



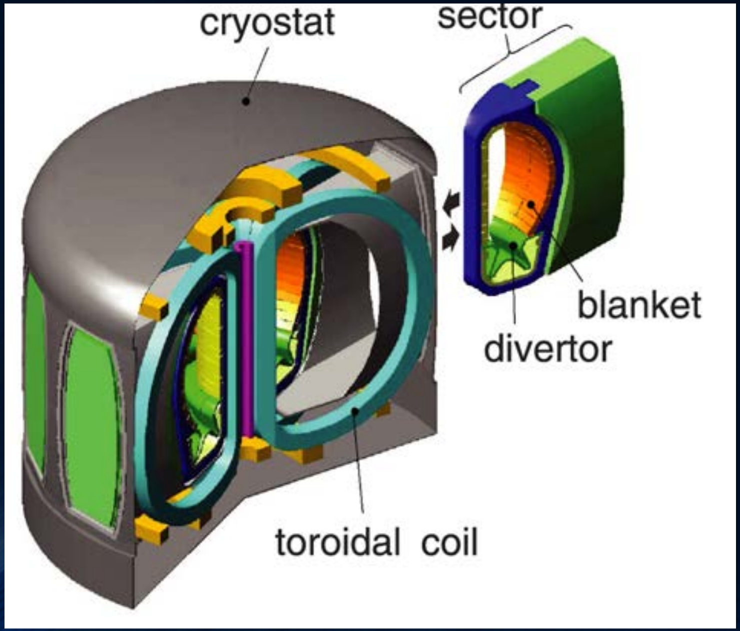


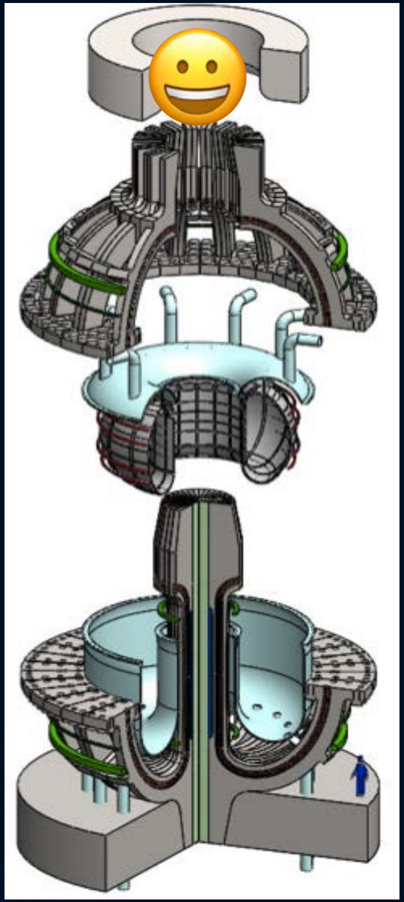
Auxiliary part detail

- Machine would operate ~20 K and allow resistive joints

F. Mangiorotti, MIT Ph.D. thesis

Demountable Superconductor Coils Have a Profound Effect on Modularity of Fusion Design





Twisted Stacked-Tape Cable (TSTC)

For example:

1. REBCO tapes are **stacked** between two thick copper strips.

2. The stacked-tapes with the copper strips are loosely **wrapped** with a fine stainless steel wire.

3. Then the stacked-tape cable is **twisted.**

Stacked-Tape Twist-Winding (STTW) Magnets Method for 3D Curved racetrack or saddle coi magnetl

A curved saddle winding of 50 YBCO tapes on a 50 mm diameter tube.

Stacked tape cable is twisted during winding.

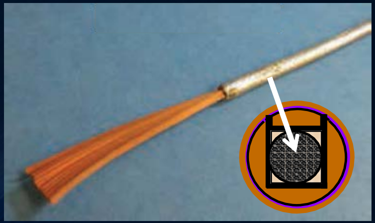
3D accelerator magnets, generator and motor magnets

TSTC Conductor : Basic conductors

TSTC basic conductors to fabricate multi-stage twisted cable.

Wrapped with copper foi soldering

Tapes vertically mounted in a helical groove on copper rod



TSTC conductor in a groove

30-tape (3 mm width) braided-sleeved soldered round conductor (6 mm diameter)

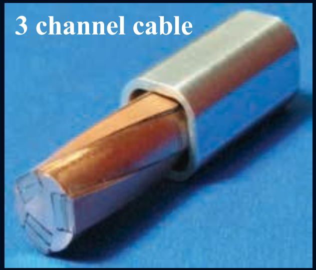
TSTC Conductor : Scale-up industrial fabrication

H-Channel TSTC Conductor

40 tape dual-stack cable

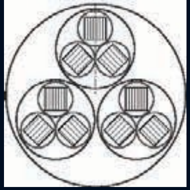
CICC mockup of TSTC conductor

40 YBCO tapes



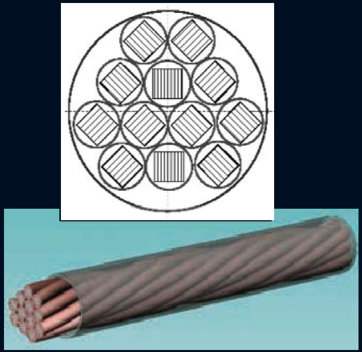
20 YBCO tapes in each helical groove

Multiple-stage conductor

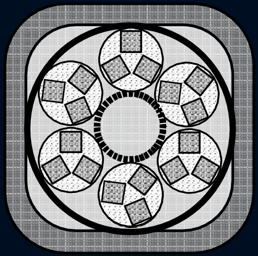


3x3 cable

Hexa-cable CICC



12 sub-cable conductor



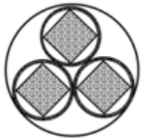
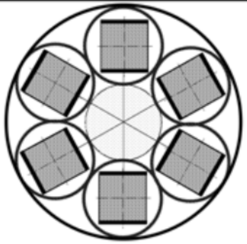
3 x 6 CICC

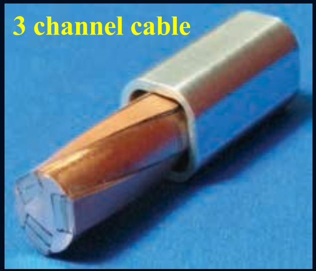
Large TSTC Conductor Current Capacity

Estimated critical current

Based on SuperPower SCS4050-AP (2012), 4 mm width, 0.1 mm thickness REBCO tape.

Tape critical current : 180 A at 17 T and 4.2 K

Conductor	Tape width (mm)	Tape current (A)	Number of Tapes	Critical Current (kA)	Cable Diameter (mm)	Conductor Cross-Section
Single-stage	4	180	40	7.2	7.4	
	6	270	60	16.2	11.1	
	12	540	120	64.8	22.2	
Triplet	4	180	120 (40 x 3)	22	16	
	6	270	180 (60 x 3)	49	24	
	12	540	360 (120 x 3)	194	48	
Hexa	4	180	240 (40 x 6)	43	23	
	6	270	360 (60 x 6)	97	35	

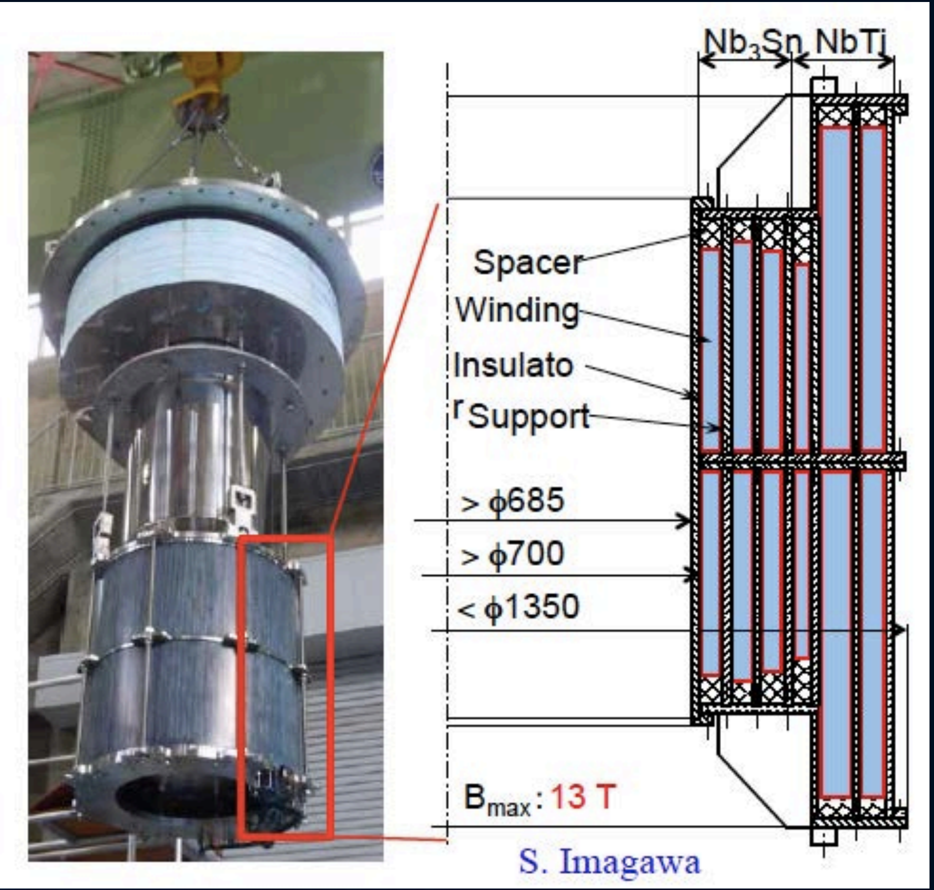


4 mm Tape Hexa CICC

(26 mm x 26 mm)

NIFS New Superconductor Test Facility

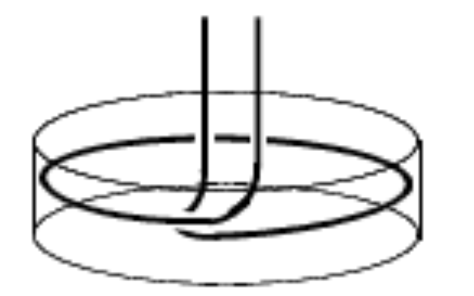
Max. Field: 13 T
Bore: 700 mm
Sample Current: 50 kA
Temperature: 4-50 K

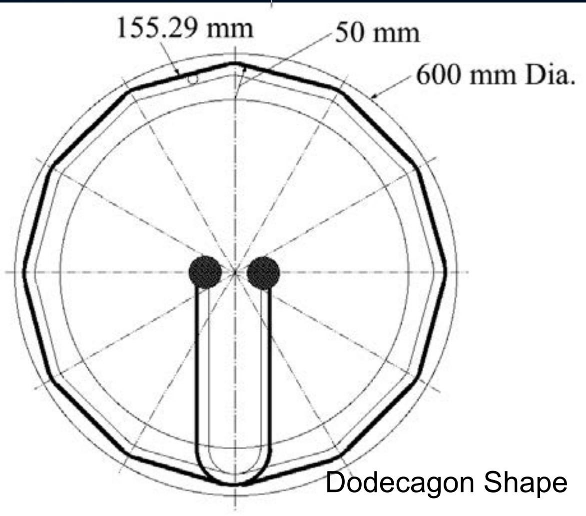


N. Yanagi, et al., 3rd *HTS4Fusion*, ENEA/Tratos, September, 2015.

High field, high current NIFS test sample

One turn coil sample





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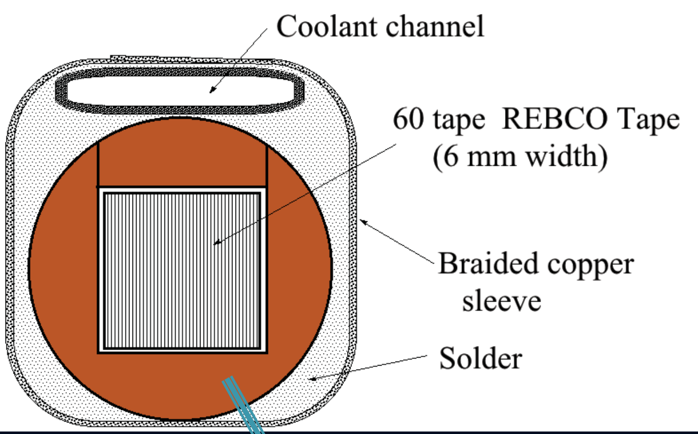
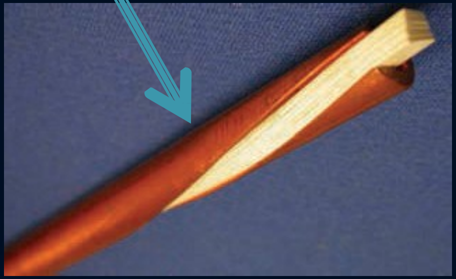
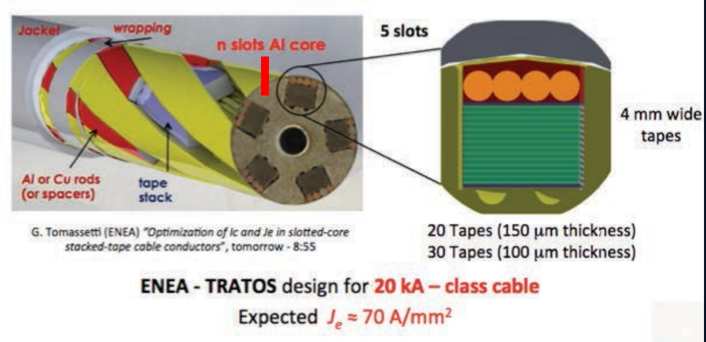
Conductor cross-section





Developments of TSTC type conductors at ENEA and PSI

ENEA



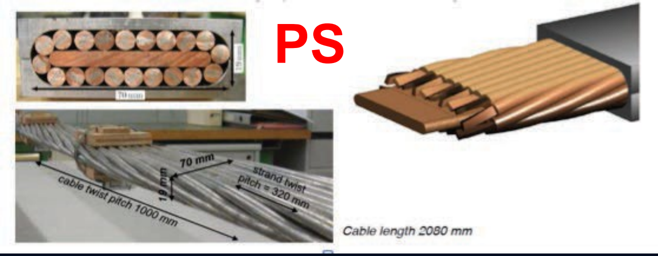
15 T Magnet

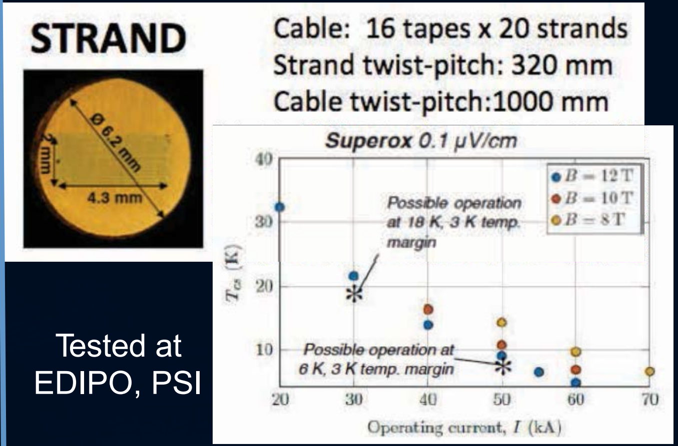
Total conductor length: 224 m Inner diameter (bore): 550 mm

HTS CICC insert in 7 T background field (ENFASI NbTi magnet)

A. Augieri, et al., 3rd *HTS4Fusion*, ENEA/Tratos, September, 2015.

PS





Tested at EDIPO, PSI

D. Uglietti, et al., 3rd *HTS4Fusion*, ENEA/ Tratos, September, 2015.

Summary

- Fusion energy has stagnated
  - Burning plasma devices are too big and too expensive as designed
- High magnetic field is the key to enabling high performance in small volume
- Breakthroughs in technology are needed
  - REBCO HTS tape is the 'game changer'
- A new class of tokamaks based on the use of REBCO can accelerate putting fusion power on the grid