Superconductivity:

Challenges and Opportunities

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Wai-Kwong Kwok, Argonne

<u>Outline</u>

Energy Challenge - BRN Workshops

Grid Challenges

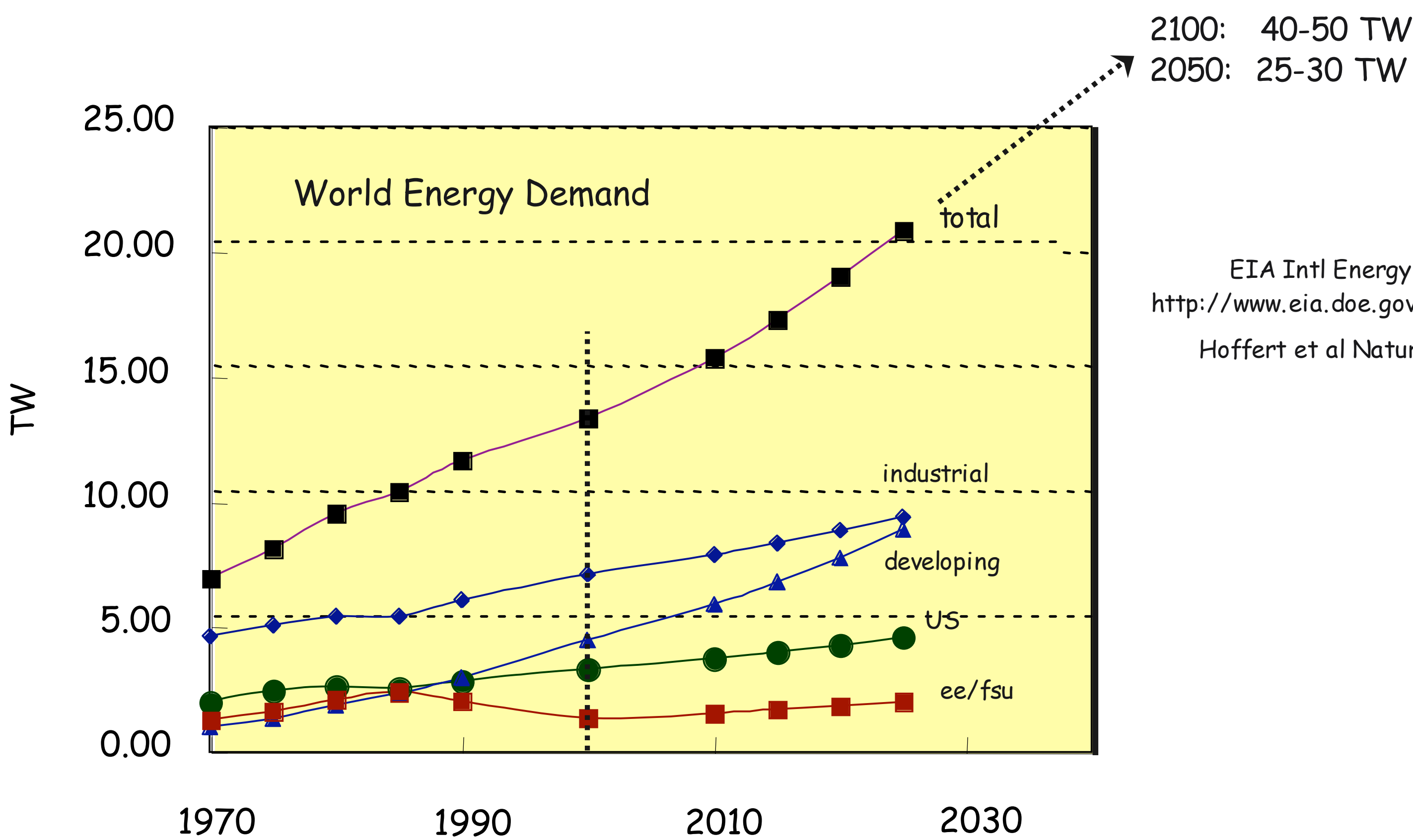
Superconductivity Solutions

Transformational Needs

BES-EDER Opportunities

APS March Meeting
March 6, 2007

The Energy Challenge



EIA Intl Energy Outlook 2004
http://www.eia.doe.gov/oiaf/ieo/index.html

Hoffert et al Nature 395, 883,1998

Double demand by 2050

Triple demand by 2100

Challenge for production, delivery and use

BES Basic Research Needs Workshops

2003

2003

2005

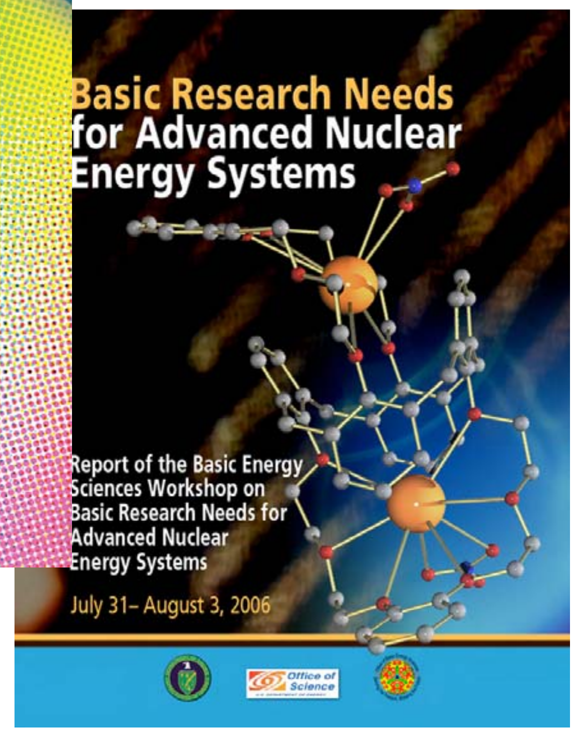
"Considering the urgency of the energy problem, the magnitude of the needed scientific breakthroughs, and the historic rate of scientific discovery, current efforts will likely be too little, too late. Accordingly, BESAC believes that a new national energy research program is essential and must be initiated with the intensity and commitment of the Manhattan Project, and sustained until this problem is solved."

BESAC Report, February 2003

BES Basic Research Needs Workshops 2006

May 2006

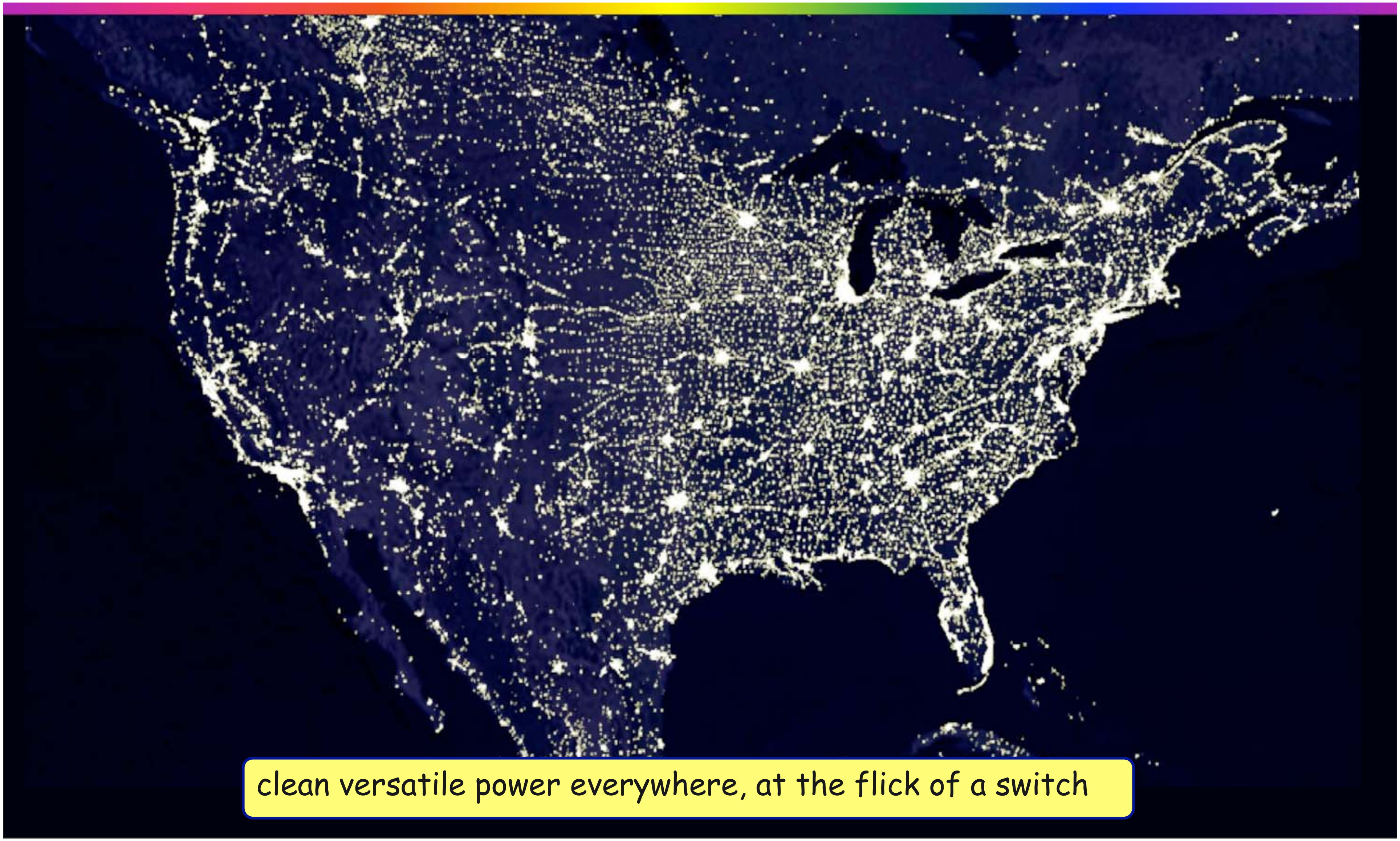
May 2006



August 2006

http://www.sc.doe.gov/bes/reports/abstracts.html

The Grid - the Triumph of 20th Century Engineering



clean versatile power everywhere, at the flick of a switch

The 21st Century: A Different Set of Challenges

capacity

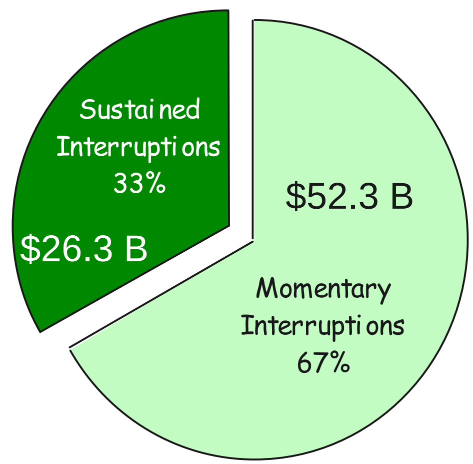
growing electricity uses
growing cities and suburbs
high people / power density
urban power bottleneck

2030
50% demand growth (US)
100% demand growth (world)

reliability
power quality

average
power loss/customer
(min/yr)

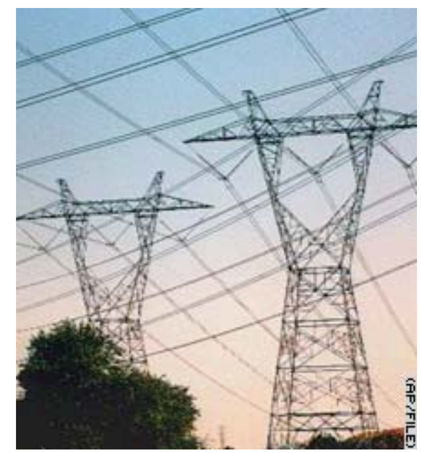
US	214
France	53
Japan	6



$79 B economic loss (US)

LaCommare & Eto, Energy 31, 1845 (2006)

efficiency
lost energy



62% energy lost in production / delivery

8-10% lost in grid

40 GW lost (US)
~ 40 power plants

2030: 60 GW lost
340 Mtons CO_2

BES Workshop on Superconductivity, May 8-11, 2006

Workshop Co-chair: John Sarrao, LANL
Co-chair: Wai-Kwong Kwok, ANL

Panel Chairs

Materials: I. Bozovic (BNL)
Phenomena: J.C. Davis (Cornell)
L. Civale (LANL)
Theory: I. Mazin (NRL)
Applications: D. Christen (ORNL)

Plenary Speakers

Paul Chu, Alex Malozemoff, George Crabtree,
Mike Norman, Z.X. Shen

Pat Dehmer, DOE-Basic Energy Sciences
Jim Daley, DOE-Electricity Delivery and Energy Reliability

Workshop Charge

"identify basic research needs and opportunities in superconductivity with a focus on new, emerging and scientifically challenging areas that have the potential to have significant impact in science and energy relevant technologies"

Participants
~ 100 researchers, representing
7 countries, 9 national labs,
28 universities, spanning
basic and applied research

BES Workshop Report

Electricity is our most effective energy carrier

- *Clean, versatile, switchable power anywhere*

Power grid cannot meet 21st century challenges

- *Capacity, reliability, quality, efficiency*

Superconducting technology is poised to meet the challenge

Present generation materials enable grid connected cables and demonstrate control technology

Basic and applied research needed to lower cost and raise performance

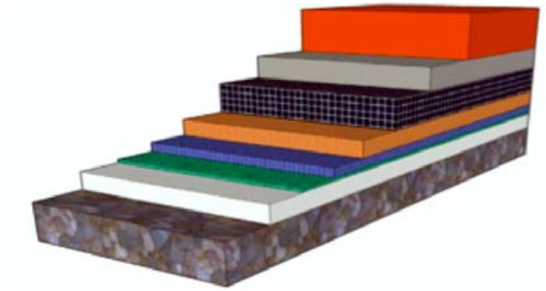
High risk-high payoff discovery research for next-generation superconducting materials

- *Higher temperature and current capability*
- *Understand fundamental phenomena of transition temperature and current flow*

http://www.sc.doe.gov/bes/reports/abstracts.html#SC

Research Challenges and Opportunities

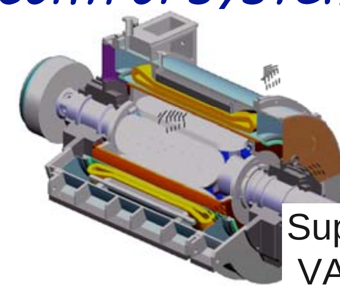
Superconducting Cable



Superconducting Power Control

Smart, self-healing control systems

SC-FCL

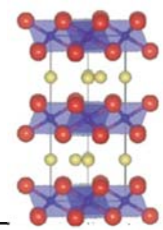


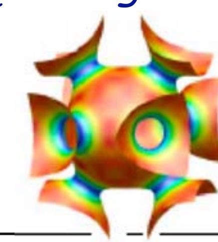
Super VAR

Control Vortex Matter

Next Generation Materials

Higher T_c and J_c in magnetic field





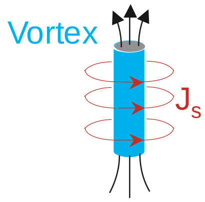
The Key: Superconducting Materials

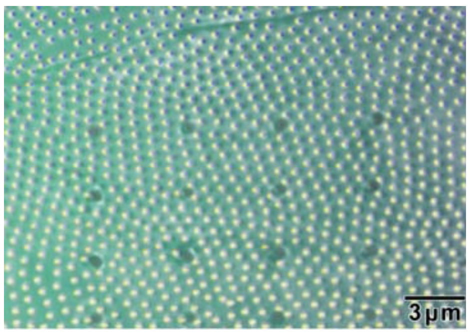
	1G 'multi-filament wire'	2G 'coated conductor'	"3G" 'enhanced pinning'	Transformational New Materials
Self-field cable	3x copper	5x copper	5x copper	10x copper
H = 0.1- 1 T transformers	0.2x copper @77K	1x copper @77K	2x copper	5x copper
H = 1- 5 T rotating machines	0.01x copper @77K	0.1x copper @77K 1x copper @ 65K	1 x copper	5x copper
Anisotropy	> 100	7	1	low
Key Issues	high materials cost: Ag	high process cost: multi-layer architecture	isotropic structure, pinning, and critical current	low materials/ process cost: simple architecture
Operating Temperature	self-field: 77 K in field: 30 K	self-field: 77 K in-field: 50 K	100K 77 K	200 K - room 200 K

next generation superconductors needed to transform the grid

Control Vortex Matter: a multi-scale challenge

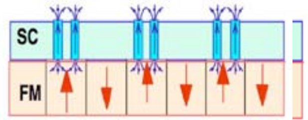
Vortex: nano-sized quantum of magnetic flux



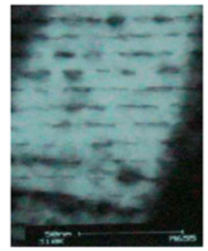


Determines the full electro-magnetic behavior of superconductors

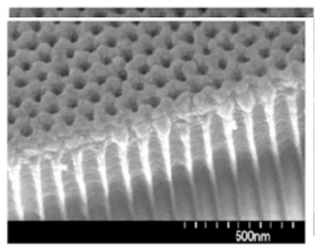
Novel Pinning Schemes



Magnetic pinning arrays

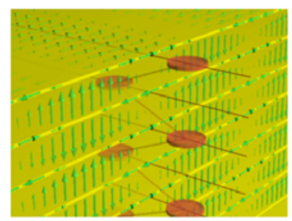


Facilitate isotropic pinning



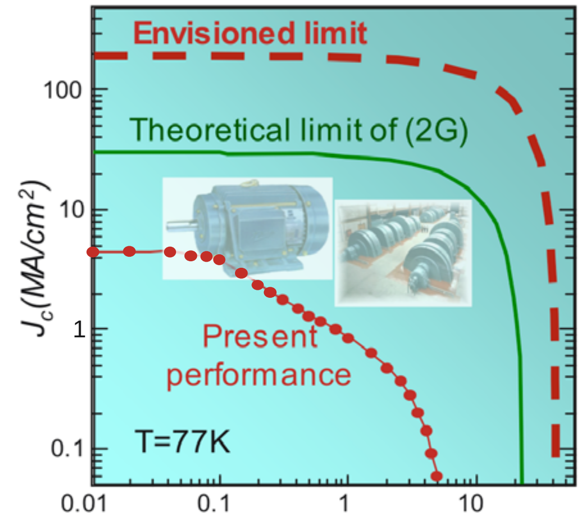
Self-assembled nano pin sites

Crossing vortex lattices



Goals…

Achieve highest J_c



Learn to control the behavior of vortex matter from nano to bulk behavior

Next Generation Materials

~ 50 copper oxide superconductors

Highest Tc = 164 K under pressure

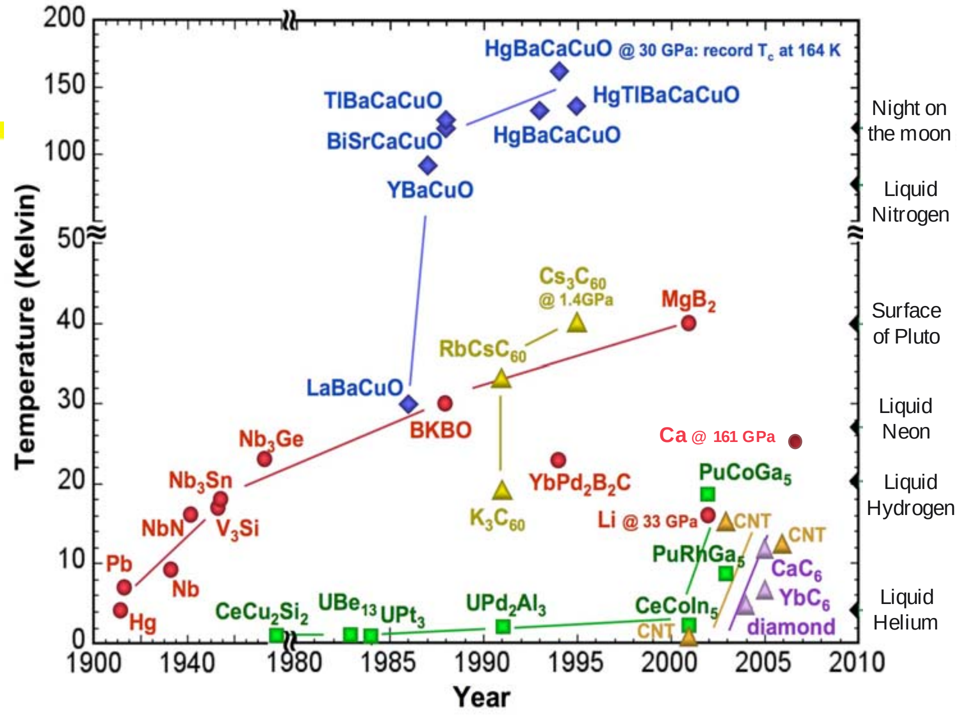
(1/2 Room Temp)

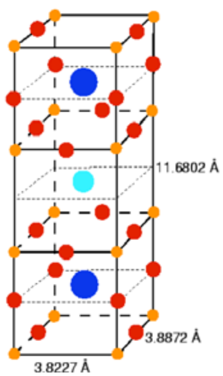
Only class of high T_c superconductors ?

High T_c superconductors $\geq$ 4 elements

55 superconducting elements

-> 55^4 ~ 10 million quaternaries





Search strategies for new superconductors

- Quaternary and higher compounds
- Layered structures
- Highly correlated normal states
- Competing high temperature ordered phases

Target Properties

Higher Tc &

Jc

isotropy

Ductility

…

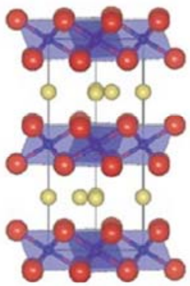
Challenge

Discover next generation complex superconductors

Superconductors by Design

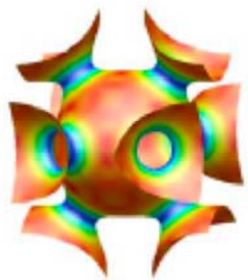
Discovery by serendipity: Hg (1911), copper oxides (1986), MgB_2 (2001), $NaCoO_2{:}H_2O$ (2003)

Discovery by empirical guidelines: competing phases, layered structures, light elements, . . .
B-doped diamond (2004), CaC_6 (2005)



Crystal Structure
Composition

+



Electronic Structure
Density functional theory

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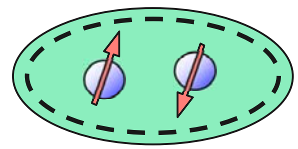
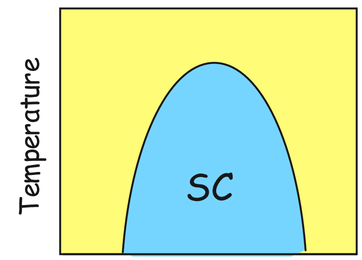


Pairing Mechanism
phonons (classical BCS)
spin fluctuations
valence fluctuations

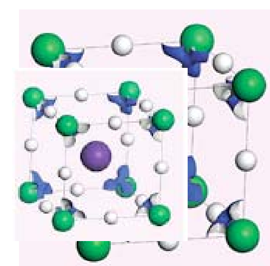
=



Superconductivity

Computationally designed superconductors

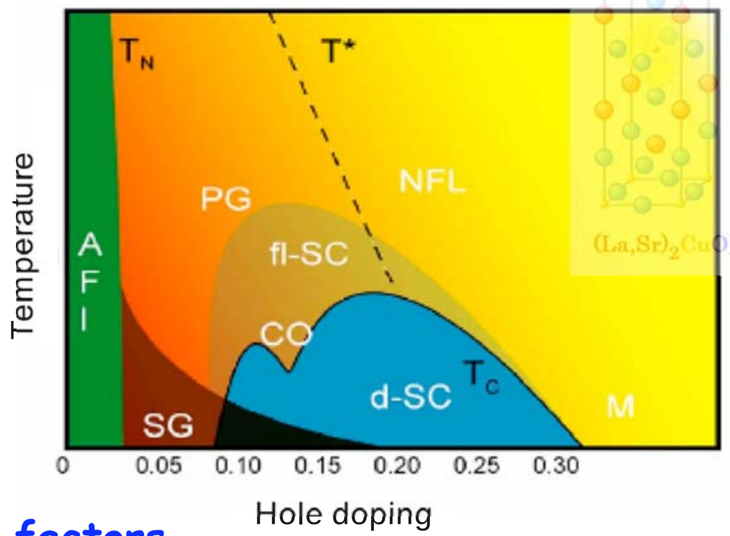
- Electronic structure calculation by density functional theory
- Large scale phonon calculations in nonlinear, anharmonic limit
- Formulate "very strong" electron-phonon coupling (beyond Eliashberg)
- Determine quantitative pairing mechanisms for high temperature SC



J. Mater. Chem., 2006
Computed metal hydride superconductor

Challenge: Create a paradigm shift to superconductors by design

Find the Superconductivity Mechanisms



Higher T_c / New Mechanisms

High temperature "fluctuating superconductivity"

in the pseudo-gap region and 'normal state' vortices?

p-, d-wave Cooper pairing

Two band superconductivity

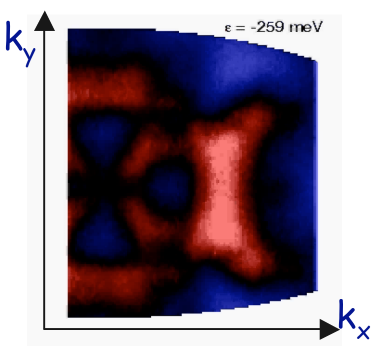
multiple pairing mechanisms

Relate superconductivity to neighboring normal phases

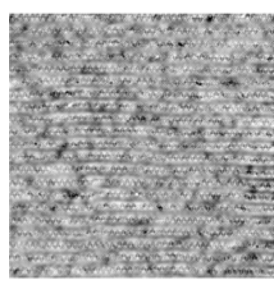
Find the simplifying emergent concepts

"Map the genome" of high T_c: find the controlling factors

Using new tools with unprecedented resolutions

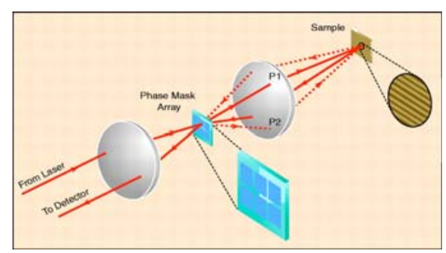


ARPES

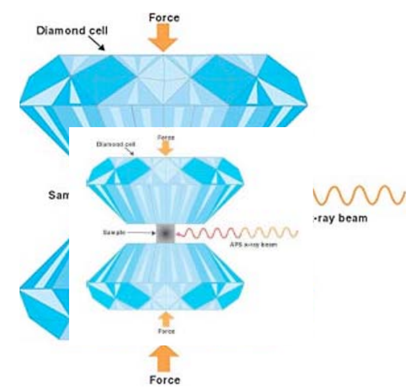


600 Å

STM



Pico-sec Spectroscopy



Extreme Envrionments

Grand Challenges of Superconductivity:
new materials & phenomena

Achieve a paradigm shift from materials by serendipity to materials by design

Predict and control the electromagnetic behavior of superconductors from their microscopic vortex and pinning behavior

Discover the mechanisms of high-temperature superconductivity

Transform the power grid to deliver abundant, reliable, high-quality power for the 21st century

- first steps within reach
- full transformation requires breakthrough basic research

Superconductivity Research Continuum

Discovery Research	Use-inspired Basic Research	Applied Research	Technology Maturation & Deployment
▪ Room-temperature superconductor *(Grand Challenge)* ▪ Superconductors by design *(Grand Challenge)* ▪ Atomic scale control of materials structure and properties ▪ Tuning competing interactions for new phenomena ▪ Unravel interaction functions generating high temperature superconductivity ▪ Predictive understanding of strongly correlated superconductivity ▪ Microscopic theory of vortex matter dynamics ▪ Nano-meso-scale superconductivity	▪ **100K isotropic SC *(Grand Challenge)*** ▪ **Achieve theoretical limits of critical current *(Grand Challenge)*** ▪ **3-d quantitative determination of defects and interfaces** ▪ **Intrinsic and intentional inhomogeneity** ▪ **"Pinscape engineering" and modeling of effective pinning centers** ▪ **Next Generation SC wires**	▪ Technology Milestones: ➢ **2G coated conductor carrying 300 A x 100 m (2006)** ➢ **In-field performance for 50 K operating temperature** ➢ **electric power equipment with ½ the energy losses and ½ the size** ▪ **wire with 100x power capacity of same size copper wires at $10/kiloamp-meter.** ▪ **Assembly and utilization R&D issues** ▪ **Materials compatibility & joining issues**	▪ Cost reduction ▪ Scale-up research ▪ Prototyping ▪ Manufacturing R&D ▪ Deployment support
Office of Science BES		Technology Offices EDER	

Perspective

Electricity is our most effective energy carrier - clean, versatile, pervasive

The grid cannot meet 21^{st} challenges: *capacity, reliability, quality, efficiency*

Superconductivity has solutions:

- Cable: five-fold or more increase in capacity
- Power control: Smart, self-healing control of faults and reactive power
- Safe, small, efficient transformers for urban power bottleneck

Research challenges:

- 10-fold increase in critical current, 10-100 fold reduction in cost
- Understand dynamics of vortex matter, mechanism of superconductivity
- Discover new materials: higher transition temperatures, lower anisotropy
- Paradigm shift: superconductors by serendipity $\Rightarrow$ superconductors by design

Superconductivity is "Pasteur's science" - fundamental breakthroughs drive applications

How can you help?

Read the workshop report; feedback welcome

Help spread the message, especially the sense of urgency

Articulate grand challenges to the left of the four-column chart