Nb$_3$Sn superconductors for accelerator magnets

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Magnets are key components for circular accelerators

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

➢ $B \approx 0.69 \cdot W \cdot J$. $J$: 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.

### Table

<table>
<thead>
<tr>
<th>Superconductor</th>
<th>$T_c$, K</th>
<th>$B_{c2}$, T</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi – the most widely-used superconductor (for MRI)</td>
<td>9.2</td>
<td>15</td>
</tr>
<tr>
<td>Nb$_3$Sn – the 2$^{nd}$ most widely-used superconductor</td>
<td>18</td>
<td>31</td>
</tr>
<tr>
<td>High-$T_c$ superconductor, BSCCO, ReBCO</td>
<td>&gt; 80</td>
<td>&gt;100</td>
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At a fixed temperature, there is a $J_c$-$B$ curve.

$T_c$ (critical temperature), $B_{c2}$ (upper critical field), $J_c$ (critical current density).
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.
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$_3$Sn superconductor to generate 16 T field, in a 100km-long tunnel.

**Why Nb$_3$Sn?**

Nb$_3$Sn 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$_3$Sn conductors will be used, which accounts for nearly half of the total cost of the accelerator.
Nb$_3$Sn superconductors: history and current status

- Nb$_3$Sn is used in the form of wires. The first Nb$_3$Sn 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.
2. Particle accelerators.
3. NMR.
4. Other research-use magnets.

The NMR and research-use magnets using Nb$_3$Sn can reach 23 T, and are commercial.

600 tons of Nb$_3$Sn conductors are in use for ITER.
Nb$_3$Sn conductors are in use for High-Luminosity upgrade of LHC.
Significant improvement of Nb$_3$Sn $J_c$ is still needed

So, are we ready to use Nb$_3$Sn conductors to build the 16 T magnets for FCC yet?

What if we cannot improve the $J_c$?

~50% increase of $J_c$ is needed!!

~70% more conductors are needed!
Improvement of Nb$_3$Sn $J_c$ is no easy thing

➢ The record $J_c$ of Nb$_3$Sn conductors has plateaued for nearly two decades.

➢ Extensive efforts have been made in Nb$_3$Sn community to improve this record, but no success.

Need revolutionary techniques to improve Nb$_3$Sn $J_c$!
What is a Nb$_3$Sn wire like?

A life cycle of a Nb$_3$Sn 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$_3$Sn

Unreacted wire: A filament: no Nb$_3$Sn yet

Reacted filament: Nb$_3$Sn grains:

Wind & react: because Nb$_3$Sn phase is brittle. Once it is formed, no deformation is allowed.
What determines $J_c$ of Nb$_3$Sn

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 $F_L = J \times B$.
- If fluxons move, energy dissipates $\varepsilon = v \times B$.
- 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$_3$Sn 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$_3$Sn $J_c$, we need more flux pinning centers.

But in conventional Nb$_3$Sn, there is limited room in reducing grain size.

Then what?
A new technique to significantly improve $J_c$ of Nb$_3$Sn

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$_3$Sn subelement:

The new technique:

X. Xu et al., US Patent # 9916919, 2018
What can this new technique do?

1. Significant refinement of Nb$_3$Sn grain size: 100-150 nm → 50-70 nm

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$_3$Sn superconductors:**

Huge boost of $J_c$ is achieved!

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$_3$Sn 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.
7. Others …

All of these must be good for a good Nb$_3$Sn superconductor.
Thank you for your attention