Prospects and Challenges of the Use of HTS Materials for Fusion

L. Bromberg
MIT Plasma Science Fusion Center
In collaboration J.V. Minervini, J.H. Schultz and the ARIES team
Organization of talk

• Brief status of HTS materials for magnets
• Present HTS magnet development
• Application of HTS materials to fusion
  – Motivation
  – Potential
  – Challenges
• Conclusions
Facts on Superconductors

Three Critical Parameters:
- Critical temperature, $T_c$
- Critical magnetic field, $H_c$
- Critical current density, $J_c$
YBCO Tape (2nd Generation-HTS)

- SuperPower (Latham, NY) uses a reel-to-reel system for tape production
High throughput manufacturing routine in FY’09

- **IBAD MgO** process speed: 360 m/h*. Three 1,400 m IBAD MgO tapes produced weekly (12,600 m weekly production*)
- Process speeds of homo-epi MgO & LMO are high: 345 m/h*
- Simultaneous deposition of homo-epi MgO & LMO processes - combined two process steps into one, eliminating 1 set-up time

[Diagram showing deposition process]

- 4 buffer layers deposited on 1,400 m tapes routinely with one pilot buffer system. Weekly production*: 8,400 m
- When planarization is introduced, buffer throughput will double to 16,800 m/week*

*Electropolishing and 5-layer buffer stack manufacturing of 1,400 m tapes was in routine production mode in FY09*
YBCO 2\textsuperscript{nd} generation tapes properties
Field dependence of $I_c$ in H//tape of standard production wire
FY08: Excellent in-field performance at 65 K, 3 T

- Title III Phase 3 program goal is $J_e$ without stabilizer of 15,000 A/cm² at 65 K, 3 T
- Minimum $I_c = 267$ A/cm corresponds to $J_e$ of 41,000 A/cm² at 65 K, 3 T
- $I_c$ perpendicular to tape = 340 A/cm corresponds to $J_e$ of 52,300 A/cm²

Data from Y. Zhang, M. Paranthaman, A. Goyal, ORNL

<table>
<thead>
<tr>
<th>$I_c$ (77 K, 1 T)</th>
<th>2008 Zr-doped (Gd,Y)BCO</th>
<th>2007 (Gd,Y)BCO</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \parallel c$</td>
<td>340 A/cm</td>
<td>181 A/cm</td>
<td>88%</td>
</tr>
<tr>
<td>Minimum $I_c$</td>
<td>267 A/cm</td>
<td>160 A/cm</td>
<td>67%</td>
</tr>
</tbody>
</table>
High current metric: Capability of ~1000 A in 12 mm widths achieved!

Over 1+ m length, \( I_c = 976 \text{ A} = 813 \text{ A/cm} \)

3.3 \( \mu \text{m} \) film made in 10 passes: \( I_c = 976 \text{ A} = 813 \text{ A/cm} \) (\( J_c = 2.44 \text{ MA/cm}^2 \))

2.1 \( \mu \text{m} \) film made in 6 passes: \( I_c = 929 \text{ A} = 774 \text{ A/cm} \) (\( J_c = 3.68 \text{ MA/cm}^2 \))

All achievements using production buffer tapes

\( I_c \) measurement using continuous dc current (no pulsed current) across entire tape width of 12 mm. No patterning
Magnet applications
SuperPower I.
\[ B_{\text{max}} = 26.8 \, \text{T} \]
\[ \Delta B = 7.8 \, \text{T} \]

SuperPower II.
\[ B_{\text{max}} = 27 \, \text{T} \]
\[ \Delta B = 7 \, \text{T} \]

NHMFL I.
\[ B_{\text{max}} = 33.8 \, \text{T} \]
\[ \Delta B = 2.8 \, \text{T} \]

NHMFL II.
\[ B_{\text{max}} = 20.4 \, \text{T} \]
\[ \Delta B = 0.4 \, \text{T} \]

During construction

H.W. Weijers et al., Technology for High Field Magnets with YBCO Conductors, US-Japan workshop, Dec 14, 2009
Performance of all three coils exceeded DOE FY09 milestone of 2 T at 65 K

<table>
<thead>
<tr>
<th>Temperature</th>
<th>K</th>
<th>4.2</th>
<th>65</th>
<th>77</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil Ic - self field</td>
<td>A</td>
<td>201.9</td>
<td>48.0</td>
<td>26.8</td>
</tr>
<tr>
<td>Amp Turns @ Ic- self field</td>
<td>A-turns</td>
<td>~ 746,222</td>
<td>~ 177,408</td>
<td>~ 99,052</td>
</tr>
<tr>
<td>Je @ Ic, self field</td>
<td>A / mm²</td>
<td>313.5</td>
<td>74.5</td>
<td>41.6</td>
</tr>
<tr>
<td>Central field – self field</td>
<td>T</td>
<td>10.4</td>
<td>2.49</td>
<td>1.39</td>
</tr>
<tr>
<td>Background field</td>
<td>T</td>
<td>19.89</td>
<td>3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Coil Ic in background axial field</td>
<td>A</td>
<td>144</td>
<td>31</td>
<td>18</td>
</tr>
<tr>
<td>Amp Turns @ Ic in background field</td>
<td>A-turns</td>
<td>~ 532,224</td>
<td>~ 114,576</td>
<td>~ 66,528</td>
</tr>
<tr>
<td>Je @ Ic, in background axial field</td>
<td>A / mm²</td>
<td>223.6</td>
<td>48.1</td>
<td>28.0</td>
</tr>
<tr>
<td>Total Central Field – in background field (axial)</td>
<td>T</td>
<td>27.4</td>
<td>4.60</td>
<td>1.93</td>
</tr>
</tbody>
</table>

- At 65 K: 2.49 T in self field and 4.6 T in 3 T background field
- Achieved similar 65 K field with Zr wire even with substantially lower zero-field I_c, less wire and larger bore coil
# 32 T Magnet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total field</td>
<td>32 T</td>
</tr>
<tr>
<td>Field inner YBCO coils</td>
<td>17 T</td>
</tr>
<tr>
<td>Field outer LTS coils</td>
<td>15 T</td>
</tr>
<tr>
<td>Cold inner bore</td>
<td>32 mm</td>
</tr>
<tr>
<td>Uniformity</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>1 cm DSV</td>
</tr>
<tr>
<td>Current</td>
<td>186 A</td>
</tr>
<tr>
<td>Inductance</td>
<td>436 H</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>7.54 MJ</td>
</tr>
</tbody>
</table>

Tentative: pancake winding for inner coil, layer winding for 2 larger HTS coils

Cables
LIPA HTS Cable Concept

- Outer Cable Sheath
- Outer Cryostat Wall
- Inner Cryostat Wall
- LN₂ Coolant
- Protection Layer
- Copper Shield Stabilization
- HTS-Shield
- High Voltage Dielectric
- HTS Tape
- Former

- American Superconductor
- LIPA (Long Island Power Authority)
- US Department of Energy
- Air Liquide
- Nexans
Carpet Stack HTS Cable
(M. Takayasu, J. Minervini, L. Bromberg)

• Basic Carpet Stack
  HTS tapes are stacked and twisted together.
  The tapes can be soldered or insulated.

• Base element former
  Conducting or non-conducting
  Structural

Patent pending
HTS in Fusion
Motivation
The PSI Science Challenge & Fusion Economics are inextricably linked

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<th>Fusion Viability</th>
<th>PSI Science</th>
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<tr>
<td>1. High average neutron power loading</td>
<td>1. High average exhaust power P/S ~ 1 MW/m²</td>
</tr>
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<td></td>
<td>2. Energy throughput &gt; 30 TJ/m² delivered by energetic plasma ions.</td>
</tr>
<tr>
<td>2. Continuous 24/7 power production.</td>
<td></td>
</tr>
<tr>
<td>3. High ambient temperature.</td>
<td>3. Fundamental new regime of physical chemistry for plasma-facing materials.</td>
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Maximum continuous Heat removal
~10 MW/m²

D. Whyte, MIT, *Designing a 24/7 Fusion Device: Towards Solving Plasma-materials Issues*, MIT presentation 1/22/2010
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</tr>
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The Energy-Sustainment Chasm

D. Whyte, MIT, Designing a 24/7 Fusion Device: Towards Solving Plasma-materials Issues, MIT presentation 1/22/2010
Vulcan + The Energy Sustainment Challenge Properly and Inextricably Links Core & Edge in a range that matches reactor parameters.

<table>
<thead>
<tr>
<th></th>
<th>ARIES*</th>
<th>FDF</th>
<th>Vulcan</th>
<th>Why?</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m)</td>
<td>5.2-5.5</td>
<td>3.2</td>
<td>1.25</td>
<td>Minimize PFC surface area &amp; $P_{\text{heat}}$</td>
</tr>
<tr>
<td>$A \equiv R/a$</td>
<td>4.0</td>
<td>3.5</td>
<td>4.0</td>
<td>Similarity</td>
</tr>
<tr>
<td>$P_h/S$ (MW/m²)</td>
<td>0.85-1.1</td>
<td>0.87</td>
<td>0.9</td>
<td>Global power exhaust for CD / PSI</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>yr</td>
<td>weeks</td>
<td>arbitrary</td>
<td>Integrate PSI at CTF/DEMO timescales</td>
</tr>
<tr>
<td>B (T)</td>
<td>6-8</td>
<td>6</td>
<td>&lt; 8</td>
<td>Similarity of CD &amp; Edge physics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Demontable SC coils --&gt; maintenance</td>
</tr>
<tr>
<td>n (10²⁰ m⁻³)</td>
<td>1.7-2.3</td>
<td>2.4</td>
<td>1.5 - 4</td>
<td>Access large range of non-inductive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>scenarios over wide density range for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>edge exploration &amp; similarity</td>
</tr>
<tr>
<td>$P_{\text{CD}} / P_{\text{heat,ext}}$</td>
<td>~ 1</td>
<td>~ 1</td>
<td>~ 0.2 - 1</td>
<td>SOL collisionality</td>
</tr>
<tr>
<td>$\nu_N^{\text{sOL}}$ &amp;</td>
<td>0.25-0.38</td>
<td>0.27</td>
<td>0.12 - 0.36</td>
<td>Match divertor plasma T and n</td>
</tr>
<tr>
<td>$n_{20}^{7/2} R$</td>
<td>40-90</td>
<td>54</td>
<td>4 - 170</td>
<td>SOL T similarity &amp; heat removal</td>
</tr>
<tr>
<td>Upstream $q_\parallel$ (GW/m²)</td>
<td>3-5</td>
<td>3.9</td>
<td>~ 4-5</td>
<td></td>
</tr>
</tbody>
</table>

*ARIES-AT, RS

D. Whyte, MIT, Designing a 24/7 Fusion Device: Towards Solving Plasma-materials Issues, MIT presentation 1/22/2010

*Stangeby upstream separatrix figure of merit
For achieving conduction limited divertor $= n L_{\parallel}/T^2/1.5 \times 10^{17}$
HTS in Fusion
BSCCO 2212 layered pancakes on silver
(L. Bromberg, MIT, 1997)
VULCAN Magnet
Design considerations

• 1.25 m, 7 T on axis
• Peak field ~ 12 T
• If tape parallel to field:
  – Current at 12 T, 54 K ~ similar as self-field at 77 K
• If tape perpendicular to field:
  – Current at 12 T, 50 K ~ 0.5 as self-field at 77 K with materials with good pinning
Plate design

- 180 plates in the magnet
  - 2° per plate
  - Plate thickness (max/min): 2.2 cm/1.1 cm
- 240 kA-turns per plate
- 12 kA per cable
- 22 cables per plate
- Cooling channels directly on plates
Magnet cooling

- High pressure He cooling the plates directly, at about 55 K.
- Cooling channels in plates
- Manifolding also in the plates
- Cooling of the joints?
Joints
Lap-joints

- Joint fixture made at MIT, tests carried out at Creare

---

Fig. 3. Joint Fixture. Joints are connected and loaded in series. Voltage taps on either side of each joint are used to measure joint resistance.

Joint Loading Fixture.
Fig. 6. Test Results. Measured resistance versus applied load for two lap joints: a dry joint between two unmodified Hermetic tapes (brass); and a shunt joint between two copper-laminated YBCO tapes soldered onto the Hermetic BSCCO tapes.
Lap-joints

• Developed with very low resistance
• Quick-disconnect unit has been built using demonstrated approach
• Connector has multiple tapes, multiple joints
• Connector being tested on-ship for deGaussing applications
# Joint dissipation

## Tapes
- **width**: mm 10
- **Current**: A 300

## Cables
- **Number of tapes**: 40

## Plates
- **Number of plates**: 180

## Joints
- **Length per cable**: mm 100
- **Length per tape**: mm 2.5
- **Resistance per tape**: Ohm 1.28E-07

## Dissipation
- **per tape**: mW 12
- **per cable**: W 0.46
- **per plate**: W 10
- **Total dissipation**: W 3650
- **Refrigerator (1/5 of Carnot)**: W 50000
Joints

- Considered several joint geometries
  - Scarf joints to minimize resistance across joints
- This area is critical and needs substantial funding for proof-of-concept
- A concept that combines C-MOD and DIII-D joints may be feasible
Geometry of joints

Case A  Case B  Case C
Magnet topology

• Case B is the most likely
• Can use used with superconducting OH transformer
• Volt-second limitation:
  – For the present geometry ($B_{OH}$ in T):
  – $\Phi \sim 1.2 B_{OH}$ V s
  – 20 Vs for $B_{OH} \sim 8$ T
Reliability of joints

• Very large number of joints
• Joints need to accommodate imperfections
• Hyperconducting compliant layers
  – Place a superconducting material in a soft matrix.
  – Good metallurgical bond between the matrix and the superconductor.
  – Disperse the SC material within the matrix such that SC-SC distance is small
    • Short bridges of relatively high resistivity material between SC materials
Matrix

- Soft matrix, maybe with ridges in order to yield when surfaces in contact
  - When applying pressure, matrix deform and flows to regions with lower pressure, allowing hard SC materials to approach each other
- Silver (unannealed), indium, low temperature solders, “woods metal”
Hyperconducting compliant layers

- **Matrix**
  - Soft matrix, maybe with ridges in order to yield when surfaces in contact

- **SC**:

- Could be in the form of HTS powder, or finely cut SC filaments
  - Filaments cut into small pieces
  - HTS materials could be used for applications at either high or low temperatures
Hyperconducting compliant layers

- Voltage in the case of HTS tapes: $1.48 \times 10^{-8}$ V
- Voltage in the case of just plain solder: $3.8 \times 10^{-8}$ V
- All the action occurs in the solder region
- About 2.5 times lower resistivity
- In order to do better, need to really minimize bridging through normal regions
- Potentially can do substantially better than this
  - Need high fill fraction
  - Can be increased by using polydisperse powders
Current transfer between tapes
FY09: Another new record kilometer wire

- Minimum current ($I_c$) = 227 A/cm over 1030 m
- $I_c \times$ Length = 233,810 A-m

77 K, $I_c$ measured every 5 m using continuous dc currents over entire tape width of 12 mm (not slit)

Voltage criterion = 0.2 microvolt/cm

Except for three spots, $I_c$ of rest of 1,030 m > 300 A/cm $\rightarrow$ 4mm: 120 A

Current shunting

- Cu, thickness 20 μm, $\sigma \sim 4 \times 10^8/\Omega \text{ m}$
- Solder, thickness 20 μm, $\sigma \sim 6.7 \times 10^7/\Omega \text{ m}$
- HTS thickness, 2 μm
With side tape, solder

Current density $\sim 2.5 \times 10^{10}$ A/m$^2$ in HTS, or 100 A

Assumption that side contact is 4 mm (scale resistances by that number)

Voltage $\sim 162 \, \mu$V

Resistance per tape period $\sim 1.6 \, \mu$Ω
Shunting of the cable

- The presence of the tape on the side decreases the resistance from the bottom of the stack to the top of the stack by a factor of about 200 (normalized to 4 mm wide contact)
  - $3 \mu\Omega$ vs $320 \mu\Omega$
- Can be used to control tape-to-tape transconductance, allowing for increased performance of a given tape, at marginally increased dissipation
- Need to determine performance of shunted cables
Protection
Magnet quench

• Due to very high heat capacity and very high field/current of operation, HTS will not be subject to flux jumping higher temperatures
• Speed of propagation is very slow, if there is a normal zone there will be very small external evidence until arc develops.
• Severe issue for “dry” magnets
• Needs:
  – Better methods for determining quench
  – Better methods for internal dump
Temperature sensors
Fiber optic Brillouin scattering
Spontaneous Brillouin

- Single end approach with 2 lasers
  - 1 frequency-shifted local oscillator
  - 1 pulsed probe
    - (pulse width ~ spatial resolution)
  - Measure
    - Signal Amplitude
    - Linewidth
    - Frequency shift

Unique Determination of $T$ & $\varepsilon$

Contours of Relative Frequency Shift ($R$), Intensity ($B$), and Linewidth ($G$)

Microstrain

Temperature (K)

Fusion Technology and Engineering Division
Accuracy as a Temp & Strain Sensor

- Accuracies after applying the previous conditions
  - Cryogenic temperature accuracy is ± a few degrees
    - Better than ± 1 degree for the 4-25 K range
  - Cryogenic strain accuracy is ± 100 με or better (5 % of expected measurement)
Energy dump (internal)
Eddy Current Quench

• AC fields will result in conductor heating

  Can we use this heating for quench?

• Options:
  – Use ripple in the SC conductor current
    • Energy/power required ~ 2 B $\Delta B_{\text{ripple}}$
    • Ratio of ripple energy to SS energy ~ 2 $\Delta B_{\text{ripple}} / B$
  – Use separate system for heating
    • Magnetic fields that are normal to the steady stage magnetic field
    • Energy/power required ~ $(\Delta B_{\text{ripple}})^2$
    • Ratio of ripple energy to magnet energy ~ $(\Delta B_{\text{ripple}} / B)^2$
      – Having the ripple magnetic field be normal to the steady state field at all locations results in $M = 0$ (mutual inductance).
      – In practice there should be some coupling (due to fringing fields, for example), and thus $M \sim 0$.
  – Heating element does not have to be in intimate contact with the coil

Quench requirements

- In order to quench the magnet, it is necessary to raise the temperature of the conductor by 1-2 K, maybe more in the outer turns with lower fields
- $\Delta T \sim 3K$.
- If magnet is with He (pool or flowing), then heat capacity $\sim 1 \text{ J/cm}^3$
- If magnet is dry, then the energy required to quench is on the order of 0.01 J/cm$^3$ (for 4 K temperature change, so this should quench almost all the magnet, with the possible exception of the lowest field turns).
  - Concept attractive for dry magnets
Schematic diagram for one potential setup in cyclotron magnet
Conductor for the K250

Eddy current flows

[Diagram showing conductor dimensions and eddy current flow]
Magnetic Field Shaping Using High Temperature Superconducting Monoliths

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T. Brown, P. Heitzenroeder and M. Zarnstorff
Princeton Plasma Physics Laboratory

A. Boozer
Columbia University

Supported by Princeton University Subcontract Award Number S00828F
Objectives of the concept

• Superconducting monoliths can be used to shield/trap magnetic fields
  • HTS monoliths can operate without flux jump because of high thermal stability
• Can superconducting tiles be used to modify fields generated from simple coils?
  • Simplify coil geometries for stellarators
  • Improved access
Modeling tokamaks/stellarators

- Bulk superconductor can be treated as perfect diamagnetic material
- Stellarator is complex 3-D geometry
  - To understand multiple tile performance started out analyzing 2-D geometry
  - Axial symmetry of set of coils that simulate a toroidal magnet at the midplane
  - Relevant to ripple reduction in tokamaks
Conclusion

- Magnet technology for use of HTS magnets is developing, not as mature as LTS magnets
  - Potential for innovation
- HTS offers a unique opportunity for near term devices in fusion
  - Demountable, good for access
  - Low electrical power requirements, good for long operation
  - Materials exist today, at costs that are not prohibitive
- R&D is required:
  - Cable construction
  - Magnet cooling
  - Joints
  - ...
Additional slides
Alternative calculations

• For $M \sim 0$, it is necessary that for each element with $B+\Delta B$, there is a corresponding on with $B-\Delta B$ [read $B_z$]

• The, energy change ~

\[ B^2 - (B+\Delta B)^2 \sim B^2 - (B+DB)^2_{upper}/2 - (B-\Delta B)^2_{lower}/2 \sim \Delta B^2 \]

• In this case, the energy change is proportional to $\Delta B^2$, not to $\Delta B$ $B >> \Delta B^2$

• It should be noted that although the external voltage for the AC circuit is small, it is possible that the internal voltages are high.
Alternatives with $M \sim 0$
Cost of tapes

• Length of tapes in inner leg
  – 250 km (related to 4 mm tape, but 1 cm for VULCAN)
  – $40/m (4 mm wide)
  – Cost of HTS for inner leg: 20M$
  – Cost for all machine ~ 3x, or about 60 M$
Field dependence of $I_c$ in $H//c$ of standard production wire

$I_c/I_c$ (77K, 0T) vs. Field (perpendicular)
Great strides made in FY09 in all key metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>2005 review</th>
<th>2006 review</th>
<th>2007 review</th>
<th>2008 review</th>
<th>2009 review</th>
<th>Improvement in past 1 year</th>
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</thead>
<tbody>
<tr>
<td>$I_c$ over 200 m (A/cm)</td>
<td>106</td>
<td>246</td>
<td>227*</td>
<td>314*</td>
<td>378*</td>
<td>20%</td>
</tr>
<tr>
<td>$I_c$ over 500 m (A/cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_c$ over 1,000 m (A/cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length with $I_c$ &gt; 300 A/cm (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_c \times L$ (A-m)</td>
<td>22,000</td>
<td>70,520</td>
<td>102,935</td>
<td>200,580</td>
<td>300,330</td>
<td>50%</td>
</tr>
<tr>
<td>$I_c$ (A/cm) at 77 K, 0.52 T over 100 m lengths</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil: Field at 77 K (T)</td>
<td>0.73</td>
<td>1.38</td>
<td></td>
<td></td>
<td></td>
<td>89%</td>
</tr>
<tr>
<td>Coil: Field at 65 K (T)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>
We must address the energy sustainment “chasm” to CTF & DEMO

• CTF (Q ~ 3) cares about energy fluence, period.
  • Power density x Δt: BOTH MATTER!
  • Must also have a closed Tritium fuel cycle! Orders of magnitude required improvement from present devices & ITER

• DEMO: Combines burn Q > 25 + Power/m² x Δt.
  • $P_{\text{ess}}/S \sim 1/4 P_{\text{n}}/S \sim 1 \text{ MW/m}^2 \times 3 \times 10^7 \text{ s} \sim 1$ full-power year
  • Ambient temperature > 800 C for thermal efficiency
    • Therefore CTF must also have high T walls to test components.

• Present track of devices, including ITER, do not address energy sustainment issues required for CTF or DEMO
  • $P/S \times$ pulse duration too small by $10^3 - 10^6$
  • Water-cooled, low-T walls: completely irrelevant physical chemistry

• Conclusion: Need a sustained, reactor-level power density, hot-wall experiment to fill this chasm.
Example

- Low temperature solder
- HTS power about $2/3$ of the thickness of the solder
- About 30 microns thick overall
- HTS tapes with 20 microns of electrolytically deposited copper (i.e., high conductivity)
- Neglect substrate (which, anyway, is insulated through ceramic layers).
Model results

- Assume a given current density (low, 25 kA/m²)
- 2-D calculation
- Voltage = 0 at the left
- Voltage at the right used to determine effective resistivity
- “HTS layer” is thick to ease meshing, has no impact on results
- Drawings with different vertical/horizontal axis
  - Solder conductivity ~ 4 \times 10^6 /\text{Ohm m}
  - Copper conductivity ~ 2 \times 10^8 /\text{Ohm m}