Superconducting Magnets and Fusion
Inseparable Companions

Pierluigi Bruzzone

EPFL-SPC, Villigen, Switzerland
Outline

The Role of Superconducting Magnets in Fusion

The Requirements for DEMO Magnets

Feasibility, Cost and Common Sense
Superconductivity as enabling Technology

In many applications, superconductivity must compete with conventional technologies, e.g. copper for transmission lines, transformers, generators or batteries and flywheels for energy storage. In such cases, the progress is slow and the reluctance to accept cryogenics and big investment is large.

In HEP, full body MRI, high field NMR and fusion, superconducting magnets are the enabling technology, suggesting “no competition”. However…

Fusion is realized only by superconducting magnets (enabling technology), but electricity can be obtained by other conventional technologies.

Superconductivity enables fusion, but if superconducting magnets are too expensive, superconductivity can kill fusion as an energy source.
The weight of Magnets

In the ITER cost estimate (2002), the magnet system makes up to 28% of the total capital cost.

Although the magnets cost estimate of 2002 (1.1 B$) is exceeded by a factor of 3-4, the percentage value in the breakdown is kept.
Technical Challenges from Yesterday

• In the conductor design, the Stability against flux jumps was perceived as a key challenge and the efforts were directed to rock stable conductors (T15, CICC, Tore Supra). Actually, because of the available multi-filamentary composites and the moderate operating current density, transient stability was never an issue for fusion magnets.

• The piston Refrigerators of the seventy’s were not adequate for large plants. The cooling challenges were solved by the turbine refrigerators and later by the circulators.

• The current distribution and inter-strand insulation became a challenge for several magnets (T7, DPC-U, Polo): the lessons led to
  • Full transposition.
  • Non-insulated strands in cable.

• A major challenge was also the technology transfer from labs to industry.
The Technology Heritage from Yesterday

• Because of the large stored energy, with the high mechanical loads, the **forced flow** conductors and **impregnated** windings prevailed over the pool cooled, helium transparent coils.

• The **HTS current leads** established quickly as unquestioned component for the fusion magnets, allowing very high operating current at low heat load.

• Refrigerators up to 20 kW/unit and **cryogenic** components (circulators, valves) match the requirement for increasing size and power.

• The increased confidence in the technology and the prohibitive cost put an end to the large **Demonstrators**, restricting the spirit of innovation and the straight comparison of technology options.
The technical Challenges of Tomorrow - DEMO

The name “DEMO” is used in different contexts to point at a future device, with the aim of demonstrating the production of electricity by fusion.

As the DEMO’s are national projects, there is no need of convergence on a common layout. “DEMO” may be

- either a tokamak or a stellarator,
- either a pulsed or steady state machine
- either a big or small device

The list of common requirements for the DEMO magnets is very qualitative, e.g. “radiation resistant”, “conservative”, “reliable”, “long lasting”, etc.

As soon as the requirements for magnets become quantitative, e.g. peak field, neutron fluence, pulsed field rate, operating temperature, heat loads, operating voltage, etc., no common value can be extracted.
High Current Cables for DEMO

Both the “large size / medium field” and the “small size / high field” magnets for DEMO have a common feature, i.e. the large AmpereTurn (range of several MAT) and the large stored energy (range of GJ/coil). The dump Voltage, $V_d$, the operating current, $I_{op}$, and the stored energy, $E$, are linked by basic equations

\[
V_d = L \frac{I_{op}}{\tau} \quad E = L \frac{I_{op}^2}{2} \quad V_d \cdot I_{op} = 2 \frac{E}{\tau}
\]

The dump time constant, $\tau$, must be kept short to allow an effective energy extraction in case of quench (very long $\tau$ would imply very low $J_{cu}$, i.e. the cu cross section would blow up the size of the coil).

To keep the dump Voltage to a reasonable safe range, say $V_d < 10 \text{ kV}$, the operating current must be in the range of 50-100 kA.

High Current Cables are required for all DEMO’s
HTS for DEMO?

Since 1998, the proposals for fusion devices made by HTS magnets populate the literature, praising the advantages and potentials.

T. Ando et al. 1998

20 years later, HTS are in common use for current leads, but only a desktop-tokamak (ST25) with 0.1 T field is actually realized in 2015. No fusion device with HTS magnets is in construction today.
Is HTS “enabling technology” for DEMO?

For magnets with peak field $> 20$ T or operating temperature $>18$ K, HTS is the “enabling technology”, because the operating range is out of reach of Nb$_3$Sn. Over a wider range, say $B > 15$ T and $T > 10$ K, HTS is competitive in terms of current density.
Fusion Design Studies with HTS

A number of conceptual design studies today includes HTS either as an option or as baseline:

- **FFHR Helical Device (J)**
- **EUROfusion DEMO, Hybrid CS (EU)**
- **CFETR, Hybrid CS (CN)**
- **SPARC (US)**
- **FNSF (US)**

Three high current (>50 kA) prototype conductors from EU, US and Japan have been tested in the past five years.
Attractive and challenging features for HTS

- $\frac{dJ_c}{dT}$ is flat in HTS, allowing large temperature excursions without quench, e.g. to adsorb large transient heat loads.

- $T_{op} / T_c < 0.1$, causing very slow quench propagation, i.e. a difficult protection for quench events (very large hot spot temperature).

- HTS are brittle materials, with very small elastic range, causing strain/stress management problems in high current cables.

- The neutron radiation tolerance of HTS is poorer than Nb$_3$Sn, with degradation occurring already at $3 \cdot 10^{22}$ m$^{-2}$.

- Despite some price reduction in the last decade, HTS remain $\approx 10$ times more expensive than Nb$_3$Sn
The Cost Issue

In ITER, the cost is a challenge because it exceeds the agreed budget. As soon as the stakeholders agree to increase the budget, there is no cost issue for ITER.

The cost challenge for DEMO magnets will be much tougher than ITER. The issue will be not “stay in the budget”, but convince the utilities that the investment can be paid back.

The magnets, representing about one third of the capital cost (not in case of HTS) play a major role in the cost structure of DEMO.

Small magnets are expected to cost less than big magnets if the same materials and technology is applied. However small devices produce less power than large devices, so the cost per Watt is not much different over a broad range of DEMO layouts.
The overnight cost for fusion

The capital cost in proportion to the electric power ("overnight cost", $/W) must be closely monitored to qualify fusion vs. other energy sources.

If ITER would produce 500 MW electricity, the overnight cost would be in the range of 40-50 $/W. To be competitive, the capital cost of a DEMO of the same size of ITER must decrease by one order of magnitude.

That’s the main challenge for the DEMO designers.