Transforming the Grid with Superconductivity

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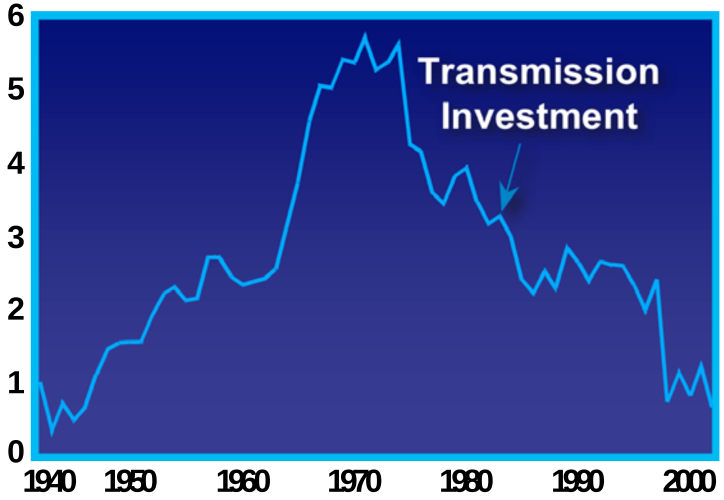
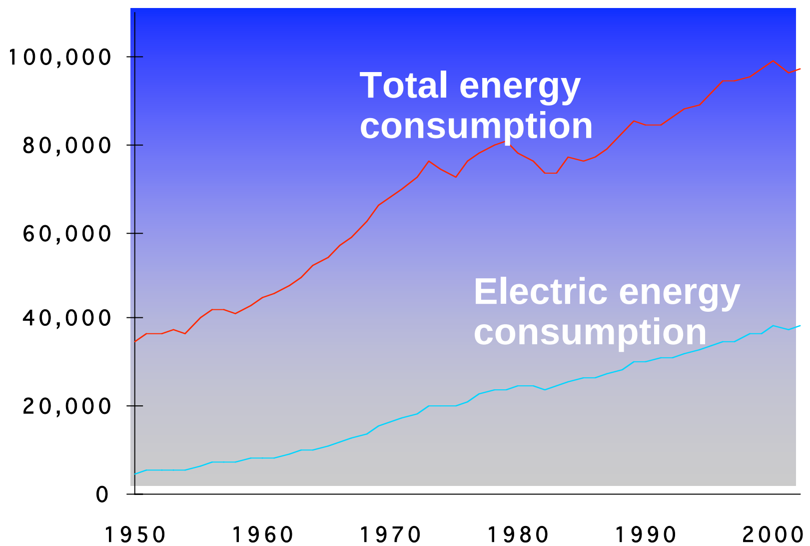
Basic Research Needs for Superconductivity
APS March Meeting
Denver CO, March 6, 2007

US Electric Power System is under Severe Stress

The underlying problem: Under-investment in electric power grid while demand for electric power steadily increases





Source: EIA

Under-investment has spawned a host of technical problems

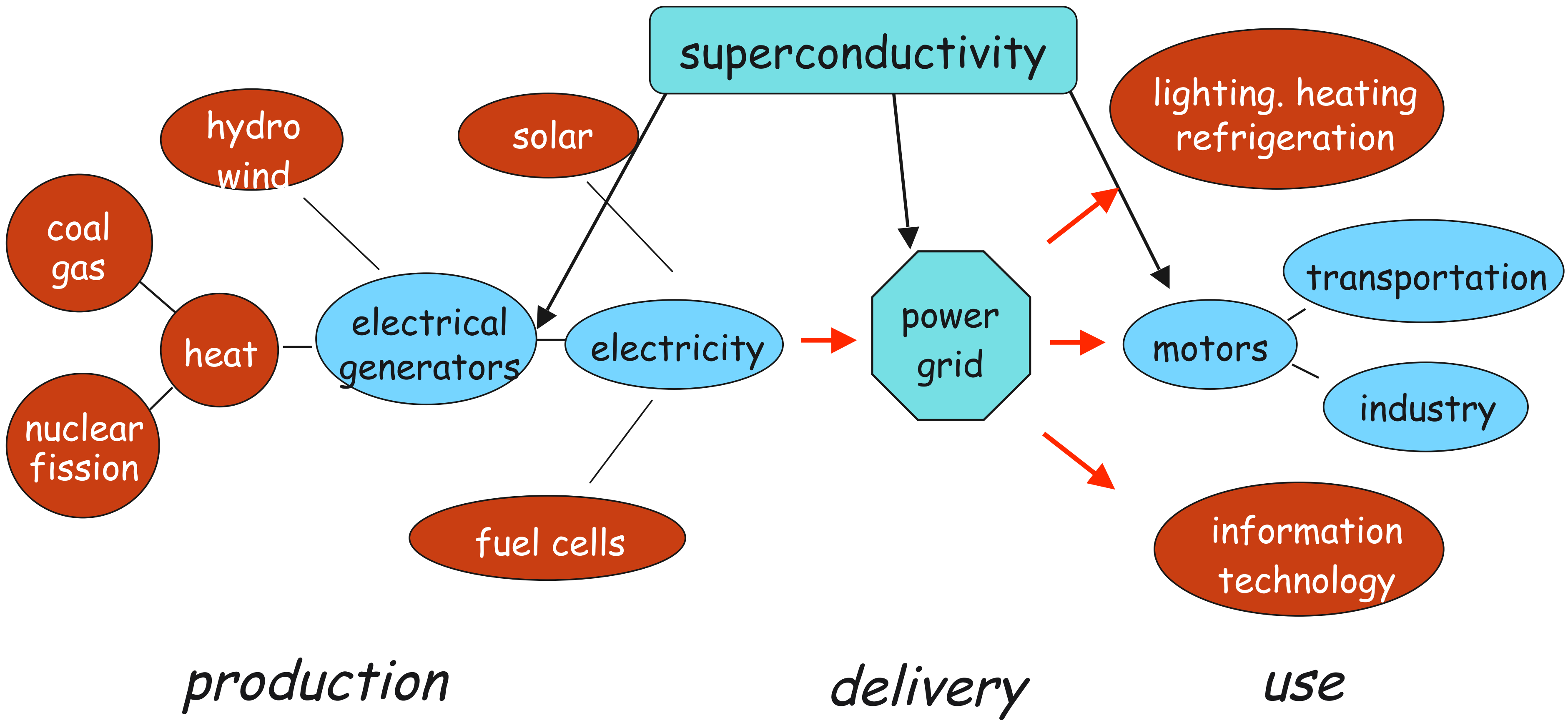
Grand Challenges in Electric Power

- Demand growing relentlessly, doubling by 2050, tripling by 2100, plus need to reduce dependence on foreign oil and to cut CO_2 emissions
  - **Need a major enhancement in overall electric energy efficiency**
    - *Increasing grid efficiency*
    - *Electrification of transportation*
    - *Reurbanization*

- Power outages and disturbances cost >10B$ per year
  - **Need a secure and ultra-reliable grid**

- Environmental issues growing
  - **Assure an environmentally clean energy infrastructure**

Superconductors: In the Right Place at the Right Time for Major Role in Upgrading the Electric Energy System



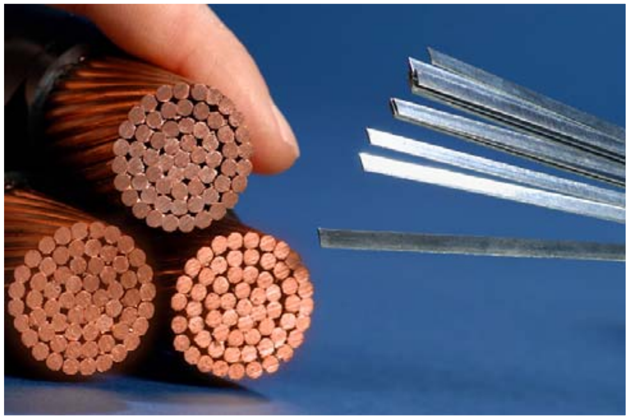
First Round: Low Temperature Superconductors ($Max\ T_c$ 23 K): NbTi, Nb_3Sn

- Widely and successfully used for high energy physics, MRI, laboratory magnets…
- For electric power? - many LTS demonstrations
  - Ac cable - Brookhaven Nat'l Lab
  - Dc cable - LANL
  - Motors, generators - Westinghouse, Siemens, GE, Alstom, Super-GM (Japan)
  - Fault current limiters - ABB, Toshiba, Alcatel-Alsthom
- Only commercial LTS electric power product - AMSC's 2.6 MJ SMES (Superconducting Magnetic Energy Storage)
  - Units installed in northern Wisconsin, Texas
  - Utility, industrial power quality focus now on reactive power

Key barriers: cost, cooling complexity, stability, contingency limit

Present Round: High Temperature Superconductors (BSCCO, YBCO, etc. – T_c up to 135 K)

HTS wire - 150x current and power density of copper



Pancake coil for motor rotor

1000 m reel of HTS wire commercially available

Coil for magsep solenoid magnet

HTS facilitates first generation of commercial superconductor power equipment

The Future: New Superconductors?

- MgB_2 – low cost, low anisotropy
  - Superconductivity discovered in 2001
  - Higher T_c (≤39 K) and H_{c2} than Nb_3Sn

- Future discoveries?
  - Ultra-high T_c
    - *As $\xi \sim \hbar v_F / kT_c$ gets smaller*
      - Flux creep barrier ~ ξ^n drops
      - Practical J_c drops
      - Grain boundaries barriers grow
    - *How can one design ultra-high T_c superconductors to be useful?*
  - Low anisotropy
  - Deformable materials

New discoveries will continue, opening new opportunities in energy

Enhancing Efficiency in the Electric Power Grid

- 7-10% of 1 Terawatt US electric power now lost in grid
  - Superconductor equipment could cut this by half, save 50 Gigawatts!
  - Reducing delivery bottlenecks even more impactful
    - *E. g. superconductor cables bringing 50%-efficient generation to cities, replacing 30%-efficient "reliability-must-run" generators*

- Dc supergrid: a radical leap in grid efficiency
  - Westinghouse's ac grid won out over Edison's dc grid
    - *Reduced I^2R loss by efficient transformers, high voltage*
  - Superconductors break this paradigm
    - *$I^2R = 0$ enables high dc current, low voltage*
  - Can we do even better in a hydrogen economy?
    - *Liquid hydrogen as cooling medium for supergrid (Grant-Starr)*

Enhancing Energy Efficiency by Electrification of Transportation

- Electric vehicles ~2x more energy efficient than gas in original BTU content of oil
  - *'A 5% penetration of plug-in vehicles in Manhattan will create a 50% increase' in rate of demand growth*

    - ConEd, 11/15/05
  - Superconductors key in enabling urban grids to handle this demand

- Maglev an efficient alternative to intracontinental aviation
- Military ship propulsion with HTS motors - 15% efficiency gain at half speed over conventional motors

Japanese Maglev flies with HTS coils, (courtesy CJR)

Enhancing Efficiency by Opening the Urban Power Bottleneck

- Reurbanization driven by rising energy costs
- Requires more power capacity in dense urban areas
- But overhead lines near impossible to permit, underground infrastructure clogged

New York then

New York now: it only gets worse!

Lower Manhattan underground infrastructure (Courtesy of Con Edison)

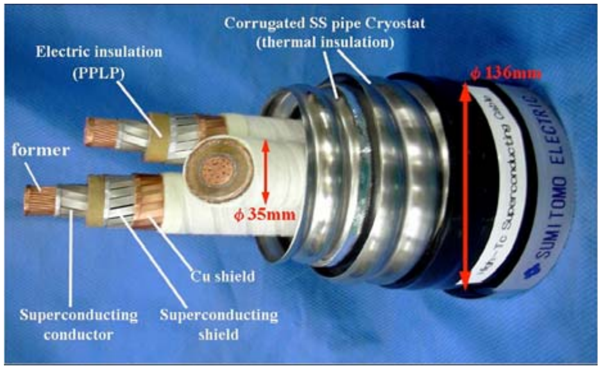
Getting Power in to Our Cities

Need underground power cables which are

- High capacity
- Compact, light – easy to install by retrofitting existing ducts or boring
- Non-interfering (no EMF or heat)
- Low voltage for easy permitting

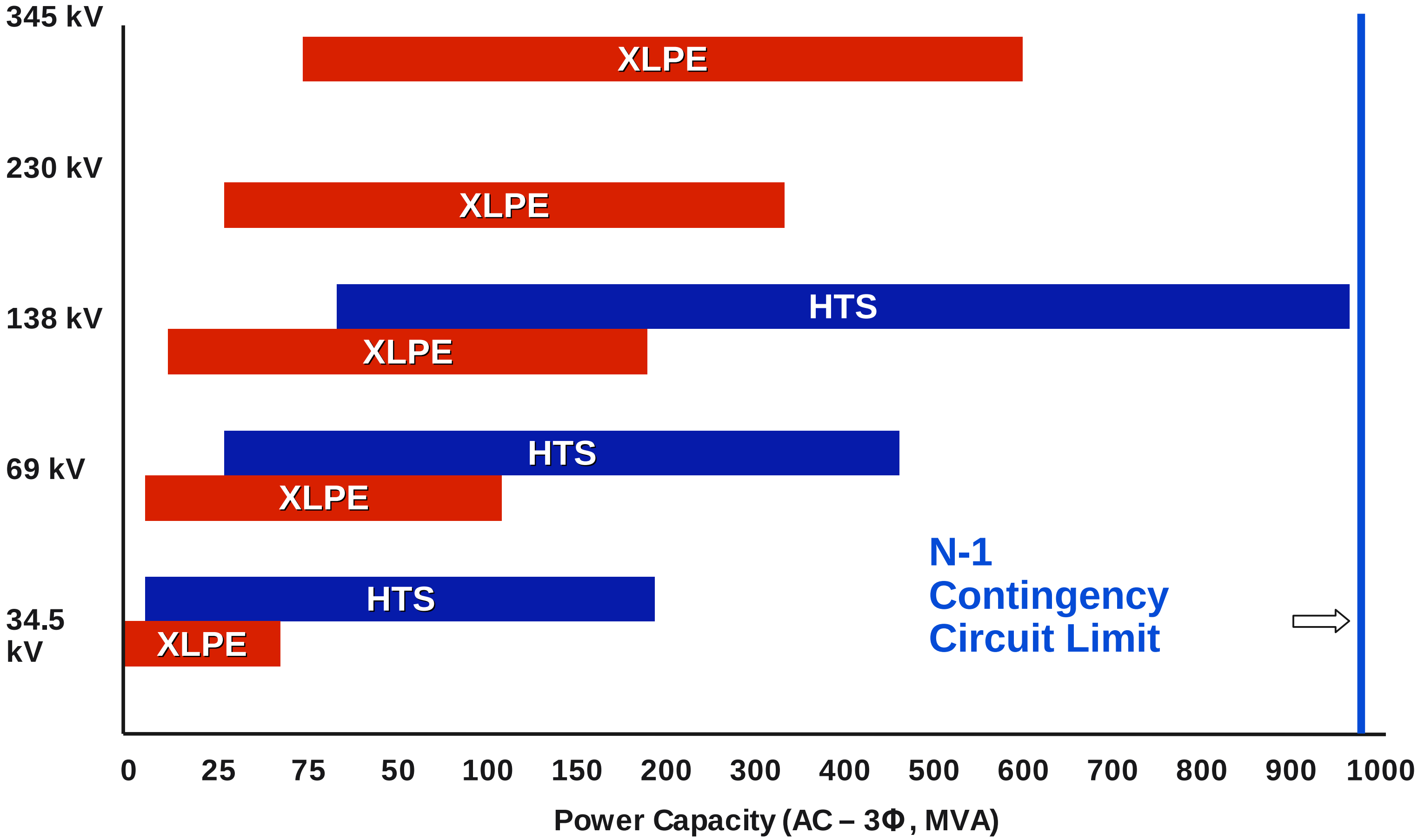
Superconductors - the ideal solution!

Detroit Edison cable installation (Courtesy, Pirelli)



HTS cable for Albany installation (Courtesy, SEI)i

HTS Cable Driver: 3-5x Power of Conventional XLPE Copper Cables at Lower Voltage



HTS enables more capacity at lower voltage; simplifies permitting

Major HTS Cable Demonstrations Underway

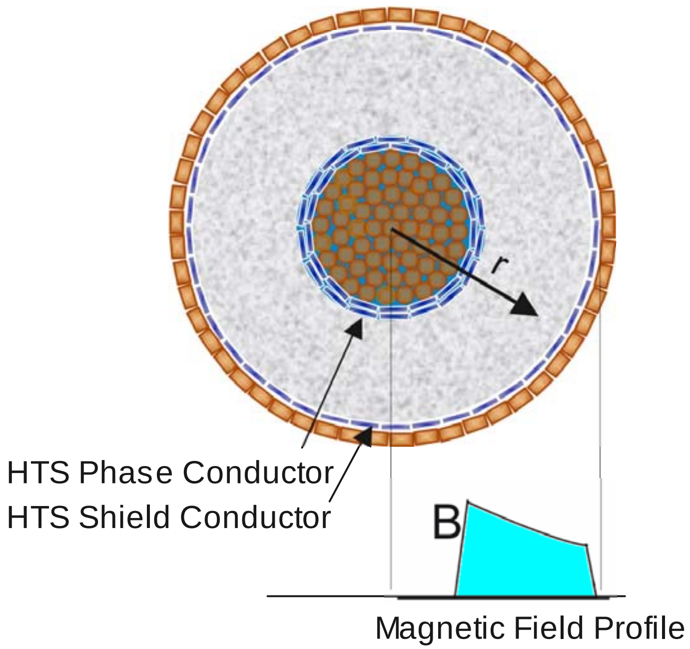
Terminations

HTS 3-phase cable

Bixby substation, AEP, Columbus OH
13.8 kV, 2400 A 200 m cable system
by Ultera (Southwire/nkt cables)
In-grid operation since July 2006

Establishing Secure, Reliable Grid: Overcoming Kirchoff's Laws

Grounded HTS cable shield conductor
- Full shielding – no EMF



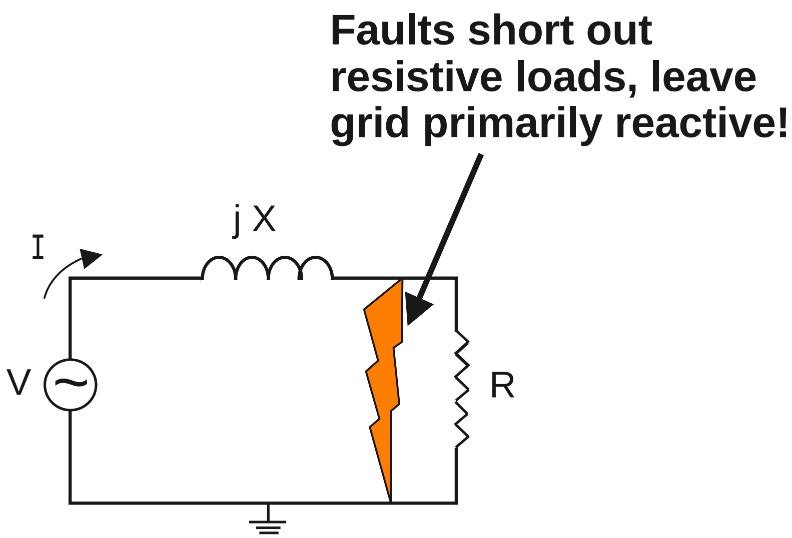
Low inductance enables economic ac current control with phase angle regulator

$$PowerFlow = \frac{(V_S)(V_R)\sin\theta}{Z}$$

PAR (courtesy, Mitsubishi)

Ac power flow control can revolutionize grid reliability

Establishing a Secure and Reliable Grid: Controlling Fault Currents in Urban Grids

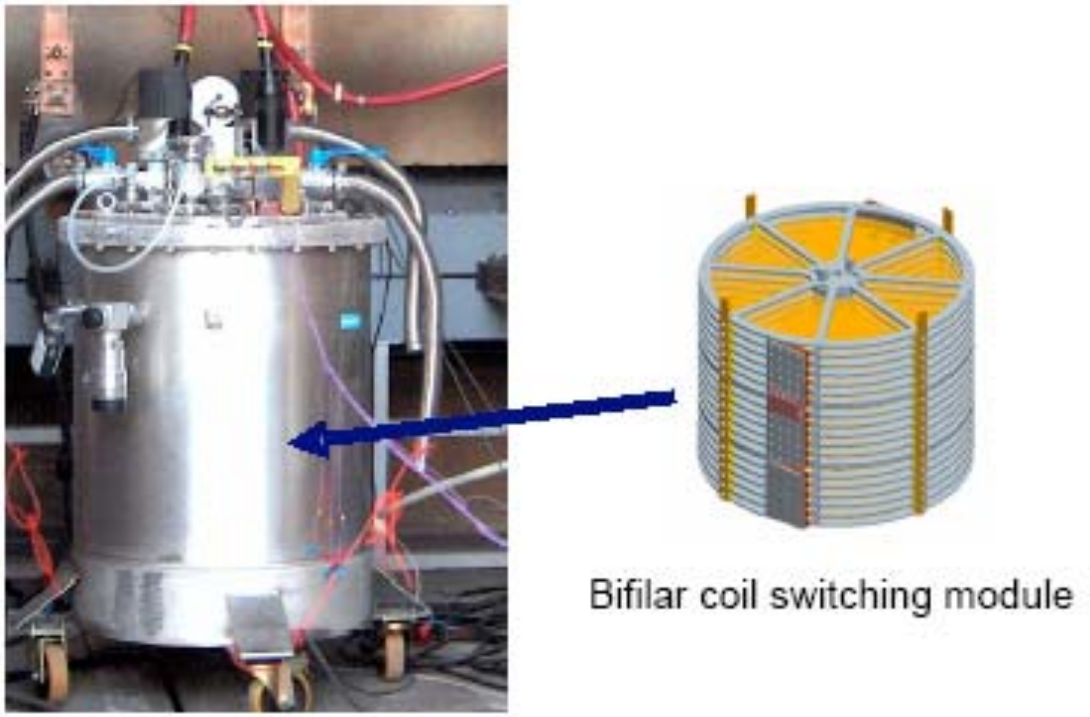


- Every added power source adds parallel output impedance
  - increases fault current
- In large urban grids, fault currents can exceed 60,000 A
  - approaching maximum breaker capability!

Need a solution, or must drastically reconfigure and break up the grid

Superconductors Enable "Resistive" Fault Current Limiters

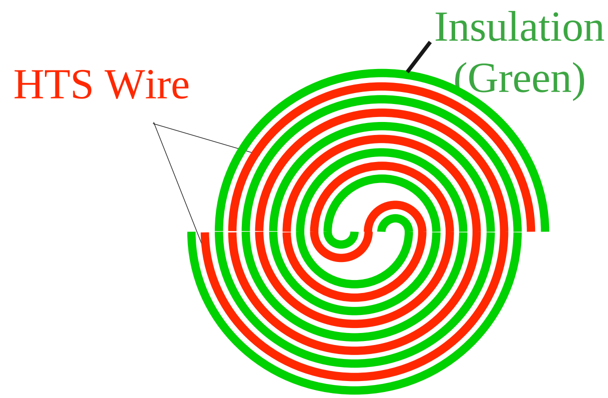
- Superconductors -"smart" materials, switch to resistive state above critical current
- Many FCLs prototyped around the world; challenge to make them scalable or economic
- New opportunity to design a practical FCL using 2G HTS wire (YBCO coated conductor)

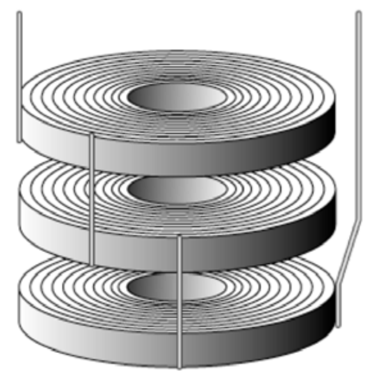


2.25 MVA, 13 kV class, resistive FCL,
28 kA short circuit current
reduced to 3 kA
(Siemens/AMSC, 2007)

Components for Cost-Effective Commercial Fault Current Limiter

Bifilar Coil





Stabilized

Low Inductance

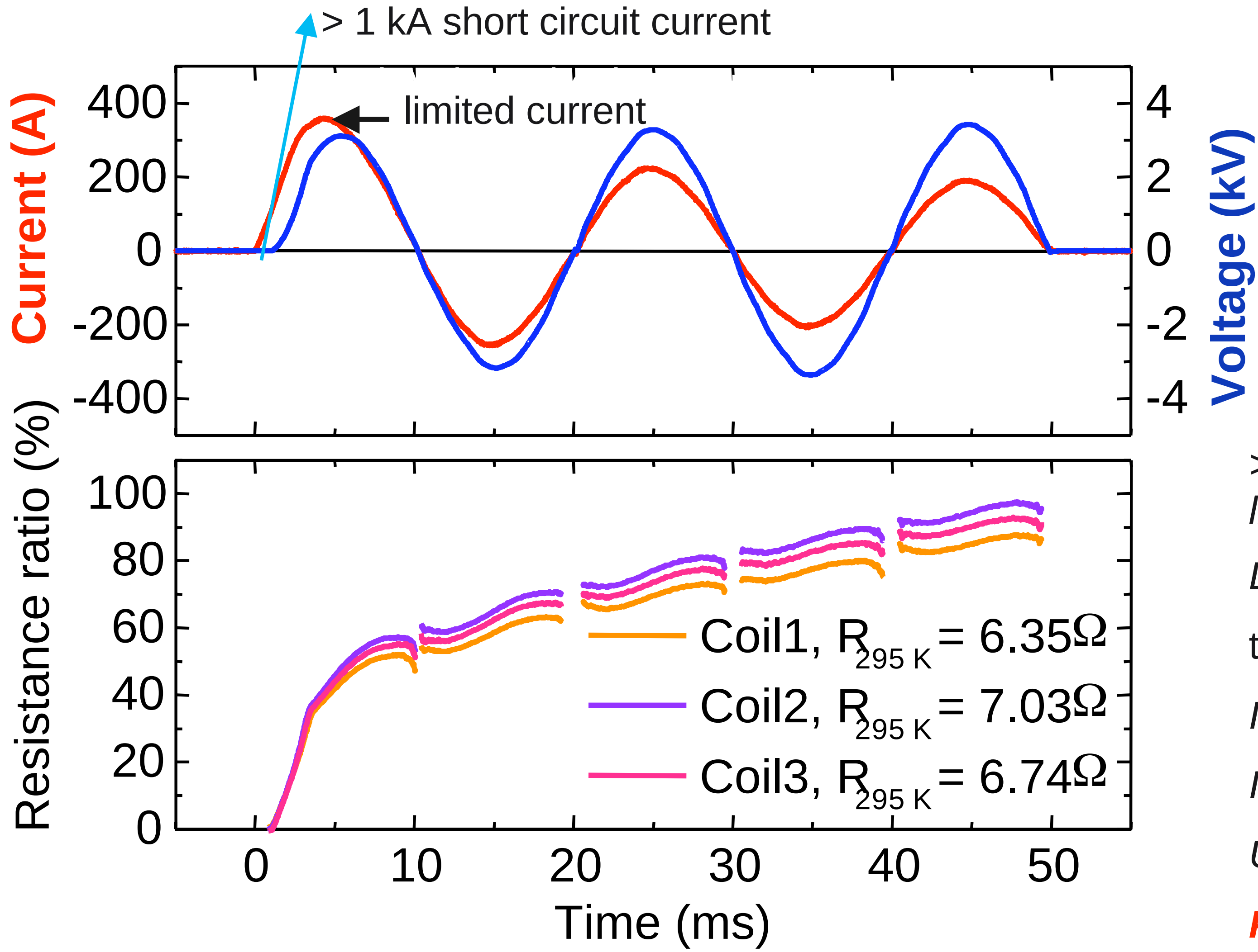
Module

2G HTS wire cross-section

Low-cost laminated stabilizer (stainless steel)

Coils connected in series and parallel to meet utility voltage and current specs

Example of Resistive FCL Switching Response



Why is limited current so much larger than Ic? Need study of dynamics in flux flow state

>1 kA short-circuit current limited to ~ 200 A_{rms}

L_{total} = 57 m

three coils in series

I_c = 70.7 A

I_{nom} = 50 A

U_{nom} = 2400 V_{rms}

P_{nom} = 120 kVA

Establishing a Secure and Reliable Grid: an Urgent Need

Significant power blackouts becoming all too frequent

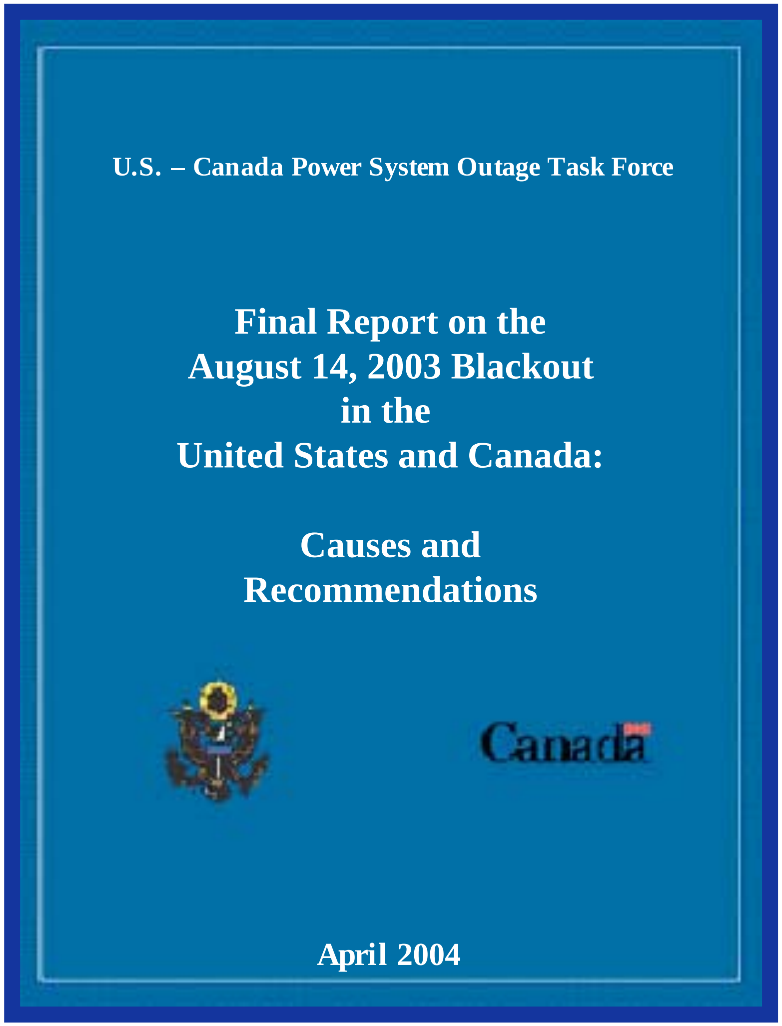
Inadequate Reactive Power: a Critical Weakness of the US Grid

- "…the blackout on August 14, 2003 was preventable. It had several direct causes and contributing factors including:

  #1. Failure to maintain adequate reactive power support..."

- Reactive power measured in "VARs"

- Think VARs


U.S. – Canada Power System Outage Task Force

Final Report on the August 14, 2003 Blackout in the United States and Canada:

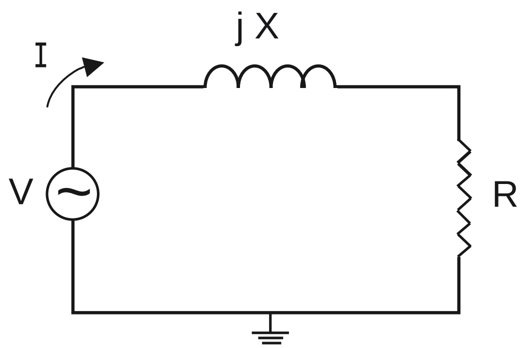
Causes and Recommendations

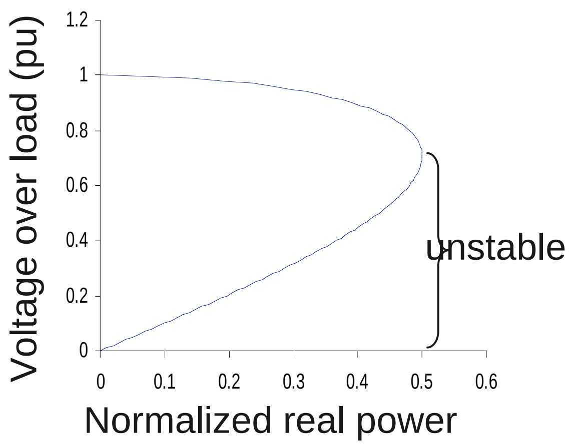
Canada

April 2004

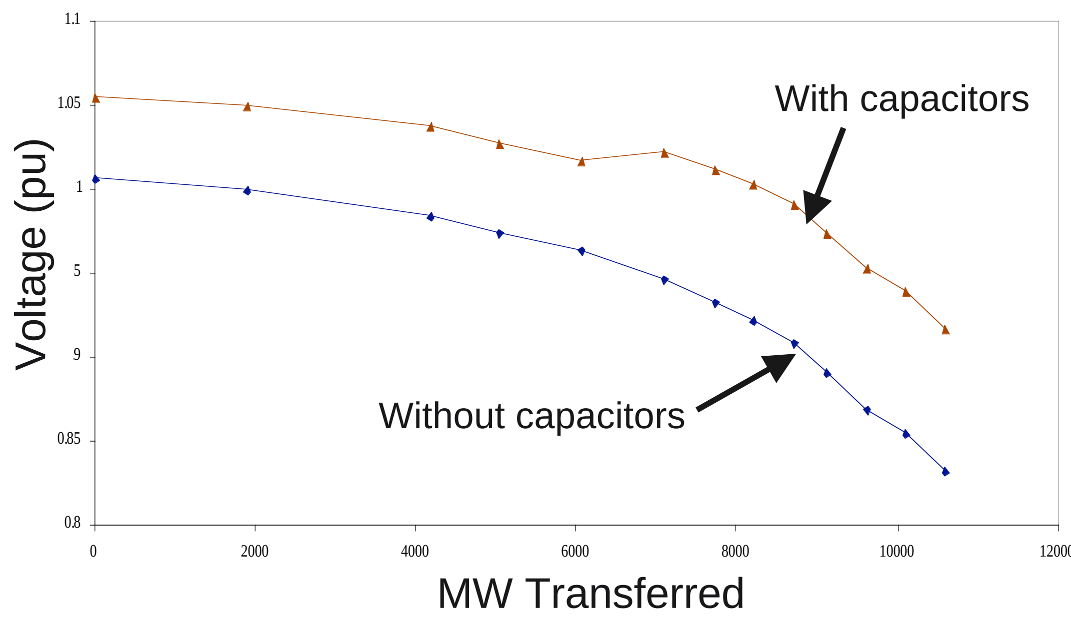
Voltage Collapse from Inadequate Reactive Power: "Nose Curve"

a) Simple model:





b) Real case (courtesy of D. Bradshaw, TVA)

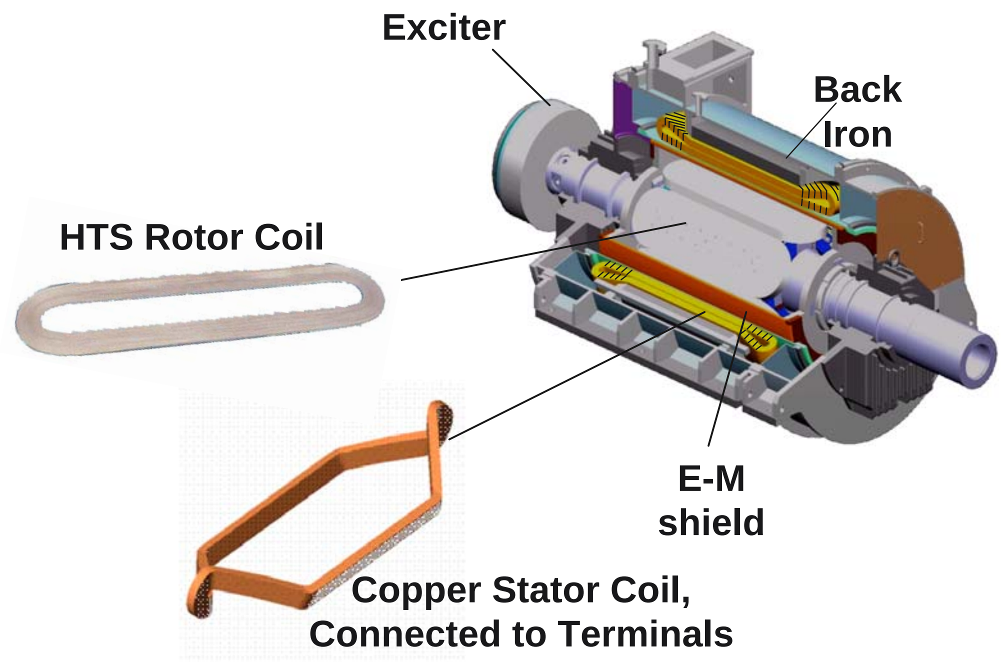


Need dynamic compensation of VARs for grid stabilization

HTS Dynamic Synchronous Condenser for Grid Stabilization

- Synchronous condenser: rotating machine - generator without prime mover
  - Injects either capacitive or inductive VARs into grid for
    - *Power factor correction*
    - *Instantaneous mitigation of voltage disturbances*

- HTS system solves key limitations of conventional copper-based synchronous condenser
  - Compact rotor coils enable high VAR output in small frame: lowers $/kVAR
  - Compact system, easily sited
  - Superconductors eliminate thermal fatigue from cycling rotor coil current – main source of failure of conventional systems



HTS Rotating Machinery Progress

- Synchronous condenser builds on rapidly progressing HTS motor technology

36.5 MW AMSC ship propulsion motor in assembly at Navy facilities

- ±8 MVAR AMSC synchronous condenser successfully tested at TVA substation
- Two ±12 MVAR commercial units on order

8 MVAR synchronous condenser

Synchronous condenser - world's first commercial HTS product for power grid

Assuring an Environmentally Clean Electric Power Infrastructure

- Superconducting power equipment avoids use of oil – a contaminant and fire hazard
- Closed cycle liquid nitrogen and/or cryocoolers
  - Non-contaminating
  - Non-flammable
- Superconductor's high efficiency reduces unnecessary pollution and CO_2 emission at energy source

Superconductivity – basis for a green and clean technology

If HTS is Already Moving to Commercialization, What Basic Research Remains to be Done?

- Most desired superconductor functionalities (high current density, robust mechanical properties) have already been achieved,
  - But still at too low a temperature
  - With processes which could be simplified

- The main challenge is:

COST

And cost translates quickly into a host of fundamental research challenges

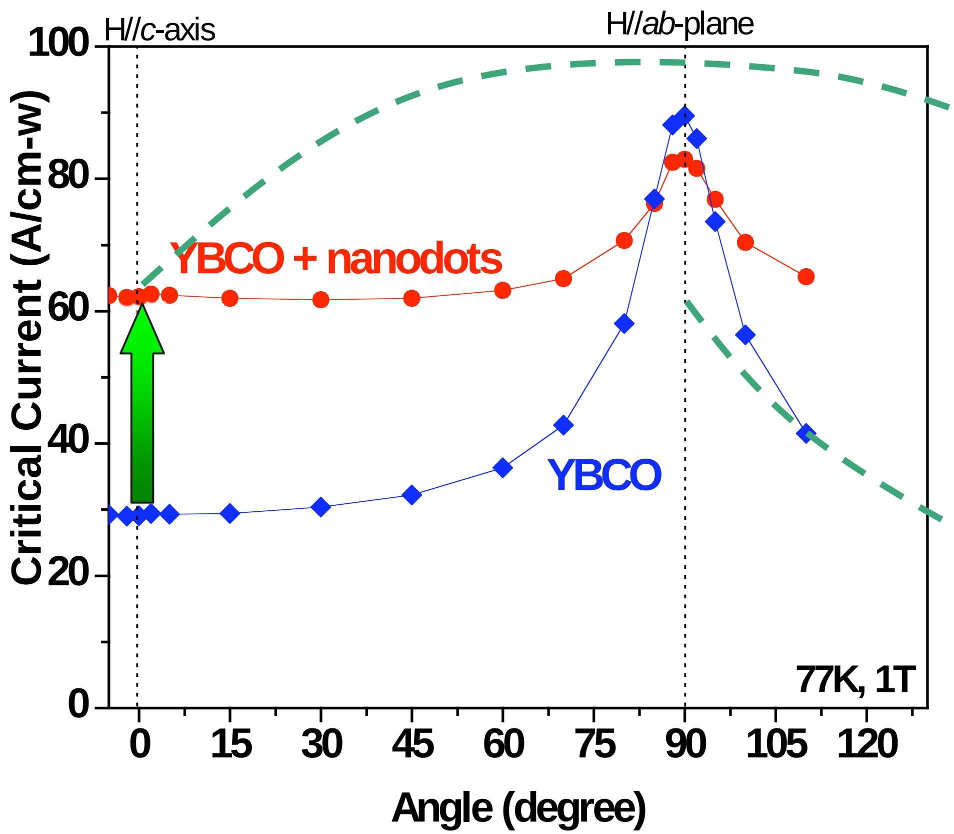
Basic Research Needs

- Lowering cost by reducing $/kAm: lower cost processes, higher I_c
  - 1G HTS wire now $150/kAm
  - Copper in cable:$30-65/kAm
  - DOE goal: $10/kAm
  - 2G HTS wire (YBCO coated conductor) – on path to beat copper

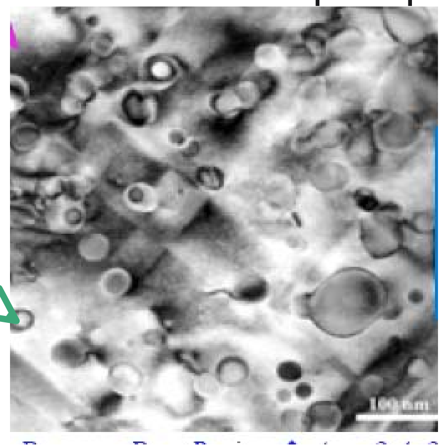
- Lowering cost by reducing cryogenic requirements
  - Higher temperature operation
    - *Enable YBCO 65-77 K operation in field*
      - Improved pinning
      - Reduced grain boundary current limitation
    - *Higher temperature superconductors*
  - Lower ac loss

- Assuring reliability through electrical, thermal stability to overcurrents, defects
  - Conducting buffer layers in 2G HTS wire architectures
  - Understanding high current, flux flow behavior, hot spots

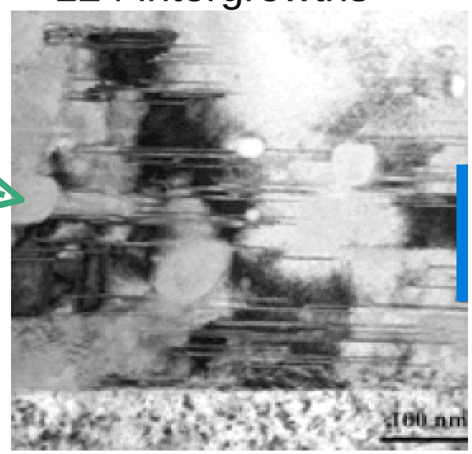
Complex Field-Angle-Dependent Pinning Phenomena in YBCO Coated Conductors



"Nanodots" – oxide precipitates



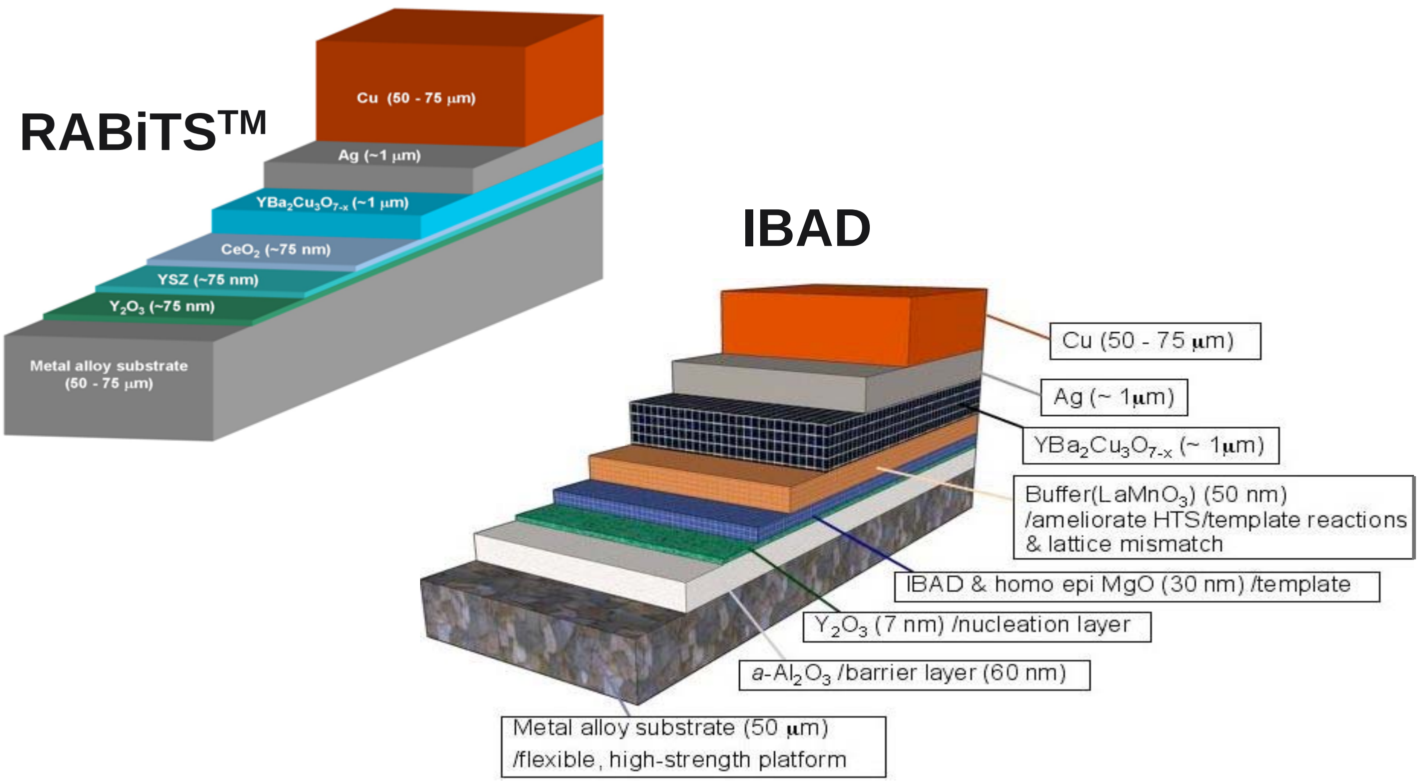
124 intergrowths



Basic research needed to understand and control pinning

Basic Research Needs: Lowering Wire Cost by Fundamental Process Improvements

2G HTS wire (YBCO coated conductor) architectures have many layers!



Must simplify architectures, invent new and simpler texturing approaches

Summary

- Superconductivity is in the right place at the right time to address grand challenges of energy delivery and use:
  - Major increase in energy efficiency and capacity
    - *Higher efficiency grid equipment*
    - *Electrification of transport*
    - *Breaking power bottlenecks for reurbanization*
  - Secure and ultra-reliable grid through
    - *Power flow control*
    - *Fault current control*
    - *VAR management*
  - Environmentally green and clean technology

- HTS electric power equipment revolution is starting, but full impact hinges on enhanced performance and cost reduction facilitated by basic research

Superconductivity research critically needed to fully meet the grand challenges