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Nb_3Sn superconductors for accelerator magnets

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Accelerator Physics and Engineering Webinar, FRIB, MSU

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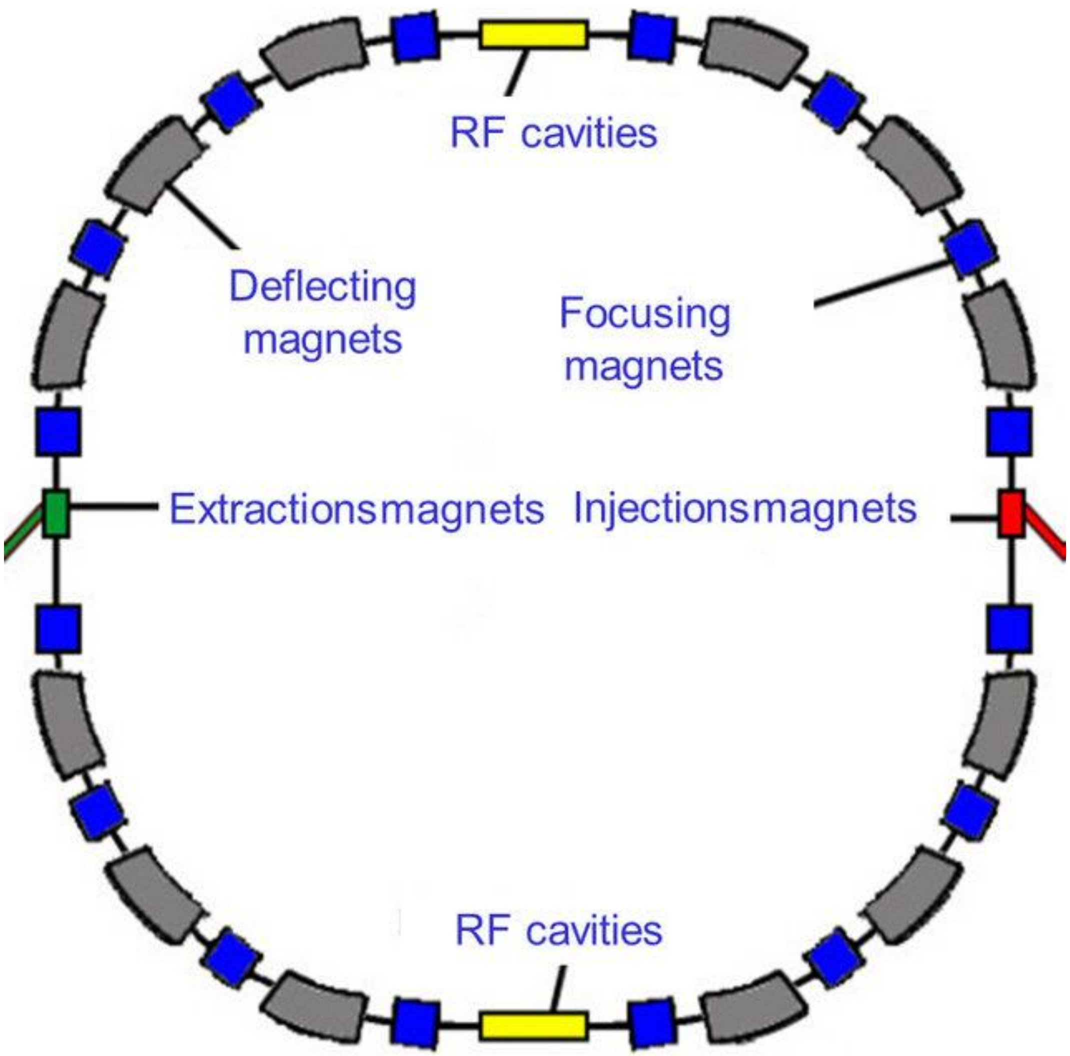
Magnets are key components for circular accelerators

Typical components of a circular accelerator:



The components that require **superconducting magnets**: **Deflecting & Focusing magnets**, because they require high magnetic fields, which can only be efficiently provided by superconducting magnets.

They are major components.

Deflecting magnets determine the beam energy:

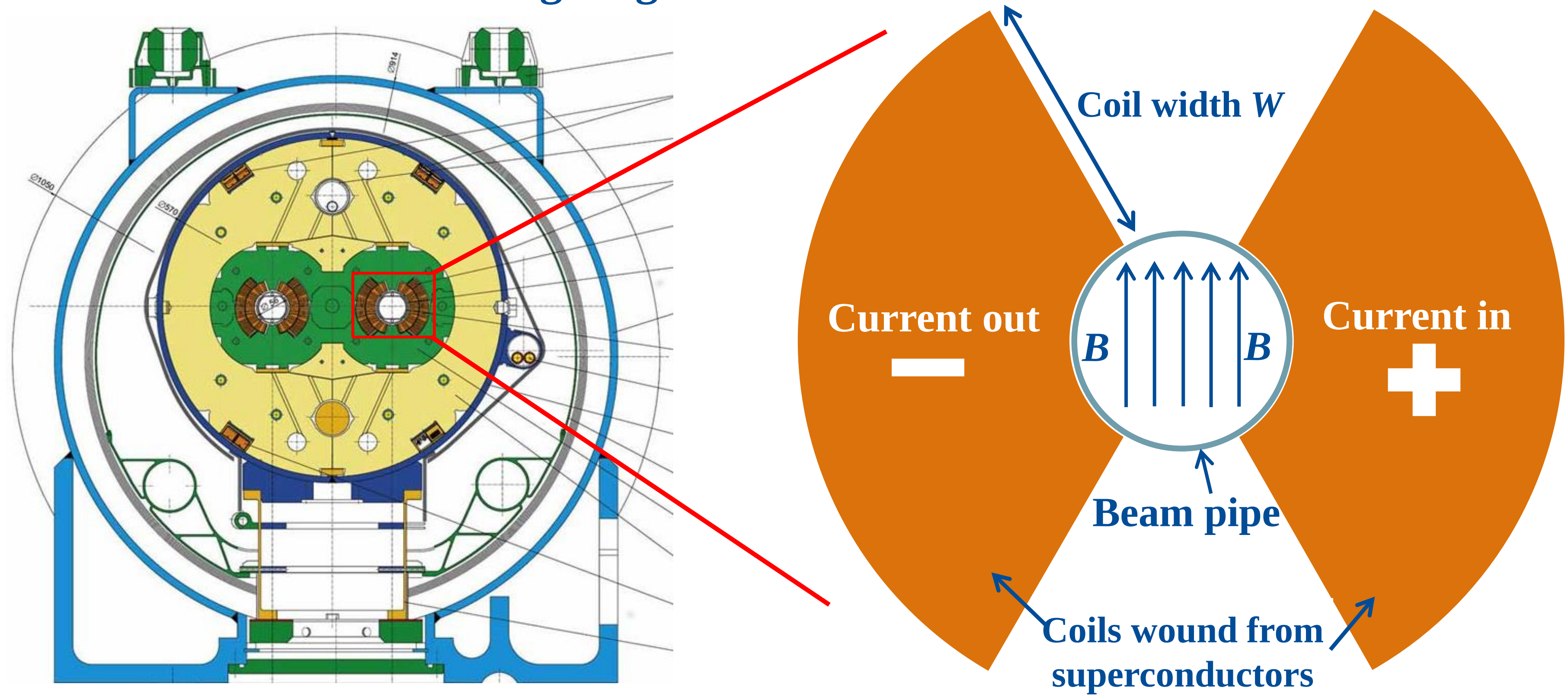
$E \approx 0.3R \cdot B$

E: in TeV. *R*: in km. *B*: in T.

How to make a powerful deflecting or focusing magnet

Schematic of LHC deflecting magnet:

Schematic of a deflecting coil:



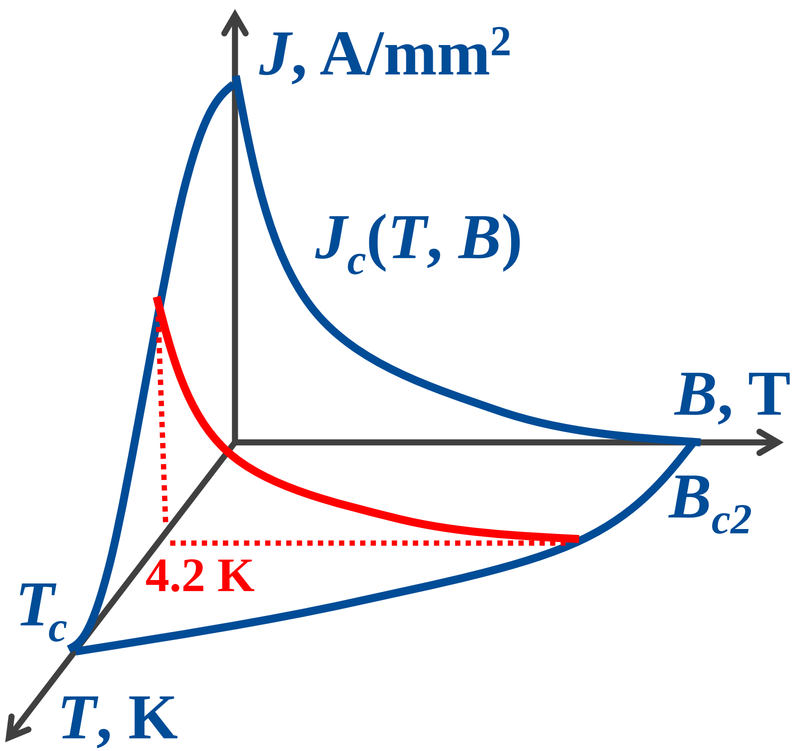
- **$B \approx 0.69W \cdot J$**. J: electric current density in the coil in A/mm^2.
- To increase B, we can increase W and J.
- This is also true for focusing magnets.

Superconductivity is limited by 3 parameters: *T*, *B*, *J*

Can the superconductors carry as much *J* as needed w/o resistance?

-- Not really! Superconductors are limited by three factors: *T*, *B*, and *J*.

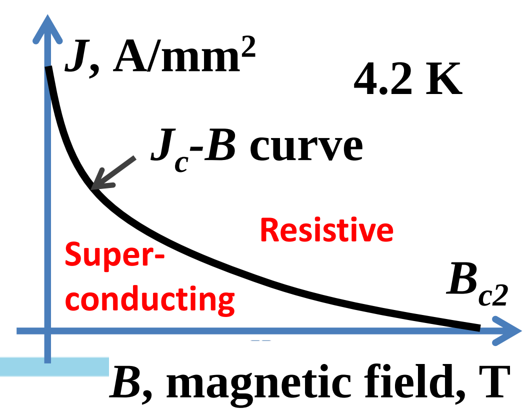
For each superconductor, there is a critical surface: only when the (*T, B, J*) fall below this surface, can it be superconducting.



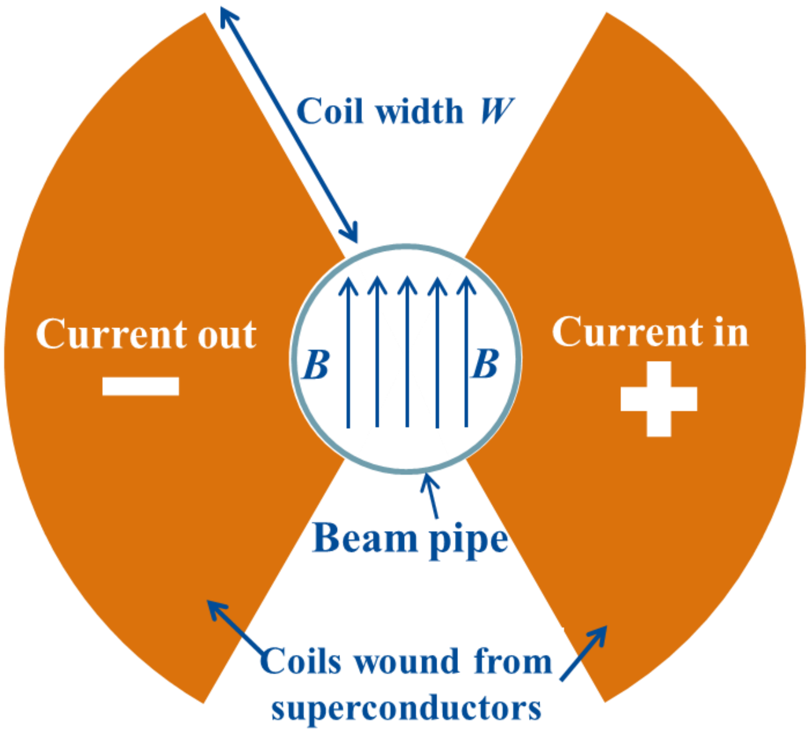
T_c (critical temperature), B_{c2} (upper critical field), J_c (critical current density).

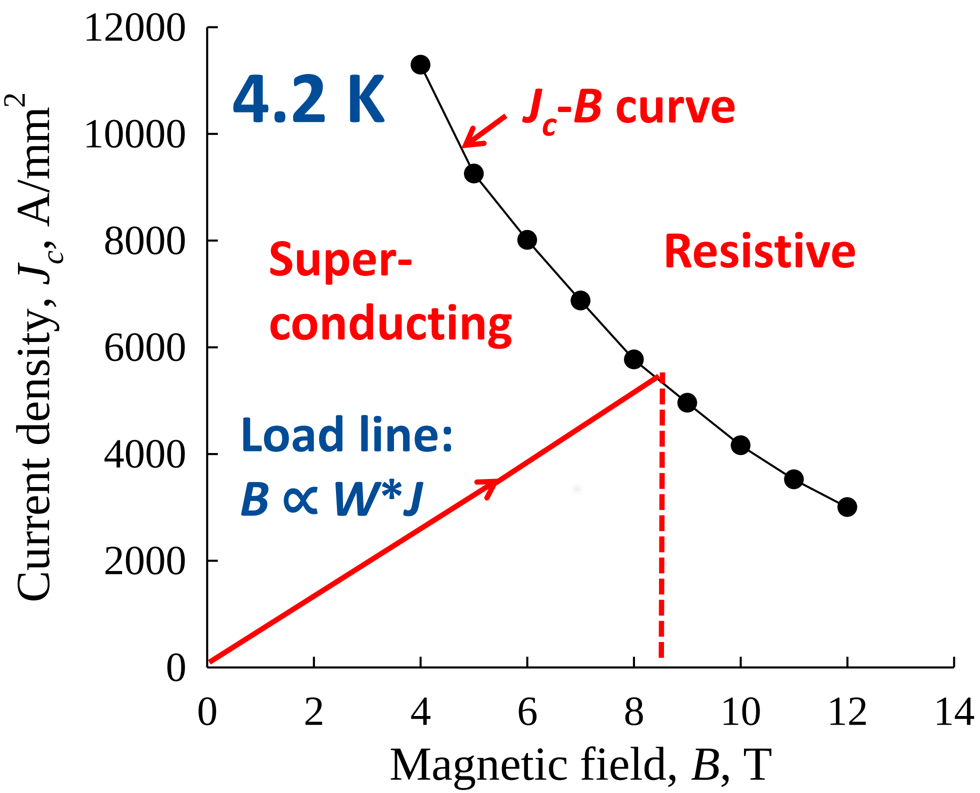
	T_c, K	B_{c2}, T
NbTi – the most widely-used superconductor (for MRI)	9.2	15
Nb_3Sn – the 2nd most widely-used superconductor	18	31
High-T_c superconductor, BSCCO, ReBCO	> 80	>100

At a fixed temperature, there is a J_c-B curve.



Why the J_c-B curve is critical for superconductor application





- **The intersection of the load line and the J_c-B curve determines the maximum achievable field.**
- **Two ways to achieve higher field: larger *W* or higher J_c.**
- **However, coil size and cost increase sharply with *W*.**
- **This is why we need high J_c for superconductors.**

Future Circular Collider (FCC)

So far the circular collider with the highest collision energy of particles is the Large Hadron Collider (LHC): 13 TeV.

A plan to go to higher energy – Future Circular Collider (FCC): 100 TeV.

The deflecting magnets will use Nb_3Sn superconductor to generate 16 T field, in a 100km-long tunnel.

Why Nb_3Sn?

Nb_3Sn is the only practical superconductor for building accelerator magnets above 10 T in the next few decades.

- NbTi: mainly used for 3-8 T. ~9 T is its limit for accelerator magnets.
- High-Tc superconductors (HTS): still many technical problems, not affordable.

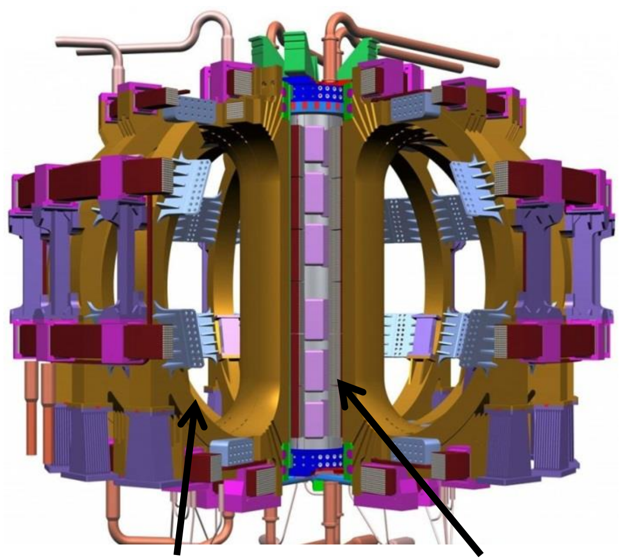
A major consideration for such a large project is **cost**.

It is estimated that ~8000 tons of Nb_3Sn conductors will be used, which accounts for nearly half of the total cost of the accelerator.

Nb_3Sn superconductors: history and current status

- Nb_3Sn is used in the form of wires. The first Nb_3Sn wire was made in 1970.
- Five decades of R&D makes it a technical, mature conductor for magnet application.
- Mainly used for high-field (>10 T) magnets beyond NbTi range.

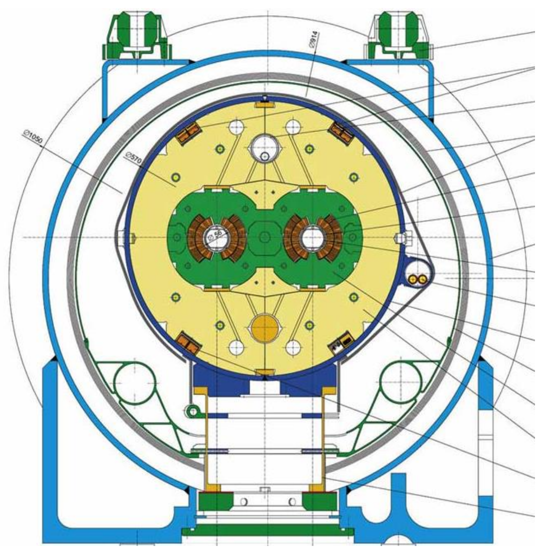
1. Experimental Fusion Reactors.



18 toroidal field coils **Central solenoid**

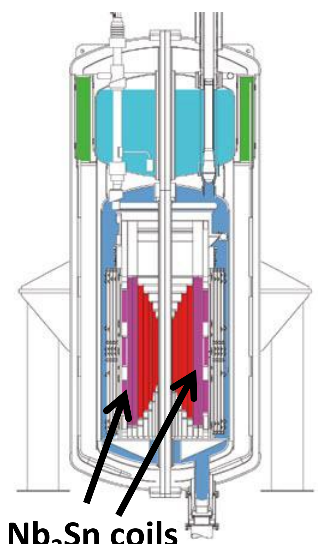
600 tons of Nb_3Sn conductors are in use for ITER.

2. Particle accelerators.



Nb_3Sn conductors are in use for High-Luminosity upgrade of LHC.

3. NMR.

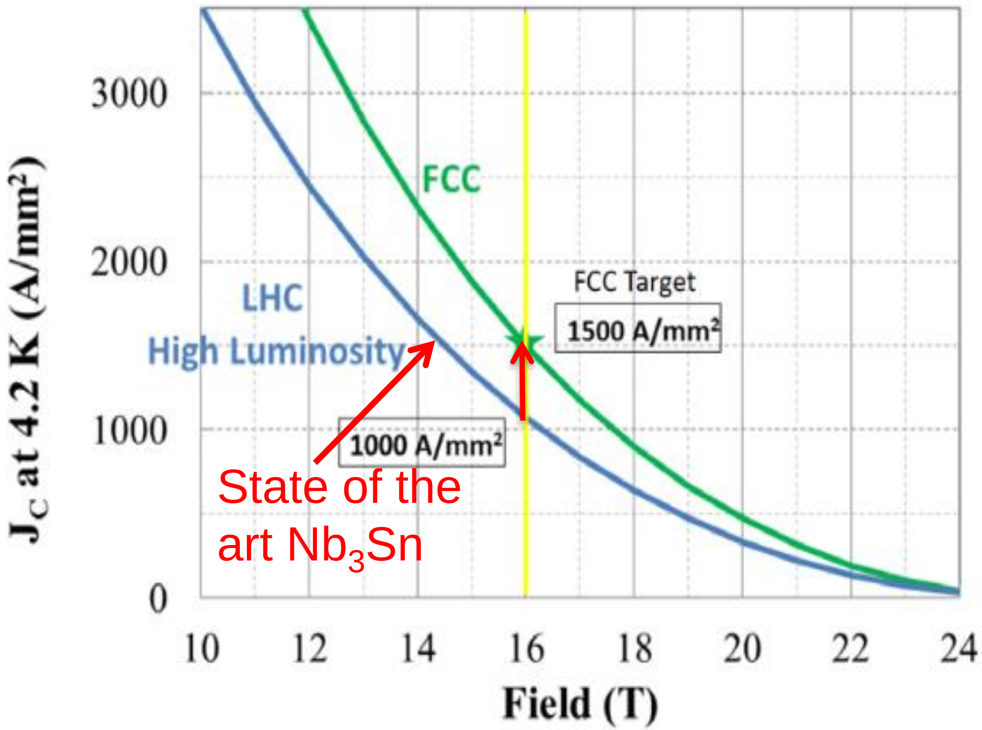


4. Other research-use magnets.

The NMR and research-use magnets using Nb_3Sn can reach 23 T, and are commercial.

Significant improvement of Nb_3Sn J_c is still needed

So, are we ready to use Nb_3Sn conductors to build the 16 T magnets for FCC yet?

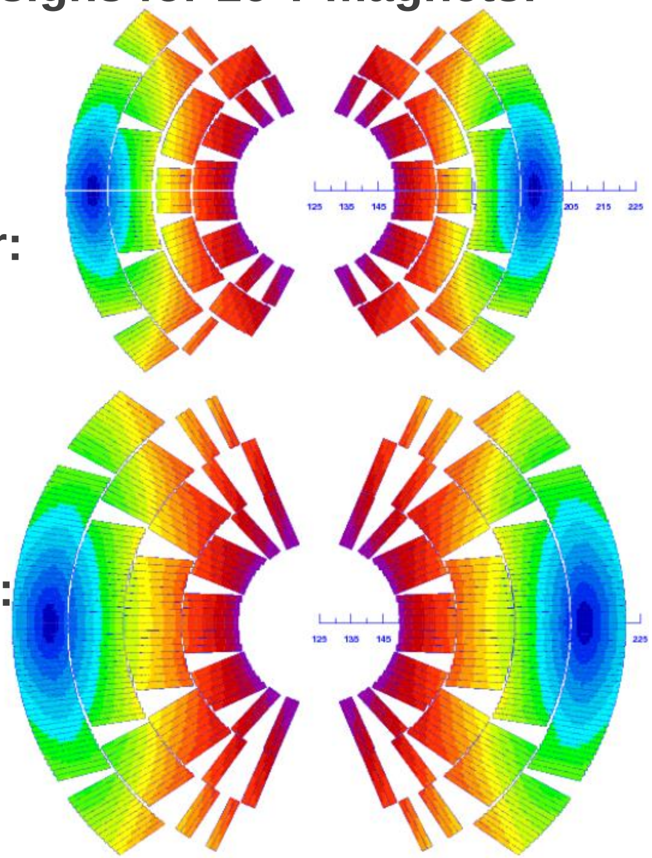


What if we cannot improve the J_c?

Designs for 16 T magnets:

Using the FCC conductor:

Using the state-of-the-art conductor:

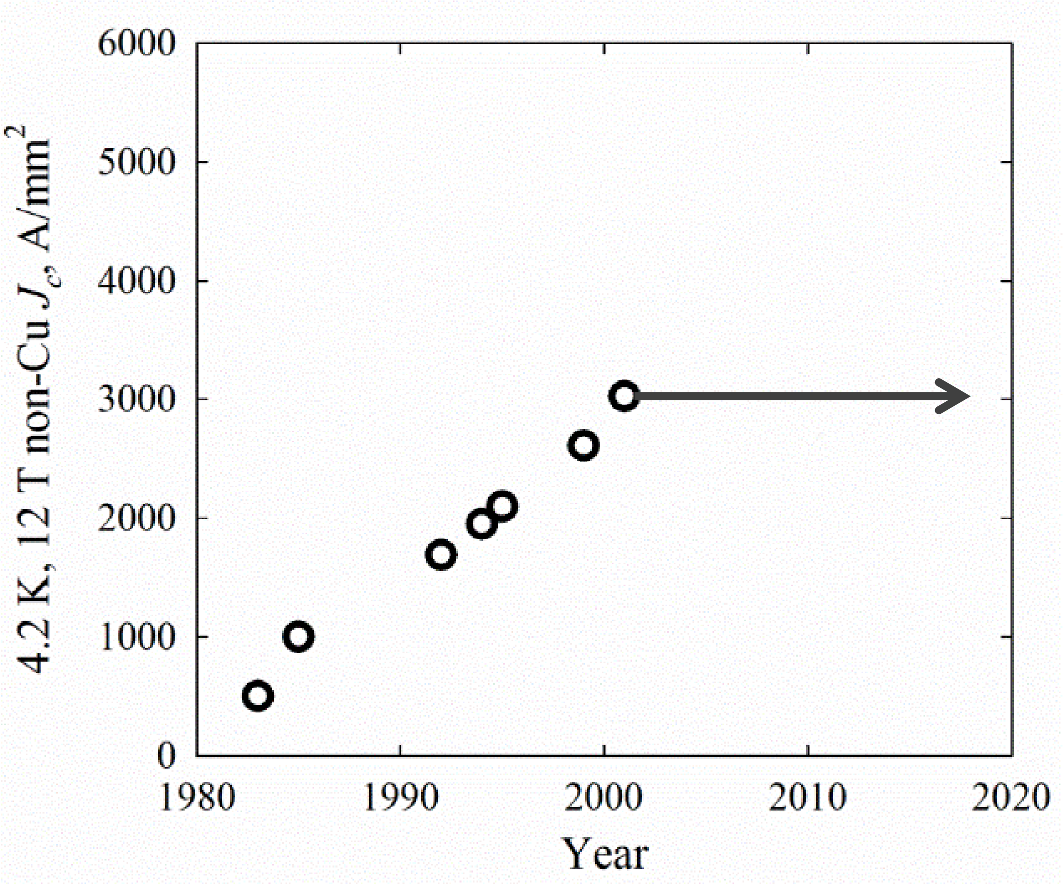


~50% increase of J_c is needed!!

~70% more conductors are needed!

Improvement of Nb_3Sn J_c is no easy thing

Nb_3Sn J_c vs time:



- The record J_c of Nb_3Sn conductors has plateaued for nearly two decades.
- Extensive efforts have been made in Nb_3Sn community to improve this record, but no success.

Need revolutionary techniques to improve Nb_3Sn J_c!

What is a Nb_3Sn wire like?

A life cycle of a Nb_3Sn wire:

A billet composed of precursors (made of Sn, Cu, Nb, etc.)

↓ **Extrusion, drawing**

Final-size wire (unreacted state)

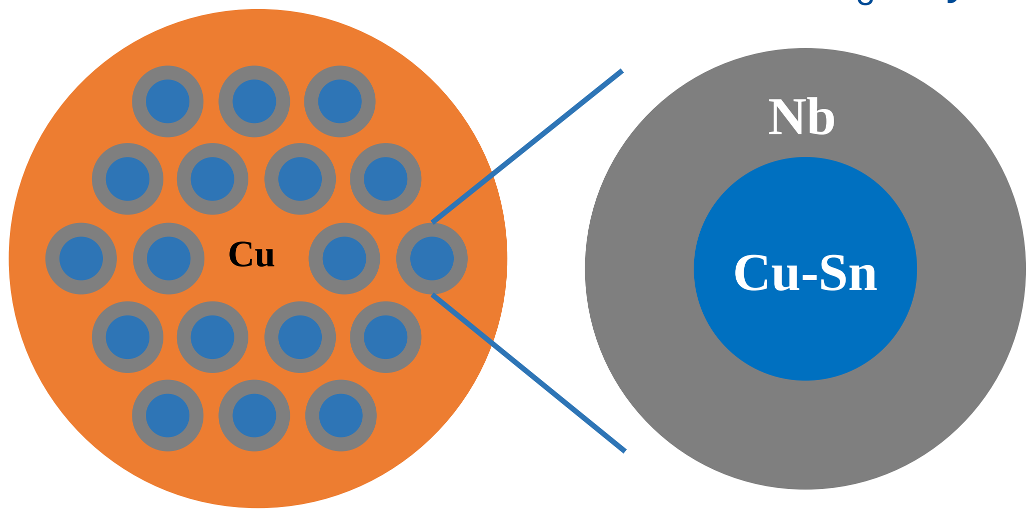
↓ **Winding**

A coil or magnet

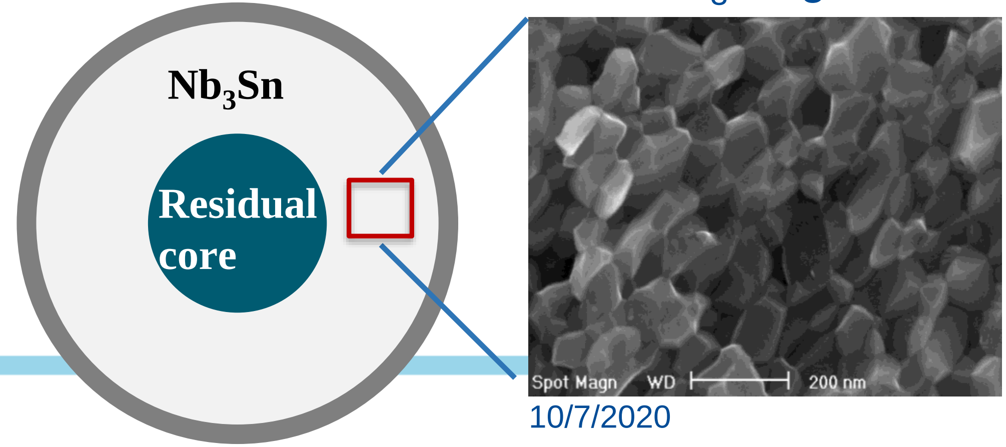
↓ **Heat treatment (e.g., 675° C/100h)**

Superconducting Nb_3Sn

Unreacted wire: A filament: no Nb_3Sn yet



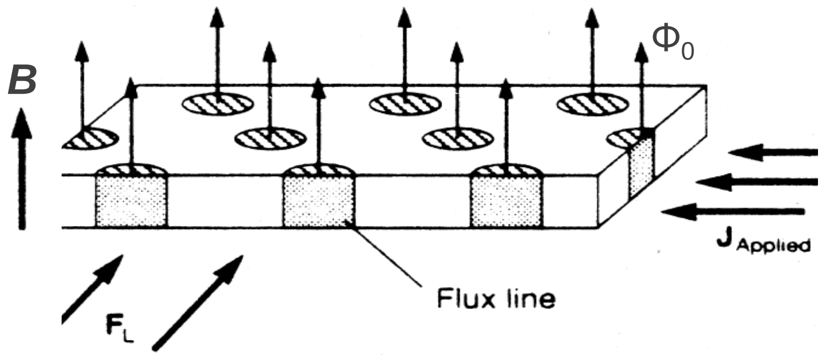
Reacted filament: Nb_3Sn grains:



Wind & react: because Nb_3Sn phase is brittle. Once it is formed, no deformation is allowed.

What determines J_c of Nb_3Sn

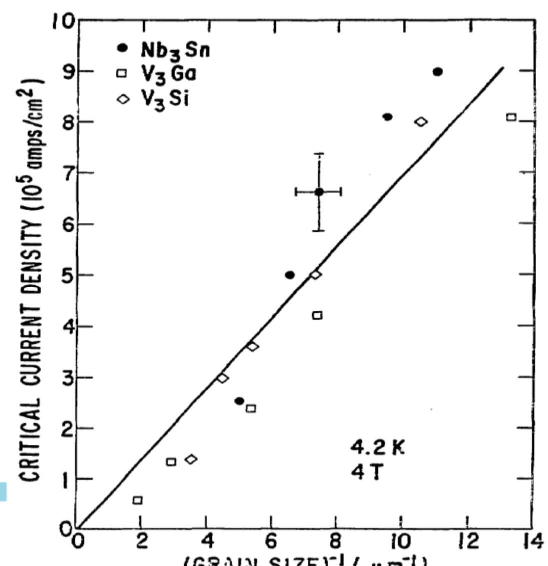
A superconductor in a magnetic field is penetrated by fluxons.



- Fluxons arrange into hexagonal lattice.
- If the superconductor carries a current *J*, fluxons move under $\boldsymbol{F_L} = \boldsymbol{J} \times \boldsymbol{B}$,
- If fluxons move, energy dissipates $\boldsymbol{\varepsilon} = \boldsymbol{v} \times \boldsymbol{B}$.
- Crystal defects pin fluxons from moving: i.e., the flux pinning force balances the F_L.
- As *J* rises, eventually fluxons break free.
- J_c is decided by highest pinning force (F_p) that the defects can provide: $J_c = F_p/B$.

Only those crystal defects with size similar to the coherence length are effective flux pinning centers.

- The flux pinning centers for conventional Nb_3Sn are grain boundaries.
- Smaller grain size leads to more grain boundaries, and higher F_p and J_c: $J_c \propto 1/d$.



To improve Nb_3Sn J_c, we need more flux pinning centers.

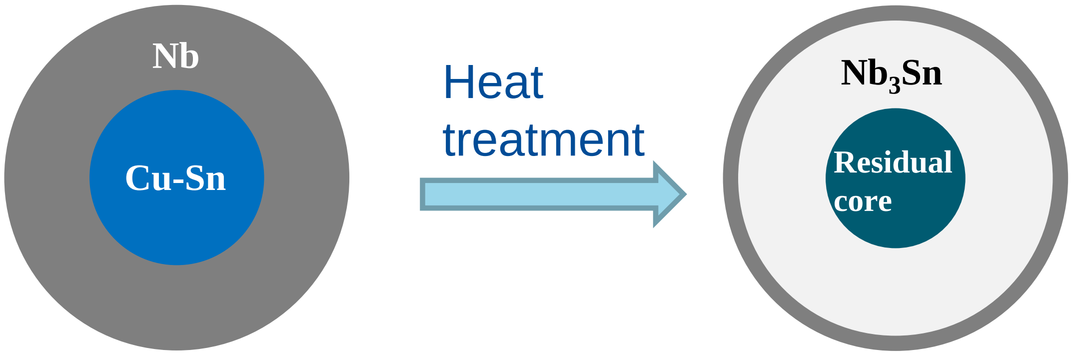
But in conventional Nb_3Sn, there is limited room in reducing grain size.

Then what?

A new technique to significantly improve J_c of Nb_3Sn

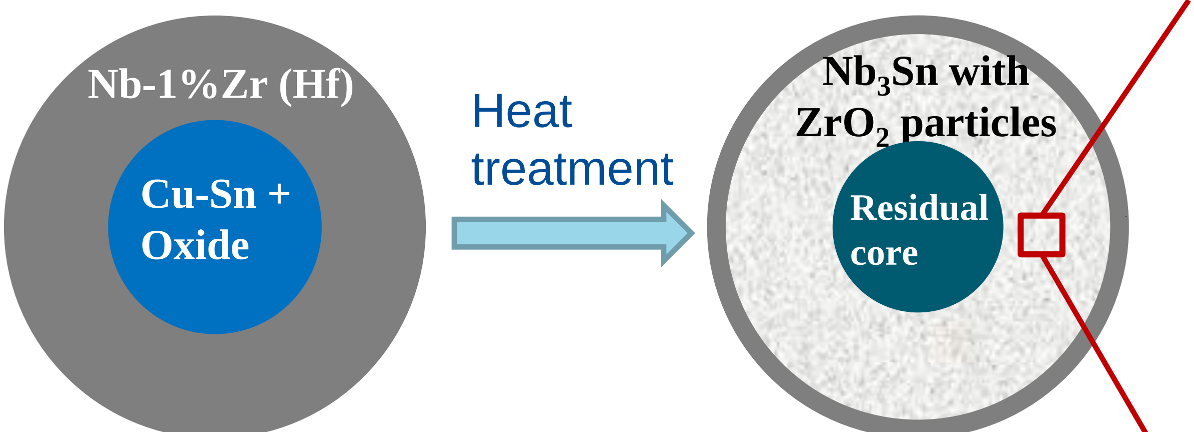
One innovative way is to create "artificial pinning centers" (APC).
This was heavily pursued since the 1980s, but had not be successful, until …
In 2014 we successfully achieved this using the internal oxidation technology.

A present-day Nb_3Sn subelement:

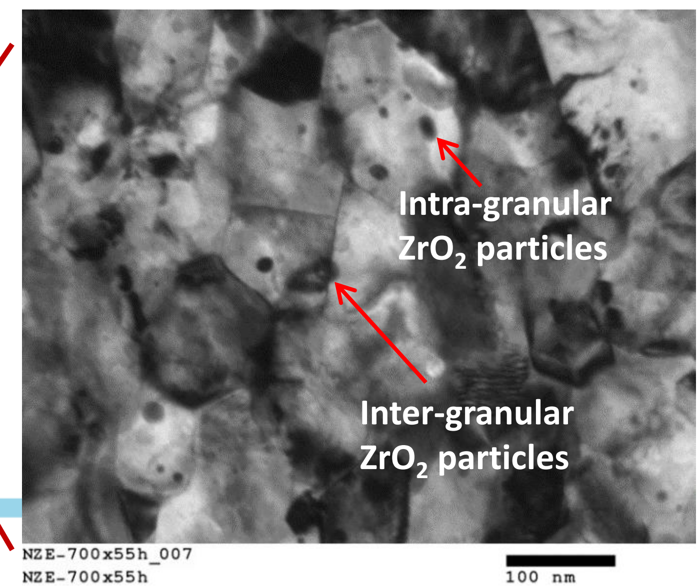


X. Xu *et al.*, *US Patent # 9916919*, 2018

The new technique:

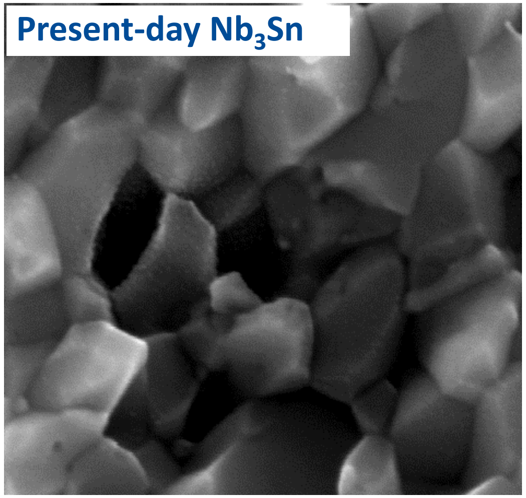


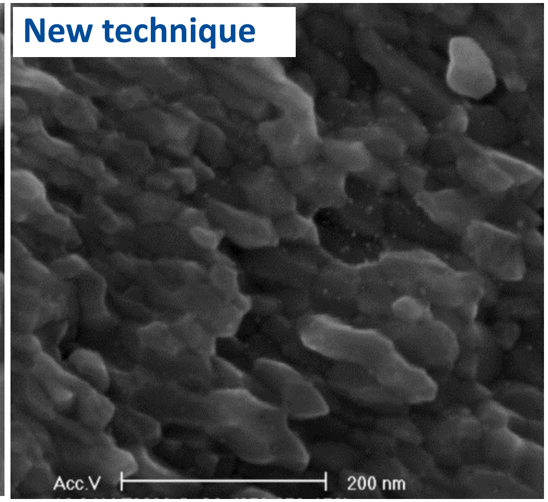
ZrO_2 or HfO_2 particles (2-15 nm):



What can this new technique do?

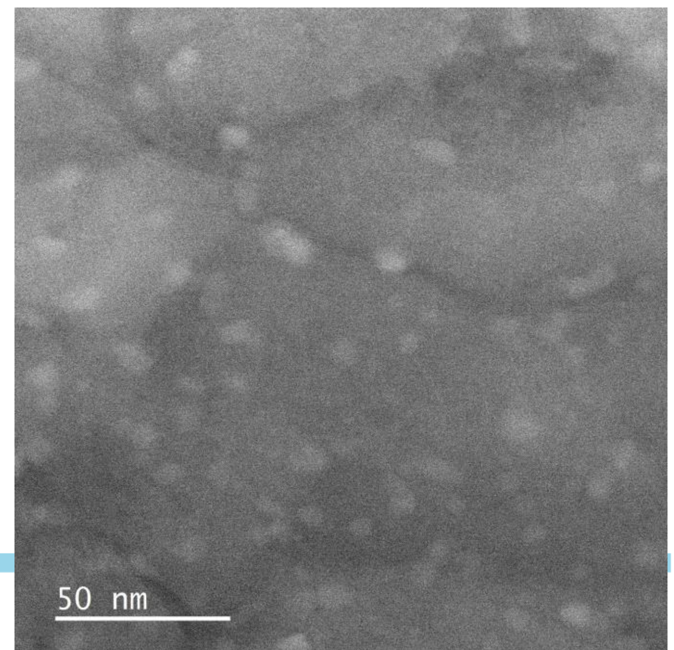
1. Significant refinement of Nb_3Sn grain size: 100-150 nm → 50-70 nm





X. Xu, M.D. Sumption, X. Peng, Adv. Mater. 27 (2015) 1346-1350.

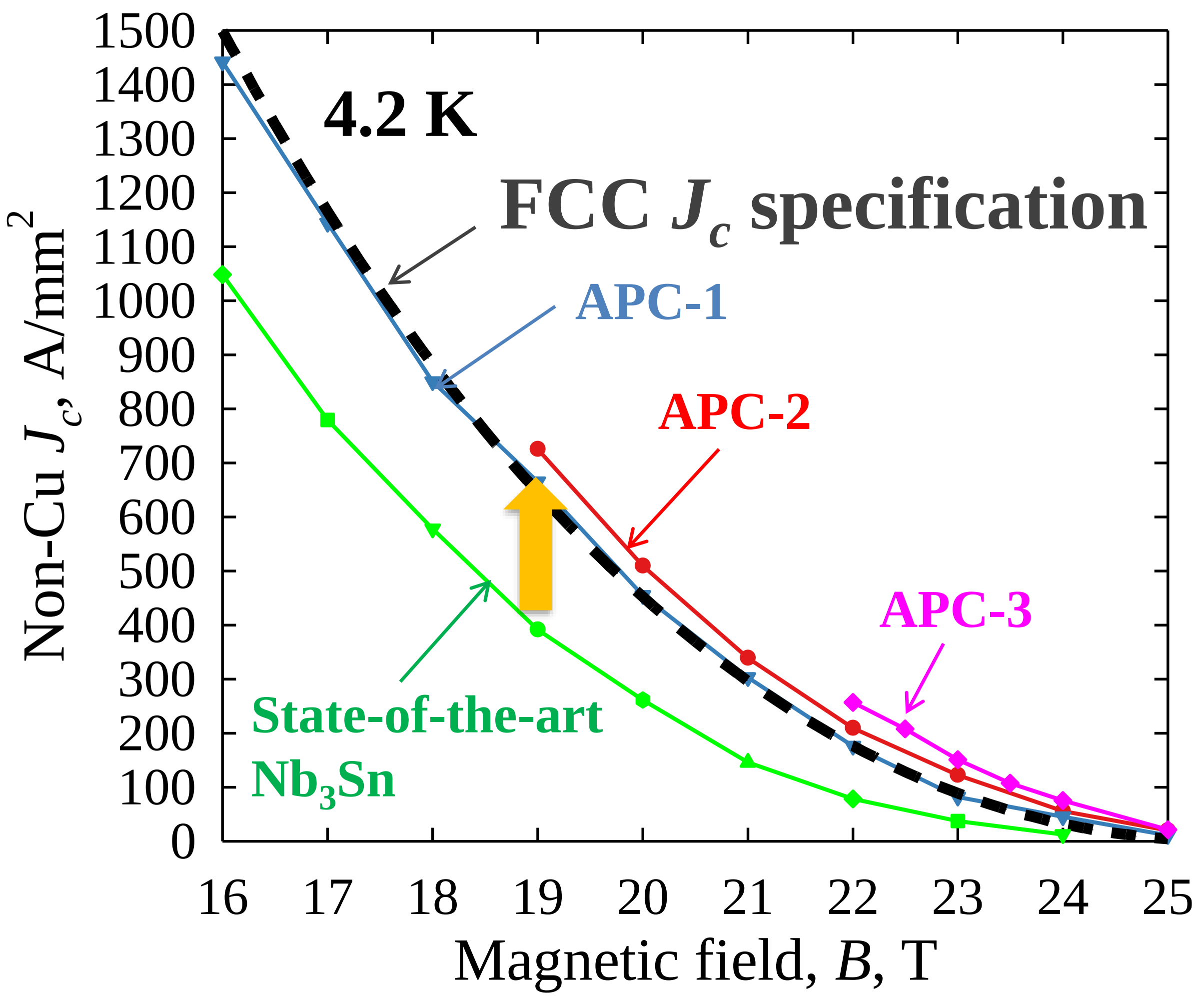
2. Generation of high-density oxide particles with suitable size as flux pinning centers



Both these two effects lead to significantly more flux pinning centers, and thus higher J_c.

J_c of the new APC Nb_3Sn superconductors:

Huge boost of J_c is achieved!



X. Xu, X. Peng, J. Lee, J. Rochester, M.D. Sumption, Scr. Mater. 186 (2020) 317-320

Now the new APC wires are still in the development stage.

We are working to make them magnet-grade conductors asap.

Other requirements for Nb_3Sn superconductors

J_c is the most important parameter, but there are other properties that are also important. A few examples:

(1) The cleanliness of the Cu matrix.

(2) Small degradation after cabling.

(3) Stress and strain tolerance.

(4) The electro-magnetic stability.

(5) Small subelement size.

(6) Small persistent-current magnetization.

(7) Others …

All of these must be good for a good Nb_3Sn superconductor.

Thank you for your attention